THE ROLE OF WEATHER AND TOPOGRAPHY IN THE AIRBORNE DISPERSAL OF PARTICULATE MATTER IN KENT

VIRGINIA NICOLÁS PEREA

A thesis submitted in partial fulfilment of the requirements of the University of Greenwich for the Degree of Doctor of Philosophy

2011

Declaration

"I certify that this work has not been accepted in substance for any degree, and is not concurrently being submitted for any degree other than that of Doctor of Philosophy being studied at the University of Greenwich. I also declare that this work is the result of my own investigations except where otherwise identified by references and that I have not plagiarised the work of others".

Student's signature_____ Date _____

Supervisor's signature_____ Date _____

Acknowledgements

There are many individuals who contributed to the production of this thesis through their moral support, advice or participation. I would like to express my most sincere gratitude to them all.

I am indebted to Dr. Peter Burt for his patience, careful supervision and encouragement throughout the years. It has been both a privilege and a pleasure to have experienced the opportunity to be taught by such an extraordinary person. I sincerely thank you for being the sort of supervisor every student needs - supportive, enthusiastic and inspiring.

The first two years of this research were financed by Inter-reg III grant under the European Regional Development Fund (ERDF). I would like to thank the Natural Resources Institute for providing financial support during my last PhD year. I am grateful to all the staff in the NRI for their moral support and understanding all the way through, especially to Professor Andrew Westby, Katy Oliver and Dudley Farman.

I would also like to extent my gratitude to the Kent County Council and the Environmental Research Group (ERG) at King's College London, for providing us with the data to produce this thesis.

I would like to thank my family and friends for their understanding, encouragement and support over the years of my candidature. I am a very fortunate to count with some many amazing people in my life. To Genaro, Alberto, Vane, Maria Elena, Rocío, Leticia, Gaelle, Laura, Iñaki, Puy, Billy, Gemma and Wane for your friendship and your unconditional encouragement all the way through. To my siblings, mi little gorriona Loles and Manolín for making me realise that if you believe, you can (just need to want it bad enough). To my parents in law, Dave and Jackie, for always being so supportive and encouraging. I am very grateful to my parents, Loli y Manolo, for pushing me always to go further and never stop dreaming!

My husband Chris has always been the greatest support through the whole process, encouraging me to keep going when frustration and other problems drained my motivation. His support not only emotionally if not financially as well as his love, help and encouragement cannot be thanks enough.

Abstract

Local weather data (wind direction, wind speed and temperature) from meteorological stations and daily synoptic data have been examined in relation to airborne particulate material (PM_{10}) concentrations recorded at 17 pollution monitoring sites throughout Kent for the period 2000 to 2008, as an aid to understanding dispersal patterns in relation to topography.

In general, local and synoptic wind direction patterns followed the same trends: the yearly distribution is dominated by southwesterly winds, followed by winds from the west and the northwest. Detailed analysis of local wind patterns at four sites (two coastal and two inland) strongly suggested the presence of seas breezes, reaching maximum frequency between March and August and fewest occurrences between November and February. Transport of PM_{10} over 30 km inland was also inferred.

In addition to local wind transport, the location of the pollution monitoring sites and their environment are key to explaining the differences in PM_{10} concentrations recorded between the sites. The 10 sites located on roadsides registered the highest number of particle counts, followed by the five sites located within urban areas. The lowest amount of particles was found at the two rural sites. The five roadside sites closest to London (two in Gravesham and three in Dartford) exceeded the daily recommended amount of 50 $\mu g/m^3$ several times each month, probably reflecting the increased road traffic in those areas.

Aside from the variation in PM_{10} amount between sites, seasonal differences were also observed, with the lowest amount of PM_{10} recorded in the autumn and the highest in spring.

Episodes of pollution affecting the whole of Kent were also observed. These were more clearly related to the synoptic situation rather than any local wind variations and appear to indicate regional or trans-boundary pollution transport. The latter is also supported by preliminary evidence from a PM_{10} trap sampling at a site on the south coast.

Table of Contents

List of Tables

List of Figures

List of Appendices

Acronyms

ASEAN	Association of Southeast Asian Nations
APEG	Airborne Particles Expert Group
AQMA	Air Quality Management Areas
BAF	British Aerobiology Federation
BVST	Burkard Volumetric Spore Trap
CRP	Committee for Research Particles
DEFRA	Department for Environment, Food and Rural Affairs
DETR	Department of Environment, Transport and the Regions
E	East (referring to the cardinal point or wind direction)
EPAQS	Expert Panel on Air Quality Standards
EPA	Environmental Protection Agency (USA)
ERG	Environmental Research Group (Kings College)
EU	European Union
GMT	Greenwich Meridian Time
HMSO	Her Majesty's Stationery Office
KAQP	Kent and Medway Air Quality Partnership
KCC	Kent County Council
KEAQP	Kent Air Quality Partnership
LAQM	Local Air Quality Management area
N	North (referring to the cardinal point or wind direction)
NAEI	National Atmospheric Emissions Inventory
NARSTO	North American Research Strategy for Tropospheric Ozone
NETCEN	National Environmental Technology Centre
NE	Northeast (referring to the cardinal point or wind direction)
NW	Northwest (referring to the cardinal point or wind direction)
PM	Particulate Matter
PM_{10}	PM_{10} stands for Particulate Matter of less than 10 millionths of a metre (10 micrometers or 10 um) in diameter

RPAPM	Research Priorities for Airborne Particulate Matter
SEIPH	South East Institute of Public Health
S	South (referring to the cardinal point or wind direction)
SE	Southeast (referring to the cardinal point or wind direction)
SPM	Suspended Particulate Matter
SW	Southwest (referring to the wind direction)
UK	United Kingdom
UNECE	United Nation Economic Commission for Europe
USA	United States of America
W	West (referring to the cardinal point or wind direction)
WHO	World Health Organisation

Chapter 1

Introduction and thesis overview

1.1 General Introduction

This thesis reports the results of an investigation into the role of topography on the concentration and dispersal of airborne pollutants in the Southeast of England during the period 2000 to 2008. In recent years air pollution has become one of the main environmental issues concerning the population. One of the main areas of increased interest is anthropogenic (i.e. human-created) pollution, which is becoming a recognised health hazard, as well as having an effect on global warming (Bower *et al.*, 2006; DETR, 2006; AQEG, 2007; Pearce *et al.*, 2011).

Although most of the lethal smogs (primarily caused by burning coal) in London and many other major cities have significantly decreased, air pollution still remains a problem in the UK. Pollution episodes still occur in London and other cities during periods of calm weather, but they are caused mainly by the increase in the contribution of motor vehicle emissions (Bower *et al.*, 2006). The Air Quality Expert Group (AQEG) (2007) has drawn attention to the fact that one of the highest pollution episodes on record, in August 2003, increased mortality levels in London by about 10% (Sections 3.5.2 and 4.5.2). According to the British Department of Transport, Environment and the Regions (DETR), air pollution from man-made sources is currently estimated to reduce the life expectancy of every person in the UK by an average of eight months (DETR, 2006).

One of the major pollutants identified to be causing health effects is particulate matter (PM) (also known as particles). This is liquid or solid material present in the atmosphere that can be small enough, 0.1 μm in diameter or less, to travel deep into the lungs, increasing respiratory and cardiovascular diseases within the population as well as contributing towards premature deaths (Dockery *et al.*, 1993; Pope *et al.*, 1995; Schwartz *et al.*, 1996 and Donaldson and MacNee, 1998, Valavanidis *et al.*, 2008; Bollati *et al.*, 2010, see also Section 1.2).

Particles of importance in air pollution span a broad size range from the extremely small, only a few nanometres in diameter, to more than 1,000 micrometres (one micron or micrometre (1 µm), equals one-millionth of a metre 10^{-6}). The main focus of this study is on PM_{10}, this term refers to particulate matter up to 10 µm in diameter. Due to their size, these particles have the greatest potential of reaching the deepest parts of the lungs (DETR, 2007; Valavanidis *et al.*, 2008).

The purpose of this research has been to derive a clearer understanding of the distribution and dispersion of PM within the Southeast of England (Figure 1), (no similar or analogous studies, combining topography, local winds, local weather and a possible trans-boundary influence as an understanding of PM dispersal have been found for the studied region). In order to achieve this, the influence of topography on airflow, wind patterns and local weather needed to be understood with the aim of being able to determine their role in the distribution and dispersal of particulate matter within the area. The Southeast of England combines many geographical and climatological characteristics, therefore, it was decided to examine each of the environmental components (for example, local and broad-scale winds, varied topography, trans-boundary pollution and urban plumes) that could affect the dispersion of PM within the study region.

This chapter will introduce terms such as air pollution and its main types and causes (Section 1.2). The trans-boundary pollution concept is described in Section 1.2.1 and an explanation of why it is necessary to define this term and how it relates to the present study is presented. This is followed by a review of the background studies preceding this research (Section 1.3) and a brief overview of the study area (Section 1.4). Section 1.5 provides an overview of the structure of the rest of this thesis.

1.2 Air Pollution Overview

Air pollution occurs when airborne substances (solids, liquids or gases) build up in concentrations sufficiently high to cause direct or indirect damage to humans, animals, plants, ecosystems, structures or works of art (Harrison, 1990; Ahrens, 1994; Pepper *et al.*, 1996; Arya, 1999; Jacobson, 2002; Seinfeld and Pandis, 2006). Many authors (for example, Stern, 1973; Seinfeld, 1986; Parker, 1989; Ahrens, 1994; Pepper *et al,*. 1996; Arya, 1999; Yin *et al,*. 2005) refer to air pollution being caused by two types of sources: one being

natural and the other anthropogenic, although Jacobson (2002) states that air pollution only occurs when pollutants emitted by anthropogenic sources build up in concentrations high enough to produce harm to animals, including man and plants.

The main natural sources of air pollution are: winds eroding dust from cultivated farm fields, dust storms, ocean waves (releasing sea salt), vegetation (releasing pollen and spores), wild fires, volcanic eruptions and natural gaseous emissions (Ahrens, 1994; Pepper *et al.*, 1996; Seinfeld and Pandis, 2006). Principal anthropogenic sources are fuel combustion, industrial processes and transportation sources such as automobiles (RPAPM, 2004; Seinfeld and Pandis, 2006). These can interact but several studies such as APEG (1999), DETR (2000), Bower *et al.* (2006) and AQEG (2007) claim that almost all the atmospheric pollution in Britain is made by the burning of fuels, although there are contributions from fuel handling, chemical processes and natural sources (especially sea salt).

When considering their composition, air pollutants fall into two broad categories: gases and particulate matter (Parker, 1977; Ahrens, 1994; Pepper *et al.*, 1996). Jacobson (2002) distinguished gases from particles: a gas consists of individual atoms or molecules that are separated, while a particle consists of aggregates of atoms or molecules bonded together. As a result the particles are normally larger (>0.01 $\mu g/m^3$) than a single gas atom or molecule (<0.001 $\mu g/m^3$). Jacobson (2002) also added that particles contain liquids or solids while gases are in their own phase state.

In order to tackle air pollution and, encouraged by the EU air quality legislation, the United Kingdom government created the National Air Quality Strategy published by the DETR in 1998 and reviewed in 2000, 2003, 2005 and 2007. The Strategy addressed the following type of air pollutants: benzene, 1.3-butadiene, carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), particulate matter (PM_{10}) lead and sulphur dioxide (SO_2). These pollutants were selected on the assessment of the effects of each pollutant on human health and/or the environment. Overall, the lower concentrations of these pollutants in the atmosphere can broadly be taken to achieve a certain level of environmental quality. This investigation will focus on particulate matter. Its characteristics and recommended daily exposure levels are described in Section 2.2.

Most authors make a distinction between different types of air pollutants and their priority within the global environmental agenda. For instance, Jacobson (2002) divides air pollution into five main categories: indoor air pollution, outdoor air pollution, pollution producing acid deposition, pollution producing a stratospheric ozone reduction and air pollution contributing to global climate change. In contrast, Arya (1999) distinguishes between three different types of air pollution according to the spatial scale where the pollutants are dispersed. The first type consists of local or urban air pollution, which includes local air pollution from a variety of urban sources, as well as indoor pollution. The second type refers to regional and continental air pollution, for instance transport of sulphur and nitrogen oxides from major industrial areas to other regions where they are washed out of the air as acid precipitation. The final type of air pollution is spread over a larger area: this type is usually referred to as global air pollution, also made up of the chemical components described above and its possible consequences include changing the climate over periods of decades or centuries. The present study considers pollution within the second category, involving the study of air pollution not only in one specific region but also the exchange of pollution between the surrounding areas.

1.2.1 Trans-boundary pollution

Air pollution is often considered to be a phenomenon exclusively affecting large urban centres and industrialised regions. This concept is assumed because of the high concentration of pollutants found in these areas, but air pollution is a global problem, since pollutants ultimately become dispersed throughout the entire atmosphere having an impact at all the range of spatial scales (Seinfeld, 1986; WHO, 1992; Seinfeld and Pandis, 2006; Pearce *et al.*, 2011). As a consequence of these observations, the term trans-boundary pollution was introduced (WHO, 1992; UNECE, 2004). Air pollution is a trans-boundary phenomenon; in other words, it cannot be contained in one specific country. Urban air pollution, in the form of urban plumes, can be transported by atmospheric winds to areas far away from its source region. Atmospheric processes can transport it over hundreds or even thousands of kilometres without regard for national boundaries: consequently, its effects can impact on an area remote from the source (UNECE, 1979; Seinfeld, 1986; WHO, 1992).

Long-distance (trans-boundary) transport of airborne particles has been documented from around the world (Seinfeld, 1986; King and Dorling, 1997; Buchanan, 2002; Salvador *et al.* 2011; Pearce *et al.,* 2011). Several studies have shown that the Arctic's high levels of pollution come from anthropogenic sources (Elsom, 1992; UNECE, 2004; ASEAN, 2006). Since the Arctic has few local sources of pollution, most of the contaminants affecting it have therefore travelled many kilometres from low and mid-latitude sources (Elsom, 1992; ASEAN, 2006; UNECE, 2004; Scholastic, 2006). Elsom (1992) draws attention to the fact that Europe and Asia seem to be the principal sources of pollution in the Arctic region. Therefore, scientists are concerned not only about the effects on the fragile ecosystem but also about the climatic effects of the pollution (Elsom 1992; ASEAN, 2006; Scholastic, 2006).

Recent trans-boundary studies from across the UK (such as, Buchanan, 2002 and Rigby *et al*., 2006), have reported significant elevated mean particulate concentrations: the back trajectories suggest a significant continental European contribution. The long-range transport of pollutants is significantly influenced by synoptic scale meteorological patterns (ranging approximately from 1000 to 2500 km), so if climate change affects the frequency of these synoptic patterns, the frequency of pollution episodes occurring in the UK is also likely to be altered (King and Dorling, 1997; Buchanan, 2002).

Authors such as Steadman (1997), King and Dorling (1997), Malcom *et al.* (2000) and Buchanan *et al.* (2002) suggested that during episodes of pollution, measurements of PM_{10} from rural areas become as elevated as those from urban areas. These results would indicate that PM_{10} may originate from outside the local area and even from outside the UK as a consequence of trans-boundary transport of pollution from the near continent (AQEG, 2005; Rigby *et al*., 2006). Furthermore, King and Dorling (1997) believed that these concentrations of particulate matter would be mainly entering the country from the Southeast.

1.3 Background to the research

This thesis has evolved as an output from research initially undertaken as a component of an InterReg III project *"Aerosol Transport in the Trans-Manche Atmosphere (ATTMA)"* (InterReg IIIc, 2004; Ramon *et al.,* 2005; Santer *et al.,* 2007; Vidot *et al.,* 2007; Plainiotis *et al.,* 2005, 2010). The InterReg programme is an initiative funded by the European Regional Development Fund (ERDF).

The project was based on Franco-British cross-border cooperation; ATTMA was an interdisciplinary project (combining remote sensing, modelling, and local observations) with the common aim to understanding the main sources and dispersion of particulate matter within the English Channel region.

The project was divided in to three main themes: the study of local PM_{10} and wind patterns (Nicolas-Perea *et al.*, 2005), the development of Earth Observation tools that could provide maps of PM from satellite imagery, allowing the identification of peak location concentrations by determining the concentration gradients between the surface monitoring stations (Ramon *et al.,* 2005; Santer *et al.,* 2007; Vidot *et al.,* 2007) and finally the use of Lagrarian particle dispersion models to understand the dispersion patterns and identify sources responsible for episodes detected (Plainiotis *et al.,* 2005, 2010).

Therefore, this thesis focuses on providing an overview of the *in situ* data (i.e. measurements readily available to local authorities) collected on the ground over a period of nine years. This has been achieved by examining the influence of topography on airflow, wind patterns and local weather, as well as on local sources or trans-boundary and regional episodes of pollution, in order to determine their role in the distribution and dispersal of particulate matter within the area.

Previous work under the InterReg scheme, InterReg II (June 1999 to October 2001), investigated aspects of the automatic characterisation and source apportionment of a broad spectrum of airborne particulate matter, using a scanning electron microscope (SEM) and associated image analysis techniques, with the aim of developing techniques more readily available to the majority of those interested in particulate monitoring (Odle, 2004). These investigations raised a number of important issues related to the robustness of results using SEMs to identify airborne particulates, primarily when it became clear that currently there is insufficient technology available to achieve this in a cost-effective manner. Another, more pressing, issue identified during the InterReg II project was the need to develop a more comprehensive consideration and understanding of local weather and topographical influences on the distribution and dispersal of particulate matter in the >1μm size range (Burt, 2000; Odle *et al.*, 2002; Odle, 2004. Filling this gap in our knowledge is essential if airborne material is to be ascribed accurately to a source (or series of sources), although

accurate source-apportionment is not easy (Odle, 2004). This should then enable more focused policy formation and implementation. The work undertaken during InterReg II required development and integration into a wider understanding of the interaction between the synoptic (trans-boundary) influences and the more local, confounding, influences on particle dispersal, particularly the relationship between local winds and topography.

The Airborne Particles Expert Group (APEG) (1999) has pointed out that the Southeast of England tends to experience higher background PM_{10} pollution areas than other parts of the UK due to its proximity to continental European sources. Furthermore, the European Monitoring and Evaluation Program (EMEP) data show only modest PM_{10} concentration gradients across the country, with the highest concentrations in the southeast. This is consistent with contributions of man-made particles from the European continent adding to UK-generated pollution in the atmosphere as well as movement across-country in the prevailing westerly winds (APEG, 1999; EMEP, 2005).

All these factors make the study area for this project an ideal site for this type of investigation. Due to its proximity to mainland Europe, it is the area most likely to be affected by airborne pollution dispersal from northern France, and satellite imagery shows the dispersal of pollution plumes from there to Southeast England (APEG, 1999; EMEP, 2005; Santer, 2005) However, the fate of such plumes on arrival over Kent is not known (APEG, 1999; Odle, 2004).

The importance of the present study relies on providing a clearer understanding of the relationship between particulate matter pollution arriving from the mainland, topography and local weather measurements, as well as its influence on particulate dispersion.

1.4 Overview of the study area

The study area for this project is Kent (Figure 1). Much of this area is bordered by coast, with complex valley systems in Kent running between 10 and 20 km inland. Kent is also very close to the largest urban area in the UK: the city of London. Due to its southeastern location, Kent is the closest county to the near continent. All of these factors make Kent an ideal site for an investigation into topographically modified airflows, trans-boundary flow

and the dispersion of particulate matter as a consequence of these. A broader outline on the study area is provided in Section 2.5.

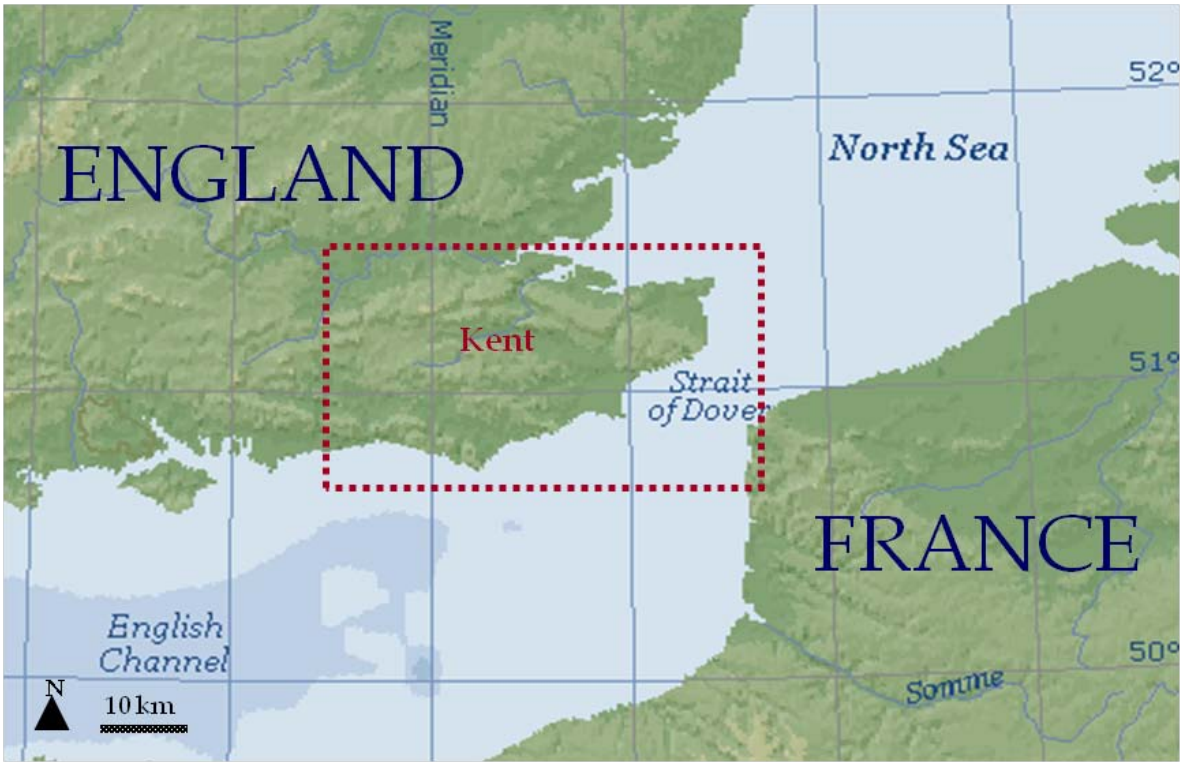


Figure 1: Map showing the studied area highlighted.
Adapted from Microsoft Encarta 2003.

1.5 Structure of the thesis

This thesis is organised into five chapters. Chapter 1 has provided an overview of the main ideas that encouraged this research as well as introducing the background of the project and an outline of the study area.

Chapter 2 presents a literature background including: a brief overview of the particulate material characteristics, discussing their sources, the impacts that PM_{10} has on humans and within the environment as well as describing the main dispersion and removal process from the atmosphere (Section 2.2). The next section (2.3) provides an outline of the atmosphere and more specifically the factors (such as, local or small scale winds) affecting the lower troposphere. Section 2.4 addresses the main types of local wind that can be found within the studied area, and how these atmospheric factors could be affecting the dispersion of particles. Section 2.5 describes the geographical and topographical features of the study area. Finally, Section 2.7 summarises the basic notions of British climate and local weather.

Chapter 3 details the methodology used during the present study. The chapter is divided into five main sections. Section 3.2 focuses on the extraction and analysis of the wind data, firstly at a local site and then extended to other sites in Kent. The second focus of this thesis (Section 3.3) concerns the extraction, analysis and comparison of particulate matter data at various sites within Kent, in order to investigate similar patterns affecting the sites, and therefore understand the dispersion of particles over the county. Section 3.4 evaluates the similarities and links between the two previous sets of data. This section includes a detailed comparison between the weather and the PM data; this was carried out with the intention of assessing the influence of the local weather and particularly the role of wind direction in the PM distribution throughout the study site. Section 3.5 gathers the knowledge gained on the two previous sections, the analysis of the wind patterns as well as the PM distribution and evaluates two episodes of pollution within the area. Lastly, Section 3.6 describes the setting of the monitoring trap used to sample PM, as well as the sampling strategy and the different approaches assessed to analyse the obtained data.

Chapter 4 follows the same structure configured for the methodology (Chapter 3), with a few annexes, presenting and discussing the results obtained during this investigation. The results were assessed within the context previously described in the literature background; taking into consideration all features of the study area, as well as analogous studies and limitations found during the process of this investigation.
Firstly, the results from the analysis of the weather data are explained (Section 4.2), followed by the results from the analysis of the PM_{10} data (Section 4.3). Results from both sets of data, wind direction and PM were then appraised together (Section 4.4). Section 4.5 evaluates the influence and behaviour of the most common pollution episodes in two case studies. Section 4.6 discusses the data obtained from the monitoring site at Dover. The last part of the chapter (Section 4.7) summarises the main outcomes of this investigation.

Finally, Chapter 5 assembles the conclusions of the thesis and presents suggestions for further work that could be undertaken in this field of research.

Chapter 2

Background and literature review

2.1 Overview of Chapter 2

The following chapter defines particulate matter, its main characteristics, sources and their behaviour (dispersion and removal). Section 2.3 describes the atmosphere, with specific focus on the troposphere and the planetary boundary layer as well as explaining some of the main atmospheric motions. In addition, Section 2.4 addresses the main types of local or small scale winds. Section 2.5 introduces the study area, describing its main topographical and geographical (physical and human) characteristics and finally, Section 2.6 outlines basic notions of British climate and local weather.

2.2 Particulate matter

Particulate matter (PM) is the collective term used to define particles (of diverse size, shape, composition and origin) found in the air. This includes dust, dirt, soot, smoke and liquid droplets (Stern *et al.*, 1993; DETR, 1998; Pope, 2000; EPA, 2004; SEIPH, 2004; McMurry *et al.*, 2004; RPAPM, 2004; Harrison, 2004).

Air quality limit values for PM_{10} were set at the European wide level by the first Daughter Directive (99/30/EC) under the air quality framework directive (96/62/EC). The amount of exposure is often measured in micrograms of substance *per* cubic metre of air ($\mu g/m^3$). The Daughter Directive stipulates that by the start of 2005 the daily mean PM_{10} concentration should have not exceeded 50 $\mu g/m^3$ on more than 35 occasions per year and that the annual mean should not exceed 40 $\mu g/m^3$. Additionally an indicative limit value was set for 2010 when the daily mean PM_{10} concentration should not exceed 50 $\mu g/m^3$ on more than seven occasions per year, and the annual mean should be less than 20 $\mu g/m^3$ (Querol *et al.*, 2004; European Commission 2005; AQEG, 2005, 2007). At the time of writing this thesis the legislation has been reviewed and an extension to achieve these values has been given to the city of London until June 2011 (European Commission 2010).

The UK Government in their Air Quality Strategy (published in 1998, 2000, 2003 review in 2005 and 2007) set the objectives for particulate matter levels to be achieved based on the 2005 EU limit values for PM_{10} (AQEG, 2005, 2007; Bower *et al.*, 2006). The main

two objectives set by the UK governments are: a total daily concentration of 50 µg/m^3 with up to 35 exceedences a year, and the other, an annual objective, aims to obtain a yearly average of 40 µg/ m^3 or lower, in order to protect the population from longer exposures (DETR, 2000; Hare *et al*., 2002; Bower *et al*., 2006). These two objectives (in relation to the data collected during the process of this investigation) will be analysed in Section 4.3.

A description of particles requires specification of not only their concentrations but also their types, size, chemical composition and morphology (Harrison, 1990; Arya, 1999; Jacobson 2002; McMurry *et al.*, 2004). In the following sections these features are described with the purpose of providing a clearer understanding of particulate matter pollution.

2.2.1. Historical background

Environmental concern for the adverse effects of air pollution dates back many centuries. Many authors, such as Parker (1977), Ahrens (1994) and Ayra (1999), state that human activities have caused air pollution ever since mankind starting building fires, but that pollution became a problem after the Industrial Revolution (1750s) and, more specifically in the last 200 years. At the start of the Industrial Revolution, air pollution came to be regarded as a serious problem only for large cities and commercial centres. With the invention of the automobile, however, air pollution increased significantly in urban and industrial areas. It is little wonder that early efforts in air pollution control were primarily directed toward improvement of air quality in those areas, even when unpopulated areas far from cities may have been affected by long-range transportation of pollution (Pepper *et al.*, 1996; Scorer 2002).

The city of London had always suffered intense smog episodes: furthermore, the development of air pollution control in Britain was strongly influenced by the occurrence of one of these episodes, the London smog episode, or Great London Smog as it is referred to, in December 1952. The Great London Smog occurred at a time when temperatures were below freezing (due to high pressure (Figure 2) trapping the air over the city) led to 4,000 deaths, especially among the elderly, due to bronchitis and other respiratory illnesses (Parker, 1977; Harrison, 1990; Jacobson, 2002; Scorer, 2002).

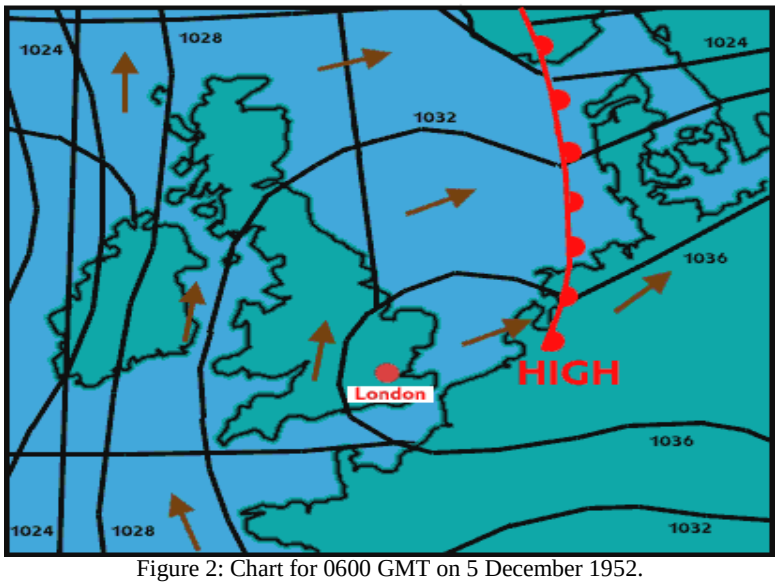


Figure 2: Chart for 0600 GMT on 5 December 1952.
Source: www.metoffice.gov.uk/education

This was one of the main turning points affecting pollution policy, influencing the first Clean Air Act to come out in the UK in 1956, followed by other Clean Air Acts in 1968, and 1974, until the actual UK National Air Quality Strategy in 1998.

Traditionally the most common air pollutants in urban environments included: sulphur dioxide (SO_2), the nitrogen oxides (NO_x), carbon monoxide (CO), ozone (O_3), particulate matter (PM) and lead (Pb) (WHO, 1992). Nevertheless, since the first Clean Air Act became law in 1956, there has been a steady reduction in PM emissions into the air over Britain (Figure 3) (Seinfeld, 1986; Harrison, 1990; Elsom 1992; Scorer, 2002).

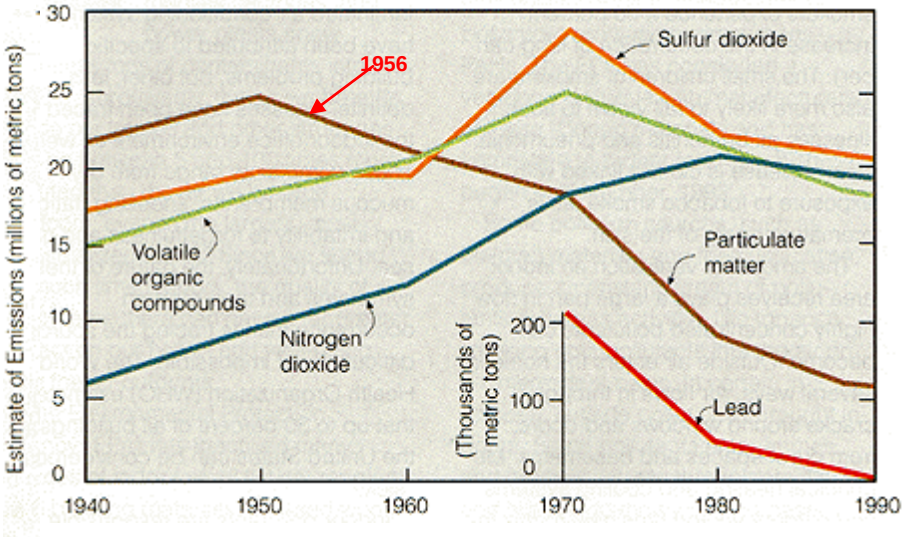


Figure 3: Illustrates air pollution trends between 1940 and 1990, showing the decrease in the emissions of particles since the introduction of the Clean Air Act in 1956.
Adapted from (Ahrens, 1994).

Particulate matter, the main focus of this study, was the first category of air pollutant that was subjected to air pollution control regulations (Meetham *et al.*, 1981; Harrison, 1990; Ahrens, 1994; EPA, 2004). The reason for this early attention was the tendency for large-

diameter particulate matter to settle on houses, deposit and discolour urban buildings and reduce visibility in the main cities (Meetham *et al.*, 1981). With the Clean Air Acts (from 1956 onward) in mind, only over the last 30 years have the developments in fluid dynamics, physical chemistry, measurement technology and epidemiological studies meant that it has been possible to further the investigation into airborne particles (Bower *et al.*, 2006). As a result, the origins, properties and behaviour of PM can be described now in great detail.

2.2.2 Types of particulate matter pollution

Over the years there has been some confusion over the right definition of particulate matter and its types. Some authors, such as Hindy (1984) and Lyons and Scott (1990), defined an aerosol as a gas containing particles of small size, and, therefore, with a small settling velocity. Against this description, Pepper *et al.* (1996), Arya (1999) and Jacobson (2002) claimed that aerosols are types of particulate matter that exist in the atmosphere under normal conditions, rather than a gas containing particles.

Jacobson (2002) made a clear differentiation of this concept separating the two main types of particulate matter, aerosol and hydrometeor particles. The former is a single liquid, solid or mixed-phase particle among an ensemble of suspended particles. The latter (the hydrometeor) is an ensemble of liquid, solid or mixed-phase water particles suspended in or falling through the air (Jacobson, 2002). A hydrometeor particle is a single particle: examples of hydrometeor particles include cloud drops, ice crystals, raindrops, snowflakes and hailstones (Seinfeld, 1986; Jacobson, 2002). The main differences between the two types of particles are that the hydrometeor particles contain much more water than the aerosol particle and generally form from physical processes in the air (Seinfeld, 1986; Jacobson, 2002; McMurry *et al.*, 2004). In addition, hydrometeors are from a natural origin whereas gases and aerosol particles may enter the air naturally, by anthropogenic emissions or by chemical processes in the air (Jacobson, 2002).

Air pollutants, and more specifically in this case, particulate matter, can be classified depending on the way they reach the atmosphere.

Primary particles are those coming from a direct emission, for instance from sand. Alternatively, other particles are created as a consequence of chemical reactions with other elements, such as ammonia (contributing to formation of ammonium nitrate): they are termed secondary particles (Seinfeld, 1986; Elsom, 1992; Jacobson 2002; McMurry *et al.*, 2004). This will be further discussed in Section 2.2.5 where the different types of

sources are identified. Furthermore, one of the most widely known types of particulate matter pollution is smog. This is a term referring to a synthesis of smoke and fog. Smog is usually found over metropolitan communities and it is caused by vast quantities of pollutants emitted from anthropogenic sources during periods when weather conditions fail to disperse the pollution away from the city (Meetham. *et al.*, 1981; Elsom, 1992; Jacobson 2002). During the process of this investigation some examples of "smogs" in the study area have been revised, and the different factors involved analysed. Results are shown in Section 4.5.

2.2.3 Sizes of atmospheric particles

The most important characteristic of particulate matter is the particle size (Stern. *et al.*, 1973; Oikawa, 1977; Elsom, 1992; Scorer, 2002; Harrison, 2004; EPA, 2004; Jacobson, 2002). This property has the biggest impact on the behaviour of particulate matter in the atmosphere, monitoring equipment and in the respiratory tract (Dockery, 1996; Pope 2000).

Most authors refer to a particulate size in terms of its aerodynamic diameter (DETR, 1998; EPA, 2004). This concept of aerodynamic diameter is very clearly described by DeCarlo *et al.* (2004) as the diameter of an idealised sphere with standard density that settles at the same terminal velocity as the particle of interest. The aerodynamic diameter increases when increasing the particle size (DETR, 1998; Jones and Harrison, 2004; EPA, 2004; RPAPM, 2004).

Particles of importance in air pollution vary across the size spectrum from the tiniest particles sized in nanometres, equivalent to molecular clusters, to very large particles, such as pollen grains and windblown sand (Figures 4 and 5) (Seinfeld, 1986; RPAPM, 2004). The most common classification divides them in four size categories: ultrafine, fine, coarse and supercoarse (Figure 4) (Stern. *et al.*, 1973; Elsom, 1992; Harrison, 2004; EPA, 2004).

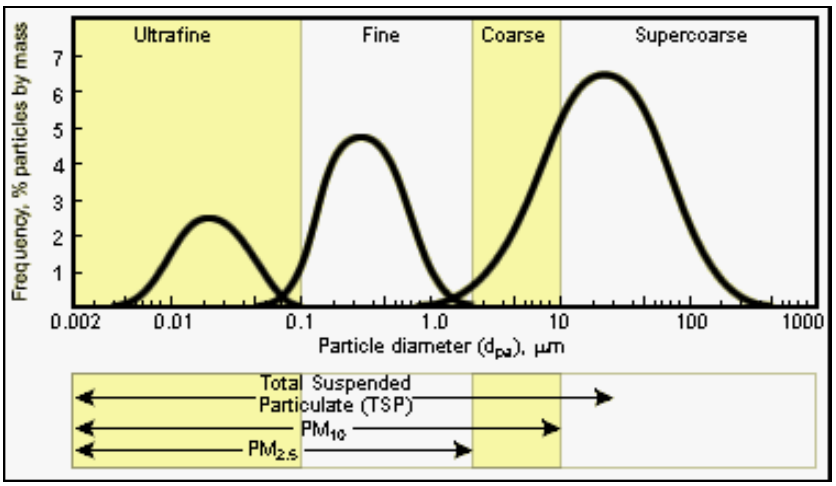


Figure 4: The tri-modal distribution of PM in the Atmosphere.
Source: www.epa.org

By convention, suspended particulate matter (SPM) is the term used to refer to particles ranging in size from 0.1 µm to about 30 µm in diameter (Figure 4): smaller material is generally considered to be dissolved within the atmosphere (EPA, 2004). This means that most of the particles described in the previous paragraph would be included in the suspended particulate matter category.

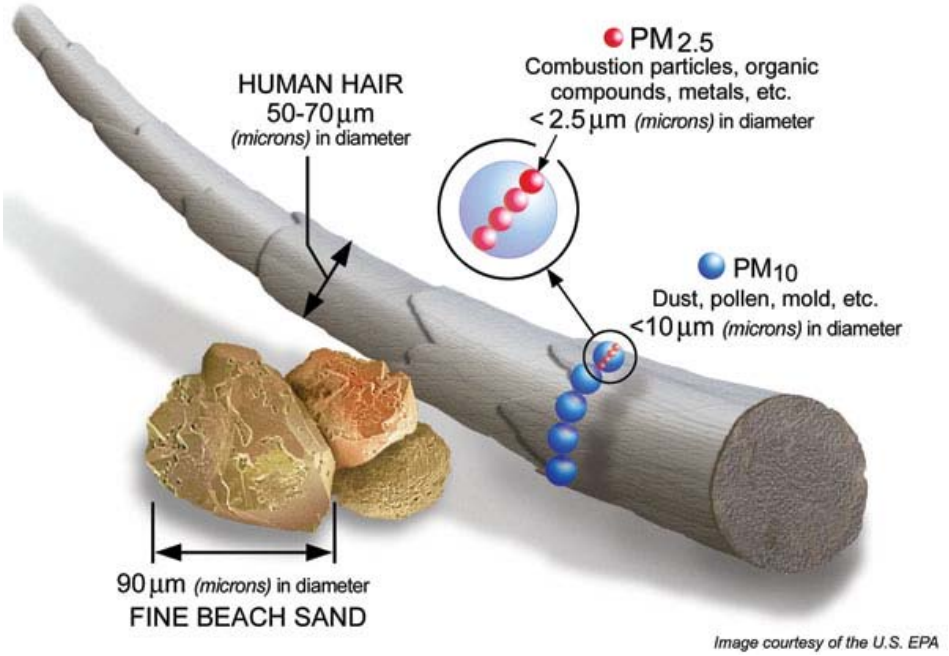


Figure 5: Comparison of the size of PM to a grain of sand and a human hair.
Source: www.epa.gov

PM_{10}, the category this study will mainly focus on proves to be of special interest because they are small enough to penetrate deep into the lungs and potentially cause significant health risks (Moran and Morgan, 1988; Henderson and Robinson, 1991;

Elsom, 1992; Harrison, 2000; EPA, 2004; McMurry *et al.,* 2004; DETR, 2004) (Figure 5). Smaller particles, such as $PM_{2.5,}$ settle slowly in the atmosphere whereas larger particles are not readily inhaled and are removed relatively efficiently from the air by natural sedimentation (Section 2.2.8, Figures 9 and 11). Normal weather patterns can keep fine and coarse particles (including particles up to 10 μm in diameter) airborne for several hours to several days and enable them to cover hundreds of kilometres (EPA, 2004). This idea will be developed in further sections, collectively with the notion of particles sizes being linked to their potential for causing health problems (Sections 2.2.6 and 2.2.8 respectively).

2.2.4 Particulate matter composition and morphology

Among atmospheric constituents, particulate matter is unique in its complexity. Particulate matter has no general chemical constitution and may in fact vary over space and time or be multifaceted (Harrison, 2000). Oikawa (1977) claimed that the particular concentrations and composition depend very much on the local conditions. Examples include: soot, smoke, dust, ash, asbestos fibres, pesticides, salt (NaCl), as well as some metals (including mercury, iron, zinc, copper and lead) and higher hydrocarbons formed by the incomplete combustion of hydrocarbon fuels. Sulphur dioxide (forming sulphate particles), ammonia (contributing to formation of ammonium sulphate and ammonium nitrate) and nitrogen oxides (forming ammonium nitrate with ammonia) (Parker, 1977; Elsom, 1992; Pepper *et al.*, 1996; RPAPM, 2004).

Chemical composition varies depending on the particle size. The major components of the fine fraction of the atmosphere are primarily sulphates (up to 80 % of the total suspension), nitrates, ammonium compounds, lead, carbon-containing material including soot and organic matter.

In urban-industrial air, suspended particulates may consist of a wide variety of materials depending on the specific types of mining, milling or manufacturing. Urban-industrial particulates usually include a diverse selection of trace metals such as lead, nickel, iron, zinc, copper, magnesium and cadmium. In addition, these particles can also contain asbestos fibres, pesticides, fertilizer dust, fungal spores and pollen (Moran and Morgan, 1988; Henderson and Robinson, 1991; Pepper *et al.*, 1996; RPAPM, 2004; McMurry *et al.*, 2004). Turning to the subject of particulate matter morphology, it has been suggested that particles emitted from air pollution sources have different densities and shapes,

including solid or hollow spheres, flakes, fibre, aggregate, or any numerous other solid irregular shape (Moran and Morgan, 1988; Jacobson 2002; McMurry *et al.*, 2004).

Studies in recent years have suggested that the composition and morphology of particles can play an important active role in atmospheric chemistry processes (Harrison, 1990; McMurry *et al.*, 2004; Harrison, 2004). Particles may act as a surface for heterogeneous catalysis i.e. acceleration of a chemical reaction or, more importantly, can provide a liquid phase reaction medium. Particle droplets, in humid temperate climates such as the one in the UK, can provide a medium for reaction solutes, as well as a medium for reaction with gases and their components (Figure 11) (Harrison, 1990; RPAPM, 2004).

2.2.5 Sources of particulate matter

Particulate matter in ambient air is a mixture of different types of particles having different sizes and chemical composition, and originating from a diverse array of emission sources (Sections 2.2.2 and 2.2.4). They come from a variety of sources such as cars, trucks, buses, factories, power stations, construction sites, tilled fields, unpaved roads, stone crushing, burning wood, agricultural land and the sea (as a source of marine salt particles) (Seinfeld, 1986; Elsom, 1992; Ahrens, 1994: Pepper *et al.*, 1996; Jacobson, 2002; Seinfeld and Pandis, 2006; AQEG, 2007).

The particles that are emitted directly into the air, such as dust or sea salt, are termed primary particles. Additional particle species, termed secondary particles, such as nitrogen oxides (forming ammonium nitrate with ammonia), are formed in the air from chemical reactions between the primary particles, interactions with gases from burning fuels, sunlight or water vapour. These secondary particles can condense on existing particles or be left as the residue of evaporated cloud droplets (Section 2.2.8) (Seinfeld, 1986; Harrison, 1990; KAQP, 1999; NARSTO, 2003; McMurry *et al.*, 2004; AQEG, 2007).

The sources of primary particles can be natural or anthropogenic. Natural sources of air pollution include: winds eroding dust from cultivated farm fields, from the beach, desert, soil, and rock; dust storms, ocean waves (sea salt), wind-borne pollen, fungi, moulds, algae, yeasts, bacteria and debris from live and decaying plant and animal life wild fires, volcanic and other geothermal eruption, natural gaseous emissions and particles entering the troposphere from outer space (Seinfeld, 1986; Elsom, 1992; Ahrens, 1994: Pepper *et al.*, 1996). However, Legge and Kruppa (1986) claim that particles such as sea salt,

volcanic emissions, spores and pollens are only present at a low amount (less than 12% of the total emissions) in the UK atmosphere.

Emissions of particulate matter attributable to the activities of humans include: fuel combustion and industrial processes (e.g. coal-burning power stations), mechanical processes (e.g. quarrying), transportation sources (such as motor vehicles, ships and aircraft) homes, offices buildings (fossil fuel burning to produce heating) and non-industrial fugitive sources (such as roadway dust from paved and unpaved roads) (Seinfeld, 1986; Ahrens, 1994; Pepper *et al.*, 1996; RPAPM, 2004). QUARG (1996) reported that road transport is responsible for 86 % of PM_{10} emissions in London City. Another case in point is agricultural activity: accelerating the erosion of the soil by the wind results in an increase on the level of dust in the air (Henderson and Robinson, 1991). This last suggestion needs be taken into consideration in the current study area due to the high percentage of agricultural land cover in Kent (KCC, 2005) (Section 2.5.2).

Secondary particles form in the atmosphere as a result of chemical reactions that lead to the formation of substances of low volatility, which consequently condense into the solid or liquid phase, thereby becoming particles. Most secondary particulate matter occurs as sulphates and nitrates formed in reactions involving sulphur dioxide (SO_2) and nitric oxide (NO_x) (Seinfeld, 1986; Harrison, 1990) (Figure 11). The percentage of the fine particle fraction that is secondary usually exceeds 50 % in urban areas or megacities such as London (WHO, 1992). The formation of secondary particulate matter takes hours or days. During the period that the process lasts the air containing the pollution can travel long distances causing in many cases a trans-boundary pollution phenomenon (Section 2.2.8) (Stern *et al.*, 1973; Oikawa, 1977).

2.2.6 Human and environmental effects of PM_{10}

2.2.6.1 Human health effects

Many epidemiological studies (for example from Dockery *et al.* (1993), Pope *et al.* (1995), Schwartz *et al.* (1996), Donaldson *et al.* (1998), Buchanan *et al.* (2002) and Bowler *et al.* (2006)) have shown a strong correlation between increased PM concentrations and increased mortality, as well as respiratory and cardiovascular diseases, hospital admissions, respiratory infections, or aggravation of chronic conditions such as asthma and bronchitis. The most susceptible individuals are the elderly, children

and individuals with chronic pulmonary or heart disease, as well as people living in deprived areas (Elsom, 1992; WHO, 1992; Bowler *et al.*, 2006).

The health effects of particulates are strongly linked to particle size (Pope, 2000). Larger particulates are unable to penetrate into the narrow branches of the lungs, but smaller ones can easily reach the alveoli, where gas exchange with the blood occurs (Figure 6). Particulates larger than 10 µm are mostly trapped in the nasal cavity and throat (Figure 6), they can also produce eye irritation. Around 90 % of the particulates larger than 5 µm precipitate in the upper part of the air passages. Particulates in the same range up to 5 µm size range enter the respiratory tract and reach the deeper parts of the lungs (trachea and bronchi) (Figure 6). These small particles, less than 10 µm in diameter, cause the greatest problems, because they can get deep into the lungs, and some may even get into the bloodstream (Oikawa, 1977; Scorer, 2002; Valavanidis *et al.*, 2008; Bollati *et al.*, 2010). The constituents in small particulates also tend to be more chemically active and may be acidic and, therefore, more damaging (Dockery, 1996).

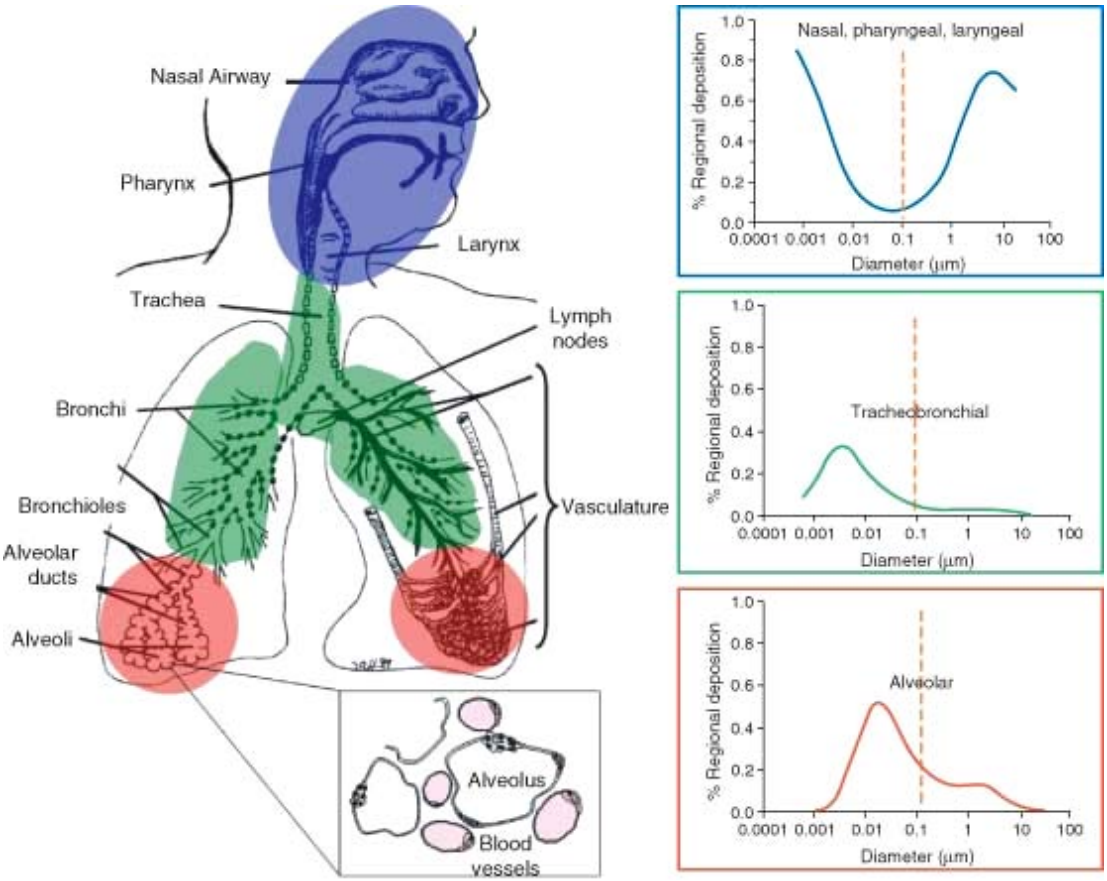


Figure 6: Illustrates the deposition of particles in the respiratory system according to diameter size.
Source: www.wiley.com

Another factor to take into consideration, apart from the size, is the duration of the exposure. Long term exposure results in the reduction of lung function, development of chronic bronchitis and even premature death (Dockery *et al.*, 1993; Pope *et al.*, 1995; Schwartz *et al.*, 1996; Donaldson *et al.*, 1998; Dockery, 1996; Pope, 2000). Short term exposures (hours or even days) can aggravate lung disease, causing asthma attacks and acute bronchitis or increase susceptibility to respiratory infections. Exposure to those particles can affect both the lungs and the heart (Pope *et al.*, 1995; Donaldson *et al.*, 1998; Dockery *et al.*, 1996; Pope, 2000; McMurry, 2004; *Valavanidis et al., 2008*).

2.2.6.2 Environmental and atmospheric effects of PM_{10}

Besides the risks to human health, the most direct effect of particulate matter pollution is to reduce incoming radiation and sunshine, therefore affecting climate and visibility. The reduction of visibility is caused by the absorption and scattering of solid and liquid aerosols, therefore relative humidity plays an important role; the effect of suspended particulate matter alone (dry haze) is restricted to relative humidity below 70 %. As a consequence of this, during the 1930s and 1940s many urban areas in Europe and North America received only 50 % of their potential bright sunshine in winter, making it very common for cities such as London to require street lighting throughout the day in winter. At the present time this has improved due to the reduction in the emissions of particles (Henderson and Robinson, 1991; Elsom 1992; Jacobson, 2002). According to KCC (2005) “photochemical episodes”, or episodes of pollution where the visibility is reduced significantly due to the high concentration of pollutants in the air, are relatively common in Kent during warm summer periods. The timing and severity of these episodes depends upon the meteorological and geographical conditions affecting the area (Jacobson, 2002). One of the most recent and severe photochemical episodes affecting the southeast of England occurred during a heatwave in August 2003. This episode lasted for eight consecutive days; the highest temperatures had a significant influence on the atmosphere of polluted urban environments, where high temperatures greatly increased the rate of smog formation (Section 2.2.2) (Pepper *et al.*, 1996; KCC, 2005). The August 2003 pollution episode was examined as a case study during the process of this investigation (Section 4.5.2, Chapter 4).

In the UK and other heavily industrialised countries, visibility reduction tends to correlate closely with the concentration of aerosol sulphate, a component tending to be present in sizes optimum for scattering of visible light (Harry, 1990; Scorer, 2002). In

very dry climates, such as deserts, a visibility reduction is primarily associated with dust storms and is thus correlated with airborne soil (Harrison, 1990). The levels and trends of particle concentrations are consequently important to follow. The main difficulty is that the complexity of any model developed to characterise and chase particle concentrations and dispersion increases tremendously as soon as topographic effects on airflow are introduced (McMurry *et al.*, 2004).

Animals may be expected in general to suffer the effect of airborne particles similarly to human beings. Excessive amounts of particulate material also affects vegetation by covering the leaves and reducing the absorption of carbon dioxide, as well as impeding the intensity of the sunlight reaching the inside of the leaf (Meethem. *et al.,* 1981; Elsom, 1992). In addition to these impacts, there are also additional costs relating to environmental damage through acidification of ecosystems and damage to crops and forests: however, these are often notoriously difficult to quantify (Bower *et al.,* 2006).

Other effects would include atmosphere turbidity and a reduction of visibility that impairs the operation of aircraft and/or motor vehicles produced by the presence of enough small particles (0.1 μm to 10 μm in size) in the atmosphere to produce haziness (Parker, 1977).

During March and April of 2010, the eruption of the Eyjafjallajökull volcano in Iceland followed by a continuous sequence of volcanic events and the plume originated by it emissions caused the worst UK's airspace restriction in living memory (VAAC, 2010; Met Office, 2010; BBC News, 2010) (Figure 7).

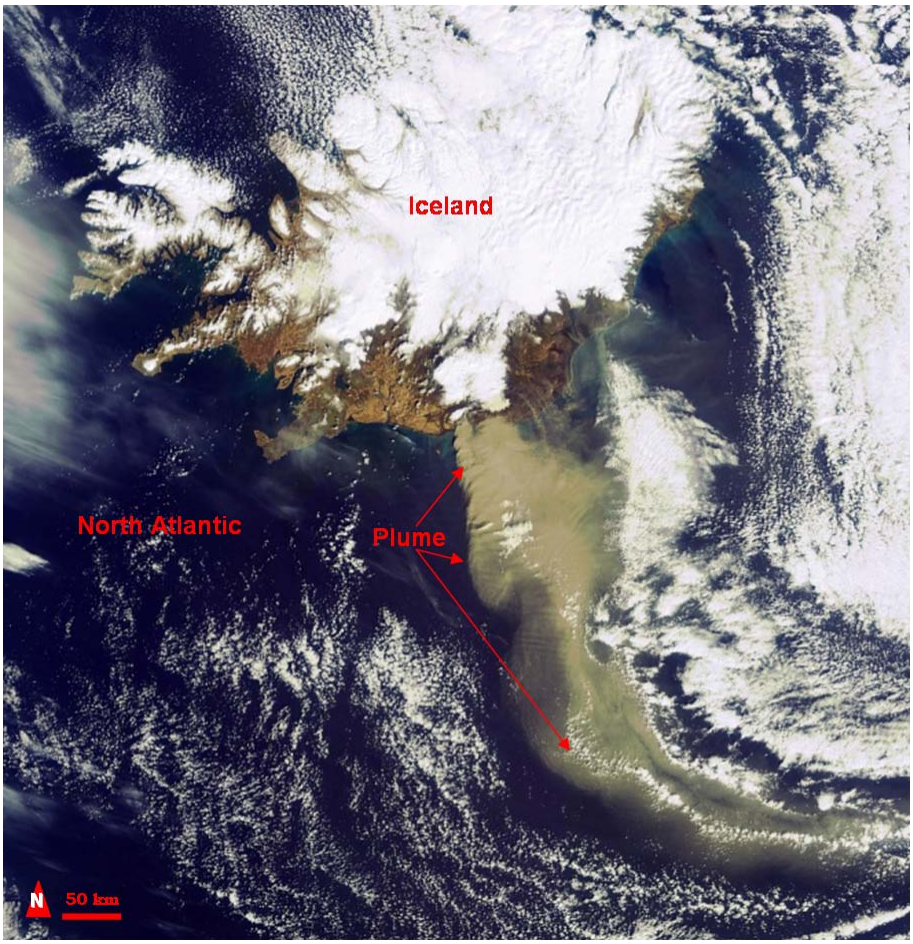


Figure 7: This image was taken on the 19 of April 2010 by ESAS's Envisat Satellite, a heavy plume of ash from the Eyjafjallajökull volcano in Iceland is seen travelling in an approximate southeasterly direction. Adapted from www.spacegizmo.com

The weather conditions at the time of the eruption meant that the volcanic ash plume moved towards the west and southwest covering a large area of Europe, causing widespread disruption to aviation (Met Office, 2010) (Figure 7).

The plume that is often seen above an erupting volcano is composed primarily of ash and steam. The very fine particles may be carried for many miles, settling out as a dust-like layer across the landscape: this is known as an ashfall (Met Office, 2010). Volcanic ash can have a major impact on aircraft, potentially causing engines to fail. Experts have warned that the tiny particles of rock, glass and sand contained in the ash cloud from the still-erupting volcano could be sufficient to jam aircraft engines (Met Office, 2010; VAAC, 2010).

2.2.7 PM_{10} traps and sampling techniques

The assessment of the potential environment and human health effects of particulate matter in the atmosphere requires detailed physical and chemical characterisation of the particles themselves (Wight, 1994). Air sampling and monitoring is part of the overall exposure assessment process which is aimed at defining an individual's or group's

exposure to chemical, physical and biological agents in the environment (Wight, 1994: Zhang, 2007).

According to Mc Dermott *et al.* (2004), there are two main categories of sampling techniques: sample collection devices that are analysed in the laboratory and direct reading instruments. When using a sampler collection device, a sample is collected in the field and returned to the laboratory for analysis. In addition, there are several direct-reading instruments and types of monitoring equipment that provide real time data on the contaminants levels.
Pump based sampling is one of the most common methods used: it is also the method chosen for this investigation (see following section). This sampling method involves a calibrated battery-powered pump, collection device and connection tubing. Some procedures may also involve an airflow control valve, an airflow measuring device and a special particle size separator device (Wight, 1994; Mc Dermott *et al.*, 2004).

2.2.7.1 Burkard Volumetric Spore Trap

The instrument chosen during the process of this investigation to sample trans-boundary material was a Burkard Volumetric Spore Trap (BVST) (Burkard Manufacturing Co. Ltd, Hertfordshire, WD3 1PJ, UK) (Figures 36 and 38). The Burkard Volumetric Spore Trap is the standard model of the "Hirst automatic volumetric spore trap" having a proper clockwork mechanism (see Section 3.6.2). Traditionally the BVST has been mainly applied to aerobiological studies (such as the capture of spores and pollen). However, it has been found to be very advantageous in PM studies. It was designed by Hirst in 1952 specifically for the study of the airborne dispersal of plant disease fungi but because it enables the visual identification of airborne particles in the range of 6 µm to 100 µm, it has been used extensively in plant pathology and the study of respiratory allergens (Gregory, 1974), as well as in the field of PM research (Battarbee *et al.*, 1997; Long, 1998; Long and Rose, 1999; Mackay *et al.*, 1999; Odle, 2002, 2004).

At the end of a 7-day run, the sampling tape is removed, cut into sections representing hourly or daily periods, and then examined microscopically (Section 3.3.4). In this way, it is possible to distinguish clearly between night-released and day-released spores or other particles, and also to relate the types of particle to different weather conditions (e.g. humid or dry periods) while the apparatus was running. The Burkard spore trap is commonly used for continuous monitoring of spore or pollen loads in the air. For

example, these traps are commonly sited on hospital roofs, meteorological stations and other public buildings, and provide public information through television and radio broadcasts.

The BVST is a cost-effective instrument as well as providing a good temporal resolution, making possible the analysis of individual particles. In addition, it is a relatively portable instrument, which can be operated by a battery or solar power as well as mains electricity (British Aerobiological Federation (BAF), 1994; www.burkard.co.uk, 2007) (Section 4.6).

2.2.8 Particulate matter dispersion and removal processes

Once they are emitted, primary and secondary particles mix rapidly with the surrounding atmosphere. New particles can exist for several days depending on removal processes. During their life time, while being dispersed and before they settle, some particles are changed by processes such coagulation (or agglomeration) and chemical reaction (McMurry *et al.*, 2004). These are addressed in Section 2.2.8.2 as an aid to comprehending the removal processes affecting particles.

2.2.8.1 Factors affecting PM dispersion

Particulate matter dispersion is a very complex process affected by many variables. Some of these variables may be associated between themselves: one affecting the other. They are explained in the following paragraphs.

The physical and dynamic characteristics of the atmosphere allow it to be the vehicle used for particles to make their journeys, affecting the whole process from source to deposition. Atmospheric winds, for example, determine the pathways and speeds at which pollutants are transported away from sources (Seinfeld, 1986; Arya, 1999). When vast quantities of pollutant are discharged into the air, the wind speed determines how quickly the pollutants mix with the surrounding air and how fast they move away from the source. If the wind is calm pollutants are not easily dispersed and they tend to become more concentrated (Parker 1989; Ahrens, 1994).

Other atmospheric processes, such as the vertical variation of temperature greatly influence atmospheric stability (i.e. the resistance of the atmosphere to vertical motion) and hence the mixing of polluted air with clean air significantly influencing particle deposition rates (Parker, 1989; WHO, 1992; Pepper *et al.*, 1996; Barry and Chorley, 1998; Arya, 1999; Parker and Kinnersley 2004).

In addition, it has to be considered that most of these atmospheric processes such as wind speed and turbulence are affected by topographical features and surface roughness. These factors strongly influence the extent to which emissions are diluted by the wind (Goosens, 1988, Bridgman, 1990; Offer and Goosens, 1995; Mason *et al.*, 1999; Parker and Kinnersley, 2004). Meetham *et al.* (1981) claim that observations of atmospheric pollution in Britain have suggested that the average life of a smoke particle before deposition on land must be one or two days, although this will be affected by the conditions of the individual variables described above.

Seinfeld (1986) and Arya (1999) suggested that a study on the transport or dispersion of pollutants must include a detailed inventory of all the anthropogenic and natural emissions in an area (estimated for each horizontal grid area), land use, topography and regional meteorology, as well as including all the dispersion characteristics and all the parameters affecting transport, diffusion, transformation and removal processes of particulate matter. This suggestion has been examined and taken into consideration when creating the methodology applied during the process of this investigation (Sections 3.3 and 3.6).

The ability of a particle to remain suspended in the air depends essentially on its size (Figure 8) (Stern. *et al.*, 1973; Parker 1977; Harrison, 1990; Elsom, 1992; McMurry *et al.*, 2004). This feature is especially important when observing their dispersion behaviour in the atmosphere and the rate of deposition. Large size particulate matter (>10 μm in diameter) falls rapidly settling under the influence of gravity, while fine light particles remain suspended for longer (Parker 1977; DETR, 1998). The larger the particulate the shorter the distance it will be carried from the source, whereas the smaller the particulate the easier it can be carried on the wind and the further it will be deposited (Legge and Krupa, 1986) (Figure 8).

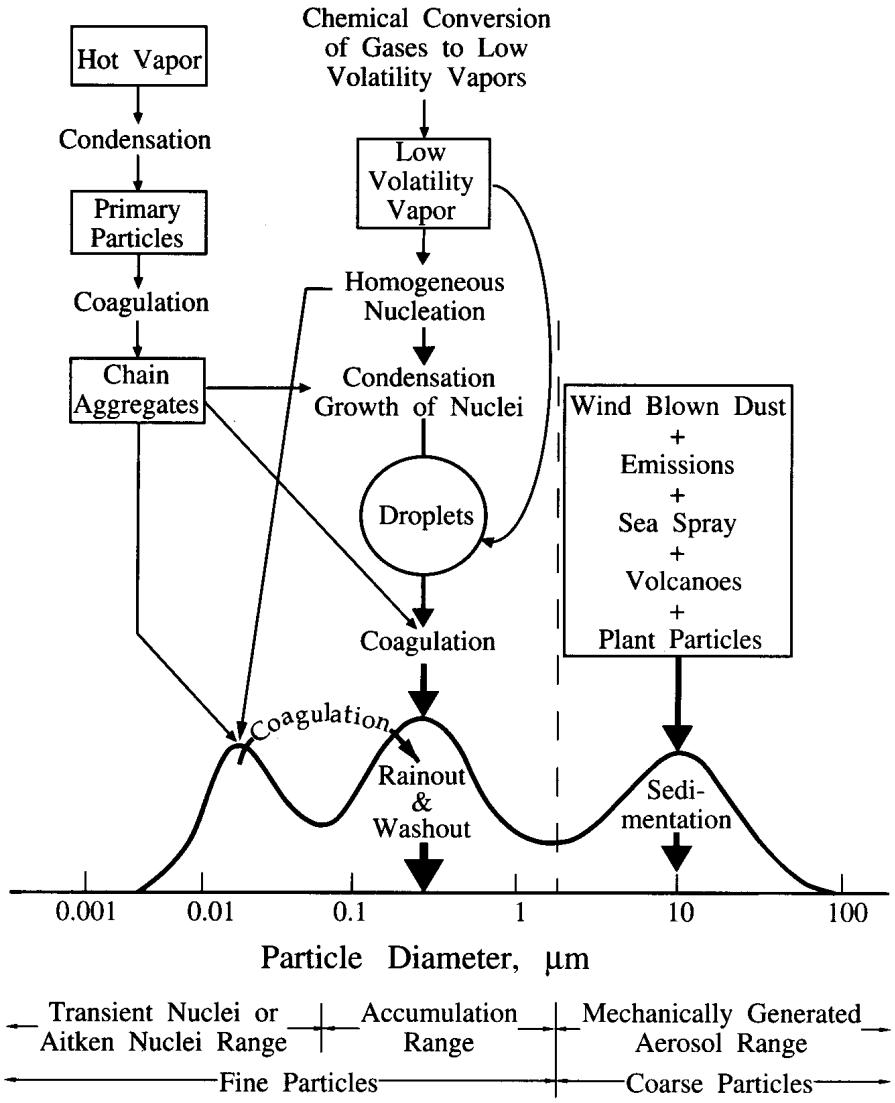


Figure 8: Idealized schematic of the distribution of particle surface area of an atmospheric particle. The principal modes, sources and particle formation and removal mechanism are indicated. Adapted from Seinfeld (1986) and Arya (1999), originally published by Whitby and Cantrell (1976).

Particles greater than 10 µm in diameter are large enough to settle quite quickly from the atmosphere under the influence of gravity and can cause nuisance through their ability to deposit on horizontal surfaces (Figure 8), creating dust soiling, whilst the smaller particles are most notable for the health hazard which they present (Harrison, 2004). Particles smaller than about 10 µm in diameter are able to remain airborne for hours or days, and, in some cases, even weeks (Seinfeld, 1986; McMurry *et al.*, 2004). It is in this range of particle sizes that the main focus of this investigation resides. Particles less than 5 µm in diameter tend to form stable suspensions and particulate matter smaller than 0.1µm show a low sedimentation velocity and moves with the wind so is very unlikely to settle (Parker, 1977).

The movement of particulates smaller then 0.1µm resembles that of a gas and is possibly identical to diffusion (Oikawa, 1977; Jacobson 2002). Such small particles easily absorb gases, collide with each other, and undergo adhesion (between themselves or with nearby surfaces) (Figure 8) (Seinfeld, 1986). It is probable, therefore, that particulates smaller than 1µm exert a stronger influence on human health and the environment (Oikawa, 1977; Seinfeld, 1986, Arya, 1999; McMurry *et al.*, 2004).

2.2.8.2 PM removal processes

Wet and dry mechanisms remove particles from the atmosphere.

2.2.8.2.1 Wet Deposition

Wet deposition is defined as the process by which airborne pollutants, in this case particles, are absorbed into precipitation (water droplets, ice particles and snowflakes) and are deposited onto the Earth's surface during precipitation (Figure 9) (Seinfeld, 1986: Arya, 1999). Wet deposition would also include the attachment of particles to cloud droplets by the various physical mechanisms during cloud formation (Arya, 1999). In many cases, due to this process, particles or aerosol can transform into hydrometeors (Section 2.2.2).

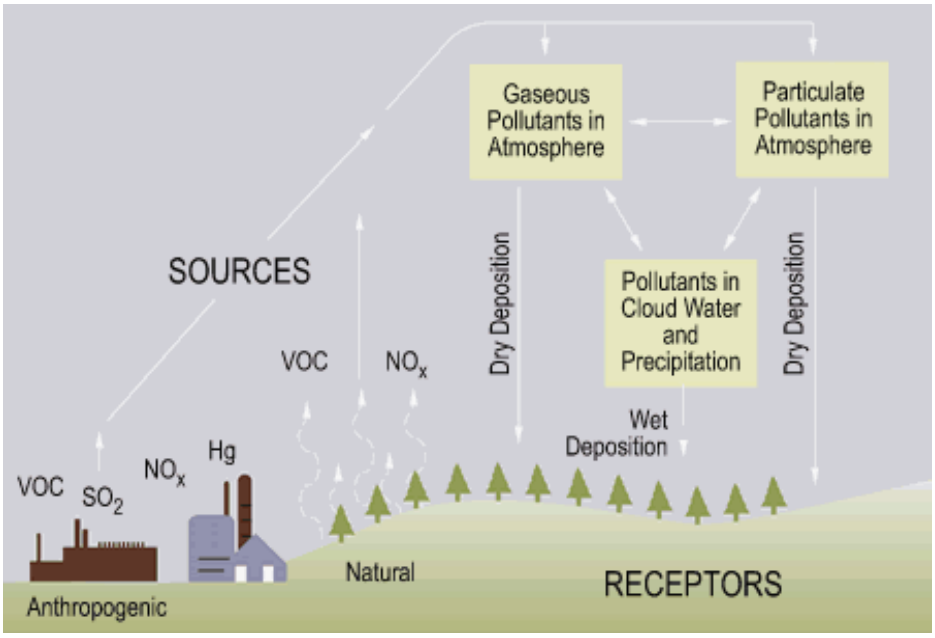


Figure 9: Illustration of wet and dry deposition processes.
Source: www.solcomhouse.com

2.2.8.2.2 Dry Deposition

Dry deposition involves the transfer and removal of gases and particles at surfaces without the intervention of precipitation (Figure 9).

The various transfer mechanisms leading to dry deposition are complex and involve micrometeorological characteristics of the atmospheric surface layer (Seinfeld, 1986: Arya, 1999). Turbulent transport occurs within this surface layer producing the physical and chemical properties of dry deposition. Atmospheric stability also has a strong influence on mean wind distribution and turbulence in the surface layer and therefore on dry deposition (Arya, 1999) (Figures 8, 9 and 10).

The particles' removing mechanism on surfaces operates in parallel with gravitational settling of the larger particles (Harrison, 1990). Once particles are in the atmosphere, their size, number and chemical composition are changed by several mechanisms, until ultimately they are removed by natural processes. Particles whose diameters are 10 µm or larger generally settle out of the atmosphere in less than a day, whereas particles whose diameter are 1 µm or less can remain suspended for weeks (Figure 8 and 10). Most pollutants have a short enough life to prevent their accumulation in the atmosphere (Stern *et al.*, 1973; Seinfeld, 1986; Pepper *et al.*, 1996).

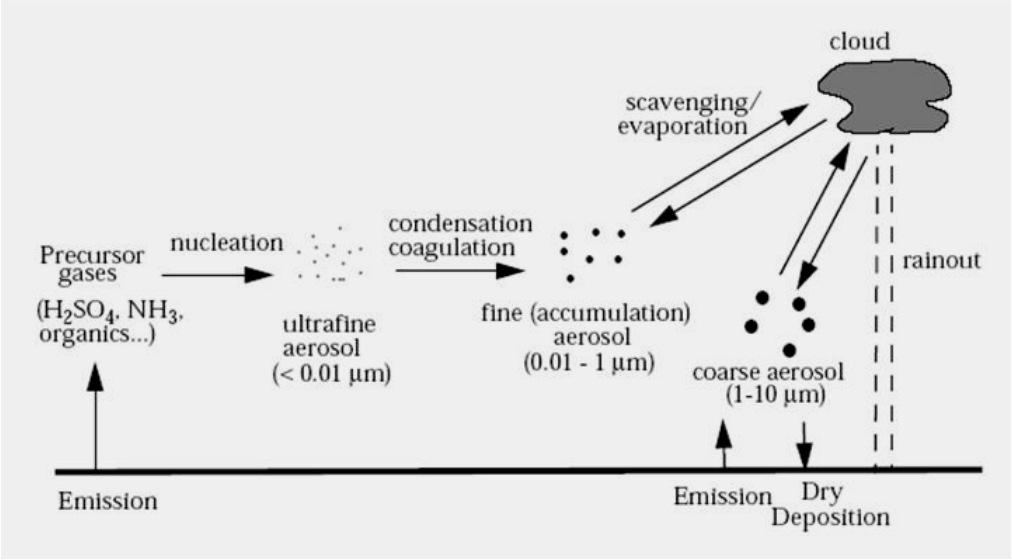


Figure 10: Production, growth and removal of atmospheric particles.
Source: www.uio.no

The main mechanisms for the removal of particles are agglomeration, sedimentation and impaction. When particles collide in the air they tend to adhere to each other because of attractive surface forces, thereby forming progressively larger and larger particles by agglomeration. The larger a particle becomes, the greater its weight and the greater its likelihood of falling to the ground rather than remaining airborne (Figure 8 and 10). The process of particles falling out of the air to the ground is called sedimentation. Washout of particles by precipitation, mist or fog is a common form of agglomeration and sedimentation. Other particles leave the air by impaction onto and retention by the solid surfaces of vegetation and buildings.

Close to the ground the main mechanism for particle removal is settling and impaction on surfaces whereas at altitudes of about 100 m, wet deposition is the predominant removal mechanism (Stern *et al.*, 1973; Seinfeld, 1986) (Figures 8, 9 and 10).

2.2.9 Summary of Section 2.2

Particulate matter (PM) is the collective term usually used to define particles (of diverse size, shape, composition and origin) found in the air. This includes dust, dirt, soot, smoke and liquid droplets.

Particles of importance in air pollution span a broad size range from the extremely small, only a few nanometres (billionths of a metre,10^{-9}) in diameter to more than 1,000 micrometres (one micrometre (1 µm) or micron, equals one-millionth of a metre 10^{-6}). The particle size has the biggest impact on the behaviour of particulate matter in the atmosphere, monitoring equipment and in the respiratory tract.

Particulate matter has no general chemical constitution and may in fact vary over space and time or be multifaceted. Particles originate from a diverse array of emission sources. They are classified depending on the way they reach the atmosphere. Primary particles are those coming from a direct emission, for instance from sand or sea salt. Alternatively, other particles are created as a consequence of chemical reactions with other elements, such as ammonia (contributing to formation of ammonium nitrate); they are termed secondary particles.

The sources of primary particles can be natural or anthropogenic. Natural sources of air pollution include winds eroding dust from cultivated farm fields, from the beach, desert or pollen. Emissions of particulate matter attributable to the activities of humans include fuel combustion and industrial processes.

Many epidemiological studies have shown a strong correlation between increased PM concentrations and increased mortality, as well as respiratory and cardiovascular diseases. The health effects of particulates are strongly linked to particle size. Larger particulates are unable to penetrate into the narrow branches of the lungs, but smaller ones can easily reach the alveoli. Particulates larger than 10 µm are mostly trapped in the nasal cavity and throat whereas particulates in the 0.1 µm or smaller to 5 µm size range enter the respiratory tract and reach the deeper parts of the lungs. Besides the risks to organisms, the most direct effect of particulate matter pollution is to reduce incoming radiation and sunshine, therefore affecting climate and visibility.

Particulate matter dispersion is a very complex process affected by many variables. Atmospheric winds, for example, determine the pathways and speeds at which pollutants are transported away from sources. In addition, it has to be considered that most of these atmospheric processes such as wind speed and turbulence are affected by topographical features and surface roughness.

The ability of a particle to remain suspended in the air depends essentially on its size. Large size particulate matter (>10 μm in diameter) falls rapidly, settling under the influence of gravity, while fine light particles remain suspended for longer, being able to remain suspended in air for weeks.

The larger the particulate the shorter the distance it will be carried from the source, whereas the smaller the particulate the easier it can be carried on the wind and the further it will be deposited.

The particle removal processes are wet and dry mechanisms. Wet deposition is the process by which particles are deposited onto the Earth's surface during precipitation. Alternatively, dry deposition involves the transfer and removal of particles at surfaces without the intervention of precipitation. The main mechanisms for the dry removals of particles are agglomeration, sedimentation or impaction. When particles collide in the air they tend to adhere to each other because of attractive surface forces, thereby forming progressively larger and larger particles by agglomeration. The larger a particle becomes, the greater its weight and the greater its likelihood of falling to the ground rather than remaining airborne. The process of particles falling out of the air to the ground is called sedimentation. Other particles leave the air by impaction onto and retention by the solid surfaces of vegetation and buildings.

2.3 The Atmosphere

The atmosphere is in constant motion on scales ranging from short-lived local winds to global scale wind belts circling the Earth (Barry and Chorley, 1992). Therefore, the atmosphere is the vehicle used for particle movements, affecting the whole process from source to deposition. Atmospheric winds, for example, determine the pathways and speeds at which pollutants are transported from the sources. Another physical process such as the vertical variation of temperature greatly influences atmospheric stability and hence the turbulent mixing of polluted air with clean air (Pepper *et al.*, 1996; Ayra, 1999).

The chemical and physical reactions and interactions that take place in the atmosphere affect the composition and distribution of particles (McMurry *et al.*, 2004).

The atmosphere is classified on the basis of layers according to the vertical distribution of temperature: troposphere, stratosphere, mesosphere and thermosphere (Figure 11) (Ayra, 1999). The troposphere is the lowest layer (Figure 11) it is in this layer where the main dispersion of pollution takes place and where weather processes occur (Pepper *et al.*, 1996; Ayra, 1999).

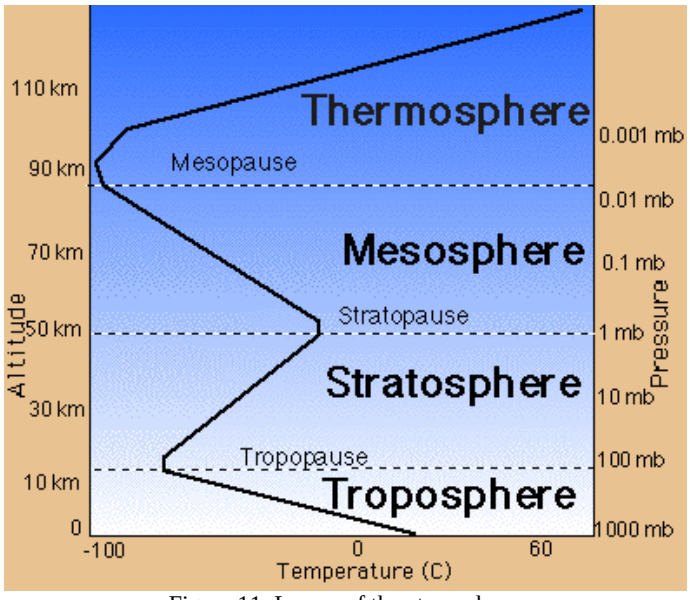


Figure 11: Layers of the atmosphere.
Source: www.aerospaceweb.org

2.3.1 Troposphere

The troposphere is generally unstable and well mixed. It extends up to around 18 km or so in the tropics but only up to 9 to 12 km in temperate latitudes, such as Britain (Pepper *et al.*, 1996; Scorer. 2002).

The troposphere is divided into the free troposphere and the planetary boundary layer (i.e. the nearest part to the ground surface). The free troposphere is the layer between the planetary boundary layer and the tropopause (this is the transition zone between the troposphere and the stratosphere).

2.3.2 The planetary boundary layer

The region of the atmosphere governing transport and dispersion of pollutants is the planetary boundary layer (PBL), roughly the lower 2,000 m which forms the atmospheric interface between the troposphere and the ground surface. The planetary boundary layer

reaches maximum activity in the afternoon, when flow of air heated at the surface raises upward (Figures 12b and 12c). At night, when the temperature drops, the boundary layer can shrink to about 100 m deep depending on the conditions (for example, temperature and winds) (Figures 12a and 12d) (Seinfeld, 1986; Pepper *et al*., 1996; Arya, 1999; Scorer 2002; Seinfeld and Pandis, 2006). Figure 12 illustrates temperature conditions, winds, and air movements at four different times during daylight hours in an ideal 24 hour thermal cycle: there is considerable variation between these patterns.

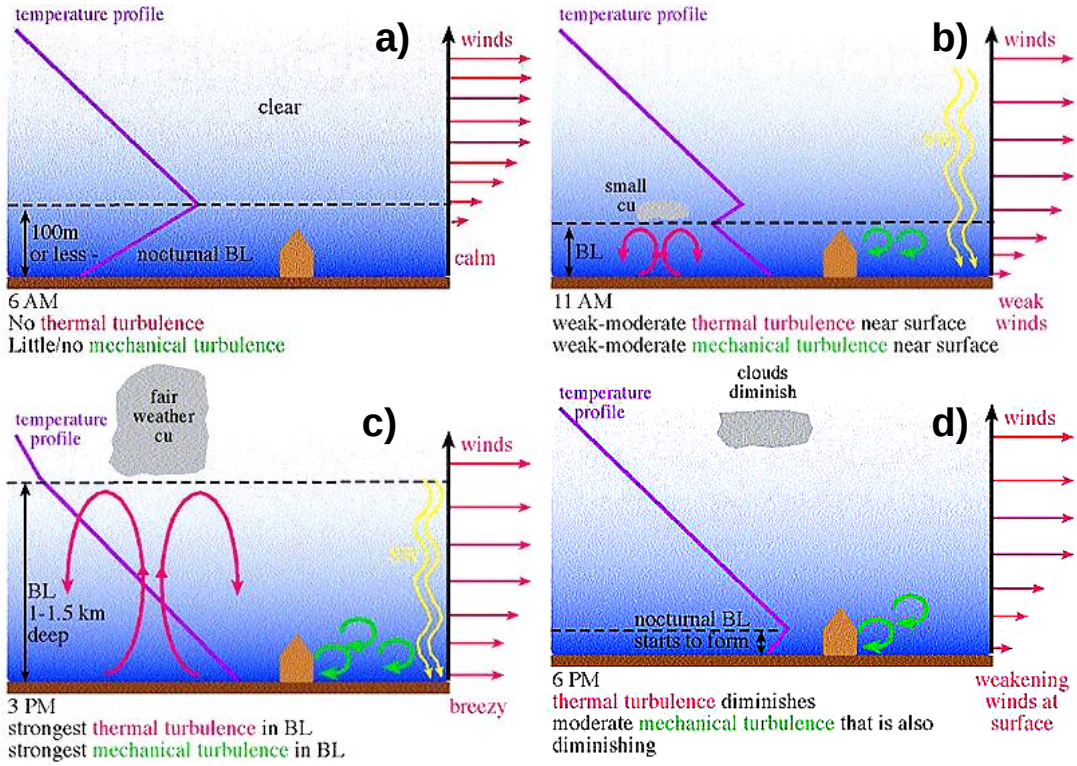


Figure: 12: Boundary layer behaviour over a 24 hours cycle.
Source of diagram: www.fas.org

Atmospheric conditions have a major effect upon pollutant dispersion. Once these pollutants are emitted, their concentrations are controlled by atmospheric motion, which is affected by winds, atmospheric stability and the vertical temperature variation within the boundary layer (Pepper *et al*., 1996; Arya 1999; Scorer, 2002).

Atmospheric stability is defined as the resistance of the atmosphere to vertical motion. The degree of stability or instability of an atmospheric layer is determined by comparing the temperature lapse rate with the appropriate adiabatic rate (i.e. the rate of temperature change occurring within a rising or descending air parcel, temperature decrease as altitude increase) (Seinfeld and Pandis, 2006).

The stability of the boundary layer largely determines pollutant concentrations and how quickly pollutants are moved upward from their ground sources on different time scales (emissions rates, chemical transformations and deposition rates must also be taken into account) (Seinfeld, 1986; Pepper *et al.*, 1996; Arya, 1999). The dilution of pollution in the mixing layer is attributed to thermal and mechanical turbulence (Figure 12) whilst the horizontal transport of pollutants is due to the wind field (Vecchi *et al.*, 2004; Pepper *et al*., 1996).

Research by Ridgy *et al*. (2006) based on data analysis for several sites in the UK, suggested that wind speed and boundary layer height were both found, on average, to be lowest in the southeast compared to the rest of the UK (e.g. PBL height can change by 10% of a summer midday mean). Their study suggested this is because of warm air advection (i.e. the process in which the wind blows from a region of warm air to a region of cooler air) from continental Europe. Furthermore, Rigby *et al*. (2006) also reported that the London boundary layer is generally deeper than in rural locations. This would mean that Kent, where the highest percentage of the land cover is agricultural land (KCC, 2005) (Section 2.5.2), as well as its eastern location, affected by the warm air advection from the near continent would have a shallower boundary layer than anywhere else in the UK, which would be an important point to take into account for the current study of PM dispersion within the region.

2.3.3 Atmospheric motions

Pollutant dispersion mechanisms depend on the topography and the weather conditions in the study area; both factors strongly influence the concentrations of particles (Pepper *et al.*, 1996). Even when emissions are relatively constant, pollution concentrations can quickly change due to the atmospheric conditions. Meetham *et al.* (1981) suggested that wind direction is the only weather variable which is likely to affect differently the pollution in different areas.

Wind determines the horizontal movement of pollution in the atmosphere. Pollution emitted from a point source, such as a smokestack, is generally dispersed downwind in the form of a “plume”, (this concept in relation to the current study is assessed in Section 4.4). The wind speed establishes the rate at which the plume contents are transported. Strong winds flowing over rough land surfaces enhance mixing of air by producing shear stress (mechanical mixing) (Figure 14a) much like that created when an electric fan

circulates air in a room. The wind direction also establishes the path followed by the pollution (Pepper *et al.*, 1996).

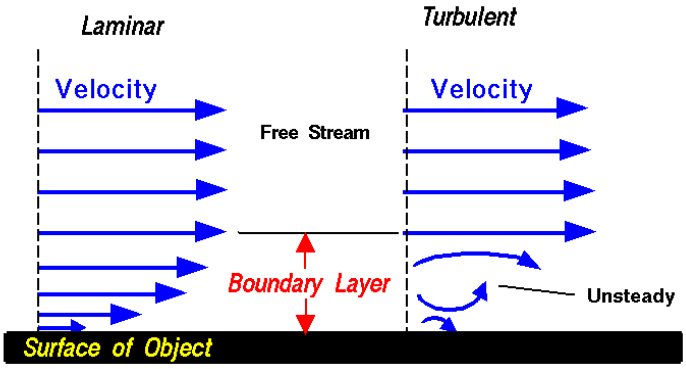


Figure 13: Planetary boundary layer diagram showing laminar and turbulent flow.
Source: www.nasa.gov

Stable air flowing over even surfaces tends to be smooth, or laminar (Figures 13). Unstable air or strong winds flowing over rough surfaces that varies continuously in time produces turbulences. This irregular air motion, known as turbulence, causes the diffusion of pollutants and may be either mechanical or thermal in nature (Figure 14). At the surface, turbulence is commonly identified in terms of eddies, whirls, and gusts aloft it is associated with "bumps" whilst flying (Lyons and Scott, 1990; Arya, 1999).

Thermal turbulence is produced by variations in solar heating of the surface and also depends on the thermal stability of the atmosphere (Figure 14b).

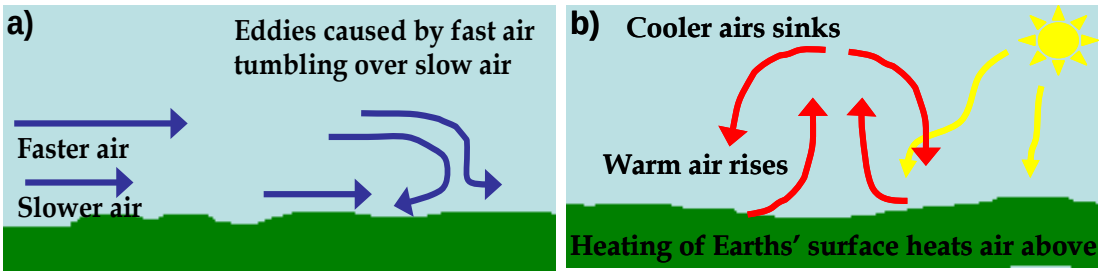


Figure 14: Illustrates examples of mechanical (14a) and thermal turbulence (14b).
Reworked copy from www.rpi.edu

Mechanical turbulence arises from the movement of air over the Earth's surface, the greater the surface roughness, the greater the turbulence (Figure 14a) (Meetham *et al.*, 1981; Lyons and Scott, 1990; Pepper *et al.*, 1996; Arya, 1999).

2.3.4 Summary of Section 2.3

The atmosphere is divided into layers according to the vertical distribution of temperature; troposphere, stratosphere, mesosphere and thermosphere. The troposphere

is the lowest layer and the layer where weather processes as well as the main dispersion of pollution takes place.

The troposphere is divided into the free troposphere and the boundary layer. The planetary boundary layer (PBL) is the lowest layer of the troposphere, forming the atmospheric interface between the troposphere and the ground surface.
The planetary boundary layer reaches its maximum activity in the afternoon (reaching up to 2 km), when the warmer air at the surface rises upward. At night, when the temperature drops, the planetary boundary layer can shrink to about 100 m depth. The stability of the PBL largely determines pollutant concentrations and how quickly pollutants are moved upward from their ground sources on different time scales. Research by Ridgy *et al*. (2006) based on data analysis for several sites in the UK, suggested that wind speed and boundary layer height were both found, on average, to be lowest for southeast airflow in comparison to rest of the UK. This research also reported that the London boundary layer is generally deeper than in rural locations.

The air motion known as turbulence causes the diffusion of pollutants may be either mechanical or thermal in nature whilst the horizontal transport of pollutants is due to the wind field. Wind determines the horizontal movement of pollution in the atmosphere. The wind direction also establishes the path followed by the pollution.
Thermal turbulence is produced by variations in the solar heating of the surface whereas mechanical turbulence arises from the movement of air over the Earth's surface, the greater the surface roughness, the greater the turbulence.

2.4 Local Wind Systems

Local or small scale (within a 40 km radius) winds often occur at a place according to its topography. Their circulation typically ranges from less than one to hundreds of kilometres across, and generally last from a few hours to a day (Seinfeld, 1986; Ahrens, 1994; Arya, 1999).

There is a large number of studies where the influence of topography on airflow has been evaluated, for example, Lyons and Olsson (1973), Segal *et al.* (1988), Khurshudyan *et al.* (1990), Thompson (1993), Varvayanni *et al.* (1995), Offer and Goosens (1995), Castro *et al.* (1996), Goosens (1996), Thielen and Gadian (1996), Raupach and Finnigan (1997), Arya, (1999), Whiteman (2000), Laird *et al.* (2000), Kondo *et al*. (2002) and Evtyugina,

et al. (2006). However, no specific studies on topographic airflow in Kent have been found. Nevertheless, many topographic flow studies focused elsewhere have been examined, as in the following examples: Lyons and Olsson (1973), Varvayanni *et al.* (1995), Offer and Goosens (1995), Castro *et al.* (1996), Goosens (1996), Thielen and Gadian (1996), Raupach and Finnigan (1997), Arya, (1999), Whiteman (2000), Laird *et al.* (2000), Kondo *et al*. (2002), Buchanan *et al.* (2002) and Evtyugina, *et al.* (2006).

The literature review focuses on studies of regional airflows affected by similar features to the ones found in the study area (Section 2.5). These analogue studies can be related to Kent and provide clues on how airflow might behave in areas with similar topographical features, such as coast (Section 2.4.1), mountain or hill winds (Section 2.4.2) and airflow behaviour over urban areas (Sections 2.4.3, 2.4.4 and 2.4.5).

2.4.1 Coastal winds (sea and land breezes)

The proximity of Kent to the North Sea and the English Channel can lead to local on-shore and off-shore wind patterns. The uneven heating rates of land and water during the day cause this mesoscale (i.e. regional or up to 100 kilometres in diameter) type of coastal wind (WHO, 1992; Barry and Chorley, 1998). These wind patterns are a type of thermal circulation termed sea or land breezes depending on where they are generated (Ahrens, 1994). Land surfaces are poor conductors of heat: their temperature increases rapidly in sunshine and decreases equally quickly at night. Because of this, as the sea warms up and cools down more slowly than the land, it creates temperature contrasts at different times of year. These contrasts produce local land and sea breezes along coastlines (Seinfeld 1986; Moran and Morgan, 1989; Ahrens, 1994; Barry and Chorley, 1998) (Figure 15).

On a larger scale the sea acts as a reservoir of heat during the summer, keeping coastal regions milder than regions inland in the autumn. In summer, the sea warms up slowly providing sea breezes that keep temperatures near coasts below those inland. It also helps to explain why, overnight temperatures near the coast are often higher than inland (Moran and Morgan, 1989; Parker, 1989; Henderson and Robinson, 1991; Ahrens, 1994).

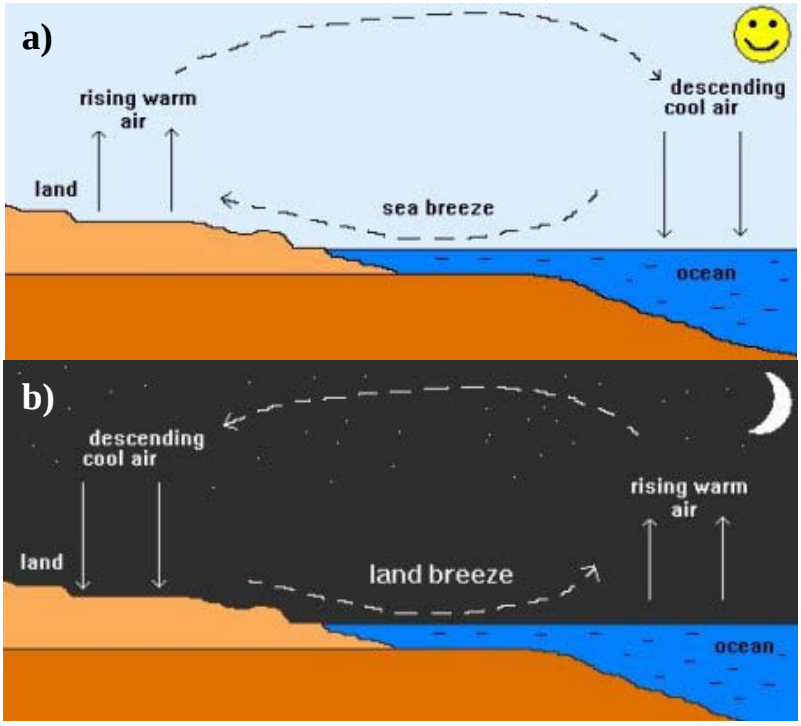


Figure 15: Illustrations of the sea 15a and land breeze processes 15b.
Source: www.ace.mmu.ac.uk

Recent studies carried out in Portugal indicate that the coastal breezes play an important role in the air circulation during summer and, consequently, affect the regional air pollutants' distribution (Evtyugina *et al.*, 2001 and 2006). Particularly, the sea breeze was suggested to be responsible for the transport (up to 50 km inland) of air pollutants emitted at the coastal urban and suburban zones (Van Dingenen *et al.* (2004); Putaud *et al.* (2004)).

These similar wind patterns bringing wind up to several kilometres inland have been observed in many places around the world: these types of local winds normally play an important role in PM dispersion (Lyons and Olsson, 1973; Seinfeld, 1986; Parker, 1989; Laird *et al.*, 2000, Arya, 1999; Buchanan *et al.*, 2002). For instance, a study by Rigby *et al*. (2006) suggested that a sea breeze from the east affecting the UK could facilitate the dispersion of particles arriving from the near continent. The wind flow can transport pollutants, dust and chemical agents throughout coastal metropolitan areas, representing a significant air-quality problem. This problem has long been studied within the Great Lakes area where it was observed that localised winds can extend a few kilometres in to sea or in this case, the lakes, as much as 20 km inland (Lyons and Olsson 1973, Parker, 1989; Laird *et al.*, 2000). Measurements made at Chicago on the shore of Lake Michigan suggest that there is a closed circulation cell over the shore line and that emissions released from chimneys within the flow layer inland, rise in the convection up-draught at

the sea breeze and return in the layer aloft (Lyons and Olsson, 1973; Parker, 1989; Arya, 1999; Laird *et al.*, 2000).

Because of sea breezes bringing concentrations inland the pollution values are appreciably higher than would otherwise be expected (Lyons and Olsson, 1973: Parker, 1989; Arya, 1999). This remark will be taken into account during the course of this investigation, as well as that, the potential patterns within the Kent coastline will be examined.

2.4.2 Mountain and valley airflow

Along mountain slopes that are exposed to intense solar heating, a localised air circulation may be developed that reverses direction between day and night. These two types of circulation are known as mountain and valley breezes (Moran and Morgan, 1989; Ahrens, 1994; Barry and Chorley, 1998) (Figure 16).

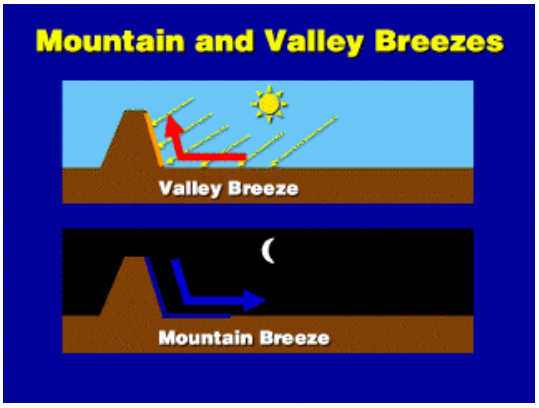


Figure 16: A schematic representation of mountain and valley breezes.
Source: www.atmos.ucla.edu

The valley breeze, or anabatic flow, is produced when valley walls facing the Sun absorb the solar radiation and the air in contact is heated. The heated air, being less dense than the air above the valley, rises as a gentle upslope wind. As a consequence cumulus clouds may develop near the mountain top. On the other hand, the mountain breeze, or katabatic flow, is produced at night with clear skies and intense radiational cooling. The mountain slope cools rapidly and the air in contact with the slope is chilled. The cooler, denser, air glides down the slope into the valley (Moran and Morgan, 1989: Ahrens, 1994; Barry and Chorley, 1998). Air pollution concentrations in mountain valleys tend to be greatest during the colder months. During the warmer months, daytime heating can warm the sides of the valley to the point that upslope valley winds vent the pollutants upward (Ahrens, 1994).

Many studies in Europe and North America have reported on valley airflow systems and PM dispersal in sites with topography similar to Kent (Section 2.5.2) (Goosens, 1988, 1996; Offer and Goosens, 1995; Mason *et al.*, 1999; Parker and Kinnersley, 2004). Airflow within valleys is important for modelling and predicting patterns of air pollution dispersal (Khurshudyan *et al.*, 1990; Segal *et al.*, 1988) and the concentrations or dispersal of suspended particles (Thompson, 1993).

In the current study, these type of mountain and valley breezes may occur in the North Downs and the Greendsand Ridge (Figure 25) and may affect the dispersion of particles both ways, emissions coming from the north of the county and the city of London, as well as affecting the trans-boundary dispersion of PM arriving from the continent. This assumption is developed and evaluated in Sections 3.3 and 3.4.

2.4.3 Heat island effect

Urban areas with multiple intersecting paved roads, dense irregular buildings and impervious surface materials, are different from the suburbs both in materials and geometric structures (WHO, 1992). This has implications for the energy and moisture balance; the city centre is frequently a few degrees warmer than the outskirts (the heat-island effect) and this may lead to the generation of a thermal breeze circulation, analogous to a sea breeze effect (Strauss and Mainwaring, 1984; WHO, 1992; Arya, 1999). This regional circulation takes the form of warmer air rising in the city centre and moving out to the suburbs, while the cooler air is drawn into the city centre from the outskirts and rural fringes (Strauss and Mainwaring, 1984) (Figure 17).

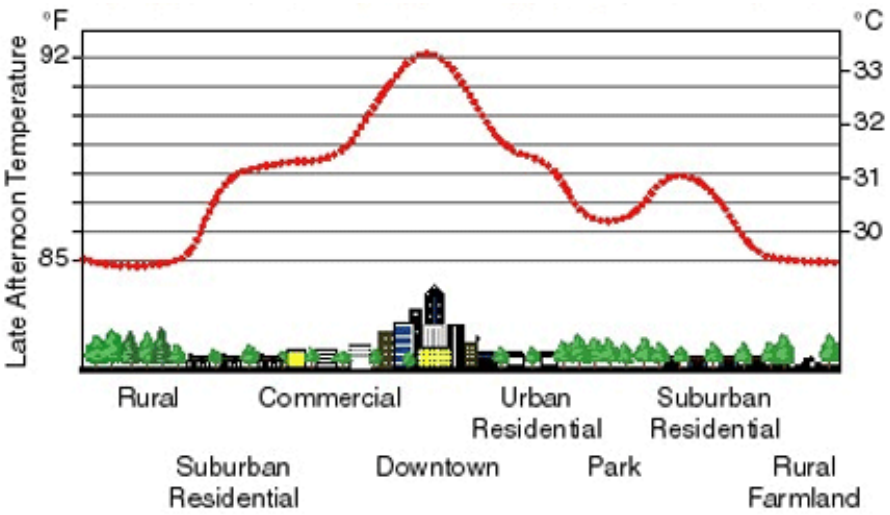


Figure 17: Illustrates an urban heat island profile.
Source: www.metoffice.gov.uk

The result is that pollutants are spread throughout the urban area. Cities turn into heat islands in comparison with surrounding countryside in both summer and winter (Lee, 1979; Strauss and Mainwaring, 1984; Elsom, 1992; WHO, 1992; Ahrens, 1994; Arya, 1999). This effect has now been observed in many cities around the world (WHO, 1992; Ahrens, 1994). Figure 18 illustrates an example of London's heat island effect.

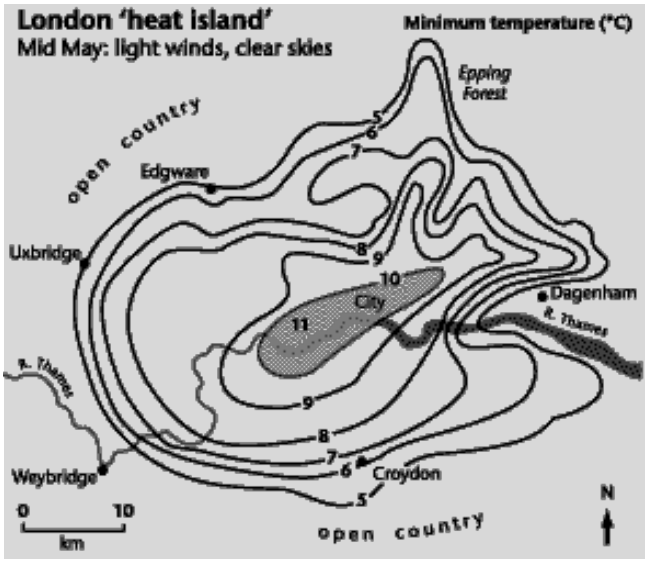


Figure 18: London heat island effect.
Source: www.metoffice.gov.uk

These types of thermal inversions (Figure 19a) are a particular problem in temperate and cold climates. Under normal dispersive conditions, hot pollutants rise as they come into contact with colder air masses with increasing altitude (Lee, 1979; Strauss and Mainwaring, 1984; Elsom, 1992). However, under certain circumstances the temperature may increase with altitude and an inversion layer forms a few hundreds of metres above the ground (Ahrens, 1994; Scorer 2002).

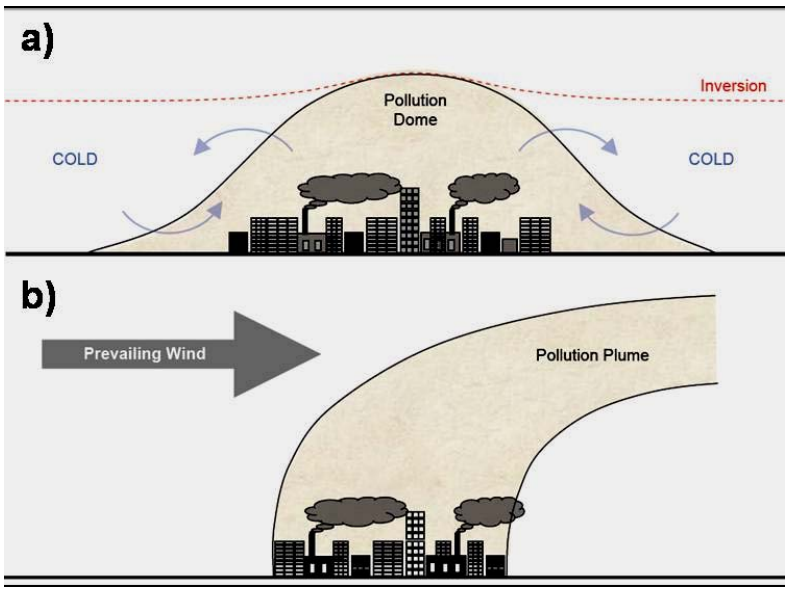


Figure 19: Examples of pollution dome.
Source: www. Metoffice.gov.uk

This inversion layer (Figure 19a) may then trap pollutants close to the emissions source and act as a heat cover (pollution dome) prolonging the inversion (Elsom, 1992; Ahrens, 1994; Scorer, 2002). These conditions are of greatest concern when the absence of strong winds to both disperse the heat and bring in cooler air from rural and suburban areas (Figure 19b). They can lead to some extreme pollution episodes such as the one occurring in London during August 2003. This severe episode of pollution was caused by high pressure causing one of the most severe heatwaves that has ever affected the southeast of England; temperatures exceeded 32°C on eight consecutive days from 4th of August. The pollution episode lasted more than a week ending with an influx of clean air masses of oceanic origin arriving from the southwest (Section 3.5.2 and Section 4.5.2).

2.4.4. Airflow within the urban environment

The local topography of a landscape can have a profound influence on airflow characteristics and cause modifications to broader synoptic scale winds. For example, hill crests are windier than valleys, topography strongly modulates cloudiness and precipitation. Wind flow is determined by the geographical features and elevation of the area (Figure 20) (Strauss and Mainwaring, 1984; Pepper *et al.*, 1996; Raupach and Finnigan, 1997).

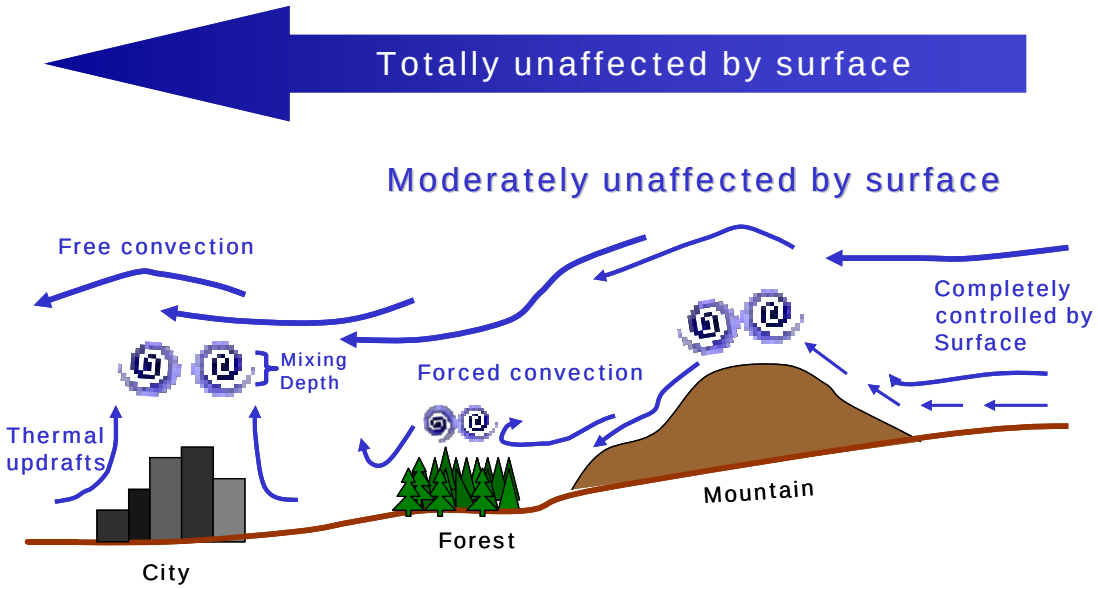


Figure 20: Diagrammatic representation of airflow, mixing and relative velocity over varying terrain as affected by height.
Reworked copy from Pepper et al. (1996).

Isolated hills which act as barriers to the wind have flows that are very similar to flow patterns around obstacles (such as buildings) (Figure 20 and 21). The major differences are those of scale. In addition, topographic features tend to be more rounded than most urban obstacles (Figure 20). The resultant flows tend to be smoother, although turbulence can be produced (Moran and Morgan, 1989; Barry and Chorley, 1998).

A city acts as a much rougher surface than rural areas, leading to a decrease in wind speed. The buildings tend to act as obstacles to the wind flow. The result is often known as the "urban plume" this is an increase in turbulence within the city and the development of a distinct internal boundary layer which forces the wind flow to rise over the city (Figure 19b) (Henderson and Robinson, 1991; Scorer, 2002).

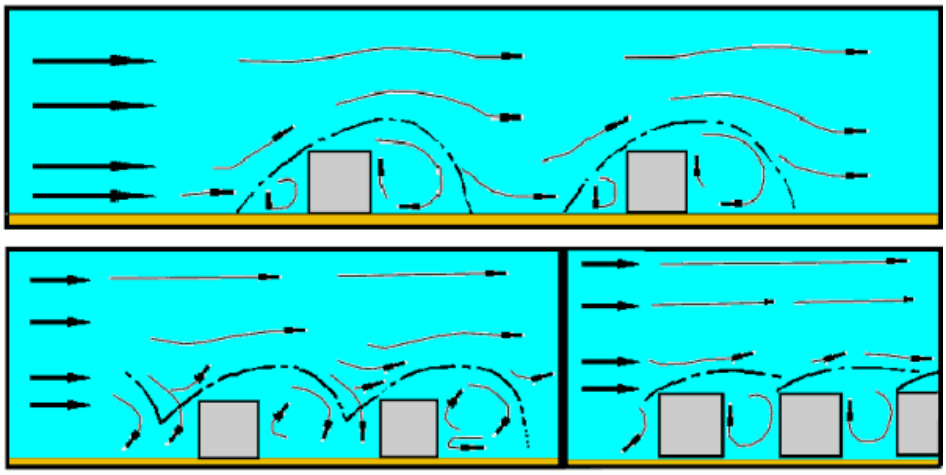


Figure 21: Urban wind flow patterns with various simple building shapes and spacing
Source: www.islandnet.com

Another type of flow to be found over buildings and other structures and can have a great effect upon the dispersion of pollutants is the street canyon. This is the term used to define the dispersion of pollutants by the prevailing winds that is stopped by tall buildings on each side of a road (WHO, 1992).

Kent has a distinctive dispersed settlement pattern (Figure 22): 12 % of Kent's land cover is urban area (KCC, 2005). These types of flow (urban plume and airflow over buildings) are likely to be found in larger urban areas such as Maidstone, the Medway area, Ashford, Canterbury, Folkestone Deal and London surroundings (Gravesham and Dartford).

Figure 22: Map showing main urban areas in Kent and the interurban routes.
Adapted from: www.kent.gov.uk/environment/

2.4.5 Summary of Section 2.4

Local or small scale winds often occur at a place according to its topography. Their circulation typically ranges from less than one to hundreds of kilometres across, and generally last from a few hours to a day.

The proximity of Kent to the North Sea and the English Channel, can lead to local on-shore and off-shore wind patterns. These wind patterns are a type of thermal circulation termed sea or land breezes depending on where they are generated. Due to the topography of the study area, local winds taken place in mountains and valley are also considered. In addition, a city acts as a much rougher surface than rural areas, leading to a decrease in wind speed. The buildings tend to act as obstacles to the wind flow, therefore airflow over urban areas was also taken into account.

2.5 Study area

2.5.1 Location

The study area for this project is Kent, a county located in the Southeast of England. The county is also very close to mainland Europe (34 km (21miles)) at the narrowest part of the Channel (Figure 1).

2.5.2 Kent topographical features and characteristics

Kent is exposed to widely varying elements of the sea and weather. The coastline stretches over 500 km (300 miles). The county is bounded on the north by the North Sea and the Thames Estuary, the east and south coast are bordered by the English Channel (Nicolson, 1988; KCC, 2005).

Kent has complex valley systems running between 10 and 20 km inland, so it provides an ideal site for an investigation into topographical-modified airflows and, as a consequence, the dispersion of particulate matter (Figure 23).

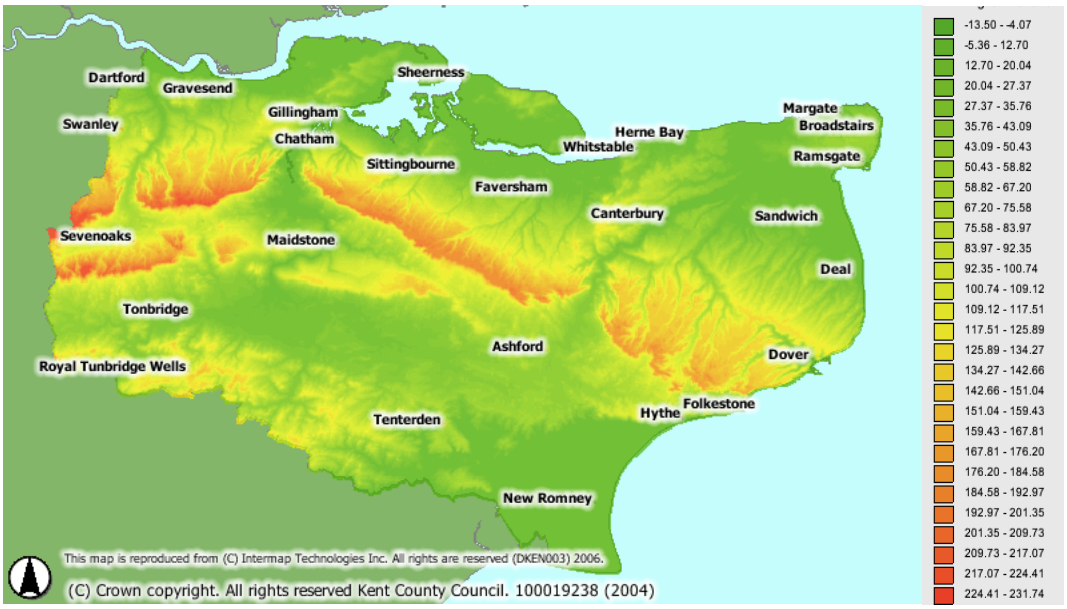


Figure 23: Digital elevation map of Kent
(Note: Digital elevation model values are shown in meters).
Source: www.extranet7.kent.gov.uk/klis/home.htm

According to Kent County Council (KCC 2004, 2005), Kent is still predominantly an agricultural county (67% of the total land cover is agricultural land). The urban area takes up 15 % of the county, while the other 18 % is split between wetland (2 %), coastland (4 %) and woodland areas (12 %).

Although there are no mountains or moors, the topography of Kent, however, is complex in places, with areas of well-defined elevation such as the Greensand Ridge at Sevenoaks, a long coastline and a relatively flat inland area called the Weald that stretches over an area of approximately 112 km long and 50 km wide (Figure 25).

The major geological features of the county are determined by a series of ridges and valleys running east-west across the county. These are the results of weathering affecting the Weald (Figure 24). The Weald consists of an upper layer of chalk above subsequent

layers of upper greensand, upper clay, lower greensand, lower clay and red sandstone. The ridges and valleys formed as the exposed clay eroded faster than the exposed chalk, greensand, or red sandstone (Figure 24).

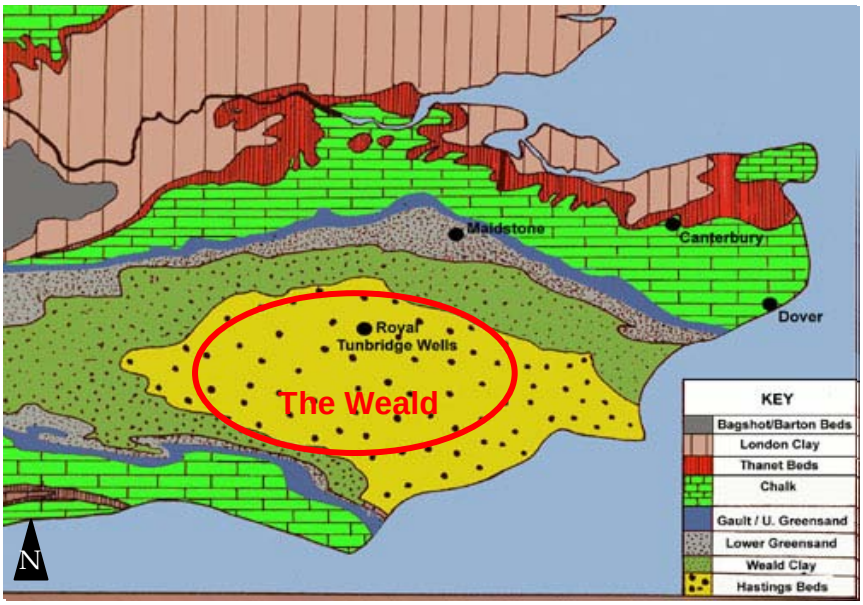


Figure 24: Geological map of Kent.
Source: www.kentrigs.org.uk

The three major rivers, the Darent, Medway and Great Stour have cut their way down through the chalk, creating wide river valleys, with their floodplains and alluvial soils which is one of the main factors affecting topography (Nicolson, 1988; Kent Downs web site, 2007) (Figure25).

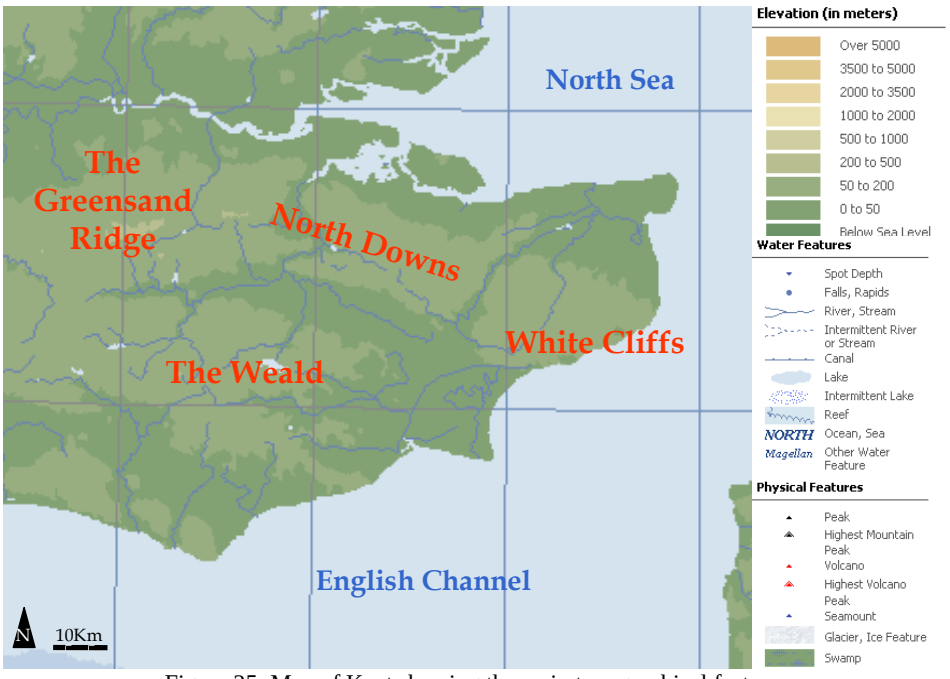


Figure 25: Map of Kent showing the main topographical features.
Adapted from Microsoft Encarta (2003)

The main topographical landscape features in Kent distinguished by Kent County Council (2005) (Figure 25) are:

- North Downs, extending throughout the county, containing the chalk grassland (very important for wildlife habitats), ancient woodlands, sands, clays and fruit growing. Located in the northern part of the country.
- The Greensand Ridge, limestone geology rises as the dramatic scarp of Toys Hill south of Sevenoaks, extensive woodlands and heath. The top of the Greensand Ridge at Sevenoaks is southeast England's highest point at 250 m.
- The Weald, great tracts of clay lowland forming heavy, wet, often waterlogged land.
- The White Cliffs, between Dover and Deal, facing the English Channel.

2.5.3 Sources of particulate matter in Kent

Kent's major seaports are among the UK's busiest transport gateways (KCC, 2005). The main focus of Kent's port function is the Dover Strait and operations between Dover (Port of Dover) and Cheriton (Channel Tunnel) and Nord Pas-de-Calais (France). This short stretch of water is widely acknowledged to be the busiest cross-channel transport corridor in the world and reinforces Kent's status as the Southeast's principal maritime gateway.

Figure 26: Kent's motorway network.
Source: www.highways.gov.uk

Consideration also needs to be taken of the levels of traffic affecting the county, Kent is a major transport corridor between the UK and the continent, its motorway and trunk road network is over 400 km in length (Figures 22 and 26).

Major roads in Kent carry around 88,500 vehicles per day compared to the national average of 80,100 vehicles a day (KCC, 2005). Two of the busiest motorways in the

whole of the UK, the M20 (from the Eurotunnel (Folkestone) to London) and the M2 (communicating Dover Port with the Capital), run through the middle of the county (KCC, 2005) (Figure 26).

According to the National Emissions Centre (2006, 2010) the higher levels of PM on the county are located mainly in the northwest part (heavily industrialised area) closer to the city of London. However, in addition to the elevated levels of PM in the Capital and its surroundings, it can be observed in Figure 27 that there is a high level of particulate matter in the Dover area and the English Channel. This could be related to emissions from the ferries crossing the English Channel, or a plume arriving from the near continent, these hypotheses will be investigated during the course of this research, as well as any other possible factors contributing to the elevated number of particles in the area.

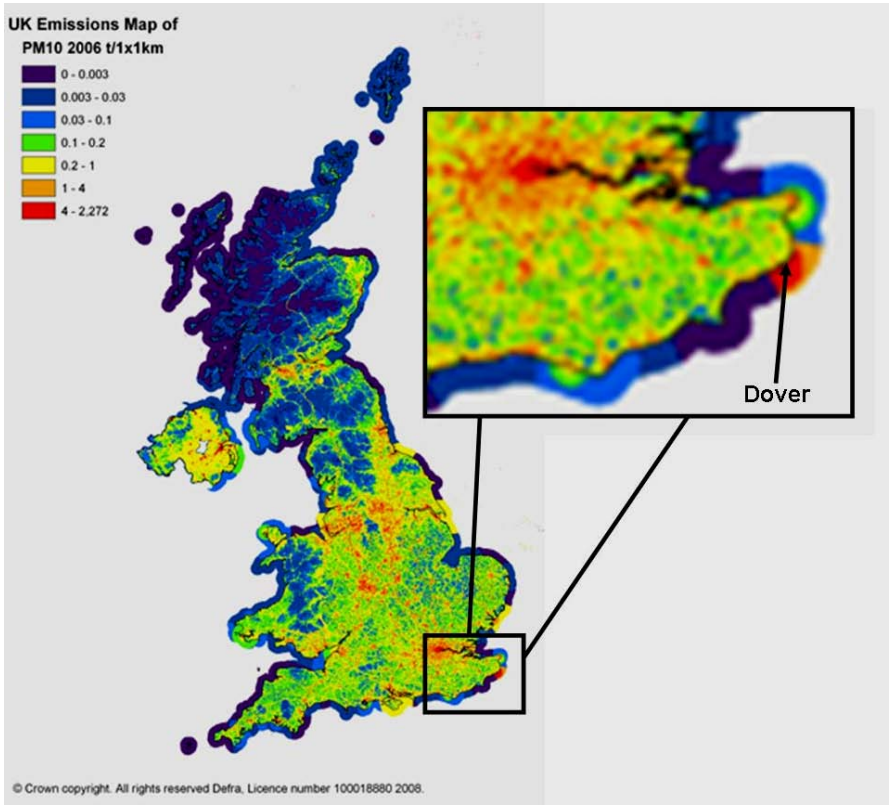


Figure 27: Map showing UK PM_{10} emissions for 2006 (zoom in on the southeast of England). Source: www.naei.org.uk

Kent County Council (2005) noted that six of the 13 districts in Kent are affected by high emissions of $PM_{10,}$ exceeding the European Union limit values and the UK Air Quality Strategy annual targets (Section 2.2.2). These districts are all located in the western and northern part of the county: Dartford, Gravesham, Maidstone, Sevenoaks, Tonbridge and Medway (Figure 28).

This could mean that PM values are mainly affected by the city of London. Nevertheless, this thesis evaluates this and other hypotheses and estimates whether the PM values registered over the county are caused by local sources or influenced by a trans-boundary process.

Figure 28: Map showing all Kent districts, underlined in red are the districts with higher level of PM_{10}. (Adapted from: www.kent.gov.uk)

However, air pollution is not an issue that can be tackled in isolation within Kent. The influence of the city of London and Europe on Kent's air is significant, focusing the need for working together with neighbouring areas and looking into the influence of trans-boundary pollution to and from the near continent (Section 4.6).

2.5.4 Summary of Section 2.5

Kent is located in the southeast of England. It is bounded on the north by the North Sea and the Thames Estuary, and on the east and south coast is bordered by the English Channel. Kent is very close to mainland Europe (34 km (21miles)). Its topography can be described as mainly flat (no mountains or moors). The major geological features of the county are determined by a series of ridges and valleys running east-west across the county. The main topographical landscape features are: the North Downs, the Greensand Ridge, the Weald and the White Cliffs.

Dover, the busiest port in the UK, is located in Kent, as a result the county is a major transport corridor between the UK and the continent, its motorway and trunk road network is over 400 km in length. The influence of the city of London and Europe on Kent's air is also significant, contributing to the high emissions of PM. Due to its south-eastern location, Kent is the closest county to the near continent. All of these factors make Kent an ideal site for an investigation into topographical-modified airflows, trans-boundary flow and the dispersion of particulate matter as a consequence of these.

2.6. Weather systems

Particles are airborne: therefore they can be affected by wind direction and speed, precipitation, air pressures and other meteorological conditions (Legge and Krupa, 1986; Pepper *et al.*, 1996). Arya (1999) states that by the time macro-scale transport become effective, pollutants from individual sources have undergone successive diffusion and dispersion by micro-scale and synoptic (or large) scale systems. A review of all weather scales which affect the journey of airborne particles within the study area is shown within this section.

2.6.1 British airflow patterns

The British Isles (50̊ –60˚N, 2˚E–10˚W) are exposed to trains of low pressure systems from the Atlantic and are well ventilated by the dominant south-westerly winds. Wind directions from southwest-west-northwest dominate the whole year distribution. More locally, topographical features modify the general pattern of wind speed and direction by the presence of land blocks or deep valleys give rise to local variations (Parker, 1989; Pepper *et al.*, 1996).

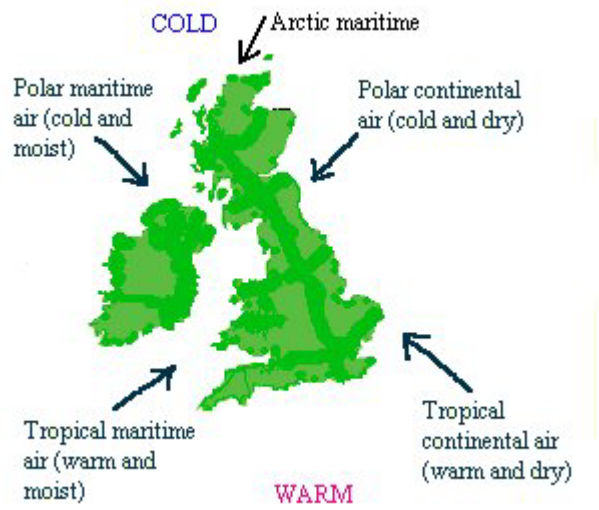


Figure 29: Main categories of air masses affecting the British Isles.
Source: www.ace.mmu.ac.uk

Emphasis throughout has been given to the major categories of airflow affecting the British Isles (as defined by Lamb, 1972). Lamb identified seven airflow patterns in Britain. These airflow types are: westerly (W), north-westerly (NW), northerly (N), easterly (E) and southerly (S) types-referring to the compass direction from which the airflow and weather systems are moving and cyclonic (C) or anticyclonic (A) types when a depression or a high-pressure cell dominates the weather map.

On an annual basis, the most frequent airflow type is westerly, including cyclonic and anticyclonic subtypes. The westerly type involves unsettled weather with variable wind direction as depressions cross the country. It has been characterised for being mild and stormy in winter, whilst generally cool and cloudy in summer (Parker, 1989; Barry and Chorley, 1998).

2.6.2 Synoptic weather systems

Synoptic scale systems (circulations of this magnitude dominate regions of hundreds to even thousands of square kilometres) such as air masses, fronts and mid-latitude depression, greatly influence and determine the day-to-day weather (Ahrens, 1994). Synoptic weather systems affect the dispersion of pollutants released in the lower part of the atmosphere on a time scale of a day or longer (Pepper *et al.*, 1996; Arya, 1999).

Once particles are airborne, their transport is largely governed by weather conditions. Certain weather patterns favour light winds and thus inhibit the dispersal of particles (VanCuren, 1999). Over a broad area at the centre of an anticyclone, for example, horizontal air pressure gradients are weak and consequently, winds are very light or calm, so particles do not disperse readily. On the other hand, with a mid-latitude depression, steeper air pressure gradients mean stronger winds and more rapid dispersion of the particles. This will indicate that most of the dispersion of particles occurring in the UK is influenced by the westerly type main airflow (Henderson and Robinson, 1991; Moran and Morgan, 1989; Franzen *et al.*, 1995; Raupach and Finnigan, 1997; Buchanan *et al.*, 2002).

2.6.3 Local weather and Climate (Kent County)

Southeast England combines the highest average daytime temperatures found in the British Isles with the highest sunshine averages on the British mainland (Figure 25) (UK Met Office, 2005). North-facing resorts along the east coast, such as Herne Bay and Whitstable, being backed by the Downs to the south, can feature in several of the highest recorded spring and autumn temperatures. The occurrence of many extreme spring, summer and autumn maximum temperatures in the London area may not reflect the "urban effect" so much as the capital is favourably sheltered to the south by the North Downs (described in Sections 2.5.2 and 2.5.3) (Figure 25 and 26).

Generally between 635 and 760 mm (25 and 30 inches) of rainfall are recorded every year in Kent (UK Met Office, 2005). The rainfall distribution within the county is highly influenced by its main topographical features, the North Downs and the Weald (Section 2.5.2, Figure 24 and 25) (Met Office UK reports, 2006).

2.6.4 Summary of Section 2.6

Synoptic scale systems such as air masses, fronts, mid-latitude depression, greatly influence and determine the day-to-day weather. These synoptic systems affect the dispersion of pollutants released in the lower part of the atmosphere on a time scale of a day or longer. Most of the dispersion of particles occurring in the UK is influenced by the westerly type main airflow.

The British climate is characterised by warm summers, cool winters, and precipitation throughout. The British climate is relatively mild for its latitude because it is influenced by North Atlantic Drift originating from the Gulf Stream warmth. The Gulf Stream is a warm surface ocean current which originates in the Gulf of Mexico and flows northeast across the Atlantic, driven by the prevailing southwest winds.

The weather in the Southeast of England combines the highest average daytime temperatures found in the British Isles with the highest sunshine averages on the British mainland. It seems that the rainfall distribution in Kent is influenced highly by its main topographical features, mainly the North Downs and the Weald.

2.7 Summary of Chapter 2

Chapter 2 has aimed to provide a clearer understanding of the relationship between particulate matter pollution and the environmental factors affecting their dispersion. These factors include: geographical features of the studied area, topographically modified airflows local and broad-scale winds, atmospheric motions, climate, local sources as well as trans-boundary pollution.

The first Section, 2.2, addresses PM, their characterisation, discussing their sources, the impacts that PM has on humans and within the environment as well as describing the main dispersion and removal process from the atmosphere. The other five divisions describe physical processes that affect their dispersion.

Section, 2.3, described the atmosphere and its scales ranging from short-lived local winds to global scale wind belts circling the Earth. The atmosphere is the vehicle used for particles to make their journeys, affecting the whole process from source to deposition.

Section 2.4 addresses the main types of local wind that can be found within the studied area. During the literature review, analogue studies were examined that can be related to Kent and provide clues on how airflow might behave in areas with similar topographical features.

The following division (Section 2.5) introduces the study area, describing its main topographical and geographical (physical and human) characteristics that made Kent an ideal location for a study of these characteristics.

Finally, Section 2.6 outlines basic notions of British airflow, synoptic weather patterns and local weather affecting the studied area.

Chapter 3 explains the specific methods used during the process of this investigation and describes the analysis of the local wind patterns affecting the study area as well as the PM emissions and the relationships between both sets of data.

Chapter 3

Methodology

3.1 Overview of Chapter 3

In Chapter 2, the complexity involved in the process of this investigation has been perceived. The study of the dispersal of PM_{10} requires several variables to be taken into account, such as local weather patterns, topography affecting airflow, contributions from trans-boundary pollution and local emissions.

Consequently, the research methodology has focussed on five main themes. Firstly, the analysis of wind data on two scales (local and synoptic) (Section 3.2). Secondly, analyses of PM_{10} capture patterns were considered, as well as assessing the relationship between local factors and PM_{10} distribution (Section 3.3). This was then followed by a comparison between the weather data and the PM_{10} data, in order to assess the influence of the local weather and particularly the role of wind direction in the PM_{10} distribution throughout the study site (Section 3.4). Section 3.5 describes the methodology developed in two case studies. These case studies have been chosen as examples based on the main types of pollution episode affecting the UK. The last part of this chapter, Section 3.6, describes the setting of the monitoring trap used to sample PM in relation to trans-boundary dispersion, as well as the sampling strategy and the different approaches assessed to analyse the data collected.

3.2 Wind data

3.2.1 Local wind data from Lower Stoke

At the beginning of this investigation weather data from Lower Stoke, in the north of Kent (Figure 31), were used as ‘test’ material to develop and evaluate the methodologies. The data were provided electronically by the Environmental Research Group (ERG) (http://www.kentair.org.uk/kent/asp/ContinuousData.asp) at Kings College, London. The local wind data covered the period 2000 to 2008. Having refined those methodologies, they could be applied to local wind data from the other sampling sites, at a later date.

Although data on air pressure, rainfall, temperature, wind direction and wind speed were obtained in order to draw a clearer picture of what was occurring in the study area, for the purpose of this study only the wind direction and wind speed records were required for detailed analysis.

The data sets were received in a disorderly format (see Appendix A). The first step to allow the use and analysis of the data was to organise it and separate the data by date in different spreadsheets.

The re-organisation of the data was a complex process due to the large number of records: the wind data were collected every 15 minutes, generating 96 records *per* day, which adds to a total of 315,648 records over the nine years study.

This information had to be organised into hours, days, months and years. The easiest method found to achieve this was by using filters in Microsoft Excel and grouping the data by the variable chosen, in this case wind direction or wind speed (an example can be seen in Appendix B).

3.2.2 Extraction of local wind data

The wind direction data were given in degrees which meant that the estimation of the frequencies was very complicated. In order to simplify things, a method was created to represent degrees as text or character format.

The method devised was to use a conditional formula in a spreadsheet. This formula was based upon 360 degrees divided equally between the eight main points on a compass (N, NE, E, SE, S, SW, W and NW) to give a 'window' of 45 degrees *per* point (Figure 30).

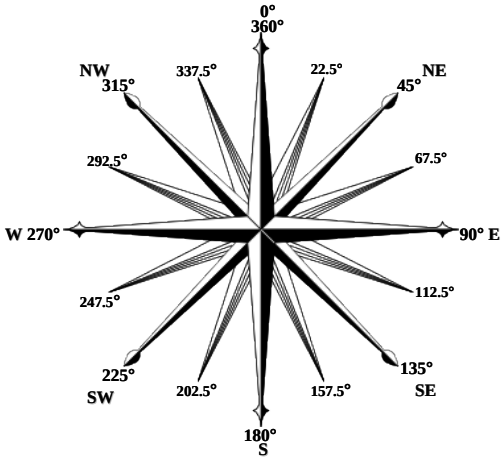


Figure 30: A compass rose showing the degree number given corresponding to each cardinal direction. Adapted from Microsoft Clipart, 2008.

The formula then took the given input of degrees, and checked which window it fitted into. This generated a character output of the corresponding portion of the compass. The formula and sample output can be seen in Appendix C. Once the formula was applied, frequencies were calculated for the eight compass point directions, counting the number of times that every value was repeated. From this point it was then possible to find wind direction frequencies and begin to examine the data statistically (Section 3.2.6).

3.2.3 Analysis of the local wind direction data from Lower Stoke

The main focus of this part of the investigation was to identify patterns in the wind direction and to determine whether or not these were influenced in any way by seasonality.

In a first approach, the data sets were divided into three-month intervals: January to March, April to June, July to September, and October to December. Based upon the frequencies calculated, charts including the data from the nine target years were produced in order to examine variations in wind direction during seasons.

Each individual monthly set was also evaluated for comparison and each selected week was then compared with the same period throughout the nine years. This examination aimed to find any changes of wind direction or patterns affected by seasonality in the study area. These changes of wind directions can often be attributed to either the increase or decrease of temperature caused by variation in insolation warming or cooling the land, or to the influence of synoptic scale winds.

A more detailed analysis was then carried out, to investigate specific patterns or relationships. Bearing in mind that the data were given every 15 minutes, the data for every month were organised every 12 hours using filters (one set from 00.00 to 11.45 GMT and the other from 12.00 to 23.45 G.M.T). These times were chosen to best correspond with the coolest and warmest parts of the day, respectively, as well as an aid to investigate any correlation between sunrise and sunset (and the changes in wind direction link to temperature variation during these periods), these changes were noted and compared.

Furthermore, it was decided to carry out a final analysis of the data by studying the correlation between wind direction shifts and fluctuation in temperature through the day (with a special focus on sunrise, sunset and afternoon). This methodology is described in more detail in Section 3.2.7.

3.2.4 Synoptic data

Daily synoptic charts showing surface level atmospheric pressure at 00.00 GMT were obtained electronically from the European Meteorological Bulletin (Deutschen Wetterdienstes, Offenbach, in Germany http://www.westwind.ch). As with the local sets, the synoptic data collected covered the period 2000 to 2008 (an example of a synoptic chart can be seen in Appendix D). The charts were used to extract wind speed, wind direction, cloud cover and past and present weather. Wickham (1970) suggested carrying out this method with the purpose of archiving enough data to form a coherent picture of the weather patterns over the study area (an example of the raw data collected is shown in Appendix E).

A record was made of the main wind direction every day and the wind direction data recorded were imported to Excel spreadsheets. From these data, frequencies of wind direction were extracted by counting the number of times that every value was repeated *per* year. Charts of the frequency distributions were produced in order to identify different wind directions during seasons in all the years.

3.2.5 Comparison between the local wind data and the synoptic data

The locally-measured wind directions at Lower Stoke (Section 3.2.3) were compared with those assessed using the daily synoptic scale data (Section 3.2.4), in order to identify any topographically-induced local wind systems, the presence of which may be masked by looking at synoptic-scale weather only (see also Section 2.7).

In an earlier stage, the results of the wind direction frequencies at Lower Stoke were compared with those extracted from the synoptic charts. Values of Log (Frequency + 1) (to account for low catch frequencies) were calculated for both sets of data, and the data were then compared and presented in a graphical form (see Section 4.2.3).
However, there were some issues found with that method, and it was changed, the reasons for this are explained as part of the results in Section 4.2.3. Consequently, another method needed to be created to be able to compare the two sets of data. The main difficulty found was that the synoptic data consist of just one daily value whereas the local data consisted of 96 records *per* day. As a result, it was decided to calculate the median wind direction of each day in order to produce a unique value for that day; this was compared with the synoptic

value. Both sets of data (local and synoptic) were then represented in graphical form, compared and their correlations between years calculated.

3.2.6 Comparison of all available wind data sets

The ERG website had six further sites with weather data available: Dover (Langdon Cliff), Gravesham (A2), Lower Stoke, Sevenoaks, Swale (Ospringe and Sheerness), as well as Thanet (Manston airport) (Figure 31). The data from these sites were extracted and the methodology already outlined in Sections 3.2.2 and 3.2.3 was employed.

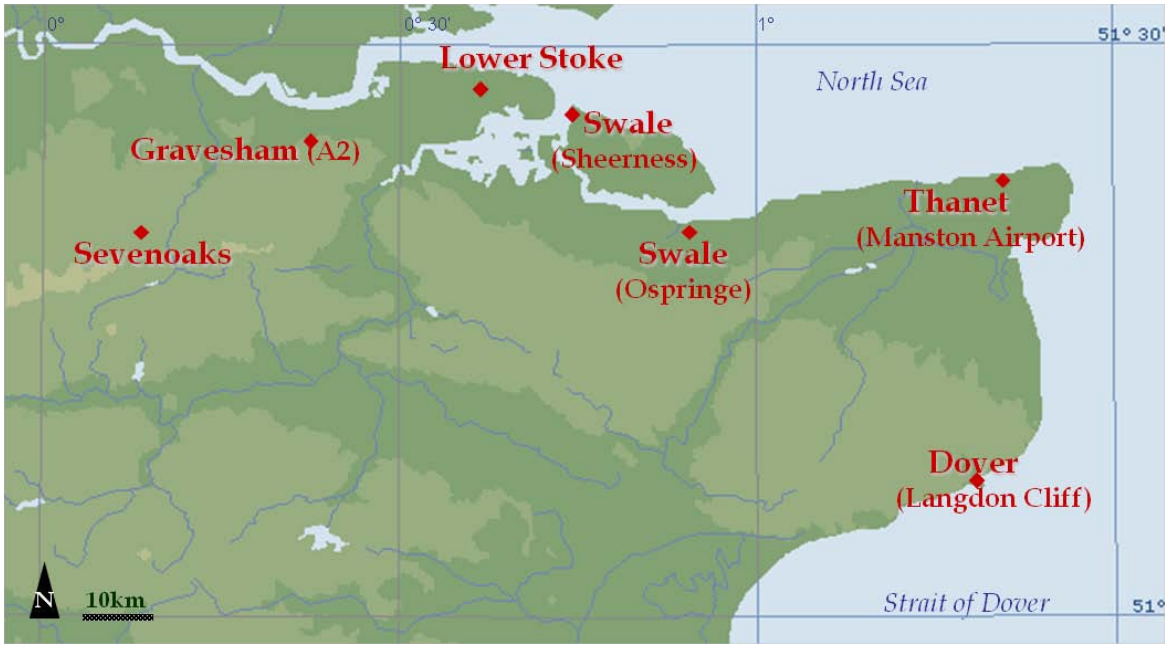


Figure 31: Weather data stations available.
Adapted from Microsoft Encarta (2003).

The sets of data analysed were taken from 2000 to 2008. As a standard approach to providing a meaningful data set to work with, no sites with less than five years of continuous data were examined (Table 1). Unfortunately, however, the data sets at each of these sites are not complete (Appendix F), so direct comparison of the wind statistics between sites had to be undertaken carefully.

The ERG categorises its sites depending on their environmental background, if they are by a road they are considered under the roadside category, otherwise rural or urban. This information enabled a clearer understanding to be gained of the sampling environment. Table 1 shows all the available sites as well as their location, environmental background type and the date since they are available.

Table 1: Shows all sites with weather data available, their UK national grid co-ordinates, the type of environmental background (as defined by the Environmental Research Group) as well as the date they were made available.

Sites	Grid reference (E,N)	Environmental background	Data available from
Dover (Langdon Cliffs)	633698,142292	Urban	2003
Gravesham (A2)	562613,172075	Busy roadside	1999
Lower Stoke	83133,176200	Rural	1997
Sevenoaks (Greatness)	553600,16800	Urban	2001
Swale (Ospringe)	600201,160895	Roadside	2004
Swale (Sheerness)	591750,174750	Urban	2004
Thanet (Manston airport)	635931,165331	Urban	2003

Local wind data sampled every hour were extracted from the ERG website and imported into Excel spreadsheets and prepared following the same procedure applied to the Lower Stoke data (Section 3.2.3).

In a first approach, all the available sites were studied individually, trying to find different patterns or trends over the years, and observing if the influence of certain local sources or topographical features affecting the wind direction at each site could be found.

3.2.6.1 Wind data correlations between sites

Correlation coefficients were calculated between sites at each available year with the objective of investigating similarities or differences between the nine sets of data.

Values of the correlation coefficient are always between −1 and +1. A correlation coefficient of +1 indicates that two variables are perfectly related in a positive linear sense (Cook and Upton, 1996; Altman *et al.*, 2000). For the purpose of this study, whenever the correlation coefficient was found to be over 0.5, it has been considered that there is an association or possible link between the two sites, which would need to be investigated in more detail. The data for each site were also plotted yearly as an aid to assist explaining the correlation coefficient values, as well as examining any other possible patterns or trends found. Unfortunately, because these sets of data are incomplete, a detailed analysis of all sites throughout the nine years is not possible (Appendix F). Nevertheless, most sites have at least five years of data: these sets have been compared.

3.2.7 Sea breeze influences

During the preliminary analysis of the Lower Stoke data an increase of wind from the east was noticed (this being the nearest side to the sea). The increase occurred mainly during the warmest part of the day, escalating significantly during the warmer months of the year (Section 4.2.1). It was, therefore, considered that this increase in easterly winds could be caused by a sea breeze coming into land (Section 2.4.1) (see sites locations in Figure 31).

For that reason, it was decided that the trends of individual wind patterns should be examined for the presence of sea breezes which might influence landward and seaward dispersal of PM_{10}. Winds from the east and northeast were examined to the exclusion of the others because they are the winds most likely to come from the North Sea or the English Channel (Figure1), bringing sea breezes on to the land at the study sites. The frequency of the wind direction occurrence was recorded manually, counting the number of times in a day that the wind from that direction was blowing over a minimum period of three continuous hours (or 12 continuous entries every 15 minutes). It was decided that three hours would be the minimum time that the wind would need to be blowing from one direction to allow the study of wind patterns such a sea breezes.

This was done by dividing the day into three periods, corresponding to the night and early morning (00.00 to 09.00), the middle part of the day (10.00 to 18.00) and the evening (19.00 to 23.59) measured as GMT. These times were chosen to coincide with the main three parts of the day. The wind direction trends obtained were analysed and their relationships examined.

In a first approach, this methodology was only applied to the data from Lower Stoke. However, afterwards it was decided to extend this analysis to three other sites: Dover, Sevenoaks and Gravesham (Figure 31). The main reason for choosing Dover was chosen for its significant distance from Lower Stoke as this will provide a more diverse set of data.

This site was also selected because it would allow comparison between the sea breeze and the PM data collected at the same site, where the BVST trap was located (Section 2.2.7.1 and Section 3.5) as well as allowing the study of a possible trans-boundary pollution arriving from the near continent.

Sevenoaks ‘of the four’ is the only site located inland (more than 35 km from the coast) (Figure 31). Van Dingenen *et al.* (2004) and Putaud *et al.* (2004) in their European aerosol phenomenology studies found that sea spray was clearly identified as one of the most common components of the particles in sites located in a radius smaller than 50 km from the seashore. Therefore, Sevenoaks was chosen as an inland control, providing an interesting example to evaluate the possibility of sea breezes coming inland and consequently affecting the PM dispersion.

Lastly, Gravesham was chosen for two main reasons: it is the only site, together with Lower Stoke, with the longest duration of data available. The other reason is that this sampling site is located within the Thames Estuary; the distance from the sea is approximately 13 km allowing a more detailed comparison with the other two coastal sites and the inland site. The recorded data from the four sites have been analysed and the wind patterns at the sites compared.

3.2.8 Wind persistence analysis

As described in the previous section, two of the sites studied for sea breezes influences are very close to the coast (Lower Stoke and Dover). Previous work (Burt and Sharma, 2003) has shown that periods of persistent easterly winds (for example those occurring for more than three days continuously) are rare (once or twice a year) at Lower Stoke. The same study revealed that, generally, winds from the east and northeast are relatively short-lived, normally only persisting for a few hours before reverting to a different (variable) direction. In order to establish if that behaviour was also occurring in the data used for this project, the number of times in a year that the wind blew for more than 24 hours was noted. Moreover, this methodology was extended to the other two sites (Gravesham and Sevenoaks) previously analysed for sea breeze influence (Section 3.2.7). The results between the four sites were analysed and then compared with the intention of finding patterns or similar results.

3.3 Particulate material (PM_{10}) data

3.3.1 Range of data available

In addition to monitoring weather (Section 3.2), ERG also records the levels of pollution. For the purpose of this study, PM_{10} values from all data available at the ERG website between the years 2000 to 2008 have been used. The PM_{10} download from the ERG site (http://www.kentair.org.uk/continuousdata) has been measured using a TEOM (Tapered Element Oscillating Microbalance) analyser. This type of sampler has been used by the same group in London for the last 15 years whilst excellent for producing results every 15 minutes, it has some well documented disadvantages, in particular the loss of volatile species (driving off semi-volatile material such as ammonium nitrate and organic aerosols) (Smith *et al.,* 1997; APEG, 1999; Harrison, 2001; Charron *et al.,* 2004; Green and Fuller 2006). To correct this loss, the ERG multiplied the TEOM PM_{10} values by 1.3 before comparison with limit values. (Harrison, 2001).

The records available illustrated excellent coverage at some sites (e.g. Lower Stoke, where nine years of data are available) whilst reasonable or poor coverage at others (e.g. Thanet (Ramsgate) with only five years of data, 2004-2008). All the data used are available for at least five years. In total, 17 sites have been used: Ashford, Canterbury, Chatham, Dartford (including data from three sites; St Clements, Town Centre and Bean Interchange), Dover, Folkestone, Gravesham (A2), Gravesham (Northfleet), Lower Stoke, Luton, Maidstone (Detling) Maidstone (Fairmeadow), Swale (Ospringe), Swale (Sheerness) and Thanet (Ramsgate) (Figure 33).

As in the case of the weather data (Section 3.2.6), the ERG categorise their pollution sampling sites in accordance with the environmental background where they are located: rural, urban or roadside. This information is also shown in Figure 32.

Figure 32: Displays the 17 pollution monitoring sites location and their environmental background. Adapted from Microsoft Encarta (2003).

Data entries were recorded hourly (see an example of raw data in Appendix G). As with the weather data, because the PM_{10} data are incomplete across all the sites, this makes direct comparisons between all sites unreliable. In general, there have been numerous occasions where hourly data and whole day recordings have not been registered (see Appendix H).

When extracting the PM_{10} data from the ERG website, information was also collected about each site with regards to distance from main roads (for traffic influences on PM_{10}), proximity to a roundabout and geographical location, as well as whether the site is located in an urban or a rural area. The use of this information enabled more accurate comparisons of PM_{10} caught between sites to be carried out and it was extremely useful to have a real understanding of the factors surrounding the sampling sites.

Table 2: Sites with PM_{10} data available, their UK national grid co-ordinates, the type of environmental background were they are located (as defined by the Environmental Research Group) and the date since they are available.

Sites	Grid Reference (E,N)	Environmental Background	Data available from
Ashford	601178,143000	Roadside	2002
Canterbury	616195,157330	Urban	2001
Chatham	577487,166947	Roadside	1997
Dartford 1 (St. Clements)	558525,174709	Busy roadside	1999
Dartford 2 (Town Centre)	554117,173852	Roadside	2003
Dartford 3 (Bean Interchange)	558622,172752	Roadside	2003
Dover	632277,14113	Roadside	2001
Folkestone	61365,136720	Urban	1997
Gravesham (A2)	562613,172075	Busy roadside	1999
Gravesham (Northfleet)	562143,174387	Urban	1999
Lower Stoke	83133,176200	Rural	1997
Luton	577257,166660	Urban	1997
Maidstone (Detling)	580075,159700	Rural	1999
Maidstone (Fairmeadow)	575740,155615	Busy roadside	1999
Swale (Ospringe)	600201,160895	Roadside	2004
Swale (Sheerness)	591750,174750	Urban	2004
Thanet (Ramsgate)	638250,165250	Roadside	2003

3.3.2 Extraction of the PM_{10} data

Data from all the pollution monitoring sites were reviewed and organised using the methods outlined for the processing of the wind data in Section 3.2.3, to check for gaps in data and negative values (a negative count value of PM_{10} was used as an error flag in the records). The data had to be edited manually and then corrected and checked so that correlations between sites, and also with the wind direction data, could be made correctly.

A large focus of the work has been on identifying a methodology to compare the PM_{10} data at the different sites. This task has required careful attention as some of the data in the ERG website were given every 15 minutes while in others they were given hourly. Consequently, it was decided to use the hourly data sets because they were available at all locations.

The number of entries was too large for a spreadsheet to handle (some sites, for instance Gravesham or Lower Stoke, had over 300,000 records). Therefore, a database showing all the data available for each site needed to be created: Microsoft Access was used for this. The main reason for designing a database was to be able to compare the data for all sites at the same time and date, in order to evaluate and correlate the different sampled values at different locations over the same periods.

The process of creating the database was complex. The data had to be adapted to the right format to be exported to Microsoft Access. The first step was to create a table for each site. Each of these tables contained the recorded PM_{10} values, as well as the time and date of the data collection (see Appendix I).

Once the data points were introduced, the next step was trying to link all the sets of data by a common attribute. In order to accomplish this, a query was created. This is a tool that allows the user to create "relationships" between the different sets of data. In this case, the main link was the date and time between all sites (an example of the query can be seen in Appendix J). Moreover, once the query has been completed a table showing all PM_{10} values for all sites matching at the same specific date and time was obtained. If for a specific period there was not data available for one of the sites the cells are left blank.

3.3.3 Analysis of the PM_{10} data

The analysis of the PM_{10} data has been divided into seven different approaches. These categories have been established with the purpose of drawing a clearer picture on PM_{10} dispersal in the study area. Firstly, the PM_{10} data for each site were analysed (Section 3.3.4). Yearly graphical comparison and correlation coefficients were calculated in order to detect any relationships that wouldn't appear in the first approach (Section 3.3.5). This is followed by the analysis of the summer and winter variations of the data (Section 3.3.6). Section 3.3.7 assesses the exceedences of pollution within the study area taking into account the synoptic situation at the time of the episode. Section 3.3.8 describes the investigation of the role of topography in PM_{10} distribution over the county, whereas Section 3.3.9 looks into the relationship between site background and PM_{10} catch. Finally, Section 3.3.10 describes the study of the pollution trajectories within the study area.

3.3.4 Graphical analysis of the PM_{10} data

The PM_{10} hourly data were graphically represented with the purpose of finding visual patterns between years at the same location, or finding general trends between sites when plotting them together at the same period. With the same methodology applied for the study of the wind direction, the PM_{10} data were examined daily at first, and then monthly, followed by seasonally and, finally, yearly. All of the sets of data were then compared over the same period of time at different years in order to investigate whether there were any significant trends or patterns within the study data. Examples of the plots for every specific location over the years can be found in Appendix K.

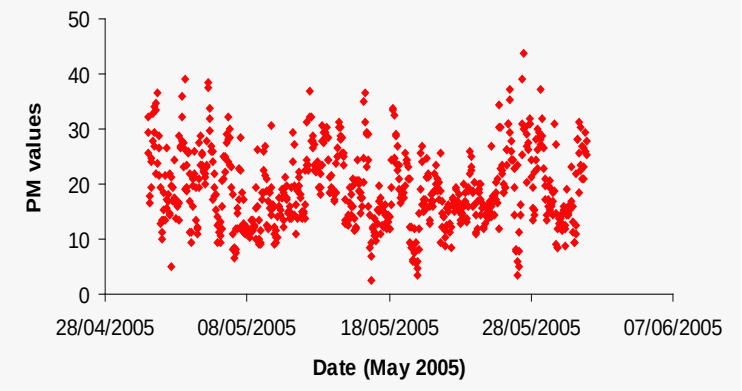


Figure 33: Example showing scatter plot of PM_{10} data from the Chatham monitoring site during May 2005.

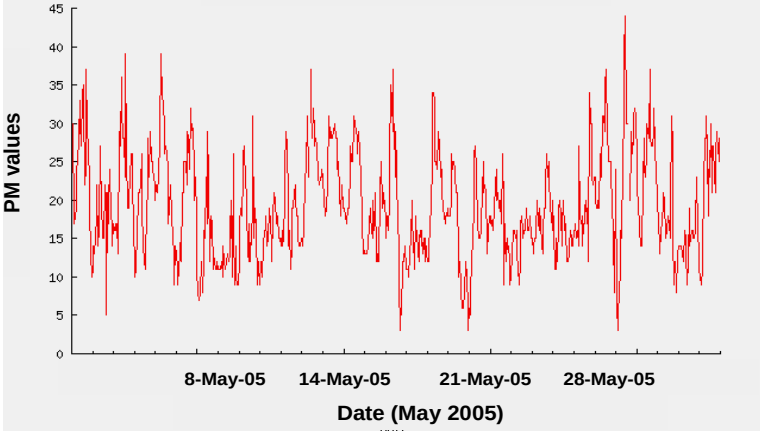


Figure 34: Example showing linear plot of PM_{10} data from the Chatham monitoring site during May 2005.

As a part of the investigation, the most appropriate way to compare the data visually was also evaluated. In a first approach, the data were represented using scatter plots: unfortunately this type of graph wasn't clear enough for the purpose of this investigation (Figure 33), and peaks of the data or specific trends were difficult to recognise. Therefore, it

was decided to plot the information linearly so that the distribution of the PM_{10} dispersion through a defined period could be observed (Figure 34).

As previously described (Section 3.3.2), it was not possible to use a spreadsheet (in Microsoft Excel) to examine the data and consequently plot the values. The use of the spreadsheet was limited to the data from just one site and no more than five years of data due to the vast number of entries. Therefore, it was decided to use a different software package known as Igor.pro Version 6 (Wavemetrics, 2009) to represent the data graphically. Figure 34 is an example of the graphs obtained in Igor.

With this in mind, PM_{10} data at all sites were plotted linearly, and analysed by comparing each with every other site in order to try and identify patterns. When peaks in PM_{10} were found at a site on a certain date, the data from that site were then compared to other sites to see if the peaks between sites were connected, or if there was evidence of any common or similar patterns. Examples of the graphical representation for every specific location over the years can be found in Appendix K.

3.3.5 Correlations between all sites

As previously described in Sections 2.2 and 2.5, the major mechanisms contributing to airborne particulate matter in a region are highly variable, including natural as well as pollution sources, chemical reactions in the atmosphere, long-range transport effects and meteorological conditions (Yin *et al.,* 2005). In order to develop an understanding of local and remote sources of particulate matter, as well as of the factors influencing its temporal and spatial variability in urban areas it was decided to calculate correlations coefficients between the time series at all available sites (Battarbee *et al.,* 1997; Deacon *et al.,* 1997; Harrison and Deacon, 1998; Grivas *et al.,* 2004; Vardoulakis and Kassomenos, 2008). The matrices with the values obtained can be found in Appendix L. To assist the analysis, the PM_{10} concentration recorded for each site at every year was also presented in a graphical form together with the correlations to help explain the results (Section 4.3.2 and Appendix L). These data are directly comparable since they were obtained with similar sampling and analytical methods, covering the period 2000 to 2008.

3.3.6 Summer and winter variations of PM_{10} data

Studies by Stedman (1997), Ryall *et al.* (2002), Apsimon *et al.* (2001), Namdeo and Bell (2005) in the UK and Vecchi *et al.* (2004) in the Milan area (North Italy) have suggested a strong seasonal variation of PM concentrations with the highest values during the winter months (these are from December to March). These studies suggested that during cold calm periods of weather in the winter months, pollution emissions are trapped close to their sources and cannot disperse. Therefore, given the numerous sites with different locations in the study area, it was decided to investigate seasonal variation in PM_{10} levels. The comparison was carried out for 12 of the 17 sites (excluding those sampling sites that were too close to the city of London because it was considered that the observations of seasonal patterns at these sites may be influenced by an urban heat island effect (Section 2.4.3). This theory is developed further during the results discussion (Sections 4.3.4.2 and 4.3.5.4)

The comparisons were carried out using the same PM_{10} data already extracted as detail in Sections 3.3.1 and 3.3.2. The data compared were divided into two sets of three months each, according to the colder and warmer periods of the year. The first group reported the values from the winter period from the 1st of December up to end of February. The second group comprise the summer months, from the 1st of June to the 31st of August. In total, 86 completed trimesters were compared. Some sites (such as, Swale (Ospringe), Swale (Sheerness), Thanet and Ashford) did not have continuous data available for the nine years that were compared, however, there are at least five years of data available for all sites. (Appendix M).

It may be worth mentioning that as a general assumption, changes were expected in the PM_{10} levels in those sites closer to the coast where the PM_{10} concentration could be affected by a sea breeze influence (Section 2.4.1) or in urban sites where the levels could rise in the colder months due to the use of heating systems (Section 2.4.4). These assumptions, together with the results from the seasonal comparisons of the data, are evaluated in Section 4.3.3.

3.3.7 High levels of PM_{10} pollution

Several authors, such as Seinfeld (1986), Stedman (1997), Arya (1999), VanCuren (1999), Merefield (2002) and Buchanan *et al.* (2002) suggested that exceeding the air quality guidelines is predominantly linked to a national and trans-boundary pollution event.

Consequently, it was decided to examine those days which experienced high peaks of PM_{10} (50 µg/m^3 or above), (this is the daily recommended amount by the UK Government in their Air Quality Strategy (2005)).

With this in mind, the annual average concentrations of PM_{10} for each site over the studied period were calculated. Once this method was applied and the results evaluated, it was decided to extend the methodology. The monthly frequency distribution of higher PM_{10} episodes was recorded, noting the number of days in each month that the PM_{10} values were over the recommended amounts for longer than two hours. This analysis was carried out with the purpose of allowing the analysis of seasonal distribution of PM_{10}.
For those sites closer to the city of London, it was decided also to record the number of times that the values exceed double or over the recommended amounts, (i.e. 100 µg/m^3), chosen to show a clear indication of exceedences on those sites. The tables showing all results for every examined month and year can be seen in Appendix N.

3.3.8 The role of topography in PM_{10} distribution

Having examined the wind directions and PM_{10} distributions at the sampling sites, as well as the seasonal variations, it was necessary to consider the role of topography when comparing catches, on the basis that local environments could modify catches in particular ways.
In order to identify any patterns in PM_{10} catch that could be linked to the topography of a particular area, sites with the same type of topographical features were first compared and then evaluated with those with different topographical features.

With this in mind, Kent was divided into four different areas according to its main topographic features (previously described in Section 2.5.2 (Figure 25)).
The four categorised areas with their sites included are (Figure 35):

- **North Downs** (Canterbury, Chatham, Luton, Maidstone (Detling), Swale (Ospringe)).
- **Coastal Sites** (Dover, Folkestone, Lower Stoke, Swale (Sheerness), Thanet (Ramsgate)).
- **South Downs** (Ashford, Sevenoaks and Maidstone (Fairmeadow)).
- **Sites closer to London** (Dartford (St Clements, town centre and Bean Interchange) and Gravesham (A2 and Northfleet)).

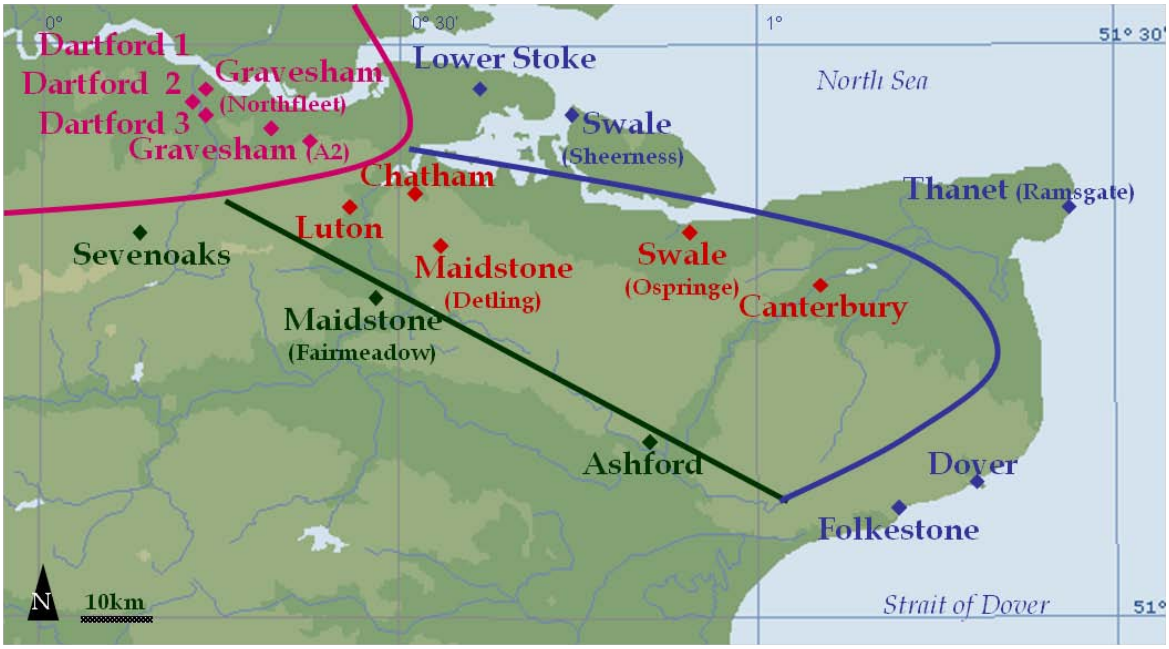


Figure 35: The four areas in which Kent has been divided –based on their topographic features, with pollution monitoring stations highlighted
Map adapted from Microsoft Encarta.

Correlations previously calculated were also re-examined by grouping them depending on the topographical features affecting the sites.

3.3.9 The relationship between site background and PM_{10} catch

As part of the investigation, sites with the same type of environmental background were also analysed to see if any other common trends or patterns were possible due to the common background affecting them (rural, urban or roadside background). For instance, Dover and Swale (Ospringe) are both located on a roadside (Figure 32), comparisons were taken to see if the PM_{10} levels increase or decrease at the same time and if their fluctuation levels depend on local traffic or if there are any other factors affecting the PM_{10} distribution.

3.3.10 Analysis of pollution trajectories

Although analysis has focused on patterns of PM_{10} captured at individual sites, it is possible that the same episodes of pollution affected two or more sites at the same time. It was, therefore, important to consider wind speed affecting the study sites. Wind speed has a dual effect on suspended and airborne particulate matter. First, wind speed determines the distance to which different sized particles may be transported (Seinfeld, 1986). Second, wind speed greatly affects the dispersal rate of particulate matter. When the wind speed is higher,

pollutants have a greater dispersal rate. However, when the speed is lower or calm, one would expect the PM_{10} levels to increase (Ahrens, 1994; QUARG, 1996; Arya, 1999).

In order to investigate the wind speed at the sites, the distance between sites and the time that the pollution could take to be delivered from one site to the other needed to be considered. As a first approach, the distance between sites in a straight line was measured on maps of the study area (Ordnance Survey, Scale 1:25,000, numbers 149 150 137 and 138) by measuring the distance between sites with a ruler and applying the map scale to convert this to kilometres. At a later stage, these measurements were corroborated using a tool called Google Maps Distance Calculator (GMDC) (www.daftlogic.com/projects-google-maps-distance-calculator.htm). GMDC calculates the distance between two or more points anywhere on the Earth. In other words, the distance between A and B. Once the map is displayed click on the map to place the first marker and then click again to position the second marker. The distance between the points will then be displayed on the screen (an example of this tool can be seen in Appendix O).

The wind speeds at each of the sites with wind data available (Dover (Langdon Cliff), Gravesham (A2), Lower Stoke, Sevenoaks, Swale (Ospringe and Sheerness), as well as Thanet (Manston airport) (Figure 31) (Table 1)) were recorded by the ERG and the data were obtained from their website. Unfortunately, the wind speed data from Sevenoaks were not available (Appendix F). In addition, the data from Thanet (Manston) and Dover (Langdon Cliff) couldn't be used for this phase of the analysis, these two sites only record meteorological data, the sites in the same area (Thanet (Ramsgate) and Dover (town centre)) recording PM_{10} are too distant from the weather station to be able to demonstrate pollution trajectories.

From the remaining sites, two pairs were chosen to reflect possible wind trajectories. Lower Stoke to Sheerness was chosen to identify possible particulate transport during west/northwest persistent winds. Furthermore, the Lower Stoke to Gravesham pairing was chosen to study wind persistence from the northeast.

The data were first filtered by wind direction, and then filtered by PM_{10} count (selecting data points greater than 30 $\mu g/m^3$, so transportation is more likely to occur (Seinfeld, 1986; Arya, 1999; McMurry *et al.*, 2004)). Lastly, the data were examined for more than three hours persistence so a pattern could be observed. Examples of the data can be seen in Appendix P.

The time that the particles would take to move on the wind from one site to the other was calculated by applying the following formula: Time=Distance/Velocity (Wind Speed).

The PM_{10} data from the first site in the pair was plotted, the data from the second site were then overlaid using the calculated time shift (as explained above) to enable possible particulate matter transportation to be studied. If the two sites follow the same pattern, it is possible that the material moves from one site to the next.

3.4 Assessment of the role of wind direction in PM_{10} distribution

In Sections 2.3 and 2.6, the ways in which the physical and dynamic characteristics of the atmosphere allow it to be the vehicle for particles to make their journeys, affecting the whole process from source to deposition, were highlighted. Atmospheric winds, for example, determine the pathways and speeds at which pollutants are transported from sources (Seinfeld, 1986; Arya, 1999) (Section 2.2.8).

This section focuses on the assessment in more detail of specific trends, affecting the data sets analysed in the two previous sections (Section 3.2. and Section 3.3), and more specifically focusing on occasions where the influence of wind direction on the PM_{10} dispersion could be observed. Some of these may include an association with local winds (for instance sea breeze), trends affected by synoptic events or any other peculiarity found connecting PM_{10} dispersion to wind direction.

3.5 Pollution episodes (case studies)

According to many authors (for example Seinfeld, 1986; Pepper *et al.,* 1996; Arya, 1999; Bower *et al.*, 2005), the two main types of pollution episode in the UK are winter and summer smogs. An example of each of these pollution episodes in relation to the study area is given in this section. Such cases are useful, as they provide identifiable times of increased pollution loading in the atmosphere, often with recognisable causes and/or source areas.

3.5.1 Winter pollution episode (Bonfire Night)

Bonfire Night (on or around 5^{th} of November each year) provides an interesting example of an emissions-driven winter episode. Given cold, stable weather (poor conditions for dispersing emissions) widespread bonfires may result in elevated levels of PM_{10}.

The weather can play a very important role in the PM_{10} concentration. If it is windy, it is easier for the pollution to be diluted; while if there is high pressure affecting the area the pollution levels can last for a few hours or days. If it is cold, still and foggy, pollution can be trapped close to the ground and allowed to build up over time causing a winter smog episode (Pepper *et al.*, 1996; Arya, 1999; Bower *et al.*, 2005; Jacobson, 2002).

The data analysed includes the first nine days of November (four days either side of Bonfire Night) for every studied year and sampling site. This approach allows the 5th November to always be shown in the centre of the graphical representation, enabling the observation of the PM_{10} patterns before and after the date, through different years. Although, the exact dates vary from year to year, these dates are likely to have been when major fireworks displays and celebrations will have taken place. During the analysis, the synoptic conditions as well as the wind direction has been also examined.

3.5.2 Summer pollution episode (August 2003)

During the summer of 2003, Britain suffered one of the most severe heat waves and droughts of the last three decades (Bower *et al.*, 2006; AQEG, 2007). Faversham in Kent, recorded the UK's highest ever temperature of 38.5°C on 10th August (Met Office, 2007). In the southeast of England, maximum temperatures exceeded 32°C on the eight consecutive days from 4th August. The highest temperatures had a significant influence on the atmosphere of polluted urban environments, where high temperatures greatly increased the rate of smog formation (Pepper *et al.*, 1996).

The August 2003 pollution episode lasted until around the 16th August ending with an influx of clean air masses of oceanic origin arriving from the west (Met Office, 2007). This brings a typical example of a summer smog pollution episode. For a potential episode of severe air pollution a few factors are needed. These include many sources of air pollution. Hot and sunny weather with high temperatures accelerate chemical reactions in mixtures of emitted air pollutants (a high pressure area that becomes stationary over the region), low humidity and light surface winds that are unable to disperse the pollutants (Seinfeld, 1986; Ahrens, 1994; Arya, 1999; Jacobson, 2002).

August 2003 data at all sites have been examined and compared between sites. Higher pollution levels were compared to distinguish if local sources contributed to the PM_{10} levels or to check whether the pollution episode is associated with synoptic conditions.

3.6 Particle trap at Dover

3.6.1 Sampling strategy

Data from the ERG sampling network provided information about the occurrence and spread of particulate material within Kent, but further data were required in order to assess potential PM transport from the near continent. It was decided to locate a sampling instrument in an area where the material coming directly from the near continent could be assessed. The sampling site chosen was Dover, providing an ideal location to sample PM from the continent into the UK (Figure 37). The monitoring site is located approximately 77 kilometres (48 miles) southeast from the University of Greenwich Medway Campus.

3.6.2 Sampler

The Burkard Volumetric Spore Trap (Figure 36) is a compact unit with a built-in vacuum pump, designed to run continuously for periods of up to seven days. The air containing the material to be sampled is drawn through an orifice (the opening or mouth of the sampler, 2x14mm) by suction from the vacuum pump. Air is drawn in through the orifice at a flow rate of 10 litres *per* minute: the method of sampling is designed to mimic the inhalation of pollen at normal human breathing rates (Caulton *et al*., 1992; BAF, 1994).

The particles impact directly on to an adhesive-coated transparent plastic tape (Melinex) supported on a clockwork-driven rotating aluminium drum unit mounted in the rotating head of the trap. The BVST faces the wind due to the presence of the wind vane, thus the particles are trapped from the air coming from the running wind direction.

The clockwork mechanism moves the collecting surface past the inlet orifice at the rate of 2 mm *per* hour over a period of seven days. The Melinex is covered with a wax coating which acts as an adhesive surface to trap the airborne particles. After sampling, the Melinex strip is cut into daily sections for mounting on to microscope slides and sealed with cover slips for microscopic examination (see Sections 3.6.4 to 3.6.7). The trap was powered by a 12 volt car battery with one site visit each week required to change the sampling drum. The battery was replaced every other week.

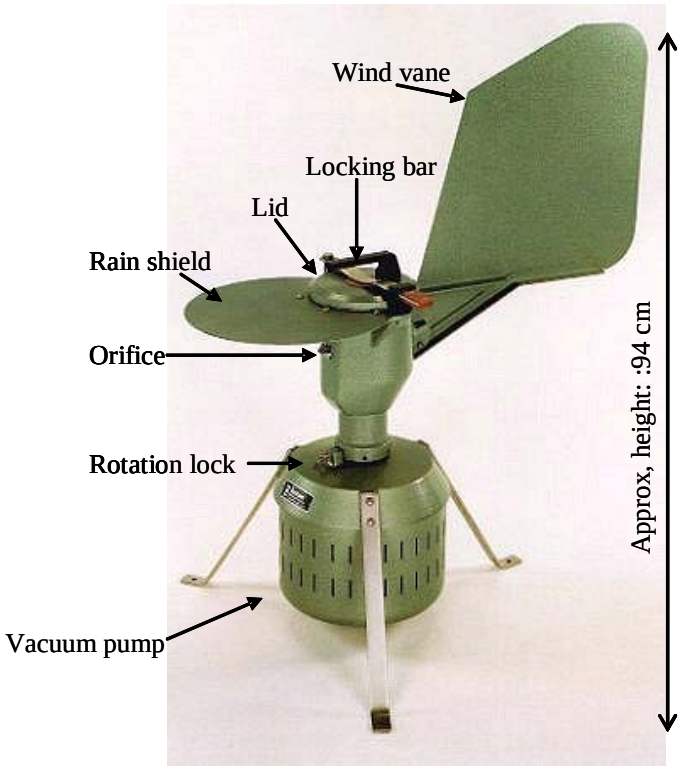


Figure 36: Burkard Volumetric Spore Trap.
Source: Photo adapted from http://www.burkard.co.uk.

3.6.3 Location and period of sampling

A seven-day recording Burkard Volumetric Spore Trap was installed at the Coastguard site on Langdon Cliffs, CT16, Dover (grid reference TR 341 425) (Figure 37a). The site is one of the higher places in the area (approximately 30 m above sea level) most of the surrounding areas are grassland or agricultural land (Nicolson, 1987; KCC, 2005; www.whitecliffscountry.org.uk, 2007).

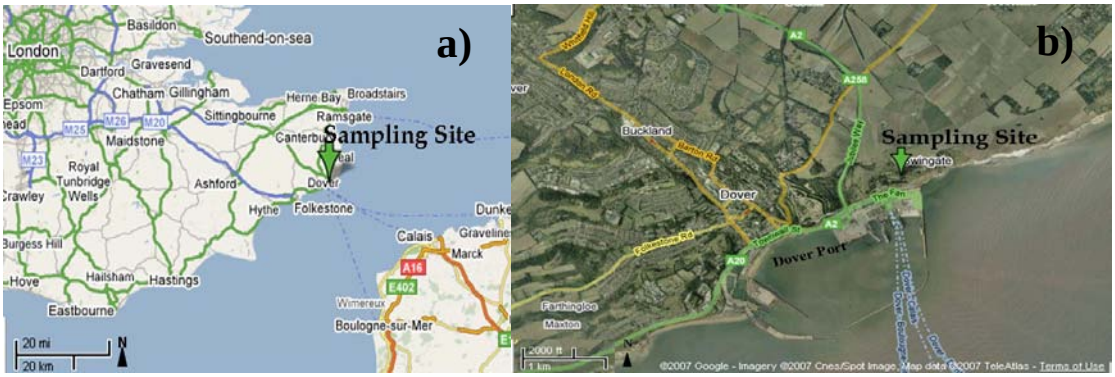


Figure 37: Displays the location of the sample site. Image 37a illustrates the location of the site in relation to the Southeast of England, whereas Figure 37b shows a satellite image of the area where its proximity to the English Channel as well as the main port (and the ferry traffic) can be observed.
Maps adapted from: www.maps.google.co.uk.

The BVST was located in an area exposed to the sea (and therefore the near continent) (Figure 38) with the intention of sampling PM blown across the channel by the wind.

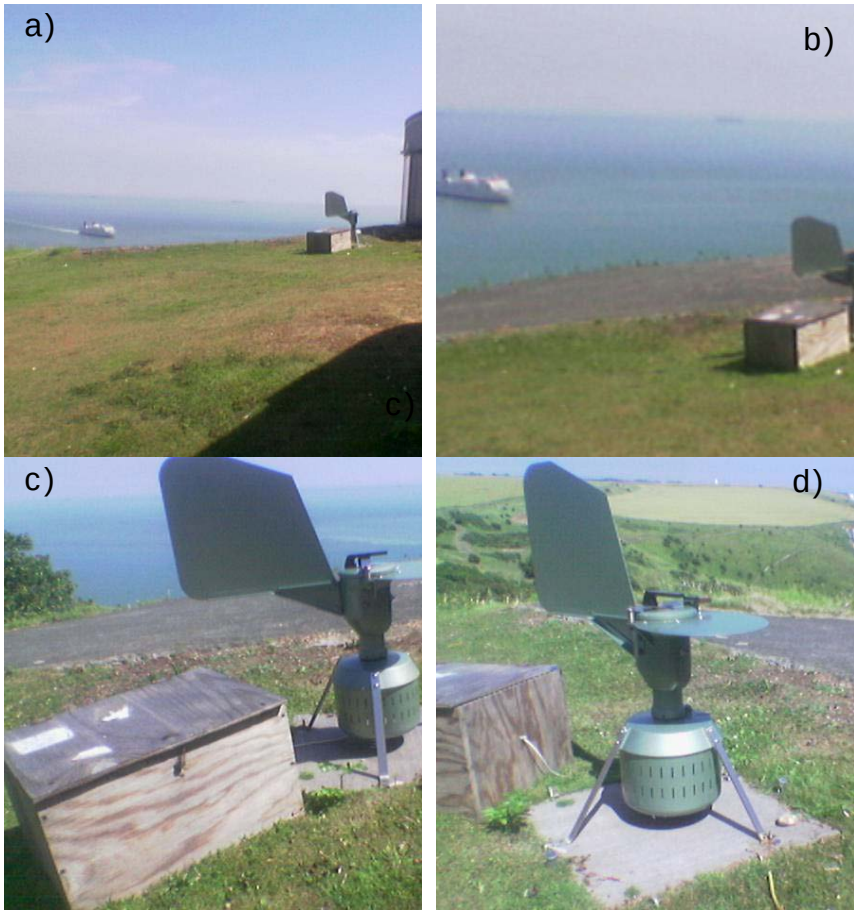


Figure 38: Compilation of four photos illustrating the particle trap location at Langdon Cliffs, Dover. (Photo 38a) shows the location of the trap with the building on the right and the English Channel in the back, photos 38b and 38c illustrate a closer photo of the trap, with the sea in the background. In photo 38d the white cliffs can be seen behind the trap).

The PM sampling at this site was carried out for a period of 14 months, from the 21st July 2005 to the 30th September 2006.

3.6.4 Preparing the drum

The standard British Aerobiology Federation (BAF) methodology has been followed for the purpose of operating the trap and preparing the slide material (Caulton *et al.*, 1992; BAF, 1994). An example of all the materials used (Sections 3.6.5 and 3.6.6) can be seen in Figure 39.

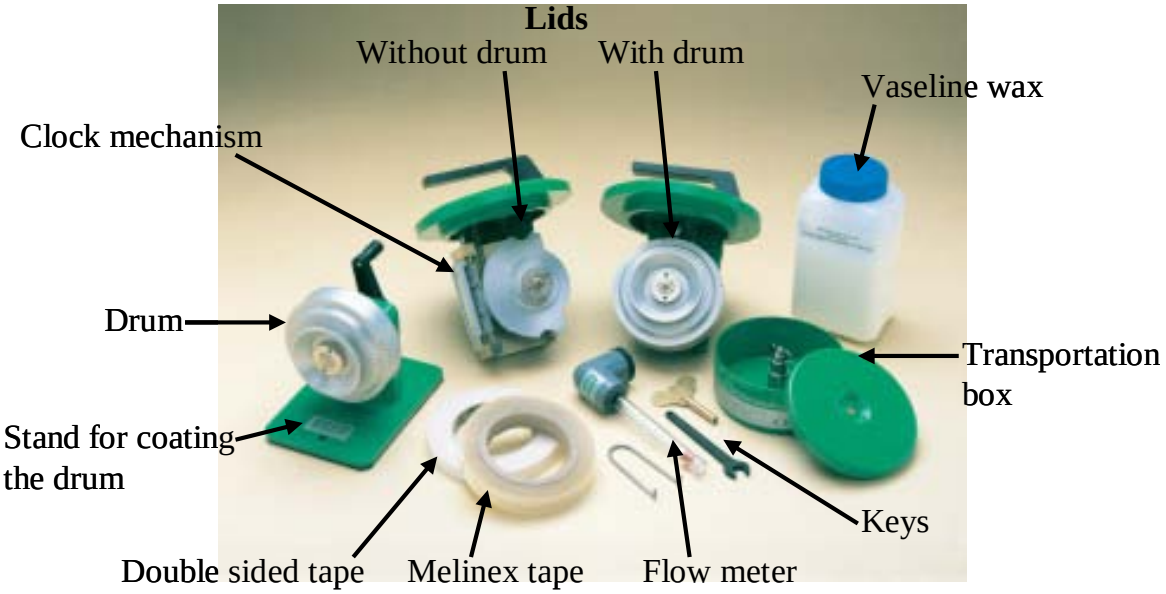


Figure 39: Equipment used for the preparation and changing of the drum.
Photo adapted from www.burkardscientific.co.uk.

To prepare the drum for use, it was first cleaned thoroughly with a dry, lint free, tissue, and then mounted on a drum stand with a roller assembly. A 2 cm by 1 cm strip of double-sided adhesive tape was cut and placed on the drum between the two distinctive black marks (Figure 40).

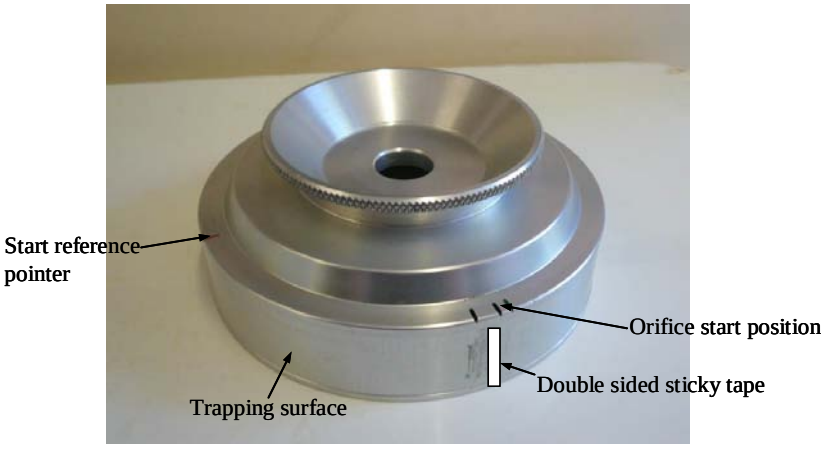


Figure 40: Photograph of the drum (indicating the trapping surface, start reference pointer as well as the orifice position and where the double sided sticky tape is should be located).

One end of the Melinex tape was placed halfway across the double-sided tape and pressure applied to secure it. The Melinex tape was wrapped around the drum, ensuring that the tape was tight against the rim, and stuck on to the remaining exposed adhesive tape. The tape was trimmed with a pair of scissors so that the two ends of the tape butted up against each other.

The Melinex was fitted to the drum and was coated with liquid Vaseline wax (heated until it melted in a beaker on a hot plate prior to application). The Vaseline was applied using a soft brush by rotating the drum mounted on a stand (Figure 39), while holding the brush to the surface of the Melinex, making sure the entire surface was covered. Any excess wax was removed with an aluminium scraper. After coating, the prepared drum was placed into a clean container for transportation to the trap site.

3.6.5 Changing the drum

Records of the days/times that the trap was changed, airflow rates and any problems encountered were kept (Appendix Q). To change the drum, the revolving part of the trap was locked using the anti-swivel pin in the block of the base plate (Figure 36). Following this, the air flow through the trap was checked using a flow meter provided by the manufacturer. Most of the time the flow was found to be stable - the only occasions when it was found to be low or zero was when the battery wasn't working. The trap was found not to be working correctly on two occasions during the 14 months sampling period (the third week of January 2006, and the last week of September 2006, just before the trap was removed).
Once the trap was locked and the airflow checked, the Melinex inside the drum was marked through the orifice by a needle, to show the exact position of the end of the sampling run. The locking bar on the trap head was released, the drum was removed (carefully, avoiding touching the waxed tape) and placed into a clean container. Before inserting the new drum, the clock mechanism attached to the lid was wound.

The prepared drum was taken out of the container and placed over the clock mechanism of the sampler with the red mark on the drum aligned with the red mark of the lid of the trap (Figure 39 and 40), which ensured that the start of the tape was over the orifice. The clock assembly was placed in the trap, secured with the locking bar and the tape was then marked by needle through the orifice (to show the start of the sampling run). The locking pin (Figure 36) was removed to allow the trap to rotate freely so that the orifice was oriented into the wind.

3.6.6 Mounting of the tape (preparation of the slides)

The first step was to prepare the microscope slides where the Melinex carrying the particles was to be mounted. The slides were checked to ensure they were clean and free of grease or

finger marks. Each slide was labelled with the date, the start time of the sampling run (this is the time when the drum was changed, it is the same time as noted in the trapping log) and the site where the sample was taken.

A drop of distilled water was laid on the middle of each slide using a small pipette, to provide a better adhesive surface for the Melinex tape. The drum was placed on the drum stand. The tape was removed from the drum with a pair of forceps peeling it off from the sticky tape and pulling it away from the drum, ensuring that the surface was not touched beyond the start point scratched by the needle and avoiding any stretching of the tape when removing the tail end from the securing double sided tape.

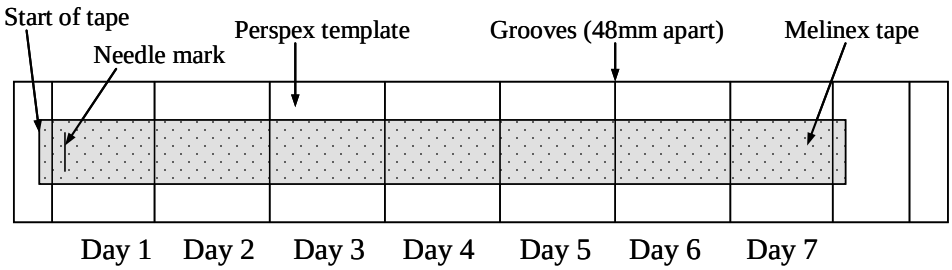


Figure 41: Melinex tape on the Perspex template.

The tape was laid on a Perspex cutting template (Figure 41) marked out in days so that the start on the template was aligned with the start of the first day of the sampling marked by the needle when the drum was changed. The tape was then held in position at the preceding daily mark line and cut, working back through the week from the last day of sampling. Each daily segment was transferred with forceps to the prepared slide for that day making sure that the day start point was just below the label and the trapping surface was uppermost. Once in place, the tape was readjusted if necessary to make sure it was mounted straight (Figure 42a).

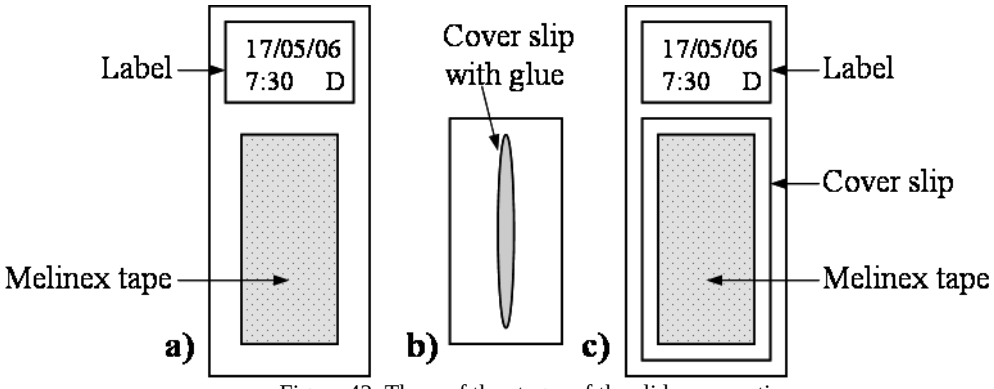


Figure 42: Three of the stages of the slide preparation.

In order to protect the sample from further contamination or damage, it was sealed with a cover slip, secured by a clear liquid adhesive (Gelvatol). The adhesive was applied in such a way so as to avoid the introduction of air bubbles or moving the deposited particles. A small amount of Gelvatol was applied to the middle of the cover slip along its length (Figure 42b) before the coverslip was carefully placed over the sample, ensuring that the tape was completely covered. The prepared slides (Figure 42c) were allowed to dry for one week at room temperature.

3.6.7 Optical Microscopy

The compound microscope used to examine the slides was a Leica DMRB (Leica Inc., Wetzlar, Germany) equipped with a feed into a Scion LG-3 frame-grabber card (Scion Corporation, Frederick, Maryland, 21701, U.S.A). Images were captured and saved as bitmap image files in a PC connected to the microscope. The program used to save the images in the PC was a version of Scion Image for Windows (Scion Corporation, Frederick, Maryland 21701, USA).

The slides were examined at x400 magnification (standard procedure recommended by the BAF (1994)); this magnification is usually adequate to determine when the highest amount of particles was collected over a period of 24 hours and also what type of material was collected (Caulton *et al*., 1994).

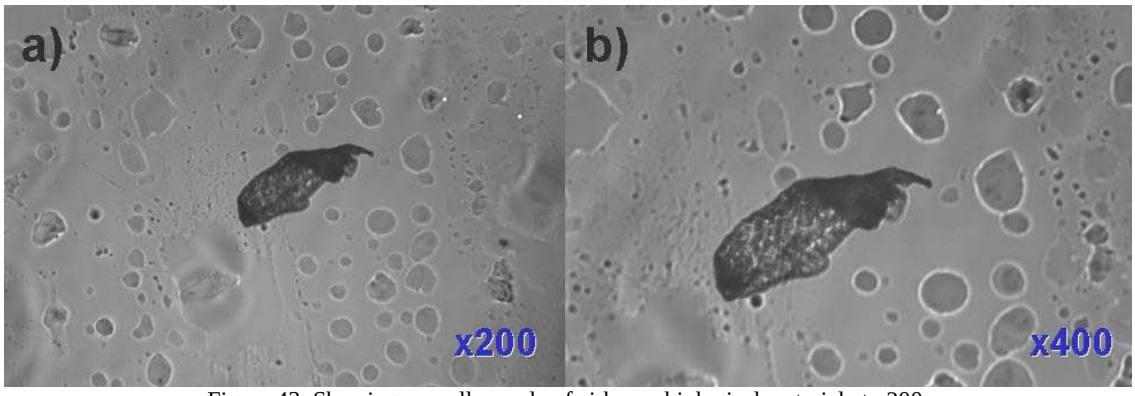


Figure 43: Showing a small sample of airborne biological material at x200 magnification and the same sample at x400 magnification

3.6.7.1 Particle identification

The visual identification of particles through the microscope was based on colour, shape and size. Three of the most common types of primary particles (i.e. those directly emitted to the

air) expected to be found are particles coming from anthropogenic activities, biological particles (such as pollen) and sea salt particles blown by the wind due to the proximity of the sampling site to the shore.

The first and main focus of attention for this research was anthropogenic particles (coming from combustion processes as well as metal refining, Figure 44a). These man-made particles are relatively easy to identify through the microscope. If they come from combustion products, they tend to be black or very dark and opaque with some irregular shapes, porous and rough surface with some straight sharp edges (McCrone *et al*., 1967). Soot particles include all the previous characteristics as well as tending to be spherical. Furthermore metal and refining processing particles are extremely small (less than 1µm) normally appearing in large agglomerates (McCrone *et al*., 1967; Nicholson, *et al.*, 1991; Battarbee *et al*., 1997; Long, 1998; Long and Rose, 1999; Mackay *et al.*, 1999; Odle, 2002, 2004) (Figure 44a).

The second type, biological material (for example pollen, fungi, plant fragments) (Figure 44b), are usually easily recognizable: they are symmetrical and patterned. Some common examples include: small grain, translucent, oval or sphere shape and small if they are pollen, or transparent, colourless to yellow fibres with small surfaces such as cereals pieces or fragments of plants blown by the wind (McCrone *et al*., 1967).

The third possible material found is sea salt particles, whole or broken, transparent, colourless with yellowish edges due to light scattering by the optical discontinuities within the particle (McCrone *et al*., 1967) (Figure 44c).

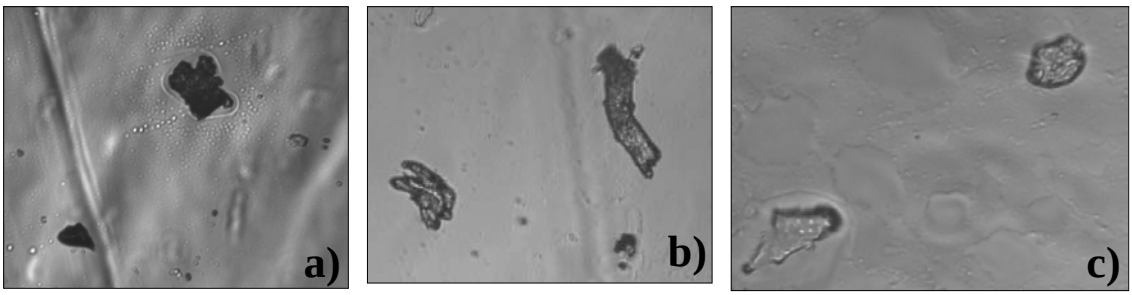


Figure 44: a) shows an example of particles from an anthropogenic source, this example was taken on the 25th July 2006 at 10:00 a.m. b) shows biological material (plant fragments) collected on the 30th September 2005 at 6 p.m. c) illustrates sea salt, this sample was taken on the 5th May 2006 at 11 a.m. For all three samples x400 magnification was used.

3.6.7.2 Particle counts

Different methods have been reviewed in order to find the best way to count the particles sampled. Frenz (2000) and Odle (2004) suggested the use of a longitudinal transect. However, pollen studies by Caulton *et al.* (1992), Sterling *et al.* (1999) and the BAF (1994) recommend the standard counting convention which suggested the use of a 12 bi-hourly transverse traverses (Figure 41). The same method has been applied for counting PM, one of the advantages of using this method is to be able to identify the approximate time at which a particular group of particulates were caught. This choice of method is discussed in more detail in Section 4.6.2

The slide was placed on the microscope's stage, positioning the beginning of the Melinex strip (corresponding to the start of the sampling day) at the first field of view using the Vernier scales on the microscope's mechanical stage and viewed by moving the slide from right to left, (starting at the top and working the way down). Some slight focussing

adjustments were sometimes needed to calibrate the field of view in each slide (caused by the variations in the thickness of the wax layer or the presence of air bubbles on the slides).

The first traverse (on the Melinex tape/slide) can be made by moving the tape 3 mm for the first segment (which would correspond to the day that the trace begins, in this case, Thursday morning) and 2 mm for the rest of the segments, starting from the first moment of trapping. By definition, the width of the traverse equals the width of the eyepiece graticule, irrespectively of the magnification (BAF, 1994). In the microscope used for this study, the width of the traverse was 300 µm. Each slide was divided into 12 individual segments (one every two hours or 4 mm between traverses) and the number of particles present in each of the 12 segments was quantified (Figure 45). In order to be consistent, any particle touching or crossing the edge was including in the count.

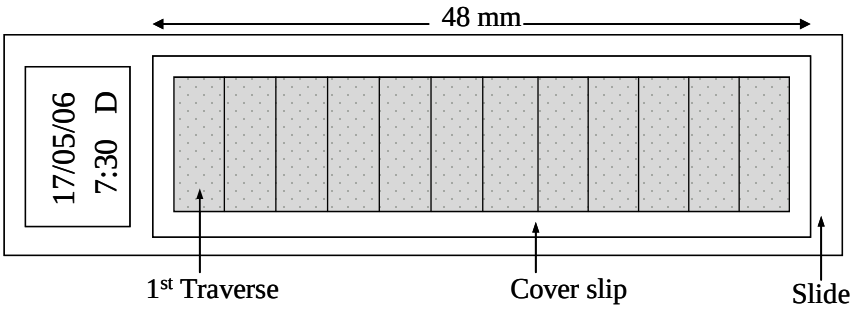


Figure 45: Slide showing the 12 traverses.

During the process of PM counting, the methodology had to be slightly adapted to the conditions found. In a first approach, particles were subjectively categorized by an estimate of the percentage of the field of view covered by particles in the following way: up to 30 % covered was classified as low, 30 to 60 % covered was medium, above 60 % covered was high and above 90 % covered very high. When going through the slides trying to categorize them, it was found that most of the slides fell in the low/medium category. Due to the lower number of particles caught, this methodology wouldn't provide an accurate representation of the material found. Therefore, it was slightly modified and instead of showing particles caught by percentage, they were counted by number.

The scores were decided upon the average number of particles found following the BAF guidance (1994). A low category was assigned when the number of particles was less than 25 in the portion of the traverse examined, between 25 and 50 particles was considered

medium and about 50 particles counted was high, any material found above 75 was considered very high (Figure 46).

An example of these categorizations by the number of particles found can be seen in Figure 46.

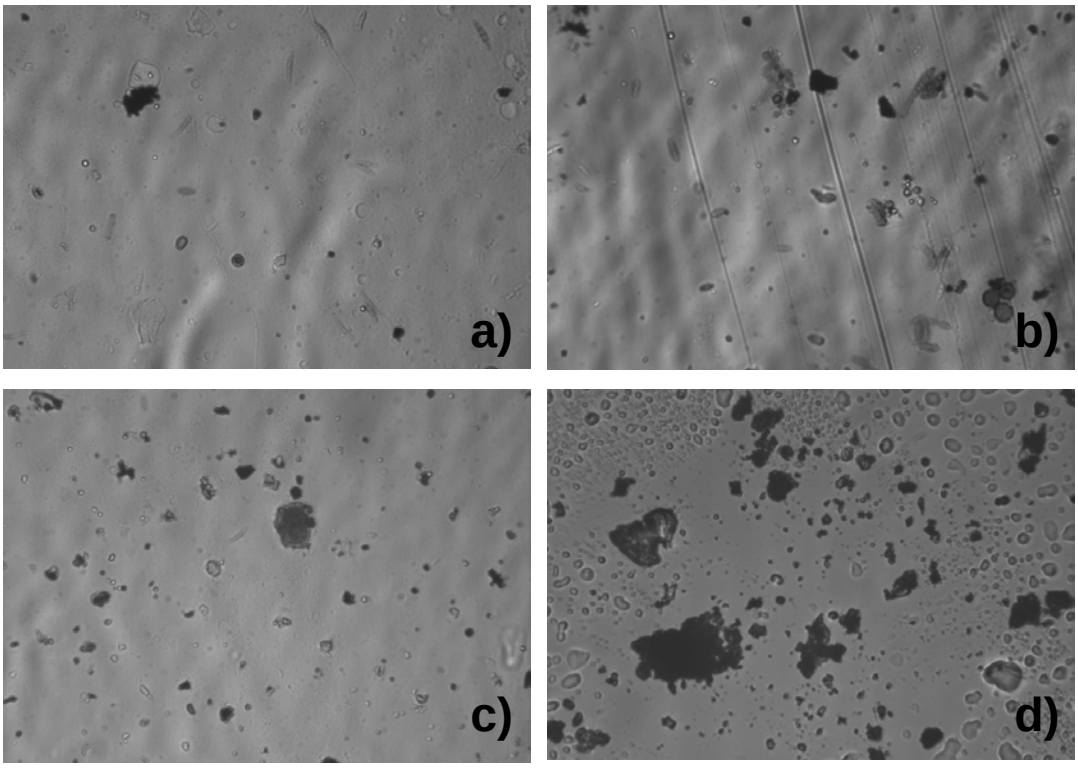


Figure 46: a) shows an example of low number of particles first caught; this sample was taken on 18th May 2006 between 8 and 10 am. b) Shows a medium capture of PM, the sample was taken on 16th August 2005 between 5 and 6 am. c) Illustrates a high level of particles trapped the sample was taken on 22nd June 2006 between 9 and 12 am. d) Represents a very high catch of PM the sample was taken 19th February 2006 between 6 and 7 pm). For all four samples magnification x400 was used.

The next step was to count the number of times that every value was repeated. These records were transferred into an Excel spreadsheet and the number of frequencies noted. From this point, it was then possible to find the frequencies and begin to examine the data statistically.

3.6.8 Trends of pollution at Dover

3.6.8.1 Trans-boundary analysis of PM

The wind direction was analysed using data from the Dover site (at Langdon Cliff), available from the ERG website (http://www.kentair.org.uk), noting when the wind was coming from the east or southeast (the two directions most likely to bring material from the near continent) and making a record of the wind persistence. Research by Rigby *et al.* (2006)

suggests that these periods of persistent winds might facilitate the dispersion of particles from the near continent.

The PM catches from the dates of wind persistence were compared to the other slides in order to see if the catches were more or less abundant when the wind was blowing from the near continent, or if there was any other relationship between the two sets of slides.

3.6.8.2 Ferry traffic

The sampling site is located within 1.5 km of Dover port (Figure 47), one of the major seaports and among the UK's busiest transport gateways. The National Emissions Centre data showed high levels of PM_{10} in the Dover area and the English Channel (Section 2.5.3, Figure 27). This could be related to emissions from the large number of ferries crossing the English Channel. The Dover Port Authority (www.doverport.co.uk; 2007) states that an average of 150 ferries per day depart and return to Dover, this number increases during holiday periods.

Figure 47: Photo of Dover port showing sampling location.
Adapted from: http://www.doverport.co.uk/ferry.asp

The busiest times of the day in relation to ferry traffic were recorded and the BVST data (examined in Section 3.6.8.1) when the wind blowing in the area was coming from the east, southeast or south (i.e. from the sea) were analysed with the objective of finding out if there was a correlation between the increase of PM caught and the increase in the number of ferries when the wind direction was blowing from the near continent.

The daily BVST results were also compared to see if there were patterns in PM capture at different parts of the days, to test if there were any times of peak data, or if the particles trapped followed any pattern.

If a sea breeze was present blowing particulates on-shore (either from across the Channel or from ferry sources in the Channel or near the coast) it would be expected to find heavier catches around midday-early afternoon rather than in early morning or late evening peaks: this assumption was then tested. Changes in PM capture around holiday times such as the beginning and end of the summer as well as the Christmas and Easter periods due to the increase in the number of ferries at these times of the year was also investigated.

3.6.8.3 Comparison between high levels of particulate matter

The particulate matter data collected by the ERG sampling site at Dover town centre were also analysed and a record was made of the time and the date when the level exceeded the 50 $\mu g/m^3$ amount recommended by the UK government (Section 2.2). This was carried out with the aim of comparing it with the data from the BVST at Dover and to check if the levels of pollution increased at the same time in both places, or if there were any kind of similarities between both sets of data.

Chapter 4

Results and Discussion

4.1 Outline of Chapter 4

This chapter presents and discusses the results obtained during the process of this investigation. The chapter is divided into five main sections following the previous classification applied in Chapter 3. Firstly, the results from the analysis of the weather data (both local and synoptic data) are presented and discussed (Section 4.2): this is followed by the results from the analysis of the PM_{10} data (Section 4.3). Results from the weather and PM_{10} data are then considered together (Section 4.4) in order to examine possible links between them. Section 4.5 evaluates the influence and behaviour of high episodes of pollution in the study area. Finally, Section 4.6 discusses the PM data obtained from the monitoring site at Dover as a trans-boundary pollution dispersal study.

4.2 Wind data results

4.2.1 Local wind data from Lower Stoke: individual results

Once the frequencies of the wind were analysed and plotted in a bar chart, it can be seen that wind directions most often observed at the study area are southwesterly (SW) followed by winds from the west (W), northwest (NW), east (E), south (S), northeast (NE) north (N) and southeast (SE) (Figure 48).

Many studies have reported that the British airflow is affected by low pressure systems from the Atlantic and, therefore, the whole year distribution is mostly effected by dominant southwesterly winds followed by winds from the west and the northwest (Parker, 1989; Pepper *et al*., 1996; Barry and Chorley, 1998; Arya, 1999) (Section 2.6).

The results from plotting the wind direction frequencies in Lower Stoke corroborate this statement. In addition, the fourth most common type of wind direction in the area is east; this result is investigated in more detail in further sections, in order to determine if there are other factors such as local topography or the proximity of the sea to the east of the site and, therefore, sea breezes, affecting the wind direction data.

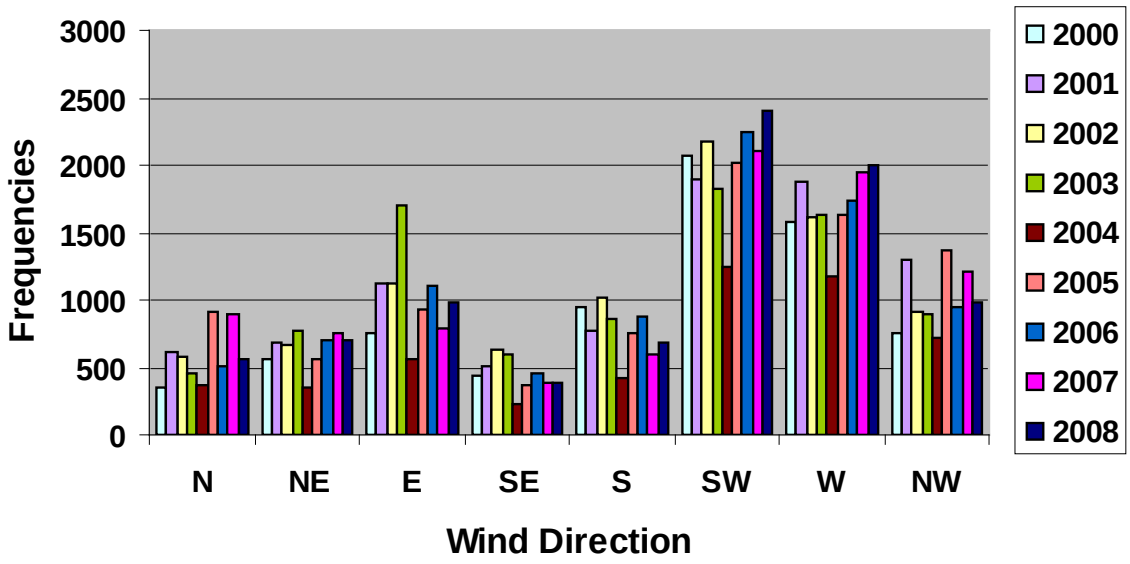


Figure 48: Shows the wind direction frequency distribution for Lower Stoke from 2000 to 2008 based on individual records one every 15 minutes.

As observed in Figure 48, wind direction patterns appear to be consistent during the years, southwesterly wind is the most common wind direction, followed by westerly and northwesterly winds. Nevertheless, during the manual manipulation of the data, a small pattern in individual sets of data was noted. It seemed to be a trend showing that the easterly types of winds occur more commonly during the middle warmer part of the day, in the hottest months of the year. Therefore, it was decided to organise and compare the data by dividing the year into four equal parts (a three month period in each) coinciding with the seasons; the data was divided this way in case there were trends disguised by plotting the yearly data together (Figure 49).

4.2.1.1 Seasonal analysis of the frequency distribution

January to March

During the winter months, the most common wind direction both visually and by average is southwesterly, closely followed by westerly, northwesterly and easterly. During some years, such as 2003, the easterly wind direction frequencies appear dominant in comparison to the other types of wind direction: this could be caused by an air mass arriving in from the coast, east of the sampling site, this theory will be developed in Sections 4.2.7 and 4.2.8. The other wind direction frequencies registered at this site (from the most frequent to the least) were northeast, north, south and southeast (Figure 49a).

April to June

Between April and June, the direction seems to be more evenly distributed through all eight principal wind directions. The first noticeable outcome is that easterly wind seems to have higher occurrence during this period compared with the other three seasons (Figure 49a, 49b and 49c). This could be a consequence of sea breeze affecting the area mainly throughout the day during some of the warmer months of the year; this idea is developed in Section 4.2.7. Nevertheless, southwesterly still appears to be the most predominant wind type, followed by westerly and easterly. Once the mean directions were calculated it was found that northwestly appears to be the fourth most common type of wind direction, closely followed by northeasterly, southerly, northerly and lastly southeasterly (Figure 49b).

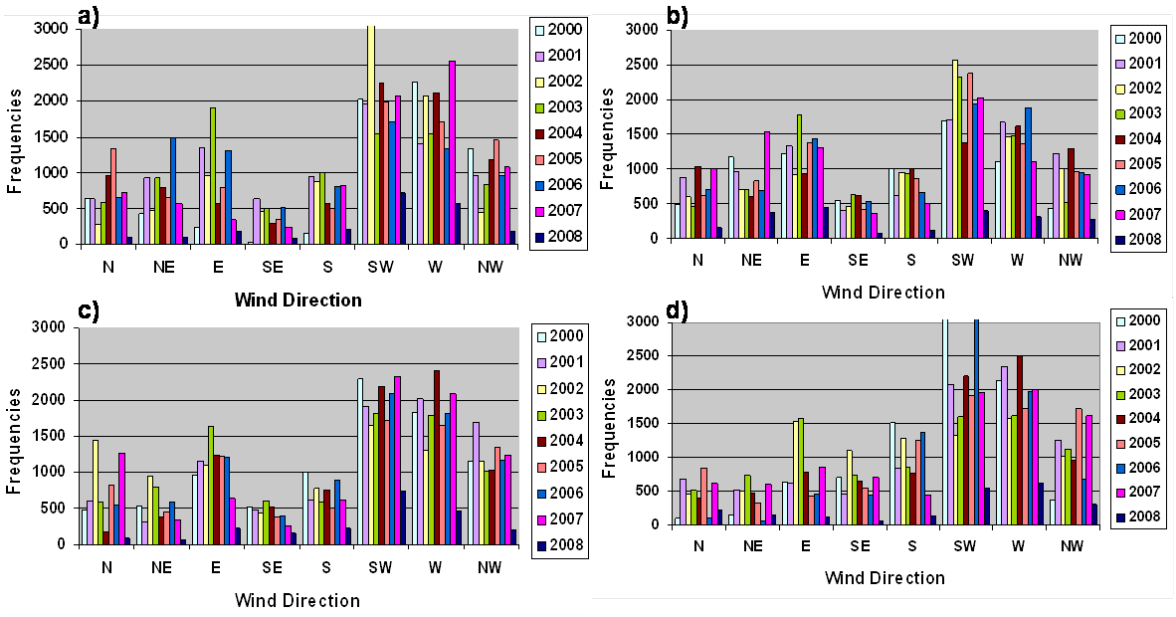


Figure 49: Seasonal wind direction frequency distribution at Lower Stoke from 2000 to 2008, Figure a) represents January to March, b) April to June, c) July to September and d) October to December.

July to September

The most common wind direction during this period is clearly southwesterly, directly followed by westerly. The frequencies are higher compared to the other periods of the year, winds from the southwest and the west are followed by wind from the northwest, east, south, north, northeast, and southeast. It is worth noting an increase of easterly winds frequencies (Figure 49c) during this period in comparison to the coldest months of the year (October to March).

October to December

Figure 49d illustrates a very close count for the number of frequencies between southwesterly and westerly. However, it appears that the southwest wind frequencies were slightly higher, followed by winds from the west, northwest, south, east, southeast, north and finally northeast (Figure 49d).

As previously noted, one of the most striking results found is the lower number of easterly frequencies compared to the warmer months which might show a sea breeze influence: this will also be investigated in Section 4.2.7.

Taking into consideration all four graphs, it could be said that the general whole year winds distribution seem to be dominated by a prevailing southwest wind, mostly followed by west and northwest. In general, easterly winds seem to be more common from April to September corresponding with the warmer months of the year.

In order to follow up these observations, it was decided to carry out a final analysis of the data by studying the correlation between wind direction shifts and fluctuation in temperature through the day (with special focus on sunrise, sunset and afternoon). For that reason, the data were divided into two sets and compared every 12 hours. No clear pattern was found, apart from that previously noted showing an apparent increase of easterly wind in the middle part of the year (Figure 49). These results are further examined in Sections 4.2.7 and 4.2.8.

4.2.2 Results of the analysis of the synoptic data

As described in Section 3.2.4, synoptic charts showing atmospheric circulations at 00.00 GMT for all nine study years were examined (Appendix D). A log was kept of the atmospheric conditions observed on the charts (wind direction and speed, cloud coverage, past and present weather). These also included the main synoptic events recorded such as, areas of high and low pressures, as well as the movements of cold, warm and occluded fronts (Appendix E). The information collected allowed the identification of weather formations affecting the local area, their behaviour and movements and, therefore, their influence on the dispersion of pollutants at ground level. This information has been used in Sections 4.3.2 and 4.3.4 to assist in the explanation of some synoptic episodes of PM_{10} recorded in Kent.

The focus of this part of the investigation relied on the wind direction data. Before the analysis was carried out, it was considered that the same wind direction patterns would be

recorded in both synoptic and local data. During the analysis of the synoptic data, the dominant wind directions found for the study area was southwest followed by northwest (Figure 50). These results were expected due to the wind patterns affecting the British Isles (Barry and Chorley, 1998) (Section 2.6.1) and the results previously found for the local data (Section 4.2.1). From the results presented in Figure 50 and accounting for variations in the frequency of observations, two other remarks can be made. The first is the low number of easterly synoptic wind entries compared to the local observations (Figure 48). The second is the high frequency of northeasterly records also compared to the local data (Figure 48).

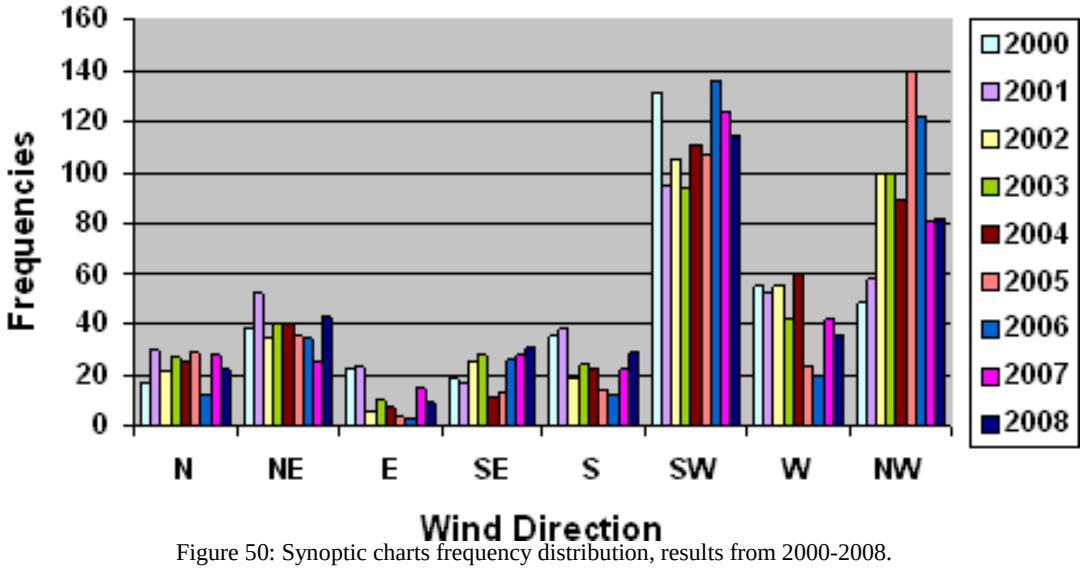


Figure 50: Synoptic charts frequency distribution, results from 2000-2008.

During the handling of the local data it was noticed that the number of easterly wind entries increased throughout the warmer part of the day (Section 4.2.1). This result might be an event that the synoptic chart is not able to show, either because the only data available were recorded once a day (00:00 GMT) and the observation may have not coincided with the local event, (and in order to observe these occurrences it would require the examination of more charts through the day or, ideally, hourly to compare both sets of data on the same scale), or because the event corresponds to a type of local (topographic) wind not large or persistent enough to be recorded by a synoptic observation.

Regarding the large number of entries of northeasterly wind identified in Figure 50, there is no obvious explanation at this point. The synoptic charts were used as a tool to show what may have taken place within the study area. Therefore, it could be possible that this increase

of northeasterly entries was caused by the wind arriving from the North Sea and across the land over the northeast part of the county.

4.2.3 Comparison between synoptic and local wind data

Through a visual analysis of the data, it can be observed that both sets differ in wind direction and frequency registered for the study area. When calculating the mean of the frequencies, these visual results become even more significant. The frequencies appear to be different in both sets of data. The only concurrence seems to be in the most common wind direction: in both sets it is from the southwest.

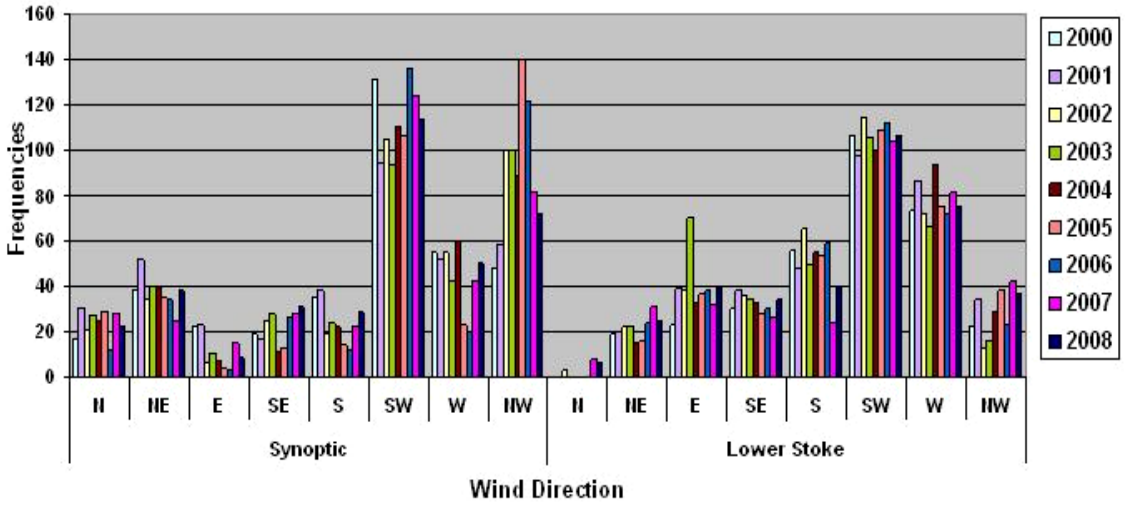


Figure 51: Comparison between wind directions as measured locally, at Lower Stoke (local data) and from synoptic charts*, from 2000 to 2008.
*Please note that Lower Stoke Data is the daily mean registered at the site while the synoptic data are a once daily measurement.

The main difference found between the two sets of data appears to be that the pattern previously noted during the analysis of the local data (Section 2.2.1) cannot be observed in the synoptic data. This pattern shows a noticeable increase in the frequencies of wind directions measured from the east, southeast and south at the local site compared to the information extracted from the synoptic charts.

The values obtained from the calculation of correlation coefficients between the two sets of data shows a significant variation between years (Table 3). However, it needs to be considered that these correlations are the results of comparing local hourly data and one daily value of synoptic data. Unfortunately, more synoptic values would be needed to allow a more accurate analysis.

Table 3: Shows the total number of daily local and synoptic values compared. The first and third rows show the total number of local daily values and synoptic daily data values compared respectively. The middle row shows the correlation coefficient values obtained between the two sets of data for each year.

	2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Total number of days with available local data compared	338	361	365	364	331	350	365	362	343
Synoptic Vs L. Stoke	0.856	0.634	0.400	0.184	0.561	0.355	0.431	0.769	0.656
Number of daily synoptic values compared	330	364	364	363	359	356	358	348	351

The lack of more synoptic data entries, together with the differences in the patterns obtained from the comparison confirm the idea that the synoptic wind direction data could not be used to infer the local wind patterns reliably. It is possible that this difference reflects a local wind regime, the patterns of local winds observed with respect to times of year and wind directions strongly support the presence of sea breezes, this idea is developed in Section 4.2.7. This would have implications for studying the dispersal of airborne particulates, as it suggests that local wind measurements are essential for assessing potential regional spread. Therefore, for the purpose of this study, it was decided not to use the synoptic wind direction data as a substitute for local data and to continue on examining the individual sets of data available and compare them in relation to the PM_{10} data.

Nevertheless the rest of the synoptic data recorded including the main synoptic events (air masses, fronts, cyclonic and anticyclonic events (Appendix E)) affecting the area were used to increase the understanding of the relationship between large-scale synoptic circulations main cause of long range transport of PM_{10} (Vidot *et al., 2007;* Plainiotis *et al.,* 2010) and air pollution in Kent.

4.2.4 General overview of local wind patterns at individual sites

The local wind direction analysis was then extended to all available sites between 2000 and 2008: Dover (Langdon Cliffs), Gravesham (A2), Sevenoaks, Swale (Ospringe and Sheerness) and Thanet (Manston airport) (Figures 31 and 52).

Initially, wind direction data from all the sites were studied individually, investigating different patterns or trends over the years and observing if the influence of topographical

features affecting the sites could be identified (examples of the graphical representation of the data can be found in Appendix K).

All sites have at least five years of data, which should help to provide a clear picture of what is occurring in the study area (Table 4). Gravesham and Lower Stoke are the only two sites with nine years of data. Special attention will be dedicated to these two sites in further sections, not only for being the two sites with the larger sets of data but also because they are sites with different environmental background and locations. Lower Stoke is a rural site; the trap is located in an exposed location, less than 2 km away from the seashore. Gravesham sampling site is located close to the city of London, next to a busy motorway, in a more sheltered area (Section 4.2.5).

Table 4: Presents the results from the graphical evaluation of the wind direction data as well as the mean calculations. The results are presented in order of frequencies; the first column shows the site location and sampling period, the other columns show the types of wind direction registering the highest values.

Site/Sampling period	**Most common wind directions**							
Dover (2003-2008)	SW	NE	N	W	NW	S	E	SE
Gravesham A2 (2000-2008)	SW	S	NE	N	W	NW	E	SE
Lower Stoke (2000-2008)	SW	W	NW	E	S	NE	N	SE
Ospringe (2004-2008)	SW	S	NW	NE	E	W	SE	N
Sevenoaks (2001-2006)	SW	W	E	S	NE	SE	N	NW
Sheerness (2004-2008)	SW	S	W	E	NE	NW	SE	N
Thanet (2003-2008)	SW	W	E	NE	S	N	NW	SE

The data from Lower Stoke (Section 4.2.1) are also presented in Table 4 to allow comparison between all available sites.

The analysis of the data for all sites confirm southwest as the most predominant local wind direction, apart from this none of the sites seem to share the same entire pattern (Figure 52). This is not an unexpected result, as previously explained in the literature review (Section 2.4); the local airflow at one specific point may be influenced by different topographical features, urban environments or weather patterns affecting the sites.

During the individual analysis of the data sets, it was observed that generally the wind directions appeared to be evenly distributed through the years at three of the studied sites: Dover, Sevenoaks and Thanet (Appendix K). Whereas the data for the other three sites

followed a common pattern, second most common wind direction for Gravesham, Ospringe and Sheerness was south. Moreover, Lower Stoke differs from all the other sites, being mainly dominated by westerly winds followed by high amount of winds from the east (Figure 52) (Appendix K).

These results are confirmed in the representation of the wind roses for each location (Figure 52). Interestingly, Gravesham, Lower Stoke and Sheerness show an increase of northeasterly winds in comparison to the other sites; this may mean that they are influenced by sea breezes or air masses arriving from the North Sea. This result is examined in more detail in Sections 4.2.6 and 4.2.7.

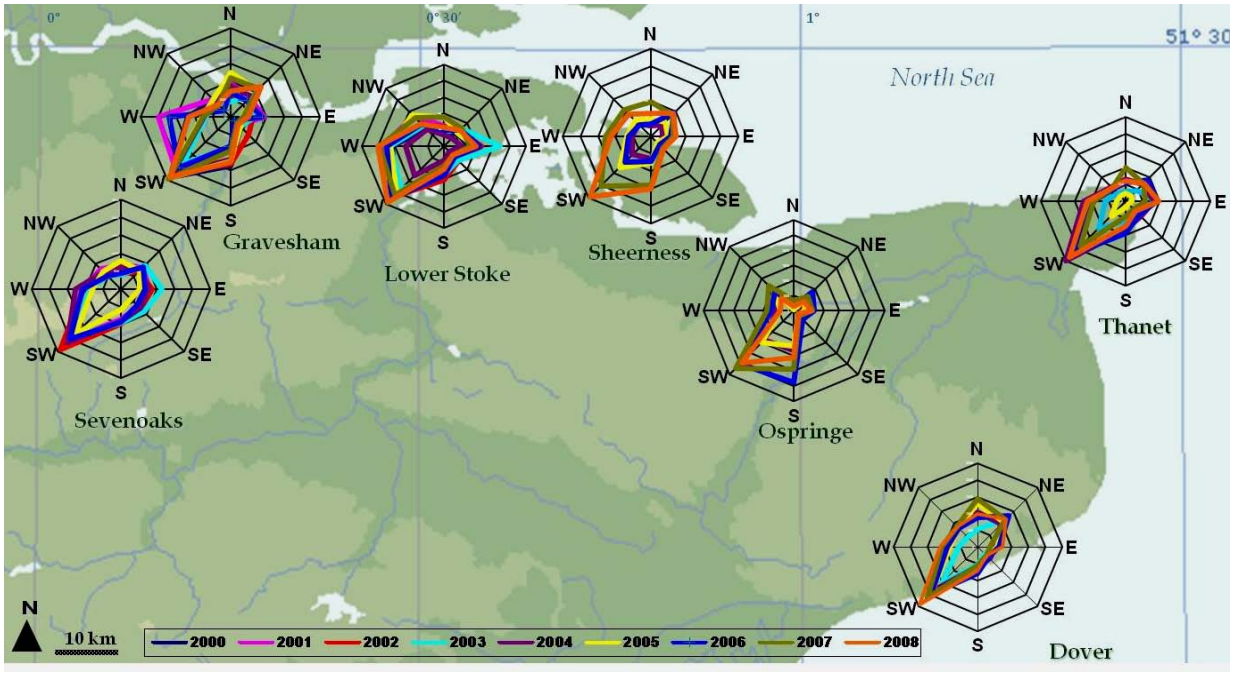


Figure 52: Map showing wind roses with data available for all studied sites
Note: A large print of this map can be found in Appendix R.
Adapted from Microsoft Encarta (2003).

Gravesham, Ospringe and Sheerness show southerly winds as the second most common wind direction (Figure 52). All three sites are located in the northern part of the county, (Figure 31) but this appears to be the only characteristic that the three sites have in common (Lower Stoke and Thanet are also in the northern part of the county, however do not appear to be affected by this pattern). For that reason, the only possible explanation could be the increase of southerly wind may be linked to a topographical feature affecting the three sites at the same time, for example, a down slope wind arriving from the north face of the North Downs (Figure 52). However, this explanation is not totally satisfactory for two reasons:

firstly, the North Downs are only a few hundred metres higher than the surrounding area, and secondly, the Sheerness sampling site is located in an island on the northern part of the county and because of its location is not likely to be affected by the same topographical features that affect the other two sites. Therefore, no suitable explanation has been found for this pattern, apart from perhaps a consequence of a synoptic influence (e.g. air masses affecting the north part of the county).

Because individual analysis of the wind data distribution did not provide a clear picture of the wind direction patterns affecting the whole area, it was decided to extend the methodology and study the data on a yearly basis, in order to investigate whether a given pattern was affecting more than one site at once.

4.2.5 Analysis of the annual correlations on wind direction data between sites

Tables 5 to 12 illustrate the correlation coefficients for all the sites where weather data for the study years were available. Unfortunately, because these sets of data are incomplete a detailed analysis of all sites throughout the nine years is not possible (Appendix F). Nevertheless, most sites have at least five years of data and these sets have been compared. The correlations are shown in chronological order.

For the purpose of this study, whenever the correlation coefficient was found to be over 0.5 it has been considered that the two sites are well correlated. The wind direction data available have been plotted yearly with the intention to assist explaining the annual correlation between sites. All of the graphs have been plotted showing the same scale to facilitate a visual comparison between them.
During the analysis, geographical features affecting the sites have also been considered in order to provide an explanation of what is happening at the site.

4.2.5.1 Wind direction data correlation coefficients for 2000

In 2000, the only sets of data available were Gravesham and Lower Stoke. The correlation coefficient between the two sites is significantly high: 0.897. This value could be explained by the location of the sites; both sites are 19.5 km apart (Appendix O), as well as the fact that they are both less than 10 kilometres away from the Thames Estuary.

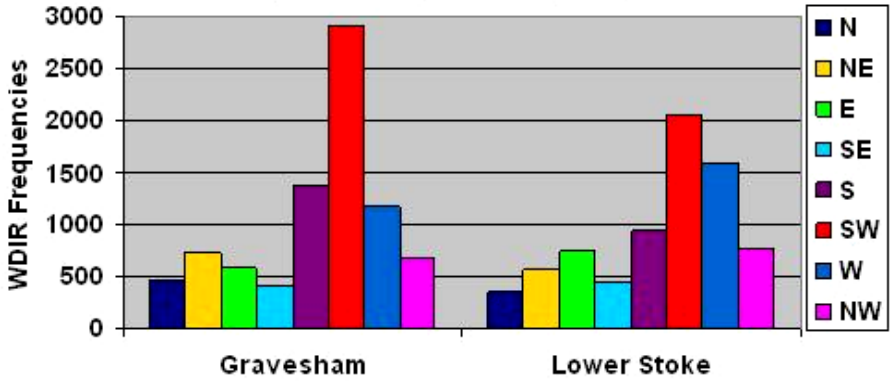


Figure 53: Graphs showing the sites with wind direction data available for 2000.

In Figure 53, the wind direction frequencies for both sites can be observed. As expected (Section 4.2.4), southwest is the most common wind direction for both sites, followed by south for Gravesham and west for Lower Stoke. Although slight variations between the two sites can be observed, they tend to follow similar patterns during this year (Figure 53).

4.2.5.2 Wind direction data correlation coefficients for 2001

Table 5 illustrates the data available for 2001. Lower Stoke and Gravesham are the two sites with the highest correlation (0.888). In Figure 54, it can be observed that the prevailing wind for this year in all sites was southwest, followed by west.

Table 5: Matrix showing correlations of wind direction frequencies between sites with available data for 2001.

	L.Stoke	**Sevenoaks**
Gravesham	0.888	0.819
L.Stoke		0.753

Furthermore, there is an apparent difference between the Sevenoaks wind direction distribution and the other two sites (Figure 54) that may help explain the correlation coefficients. This result could be a consequence of the location of the sites: Sevenoaks is located further inland than the other two sites and, therefore, as noted in Section 2.4.4, this site may not be affected by sea breezes (this is investigated further in Section 4.2.7).

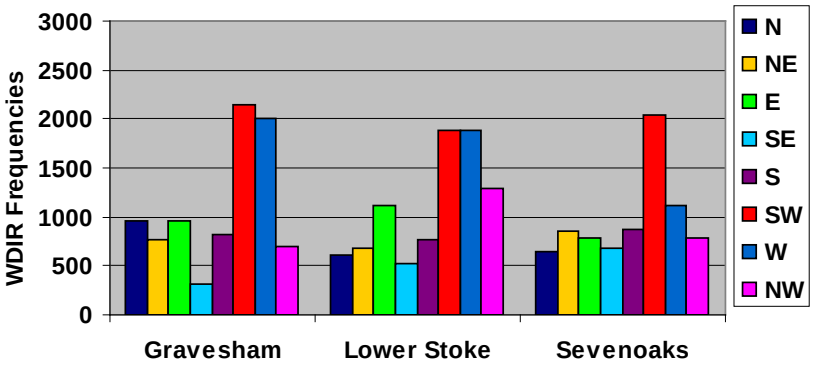


Figure 54: Graphs showing the sites with wind direction data available for 2001.

4.2.5. Wind direction data correlation coefficients for 2002

The 2002 data correspond to the same three sites as for 2001, the correlation coefficients can be observed in Table 6.

Table 6: Matrix showing correlations of wind direction frequencies between sites with available data for 2002.

	L.Stoke	**Sevenoaks**
Gravesham	0.756	0.928
L.Stoke		0.907

However, in contrast to the previous year, the higher correlation is found between Sevenoaks and Gravesham (0.928). The reason for this result is unknown, however, these two sites are closely located as well as that Lower Stoke is a coastal site. In Figure 55, it can be observed that there is not an unexpected pattern affecting the three sites: southwest is the most prevailing wind direction.

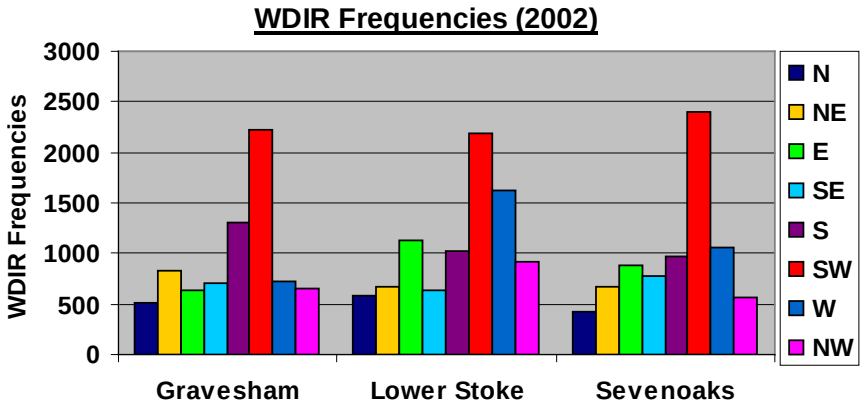


Figure 55: Graphs showing the sites with wind direction data available for 2002.

4.2.5.4 *Wind direction data correlation coefficients for 2003*

Table 7 incorporates two new sites, Dover and Thanet. These two sites are both located near to the coast and at further distances to the other sites (Appendix O). The highest correlation value was found between Sevenoaks and Thanet (0.928). This result would imply an association between the two sets of data. In contrast, the sites are in very different locations. Sevenoaks in located inland while Thanet is close to the coast; they are also 85 km apart.

Table 7: Matrix showing correlations of wind direction frequencies between sites with available data for 2003.

	Gravesham	**L.Stoke**	**Sevenoaks**	**Thanet**
Dover	0.879	0.492	0.753	0.689
Gravesham		0.630	0.886	0.834
L.Stoke			0.726	0.886
Sevenoaks				0.928

The second highest correlation was between Lower Stoke and Thanet (0.886). Examining Figure 56, there doesn't seem to be a clear pattern affecting the sites with the higher correlation coefficient in comparison to those with lower correlation coefficients. The lowest correlation was found between Lower Stoke and Dover (0.492). Both sites are near to the coast but located 61 km apart: therefore, they may be affected by different local winds.

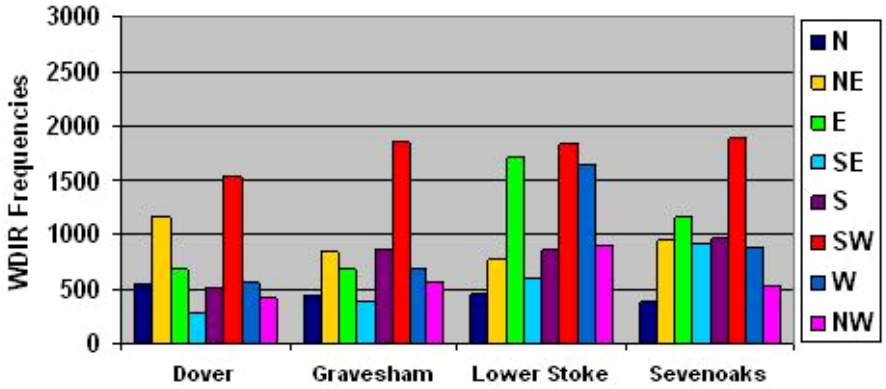


Figure 56: Graphs showing the sites with wind direction data available for 2003.

4.2.5.5 Wind direction data correlation coefficients for 2004

For 2004, the data for two more sites were added: Ospringe and Sheerness (Table 8). This time, the highest correlation coefficient was once more found to be between Sevenoaks and Thanet (0.990) closely followed by Sheerness and Ospringe (0.970) and Gravesham and Thanet (0.916). The very high correlation coefficient between Sevenoaks and Thanet is difficult to explain. As previously described, both sites are not in close proximity to each

other and they appear to have different wind patterns for the year 2004 (Figure 57). Both sites are located on the northern part of the county (Figure 31), so perhaps they are affected by the same synoptic weather episodes, for instance, air masses arriving from the North Sea.

Table 8: Matrix showing correlations of wind direction frequencies between sites with available data for 2004.

	Gravesham	L.Stoke	Ospringe	Sevenoaks	Sheerness	Thanet
Dover	0.883	0.668	0.434	0.827	0.546	0.861
Gravesham		0.572	0.722	0.894	0.778	0.916
L.Stoke			0.482	0.797	0.602	0.782
Ospringe				0.652	0.970	0.614
Sevenoaks					0.775	0.990
Sheerness						0.724

The lowest correlations were found between Dover and Ospringe (0.434) and Lower Stoke and Ospringe (0.4829). The annual patterns between the sets of data appear to be dissimilar (Figure 57). The second most common direction for Ospringe is south while for Lower Stoke and Dover they are west and north respectively.

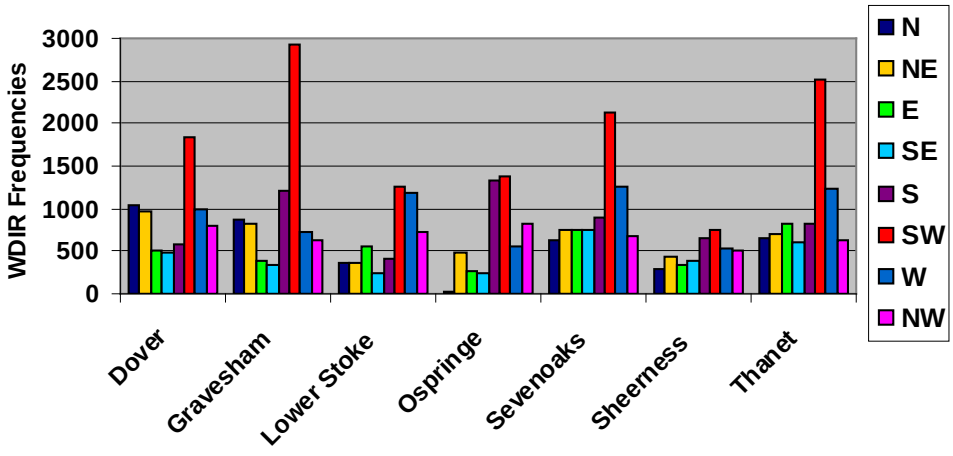


Figure 57: Graphs showing the sites with wind direction data available for 2004.

4.2.5.6 *Wind direction data correlation coefficients for 2005*

Table 9 shows the data for 2005. In Table 9, it can be observed that Sevenoaks is highly correlated with Gravesham (0.921) and Thanet (0.995). These values may be a consequence of the site locations, in the northern part of the county. Therefore, they may be affected by the same air masses arriving from the North Sea (Figure 31). However, the wind direction data sets from Dover are also highly correlated with three of the other sites: Gravesham

(0.927), Sevenoaks (0.936) and Thanet (0.917). The high correlation coefficients found between Dover and the other three sites have no clear explanation, at least all sites may be affected by same air masses or synoptic episodes affecting the whole county. The lowest correlation coefficient is found to be between Dover and Ospringe (0.482), this is a similar result to the one found in the previous year (0.434).

Table 9: Matrix showing correlations of wind direction frequencies between sites with available data for 2005.

	Gravesham	**L.Stoke**	**Ospringe**	**Sevenoaks**	**Sheerness**	**Thanet**
Dover	0.927	0.645	0.482	0.936	0.781	0.917
Gravesham		0.594	0.690	0.921	0.883	0.893
L.Stoke			0.565	0.799	0.801	0.836
Ospringe				0.649	0.875	0.640
Sevenoaks					0.894	0.995
Sheerness						0.899

In Figure 58, the wind direction distribution for all these sites can be observed. When comparing every site, it can be noted that the most common wind direction for all sites is southwest.

As explained in the previous paragraph, each individual site seems to have its own specific wind distribution throughout this year (Figure 58). However, the correlations between sites appear to be curiously high between sites more than 60 kilometres apart (for example Sevenoaks and Dover) which may indicate a synoptic or regional influence affecting all sites.

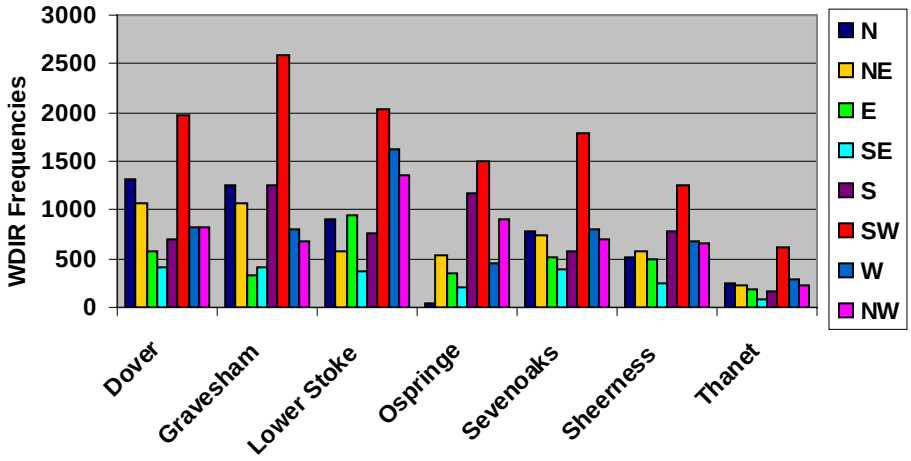


Figure 58: Graphs showing the sites with wind direction data available for 2005.

4.2.5.7 *Wind direction data correlation coefficients for 2006*

The highest correlation coefficients for 2006 were once again found for Sevenoaks and Thanet (0.972) (Table 10). The second highest correlation was between Lower Stoke and Gravesham (0.919). No values under 0.5 were found, therefore it could be said that there appears to be a significant association between the wind direction distributions at most sites during 2006. The data sets for 2006 were fairly complete (7565 data points for Thanet, 7197 for Gravesham and 8585 data points for Lower Stoke out of a possible 8760). The lowest correlation values for the third consecutive year were found among Dover and Ospringe (0.602). A correlation coefficient of 0.602 shows a relatively high association between the two sites; it is only considered low in comparison to all the other values found. There also seems to be a pattern indicating the lower correlation between the two sites in comparison to all the others. No clear explanation could be provided at this stage, other than that the two sites are relatively far apart; the Dover site is close to the English Channel and, therefore, expected to record a higher southeasterly influence while Ospringe is located in the northern part of the county (Figure 34), therefore, a sea breeze would arrive from the north or northeast. On the contrary, the second most common wind direction at this site is southerly (Figure 59).

Table 10: Matrix showing correlations of wind direction frequencies between sites with available data for 2006.

	Gravesham	**L.Stoke**	**Ospringe**	**Sevenoaks**	**Sheerness**	**Thanet**
Dover	0.693	0.685	0.602	0.841	0.836	0.862
Gravesham		0.919	0.518	0.845	0.618	0.839
L.Stoke			0.582	0.874	0.615	0.854
Ospringe				0.757	0.726	0.747
Sevenoaks					0.807	0.972
Sheerness						0.807

During analysis of the graphical representation of wind direction yearly distribution, it is evident that southwest is the most predominant wind direction at all sites (Figure 59).

In the visual comparison, Thanet and Sevenoaks are the two sites with the most similar wind direction distributions. This may help to explain the higher correlation found between both sites (0.972). In addition, Dover and Ospringe are, thus far, the two sites with the most dissimilar wind direction distribution patterns.

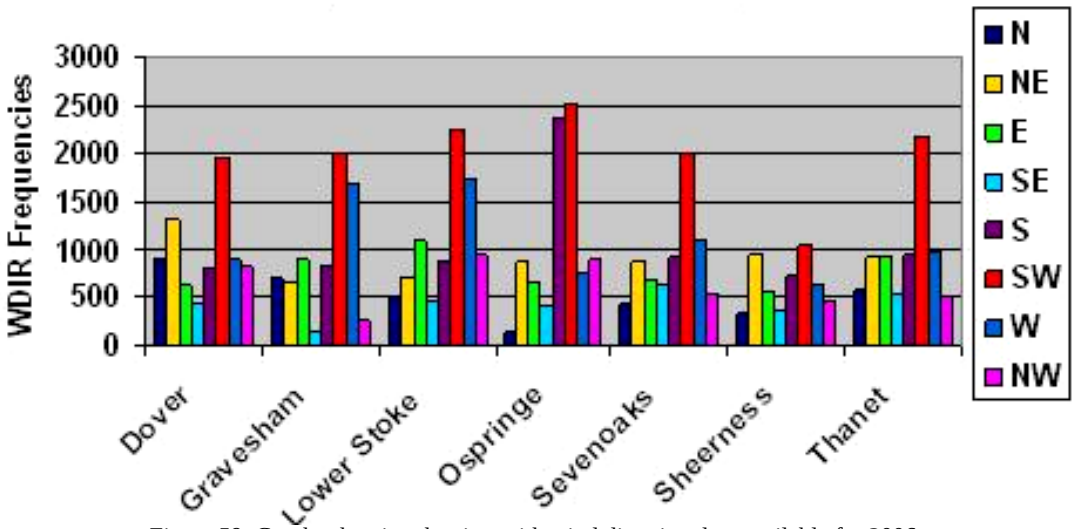


Figure 59: Graphs showing the sites with wind direction data available for 2006.

4.2.5.8 Wind direction data correlation coefficients for 2007

In Table 11, the correlations for 2007 are presented. The highest correlation coefficient was found between Thanet and Dover (Table 11) closely followed by Thanet and Gravesham (0.918) along with Gravesham and Dover (0.9070).

Following the case from the previous year, no values under 0.5 were found. There is an apparent relationship/pattern between the wind direction distributions at most sites. The lowest correlation values for the fourth consecutive year were found among Dover and Ospringe (0.517). In previous sections, it was considered that this result could be due to the location of both sites (Figure 34); one of them is located on the north coast while the other one is located on the south east coast of the county (Figure 31). However, this could be considered a vague explanation for the reason that Lower Stoke and Ospringe have the second lowest correlation values (0.558) and in this case the two sites are both closely located on the north coast of the county.

Table 11: Matrix showing correlations of wind direction frequencies between sites with available data for 2007.

	Gravesham	**L.Stoke**	**Ospringe**	**Sheerness**	**Thanet**
Dover	0.907	0.722	0.517	0.737	0.944
Gravesham		0.619	0.744	0.843	0.918
L.Stoke			0.558	0.760	0.810
Ospringe				0.916	0.607
Sheerness					0.785

The graphical representation of the wind direction distribution for 2007 does not seem to follow any clear pattern apart from the one already mentioned showing southwest as the most predominant wind direction for all the sites.

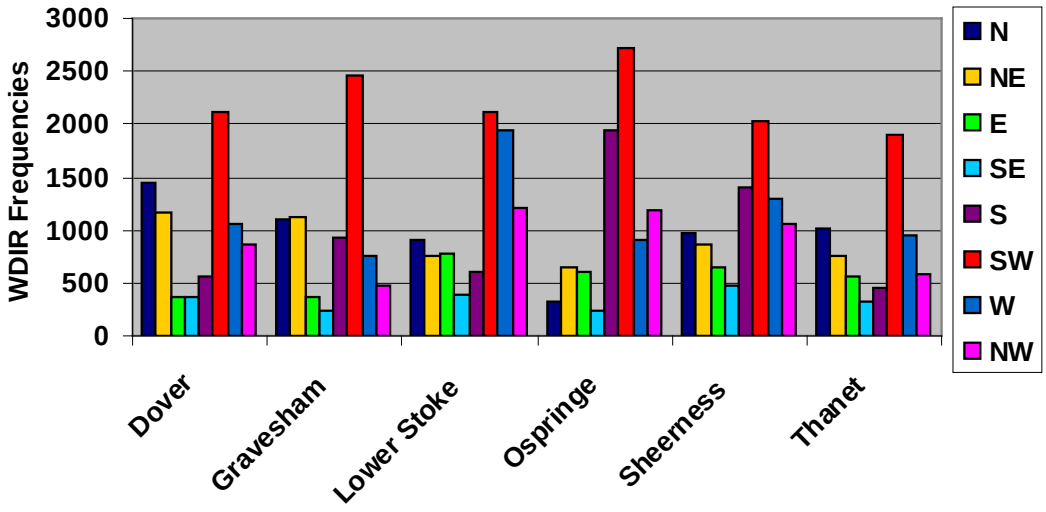


Figure 60: Graphs showing the sites with wind direction data available for 2007

4.2.5.9 Wind direction data correlation coefficients for 2008

Table 12 shows the 2008 correlation results. The highest association was found between Sheerness and Gravesham (0.955), followed by Thanet and Dover (0.936), Dover and Gravesham (0.931) and Thanet and Gravesham (0.921). For the third consecutive year, no values under 0.5 were found. There appears to be a significant high correlation affecting the wind direction distributions at most sites. The most solid justification for these results could be a synoptic influence affecting most sites over the main part of the year.

Table 12: Matrix showing correlations of wind direction frequencies between sites with available data for 2008.

	Gravesham	**L.Stoke**	**Ospringe**	**Sheerness**	**Thanet**
Dover	0.931	0.817	0.734	0.844	0.936
Gravesham		0.765	0.874	0.955	0.921
L.Stoke			0.623	0.763	0.868
Ospringe				0.963	0.823
Sheerness					0.886

Examining the graphical representation, the only other apparent pattern (rather than the most predominant wind being southwest) is that southeast winds seem to be the wind direction with the lower number of frequencies in all cases.

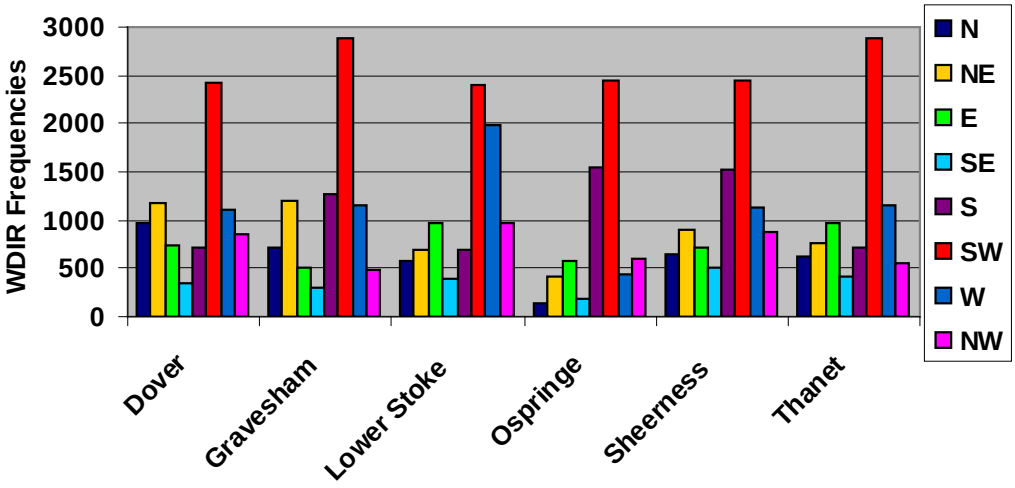


Figure 61: Graphs showing the sites with wind direction data available for 2008.

4.2.5.10 Summary of the annual wind direction correlation analysis

The analyses of the coefficient correlations for all sites have provided an idea of the difficulties involved in the description of the airflow within Kent.

For the four years (2003-2007) that sufficient data were available at both sites, Sevenoaks and Thanet registered the highest correlation values (Tables 7 to 12). Both sites are in urban locations; the main difference is that Sevenoaks is located inland, while Thanet is close to the north coast (Figure 34).

On the other hand, the lowest correlation values were found between Lower Stoke and Dover (Tables 7 to 12). No clear explanation was found for these results. It was considered that these results could be a consequence of both site's location (Figure 34): one of them is located on the north coast (Lower Stoke) while the other one (Dover) is located on the southeast coast of the county, which could imply that perhaps they could be affected by local winds patterns caused by topographical features such as sea breezes due to their coastal location rather than air masses or synoptic events affecting the whole region. The second lowest correlation values are between Lower Stoke and Ospringe and in this case the two sites are both closely located in the north of the county (only 12 km away from each other).

Generally, there is no clear explanation of why some sites may have higher correlation coefficients than others. Often, during the analysis of one specific year, the correlation between two sites could be higher and, therefore, it was assumed that this could be a consequence of features such as topography or local winds. On the other hand, the same two

site's correlation coefficients for the following years show opposite results, suggesting that the low correlation coefficients could perhaps be influenced by some other factors such as synoptic influences (e.g. air masses) or local winds.

4.2.6 General Summary of the wind direction data analysis

Lower Stoke was the first set of data to be analysed. The results obtained from this site confirm those found in the literature, reporting that the main British airflow is affected by pressure systems arriving from the Atlantic (Section 2.6) and, therefore, the whole year distribution is dominated by southwesterly winds, followed by winds from the west and the northwest (Figure 48). The fourth most common type of wind direction in the area is easterly. This result was also observed during the manual manipulation of the data: a trend was found showing that the easterly winds occur more commonly during the middle part of the day (when it is warmer), in the warmest months of the year: March to September (Figure 49).

The focus then moved to the synoptic scale (Section.4.2.2). This was expected to provide a general overview of the weather affecting the study area, but the results do not seem to represent an accurate picture of the wind direction distribution in the study area (Figure 50). There appears to be a significant difference between the synoptic and the local data when comparing them (Figure 51). Whilst southwesterly was still the most predominant wind direction, the synoptic data showed a low number of east wind entries compared to the local data (Figure 51). The correlation coefficients (Table 3) show that the association between the two sets of data seem to be significantly high. However, for a more accurate comparison a higher number of synoptic data entries would be needed.

With this in mind, it was decided that the lower value of the correlations, as well as the patterns shown on the graphs, suggested that the synoptic data could not be used to infer the local wind patterns reliably. It is possible that this difference reflects a local wind regime, possibly a sea breeze structure. This would have implications for studying the dispersal of airborne particulates, as it suggests that local wind measurements are essential for assessing potential regional spread (Section 2.4).

In a further step, the analysis was then extended to all available sites between 2000 and 2008: Dover (Langdon Cliffs), Gravesham (A2), Lower Stoke, Sevenoaks, Swale (Ospringe and Sheerness) and Thanet (Manston airport) (Figure 31) (Section 4.2.4).
All the available sites were studied individually to investigate different patterns or trends over the years and observing if the influence of certain local sources or topographical features affecting the sites could be appreciated. In summary, all sites show southwesterly as the most predominant wind direction but apart from that none of the sites have similar patterns (Figure 55). In general, Dover, Sevenoaks and Thanet appear to have more evenly distributed wind types, this observation could provide an explanation for the high correlations coefficient found between the Sevenoaks and Thanet sites. In addition, Gravesham, Ospringe and Sheerness show south as the second most common wind direction. Moreover, Lower Stoke differs from all the others, being dominated by westerly winds followed by a high proportion of wind frequencies from the east (Figure 55).

Overall, no obvious patterns or annual trends were found between the sites, during the analysis of the correlation coefficients and the chronological representation of the data (Section 4.2.6: Tables 5 to 12 and Figures 53 to 61), with the exception of some repetition among the lowest and highest correlation values (2003-2008, Tables 7 to 12). However, no clear explanation for these values was found. On occasion, the data appears to be influenced by synoptic factors such as synoptic influences (e.g. air masses) or local winds affecting two distant sites and, therefore, showing similar their values. Although these influences are not consistent through the years and therefore no clear trends can be highlighted, emphasising on the difficulties involved in the description of the airflow within a large area such as Kent, due to the many environmental factors to be taken into account (such as topographical features, urban landscape or wind patterns).

4.2.7 Sea breeze influences

During the preliminary analysis of the Lower Stoke data, an increase of wind frequency from the east was noticed (this being the nearest direction to the sea) (Figure 48). The increase occurred mainly during the warmest part of the day (10.00 to 16.00), escalating significantly during the warmer months of the year (Figure 49). It was therefore considered that this increase in easterly winds could be caused by a sea breeze coming into land (Section 2.4.1) (see site locations in Figure 31). Consequently, it was decided that the trends of individual

wind patterns should be examined for the presence of sea breezes which might influence landward and seaward dispersal of PM_{10}. Winds from the east and northeast were examined to the exclusion of the others because they are the winds most likely to come from the North Sea or the English Channel, bringing sea breezes on to the land at the study sites.

When considering the methodology to apply, it was decided to carry out the sea breeze analysis on four sites. As previously explained in Section 3.2.7, Lower Stoke and Dover are coastal sites (located within less than 2 km from the sea). As well as that, Dover was also the location chosen to carry out another experiment during the process of this investigation (Section 4.6) and, therefore, it was considered useful to carry out an analysis of the sea breeze data that could be used at a later stage.

The other sites, Gravesham and Sevenoaks, are located further inland, the Gravesham sampling site is very close to the Thames Estuary (13 km from the sea), and Sevenoaks was chosen with the purpose of providing a contrasting site (this sampling site is situated further inland 35 km from the coast), which may provide a good inland control site.

Ideally for the analysis of costal winds or thermal circulations affecting the sampling sites, it would be useful to compare the temperature data for the sampling sites to the wind direction data sets. Unfortunately, the temperature data for each specific site were not available, however, a temperature profile for the whole region was used to provide an indication if the entries for northeasterly and easterly winds would increase during the warmer weather periods (Appendix S).
Tables 13, 14, 15 and 16 illustrate the amount of east and northeast wind occurrences recorded at each of the four locations for all of the studied years. A detailed table for each individual year can be found in Appendix T. In addition, Section 4.2.7.5 shows the sum of frequencies for all sites over the studied period.

4.2.7.1 Lower Stoke site sea breeze study

Table 13 shows the number of winds from the east and northeast (lasting at least three hours at a time) for Lower Stoke. This table shows a clear increase of the wind occurrences during the warmer months (mainly from March to September) (these higher frequencies have been highlighted in bold in Table 13) This will indicate a sea breeze activity taking place in this

area, which would affect the dispersion of particulates especially during the warmest season of the year (Appendix S). As expected, the lowest frequencies were registered during the coldest months of the year (mainly from November to February).

Table 13: Number of occurrences (lasting at least three hours) of winds from east and northeast, measured at Lower Stoke from 2000 to 2008 (in bold can be seen the higher frequencies registered between March and August).

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-09.00	29	47	**64**	**55**	**66**	**63**	**70**	**51**	**41**	44	34	27
10.00-18.00	34	54	**97**	**84**	**100**	**72**	**64**	**58**	**75**	48	28	34
18.00-00.00	17	36	**53**	**50**	**67**	**52**	**52**	**48**	**40**	41	23	25

4.2.7.2 Gravesham site sea breeze study

Gravesham's sea breeze analysis shows very similar results to those found in Lower Stoke. These two sites are the closest (only 20 km apart); they are also the two sites with the largest duration of data available (2000-2008). Nonetheless, this is an unexpected result, Gravesham is situated inland, close to the Thames Estuary, although 13 km away from the sea shore, whereas Lower Stoke is a coastal site. In Table 14, it can be observed that easterly and northeasterly wind occurrences lasting at least three hours are slightly lower than for Lower Stoke (Table 13), yet these are still clearly higher during the warmer months of the year in comparison to the cooler months (these higher frequencies have been highlighted in Table 14). These results indicate that there is a clear sea breeze influence affecting this site. Moreover, this is in line with the suggestions by Van Dingenen *et al.* (2004) and Putaud *et al.* (2004) stating that sea spray was clearly identified as one of the most common components of the particles in sites located in a radius smaller than 50 km from the seashore and, therefore, a consequence of the sea breezes coming into land. These results would be most helpful when explaining the influence of wind direction into PM_{10} dispersion in Section 4.4.

Table 14: Number of occurrences (lasting at least three hours) of winds from east and northeast, measured at Gravesham from 2000 to 2008 (in bold can be seen the higher frequencies registered between March and August).

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-09.00	29	37	**61**	**55**	**45**	**71**	**62**	**72**	61	67	74	68
10.00-18.00	23	51	**71**	**64**	**86**	**65**	**83**	**68**	80	58	40	72
18.00-00.00	20	29	**54**	**52**	**64**	**55**	**61**	**65**	37	48	49	49

4.2.7.3 Sevenoaks site sea breeze study

As previously described in Sections 3.2.7 and 4.2.7, Sevenoaks is an inland site (located 35 km away from the coast), therefore, it is less likely to be affected by coastal winds. On the contrary, the results obtained during the process of this investigation show an increase of the easterly and northeasterly winds during the warmer part of the day, particularly in the warmer months of the year (Table 15), these results would indicate a sea breeze or thermal circulation coming into land.

Analogous studies based on wind patterns in the Great Lakes area observed that localised winds can extend a few kilometres in to sea or in this case, the lakes, as much as 20 km inland (Lyons and Olsson, 1973; Parker, 1989; Laird *et al.*, 2000). The results obtained during this analysis verify these suggestions, and increase the area affected to 35 km inland (distance from the Sevenoaks sampling site to the sea).

Overall, the values obtained are closer to the suggestions by Van Dingenen *et al.* (2004) and Putaud *et al.* (2004) affirming that sea breeze influences can be observed up to 50 km into land.

Table 15: Number of occurrences (lasting at least three hours) of winds from east and northeast, measured at Gravesham from 2000 to 2008 (in bold can be seen the higher frequencies registered between March and August).

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-09.00	7	14	**37**	**25**	**32**	**25**	**23**	**25**	17	6	7	10
10.00-18.00	13	24	**40**	**43**	**42**	**31**	**34**	**30**	17	9	8	8
18.00-00.00	5	10	**21**	**20**	**32**	**20**	**13**	**19**	3	7	3	4

Furthermore, the values recorded in Table 15 are lower that those found for Lower Stoke (Table 13) and Gravesham (Table 14). These results could be caused by two main factors: either the number of values is lower because there were fewer occurrences, or more likely, they could be caused by the number of data entries examined. The data for the two previous sites cover nine years (2000-2008) while for Sevenoaks there are only six years available (2001 and 2006) (Appendix F).

4.2.7.4 Dover site sea breeze study

Dover is a coastal site, located on Langdon cliffs looking out towards the sea. Due to the specific location of this sampling site, facing northeast and with a topographical barrier

behind it (the sampling site location can be seen in Figure 37, the weather sensors are located a few metres behind the BVST), it was also decided to sample northeasterly and easterly winds to allow comparison with the other three sites. The results are very similar to those found in the three previous cases. The number of entries registered seems generally lower than in the other coastal site (Lower Stoke). This is an unexpected result due to the exposed location of the site, and its proximity to the sea.

Table 16: Number of occurrences (lasting at least three hours) of winds from east and northeast, measured at Gravesham from 2000 to 2008 (in bold can be seen the higher frequencies registered between March and August).

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-09.00	19	20	**28**	**28**	**32**	**44**	**22**	**34**	25	33	14	2
10.00-18.00	19	25	**29**	**45**	**50**	**44**	**42**	**41**	44	32	27	4
18.00-00.00	13	18	**19**	**17**	**18**	**23**	**24**	**31**	18	21	17	3

4.2.7.5 Outline of the sea breeze results

During the analysis of sea breezes, the four examined sites show their highest values from March to August (Appendix T). Furthermore, the lowest occurrences were from November to February, corresponding to the coldest months of the year which would confirm the theory of sea breezes affecting not only the two coastal sites (Lower Stoke and Dover) but also the two inland sites (Gravesham and Sevenoaks) (Appendix S). These results would be very useful when assessing PM_{10} dispersion in Section 4.4.

Table 17: Total number of occurrences of winds from east and northeast recorded, measured at Lower Stoke, Gravesham, Sevenoaks and Dover from 2000 to 2008 (in bold can be seen the higher frequencies registered between March and August).

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-09.00	84	118	**190**	**163**	**175**	**203**	**177**	**182**	144	150	129	107
10.00-18.00	89	154	**237**	**236**	**278**	**212**	**223**	**197**	216	147	103	118
18.00-00.00	55	93	**147**	**139**	**181**	**150**	**150**	**163**	98	117	92	81
Totals	228	365	574	538	634	565	550	542	458	414	324	306

*Highest value *Lowest value

In Table 17, the highest and lowest entries recorded can also be observed. As expected, the data confirm sea breeze influences; the higher frequencies values for easterly and northeasterly winds were recorded during the middle part of the day in May, coinciding with the warmer periods (Table 17), whereas the lowest numbers of occurrences were recorded in the evenings of January. Overall, the middle part of the day always recorded the higher number of entries, followed by the early morning. Some other peculiarities found are, for

example, the low number of entries during the evenings in September, or the highest values registered in the early mornings in June (Table 17).

4.2.8 Results from the wind persistence analysis

In addition to the sea breeze analysis carried out in the previous section, the decision was taken to record the wind persistence for northeasterly and easterly winds at the same four studied sites. This work was based on previous work (Burt and Sharma, 2003) which observed that periods of persistent easterly winds (for example those occurring for more than three days continuously) were rare at Lower Stoke (once or twice a year). The same study revealed that, generally, winds from the east and northeast (in this case from the sea coming into land) are relatively short-lived, normally only persisting for a few hours before reverting to a different (variable) direction.

In order to establish if the behaviour was also occurring in the data used for this project, the number of times in a year that the wind blew from the east or northeast for more than 24 hours was noted. As previously explained sea breezes tend to occur over a short period of time, they are driven by temperature fluctuation and normally coincide with the warmer parts of the day. Therefore, 24 hours were chosen in order to negate any effect that sea breezes may pose on the data and allow to determine other wind persistence causes.

One of the main reasons to carry out this analysis was that the data obtained would be very useful for the investigation of the PM_{10} dispersion within the studied area, particularly when assessing trans-boundary pollution (Ramon *et al.*, 2005; Santer *et al.*, 2007; Vidot *et al.*, 2007; Plainiotis *et al.*, 2005, 2010) (Section 4.4.1). During the literature review, it was noted how several studies (King and Dorling, 1997; Stedman, 1998; Buchanan, 2002; Malcom *et al.*, 2000; Namdeo and Bell, 2005; Rigby *et al.*, 2006), suggested that a significant proportion of airborne PM_{10} responsible for exceeding air quality standards in the UK may originate from industrialised parts of mainland Europe, arriving in the southeast of England as a plume carried by easterly winds.

The results between the four sites were analysed and then compared with the intention of finding patterns or similar results among themselves.

4.2.8.1 Wind persistence analysis at Lower Stoke

The findings of Burt and Sharma (2003) that show how periods of persistent easterly wind for more than three continuous days at Lower Stoke were very unusual was reinforced in the present study (Table 18). The results show that the winds blowing from the east and northeast over a period of 24 hours continuously are in the minority in comparison to the other types of wind direction, and that events of three days wind persistence were even fewer. Days of extended steady winds from the northeast were also relatively rare at the site (Table 18).

Table 18: Wind persistence at Lower Stoke (winds from northeast (NE) and east (E)).

Grid reference 83133,176200	**Episodes of wind persistence longer than 24 hours**		**Episodes of wind persistence more than 3 days**	
Wind Direction	**NE**	**E**	**NE**	**E**
2000	4	4	--	--
2001	3	4	--	2
2002	5	--	1	1
2003	3	4	--	2
2004	4	3	--	2
2005	--	3	--	3
2006	--	--	--	--
2007	3	3	2	1
2008	5	2	2	1

4.2.8.2 Wind persistence analysis at Gravesham

The same analysis was then applied to the data from Gravesham (Table 19) and comparable results were obtained. The main difference between the data from this site and that previously analysed for Lower Stoke is that fewer episodes of less than 24 hours were registered at this site; although more northeasterly three-day wind persistence episodes were recorded than in the Lower Stoke site.

It was also observed that from the few episodes recorded, both types of persistent winds (lasting longer than 24 hours and on occasions longer than 3 days) mainly occurred during the warmer months, perhaps driven by a sea breeze influence. Gravesham is a site located inland, however, as previously noted in Section 4.2.7.2, the site is affected by sea breezes.

Table 19: Wind persistence at Gravesham (winds from northeast (NE) and east (E)).

Grid reference 562584 172075	Episodes of wind persistence longer than 24 hours		Episodes of wind persistence more than 3 days	
Wind Direction	**NE wind**	**E wind**	**NE wind**	**E wind**
2000	3	--	--	1
2001	3	1	--	--
2002	3	1	3	3
2003	2	--	5	--
2004	4	1	3	--
2005	3	2	2	2
2006	--	2	--	1
2007	--	--	4	1
2008	--	1	1	--

4.2.8.3 Wind persistence analysis at Sevenoaks

Surprisingly, there were no episodes longer than three days registered at Sevenoaks. The episodes of wind persistence longer than 24 hours were also less common than for any of the others sites (Table 20). No clear explanations for these results were found. Perhaps these results are associated with the inland location of the site (located 35 km away from the coast), therefore, it would be considered to be less likely to be affected by coastal winds.

Table 20: Wind persistence at Sevenoaks (winds from northeast (NE) and east (E)).

Grid reference 558900 167400	Episodes of wind persistence longer than 24 hours		Episodes of wind persistence more than 3 days	
Wind Direction	**NE wind**	**E wind**	**NE wind**	**E wind**
2001	2	1	--	--
2002	--	--	--	--
2003	1	1	--	--
2004	2	--	--	--
2005	1	1	--	--
2006	--	--	--	--

4.2.8.4 Wind persistence analysis at Dover

Dover generally shows a low number of occurrences in wind persistence exceeding 24 hours but considerably high over three-day periods especially affected by winds from the northeast. In addition, the wind persistence occurrences seem inconsistent throughout the years: generally these seem to be fewer events during the coolest months (Table 18). Dover is a coastal site, however, these results are unlikely to be caused by sea breezes, because of their long duration (more than 3 days), as an alternative they could be could be caused by air masses arriving from the east or northeast.

Table 21: Wind persistence at Dover (winds from northeast and east).

Grid reference 633698 142292	**Episodes of wind persistence longer than 24 hours**		**Episodes of wind persistence more than 3 days**	
	NE	**E wind**	**NE wind**	**E wind**
2003	2	--	1	5
2004	--	--	1	1
2005	--	--	2	--
2006	--	--	3	1
2007	--	--	--	--
2008	2	--	6	--

4.2.8.4 Outline of the wind persistence analysis results

Overall, the four sites show similar results with a couple of general differences. On the whole, the number of wind persistent events was found to be very low. This study reinforced the claim made by Burt and Sharma (2003) stating that periods of persistent east and northeast winds for more than three continuous days at Lower Stoke were rare, mainly because the dominant wind is southwest. Nonetheless, with this in mind, the Lower Stoke site tends to experience more 24 hour wind persistence episodes than any of the other three sites, on average twice a year. On the other hand, both Dover and Gravesham registered a larger number of wind persistence episodes lasting more than three days. In Gravesham and Dover, the wind persistence episodes tend to occur over the warmest month of the year while in Lower Stoke they are spread out without seasonality.

Sevenoaks, the sampling site located further inland, recorded the least number of wind persistence episodes. Although the wind persistence results are thought not to be linked to sea breezes (or other thermal based local wind), the site located inland is the only site not registering any wind persistence episodes. These results will be useful in further sections when assessing the PM_{10} distribution in the study area.

4.3 PM_{10} data results

The analysis of the PM_{10} data has been divided into seven different sections. These categories have been established with the purpose of drawing a clearer picture of PM_{10} dispersal in the study area. The first four sections focus on the analysis of the data collected and the patterns found. Firstly, the data for each individual site have been examined (Section 4.3.1) (Figure 32) and then the PM_{10} data have been compared yearly between all sites (Section 4.3.2); in order to provide a comprehensive interpretation of these results, this section also includes the PM_{10} data correlation coefficients for all sites. These results are followed by the analysis of the seasonal variations in PM_{10} catch (Section 4.3.3), and an assessment of the high levels of pollution within the study area taking into account the synoptic situation at the time of the episodes (Section4.3.4).
The last three sections aim to evaluate the possible causes and factors influencing PM_{10} dispersion within the study area. Section 4.3.5 looks into the relationship between site background and PM_{10} catch. Section 4.3.6 describes the role of topography in PM_{10} distribution over the county. Finally, Section 4.3.7 looks at the pollution trajectories.

4.3.1 General overview of individual sites

Following the methodology applied for the analysis of the wind direction, it was decided to carry out a detailed analysis of the hourly PM_{10} data recorded at individual sites. This method was carried out with the purpose of searching for specific patterns that may repeat throughout the years, consequently highlighting local trends. During this study, 17 individual sites have been examined. Five of those were located in an urban area, two in rural locations, one was referred to as suburban (i.e. a combination of the two preceding) and the other nine were located at roadsides (Figure 32 and Table 2). All sites have at least five years of data, which would help illustrate what is occurring in the study area. A table showing the interruption of the sampling records in the data can be seen in Appendix H.

When examining the PM_{10} levels at all sites, the UK government objectives for particulate matter levels have been considered (Air Quality Strategy, 1998, 2000, 2003, 2005 and 2007). As previously described (Section 2.2), the two main objectives set by the Air Quality Strategy are: a total utmost daily amount of 50 $\mu g/m^3$ with up to 35 exceedences a year, as well as, an annual objective aiming to obtain a yearly mean of 40 $\mu g/m^3$ or lower.

The individual analysis shows variation on the concentrations level at different sites. Some sites, such as Ospringe, Canterbury, Luton or Folkestone, very rarely exceed the daily recommended amount (50 $\mu g/m^3$), while other sites, mainly those closer to the city of London, exceed the recommended amount on a daily basis, reaching concentrations of 120-140 $\mu g/m^3$ or in some cases even higher at peak time (Table 24).

The results obtained from the analysis of the PM_{10} values indicate that the location of the sampling site and specifically the different types of sources and environmental backgrounds surrounding the trap appear the key to explaining the variation in the levels of PM_{10} registered (Figure 32). As expected, the evidence suggests that those sites located on the roadside were registering the larger number of particle counts. Overall, the higher values were found on those sampling roadside sites closer to the city of London (two in Gravesham and three in Dartford). These results could mean that the sampling may have been affected by more than one factor. The volume of traffic on the roads would be the main aspect affecting the collection levels. Furthermore, these sampling sites, due to their proximity to London, could be affected by the pollution urban plume moving across the city (Section 2.4.3). These results will be analysed in more detail in further sections.

The concentration levels for the sites outside the city of London, from lowest to highest were: Ospringe, Canterbury, Luton, Folkestone, Ashford, Lower Stoke, Maidstone (Detling), Chatham and Dover. Furthermore, Maidstone (Fairmeadow), Sheerness and Thanet were found, in contrast, to be significantly higher (exceeding the recommended amounts several times a week) although not as high as the five sites closer to London. Figure 62 illustrates all sampled sites coloured according to the level of particles found in each site; red shows the sites with the highest values, in orange the medium/high records and in yellow those few recording low levels.

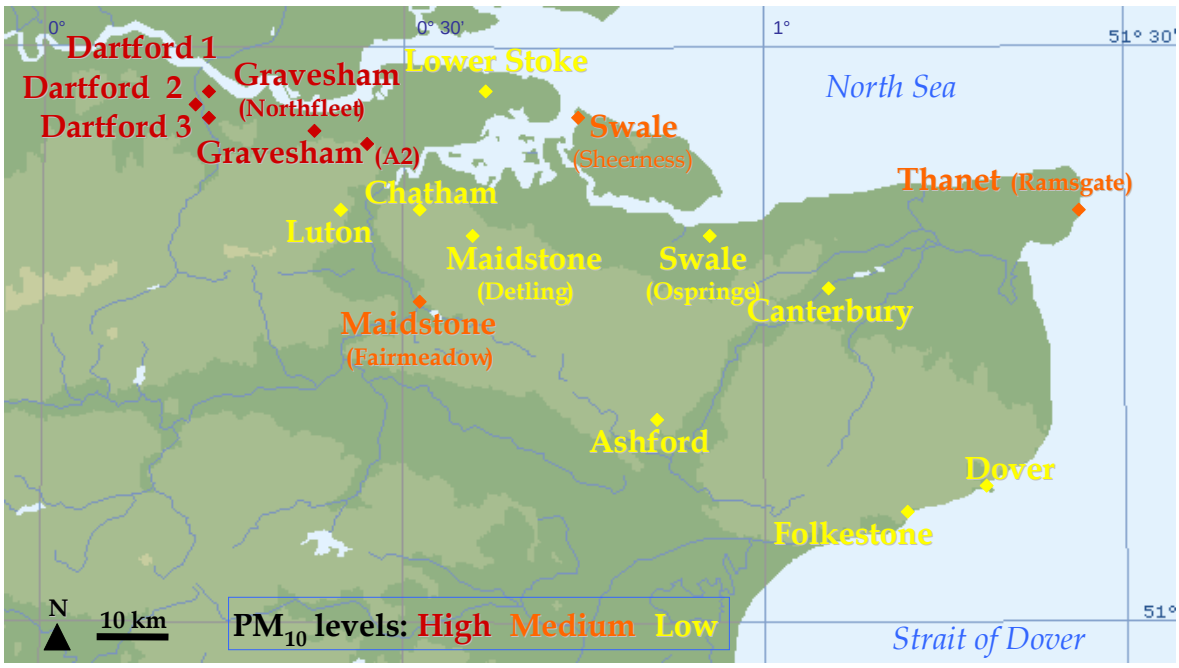


Figure 62: Illustrates all sampled sites coloured according to the levels of particles registered.

4.3.2 PM_{10} yearly trends (correlations between all sites)

The PM_{10} hourly data sets for all sites were compared annually, with the intention of observing if these same patterns were being recorded annually at different sites. In order to obtain an accurate analysis, it was decided to examine all sites together including those sites located closer to the Capital (Dartford and Gravesham). As mentioned in the methodology (Section 3.3.1), the number of sites with data available have changed through the years, the ERG added new sites in 2003 (Sheerness, Ospringe and Thanet) and removed Sevenoaks. Nevertheless, for the purpose of this study, all sites have at least five years of data (for accurate counts of gaps in the data please refer to Appendix H).

Several spatial variability studies carried out in the UK and other European countries (Battarbee *et al.*, 1997; Deacon *et al.*, 1997; Harrison and Deacon, 1998; Grivas *et al.*, 2004; Vardoulakis and Kassomenos, 2008) have used correlation coefficients to determine association between the data from nearby sampling sites, with the objective of proving that measurements from any of the selected sites could provide a reasonable description of annual air quality patterns. With this in mind and in addition to a visual analysis, the PM_{10} correlation coefficients between sampling sites in Kent were calculated; matrices showing the results can be seen in Appendix L. The graphical representation of the data as well as the correlation coefficient values for each year are

analysed and discussed in further sections with the intention of determining possible causes for the pollution levels recorded.

4.3.2.1 PM_{10} correlation coefficients for 2000

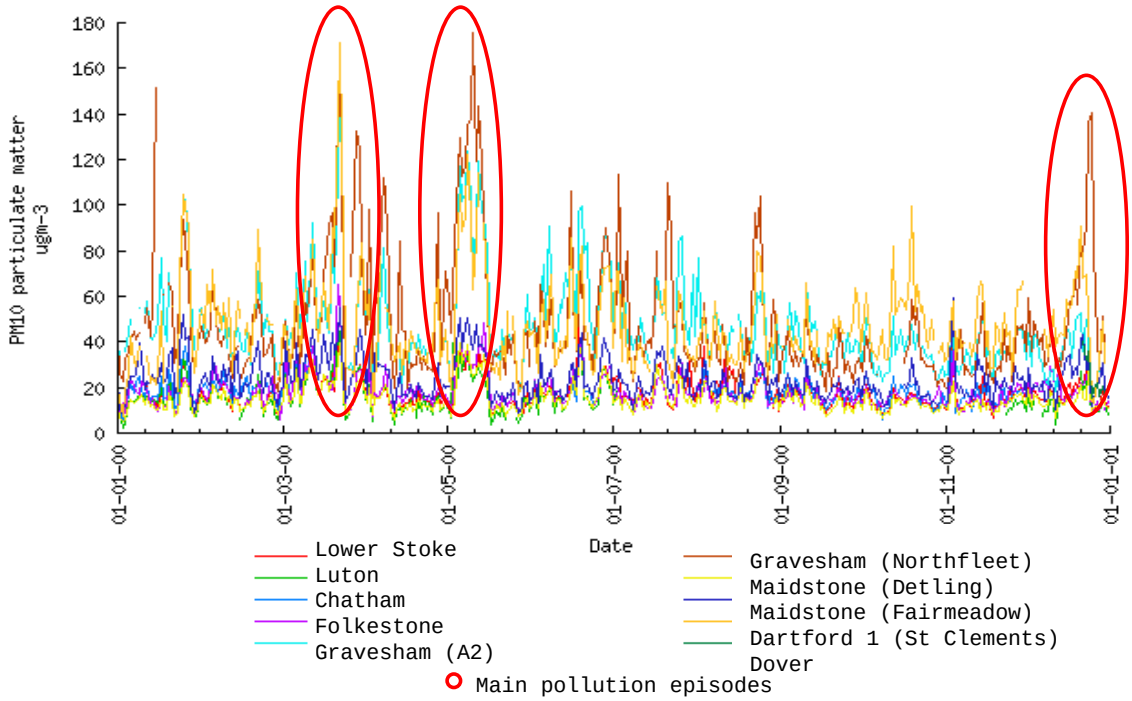


Figure 63: Illustrates the 10 sites with PM_{10} data available for 2000.

As expected, the higher PM_{10} concentrations were recorded at Gravesham (Northfleet), Graveham (A2) and Dartford 1(St Clements): these sites are located close to the city of London. It is worth noting that the concentrations for these three sites seem lower during the autumn in contrast to the other three seasons (Figure 63). The correlation coefficients do not corroborate this association as much as expected; the greater value was calculated between Gravesham (A2) and Dartford 1 (St Clements) at 0.703 (Section 4.3.42).

Overall, PM_{10} pollution levels seem to be consistently high. Three main pollution events affecting all sites have been observed (Figure 63). There was a noticeable increase in the levels during March and the beginning of April. This increase was also noted by Muir *et al.* (2006) during a study of PM_{10} pollution episodes in the UK. Muir *et al.* (2006) stated that the increase of PM_{10} levels during the early spring months could be caused by a series of air masses arriving from the southeast transporting material from the near continent. Moreover, elevated concentration levels can also be observed during the first two weeks of May. The third main peak took place over the last week of December.

The highest correlation coefficient was found between Maidstone (Detling) and Lower Stoke (0.704) while the lowest association was Folkestone and Gravesham (A2) at 0.415.

4.3.2.2 PM_{10} correlation coefficients for 2001

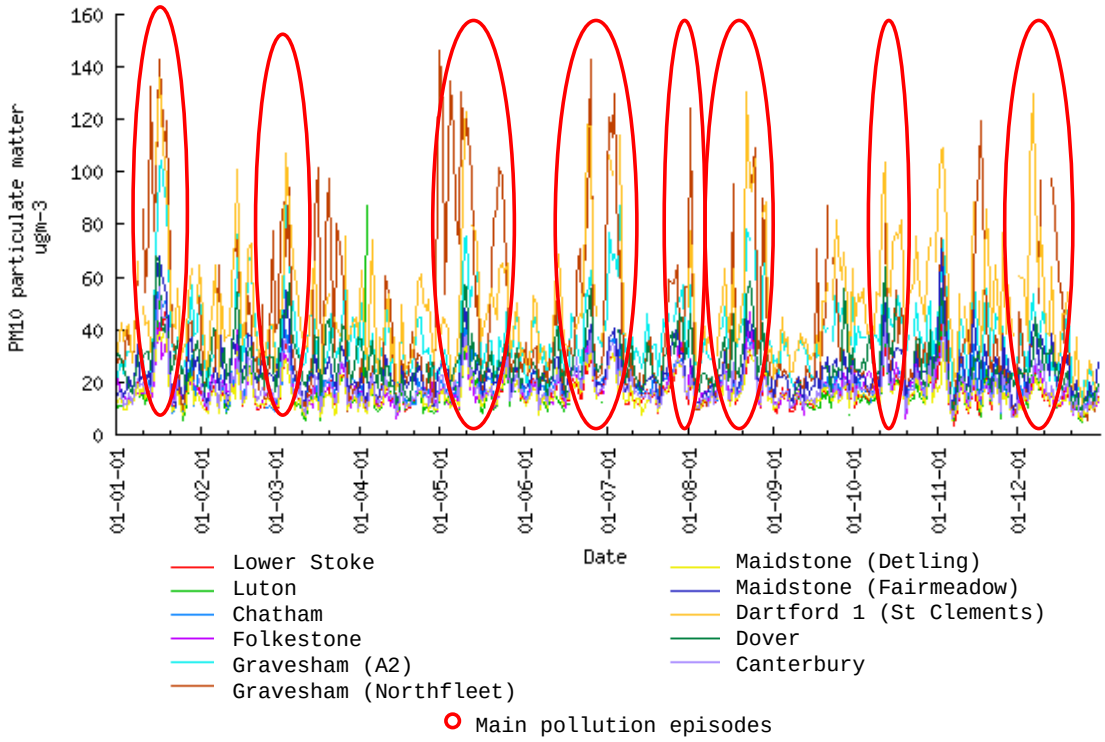


Figure 64: Shows the 11 sites with PM_{10} data available for 2001.

For 2001, there have been several pollution episodes counted, most of them involving all sites (Figure 64). These events do not seem to follow a clear pattern, instead they appear to be scattered throughout the year. This spread of episodes of pollution would corroborate those reported for Muir *et al*. (2006) during the same period, suggesting a number of synoptic plumes arriving in London from the southeast of England.

As occurred in the previous year, the highest values seem to have been registered at Gravesham (Northfleet), followed by Dartford 1 (St Clements) and Gravesham (A2). However, the correlation coefficients for these three sites don't seem to be particularly well associated. Furthermore, the correlation coefficients between the two Gravesham sites are low (0.360) which may indicate that the values are due to specific localised events rather than a synoptic influence affecting both sites.

The best correlation was found between Maidstone (Detling) and Maidstone (Fairmeadow) 0.886, both sites are closely located (6 km apart). Overall, Maidstone (Fairmeadow), an urban site located on a busy roundabout, seems to be more highly correlated to all nearby sites. The lowest correlation was recorded between Luton and Gravesham (Northfleet) at 0.234. There is no clear explanation for the low correlation value found: both sites are urban and they are located 17 km apart.

4.3.2.3 PM_{10} correlation coefficients for 2002

As in the previous years, the higher values are found at the two Gravesham and Dartford sampling stations. In addition, 2002 seems to be a year with several pollution peaks registered over the entire region. The most polluted periods appear to be from the beginning of March to June, and then from August to the middle of November, increasing again from the middle of December onwards to February the following year (Figure 65).

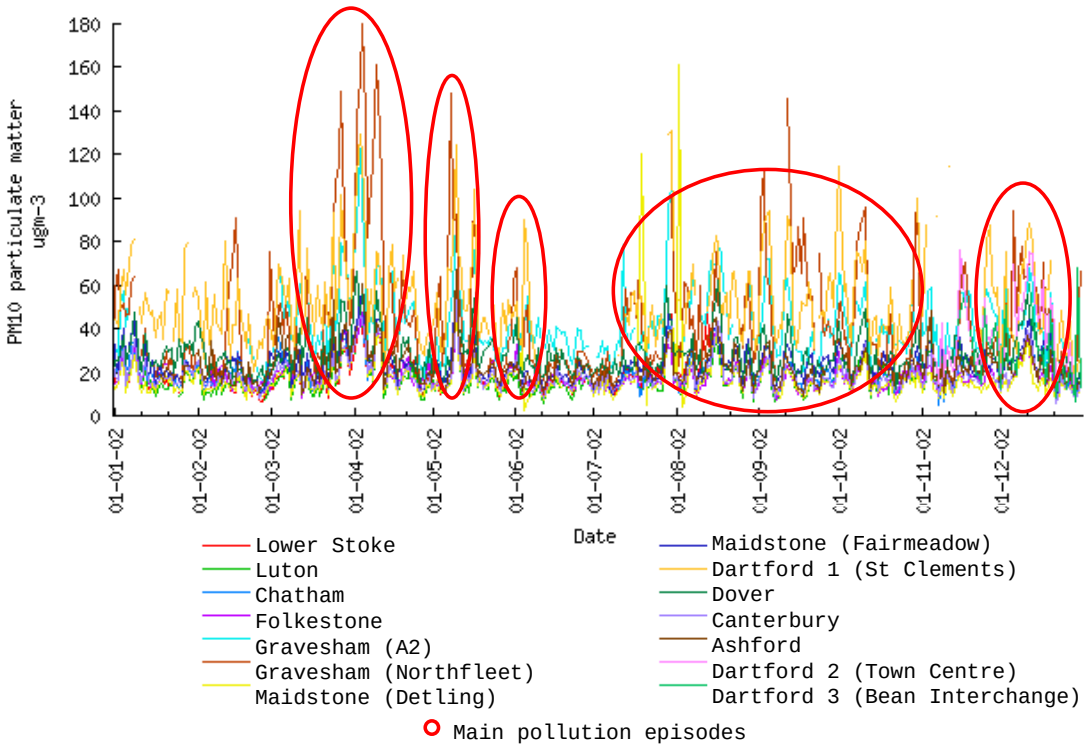


Figure 65: Illustrates the 14 sites with PM_{10} data available for 2002.

Another relevant point is the decrease of the PM_{10} quantities during July, most probably linked to the summer holidays (the Highways Agency (2010) reports a reduction of traffic levels due to reduced commuting traffic and schools being closed). There are also a couple of unusual peaks in Maidstone (Detling) in the end of July and the beginning of August. These may probably be linked to a local event (such an exhibition or fair taking place in the nearby grounds). The highest correlation coefficients for 2002 were found between Folkestone and Canterbury (0.767). On the contrary, the lowest values were for Gravesham (Northfleet) and Maidstone (Detling) (0.214). Apart from these, no other noteworthy correlation coefficients either positive or negative were found.

4.3.2.4 PM_{10} correlation coefficients for 2003

Once more, the most polluted sites were those closer to the city of London (Gravesham and Dartford). These sites appear to be well correlated showing the highest correlation values linking them at Dartford 1 (St. Clements) and Dartford 2 (Town Centre) 0.846, followed by Dartford 1 and Dartford 3 at 0.832 as well as Dartford 3 and Gravesham (A2) at 0.819. In contrast, the lowest value was found between Maidstone (Fairmeadow) and Folkestone at 0.185.

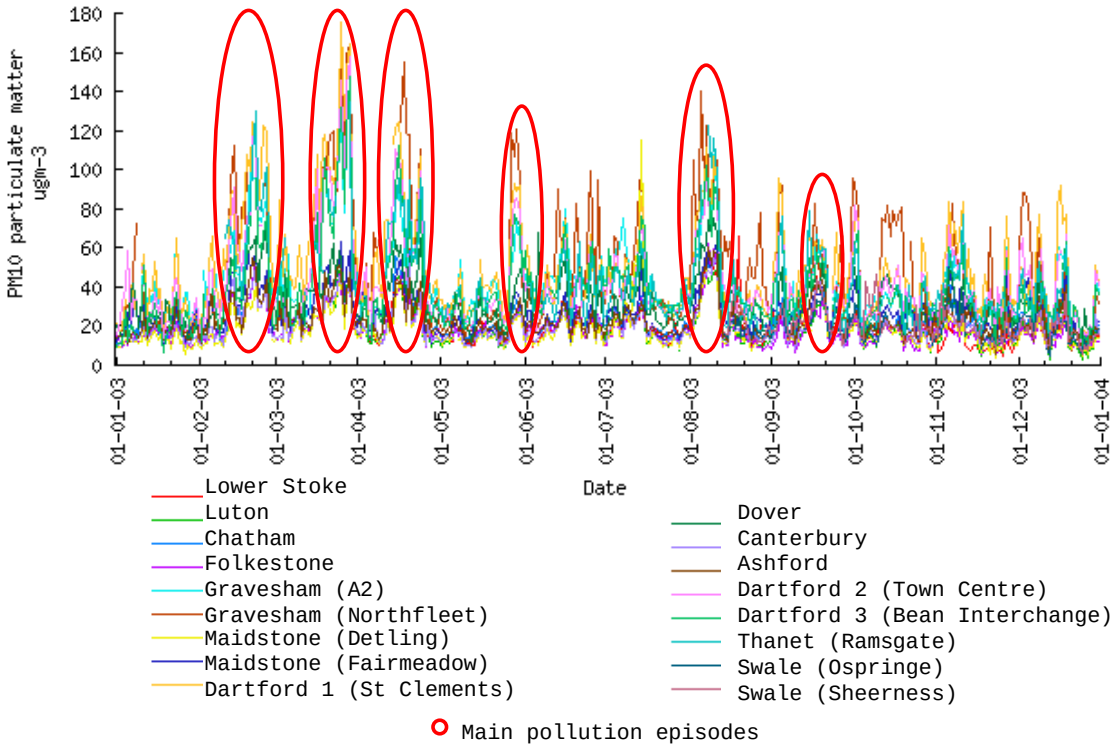


Figure 66: Shows the 17 sites with PM_{10} data available for 2003.

The explanation for this low correlation does not appear to be linked to the sites environmental background location (both sites sample in an urban background) so therefore it may be linked to other local sources affecting them. Maidstone is located in the centre of the county while Folkestone is closer to the southeast coast. The distance between the two sites is almost 50 km which assists in explaining the low correlations between the two sites.

In Figure 66, it can be observed that there are at least six pollution episodes affecting all sampling sites. Most of them occurred from March to June. These events are related to synoptic episodes of pollution plumes affecting the whole region or perhaps linked to the weather (for instance air masses affecting the whole region). The most remarkable of

episodes took place during the first two weeks of August. This synoptic pollution event has been considered by several authors as one of the most severe affecting the city of London and its surrounding areas in the last few years (Bower *et al*. 2006 and AQEG 2007). Sunny weather with high temperatures accelerate chemical reactions in mixtures of emitted air pollutants (a high pressure area that became stationary over the region (Figure 91)), low humidity and light surface winds that are unable to disperse the pollutants, the combination of all these factors during the study period caused the levels of PM_{10} within the county raise considerably (Figure 66). This specific episode of pollution will be studied in more detail in Section 4.5.2.

4.3.2.5 PM_{10} correlation coefficients for 2004

Unsurprisingly, the highest peaks were found at the Gravesham and Dartford sites. On first examination, the most remarkable feature observed at the other sites is the marginally lower daily maximum amount reached in comparison to previous years. There are five significant episodes of pollution affecting all sites. Most of these events took place between March and May as well as in the middle of August and the beginning of September (Figure 67). There are two others events observed taking place at about the same period in previous years, which may suggested seasonal patterns, one at the beginning of November most probably caused by the Bonfire Night celebrations, and the other one towards the end of December probably coinciding with the increase in the levels of traffic due to the Christmas festivities and the New Year's Eve fireworks celebrations (Figure 67).

The highest correlation was found between Folkestone and Canterbury (0.720), the lowest between Folkestone and Maidstone (Detling) was 0.125. This value appears to be much lower in comparison to the correlation coefficient from other sites (See Appendix L). The two sites are located 52 km apart, Maidstone (Detling) is a rural site located inland, in the core of the county, while Folkestone is an urban site, only a few kilometres away from the coast. Cases similar to these are studied in more detail in the sections ahead, first evaluating the effects caused by the topographical locations of the sites followed by an examination of the environmental background influences in the PM_{10} catch (Sections 4.3.5 and 4.3.6, respectively).

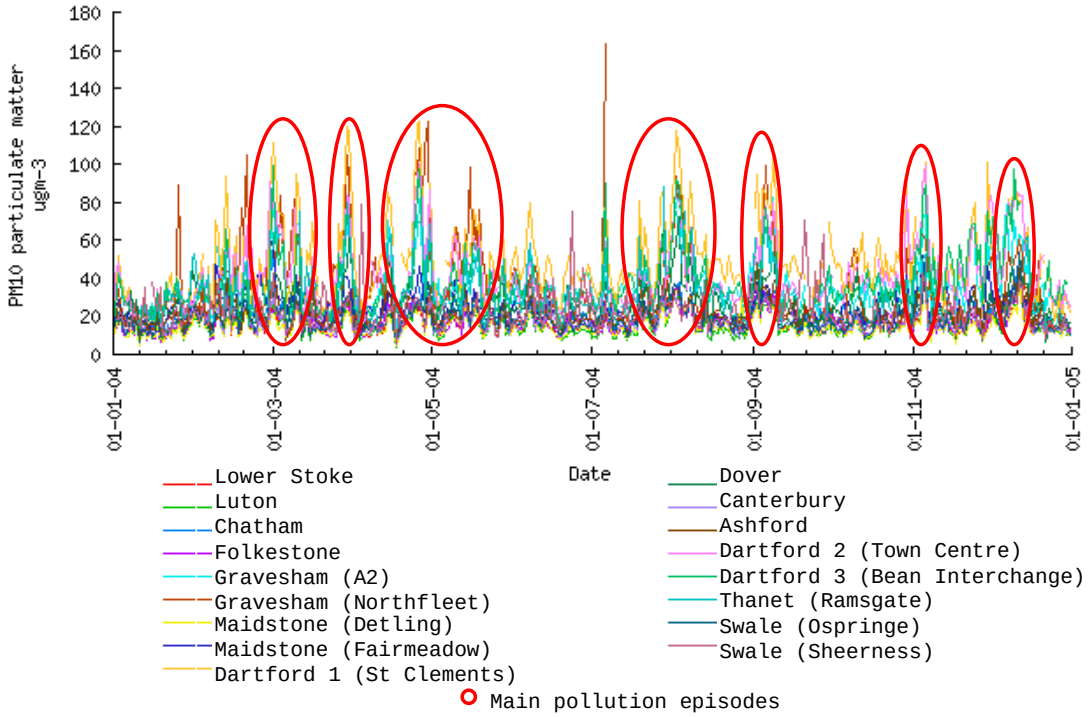


Figure 67: Illustrates the 17 sites with PM_{10} data available for 2004.

The correlation coefficients between the two sites in Swale, as well as the data from Thanet, were not considered in this case due to the high number of entries missing in all three sites (Appendix H).

4.3.2.6 PM_{10} correlation coefficients for 2005

For 2005, the most polluted sites were once more those closer to the capital. In Figure 68, a considerable increase can be noticed in the number of values from Dartford 2 (Town Centre) in comparison to previous years.

The highest correlation coefficient was calculated involving Dartford 1 (St Clements) and Dartford 2 (Town Centre) at 0.809 whilst the lowest value was found between Dartford 1 (St Clements) and Thanet (Ramsgate) (0.044). Both sites are located on busy roadsides, however, 75 km apart. In addition, the three Dartford sites are some of the most polluted sites in the country. The sampling sites are surrounded by two of the busiest motorways in Britain, the M25, an orbital motorway that almost encircles Greater London, together with the M2 and M20 communicating the capital with the Channel Tunnel and the ports of Dover (Highways Agency, 2010). As well as that, the Dartford crossing (less than 2 km from the sampling sites) is one of Europe's most heavily used crossings and complex traffic management systems (Highways Agency, 2010).

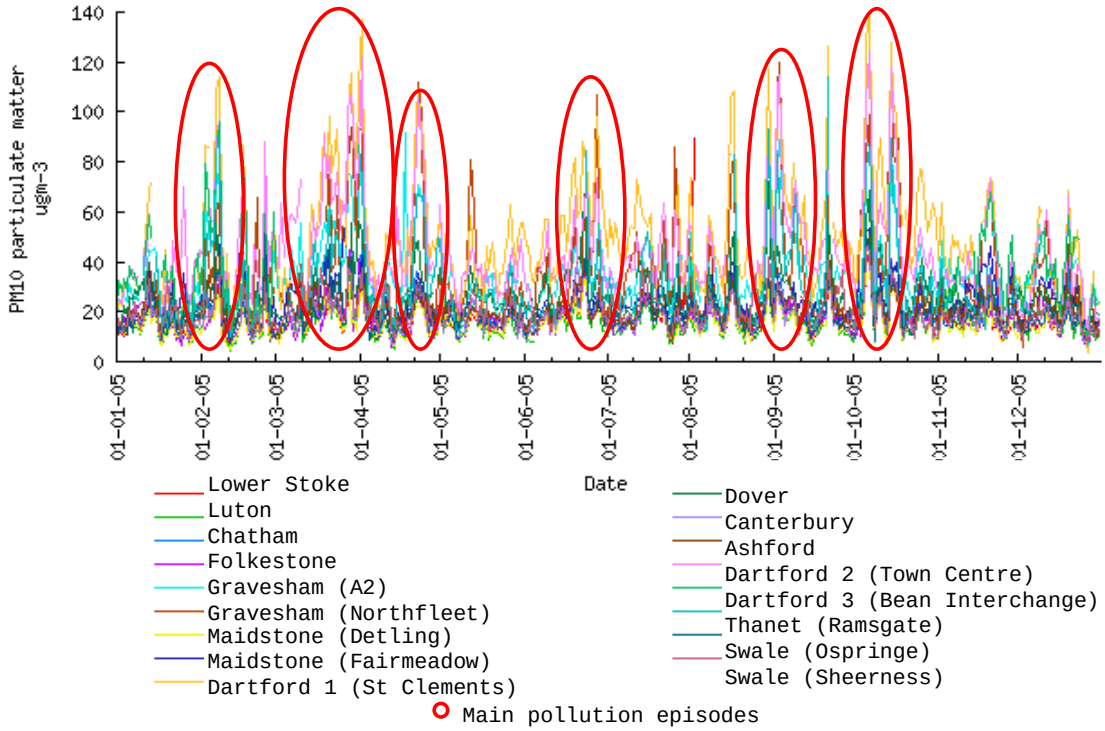


Figure 68: Shows the 17 sites with PM_{10} data available for 2005.

In general, 2005 appears to be fairly polluted all year round. There are pollution events affecting most sites almost on a monthly basis (Figure 68). This could be caused by synoptic episodes affecting the whole study area, perhaps arriving from the near continent. Charron *et al.* (2007) after analysing the data for the same period in London suggested that large PM_{10} episodes were associated with air masses coming from mainland Europe which carried large concentrations of secondary aerosols contributing to the exceedences in addition to emissions in the UK. The data presented here (Figure 68) support this finding.

4.3.2.7 PM_{10} correlation coefficients for 2006

During 2006, there were also numerous episodes of pollution affecting the whole of the county. There are increases in January, the beginning of February, March and from the last week of April until the end of July, decreasing during August but increasing again in September all the way through to December. Some of these events seem to be related to traffic levels (associated with holiday periods, for instance the decrease of levels during August or the increase around Christmas time) (Figure 69).

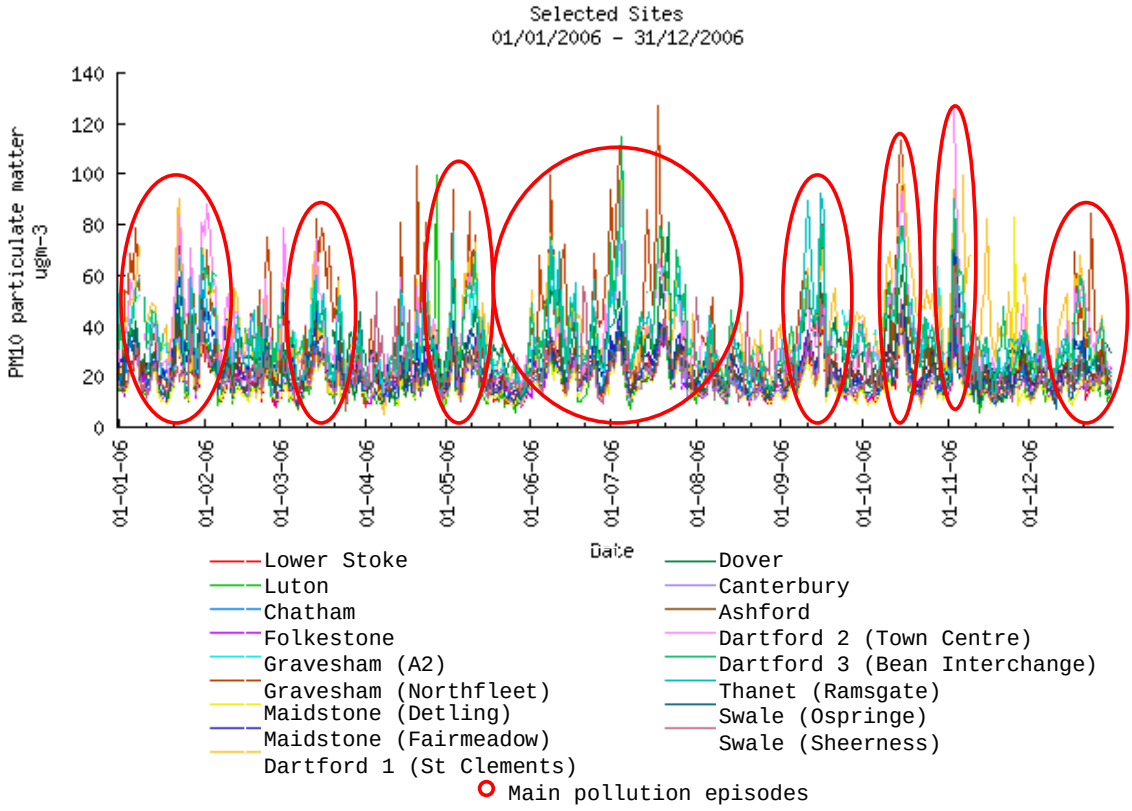


Figure 69: Illustrates the 17 sites with PM_{10} data available for 2006.

Surprisingly, this year seemed to have different patterns to the previous seven. The highest episodes of pollution were found from June to August in opposition to previous years when this period was found to be the one with the lowest amounts registered. When evaluating these results in relation to the synoptic data and the temperature profiles (Appendix S), a series of high pressures and warmer weather that took place over this period in comparison to other years may have contributed to the increase of PM_{10} catch within the study area. Hot and sunny weather with high temperatures accelerate chemical reactions in mixtures of emitted air pollutants (a high pressure area that becomes stationary over the region), low humidity and light surface winds that are unable to disperse the pollutants (Seinfeld, 1986; Ahrens, 1994; Arya, 1999; Jacobson, 2002). For instance, the events previously occurred during August 2003, due to the heatwave affecting the southeast of England at the time (Section 4.5.2). The highest correlation coefficient was found between Maidstone (Fairmeadow) and Ashford at 0.741; the lowest was calculated between Dartford 3 (Bean Interchange) and Maidstone (Detling) 0.158.

The samplers at Gravesham and Dartford recorded yet again the highest values. The biggest of these episodes took place at the end of March, continuing to register high entries up to the beginning of May (Figure 70). Because this event was noticeable at all sites, it may be assumed that this was a synoptic episode affecting the whole area.

The other two peaks worth mentioning are the patterns repeatedly found year after year coinciding with the Bonfire Night celebration and the increase of traffic on the roads linked to the Christmas festivities.

4.3.2.8 PM_{10} correlation coefficients for 2007

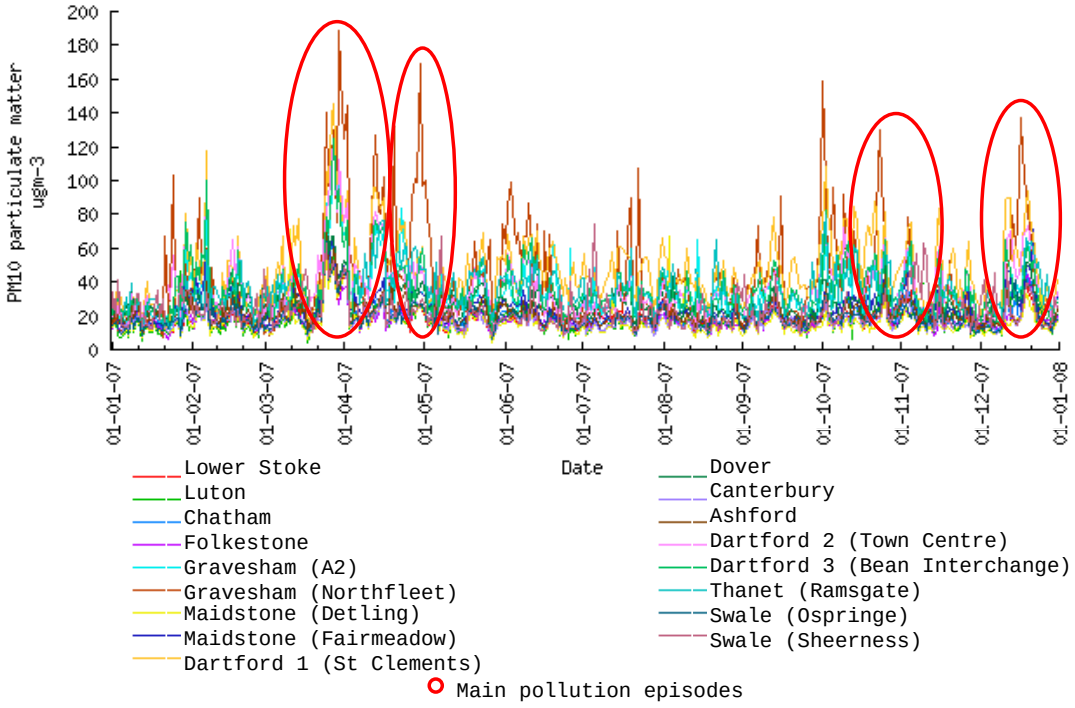


Figure 70: Displays the 17 sites with PM_{10} data available for 2007.

The highest correlation found involved Maidstone (Fairmeadow) and Chatham at 0.759. On the other hand, the lowest correlation coefficient was found between Maidstone (Detling) and Dartford 3 (Bean Interchange) (0.158).

4.3.2.9 PM_{10} correlation coefficients for 2008

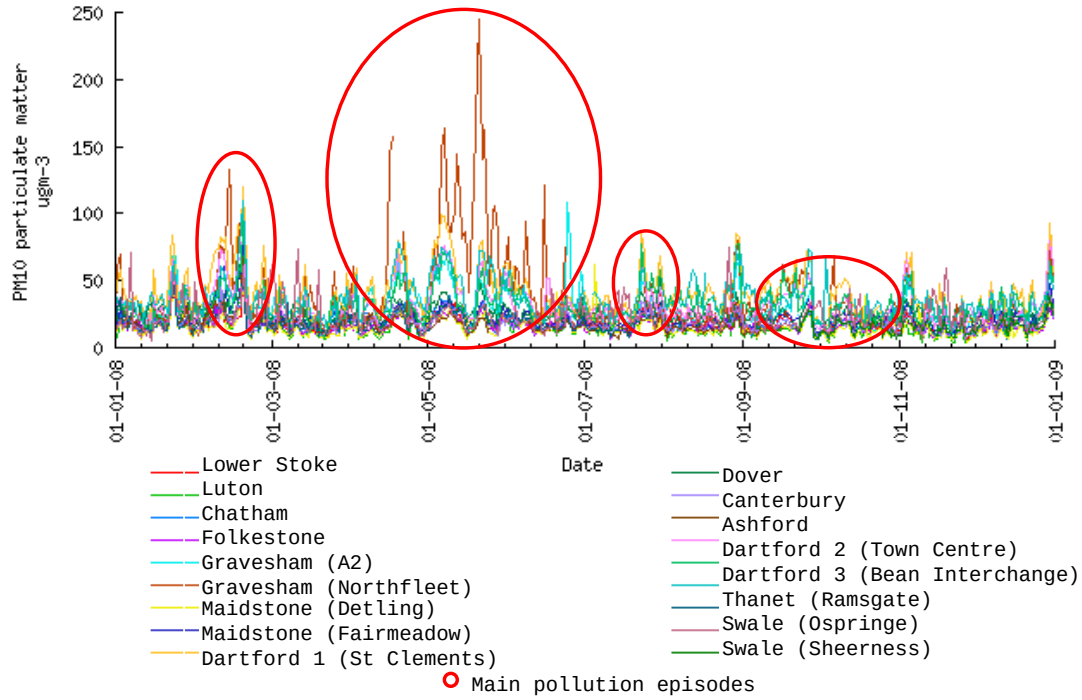


Figure 71: Illustrates the 17 sites with PM_{10} data available for 2008.

2008 generally seems less polluted than the previous years. The closest places to London still recorded the highest values, but overall there are only four highlights (Figure 71). One in the middle of February, the second one started in the middle of April carrying on all the way to July. There is a peak in the middle of August most probably heat-related (see Appendix S for temperature profiles) and another most probably weather related (as a consequence of a high pressure lasting several days) in the beginning of October (Figure 71).

The lowest correlation was 0.158, found between Gravesham A2 and Thanet (Ramsgate); the two sites are 75 km apart. Moreover, Gravesham (A2) is a sampler Moreover, the highest correlation coefficients were calculated between Gravesham (Northfleet) and Ashford (0.711). This is an unexpected result; both samplers are located on a roadside but are approximately 50 km apart.

The Ashford pollution monitoring station is located by a roadside and is therefore affected by the levels of local traffic. On the other hand, Gravesham (Northfleet) is located in an industrial site close to the Thames Estuary in the outskirts of the city of

London. Consequently, there is a number of factors that could contribute to the concentrations sampled. PM_{10} concentration could have been affected by the city background levels as a consequence of high levels of traffic (APEG, 1999: AQEG, 2005; Bower *et al.,* 2006). It could also be increased by unfavourable local dispersion or even recirculation of air inside a street canyon (Charron *et al.,* 2005). The levels could also be increased by local northeasterly wind bringing in marine aerosol from the North Sea (Gustafsson and Frazen, 2000, reported evidence of sea salt aerosol penetrating very large (quantify) distance inland). In order to determine the specific cause a source apportionment investigation would be required.

4.3.2.10 Synopsis of the yearly PM_{10} trends

During the analysis of the PM_{10} data throughout the nine targeted years, there have been a number of consistent patterns and features observed.

On the whole, most correlation coefficients between sites seem appreciably low, which may indicate that they may be primarily affected by local episodes of pollution, related either to traffic or other type of emissions, rather than a plume being transported across the county. The variations on the levels of PM_{10} sampled between different sites could indicate that results would be affected by the type of environmental background where the sampling traps are located. These results are analysed in more detail in Section 4.3.5.

Similar results were also found during the examination of the graphs. Most peaks seem to be caused by local sources. However, several of the major events recorded appear to be affecting the whole of the region. It is possible that some of these episodes could have been caused by a number of weather patterns, such as a high pressure or a persistent wind direction affecting the whole area. The synoptic data was examined for these episodes but not association was found between the years. There is a possibility that these relatively high episodes, could also been caused by plumes being transported over the region, or air masses facilitating the long transport of pollutant from further sources, this idea is studied in more detail in Section 4.3.7.

In general, six major seasonal patterns have been repeatedly observed affecting the whole of the study area. For all nine years, the highest values were found in the five sites located closer to London (these are the three sites from Dartford and the two from Gravesham). Gravesham (Northfleet) appears to be the most polluted site going over the daily recommended amount 50 $\mu g/m^3$ almost every day. The results suggest that these

five sites could be influenced by the London PM_{10} concentrations levels (Section 2.4.4). This would mean that in addition to the concentrations emitted from the local sources such as traffic, industry, heating systems and so on, the proximity to a large city would affect the PM_{10} levels recorded. A larger urban area such as London, with rougher surface than rural areas, leads to a decrease in wind speed. The buildings tend to act as obstacles to the wind flow, therefore stopping the dispersion of particles and increasing the concentrations (Section 2.4.4) (APEG, 1999: AQEG, 2005; Charron *et al.*, 2005; Bower *et al*., 2006). However, when compared with previous studies it was realised that the PM_{10} levels registered at the Dartford and Gravesham sites were very similar to those concentrations recorded on heavily used traffic roads in Central London (Harrison, 2001; Muir *et al.*, 2006; Charron *et al.*, 2007) over the same periods. In addition, the PM_{10} concentrations in Kent corroborate those from the London studies; PM_{10} concentrations at these sites are higher on weekdays than at weekends and during the day rather than at night. These outcomes are developed further in Section 4.3.4.2.

The most significant yearly trend found is that generally the autumn seems to be the season with the lowest amount of PM_{10} (with the exception of Bonfire Night) whereas the spring has the highest number of entries. Most of the high pollution events tend to start in early March fading in the middle of June. One possible explanation for this may be that these events could be a consequence of agricultural activities during the spring time or perhaps an increase of weather convection due to the warmer weather lifting up some material. These early spring related increases were also noted in previous studies carried out in London (Muir *et al.*, 2006; Charron *et al.*, 2007).

Furthermore, another regional peak has been noted between the end of August and the beginning of September, this could also be linked to agricultural activities such as the harvest of cereals, and, therefore, the increase in the number of dust/plant parts in the air.

With the exception of the hottest years (2003 and 2006), the PM_{10} levels tend to decrease during the summer months mainly July and August. This could be a consequence of the decrease of number of vehicles in the road during this time of the year due to the holiday period (for instance, no school run).

There is also another pattern registered at all sites in the beginning of November; this trend is most probably linked to the Bonfire Night celebrations. This result will be analysed in more detail in Section 4.5.1.

Other factors to be taken into account would be the decrease in atmospheric particles during the rainy periods (Nicholson *et al.*, 1991; Battarbee *et al.*, 1997). Being the larger particles (> 10 µg in diameter) more efficiently removed by washout.

Last of all, there seems to be a yearly pattern observed during the middle and towards the end December. This regional increase could be related to the increase of traffic on the road related to Christmas shopping as well as an increase in car movements around the county due to the festivities.

4.3.3 Summer and winter variations of PM_{10} records

The PM_{10} mean concentrations for winter and summer were calculated and compared as part of the seasonal analysis (a table showing the results can be seen in Appendix M). In order to allow the most comprehensive visual comparison, it was decided to divide the data into two periods; Figures 72 and 73 show the results of the seasonal averages for these two periods. Figure 72 illustrates the results for the years 2000 to 2004 whereas Figure 73 focuses on the years 2005 to 2008.

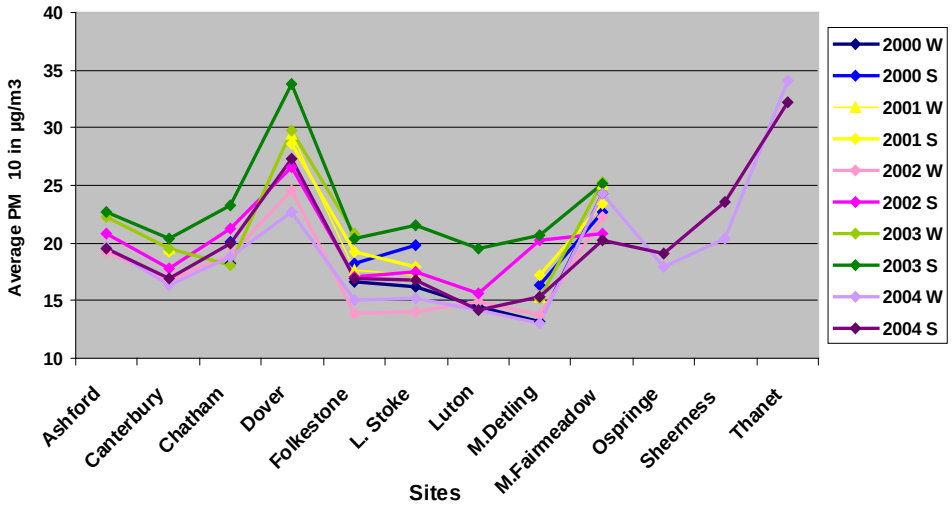


Figure 72: Displays the seasonal average (S: summer, W: winter) of PM_{10} concentrations for the years 2000 to 2004.

During the individual analysis of the studied years, it was noticed that generally (with the exception of the warmest years (2003 and 2006)) the PM_{10} levels decreased during the summer months, mainly (July and August). This was thought to be a consequence of the decrease in the number of vehicles on the road (for instance, no school run), due to the holiday period. However, when calculating the average PM_{10} value for each season and comparing them through the years, this assumption was rejected. The average concentrations (Appendix M) tend to be generally slightly higher in summer than in the winter. From the 87 seasons compared, there were 52 occasions when the summer values were higher than the winter values.

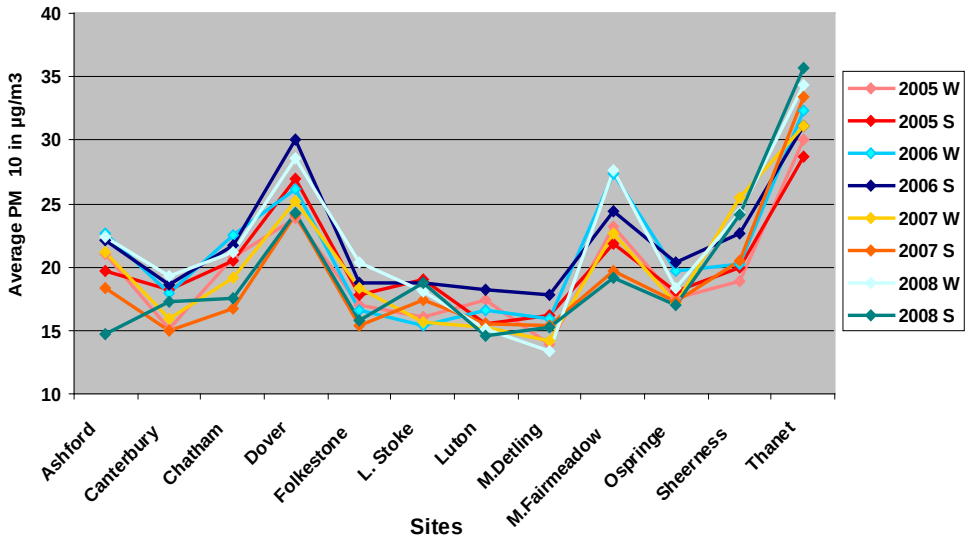


Figure 73: Displays the seasonal average (S: summer, W: winter) of PM_{10} concentrations for the years 2005 to 2008.

The average PM_{10} concentration at all the sites range from 13.07 to 35.64 $\mu g/m^3$ (being Maidstone (Detling) the site where the lowest value was found in winter 2004 and Thanet (Ramsgate) the site recording the highest concentration on summer 2008, respectively). (A table showing the average PM_{10} concentration for both seasons can be seen in Appendix M). Among the 12 sites compared, the average concentration of PM_{10} at Thanet (Ramsgate) was the highest, reaching up to 34.37 $\mu g/m^3$ for winter and 35.64 $\mu g/m^3$ for summer, reflecting the high number of emissions sources (e.g. vehicular emission exhaust) around this station (Appendix M). The PM_{10} concentration levels were also found to be high in Dover and Maidstone (Fairmeadow). In contrast, the lowest average values during both periods were registered during the winter months at Maidstone (Detling) (Appendix M).

It is worth noticing in Figure 72 that the highest peak occurred in August 2003. This particular period of time and the pollution episode that took place during this time affecting all sites at is studied in more detail in Section 4.6.2.

As a general assumption, it was expected to find changes in the PM_{10} levels in those sites closest to the coast where the PM_{10} concentration could be affected by the sea breeze influence or in urban sites where the levels could rise in the colder months due to the use of heating systems. However, the results do not seem to confirm the expectations. Generally, in some of the coastal sites the values seem to be slightly higher for summer than for winter but that does not seem to be a sea breeze influence or any other pattern or trend found (See Appendix M). Lower Stoke, Folkestone and Dover registered slightly higher values during the warmer season, but this does not appear to be the case in the other two coastal sites Thanet (Ramsgate) and Sheerness. Moreover, some urban sites, such as Luton or Canterbury, recorded the lowest concentrations (Appendix M).

Another interesting result found was that Maidstone (Fairmeadow), a sampling station next to a busy road, was the only site always recording higher values in the winter. On the other hand, Maidstone (Detling) (only 6 km away from Maidstone (Fairmeadow)) a rural site located a few yards away from an arterial road, constantly recorded the highest concentrations in the summer. These results were investigated further and it was found that the higher concentrations recorded were caused by the Kent County Show, the showground is located only a few yards away from the sampling site (Figure 74). The show takes place every summer in July, the weeks before and after the event the place is still visited by exhibitors accessing the showground.

Figure 74: Map showing the sampling site location in relation to Kent County Show grounds. Adapted from Google Maps.

Some of the results highlighted in previous paragraphs differ from the suggestions found in the literature. Several studies (Stedman (1997), Apsimon *et al.* (2001), Ryall *et al.* (2002) and Namdeo and Bell (2005) in the UK, Vecchi *et al.* (2004) in the Milan area (north Italy), and Ho *et al.* (2005) in Hong Kong, have suggested a strong seasonal variation of PM_{10} concentrations with the highest values during the winter months (from December to March). These studies suggested that during cold calm periods of weather in the winter months, as expected, pollution emissions are trapped close to their sources and cannot disperse. However, the results obtained during this study show a contradiction when compared to other studies: the mean values recorded were significantly higher in the summer than in the winter (Appendix M).

As previously reported for London (Kukkonen et al., 2005; Muir et al., 2006; Charron et al., 2007) the higher occurrence of PM_{10} episodes during warm seasons in Kent could be attributed to the larger relative contribution of secondary particles (caused by photochemical reactions) and natural particles (e.g. wind-blown dust) during hot and dry days. Unfortunately, identifying primary or secondary particles in the TEOM samples is not possible.

4.3.4 High levels of PM_{10} pollution

The UK Government in their Air Quality Strategy (published in 1998, 2000, 2003 review in 2005 and 2007) set the objectives for particulate matter levels to be achieved based on the European Union definition of limit values for mass concentrations of PM_{10} by Directive 2008/50/EC (Querol et al., 2004; European Commission 2005; AQEG, 2005, 2007). The main two objectives set by the UK government are: a maximum total daily of 50 $\mu g/m^3$ with up to 35 exceedences a year, and an annual objective which aims to obtain a yearly average of 40 $\mu g/m^3$ or lower, in order to protect the population from longer exposures (DETR, 2000; Hare *et al*., 2002; Bower *et al*., 2006). These two objectives (in relation to the data collected during the process of this investigation) are evaluated in the current Section 4.3.4.

4.3.4.1 Annual average concentrations of PM_{10}

During the individual analysis of the data sets, it was thought that Gravesham (Northfleet) was probably the most polluted site (Section 4.3.2, Figures 63-71). Nevertheless, the annual average amounts showed that the site registering the uppermost annual average values is

Dartford 1 (St Clements), followed by Gravesham (Northfleet) and the other three sites situated in the outskirts of London. The results recorded at the Dartford and Gravesham sites were similar to those recorded at one of the most renowned traffic hot spots in London, Marylebone Road (Jones and Harrison, 2006). Fuller and Green (2006) have reported that (with the exception of a few traffic hot spots in Central London) the Capital's annual mean concentrations are also below, the 2005 EU recommended limit value 40 µg/m^3 annual mean. These results suggest that the high concentrations of PM_{10} recorded in London and Kent are linked to traffic levels, but this is developed further in the following Sections.

Table 22: Annual average concentrations of PM_{10} (Sites background: Rural (green) Urban (grey) and Roadside (orange)).

Site/Month	2000	2001	2002	2003	2004	2005	2006	2007	2008
Ashford	--	--	22.20	22.58	21.05	20.74	22.26	21.38	17.62
Canterbury	--	17.98	18.49	19.58	16.91	17.16	17.93	17.33	17.38
Chatham	18.51	20.25	20.18	21.38	20.20	20.63	21.46	19.69	18.21
Dartford 1 (St. Clements)	47.15*	50.17*	53.58*	49.61*	48.94*	49.72*	38.99	46.33*	40.15*
Dartford 2 (Town Centre)	--	--	--	43.46*	41.52*	45.12*	36.93	36.75	31.61
Dartford 3 (Bean Interchange)	--	--	--	39.60	38.70	36.68	38.00	35.46	31.82
Dover	--	27.35	27.60	30.44	26.30	25.44	28.88	25.77	24.25
Folkestone	18.01	17.28	18.20	18.38	16.75	17.21	18.71	17.66	16.20
Gravesham (A2)	46.66*	37.83	42.18*	43.60*	35.96	35.53	34.77	33.21	29.26
Gravesham (Northfleet)	48.83*	42.26*	43.40*	46.62*	34.08	32.51	34.35	40.86*	36.49
Lower Stoke	17.39	16.40	17.73	18.88	16.08	16.42	17.12	17.54	17.08
Luton	15.97	15.90	16.47	18.48	14.84	15.45	17.57	17.68	14.63
Maidstone (Detling)	14.85	15.48	17.03	17.53	14.57	15.05	16.31	15.95	16.01
Maidstone (Fairmeadow)	23.31	23.81	22.63	26.01	23.63	23.39	25.02	23.95	21.69
Swale (Ospringe)	--	--	--	--	17.99	18.49	19.51	18.77	18.62
Swale (Sheerness)	--	--	--	--	21.69	19.89	21.59	23.03	22.52
Thanet (Ramsgate)	--	--	--	--	32.17	30.14	31.90	32.30	36.27

Note: *All the annual concentrations over the recommended 40 µg/m^3 are highlighted in red

The annual objective for PM_{10}, advising a yearly average of 40 µg/m^3 or lower, was frequently exceeded in four of the 17 sites studied. Nevertheless, a positive decrease in concentration levels has been recorded over the years (Table 22): on the whole, the last year of data examined (2008) is registering the lowest values. This decrease is mainly noted in

those sites sampling in traffic hot spots (Dartford (3 sites), Gravesham (2 sites), and Maidstone Fairmeadow).

Harrison (2004) suggested that the composition of PM_{10} at urban background sites in London is dominated by carbonaceous combustion particles (31.2%), secondary nitrates and sulphate (28.3%) and coarse dusts (32.3%, including sodium chloride) (attributable to re-suspension due to traffic-induced turbulence and tyre shear at the road-side location). Therefore, measures to reduce PM_{10} levels in urban areas often focus on the reduction of emissions from motor vehicles. These traffic emissions consist of exhaust particles, abrasion products from the road's surface, from tyres, brakes and clutches as well as re-suspended particles. So there is a variety of abatement measures that could be applied including: the ban of high-emission vehicles from heavily polluted areas, fitting of particle filters to diesel vehicles and optimized street cleaning (Muir *et al.*, 2006; Jones and Harrison, 2006; Charron *et al.*, 2007 Bruckmann *et al.*, 2007). A reduction of road emissions can also be achieved by the application of calcium magnesium acetate to the road's surface. However, such local measures are often not sufficient for keeping limit values (Bruckmann *et al.*, 2007).

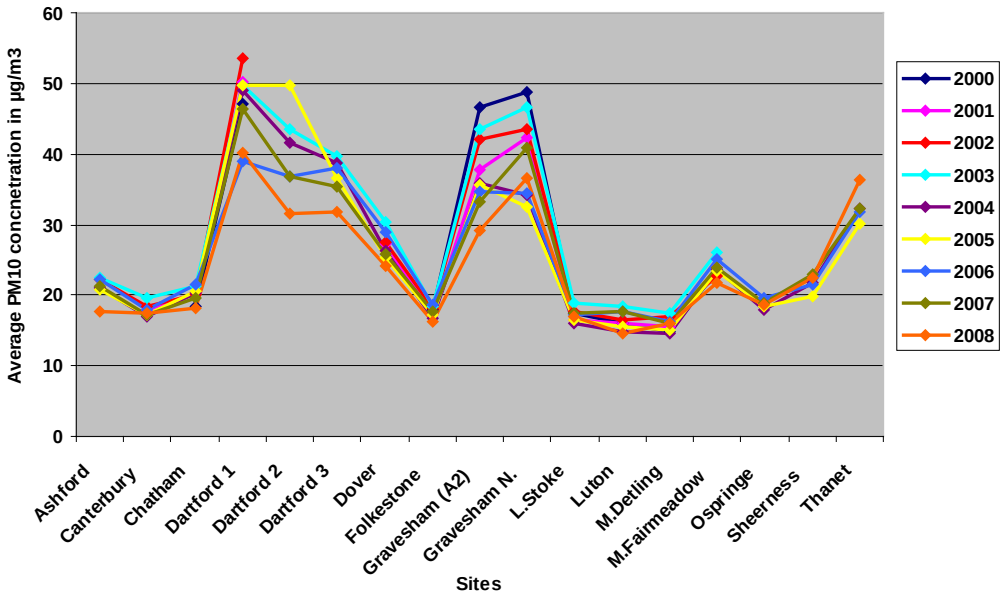


Figure 75: Graphed annual average concentrations of PM_{10}.

4.3.4.2 Monthly frequency distribution of PM_{10} episodes

With the results from the previous section in mind, it was decided to count the number of days in a year that the PM_{10} pollution level raised over the 50 $\mu g/m^3$ daily recommended levels. This analysis was carried out for all the sites. Every entry considered lasted two hours

or more. In order to investigate seasonality patterns, the results were separated by months. The values recorded at each sampling station for every individual month and year can be observed in Appendix N.

Table 23: Number of days in each month (from 2000 to 2008) when the concentration of PM_{10} exceeded 50 µg/m^3

Site/Month	January	February	March	April	May	June	July	August	September	October	November	December
Ashford*	13	39	50	27	10	6	9	17	25	18	29	25
Canterbury*	11	17	22	22	15	23	20	20	27	20	20	15
Chatham	33	41	34	24	13	16	19	26	17	17	43	24
Dartford 1 (St. Clements)	189	209	232	209	211	194	190	204	214	229	201	179
Dartford 2* (Town Centre)	89	129	125	121	109	99	82	90	122	139	111	99
Dartford 3* (Bean Interchange)	86	120	97	93	80	84	95	86	83	87	104	108
Dover	32	58	72	60	62	63	76	68	48	40	30	29
Folkestone	9	14	18	7	10	7	9	13	9	5	20	9
Gravesham (A2)	157	181	215	191	173	186	197	193	187	172	191	151
Gravesham (Northfleet)	152	196	188	175	163	164	131	154	173	169	143	164
Lower Stoke	7	4	18	9	17	9	47	55	25	10	19	5
Luton	10	12	26	21	12	5	9	21	10	19	25	14
Maidstone (Detling)	2	5	10	8	4	6	21	22	6	5	7	2
Maidstone (Fairmeadow)	54	75	91	42	31	20	30	29	31	44	67	51
Swale* (Ospringe)	13	23	29	6	10	6	11	6	10	11	10	11
Swale* (Sheerness)	38	37	56	48	24	47	55	44	53	34	41	28
Thanet* (Ramsgate)	44	66	63	62	70	65	87	84	89	57	58	38

*Sites missing data *Highest value *Lowest value
Note: a table with the missing data can be seen in Appendix H

Table 23 displays the sum of all days where the concentrations exceed the recommended amount (from 2000 to 2008) for each month at each site. The graphical results can be observed in Figures 76 and 77. Due to the large number of entries recorded for the three sites at Dartford and the two sites at Gravesham, it was decided to plot and explain these five graphs separately (Figure 76).

The methodology applied has been fairly successful, enabling the study of high pollution scoring patterns as well as allowing a more accurate examination of their relationships (Table 22 and 23). Several significant variations within the individual data sets have been found (Figure 76). They will be explained in detail in the following paragraphs.

The results from the monthly analysis of high episodes of PM_{10} corroborate those observations undertaken in previous sections (Section 4.3.2). The assessment indicates that February and March are the most polluted months, both in quantity and duration of the PM_{10} events recorded at all locations over the studied years. These results support those reported by Muir *et al.* (2006) and Charron *et al.* (2005, 2007) in studies carried out in London where the highest concentrations were found during early spring (mainly February and March) and autumn.

The causes of air pollution regional episodes could include various factors, e.g., emissions, local and synoptic-scale meteorological conditions, topography and atmospheric chemical processes. The relative importance of such factors is dependent on the geographical region, its surrounding emission source areas and the related climatic characteristics, as well as the season (Kukkonen, 2005; Pearce *et al.*, 2011).

Charron *et al.* (2007) studied the sources and factors responsible for the exceedences of the 24 hours limit value (50 $\mu g/m^3$) in London suggesting that these episodes were associated with air masses coming from mainland Europe which carried large concentrations of secondary aerosols contributing to the exceedences in addition to emissions in the UK. Furthermore, Smith *et al.* (2001) used 3-year PM_{10} data sets from three monitoring sites in London, in combination with relevant air trajectory and meteorological data, to identify factors influencing particulate pollution levels in Greater London. This study gave a strong evidence of a distant southeasterly PM_{10} source, as well as certain evidence of re-suspended particles contributing to high PM_{10} levels in London.

In addition to March, November also registered very high entries at all sites over the examined period (Table 23). These events were mainly spread throughout the first 10 days of the month and they are without a doubt linked to the Bonfire Night celebrations (Section 4.5.1; Appendix AB). Consistently the most polluted day of the year was found to be the 4th November. Every year on this day at most locations, the recommended amounts are exceeded, (sometimes registering high peaks reaching over 500 µg/m^3 (Appendix AB)). Consequently, it was decided to investigate the PM_{10} episodes linked to Bonfire Night celebrations in more detail (Section 4.5.1).

In agreement with the results previously described in Section 4.3.3 during the seasonality analysis, the lowest values were found on the colder months (mainly December and January). These results differ from those expressed by Van Dingenen *et al.* (2004) and Putaud *et al.* (2004) in their European aerosol phenomenology studies where they claimed that the highest concentration episodes are often observed in cold periods, when the pollutant dispersion tends to be least.

Another relevant point noticed in several sites was a slight drop in the concentration levels during the summer months (Table 23). It was then observed that most of these sites were located either in an urban area or close to a roadside (Ashford, Canterbury, Chatham, Dartford 1, 2 and 3, Gravesham (Northfleet), Luton, as well as both of the Maidstone sites). It is possible that there could be a relationship between the environmental factors affecting the sites and these variations. As previously observed in Section 4.3.2, these results could be linked to a decrease in the number of vehicles on the road due to the school holidays; they are examined in more detail in Section 4.3.6. It is presumed that PM_{10} levels tend to decrease during the summer months, mainly (July and August) as a consequence of the reduction in the number of vehicles in the road (for instance, no school run), due to the holiday period.

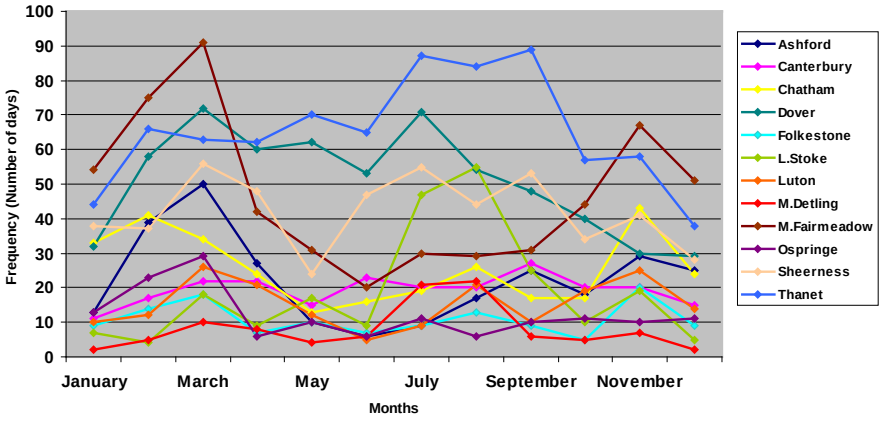


Figure 76: Monthly frequencies (from 2000 to 2008) of PM_{10} levels exceeding 50 µg/m^3.

Another pattern is observed at some of the coastal sites such as Lower Stoke, Sheerness, Thanet (Ramsgate) and Dover where the summer values seem to gradually increase in comparison to the rest of the year (Figure 76). These results will be investigated in more detail in Section 4.4.2 where the wind direction at the time of the peaks will be analysed and, therefore, to investigate if these events may be due to sea breezes bringing material inland.

Moving to the five sites closer to the city of London (Dartford (3) and Gravesham (2)) (Figure 77), the only common observation made in agreement to the results stated for the other 12 sites is that the highest values for these sites were also registered at the beginning of the spring. Furthermore, the lowest values were also found during the summer months. As previously explained, this significant decrease could be linked to a reduction in the number of vehicles during the holiday period.

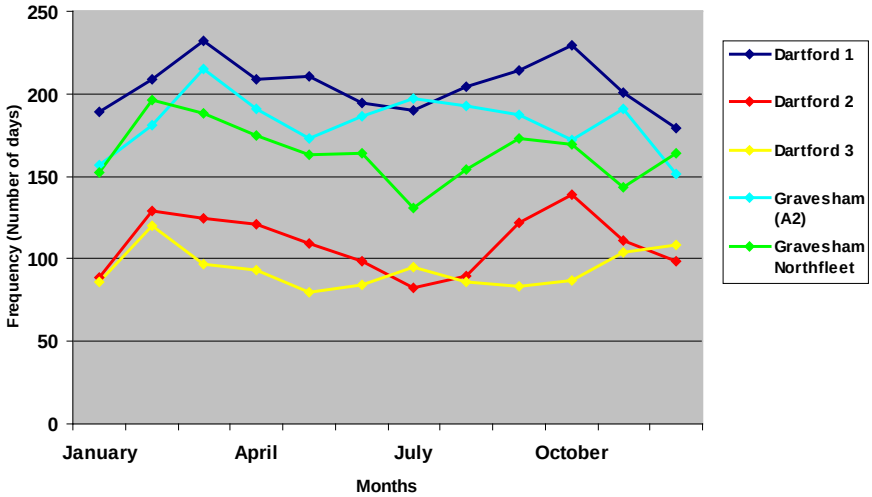


Figure 77: Monthly frequencies for the London sites (from 2000 to 2008) of PM_{10} levels exceeding 50 µg/m^3.

The PM_{10} concentrations at these five sites were found to be considerably more elevated than an initial approach expected. Therefore, it was decided to investigate the magnitude further noting the number of times than the concentrations exceed double the recommended amount (100 µg/m^3). The results can be seen in Table 24.

The results obtained in this part of the investigation cause concern. The quantity of PM_{10} sampled is considerably higher than expected. Long term exposures to high concentrations of PM_{10} result in the reduction of lung function, development of chronic bronchitis and even premature death (Dockery *et al.*, 1993; Pope *et al.*, 1995; Schwartz *et al.*, 1996; Donaldson *et al.*, 1998; Dockery, 1996; Pope, 2000). The most susceptible individuals to be affected are the elderly, children and individuals with chronic pulmonary or heart disease (Elsom, 1992; WHO, 1992; Bowler *et al.*, 2006).

Table 24: Number of days in each year (from 2000 to 2008) at five sites when the concentration of PM_{10} exceeded 100 µg/m^3.

	Dartford 1	**Dartford 2**	**Dartford 3**	**Gravesham (A2)**	**Gravesham N.**
2000	**76**	**No data available for this period**		**58**	**82**
2001	**89**			**27**	**75**
2002	**115**			**52**	**79**
2003	**103**			**33**	**68**
2004	**88**	**73**	**59**	**35**	**68**
2005	**103**	**59**	**45**	**43**	**63**
2006	**54**	**73**	**12***	**51**	**80**
2007	**83**	**36**	**42**	**48**	**87**
2008	**68**	**44**	**30**	**22**	**78**

Some authors, such as Seinfeld (1986), Stedman (1997), Arya (1999), VanCuren (1999), Merefield (2002) and Buchanan *et al.* (2002) suggested that exceeding the air quality guidelines is predominantly linked to a national and trans-boundary pollution event. Generally, it has been observed that the results obtained during this part of the investigation corroborate those suggestions. It has been noted that in more cases when the levels have been higher than the recommended amount, the cause could be a synoptic episode of pollution affecting the whole area (Muir *et al.*, 2006: Charron *et al.*, 2007) most probably

entering the UK from the south east and carried in by continental air masses (Smith *et al.*, 2001).

There is a possibility that these concentrations are worsened by synoptic episodes of pollution. However, a reduction in the annual concentrations levels has already been noted (Section 4.3.4.1) so this would indicate that they are mainly affected by local sources. Due to the locations of the sites (busy motorways or kerbsides) these are likely to be traffic emissions. If this is the case, mitigation measures would include: a ban of high-emission vehicles from heavily polluted areas, fitting of particle filters to diesel cars and optimized street cleaning (Bruckmann *et al.*, 2007). However, it would also be necessary to check patterns of PM_{10} following such mitigation measures, to ensure that they were appropriate and working.

4.3.5 The role of topography in PM_{10} distribution

The role of topography was examined in order to investigate if geographical features (both physical and human) could be affecting the PM_{10} distribution within the study area.

Several studies highlighted the influence of geographical features on PM_{10} dispersion (for example, Varvayanni *et al.* (1995); Castro *et al.* (1996) or Kondo *et al.* (2002) see also Section 2.4 where the influence of topography on airflow and therefore in the distribution of particulate matter within a given region has also been evaluated).

With this in mind, it was decided to include topographical features in the PM_{10} analysis, on the basis that the topographic features in Kent would influence the airflow in the ways identified in Section 2.4. In addition, Section 3.3.7, explained the rationale for dividing the region into four areas.

The four categorised areas with their sites included are (Figure 78):

- **North Downs** (Canterbury, Chatham, Luton, Maidstone (Detling), Swale (Ospringe)).
- **Coastal Sites** (Dover, Folkestone, Lower Stoke, Swale (Sheerness), Thanet (Ramsgate)).
- **South Downs** (Ashford and Maidstone (Fairmeadow)).
- **Sites closer to London** (Dartford 1, 2, 3 and Gravesham (A2 and Northfleet)).

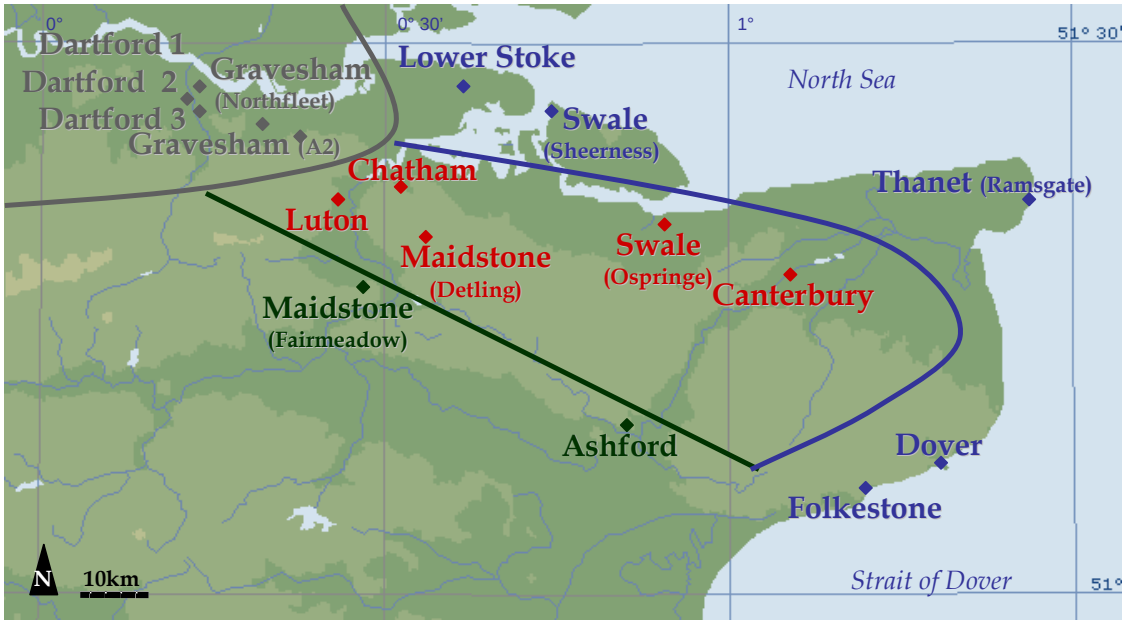


Figure 78: Shows the four areas in which Kent has been divided based on their topographic features. Map adapted from Microsoft Encarta.

In general, it appears that comparing the PM_{10} caught at the various sites within every selected area was not terribly useful. There were many data sets to be considered and trying to identify a meaningful way to compare them was difficult. In a first approach, it could be assumed that each location is unique with respect to its mix of sources of PM_{10}, its geographical features and meteorology. Therefore, the suggestion of comparing them by their main topographical features seemed a good idea. In contrast, most sites appeared to be recording the same number of regional episodes of pollution (See Figures 79 to 82). It is also worth noting that the highest values of PM_{10} recorded were also taking place during these regional events. Each individual area has been analysed and the specific results found are described in the following sections. An example of the data for the year 2007 has been provided for every section. 2007 was chosen because it had complete data sets for all sites, as well as being considered a representative example.

In each of the graphs, the period of time where synoptic pollution events were recorded has been highlighted with red circles. The correlation coefficients previously used in Section 4.3.2 (Appendix L) have been re-examined, this time with more emphasis among sites in each of the divided areas.

4.3.5.1 Coastal sites

In the graphs representing the yearly data for the sites close to the coast, the first noticeable point is that the Thanet (Ramsgate) values are significantly higher than the other sites. It is also clear that there are several important synoptic events affecting the sites all year around (the graphical representation of the data for all years can be found in Appendix U).

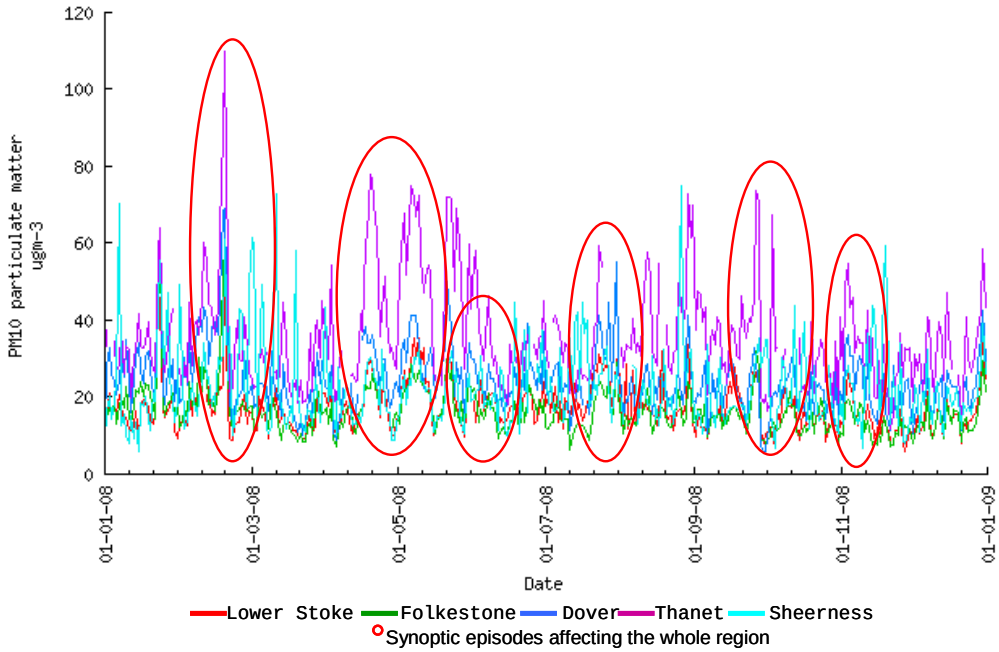


Figure 79: Coastal sites values of PM_{10} (2007).

The trends revealed by each sampling station appear to be different, with the exception of the synoptic episodes. In a first approach, it was considered that this result could be caused by the distance between the sites (Figure 79). However, not even sites close by, such as Dover and Folkestone, show similarities other than those already mentioned. What is more, no other results have been observed when studying the correlation coefficients between the costal sites.

Moreover, it could be argued that the reason each station seems to be sampling different material is that each one of them could be being affected by different sea breezes which may be responsible for their individual distribution patterns. If this was correct, the source of the particulate matter in that case would most likely be marine aerosol (arriving from sea spray) (Gustafsson and Franzen, 2000). The APEG (1999) suggested that in the UK sea salt concentrations are typically of the order of 1-3 μg/m^3. In addition, Van Dingenen *et al.* (2004) and Putaud *et al.* (2004), in investigations on European aerosol phenomenology, found that sea spray was clearly identified as one of the most common components of the particles in sites located in a radius smaller than
50 km from the seashore. This suggestion is developed in more detail in Section 4.4.2.

4.3.5.2 North Downs sites

The graphical evidence suggests that the data produced by the five sampling locations in the northern part of the county (Figure 80) is affected by significantly similar trends. Generally, it can be observed in the annual graphed data (Appendix V) that concentration levels seem to be shifting at almost the same time in most cases, with a few exceptions (for instance, individual peaks were recorded in several occasion both in Luton and Maidstone (Fairmeadow)).

Bearing in mind previous points, the causes or factors responsible for these results were carefully considered. Firstly, it was thought that the cause could be the topographical location of the sites situated on the north side of the North Downs and, therefore, affected by local winds such as valley breezes (previously described in Section 2.4). However, after considering various studies (Mason *et al.*, 1999; Parker and Kinnersley, 2004) that suggestion was rejected. The North Downs only elevate a few hundred metres (267 m at their high of point) and relatively distant from the sites location to create an anabatic flow that would affect the PM_{10} dispersion within the study sites. For that reason, it is considered not to be severe enough to be able to produce such a noticeable pattern (Appendix V). Secondly, it was considered that the outcome obtained could also be caused by the nearby location of the sites (they are all within less than 50 km radius, Figure 80). Finally, the third cause examined seems to be the most reasonable. It is probable that the significantly similar trends are influenced by the environmental background affecting the sites. Most of them,

with the exception of Maidstone (Detling, sited in a rural background) are located in an urban centre (or by a roadside also within a town). It is believed that the urban background would be the main influence affecting the results.

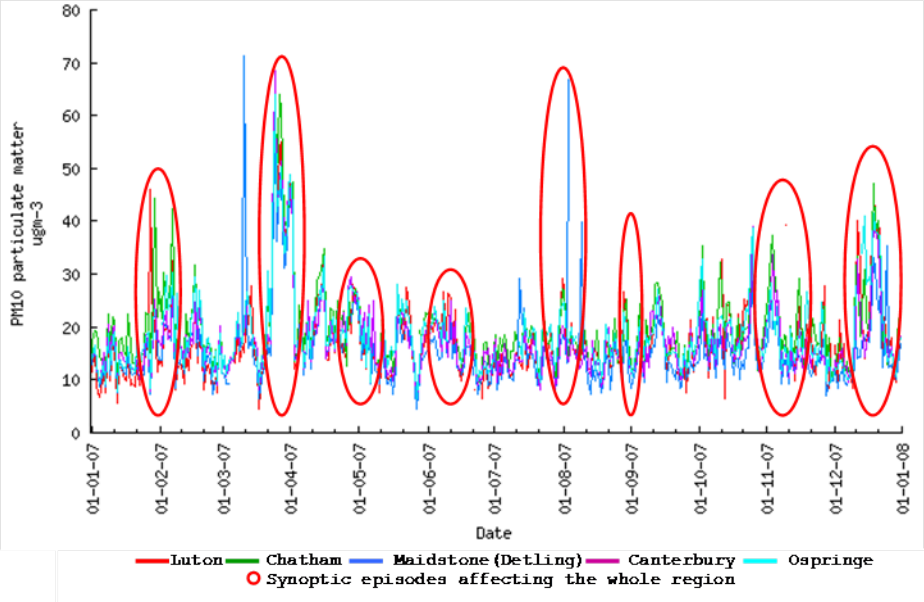


Figure 80: PM_{10} concentration levels for the North Downs sites (2007)

In contrast to the graphical analysis, the correlation coefficients between all sites are on the whole significantly low (Appendix L).

4.3.5.2 South Downs sites

Unfortunately, the data set for Sevenoaks could not be used in this analysis. The data recorded were not adequate, sufficient or reliable enough (Appendix H) to compare with the other sites and this affected the scale of the graphical representation. Therefore, it was decided to omit it for this comparison.

Ashford and Maidstone (Fairmeadow) showed substantially similar patterns in PM_{10} caught (an example of the annual distribution can be seen in Figure 81, the graphical representation for every year can be found in Appendix W). To return to an earlier point this could be caused by non-topographical factors, as both sites are located on a roadside.

The correlation coefficients between the two sets of data are significantly low for the years 2003 to 2005 ($r^2 < 0.4$). After that, the correlation value was more positive, 0.741, 0.678 and 0.621 (Appendix L). Unfortunately, there are not enough data to provide a fair explanation

of the possible factors affecting PM_{10} distribution in this area. Ideally, data from more sites within the South Downs would be necessary to be able to offer a fair representation of the wind behaviour in the area.

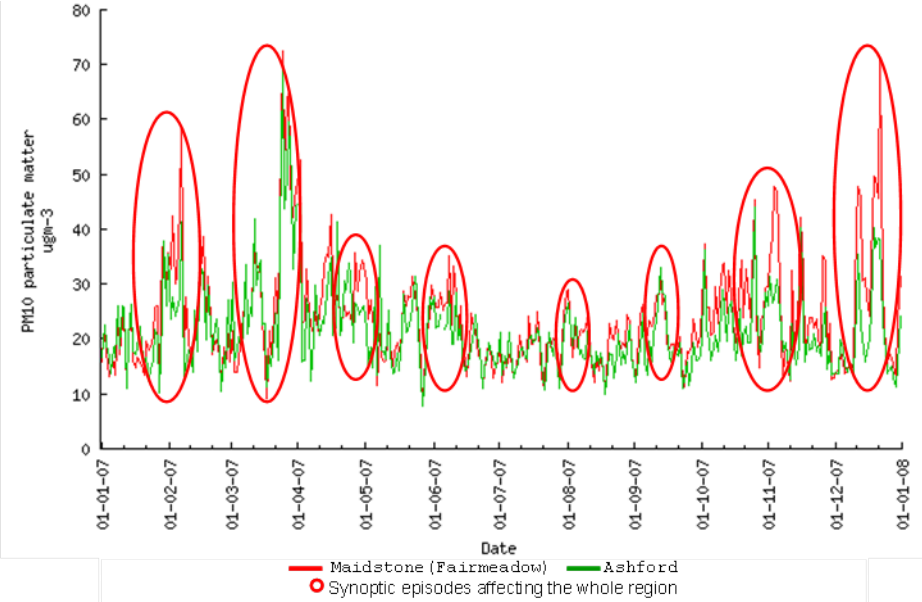


Figure 81: Graphs showing the data for the two South Downs sites (2007).

4.3.5.4 Sites located in the outskirts of London

As previously examined (Sections 4.3.1 and 4.3.2), the levels of PM_{10} at the Gravesham and Dartford sites are constantly higher than in the rest of the county and most of the time their PM_{10} levels exceed the 50 $\mu g/m^3$ recommended by the UK government in their Air Quality Strategy (2000) (Figure 77).

As expected, it seems that the concentrations recorded at the five sampled sites in the outskirts of London have been affected by a synoptic event rather than local sources (nearby roads or other local sources of emission). Furthermore, these five sites registered some of the highest correlation coefficients which corroborate the graphical results obtained.

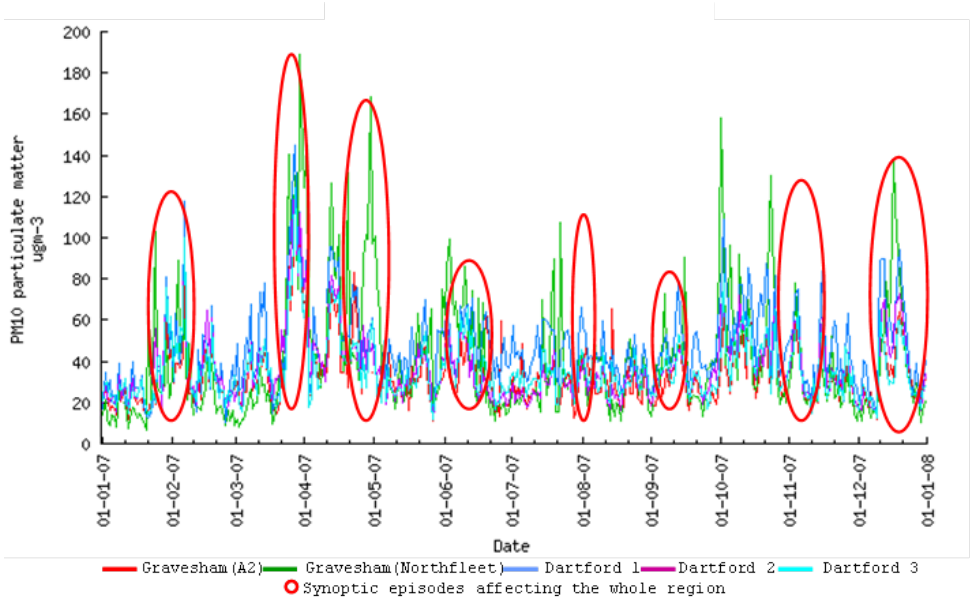


Figure 82: Gravesham and Dartford sites (2007).

Observing the graphed data in Appendix X, as well as the example provide in Figure 82, it is worth noting that the highest peaks seem to be caused by a synoptic episode of pollution affecting the whole region rather than by local sources.

Following the topographical analysis of the PM_{10} distribution, the evidence suggests that PM_{10} distribution within the study area appears to be affected by the site's environmental background as well as their geographical location. It has also been noted that higher values were recorded at most sites at the same time. Therefore, this also suggests a link to regional events. These suggestions have been taken into consideration in the following sections. First, Section 4.3.6 examines the sampling location depending on their environmental background and then Section 4.3.7 examines the possibility of air masses or other broad scale weather events as the vehicle to transport PM_{10} over the region.

4.3.6 The relationship between site background and PM_{10} catch

As described in previous sections, the environmental background where the sites are located seems to be the key for the concentrations sampled. The evidence suggests that those sites located on the roadside were registering the largest number of particle counts. Overall, the higher values were found on the five sampling roadside sites closer to the city of London (Gravesham (2) and Dartford (3)) followed by the other sites next to a busy road (such as Maidstone (Fairmeadow) or Thanet (Ramsgate). Generally, the sites with a lower number or

records are, as expected, located in a rural area (Lower Stoke and Maidstone (Detling)). Nevertheless, and in order to examine if the episodes of pollution registered followed the same patterns, the three different backgrounds were compared.

4.3.6.1 Sites sampling in a rural location

The two sites located in a rural background are Lower Stoke and Maidstone (Detling). The concentrations from these two sites were generally lower than at any of the other sampling locations (the graphs for all studied years can be seen in Appendix Y). These two sites are affected by different topographical features; Lower Stoke is close to the coast whereas Maidstone (Detling) is located inland. Nevertheless, they seem to be well associated, normally appearing to be sampling the same data, apart from a couple of high peaks episodes recorded in Maidstone (Detling). These peaks would probably be caused by a local source close to the sampling trap, as they seem to be significantly high and sporadic (see Section 4.3.3 Figure 74).

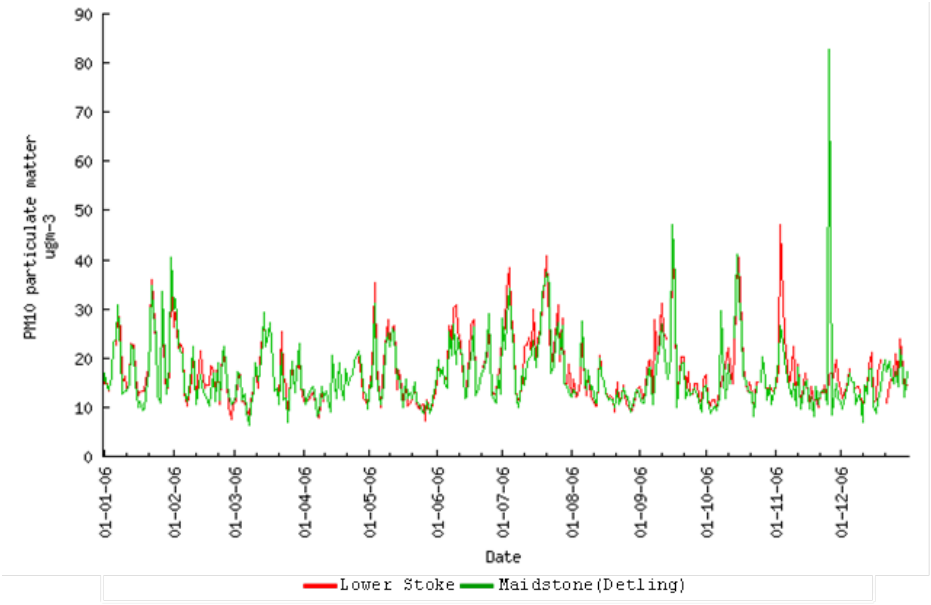


Figure 83: PM_{10} Levels from sites located in a rural background (2006).

4.3.6.2 Sites sampling in an urban background

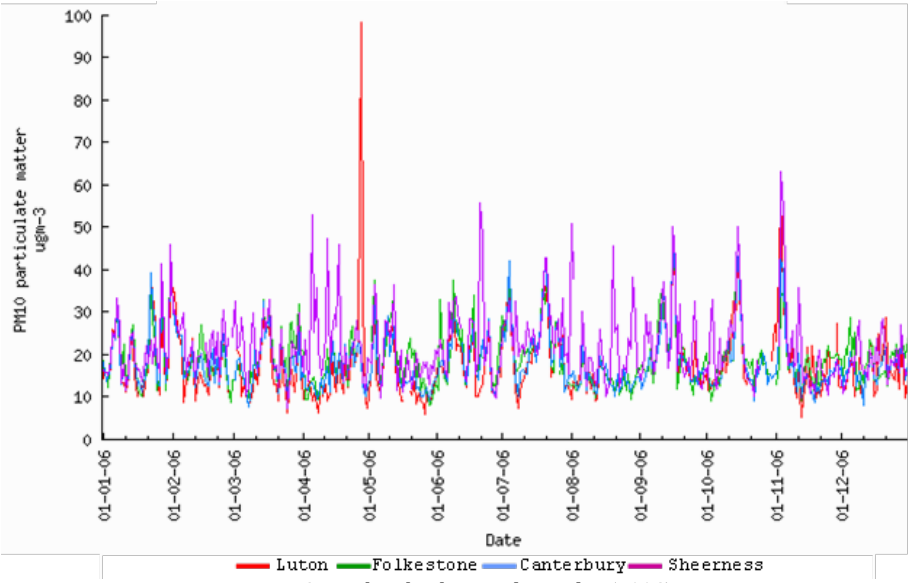


Figure 84: Urban background samples (2006).

Concentrations increase when shifting from a rural background to an urban site (Figure 84). The levels registered at all urban sites tend to be very similar, following the same trends (Appendix Z). Overall, the highest values were registered at Sheerness. This sampling station is located in an industrial area, which may assist explaining why the proportion of particles is slightly higher in comparison to the other sites.

4.3.6.3 Sites sampling in a roadside

The mean highest PM_{10} levels were found in sites close to a roadside. Aside from the five sites in the outskirts of the capital the most elevated values were noted at Thanet (Ramsgate), closely followed by Dover and Maidstone (Fairmeadow) (see all the yearly trends in Appendix AA) (Figure 85).

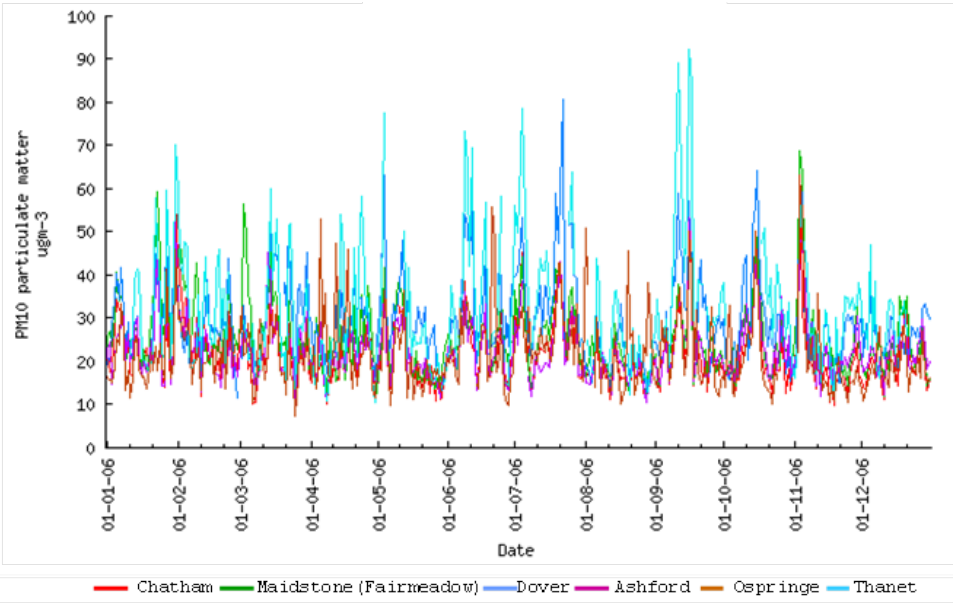


Figure 85: Roadside background concentrations (2006).

The trends appear to be very similar for all sites, which confirm the important role of the site background. The levels are noticeably affected by the levels of traffic, increasing at peak times and decreasing during the middle part of the day (KCC, 2006). This would require further investigation outside the scope of this thesis, calculating the relationships between concentrations of PM_{10} and other pollutants generally associated with road traffic emissions (for instance NOx and CO) (Smith *et al.* 2001; Harrison *et al.*, 1997; Harrison and Deacon, 1998; AQEG, 2005; Muir *et al.* 2006; Charron *et al.*, 2007; Vardoulakis and Kassomenos, 2008).

4.3.6.4 Outcome of the environmental background role

The environmental backgrounds of the site locations seem to be the key for the local amounts sampled. The evidence suggests that those sites located on the roadside were registering the larger number of particle counts within the region.

In addition, it has also been observed a series of synoptic events affecting the concentration levels at most sites during the same periods. These could be caused by air masses transporting particulate matter from sources outside of Kent, the most significant being London and mainland Europe (Smith et al., 2001; Charron et al., 2007).

Furthermore, the results show that all particulate monitoring sites across the county follow similar trends. PM_{10} concentrations at rural locations (as recorded by sites in Maidstone (Detling) and Lower Stoke) are only marginally lower than those of urban background

locations. The local contribution increases in roadside locations, but still accounts for less than half of the total pollution. This non-local nature of particulate matter dispersion makes control very difficult: local measures to combat PM_{10} pollution would only have an affect on a small percentage of the total.

4.3.7 Pollution trajectories

Up until now, the main focus of this thesis has been on two main themes: observing the patterns of PM_{10} captured at individual sites (including the seasonal distribution or the amount of particles sampled) and evaluating the possible causes and factors influencing the PM_{10} values recorded. Nonetheless, throughout this investigation it has also been noticed that on numerous occasions, these values do not appear to be linked to specific local sources. It was therefore, important to consider wind direction and velocity affecting the study sites and how the pollution plumes could be transported from site to site by local winds or air masses.

Three pairs of sites were chosen as a representation of the data using wind directions with the trajectory over each of the sets. The groupings were; Lower Stoke to Sheerness (chosen to identify transport during west/northwest persistent winds), Dover to Ospringe (chosen for southeast prevailing winds) and Lower Stoke to Gravesham (chosen to study northeast winds).

The data were first filtered by wind direction, and then filtered by PM_{10} count (selecting data points greater than 30 $\mu g/m^3$, so transportation is more likely to occur (Seinfeld, 1986; Arya, 1999; McMurry *et al.*, 2004) (Appendix P). The comparisons have focussed on periods of time when the wind was blowing in that particular direction for more than three hours. This time was chosen in order to allow transportation between one site and the other.

4.3.7.1 Northwest pollution trajectories

The first example shows data from Lower Stoke and Swale (Sheernes) The data were filtered by west-northwest winds first at Lower Stoke and then during the same period at Sheerness (Figure 86). The distance between the two sites is 10 km and the mean wind speed (Figure

86) was 3-4 m/s. Therefore, applying the formula (Time=distance/ wind velocity), it was calculated that the particles will take an hour to move 10-14 km.

Unfortunately, in this case the data do not appear to reflect the theory. The two sites do not seem to be sampling the same data. The values for Sheerness are higher than those recorded at Lower Stoke, this would mean that Sheerness may be sampling PM levels from local sources or other material arriving from a different direction (Figure 86).

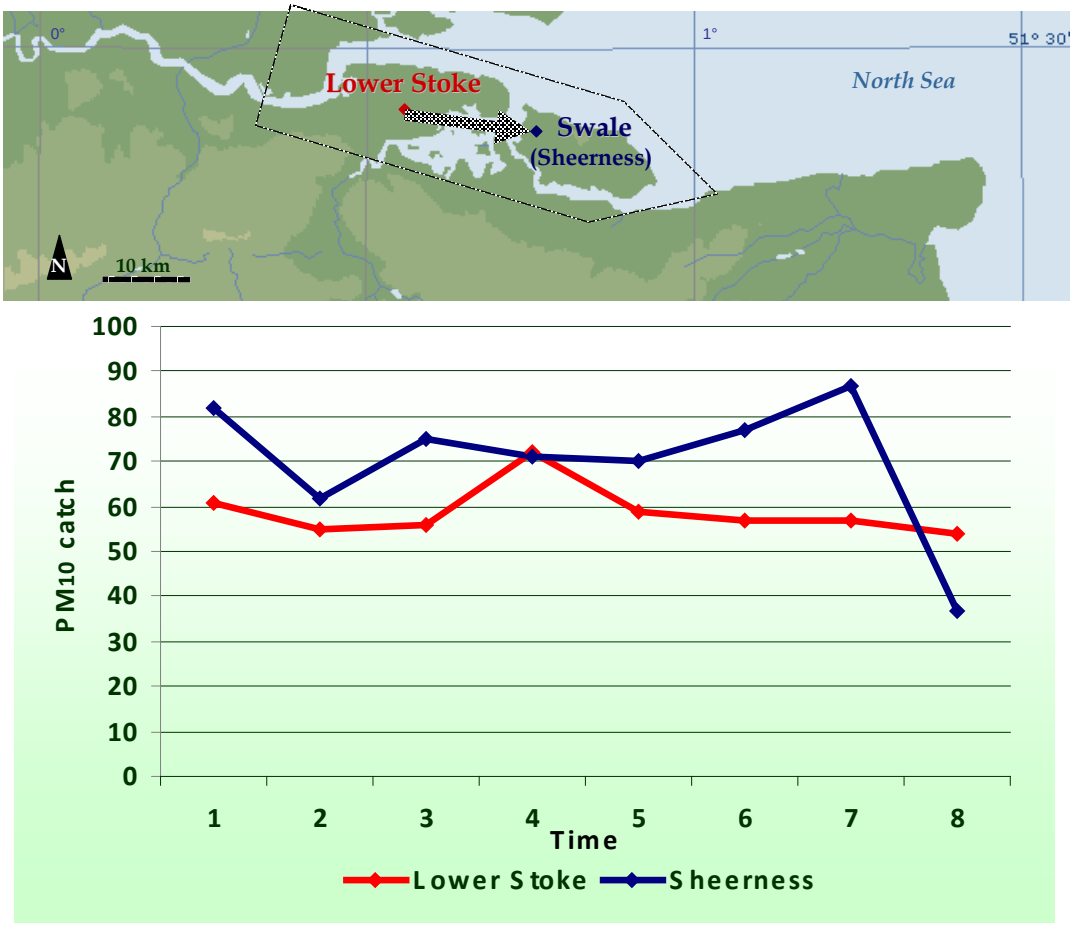


Figure 86: Shows an example of the PM_{10} data analysed for 29.03.2007 between 1 a.m. and 9 a.m. Adapted from Microsoft Encarta (2003).

4.3.7.2 Southeast pollution trajectories

The only two sites with southeasterly data available were Dover and Swale (Ospringe). These data sets were not ideal for comparison: the sites are located 40 km apart. In addition, Swale (Ospringe) is located in the northern part of the North Downs whereas Dover is situated on top of the cliffs facing the sea in the southern part of the county. However, it was

important to evaluate the possibility of particulate matter transport arriving from the near continent and these data from these two sites could be showing a trans-boundary transport. The wind direction speed at the time of this example was between 2.3 m/s and 3.1 m/s. A four hour time shift (the amount that a particle will take under these circumstances to be transport from Dover to Swale (Ospringe)) was therefore applied to the Ospringe data set.

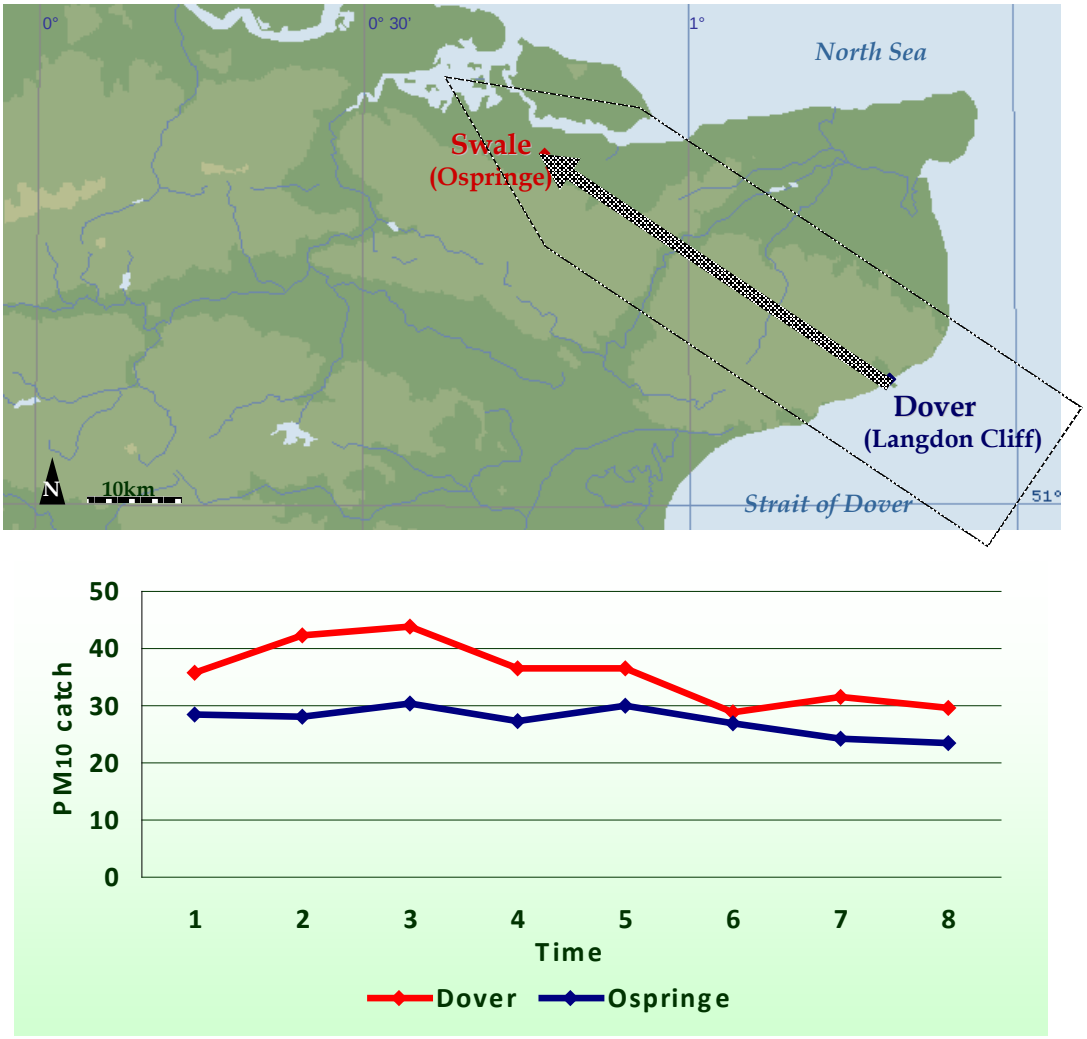


Figure 87: Shows an example of the PM_{10} data analysed for 18.10.2006 between 6 p.m. and 12 a.m. Adapted from Microsoft Encarta (2003).

Contrary to what was expected, because of the location of the sites, the data sets appear to be associated (Figure 87). There is a possibility that both sites could be sampling a plume arriving from the near continent (Figure 87).

As previously mentioned in the literature review (Section 2.2.8.1), the ability of a particle to remain suspended in the air depends essentially on its size (Harrison, 1990; McMurry *et al.*, 2004). Large size particulate matter (>10 μm in diameter) falls rapidly settling under the influence of gravity, while fine light particles remain suspended for longer (Parker 1977; DETR, 1998) The distance between Dover and Ospringe is 37 km, therefore, there is a low probability of larger particles been transported between the two sites. Furthermore, if transportation is taking place between it is possible that most of the particles carried out from one site to the other are small in diameter also known as suspended particulate matter (SPM) (ranging in size from 0.1 μm to about 30 μm in diameter). In order to determine if transportation between the two sites does occur a further analysis would be needed, including the calculation of back trajectories and a chemical analysis of the PM composition.

4.3.7.3 North east pollution trajectories

The third example focuses on the transport of particles arriving from the northeast or, in this specific case, from the sea into land, perhaps affected by sea breezes coming into land. The data were filtered by northeast winds at Lower Stoke and then during the same period at Gravesham (Figure 88).

The two sites are located 20 km apart. The wind speed at the time of this example was 4 m/s, therefore applying the formula (Time=distance/ wind velocity), it was calculated that the particles would take an hour to move 10 km so it would take under two hours to arrive from one site to the other. In order to allow accurate comparison between the two sets of data, the time was shifted two hours.

In Figure 88, it can be observed how both sets of data appeared to be associated. It is also possible that both sets of data are affected by a sea breeze bringing the material into land (Section 4.2.7) due to the time of the day. In order to establish if the material is from the sea, a chemical analysis of the data would be required.

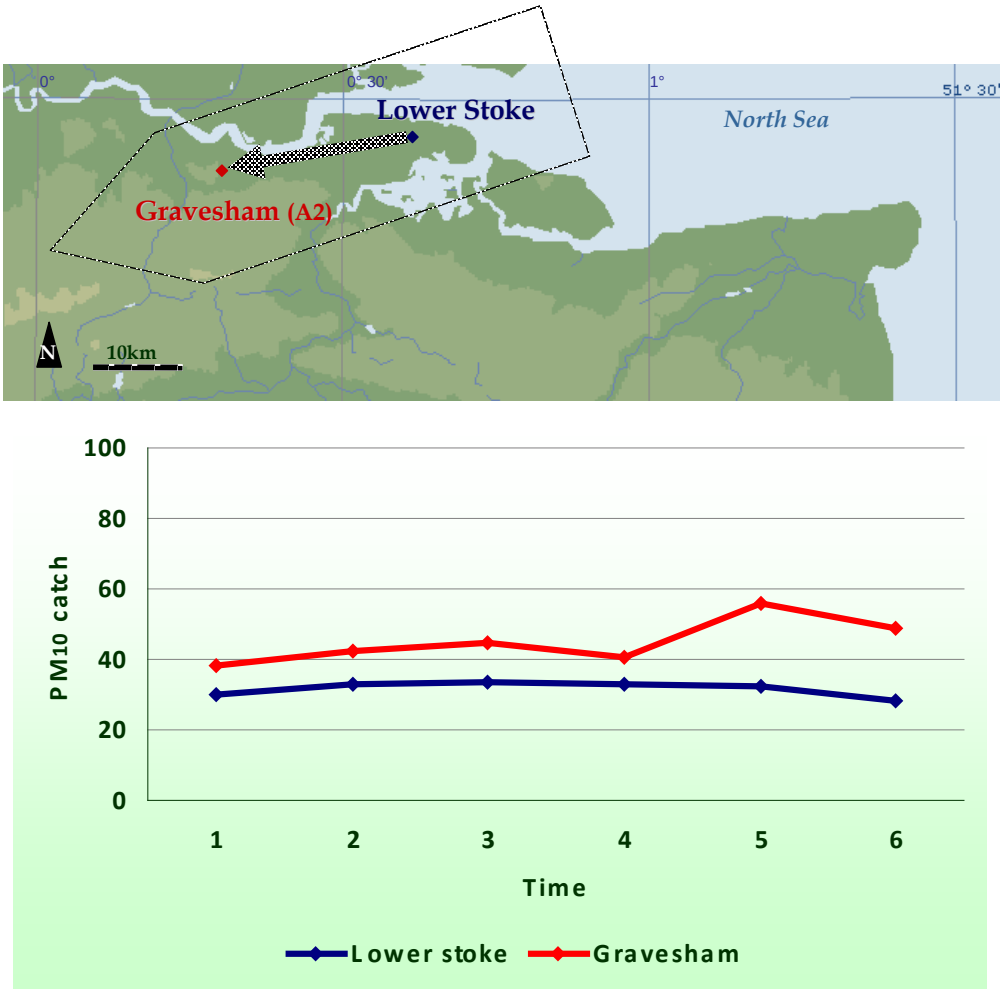


Figure 88: Shows an example of the PM_{10} data analysed for 25.02.2005 between 4 p.m. and 9 p.m. Adapted from Microsoft Encarta (2003).

4.3.7.4 Outline of the pollution trajectories

Particulate matter dispersion is a very complex process affected by many variables. Some of these variables are related between themselves, one affecting the other. In addition to other atmospheric processes, such as, the vertical variation of temperature, thermal convection or wind speed and turbulence affected by topographical features and surface roughness. These factors strongly influence the extent to which emissions are diluted by the wind (Goosens, 1988, Bridgman, 1990; Offer and Goosens, 1995; Mason *et al.*, 1999; Parker and Kinnersley, 2004). Consequently, they would also need to be taken into account.

Meetham *et al.* (1981) claim that observations of atmospheric pollution in Britain have suggested that the average life of a smoke particle before deposition on land must be one or

two days, although this will be affected by the conditions of the individual variables. Conversely, all of these factors would depend on the size of the particle sampled; the weight of the particulate will play a part and also how long it would be suspended, and therefore this information would be required to confirm the results (Harrison, 1990; McMurry *et al.*, 2004).

During this analysis, it was attempted to demonstrate how the same plume or episode of pollution could be affecting two nearby sites over the same period of time. Overall, it was difficult to find periods of time were the wind direction was affecting both sites at the same time for a period longer than four hours, as well as that wind speed and PM_{10} data should also be available during the same period to allow comparison.

Unexpectedly, two of the three pairs compared appear to be well associated which would indicate that there is a possibility that the sites are sampling the same pollution episodes in addition to being affected by local sources or the environmental backgrounds where they are located. However, these results are not definitive, further analysis would be required to determine that transportation between two sites does occur, including a back trajectory studies and a chemical composition analysis of the PM samples recorded.

4.3.8 Summary of the analysis of PM_{10} data

This thesis presents an analysis of temporal, spatial and seasonal variation of PM_{10} levels at 17 sites located within Kent. Ten sites were located at an urban roadside, five in an urban background and two were rural monitoring locations. For the duration of the analysis of the PM_{10} data throughout the nine years, there were a number of repetitive patterns and features observed. Overall, the higher values were found on the five sampling roadside sites closer to the city of London (Gravesham (2) and Dartford (3)). The most polluted site was Dartford 1 (St Clements) exceeding the daily recommended amount 50 $\mu g/m^3$ almost on a daily basis. On the other hand, the site recording the lowest concentrations was Maidstone (Detling) situated in a rural location (Figure 62).

In order to establish factors influencing the distribution of PM_{10} several methods were applied. Some of the main results are described briefly in the following paragraphs.

In general, six major trends linked to seasonality affecting the whole of the study area were observed. The autumn was the season with the lowest amount of PM_{10} recorded whereas the spring had the higher number of entries. Most of the high pollution events occurred during the spring.

A regional peak was also noted at the end of August and the beginning of September, thought to be related to agricultural activities such as the harvest of cereals, and therefore the increase in the number of dust and plant parts in the air. Another of the most remarkable trends found was a decrease during the summer months, mainly (July and August). This could be a consequence of the decrease of number of vehicles on the road due to the holiday period. In addition, the episodes of pollution associated with the Bonfire Night celebrations during the two first weeks of November were also clearly noted. Finally, another noticeable yearly pattern was observed at the end of December.

Surprisingly, and in contrast to some of the yearly trends described (considering that the PM_{10} values decreased over the summer months), the seasonal average concentrations at most sites generally tend to be slightly higher in summer than in the winter. No clear sea breeze or local wind influence was noted during the seasonal examination of the data. In contrast to the results obtained during the analysis of the high episodes of PM_{10}, were a seasonality pattern affecting the highest peaks at most coastal sites was observed.

Analysis of PM_{10} based on the topographical division was found to be neither constructive nor revealing. The PM_{10} distribution within the area does not seem to be affected by the geographical location of the sites. Nevertheless, the method applied dividing the data into four distinct areas allowed the observation of a synoptic influence affecting all studied sites. It was also worth noting that normally the highest values recorded were also produced by these synoptic events.

The results obtained during the analysis of the high episodes of PM_{10} seem to corroborate those stated early during the yearly comparison of the data. The amounts of PM_{10} sampled in the five sites closer to the London are considerably higher than permitted.

The objectives set by the UK government in the Air Quality Strategy are severely exceeded in the five sites closer to the city of London as well as most sites located near a busy road (for instance, Thanet (Ramsgate) and Maidstone (Fairmeadow)).
Regional episodes of pollution affecting the whole region were reasonably common. It appeared that some of the highest peaks registered were linked to these events, which would indicate regular trans-boundary influences affected the study area and the PM_{10} distribution.

4.4 Assessment of the wind direction role in the PM_{10} distribution

The previous two sections have examined the wind direction data in order to provide a clearer picture of the airflow affecting the studied area (Section 4.2) and the PM_{10} levels recorded in the area (Section 4.3). This section aims to assesses the most remarkable associations noted during the study of the influence of the wind direction on the dispersion of PM_{10} within the study area.

During the literature reviewed (Chapter 2), it was highlighted how the physical and dynamic characteristics of the atmosphere allow it to be the vehicle used for particles to make their journeys, affecting the whole process from source to deposition. Winds, for example, determine the pathways and speeds at which pollutants are transported away from sources (Seinfeld, 1986; Arya, 1999).
Separating trends in pollution levels caused by meteorological conditions from those caused by changes in traffic volume or emissions levels can be very difficult. Identifying trends caused through local air quality management, such as traffic management schemes, is even harder. Independent of the weather, pollution trends adjacent to a specific road may be caused by increased or decreased volumes of traffic, a change in the speed or composition of the vehicles or larger-scale influences not connected to the road itself. It seems that pollution concentrations vary from day to day depending on emissions and weather conditions. Unfavourable weather conditions can cause pollution levels to rise dramatically. Throughout this thesis, an analysis of the wind direction patterns and trend for the county of Kent has been undertaken, including the influence on airflow of topographical features.

4.4.1 Overview of sea breeze influence on PM_{10} dispersion

Throughout the analysis of the wind direction and the PM_{10} concentrations, sea breezes occurrences affecting most coastal sites have been clearly observed (Section 4.2.5). For example, Dover is a busy roadside site located within the urban centre. Therefore, it would be expected to obtain the highest values at peak time between 7 and 9 a.m. or 4 and 6 p.m. when the traffic is heavier (KCC, 2006). However, the peak values were mostly found in the middle of the day. Once this result was observed in Dover, the analysis was expanded to every coastal site.

The analyses of the sets of data suggest that most coastal sites are affected by sea breezes. Corroborating the expectations, winds from the east, southeast and northeast tend to prevail in the afternoon (between 11 a.m. and 4 p.m.) during the summer months.

During the analysis of the high levels of PM_{10} pollution (Section 4.3.4), it was observed that the frequency of the concentration levels exceeding 50 μg/ m^3 increased during the summer months in most coastal sites (with the exception of Folkestone where they remained constant throughout the year) (Table 23). The wind direction registered at the times of these events was mainly east, southeast and northeast. It was also observed that these events took part during the warmest part of the day, mainly between 11 am and 4 pm evidently indicating sea breeze episodes.

This would indicate that the high episodes of pollution at coastal sites are also driven by a sea breeze wind pattern, which could also imply that some of these concentrations would have a high marine aerosol composition (arriving from sea spray) (Gustafsson and Franzen, 2000). Van Dingenen *et al.* (2004) and Putaud *et al.* (2004), in their investigations on European aerosol phenomenology, found that sea spray was clearly identified as one of the most common components of the particles in sites located in a radius smaller than 50 km from the seashore. In addition, recent studies carried out in Portugal indicate that the coastal breezes play an important role in the air circulation during summer and, consequently, affect the regional air pollutants' distribution (Evtyugina *et al.* 2001 and 2006).

4.4.2 Synoptic episodes links to trans-boundary pollution

It has been suggested that pollution episodes exceeding the air quality guidelines are predominantly linked to national and trans-boundary pollution (Stedman (1997); Arya (1999), VanCuren (1999), Ryall *et al.* (2000), Apsimon *et al.* (2001), Merefield (2002): Buchanan *et al*. (2002)). In addition, a number of studies (Kings and Dorling (1997), Stedman (1997), Buchanan *et al.* (2002), Malcom *et al.* (2000), Namdeo and Bell (2005), Rigby *et al*., (2006); Muir *et al.* (2006) and Charron *et al.*, 2007) have reported that elevated PM_{10} concentrations, in urban and rural locations in the UK, generated outside the immediate area are generally associated with air masses arriving from the southeast and east, the direction of mainland Europe.

The results obtained during the process of this investigation tend to agree with the suggestions (Section 4.3.2 and 4.3.4). The wind direction at the time of the main pollution episodes was observed. Throughout the analysis, March and February appeared to be the months consistently most polluted, always registering the highest values, sometimes exceeding the recommended levels on a daily basis (Table 23, Appendix N). Unfortunately, the wind patterns analysis for this period was not significant. The PM_{10} concentrations recorded do not seem to be affected by the wind direction variations; no prevailing wind direction for this period was found (Section 4.2). As suggested by Smith *et al.*, (2001), Muir *et al.,* (2006) and Charron *et al.*, (2007) in their London studies they seemed to be caused by continental air masses arriving from the southeast.

Muir et al. (2006) carried out a two year (January 2002 to December 2004) study in London. During this time they identified a total of 185 days with daily PM_{10} concentrations exceeding the limit value of 50 $\mu g/m^3$ measured (data capture of 89.5%) were caused by synoptic episodes of pollution affecting the whole region.

Similar results have been reported in other places in Europe (Grivas *et al.* (2004) and Vardoulakis and Kassomenos (2008) in Greece; Querol *et al.* (2004) and Salvador et al. in Spain; Lenschow *et al.* (2001) in Germany and Kukkonen *et al.* (2005) in Oslo, Helsinki, London and Milan) suggested long-range transport of particles (affected by high atmospheric pressure areas and temperature inversion events) was the main cause of synoptic episodes of pollution affecting a whole region. Therefore, air mass back trajectory analysis may be considered as a useful complementary tool for urban air quality management in the future.

Furthermore, cluster analysis of larger numbers of atmospheric trajectories could provide a more detailed geographical allocation of long-range particle sources.

4.4.3 Other factors affecting PM_{10} distribution

As previously noted, the background location of the sites seems to be the key to understanding the different levels of local PM_{10} caught (Section 4.6). Nevertheless, there are many other factors paying an important role on the dispersion of PM_{10}: for instance, the specific sampling location. The location of a site in relation to the surrounding environment and the obstacles affecting the dispersion of particles is very important. For example, Maidstone (Detling) was the site recording overall the lowest PM_{10} concentrations levels. These results may be caused by the location of the sampling trap, not only situated in a rural area but also surrounded by open spaces that would be better ventilated than other locations (Figure 89).

Figure 89: Location of the PM_{10} trap at Maidstone (Detling).
The views showing the trap surroundings are towards the a) east, b) south, and c) west.

The five sites located east of the city of London (in Gravesham and Dartford) would undoubtedly be affected by the city's PM concentrations levels (for instance, caused by its high traffic volume (Highways Agency, 2010)). The predominant wind direction affecting the British Isles is southwesterly, followed by westerly and northwesterly. Therefore, this would mean that the most predominant wind type would be carrying material from other urban and industrial sources within the city towards the sites located east of the city, which would contribute to the elevated levels recorded at these sites. In addition to the contribution from synoptic trans-boundaries episodes, explained in the previous paragraphs, the remaining peaks found at these sites would probably be caused by local sources of pollution, mainly from an increase of traffic levels as a consequence of their close location to busy roads (Section 4.3.6).

These three preceding sections focus on the influence of local wind in PM_{10} caught, the influence of wind direction on synoptic events as well as other factors affecting airflow and therefore PM_{10} distribution. During the whole of this investigation, the complexity involved in understanding PM_{10} dispersion has been highlighted. There are major uncertainties regarding the variable spatial, temporal and chemical nature of PM_{10} and its associated pollutants.

Generally, data from the Environmental Research Group (ERG) sampling network have provided information about the occurrence and spread of PM_{10} within Kent. In order to assess potential regular PM_{10} transport from the near continent, a trap was located in Dover providing an ideal location to sample PM arriving from the continent into the UK. The results are described in the Section 4.6.

4.5 Case studies of PM_{10} pollution episodes

According to several authors (Seinfeld (1986); Pepper *et al.* (1996); Arya, (1999); Bower *et al.* (2005)), the two main types of pollution episode affecting the UK are winter and summer smogs. For this reason, it was decided to examine an example of each of these pollution episodes with relation to the study area. Such cases are especially constructive to build up an understandable representation of what is really taking place in the studied areas, as they provide identifiable times of increased pollution loading in the atmosphere, often with recognisable causes and/or source areas. The first case focused on Bonfire Night celebrations and the high levels of PM_{10} registered during this period all around the county. The second case concentrated on August 2003 (the warmest period on record) and the photochemical episode of smog that as a consequence took place.

4.5.1 Bonfire Night

Bonfire Night (on or around 5^{th} November each year) provides an interesting example of an emissions-driven winter episode.

The data analysed include the first nine days of November (four days either side of Bonfire Night) for every studied year and the results have been taken from the 17 monitoring stations with data available around the county. Figure 90 shows an example of the data examined. The rest of the graphs can be seen in Appendix AB.

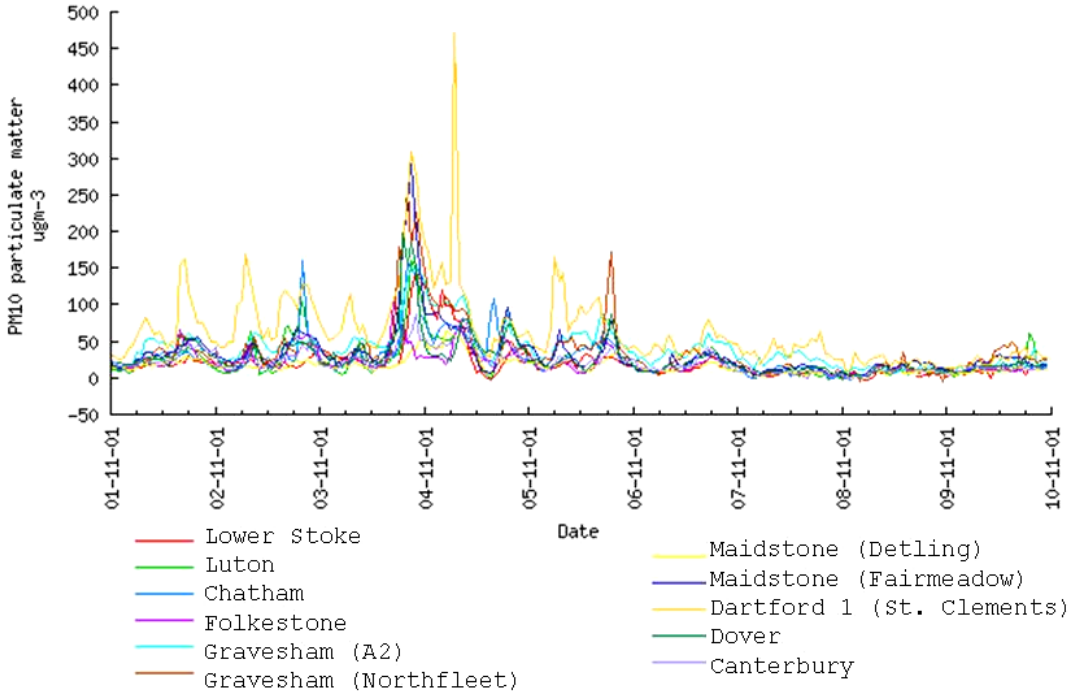


Figure 90: Bonfire Night's pollution episodes (1-9, November, 2000).

During the analysis, it has been noted that the combined effects of light winds and Bonfire Night celebrations may result in high levels of air pollution mainly during the evenings and weekends before and after every 5th November (Table 24, Figure 93 and Appendix AB). The synoptic conditions during Bonfire Night were also examined as well as the closer weekends to the 5th November. During the analysis, the synoptic conditions as well as the wind direction has also been examined using the same method previously described in Section 3.2.

It is clear that the results analysed for the dates surrounding Bonfire Night show an increase in the amount of PM_{10} recorded in comparison to other dates (Table 24). As expected, the sites closer to London (Section 4.3.2), three Dartford sites and the two at Gravesham, recorded the higher number of exceedences over the nine days period. Unsurprisingly, it was also observed that the urban sites registered higher values than rural sites, most of the Bonfire celebrations close to the town centres.

Table 24: Shows the number of times that the PM_{10} values exceeded the recommended 50 µg/m^3 daily amount over the nine first days of November. As well as this, Table 24 also illustrates the maximum value sampled (in bold) and its location in addition to the date when it was recorded. The two columns on the right also show the most predominant wind direction (WDIR) at the time of the peaks and the synoptic conditions for that period.

Year	Sites	Number of Exceedences	Maximum value (µg/m^3)	Date of highest Peak	Most predominant WDIR	Synoptic conditions
2000	Dartford 1	6	140 µg/m^3	04/11/00 (Saturday)	SW	Low pressure (rain, thunder storms and lightning)
	Gravesham (Northfleet)	4	**260** µg/m^3			
	Gravesham (A2)	3	150 µg/m^3			
	All others: Chatham Folkestone L.Stoke Luton M.Detling M.Fairmeadow	1	250 µg/m^{3}at at M. Fairmeadow			
2001	Dartford 1	9	490 µg/m^3	03/11/01 (Saturday)	W	High pressure for the first 5 days of the month and then heavy rain
	Gravesham (A2)	5	150 µg/m^3			
	Gravesham (Northfleet)	3	250 µg/m^3			
	All others: Chatham Folkestone L.Stoke Luton M.Detling M.Fairmeadow	1	250 µg/m^{3}at at M. Fairmeadow			
2002	Ashford	1	100 µg/m^3	09/11/02 (Saturday)	SW	Low pressure/ cold Front
	Dartford 1	5	**170** µg/m^3		NW	
	Dartford 2	2	90 µg/m^3		SW	
	Dover	3	90 µg/m^3		N	
	Gravesham (A2)	9	150 µg/m^3	04/11/02	NW	
	Gravesham (Northfleet)	4	130 µg/m^3	07/11/02	W	
	M. Fairmeadow	3	90µg/m^3	09/11/02 (Saturday)	N	
	All others: Canterbury Chatham Folkestone Luton L.Stoke M.Detling	1	80 µg/m^3 at Luton		N	

Table 24: Cont.

Year	Sites	Number of Exceedences	Maximum value (µg/m^3)	Date of highest Peak	Most predominant WDIR	Synoptic conditions
2003	Ashford	2	100 µg/m^3	08/11/03	E	No significant conditions took place
	Canterbury	3	55 µg/m^3	07/11/03	SE	
	Chatham	2	110 µg/m^3	02/11/03	SW	
	Dartford 1	9	195 µg/m^3	08/11/03 (Saturday)	E	
	Dartford 2	7	155 µg/m^3		E	
	Dartford 3	6	118 µg/m^3		E	
	Dover	4	80 µg/m^3	06/11/03	S	
	Folkestone	1	102 µg/m^3	01/11/03	NW	
	Gravesham (A2)	3	190 µg/m^3	08/11/03	E	
	Gravesham (Northfleet)	7	**200** µg/m^3	07/11/03*	SE	
	Luton	2	98 µg/m^3	08/11/03	E	
	L. Stoke	2	60 µg/m^3	05/11/03	SE	
	M. Fairmeadow	6	107 µg/m^3	08/11/03 (Saturday)	E	
	Ospringe	3	178 µg/m^3		E	
	Sheerness	2	190 µg/m^3	05/11/03	S	
	Thanet	8	85 µg/m^3	06/11/03	SE	
2004	Ashford	3	85 µg/m^3	05/11/04	W	High pressure, heavy rain on the 2nd
	Chatham	2	137 µg/m^3	06/11/04	SW	
	Canterbury	2	98 µg/m^3	05/11/04	W	
	Dartford 1	8	255 µg/m^3	06/11/04	SW	
	Dartford 2	8	**270** µg/m^3	06/11/04	SW	
	Dartford 3	8	205 µg/m^3	05/11/04 (Saturday)	W	
	Gravesham (A2)	7	177 µg/m^3		W	
	Gravesham (Northfleet)	4	157 µg/m^3		W	
	Dover	2	155 µg/m^3		W	
	Folkestone	2	160 µg/m^3		W	
	Luton	2	220 µg/m^3	06/11/04	SW	
	L. Stoke	2	116 µg/m^3	05/11/04	W	
	M.Detling	1	68 µg/m^3		W	
	M. Fairmeadow	5	117 µg/m^3		W	
	Ospringe	3	75 µg/m^3	06/11/04	SW	
	Sheerness	2	100 µg/m^3	05/11/04	W	
	Thanet	4	151 µg/m^3		W	

Table 24: Cont.

Year	Sites	Number of Exceedences	Maximum value (µg/m^3)	Date of highest Peak	Most predominant WDIR	Synoptic conditions
2005	Chatham	2	61 µg/m^3	08/11/05	S	Low pressure/ unsettled and warm
	Dartford 1	9	148 µg/m^3	09/11/05	NW	
	Dartford 2	5	96 µg/m^3	05/11/2005	SW	
	Dartford 3	4	89 µg/m^3	09/11/2005	NW	
	Dover	1	62 µg/m^3	05/11/205	SW	
	Folkestone	1	59 µg/m^3	09/11/2005	NW	
	Gravesham (A2)	5	**400** µg/m^3	6/11/05	SW	
	Gravesham (Northfleet)	2	64 µg/m^3	5/11/05 (Saturday)	SW	
	Luton	2	64 µg/m^3	08/11/05	S	
	M. Fairmeadow	4	75 µg/m^3	05/11/05	SW	
	Sheerness	1	57 µg/m^3	9/11/05	NW	
2006	Ashford	1	88 µg/m^3	04/11/06 (Saturday)	NW	1st -5th High pressure
	Chatham	3	290 µg/m^3		NW	
	Canterbury	2	85 µg/m^3		N	
	Dartford 1	5	292 µg/m^3		NW	
	Dartford 2	2	**820** µg/m^3		NW	
	Dartford 3	1	250 µg/m^3		NW	
	Dover	2	195 µg/m^3	05/11/06	NW	6th- 7th Dense fog
	Gravesham (A2)	2	230 µg/m^3	04/11/06 (Saturday)	W	
	Gravesham (Northfleet)	3	180 µg/m^3		W	
	Luton	1	170 µg/m^3		W	8th- 10th Low pressure (Rain)
	L. Stoke	2	106 µg/m^3		W	
	M. Fairmeadow	2	201 µg/m^3		W	
	Ospringe	1	112 µg/m^3		NW	
	Sheerness	1	90 µg/m^3		W	
	Thanet	1	160 µg/m^3		NW	

Table 24: Cont.

Year	Sites	Number of Exceedences	Maximum value (µg/m^3)	Date of highest Peak	Most predominant WDIR	Synoptic conditions
2007	Chatham	3	81 µg/m^3	04/11/07	NW	Low pressure/ unsettled
	Canterbury	2	61 µg/m^3		NW	
	Dartford 1	7	160 µg/m^3	03/11/07 (Saturday)	W	
	Dartford 2	7	165 µg/m^3	03/11/07	W	
	Dartford 3	7	**273** µg/m^3	04/11/07	NW	
	Gravesham (A2)	6	167 µg/m^3	04/11/07	W	
	Gravesham (Northfleet)	3	143µg/m^3	03/11/07	SW	
	Dover	3	91 µg/m^3	04/11/07	W	
	Luton	2	76 µg/m^3		NW	
	L. Stoke	2	83 µg/m^3		NW	
	M. Detling	1	71 µg/m^3	03/11/07		
	M. Fairmeadow	5	120 µg/m^3	04/11/07	W	
	Ospringe	2	68 µg/m^3		W	
	Sheerness	6	133 µg/m^3	05/11/07	W	
2008	Dartford 1	7	97 µg/m^3	05/11/08	SW	1st-6th Low pressure 7th-10th Snow showers/gales
	Dartford 2	4	180 µg/m^3	03/11/08	NE	
	Dartford 3	5	55 µg/m^3	05/11/08	SW	
	Gravesham (A2)	2	140 µg/m^3	05/11/08	SW	
	Gravesham (Northfleet)	3	132 µg/m^3	05/11/08	SW	
	Dover	1	52 µg/m^3	05/11/08	NE	
	Luton	3	98 µg/m^3	08/11/08	S	
	M. Detling	1	**340** µg/m^3	09/11/08	SW	
	Thanet	4	101 µg/m^3	08/11/08	S	

The data show that the PM_{10} levels are generally highest on the Saturday before Bonfire Night. The PM_{10} concentrations tend always to rise sharply after dusk peaking between 19.30 and 22.00 hours. Although they are short-lived, pollution episodes such as Bonfire Night can cause particulate concentrations to rise to several hundred microns *per* cubic metre. The highest value recorded over the studied period was at Dartford 2 Town Centre at 820 µg/m^3 on the 4th November 2006.

For the years 2005 and 2008, the uncharacteristically low concentrations of PM_{10} registered over the studied periods were almost certainly attributable to meteorological factors (Appendix AB). For example, the values registered during the beginning of November 2008 were highly affected by snow showers (Appendix AB). In November 2005, the weather was extremely unsettled with moderate to strong westerly winds bringing Atlantic air masses and providing effective dispersion at all areas of the UK (Appendixes AB). Heavy rain showers may also have helped to remove particulate components from the air as well as discouraging firework displays and Bonfire Night celebrations.

4.5.2 August 2003

According to Kent County Council (2003, 2005 and 2007) summer photochemical episodes are relatively common in Kent. Consequently, it was decided to examine in more detail a summer pollution episode.

During the summer of 2003, Britain suffered one of the most severe heat waves and droughts of the last decades (Bower *et al*., 2006; AQEG, 2007). Faversham in Kent, recorded the UK's highest ever temperature of 38.5° C on 10th August (Met Office, 2007) (Figure 91). In the southeast of England, maximum temperatures exceeded 32°C on the three consecutive days between the 4th and 6th August and then on the five consecutive days between the 8th and 12th August.

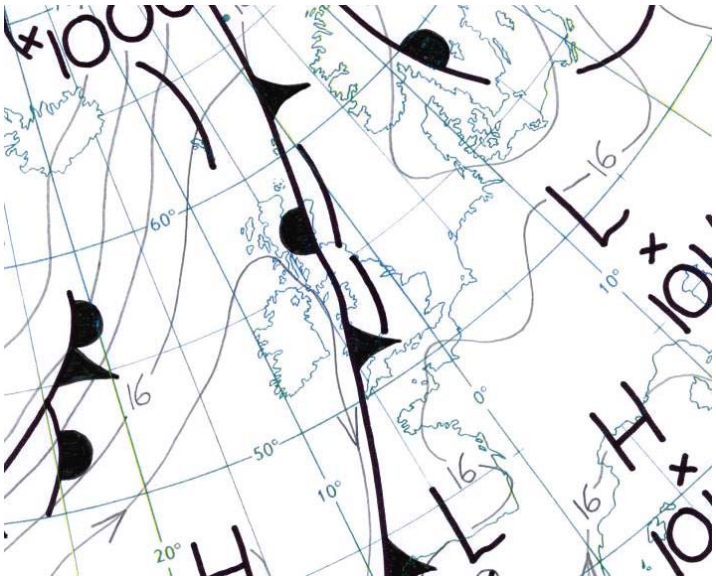


Figure 91: Weather chart for 1200 UTC on 10 August 2003

Source: www.metoffice.gov.uk

The August 2003 heatwave brought a typical example of a summer smog pollution episode. For a potential episode of severe air pollution a few factors are needed. These include several sources of air pollution, sunny weather with high temperatures accelerate chemical reactions in mixtures of emitted air pollutants (a high pressure area that becomes stationary over the region) (Figure 91), low humidity and light surface winds that are unable to disperse the pollutants (Seinfeld, 1986; Ahrens, 1994; Arya, 1999; Jacobson 2002). All these factors were present during the study period; consequently the levels of PM_{10} within the county rose significantly (Figure 92).

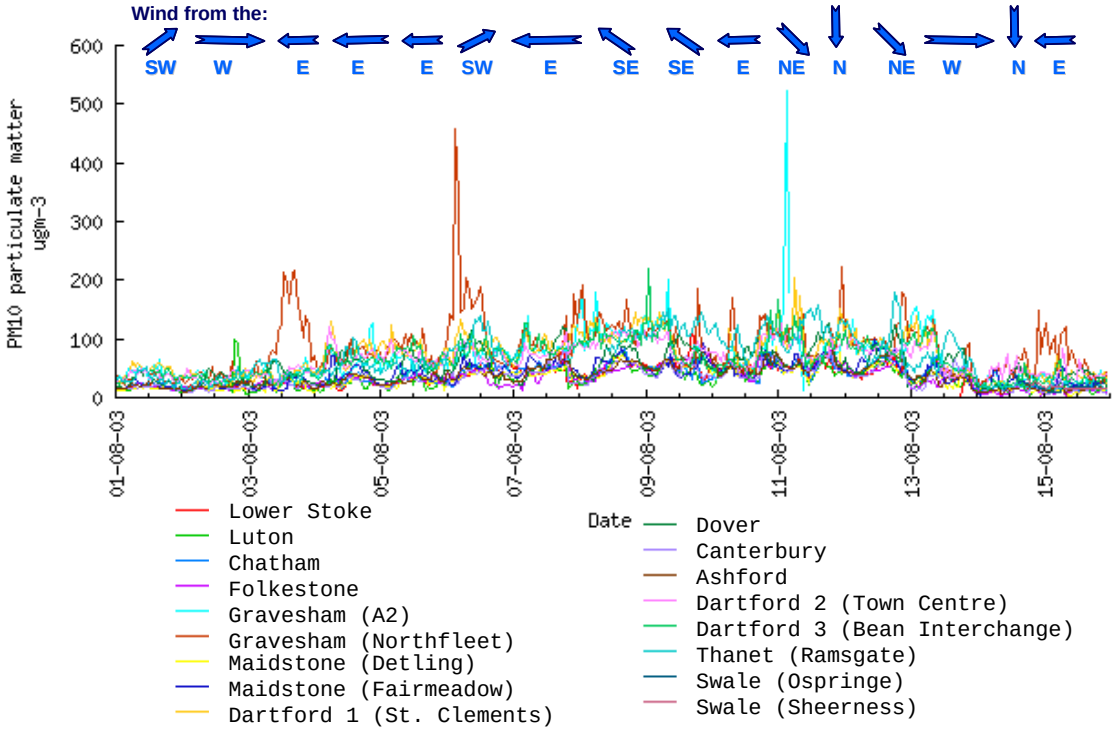


Figure 92: The PM_{10} values for all sites during the heat wave period (01-15 August 2003).

Unsurprisingly, during this period the higher values were registered at Gravesham sites near to busy motorways such as the M2 and the M25, as well as, the city of London.

The August 2003 pollution episode lasted until the 14th August, ending with an influx of clean air masses of oceanic origin arriving from the west (Met Office, 2007). In the graphs shown in Figure 92, it can be observed how the levels of PM_{10} significantly decrease after the 14th August in comparison to the two previous weeks. In Figure 92, it can also be observed how the wind direction changes from east to northeast and then to west on that day, facilitating the dispersion of pollutants.

Finally in Figure 92, it can also be observed how most peaks appear to be associated to northeastely, easterly and southeasterly winds, this result would agree with some of the studies reviewed during the process of this investigation (King and Dorling, 1997; Stedman, 1998; Buchanan, 2002; Rigby *et al.*, 2006), where it was suggested that a significant proportion of airborne PM_{10} responsible for exceeding air quality standards in the UK may originate from industrialised parts of mainland Europe, arriving to the southeast of England as a plume carried by easterly winds.

4.6 PM trap at Dover

4.6.1 General findings (and main sampling issues)

The Burkard Volumetric Spore Trap (BVST) (Sections 2.2.7.1 and 3.5.3) located at the Langdon Cliffs (Dover) was running for over a year (from July 2005 to September 2006). Most of the time, the flow was found to be stable. The only time when it was found to be low or zero was when a problem was found with the battery. This happened on two occasions (the third week of January 2006, and the last week of September on the same year, just before the trap was shut down). After the first time the trap unexpectedly stopped working, in January 2006, the trap was meticulously examined searching for possible causes that could have produced the instrument to stop, but no obvious reasons were found. It could be possible that the trap stopped sampling due to the low temperatures experienced during the coldest months of the year that would make the battery discharge faster than usual. In the second case, a problem was found, most likely as a result of the constant use and being so exposed due to the location of the site, the battery was discharging earlier that it should have been. Once this was observed and after exceeding the target year of sampling it was decided to remove the trap.

4.6.2 Collection efficiency

The collected samples were carefully processed and analysed in the laboratory (Sections 3.6.4, 3.6.5 and 3.6.6). Overall, the slides' content was generally found to be significantly low. The low amount of particles caught could be due to a number of issues such as extreme weather affecting either the trap or the battery, or other factors due to the trap location (close to the sea on the top of the cliffs). Battarbee et al., (1997) claimed that long rain period may

have an impact on the BVST atmospheric particles catches, mainly affecting those particles from biological origin. Allen (1981) also suggested that for best results during the sampling process the BVST, and more specifically the flow passing through the orifice, should suffer no disturbance by the wind speed or direction, therefore any ventilation could be due to the source, this could be a reasonable explanation for the low number of particles caught due to the exposed location of the trap (Figures 36, 38, and 93).

Figure 93: Photograph showing the trap location at Landon Cliffs.

Another potential cause could be sea salt affecting the tape surface. High levels of sea salt particles have been found both in the slides and on the trap exterior, during the process of this investigation due to the proximity of the BVST to the sea shore.

Other explanations to consider would be that a lower catch could be caused by the proximity of the trap to the building (Figure 93). Although the trap was facing towards the sea and away from the building, there is the possibility that the building could have created a shelter effect that stopped the trap from sampling correctly.

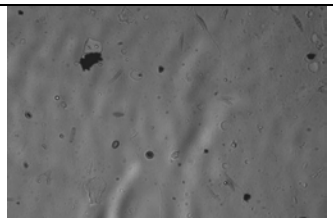
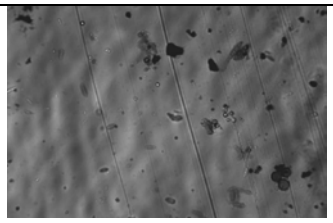
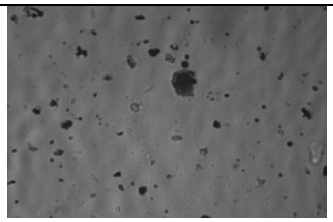
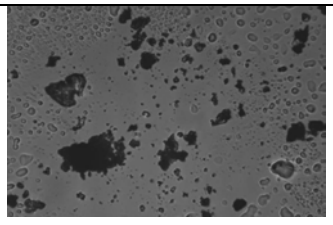
4.6.3 Particle count

Each slide was divided into 12 individual transverse segments. In a first approach, it was decided to quantify the amount of particles by estimating the percentage of the field of view covered. Due to the lower number of particles found, the methodology had to be adapted because it would not show a real representation of the sampled population. Consequently, it was decided to count the number of particles in each traverse examined and average this

number by giving a daily value according to the categories. Observations throughout the day were noted in order to observe patterns affecting the site.

The scores were decided based upon the average number of particles found following the BAF guidance (1994) for pollen counts. A low category was assigned when the number of particles was less than 25 in the portion of the traverse examined, between 25 and 50 particles was considered medium and about 50 particles counted was high. Any material found above 75 was considered as very high. A visual example of these categorisations can be seen in Table 25.

Table 25: Shows the images used to categorise the amount of particles found and the frequency value found for each category. A total of 400 days were sampled between July 2005 and September 2006.

CATEGORY	PHOTOS	FREQUENCY
LOW (25 or less)		**255**
MEDIUM (26 to 50)		**110**
HIGH (from 51 to 75)		**26**
VERY HIGH (Over 76)		**9**

The total number of sampled days was 400. Out of these, 37 were found to be blank due to the trap malfunctioning. The rest were organised in the four categories (low, medium, high and very high). The daily mean was calculated. The next step was to count the number of

times that every value was repeated. From this point, it was then possible be able to find the frequencies and begin to examine the data statistically. Table 25 illustrates the frequencies results.

The frequencies show that most of the traverse analysed fall into the low category count, 25 particles or less. This is a very disappointing result, because of the inexplicable low number of particles caught. Consequently, it is possible that these results are not showing a true representation of the sampling area. The second most common frequency is medium followed by high and then very high.

The particles were heterogeneous, with a range of size and densities. Predictably, the larger type of particles found were from biological origin (such as pollen or parts of plants), more than 50 %. The second most common type, about 35 % was sea salt particles, which may indicate a higher sea breeze influence than anticipated, followed by the 15 % of particles produced by man made sources.

During the analysis of the slides, it was generally noticed that the highest catches were taking place in the middle part of the day, mainly between 11 a.m. and 5 p.m. In the previous Section 4.4, it was observed how sea breezes played an important role in the dispersion of PM_{10} within the county sites. Therefore, there is a possibility that this increase of PM catch in the middle part of the day could be link to sea breezes coming over the land, particularly considering the location of the trap (only a few hundred metres from the seashore (Figures 36, 38, and 93).

In addition, sea salt levels appeared to be higher during the winter months, especially in the traverse corresponding to the early morning, most probably brought inland by the warmer air coming onto land.

Another observation was the significant increase of biological material from early February to August in comparison with the rest of the year. This could be related to the increase of pollination during the spring months. In previous sections, a yearly trend was observed showing an increase in the levels of PM toward the end of the summer, most probably linked to agricultural activities such as cereal harvesting (Section 4.3.2).

4.6.4 Particle distribution

Moving to the question of particle efficiency related to range of sizes caught and their distribution, the BVST trapping of particles is based on impaction. It has been reported that this method could lead to some limitations on the collection efficiency, only the larger particles with sufficient mass will impact on the tapes at the air speeds generated by this type of sampler (Gregory, 1973; Long, 1998 and Caulton et al., 1992). The PM data collected and analysed during this investigation suggest that the BVST tends to be more efficient sampling smaller size particles (see Section 4.5.2).

During the microscopy study it was also observed that the particles were not distributed evenly across the width of the slide's traverses. On most occasions, the smaller particles were found at the edges while the larger particles were biased towards the centre of the slide's traverse. This probably was due to the speed on which the particles were blown onto the tape. It was then noticed that larger particles were deposited not only in the centre of the slide if not close to the point where the tape was adjacent to the orifice. Previous work by Odle (2004) suggested that the highest concentration of all particles was found closest to the point of the orifice. On one hand, the results from this thesis would agree with those reported by Odle (2004) highlighting the considerable numbers of particles found adjacent to the sampling orifice. On the other hand, Odle (2004) suggested that particles were deposited at low concentration elsewhere on the tape. On the contrary, the results from this study show that the distribution appears to be somehow dependent on sizes. The larger particles were found close to the centre of the traverses where the sampling orifice was located, while the smaller particles were mostly found on the edges of the slide traverse.

Bearing in mind the previous points, it would be appropriate to comment at this time on a dilemma faced during the methodology process. Studies from Frenz (2000) and Odle (2004) suggested that to facilitate the sampling of the slides a number of longitudinal transects would be more efficient than dividing the slide in 12 bi-hourly transverse traverses (Section 35.6) (Figure 41). This suggestion was carefully considered and then rejected on the basis that by applying a longitudinal transect method a misleading result would probably be acquired because the most abundant number of particles appears to be located on the edges of the traverses.

Furthermore, if for the purpose of this study longitudinal transects were going to be applied, the results would disregard a vast amount of particles located on the edges of the traverses.

4.6.5 Sampling issues theory

The efficiency of the PM collection seems to be affected by a large number of variables. Most of them have already been considered in previous paragraphs, however, it has been realised that there are a few other factors worth considering. .

The impaction of the particles on the waxed Melinex tape placed on the drum may be influenced by a number of factors such as, the width of the sampling orifice, the shape of the drum, the speed carried by the particle when entering the trap, or even the amount of wax applied on the surface of the tape. The shape of the drum was found to be a very relevant point because it seems that the edges of the drum could affect the deposition of particles after entering the orifice. It appears that lighter particles could bend with the airflow over the sampling drum and place themselves on the edges or the outer part of the drum (Figure 94). Consequently, this could indicate that a large number of lighter particles will never be sampled.

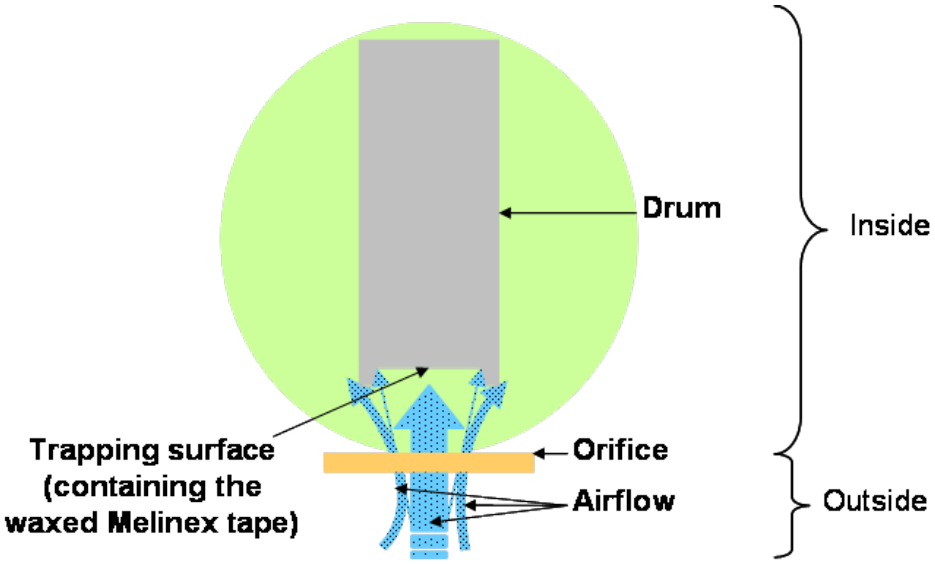


Figure 94: Transversal view of the head of the trap showing the drum and the air flow impacting.

This theory would help explain why the larger particles were found in the middle of the tape, once they entered the trap through the orifice they had too much momentum due to the speed they were carrying, therefore they maintained their trajectory and would drop/get stuck in

the middle. This would also provide an explanation as to why a large amount of mainly very small particles were found on the traverse's edges.

4.6.6 Particle deposition records

In line with the methodology reported by Caulton *et al.* (1992), Sterling *et al.* (1999) and the BAF (1994) where the standard counting convection (i.e. a 12 bi-hourly transverse traverse) was recommend, it was expected to be able to identify the approximate time at which a particular group of particulates were caught.

In contrast, due to the irregular distribution found in the traverses when analysing the samples, it would be difficult to predict with any degree of certainty a specific time when the particle was actually deposited. With this in mind, the only two clear outcomes revealed about the time of deposition are that the release of particles seems significantly higher during the day compared to the level of recorded particles during the night. The results also imply that the levels of particles collected are significantly higher during early morning (from 05.30 to 08.00) and late afternoon (15.00 to 17.00). These results are invariable throughout the sampled year.

4.6.7 Optical microscopy outcome

Optical light microscopes have been widely used in the study of airborne particles (Caulton *et al.*, 1992; BAF, 1994; Long, 1998, 2000: Odle, 2004). The optical analysis was carried out at x400 magnification; this is the magnification traditionally used for aerobiological studies.

The optical analysis of the particles through the microscope was a complex task. The low amount of particles collected, together with their uneven distribution and the large quantity of biological material found, made the evaluation very tricky.
In addition, the unevenness of the background illumination meant it was difficult to use the digital camera attached to the microscope, due to changes on the surface when applying different filters or light.

4.6.8 Particle identification results

As previously described, the identification of particles was intricate work. The software used (Scion Image for Windows) applied a background correction to smooth the view (Section 3.6.7). However, this "correction" was not consistent between different frames, so it was complicated to obtain reliable objective data. The background that the software provided could also produce erroneous adjustment that could easily confuse image analysis process, such as confusing particles with organic material. The air bubbles and deformation on the glue surface highlighted by the software could lead to mistakes. An example of the complexity faced when trying to identify the different types of particles has been illustrated in Figure 95. The image shows mainly biological material (either some sort of seed or pollens) the black particles (probably from combustion processes) have been highlighted by red circles.

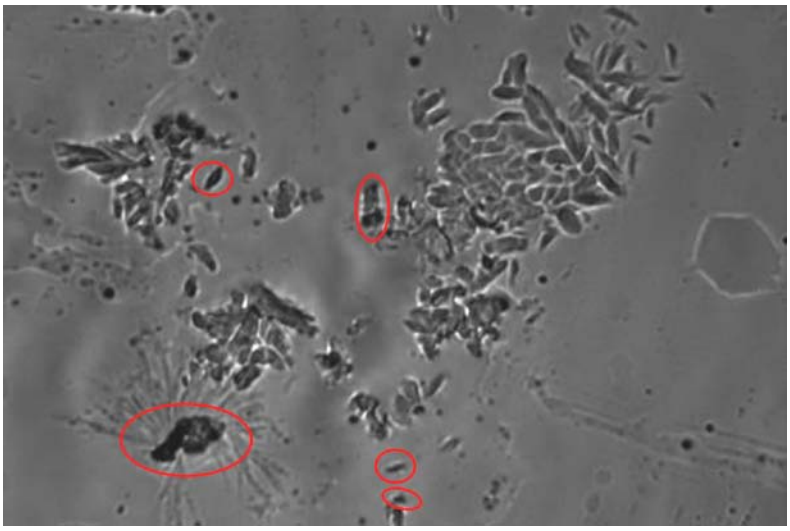


Figure 95: Illustrates an example of the difficulty found during the process of the particle identification in the optical microscope. This figure shows an example of anthropogenic particles disguised between particles of a biological origin.

The visual identification of particles through the microscope was mainly based on colour, shape and size, following guidance from previous studies by McCrone *et al*. (1967) and the BAF (1994). The particles were heterogeneous, with a range of size and densities. Predictably, the larger type of particles found were from biological origin (such as pollen or parts of plants). The second most common type was sea salt particles, followed by particles produced by manmade sources. Two examples of traverses showing the three main types of particles found are shown below (Figure 96).

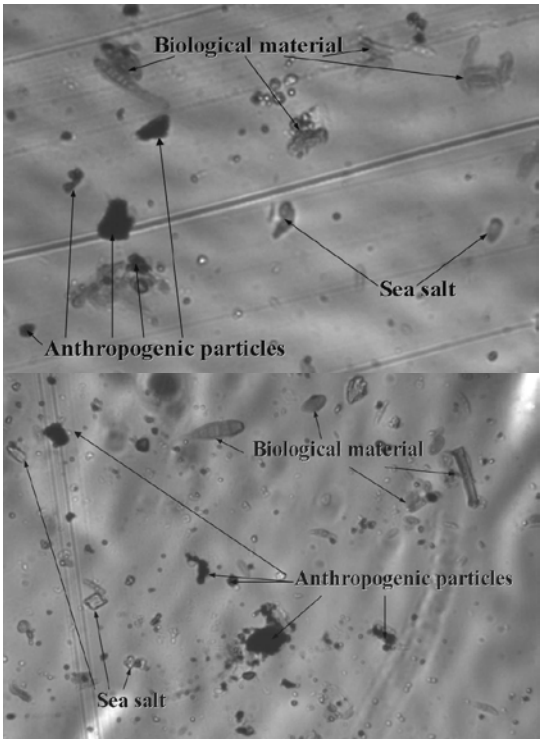


Figure 96: Illustrates two examples of images showing the three main types of particles found at the sampling site.

The biological material found has different shapes and appearances. It seemed to be mainly plant parts, pollen or fungi. The sea salt particles appear flat, smooth and transparent, often very difficult to recognise due to the density of the glue or easily confused with biological material.

The anthropogenic particles found were mainly solid, dark, either very small with sharp edges (Figure 97b) or caught in a group or agglomerates (Figure 97a). An example of the main two types of anthropogenic particles found has been illustrated in Figure 97.

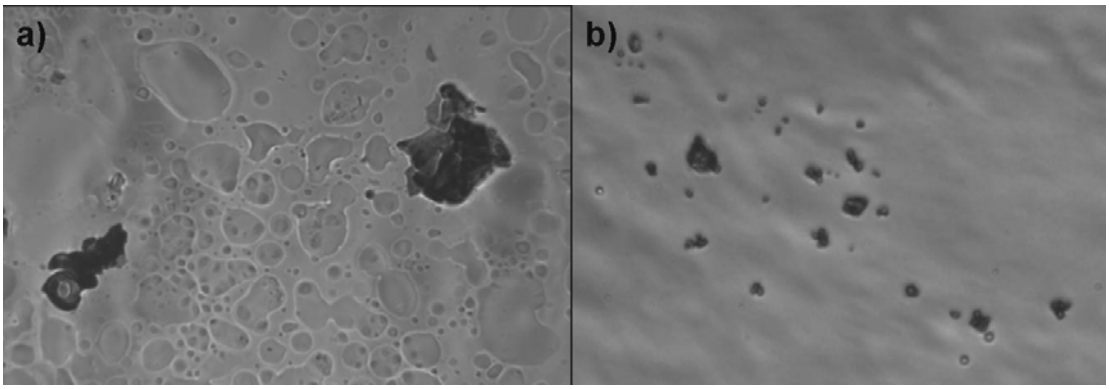


Figure 97: Illustrates two examples of the two main types of black particles found at the sampling site. Figure 97a shows an example of a larger particle

During the literature review, it was described how some particles, after being emitted, mix rapidly with the surrounding atmosphere, being able to exist for several days depending on the removal processes. During their lifetime, some of them, while being dispersed and before they settle, can collide in the air. They then tend to adhere to each other because of attractive surface forces, thereby forming progressively larger and larger particles by processes such as coagulation or agglomeration (Stern *et al.*, 1973; Seinfeld, 1986; McMurry *et al.*, 2004). The larger a particle becomes, the greater its weight and the greater its likelihood of falling to the ground rather than remaining airborne (Seinfeld, 1986). With this in mind, it is presumed that some of the material sampled by the BVST is either being emitted on the other side of the channel and being affected by these processes and transport by the local winds such as sea breeze, or emitted within the middle of the channel by the ferries and again transported inland (these assumptions are examined in more detail in Section 4.5.9).

It would be very improbable that these particles are coming from a local source or affected by the city of Dover urban background. The location of the trap with respect to the building offers a physical barrier between the trap and the town of Dover. Nevertheless, these are just conjectures based on some of the results obtained; they are examined in more detail in Section 4.5.9.

4.6.9 Trends of pollution at Dover

4.6.9.1. Trans-boundary analysis of PM

According to the NEC (National Emissions Centre), Dover shows some of the highest levels of PM_{10} in the UK (Figure 27). This result could be related to a number of factors such as local pollution, emissions from the large number of ferries crossing the English Channel or perhaps other trans-boundary events, bringing pollution from the near continent.

The BVST data were analysed with the purpose to investigate if this result was also observed within the studied data. The wind direction at Dover was analysed, noting when the wind blowing in the area was coming from the east or southeast (the two directions most likely to bring material from the near continent) and making a record of the wind persistence.

In total, there were found to be 91 days were the wind was mainly blowing from the east or the southeast (most probably as a consequence of sea breeze rather than a wind persistence episode). The slides from those dates were analysed. The results obtained were then compared to the other slides in order to see if the catches were more or less abundant than when the wind was blowing from the near continent direction or if there is any other relationship between the two sets of slides. The results are shown below in Table 26.

Table 26: Levels of PM sampled when the wind was blowing from the east (E) and southeast (SE) in comparison to the totals

Amount of PM sampled	Days when the wind was mainly E & SE	Totals number of days sampled
LOW	54	255
MEDIUM	30	110
HIGH	2	26
VERY HIGH	5	9

Through the examination of the BVST data, it was noted that a larger number of sea salt particles were collected. This result could also help corroborate the idea that some of the PM_{10} material found has been carried from the near continent. Research by Rigby *et al.* (2006) confirms that these periods of persistent winds might facilitate the dispersion of particles from the near continent. Nevertheless as previously explained in Section 4.6.2, the location of the trap with respect to the building offers a physical barrier between the trap and the town of Dover so therefore it would be very improbable that these particles are coming from a local source or affected by the city of Dover urban background. Therefore, it could be assumed that these particles are blown in by sea breezes.

In addition, the number of ferries crossing the channel was also noted. From Dover, there are ferries to Calais, Dunkerque, Ostenal and Boulogne. On average, there are 72 ferries a day (13 of them are freight only) crossing the channel. Consequently, it could be argued that some of the PM_{10} levels sampled may originate within the ferries. Unfortunately, to be able to confirm this supposition a chemical analysis on the specific composition of the particles to help clarify where they originated would be needed.

4.6.9.2 Comparison between high levels of PM

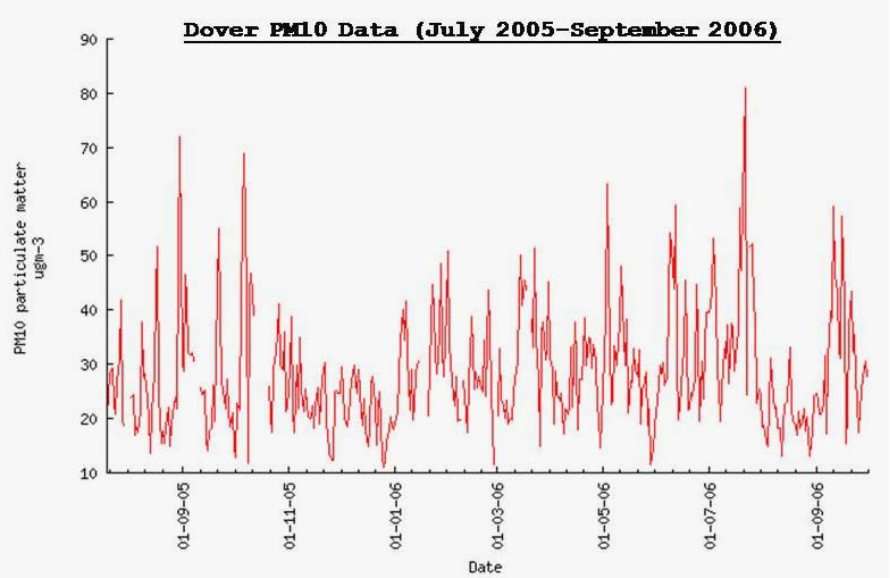


Figure 98: Graph showing an example the PM_{10} data catch for Dover.

During the time that the trap was running on the White Cliffs (400 days) (Table 26), the closest sampling station of the ERG network located in Dover's town centre registered 207 occurrences where the data exceeded the recommended 50 $\mu g/m^3$, sometimes reaching over 100 $\mu g/m^3$ (Appendix N). Almost all of the high episodes occurred when the wind was blowing either from the east or from the southeast which could be linked to a trans-boundary episode carrying concentrations from the near continent (or possibly by the ferries crossing the channel). It was also noticed that most of these high episodes were taking place in the middle of the day; this would mean that the particles may be being transported by sea breeze coming inland. For sites near the coast, sea and land breezes can significantly vary synoptic weather conditions (Oke, 1987, Simpson 1997, Barry and Chorley, 1998). These results corroborate those previously found during the analysis of PM_{10} at coastal sites (Sections 4.4.1 and 4.4.2).

The data collected by the ERG using the TEOM sampler (Sections 3.3 and 4.3) was compared to samples collected by the BVST (Section 4.6.6). During the comparison of both sets of data the only similarity found was the increase of particles sampled during the afternoon, the TEOM sampler recorded the highest peak during the middle of the day while the higher peaks in the BVST were found during early morning (from 5.30 to 8.00) and late

afternoon (15.00 to 17.00). Unfortunately, the quantities samples recorded by the BVST levels were too low to carry out a confident comparison of the results obtained with both measuring techniques.

4.6.10 Summary of Section 4.6

The BVST was located at the Langdon Cliffs (Dover) from July 2005 to September 2006. The main difficulty found was the low number of particles caught. No clear explanation was found to rationalise these results.

The total number of sampled days was 400. Out of these, 37 were found to be empty. The rest were organised into four categories (low, medium, high and very high), the scores were decided upon the average number of particles found following the BAF guidance (1994). The low frequency category (25 particles or less) recorded the higher number of entries. This was an unsatisfactory result, as well as possibly not showing a true representation of the sampling area. Overall, the highest catch was during the middle part of the day, mainly between 11.00 and 17.00.

An increase of biological material, from early February to August, in comparison to the rest of the year was also noted. Furthermore, sea salt levels appeared to be higher during the winter months, especially in the transverse corresponding to the early morning which could be linked to sea breezes.

In addition, the particles were not distributed evenly across the width of the slide's traverses. On most occasions the smaller particles were found at the edges while the larger particles were biased towards the centre of the slide's traverse. This was probably due to the speed at which the particles were blown onto the tape (as well as the impaction process). However, further analysis would be required.

The optical analysis was carried out at x400 magnification. This is the magnification traditionally used for aerobiological studies. The visual identification of particles through the microscope was mainly based on colour, shape and size generally following guidance from previous studies. The particles were heterogeneous, with a range of size and densities. Predictably, the larger type of particles found were from biological origin (such as pollen or parts of plants), more than 50 %. The second most common type, about 35 %, was sea salt particles, followed by 15 % of particles produced by man made sources.

Chapter 5

Summary, Conclusions and further work

This chapter draws together the work described in the preceding chapters (Section 5.1 and 5.2), and makes suggestions for potentially areas of future research (Section 5.3).

5.1 General summary

This thesis evolved as an output from research initially undertaken as a component of a large European multidisciplinary project studying the *"Aerosol Transport in the Trans-Manche Atmosphere (ATTMA)"* funded by the InterReg III program (InterReg IIIc, 2004; Ramon *et al.,* 2005; Santer *et al.,* 2007; Vidot *et al.,* 2007; Plainiotis *et al.,* 2005, 2010). ATTMA combined remote sensing measurements, Lagrangian modelling and local observations. The present investigation has aimed to provide an overview of the *in situ* PM_{10} and local wind data, sampled every 15 minutes at 10 m, collected from 17 pollution monitoring sites distributed around Kent during a period of nine years (2000-2008), to develop an investigation of the influence of topography on airflow, wind patterns, local weather as well as local sources, trans-boundary and regional episodes of pollution in order to determine their role in the distribution and dispersal of particulate matter within the area. Consequently, this research has focussed on five main themes: the analysis of the local wind data, followed by the analysis of PM_{10} capture patterns and the association of both of these with daily synoptic-scale wind patterns during the same period. The influence of weather patterns on PM_{10} catches was then considered in order to examine possible links between them with particular focus on two seasonal case studies. Finally, the outcomes of the use of a portable monitoring (Burkard) trap to sample trans-boundary PM dispersion were discussed.

The wind direction patterns recorded confirmed those previously presented by several studies (Parker, 1989; Pepper *et al*., 1996; Barry and Chorley, 1998; Arya, 1999) stating that the whole year distribution is dominated by southwesterly winds, followed by winds from the west and the northwest. Southwesterly winds were also the most predominant wind direction found during the analysis of the synoptic data. However, it was noted that the scale of the data was too large to highlight any local wind influences, such as sea breezes. The

extracted synoptic data were used for the assessment of synoptic events which could be affecting the broad-scale the dispersion of PM_{10}. Analysis of the local wind data strongly suggested the presence of sea breezes, especially at the coastal sites. Unfortunately, however, whilst the evidence for sea breeze presence was strong (correct direction of airflow off the sea, persistence of winds from that direction, time of onset and seasonality) there were insufficient data (especially temperature measurements) to show conclusively that sea breezes were present. Because some of the patterns of air flow matched what would be expected by the presence of sea breezes, it was inferred that these structures were present and could, therefore, be moving PM_{10}. On this basis, sea breeze presence was strongly indicated at four sites: two coastal sites (Lower Stoke and Dover) and two inland sites (Gravesham and Sevenoaks) especially between March and August. Furthermore, the lowest occurrences were from November to February, corresponding to the coldest month of the years during which temperature contrasts between land and sea are unlikely to be sufficient to generate a sea breeze flow.

Data from two sampling techniques were considered for the PM_{10} analysis. The data measured using a TEOM (Tapered Element Oscillating Microbalance) analyser from 17 sites in Kent was obtained from ERG site (http://www.kentair.org.uk/continuousdata). The second type of data used were collected by a Burkard Volumetric Spore Trap.

The Burkard Volumetric Spore Trap (BVST) is a cost-effective portable sampling technique that produces continuous high resolution records suitable for a number of subsequent studies (including PM research) (Battarbee *et al*., 1997; Long, 1998; Long and Rose, 1999; Mackay *et al.*, 1999; Odle, 2002, 2004). Unfortunately, the amount of particles collected throughout the sampling period using the BVST was very low and unevenly distributed, which made detailed analysis of the catches difficult and unreliable. Generally, the larger type of particles found were of biological origin (such as pollen or parts of plants) and these usually comprised more than 50 % of the daily BVST catch, which corroborates the results from Battarbee *et al*., (1997). The second most common type, about 35 %, was sea salt particles, followed by 15 % of particles produced by man-made sources. Only larger particles with sufficient mass will impact on the tapes at the air speeds generated by this type of sampler (Gregory, 1973; Caulton *et al*., 1992; Long, 1998; Battarbee *et al.*, 1997). During microscopy study it was also observed that the particles were not distributed evenly across

the width of the slide's traverses. On most occasions, the smaller particles were found at the edges while the larger particles were biased towards the centre of the slide matching results from similar investigations elsewhere (Odle, 2004): this was probably linked to the greater momentum carried by smaller particles when entering the trap.

The major mechanisms contributing to airborne particulate matter in Kent (as elsewhere) are highly variable, including natural as well as man-made pollution sources, chemical reactions in the atmosphere, long-range transport effects and weather conditions. Consequently, the PM_{10} analysis has focused on the PM_{10} patterns, considering their main causes.
Sources and factors affecting PM_{10} levels at urban, roadside and rural background locations in Kent were identified, taking into account the seasonal and inter-site variability of air pollution. The results obtained from the analysis of the PM_{10} concentrations indicate that the location of the sampling site and specifically the different types of environmental backgrounds surrounding the monitoring site are significant in explaining the variation on the levels of PM_{10}. The evidence suggests that those sites located by the roadside registered the higher number of particle counts, followed by those sites located within an urban background. The lowest amounts of particles were found at the rural sites. The wind data analysis regarding particle concentrations (higher levels registered in weekdays rather than weekends, and during the day in comparison to night time measurements) clearly suggest that it is human activity rather than action of the wind which is primarily responsible for the presence of particles at the sampling sites.

The investigation into differences between concentrations from a roadside sampler (for example, Maidstone Fairmeadow) and those in an urban or rural area, shows a clear relationship between coarse particles (between 1 μm and 10 μm in diameter) and traffic levels, but data to investigate this further were not available.

Seasonal patterns were observed during the analysis of the PM_{10} distribution. The autumn was the season with the lowest amount of PM_{10} recorded, with the exception of the week around Bonfire Night, whereas the spring always had the higher number of entries. February and March appeared to be the most polluted period of the year. With the exception of the hottest years during the study period (2003 and 2006) the PM_{10} levels tended to decrease

during the summer months, (mainly July and August). This could be a consequence of the decrease in the number of vehicles on the road during this time of year. Similar results were recorded by Muir *et al.* (2006) and Charron *et al.* (2007) in London, which suggested that these seasonal events could be affected by synoptic or trans-boundary pollution plume brought to the area by southeasterly winds. In order to corroborate these suggestions, future work would need to focus on calculating three dimensional trajectories to estimate the pathways followed by air masses arriving in Kent. Elevated PM_{10} levels in 2003 and 2006 could have been due to the extreme pollution episodes generated in those years by prolonged high pressure over the southeast of Britain in the summer months enhancing PM_{10} levels (both primary and secondary sources).

Regional episodes of pollution affecting the whole of Kent were reasonably common: some of the highest peaks in PM_{10} registered were linked to these events. These were more clearly related to the synoptic situation rather than any local wind variations and appear to indicate regional or trans-boundary pollution transport. Similar results were also reported in London (Muir *et al.* 2006; Charron *et al.*, 2007). During the analysis of the pollution trajectories, it was also observed that the data between sites may be associated, which could indicate that regular regional and trans-boundary influences could be affecting the study area and the PM_{10} distribution.

Background PM_{10} levels in the five sites closest to London (three sites in Dartford and two sites in Gravesham) exceeded the current EU and UK target daily values (50 $\mu g/m^3$) on a regular basis. All five sites are located by a roadside. Therefore, the volume of traffic on the roads would be the main aspect affecting the exceedence levels. Generally the results recorded at these five sites show a decrease in the concentrations levels over the last few years, probably linked to mitigation measures (such as fitting of particle filters to diesel vehicles and optimized street cleaning (Bruckmann *et al*., 2007)) applied by the local authorities. Although the measured PM_{10} levels may be of concern from a public health point of view, because the Directive Limit values are met they are unlikely to be of concern to DEFRA (and hence local authorities).

5.2 Conclusions

This thesis provides a detailed account of the behaviour of particulate matter dispersion in Kent through an analysis of local wind patterns and PM_{10} concentrations recorded at 17 different sites over a period of nine years (2000-2008). Results from the wind direction analysis showed south-westerly winds to be the most predominant wind direction in the study area. However apart from this dominance the wind direction at all the sites show an unequal distribution. These differences in the wind direction frequencies are likely to affect the local levels of particulate matter and their distribution within the study region. Detailed analysis of these local wind patterns suggested that sea breezes were present at four studied sites (two coastal and two inland) at various times. Unfortunately, the results could not be verified due to the lack of temperature data although the wind patterns suggested sea breeze behaviour with regards to wind onset and also seasonality. Also no other local wind system could be identified with a similar pattern of direction behaviour. These local winds could also influence the dispersion of PM_{10} in the studied area, prevailing winds arriving from the seashore bring sea salt particles and other material inland mainly during warmer periods. The samples obtained during the local PM analysis at Dover were relatively high in sea salt, the quantities sampled also increased during warmer periods which would corroborate these suggestions.

There are many types of airborne particle monitors available and all have advantages and disadvantages. For the purpose of this study, data from two sampling techniques were considered for the PM_{10} analysis. The data measured using a TEOM (Tapered Element Oscillating Microbalance) analyser from 17 sites and the second type of PM data used were also collected by a Burkard Volumetric Spore Trap (BVST) located in the Langdon Cliffs in Dover. The BVST, chosen for this study, is a portable trap that can be battery powered, giving a number of options to experimental design. Unfortunately, the amount of particles collected throughout the sampling period using the BVST was very low (300 or less for a 24 hour interval) and unevenly distributed (the smaller particles were found at the edges of the sampling strip while the larger particles were biased towards the centre). Generally, the larger type of particles found were from biological origin (such as pollen or parts of plants), more than 50 % of the total sample collected. The second most common type, about 35 % was sea salt particles, followed by the 15 % of particles produced by man-made sources.

The high correlation values of PM_{10} counts between sites (including those located furthest apart) as well as the outcomes of the analysis of the pollution trajectories, when it was observed that the data between sites are associated, also indicate the influence of a dispersal process affecting the whole study. February and March were the most polluted months, both in quantity and duration of the PM_{10} synoptic events recorded at all locations over the studied years. These results support previous studies carried out in London where the highest concentrations were also found during February and March, as well as the first week of November coinciding with Bonfire Night (Muir *et al.*, 2006; Charron *et al.*, 2007).

While there is strong evidence, therefore, to suggest that synoptic-scale influences are important in the dispersion of PM_{10} throughout the study area, there are insufficient data to say with certainty whether or not these events may also be considered fully trans-boundary. The data from BVST at Dover suggest that, even on days of persistent easterly and southeasterly winds from the continent, any contribution to the particulate matter caught by such trans-boundary dispersal is minimal, although there are some concerns about the reliability of the trap catches. Further investigation of this was outside the remit of the current research and clearly requires further investigation.

Despite the synoptic character of most of the episodes, the European 24 hours limit value (50 $\mu g/m^3$) was frequently exceeded at roadsides in comparison to urban and rural background sites. Overall, the highest PM_{10} concentrations were found on the five sampling roadside sites closer to the city of London (two in Gravesham and three in Dartford). These results clearly indicated that PM_{10} concentrations are affected by more than one factor, although the volume of traffic on the roads would be the main aspect affecting the collection levels at these five sites as no other local sources were present. The values recorded indicate that the pollution levels at these sites are exceeding the daily recommended amount of 50 $\mu g/m^3$ several times a week. These results would indicate that the location of the sampling site and specifically the different types of environmental backgrounds surrounding the monitoring sites are significant in explaining the variation on the levels of PM_{10}. Unfortunately it was outside the remit of the research to gather data on traffic volume and no such reliable data was available and therefore attributing such PM_{10} variation to traffic may be unrealizable but is probably not unrealistic.

Currently most of the sampling sites in the ERG network are located in the northern part of the County. In order to provide greater resolution of PM_{10} data, monitoring sites should also be added to the central and southern part of the County as well as introducing them not only in busy kerbside and roadsides to assist to monitor PM_{10} exceedences caused by local traffic, but also in rural sites to allow sampling synoptic background levels.

The five roadsides near London (two in Gravesham and three in Dartford) showed a decrease in the concentrations levels over the last nine years (from between 53-43 $\mu g/m^3$ annual average (in the years 2000 to 2003) reducing to 31-36 $\mu g/m^3$ as an annual average (in 2008)), possibly linked to mitigation measures applied by National and Local Authorities. However, these levels are close to European Directive limit values. The regional background is in occasions so large that a small contribution of local emissions would be enough to exceed the limit value. If the 2010 European targets, which are stricter than the current European Directive limit values, (stating that PM_{10} concentration should not exceed 50 $\mu g/m^3$ on more than seven occasions *per* year, and the annual mean should be less than 20 $\mu g/m^3$ (European Commission, 2005)) are to be achieved more severe abatement measures would need to be introduced, including an international reduction of emissions responsible for the synoptic levels of particulate matter from secondary origin (SO_2, NO_x, VOCs).

5.3 Further work

There is a strong need to develop some of the lines of research suggested by the work described in these thesis, but which could not be attempted as part of the work programme as it was defined.

- The recently-proposed EU Directive on Air Quality and Clean Air for Europe puts emphasis on long-range sources of particulate pollution by encouraging member states to co-operate in the abatement of PM_{10} exceedences that may be attributed to significant trans-boundary transport (European Commission, 2005). Therefore, air mass back trajectory analysis may be considered as a useful complementary tool for urban air quality management in the future. Furthermore, cluster analysis of larger numbers of atmospheric trajectories could provide a more detailed geographical allocation of long-range particle sources.

- In order to corroborate if seasonal events are linked to synoptic or trans-boundary pollution episode future work would need to focus on calculating three dimensional trajectories to estimate the pathways followed by air masses arriving to Kent.

- In order to verify that traffic is responsible for similar concentrations arising from exhaust emissions or re-suspension due to vehicle-induced turbulence a further study would be required. Several studies (Smith *et al.* 2001; Harrison *et al.,* 1997; Harrison and Deacon, 1998; AQEG, 2005; Muir *et al.* 2006; Vardoulakis and Kassomenos, 2008) have demonstrated that it should be possible to identify the probable source of PM_{10} during pollution episodes by using the ratios of concentrations of PM_{10} to the concentrations of other pollutants (generally associated with road traffic emissions (for instance NO_x and CO) monitored at the same location.

- It would be very useful to compare all the results obtained in Kent with results in France, and to carry out correlations between the two areas to see how the dispersion of PM_{10} is carried out from one to the other, and if the same episode of pollution is recorded in both areas. The data from the present work suggest that such dispersal will not take place regularly, given the prevailing wind direction which would transport airborne particulate material in to northeast France and the Low Counties. It order to achieve such an investigation it will also be necessary to take into consideration the distance between sampling sites, topographical features and wind speed to investigate if the same occurrence of PM_{10} could be registered in both sites, one after the other, in relation to wind direction.

- It will be very useful for future investigations to locate sensors in central and southern areas of Kent (such as Ashford, Tunbridge Wells or Tonbridge) to fill in some gaps in the existing pollution monitoring network. The new sites should not only be located in busy kerbside and roadsides to assist to monitor PM_{10} exceedences caused by local traffic but also in rural sites to allow sampling synoptic background levels.

- Finally, when considering issues regarding the reliability of the BVST sampling technique, for future samples it is suggested using longer cables, keeping the battery indoors so it is not affected by extreme changes in temperature and maximises trap performance.

Chapter 6

References

Ahrens, D.C. (1994). Meteorology today: an introduction to weather, climate and environment. 5th Edition. West Publishing Company. U.S.A.

Allen, T. (1981). Particle Size Measurement. 3rd Edition. Chapman and Hall. London.

Air Quality Expert Group (AQEG). (2005). Particulate Matter in the United Kingdom. HMSO Publications Centre. Great Britain.

Air Quality Expert Group (AQEG). (2007). Particulate Matter in the United Kingdom. HMSO Publications Centre. Great Britain.

Airborne Particles Expert Group (APEG). (1999). Source apportionment of airborne particulate matter in the United Kingdom (Interim Report). HMSO Publications Centre. Great Britain.

Apsimon, H. M., Gonzalez del Campo, M. T. and Adams, H. S. (2001). Modelling long-range transport of primary particulate material over Europe. *Atmospheric Environment*. **35**, 343-352.

Arya, S. P. (1999). Air pollution Meteorology and Dispersion. Oxford University Press. U.S.A.

ASEAN (Association of Southeast Asian Nations). (2006). Asean at the Centre: Annual report 2005-2006. Indonesia. www.aseansec.org. Accessed, January 2007.

Altman, D.G., Machin, D., Bryant, T. N. and Gardner, M. J. (2000). Statistics with Confidence. BMJ Books. London.

APIS, 2006. Air Pollution Information System. www.apis.ac.uk. Accessed, July 2006.

Bollati, V., Marinelli, B., Apostoli, P., Bonzini, M., Nordio, F., Hoxha, M., Pegoraro, V., Motta, V., Tarantini, L., Cantone, L., Schwartz, J., Bertazzi, P.A., Baccarelli, A. (2010). Exposure to metal-rich particulate matter modifies the expression of candidate microRNAs in peripheral blood leukocytes. *Environmental Health Perspectives.* **118**, 763-768.

Barry, R.G. and Chorley, R. J. (1998). Atmosphere, weather and climate. Routledge. Great Britain.

Barbro, J. and Deliang, C. (2003). The influence of wind and topography on precipitation distribution in Sweden: Statistical analysis and modelling. *International Journal of Climatology*.**23**, 1523-1535.

Battarbee, J. L., Rose, N. L. and Long, X.Z. (1997). A continuous high resolution record of urban airborne particulates suitable for retrospective microscopical analysis. *Atmospheric Environment*, **31** (2) 171-181.

Bridgman, H. (1990). Global Air Pollution: problems for the 1990s. Belhaven. Great Britain.

Bower, J., Lampert, J., Broughton, G., Stedman, J., Pye, S., Targa, J., Kent, A., Grice, S. (2006). Air Pollution in the UK: 2005. Report by National Environmental Technology Centre (NETCEN) for DEFRA. England.

Bruckmann, P., Gladtke, D., Kappert, W., Vogt, K., Wurzler, S., Brandt, A. (2007). The effectiveness of local abatement measures on air quality -five cases from the Rhine Ruhr region, Germany. *Gefahrstoffe e Reinhaltung der Luft.* **67**. 481-489.

Buchanan, C. M., Beverland, I. J., Heal, M. R. (2002). The influence of weather-type and long-range transport on airborne particle concentrations in Edinburgh, UK. *Atmospheric Environment.* **36**, 5343-5354.

Burkard Volumetric Spore Trap equipment, 7 day recording volumetric spore trap main web site. www.burkard.co.uk/7dayst.htm. Accessed in October 2006.

Burt, P. J. A and Pedgley, D. E. (1997). Nocturnal insect migration: effect of local winds. *Advances in Ecology research*. **27**, 61-92.

Burt, P. J. A. (2000). Automatic Characterisation and Source Apportionment of Airborne Particulates. Project Completion Report, Inter-Reg IIa.

Burt, P. J. A. and Sharma, P. (2003). Long-distance spore transport and its role in assessing climate change. Poster presented at 8th International Congress on Plant Pathology. Christchurch, New Zealand.

Caulton, E., Lacey, M., Allitt, U., Crosby, R., Emberlin, J. and Hirst, J. (1992). The Pollen Count Guide. The British Aerobiological Federation. Great Britain.

Castro, I. P. and Apsley, D. D. (1996). Flow and dispersion over topography: a comparison between numerical and laboratory data for two-dimensional flows. *Atmospheric Environment*. **31**, 839-850.

Charron, A., Harrison, R.M., Moorcroft, S., Booker, J. (2004).Quantitative interpretation of divergence between PM10 and PM2.5 mass measurement by TEOM and gravimetric (Partisol) instruments. *Atmospheric Environment.* **38**. 415–423.

Charron, A., Harrison, R.M. (2005). Fine (PM2.5) and coarse (PM2.5–10) particulate matter on a heavily trafficked London highway: sources and processes. *Environmental Science and Technology*. **39**. 7768–7776.

Charron, A., Harrison, R.M., Quincey, P. (2007). What are the sources and conditions responsible for exceedences of the 24 h PM10 limit value (50 mgm_3) at a heavily trafficked London site? *Atmospheric Environment* **41**, 1960–1975.

Cook. I. and Upton, G (1996). Understanding statistics. OUP, Oxford.

Deacon, A. R., Derwentb, R. G., Harrison, R. M., Middleton, D. R., Moorcroft, S. (1997). Analysis and interpretation of measurements of suspended particulate matter at urban background sites in the United Kingdom. *The Science of the Total Environment*.**203**, 17-36.

DeCarlo, P. F., Slowik, J. G., Worsnop, D. R., Davidovits, P. and Jimenez, J. L. (2004). Particle Morphology and Density Characterization by Combined Mobility and Aerodynamic Diameter Measurements. Part 1; Theory. *Aerosol Science and Technology*. **38**, 1185-1205.

Department of Environment, Transport and the Regions (DETR). (1998). Air pollution: what it means for your health. HMSO Publications Centre. Great Britain.

Department of Environment, Transport and the Regions (DETR). (2000). The Air Quality Strategy for England, Scotland, Wales and Northern Ireland. HMSO Publications Centre. Great Britain.

Department of Environment, Transport and the Regions (DETR). (2003). The Air Quality Strategy for England, Scotland, Wales and Northern Ireland. HMSO Publications Centre. Great Britain.

Department of Environment, Transport and the Regions (DETR). (2005). The Air Quality Strategy for England, Scotland, Wales and Northern Ireland. HMSO Publications Centre. Great Britain.

Department of Environment, Transport and the Regions (DETR). (2006). The Air Quality Strategy for England, Scotland, Wales and Northern Ireland. HMSO Publications Centre. Great Britain.

Department of Health. (1998). Quantification of the health effects of air pollution in the United Kingdom. The Stationary Office. Great Britain.

Dockery, D.W., Pope, C. A. III., Xiping, X., Spengler, J. D., Ware, J. H., Fay, M. E., Ferris, B. G., Speizer, F. E. (1993). An association between air pollution and mortality in six US. cities. *New England Journal of Medicine*.**329**, (24) 1753-1759.

Dockery, D. (1996). Health effects of acid aerosols on North American children: respiratory symptoms. *Environmental Health Perspectives.* **104**, (5) 503-511.

Donaldson, K. and MacNee, W. (1998). The mechanism of lung injury caused by PM_{10}. *Issues in Environmental Science and Technology*. **10**, 21-32.

Dorsey, J. R., Nemitz, E., Gallagher, M. W., Fowler, D., Williams, P. I., Bower, K. N., and Beswick, K. M. (2002) Direct measurements and parameterisation of aerosol flux, concentration and emission velocity above a city. *Atmospheric Environment*, **36**, 791-800.

Elsom, D. M. (1992) Atmospheric Pollution; A Global Problem. 2nd Edition. Blackwell. Great Britain.

Expert Panel on Air Quality Standards for the Department of the Environment, Transport and the Regions (EPAQS). (2000). Airborne particles: what is the appropriate measurement on which to base a standard? HMSO Publications Centre. Great Britain.

European Commission (EC). (2005*). Preliminary Draft Proposal for a Regulation of the European Parliament and Council Relating to the Emission of Atmospheric Pollutants from Motor Vehicles. European Commission.* Brussels.

Evtyugina, M.G., Nunes, T, Pio, C., Costa, S. (2006). Photochemical pollution under sea breeze conditions, during summer at the Portuguese West Coast. *Atmospheric Environment*. **40**, 6277-6293.

Franzen, L.G., Hjelmroos, M. Kallberg, P. Rapp, A. Mattson, J.O. and Brorstrom-Lunden, E. (1995). The Saharan dust episode of south and central Europe and northern Scandinavia, *Weather*. **50**:313-318.

Frenz, D.A. (2000). The effect of wind speed on pollen and spore counts collected with the Rotorod Sampler and Burkard spore trap. *Annals of Allergy Asthma and Immunology*, **85** (5) 392-394.

Google Maps Distance Calculator (GMDC) www.daftlogic.com/projects-google-maps-distance-calculator.htm. Accessed several times in 2010.

Goosens, D. (1998). Sedimentation characteristics of natural dust in the wake of symmetrical hills. *Zeitschrift fur Geomorphologie*.**324**, 499–502.

Goosens, D. (1996). Wind tunnel experiments of Aeolian dust deposition along ranges of hills. *Earth Surface Processes and Landforms*. **21**, 205–216.

Green, D., Fuller, G.W., (2006). The implications of tapered element oscillating microbalance (TEOM) software configuration on particulate matter measurements in the UK and Europe. *Atmospheric Environment* **40,** 5608–5616.

Gregory, P.H. (1974). Aerobiology of the Atmosphere. Leonard Hill. Great Britain.

Grivas, G., Chaloulakou, A., Samara, C., Spyrellis, N. (2004). Spatial and temporal variation of PM_{10} mass concentrations within the greater area of Athens, Greece. *Water, Air, and Soil Pollution* **158**, 357–371.

Gustafsson, M.E.R., Franzen, L.G., (2000). Inland transport of marine aerosols in southern Sweden. *Atmospheric Environment.* **34**, 313-325.

Hare, S., Cresswell, L., Twigg, R., Buchdahl, J. (2002). Air Pollution. Report by Atmospheric Climate and Environment Group for DEFRA. England.

Harrison, R. M. (1990). Pollution; Causes, Effects and Control. Royal Society of Chemistry. Great Britain.

Harrison, R. M. and Yin, J. (2000). Particulate matter in the atmosphere which particle properties are important for its effects on health?. *The Science of the Total Environment.* **249**, 85-101.

Harrison, R. M., Yin, J., David, M., Stedman, J., Appleby, R., Booker, J., Moorcroft, S. (2000). Studies of the coarse particle (2.5-10 $\mu g/m^3$) component in UK urban atmospheres. *AtmosphericEnvironment* **35**, 3667-3679.

Harrison, R. M. (2004). Key Pollutants-Airborne Particles. *Science of the Total Environment*. **334-335**, 3-8.

Her Majesty's Government. (2000). The Air Quality Regulations for England SI 2000/928. The Stationary Office. London.

Henderson-Sellers, A. and Robinson, P. J. (1991). Contemporary Climatology. Longman. New York.

Hidy, G. M. (1984). Aerosols; an industrial and environmental science. Academic Press. U.S.A.

Hirst, J. M. (1952). An automatic volumetric spore trap. *Annals of Applied Biology*. **39**, 257-265.

Highways Agency website, www.highways.gov.uk/ Accessed in 2010.

International Panel for Climate Change (IPCC). (2001). Climate Change 2001. Synthesis Report. Switzerland.

InterReg IIIc Programme. (2004). A European Community Initiative Franco-British Programme. www.interreg3.com. Accessed in 2004, 2006 and 2011.

Jacobson, M. Z. (2002). Atmospheric Pollution; History, Science and Regulation. University Press. Cambridge. U.S.A.

Jones, A. M. and Harrison, R. M. (2004). The effects of meteorological factors on atmospheric bioaerosol concentrations review. *Science of the Total Environment*. **326**. 151-180.

Kaimal, J. C. and Finnigan, J. J.(1994). Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford University Press. Oxford.

Kent Air Quality Partnership (KEAQP). (1999). The Kent Air Quality Monitoring Network Annual Report. Kent.

Kent County Council (KCC). (2004). Land cover and Environment Report. Kent County Council Web Site.

Kent County Council (KCC). (2006). Local Transport Plan for Kent 2006-2011. Kent County Council Web Site.

Kent County Council. www.kent.gov.uk. Accessed, May 2006.

Kent County Council Air Quality Web Site. www.kentair.org.uk. Accessed, June 2006.

Kent Wildlife. www.kentwildlife.org.uk. Accessed, July 2006.

King, A.M. and Dorling, S. (1997). PM_{10} Particulate Matter; the significance of ambient levels. *Atmospheric Environment*. **31**, 2379-2381.

Kondo, K., Tsuchiya, M., Sanada, S. (2002). Evaluation of effect of micro-topography on design wind velocity. *Journal of Wind Engineering*. **90**, 1770-1781.

Kukkonen, J., Pohjola, M., Sokhi, R.S., Luhana, L., Kitwiroon, N., Fragkou, L., Rantamaki, M., Berge, E., Ødegaard, V., Havard Slørdal, L., Denby, B., Finardi, S. (2005). Analysis and evaluation of selected local-scale PM_{10} air pollution episodes in four European cities: Helsinki, London, Milan and Oslo. *Atmospheric Environment.* **39**. 2759–2773.

Laird, N. F., Kristovich, A.R., Liang, X., Arritt, R.W Labas, K. (2000). Lake Michigan, Lake Breezes; Climatology, local forcing and synoptic weather. *Journal of Applied Meteorology*.**40**, 409-424.

Lamb, H. H. (1972). British Isles Weather types and a register of daily sequence of circulation patterns. HMSO. *Geophysical Memoir*. **116**, 1861-1971.

Lee, D.O. (1979). Influence of atmospheric stability and the urban heat island on urban–rural wind speed differences. *Atmospheric Environment* **13** (8), 1175–1180.

Legge, A. H. and Krupa, S.V. (1986). Air Pollutants and their effect on the terrestrial ecosystem. John Wiley and Sons Inc. U.S.A.

London Air Web Site www.londonair.org.uk. Accessed July 2006.

Long, X. (1998). Particulate air pollution in central London: Characterisation, temporal patterns and source apportionment. PhD thesis, University College London.

Long, X. and Rose, N. (1999). Chemical Characteristics of Individuals Airborne Particulates in Central London. Report by Jackson Environmental Institute, UCL. London.

Lyons, T. J. and Scott, W. D. (1990). Principles of Air Pollution Meteorology. Belhaven Press. London.

Lyons, W. A. and Olsson, L. E. (1973). Detailed mesometeorological studies of air pollution dispersion in the Chicago lake breeze. *Monthly Weather Review*. **101**, 387-403.

MacKay, A. W., Long, X., Rose, N. L. and Battarbee, R. W. 1999. New approaches to characterizing urban particles in central London. *Journal of Environmental Sciences.* **11** (3) 367-372.

Malcom, A. L., Derwent, R. G., Maryon, R. H. (2000). Modelling the long-range transport of secondary PM_{10} to the UK. *Atmospheric Environment*. **34**, 881-894.

Mason, J. A., Nater, E. A., Zanner, C. W. and Bell, J. C. (1999). A new model of topographic effects on the distribution of loess. *Geomorpholog*y. **28**, 223– 236.

McCrone, W.C. Draftz, R.G. and Delly, J.G. (1967). The Particle Atlas. Ann Arbor Science Publishers. U.S.A.

McDermott, H. J., Henderson, D., Shirley, A. N. (2004). Air Monitoring for toxic exposures Wiley-Interscience. John Wiley and sons publications. Canada.

McIlveen, R. (1995). Fundamentals of Weather and Climate. Chapman & Hall. London.

McMurry, P., Shepherd, M., Vickery, J. (2004). Particulate Matter Science for Policy Makers. Cambridge. A NARSTO Assessment. University Press. U.S.A.

Meetham, A. R., Bottom, D. W., Cayton, S., Henderson-Sellers, A., Chamber, D. (1981). Atmospheric Pollution; Its History, Origins and Prevention. 4th Edition. Pergamon Press. Great Britain.

Merefield, J. R. (2002). Dust to Dust. *New Sicentist*, Inside Science 153. 1-4.

Moran, J. M. and Morgan, M. D. (1991). Meteorology: The Atmosphere and the Science of Weather. Macmillan College Publishing. U.S.A.

Muira, D., Longhurstb, J.W.S., Tubb, A. (2006) Characterisation and quantification of the sources of PM_{10} during air pollution episodes in the UK. *Science of the Total Environment* **358.** 188– 205.

Namdeo, A. and Bell, M. C. (2005). Characteristics and health implications of fine and coarse particulates at roadside, urban background and rural sites in UK. *Environmental International*. **31**. 565-573.

National Atmospheric Emissions Inventory. www.naei.org.uk. Accessed, Nov. 2006.

North American Research Strategy for Tropospheric Ozone (NARSTO). (2003). Particulate Matter Science for policy makers. A NARSTO Assessment. Palo Alto, U.S.A.

Nicolas-Perea, V., Odle, R.J. and Burt, P.J.A. (2005). Topographic winds as an aid to pollution transport from northern France to Kent, southeast England. Proceedings 12th International. Conference on Modeling, Monitoring and Management of Air Pollution, Wessex Institute of Technology: UK.

Nicolson, N. (1987). Kent. Weidenfeld and Nicolson. Great Britain.

Nicholson, K. W., Branson, J. R. and Giess, P. (1991). Field measurements of the below –cloud scavenging of particulate material. *Atmospheric Environment.* **25A**, 771-777.

Odle, R. J., Burt, P. J. A. and Slipper, I. J. (2002). Characterisation of Particulate Matter using Microanalysis. Air Pollution X. Proceedings 10th International Conference on Modelling, Monitoring and Management of Air Pollution. Wessex Institute of Technology. Great Britain.

Odle, R. J. (2004). An investigation into the practical aspects of characterising airborne particulate matter using microanalysis. PhD Thesis, University of Greenwich at Medway.

Offer, Z.Y. and Goosens, D. (1995). Wind tunnel experiments and field measurements of aeolian dust deposition on conical hills. *Geomorphology*. **14**, 43-56.

Oikawa, K. (1977). Trace Analysis of Atmospheric Samples. Halsted Press Book. Tokyo.

Oke, T. R. (1987).Boundary Layer Climates. Routledge. U.S.A.

Parker, H. W. (1977). Air Pollution. Prentice-Hall Inc. U.S.A.

Parker, A. (1989). Industrial Pollution Handbook. McGrawHill Book Company. Great Britain.

Parker, R. P. and Kinnersley S. T. (2004). A computational and wind tunnel study of particle dry deposition in complex topography. *Atmospheric Environment*, **38**, (23), 3867-3878.

Pearce, J. L., Beringer, J., Nicholls, N., Hyndman, R. J., Uotila, P., Tapper, N. J. (2011). Investigating the influence of synoptic-scale meteorology on air quality using self-organizing maps and generalized additive modelling. *Atmospheric Environment.* 45. 128-136.

Pepper, I. L., Gerba, C. P. and Brusseau, M. L. (1996). Pollution Science. Academic Press. Canada.

Plainiotis, S., Pericleous, K.A., Fisher, B. and Shier, L. (2005). Application of Lagrangian particle dispersion models to air quality assessment in the Trans-Manche region of Nord-Pas-de-Calais (France) and Kent (Great Britain). *Proceedings of the 10th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes.* Crete, (Greece).

Plainiotis, S., Pericleous, K.A., Fisher, B. and Shier, L. (2010). Application of Lagrangian particle dispersion models to air quality assessment in the Trans-Manche region of Nord-Pas-de-Calais (France) and Kent (Great Britain). *International Journal of Environment and Pollution*, **40**. 160-174.

Poonam, S. (2004). A study of the dispersal of spores and pollens of agricultural importance in the Medway area as an aid to assessing the impact of changes in climate and agriculture. PhD Thesis, University of Greenwich at Medway.

Pope, C. A. III., Thun, M. J., Namboodiri, M. M., Dockery, D. W., Evans, J. S., Speizer, F. E., Heath, C. W. (1995). Particulate air pollution as a predictor of mortality in a prospective study of US adults. *American Journal of Respiratory and Critical Care Medicine.* **151**, 669-674.

Pope, C. A. III. (2000). Epidemiology of Fine Particulate Air Pollution and Human Health; biologic mechanism and who's at Risk?. *Environmental Health Perspective*. **108**, S4.

Putaud, J. P., Raes, F., Van Dingenen, R., Bruggemannb, E., Facchinic, M.C., Decesaric, S., Fuzzic, S., Gehrigd, R., Uglind, C.H., Laje, P., Lorbeerf, G., Maenhautg, W., Mihalopoulosh, N., Ullerb, K.M., Queroli, X., Rodriguezi, S., Schneiderf, J.U., Spindlerb, G., Brinkj, H., T^rsethk, K., Wiedensohler, A. (2004). A European aerosol phenomenology-Part 2:chemical characteristics of particulate matter at kerbside, urban, rural and background sites in Europe. *Atmospheric Environment* **38**, 2579–2595.

Quality of Urban Air Review Group (QUARG). (1993). Airborne Particulate Matter in the U.K. Quality of Urban Air Review Group for the Department of Environment. England.

Quality of Urban Air Review Group (QUARG). (1996). Airborne Particulate Matter in the U.K. Third Report of the Quality of Urban Air Review Group for the Department of Environment. England.

Querol, X., Alastuey, A., Ruiz, C.R., Artinano, B., Hansson, H.C., Harrison, R.M., Buringh, E., ten Brink, H.M., Lutz, M., Bruckmann, P., Straehl, P., Schneider, J. (2004). Speciation and origin of PM_{10} and $PM_{2.5}$ in selected European cities. *Atmospheric Environment.* **38**. 6547-6555.

Ramon, D., Blanchet, A., Schadkowski, C., Dilligeard, E., Santer, R. and Vidot, J. (2005). Integrated air quality monitoring service using ground networks measurements and EO products. *European Space Agency SP*. **572**. 2091-2096.

Raupach, M. R. and Finingan, J. J. (1997). The influence of topography on meteorological variables and surface-atmosphere interactions. *Hydrology*. **190**, 182-213.

Research Priorities for Airborne Particulate Matter (RPAPM). (2004). IV Continuing research Progress. Committee on Research Priorities for Airborne Particulate Matter. National Academic Press, USA.

Royal Meteorological Society. www.royal-met-soc.org.uk. Accessed, July 2006.

Ryall, D.B., Derwent,R.G., Manning, A.J., Redington, A.L., Corden, J., Millington,W., Simmonds, P.G, O'Doherty, S., Carslaw, N and Fuller, G.W. (2002). The origin of high particulate concentrations over the United Kingdom. *Atmospheric Environment.* **36** (8)1363-1378.

Rigby. M., Timmis, R., Toumi, R. (2006). Similarities of boundary layer ventilation and particulate matter roses. *Atmospheric Environment*. **40**. 5112-5124.

Salvador, P., Artíñano, B., Viana, M., Querol. X., Alastuey, A., González-Fernández, I. and R. Alonso, R. (2011) Spatial and temporal variations in PM10 and PM2.5 across Madrid metropolitan area in 1999–2008. *Urban Environmental* Pollution 2010. **4**. 198-208.

Santer, R., Ramon, D., Vidot, J., Dilligeard, E. (2007). A surface reflectance model for aerosols remote sensing over land. *International journal of Remote Sensing.* **20.** 737-760.

Schwartz, J., Dockery, D. W. and Neas, L. M.(1996). Is Daily Mortality Associated Specifically with Fine Particles? *Journal of the Air and Waste Management Association*. **46**, 927-939.

Scorer, R. S. (2002). Air pollution meteorology. Horwood Publishing. U.S.A.

Seinfeld, J. H. (1986). Atmospheric Chemistry and Physics of Air Pollution. John Wiley and sons. U.S.A.

Seinfeld, J. H. and Pandis S.N. (2006). Atmospheric Chemistry and Physics; From Air Pollution to Climate Change. 2nd Edition. John Wiley and sons. U.S.A.

Smith, S., Stribley, F.T., Milligan, P., Barratt, B., (2001). Factors influencing measurements of PM10 during 1995–1997 in London. *Atmospheric Environment*. **35**. 4651–4662.

Stedman, J. R. (1997). A UK wide episode of elevated particle (PM_{10}) concentration in March 1996. *Atmospheric Environment*. **31**, 2381-2383.

Stern, A. C., Wohlers, H., Boubel, R. and Lowry, W. (1973). Fundamentals of Air Pollution. Academic Press, New York-London.

Strauss, W. and Mainwaring, S. J. (1984). Air Pollution. Edward Arnold. Great Britain.

Stull, R. B. (1988). An Introduction to Boundary Layer Meteorology, Kluwer Academic Publishers, Dordrecht.

Thielen, J. and Gadian, A. (1996). Influence of different wind directions in relation to topography on the outbreak of convection in Northern England. *Annales Geophysicae*. **14**, 1078-1087.

UK Air Quality Archieve. www.airquality.co.uk. Accessed, June 2006.

United Nation Economic Commission for Europe (UNECE). (1979). Convention on Long-range Trans-boundary Air Pollution and its Protocols. United Nations, Geneva, Switzerland.

United Nation Economic Commission for Europe (UNECE). (2004). Clearing the Air: 25 years of the Convection on Long-range Trans-boundary Air Pollution. United Nations, Geneva, Switzerland.

U.S. Environmental protection Agency. www.epa.us. Accessed, May 2006.

Valavanidis, A., Fiotakis, K., Vlachogianni, T., 2008. Airborne particulate matter and human health: toxicological assessment and importance of size and composition of particles for oxidative damage and carcinogenic mechanisms. *Journal of Environmental Science and Health Part C-Environmental Carcinogenesis and Ecotoxicology Reviews* **26**, 339-362.

VanCurent, T. (1999). Spatial factors influencing winter primary particle sampling and interpretation. *Journal of the air and waste management association.* **49**, 3-15.

Van Dingenen, Raes, F., Putaud, J.-P., Baltensperger, U., Br.uggemann, E., Charron, A., Facchini, M.-C., Decesari, S., Fuzzi, S., Gehrig, R., Hansson, H.-C., Harrison, R.M., H. uglin, C., Jones, A.M., Laj, P., Lorbeer, G., Maenhaut, W., Palmgren, F., Querol, X., Rodriguez, S., Schneider, J., Brink, H., Tunved, P., T^rseth, K., Wehner, B., Weingartner, E., Wiedensohler, A., W(ahlin., P.(2004). A European aerosol phenomenology-Part 1:physical characteristics of particulate matter at kerbside, urban, rural and background sites in Europe. *Atmospheric Environment*. **38**, 2561-2577.

Vardoulakis, S., and Kassomenos, P. (2008). Sources and factors affecting PM_{10} levels in two European cities: Implications for local air quality management. *Atmospheric Environment*. **42**, 3949–3963

Varvayanni, M., Catsaros, N., Bartzis, J. G., Konte, K., Horsch, G. M. (1995). Wind flow simulation over greater Athens area with highly resolved topography. *Atmospheric Environment.* **24**, 3593-3604.

Vecchi, R., Marcazzan, G., Valli, G., Ceriani, M., and Antoniazzi, C. (2004).The role of atmospheric dispersion in the seasonal variation of PM_{10} and $PM_{2.5}$ concentration and composition in the urban area of Milan (Italy).*Atmospheric Environment*. **38**, 4437-4446.

Vidot, J., Santer, R., Ramon, D. (2007). Atmospheric particulate matter (PM) estimation from SeaWiFs imagery. *Remote Sensing of Environment*. **111**. 1-10.

Wavemetrics- Technical graphing and data analysis software for scientist and engineers. www.wavemetrics.com. Accessed September 2009.

Wight, G. D. (1994) Fundamentals of air sampling. Lewis Publishers. Great Britain.

Wheeler, D. and Mayes, J. (1997). Regional Climates of the British Isles. Routledge. Great Britain.

Whiteman, C. D. (2000). Mountain Meteorology: Fundamentals and Applications. Oxford University Press. Great Britain.

Wickham, P.G. (1970). The practice of weather forecasting. Her majesty's stationary office. Great Britain.

World Health Organisation and the United Nations Environmental Programme. (1992). Urban Air Pollution in Megacities of the World. 2nd Edition. Blackwell. U.S.A.

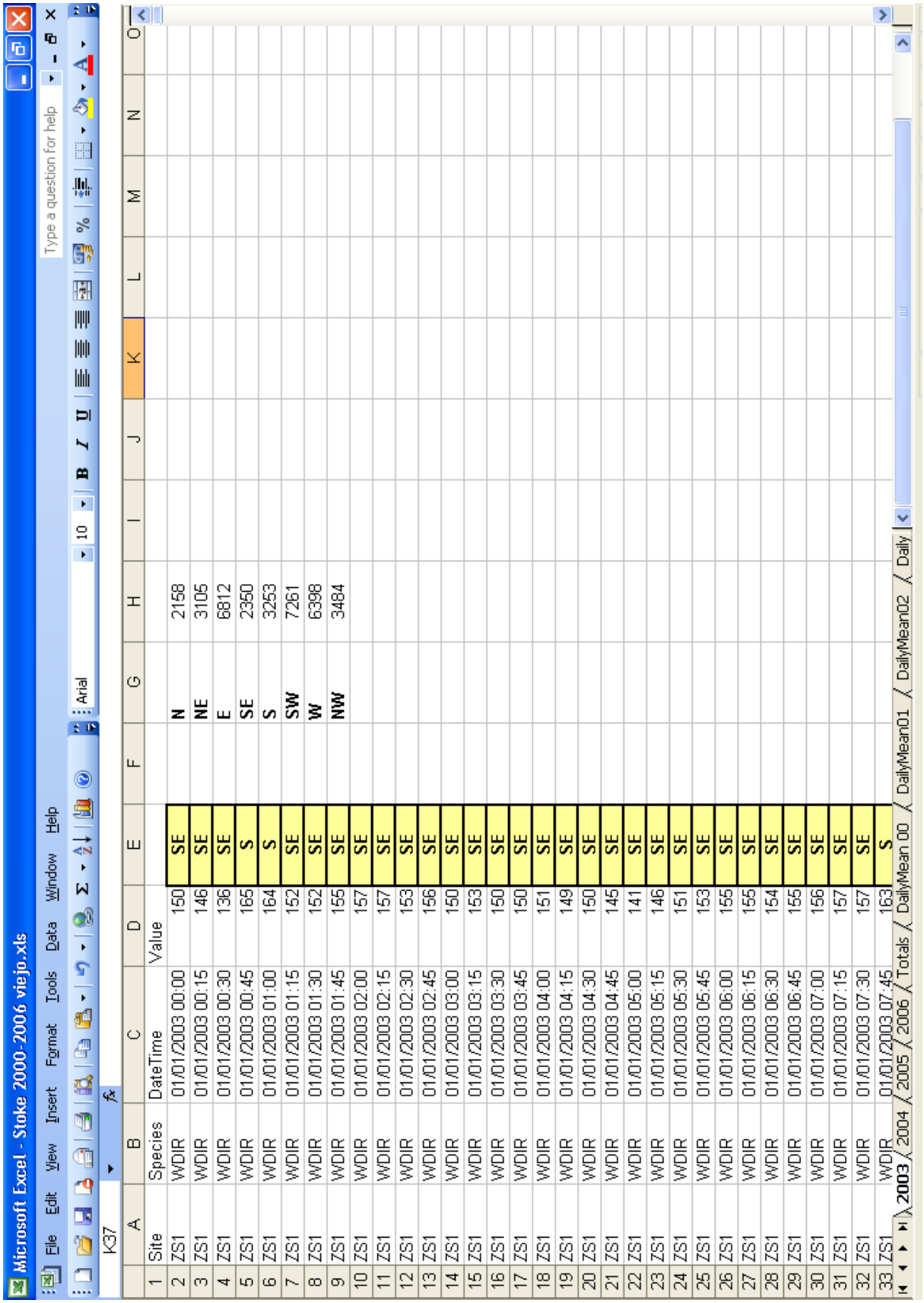
Yin, J., Allen, A. G., Harrison, R. M., Jennings, S.G., Wright, E., Fitzpatrick, M., Healy, T, Barry, E., Ceburnisb, D., McCusker, D. (2005) Major component composition of urban PM_{10} and $PM_{2.5}$ in Ireland. *Atmospheric Research.* **78**.149–165.

Zhang. C. (2007). Fundamentals of Environmental Sampling and Analysis John Wiley & sons. U.S.A.

Appendix A: Example of the raw meteorological data from Lower Stoke

Stoke weather data									
Rain		Temperature			Wind direction			Wind speed	
22 Sep 2000 0:00	0.0	22 Sep 2000 0:00	15.0		22 Sep 2000 0:00	168.0		22 Sep 2000 0:00	2.0
22 Sep 2000 0:15	0.0	22 Sep 2000 0:15	16.0		22 Sep 2000 0:15	188.0		22 Sep 2000 0:15	4.0
22 Sep 2000 0:30	0.0	22 Sep 2000 0:30	16.0		22 Sep 2000 0:30	186.0		22 Sep 2000 0:30	4.0
22 Sep 2000 0:45	0.0	22 Sep 2000 0:45	16.0		22 Sep 2000 0:45	186.0		22 Sep 2000 0:45	3.0
22 Sep 2000 1:00	0.0	22 Sep 2000 1:00	16.0		22 Sep 2000 1:00	174.0		22 Sep 2000 1:00	2.0
22 Sep 2000 1:15	0.0	22 Sep 2000 1:15	16.0		22 Sep 2000 1:15	155.0		22 Sep 2000 1:15	2.0
22 Sep 2000 1:30	0.0	22 Sep 2000 1:30	16.0		22 Sep 2000 1:30	154.0		22 Sep 2000 1:30	2.0
22 Sep 2000 1:45	0.0	22 Sep 2000 1:45	15.0		22 Sep 2000 1:45	156.0		22 Sep 2000 1:45	2.0
22 Sep 2000 2:00	0.0	22 Sep 2000 2:00	15.0		22 Sep 2000 2:00	152.0		22 Sep 2000 2:00	2.0
22 Sep 2000 2:15	0.0	22 Sep 2000 2:15	15.0		22 Sep 2000 2:15	141.0		22 Sep 2000 2:15	2.0
22 Sep 2000 2:30	0.0	22 Sep 2000 2:30	15.0		22 Sep 2000 2:30	149.0		22 Sep 2000 2:30	3.0
22 Sep 2000 2:45	0.0	22 Sep 2000 2:45	15.0		22 Sep 2000 2:45	156.0		22 Sep 2000 2:45	3.0
22 Sep 2000 3:00	0.0	22 Sep 2000 3:00	15.0		22 Sep 2000 3:00	156.0		22 Sep 2000 3:00	3.0
22 Sep 2000 3:15	0.0	22 Sep 2000 3:15	16.0		22 Sep 2000 3:15	164.0		22 Sep 2000 3:15	4.0

Appendix B: Example of the wind direction data



Appendix C: Formula applied in Microsoft Excel to convert the degrees into cardinal points

=IF(AND(X>=22.5,X<67.5),"NE","")&IF(AND(X>=67.5,X<112.5),"E","")&IF(AND(X>=112.5,X<157.5),"SE","")&IF(AND(X>=157.5,X<202.5),"S","")&IF(AND(X>=202.5,X<247.5),"SW","")&IF(AND(X>=247.5,X<292.5),"W","")&IF(AND(X>=292.5,X<337.5),"NW","")&IF(AND(X>=337.5,X<=360),"N","")&IF(AND(X>0,X<22.5),"N","")

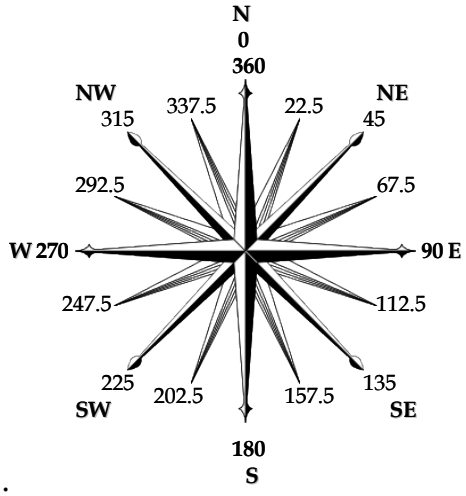
Example:

O33

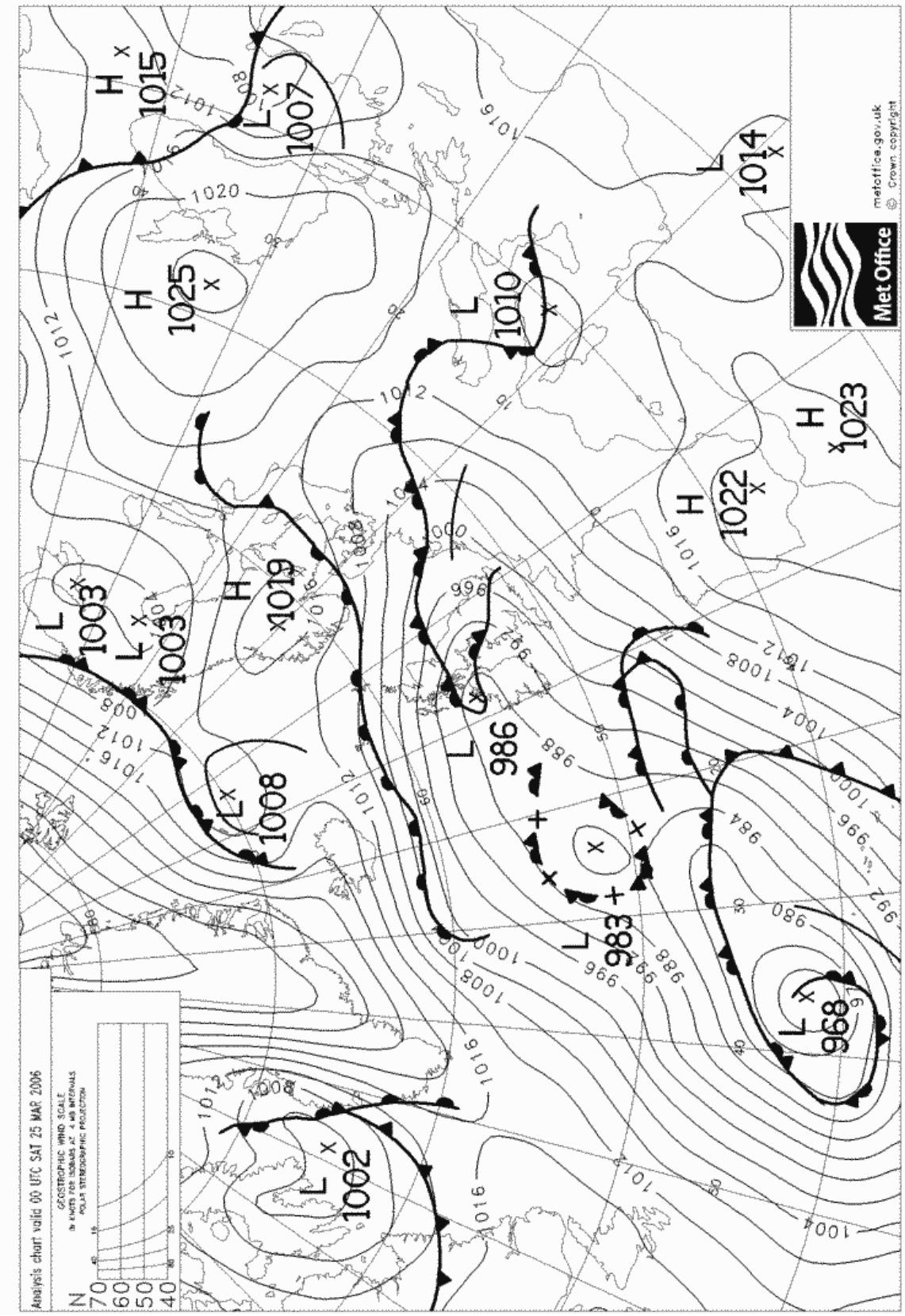
	A	B	C	D	E	F	G	H	I
1	Site	Species	DateTime	Value					
2	ZS1	WDIR	01/01/2006 00:00	271	W		N	2007	
3	ZS1	WDIR	01/01/2006 00:15	211	SW		NE	2831	
4	ZS1	WDIR	01/01/2006 00:30	216	SW		E	4394	
5	ZS1	WDIR	01/01/2006 00:45	219	SW		SE	1883	
6	ZS1	WDIR	01/01/2006 01:00	225	SW		S	3572	
7	ZS1	WDIR	01/01/2006 01:15	225	SW		SW	8772	
8	ZS1	WDIR	01/01/2006 01:30	221	SW		W	7013	
9	ZS1	WDIR	01/01/2006 01:45	215	SW		NW	3765	
10	ZS1	WDIR	01/01/2006 02:00	218	SW				
11	ZS1	WDIR	01/01/2006 02:15	221	SW				
12	ZS1	WDIR	01/01/2006 02:30	218	SW				
13	ZS1	WDIR	01/01/2006 02:45	221	SW				
14	ZS1	WDIR	01/01/2006 03:00	222	SW				
15	ZS1	WDIR	01/01/2006 03:15	237	SW				
16	ZS1	WDIR	01/01/2006 03:30	257	W				
17	ZS1	WDIR	01/01/2006 03:45	244	SW				
18	ZS1	WDIR	01/01/2006 04:00	246	SW				
19	ZS1	WDIR	01/01/2006 04:15	249	W				
20	ZS1	WDIR	01/01/2006 04:30	236	SW				
21	ZS1	WDIR	01/01/2006 04:45	258	W				
22	ZS1	WDIR	01/01/2006 05:00	262	W				
23	ZS1	WDIR	01/01/2006 05:15	258	W				
24	ZS1	WDIR	01/01/2006 05:30	262	W				
25	ZS1	WDIR	01/01/2006 05:45	264	W				
26	ZS1	WDIR	01/01/2006 06:00	270	W				
27	ZS1	WDIR	01/01/2006 06:15	271	W				

=IF(AND(D3>=22.5,D3<67.5),"NE","")&IF(AND(D3>=67.5,D3<112.5),"E","")&IF(AND(D3>=112.5,D3<157.5),"SE","")&IF(AND(D3>=157.5,D3<202.5),"S","")&IF(AND(D3>=202.5,D3<247.5),"SW","")&IF(AND(D3>=247.5,D3<292.5),"W","")&IF(AND(D3>=292.5,D3<337.5),"NW","")&IF(AND(D3>=337.5,D3<=360),"N","")&IF(AND(D3>0,D3<22.5),"N","")

The figure below shows the compass rose showing the degree number given corresponding to each cardinal direction



Appendix D: Map showing the synoptic data



Appendix E: Example of the synoptic data collected

	WDIR	SPEED	CLOUD AMOUNT	PAST WEATHER	PRESENT WEATHER	COMENTS
01/01/2000	W	5	8		Rain	
02/01/2000	S	5	8			
03/01/2000	SW	15	8			
04/01/2000	NE	10	8			
05/01/2000	SW	10	3			
06/01/2000	SW	15	8			
07/01/2000	SW	5	2			
08/01/2000	SW	20	8			
09/01/2000	NW	10	6			
10/01/2000	W	5	0			High pressure area
11/01/2000	SW	10	7			
12/01/2000	SW	20	8			
13/01/2000	S	20	8			
14/01/2000	N	5	8			
15/01/2000	NE	5	8		Rain	
16/01/2000	NE	5	7			High pressure area
17/01/2000	W	5	2			
18/01/2000	N	10	8	Mist	Fog	
19/01/2000	N	5	7			
20/01/2000	NE	5	1			
21/01/2000	N	5	8		Haze	
22/01/2000			7			
23/01/2000	N	10	0			
24/01/2000	N	5	7	Showers		
25/01/2000	NE	5	0			
26/01/2000	W	5	8		Haze	
27/01/2000	N		8	fog	lifting fog	
28/01/2000	NE		2		Haze	
29/01/2000	SW	25	8			Warm front

Appendix F: Gaps in the wind direction data

Wind Direction Data	2000	2001	2002	2003	2004	2005	2006	2007	2008
Dover			Jan to Oct	Sep to Dec	Jan	Mar	Mar & Dec	Mar	
Gravesham (A2)			Jan, Feb	Mar to Jun					
Lower Stoke	Feb								
M. Fairmeadow		Until Mar							
Sevenoaks	All year	Jan, Feb	Oct			Oct to Dec		No data available	
Swale (Ospringe)				Oct					
Swale (Sheerness)				Oct to Dec	Jan to Apr				
Thanet (Manston)						Oct			

Appendix G: Example of the raw PM_{10} data

Site (Chatham)	Species	DateTime	Value	Units
ZC1	PM10	01/01/2002 00:15	35	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 00:30	72	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 00:45	51	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 01:00	37	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 01:15	34	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 01:30	27	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 01:45	22	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 02:00	22	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 02:15	16	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 02:30	21	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 02:45	19	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 03:00	16	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 03:15	20	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 03:30	14	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 03:45	13	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 04:00	18	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 04:15	15	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 04:30	14	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 04:45	16	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 05:00	15	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 05:15	10	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 05:30	10	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 05:45	17	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 06:00	16	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 06:15	15	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 06:30	15	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 06:45	13	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 07:00	16	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 07:15	12	ug/m3 (non-Grav)
ZC1	PM10	01/01/2002 07:30	10	ug/m3 (non-Grav)

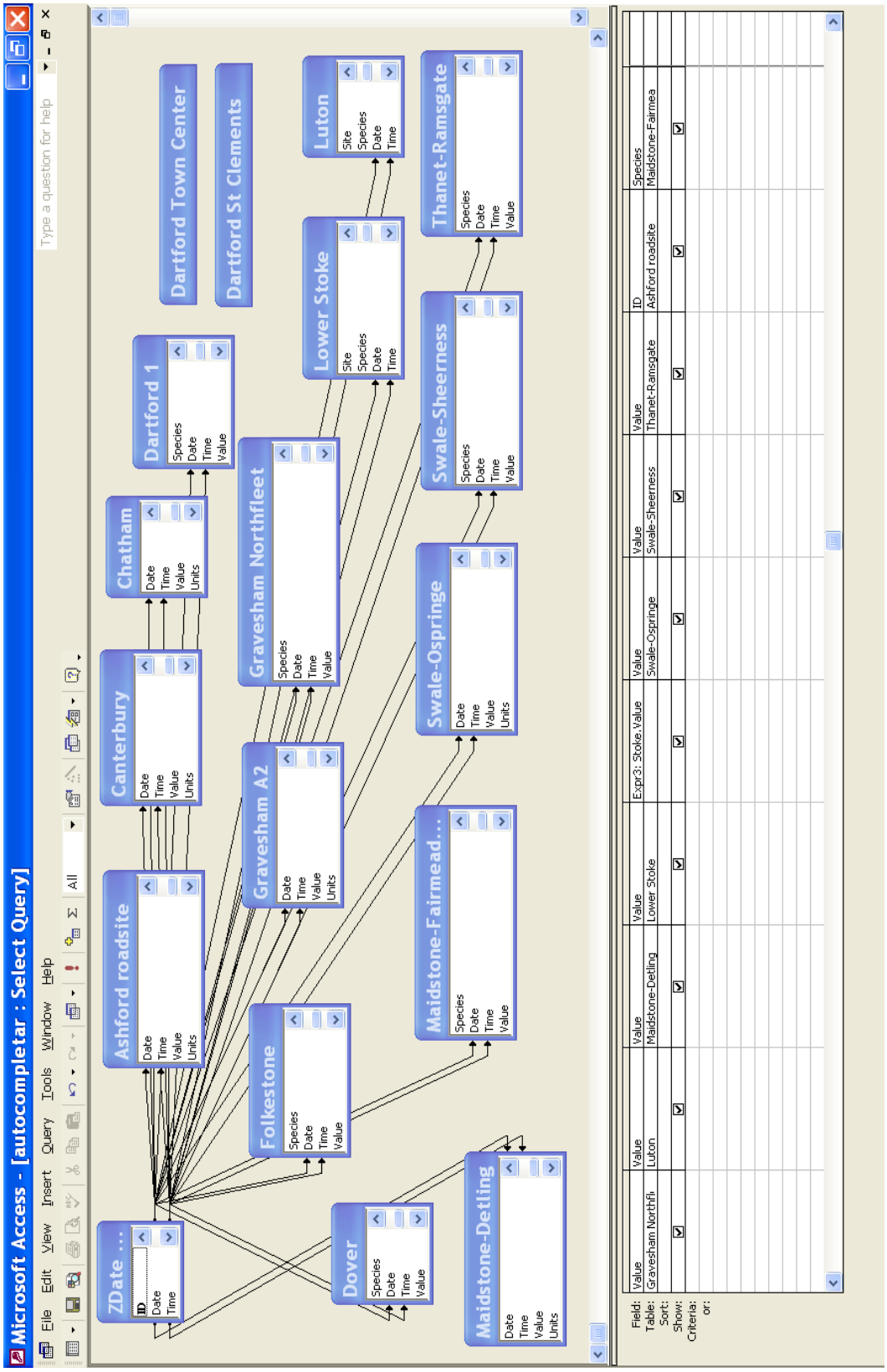
Appendix H: Gaps in the PM_{10} data

PM_{10} data available in Kent	2000	2001	2002	2003	2004	2005	2006	2007	2008
Ashford Rural	No data available-								
Ashford Roadside		Until Jan	From 17Jan		Oct				
Canterbury									
Chatham	Mar to Aug	Jan, Sep	Apr-Jun, Dec	Mar, Apr		Feb, Mar		Jan	
Dartford 1		Jul	Jun, Jul						
Dartford 2	No data available								
Dartford 3	No data available					Mar to Nov	Apr		Jan
Dover		Sep				Mar			
Folkestone		Jul	Feb			Jun			
Gravesham (A2)			Jan. Feb						
Gravesham (Northfleet)								Jan	
Luton	Jul to Dec	Jan to Mar	Jul, Dec	Jul to Dec		Jun	Sep		
M. Detling						Jul			
M. Fairmeadow					Aug				
Sevenoaks					Apr	Mar, Apr, Jun		No data available	
Stoke	Feb, Jul								
Swale (Ospringe)	No data available			From 14Aug		Jun			Sep
Swale (Sheerness)				From 14Aug					
Thanet					Oct, Nov	Mar	Apr		

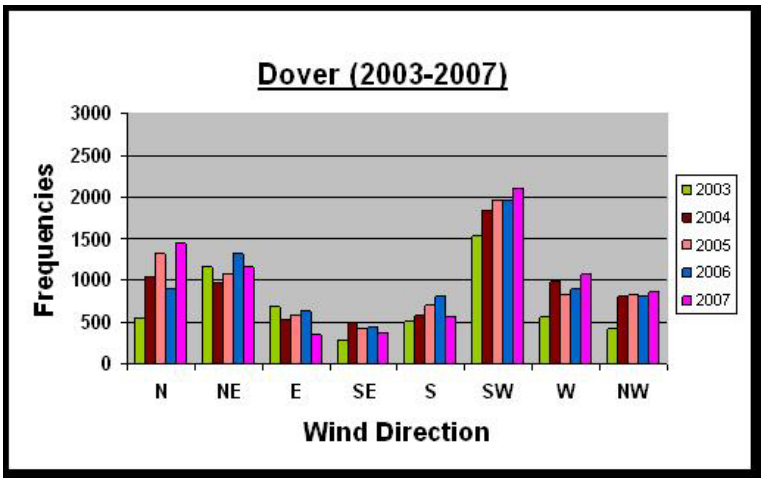
Appendix I: Example of Microsoft Access table for all sites data

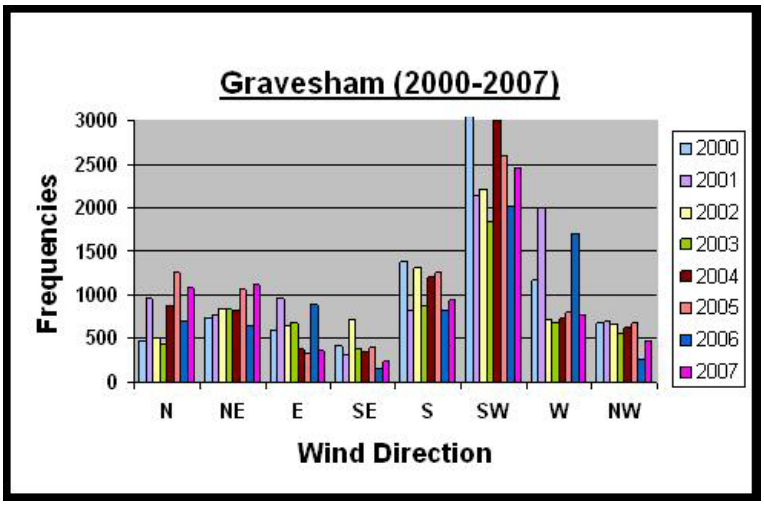
Date	Time	Ashford	Canterbury	Chatham	Dartford 1	Dartford 2	Dover	Folkestone	Gravesham A2
01/08/2003	00:00:00	14.7	17.8	14.3	23.8	29.6	19.4	17.3	30.8
01/08/2003	01:00:00	13.4	14	13	29.1	26.4	20	15.8	36.5
01/08/2003	02:00:00	14.9	15.8	12.5	24.2	27.9	19.7	16.5	35
01/08/2003	03:00:00	15	15.3	13.3	36.3	34.4	15.9	16.1	31.3
01/08/2003	04:00:00	17	15.8	15	32.5	30.8	16.5	15.2	38.7
01/08/2003	05:00:00	19.3	16.5	17.5	46.2	45	24	15.8	52.1
01/08/2003	06:00:00	24.7	17	22	62.9	44.3	33.3	16.4	43.5
01/08/2003	07:00:00	22.7	17.8	21.8	52.3	45.8	33.6	20.3	44.3
01/08/2003	08:00:00	21.6	15.5	26.8	57.9	39.7	40	24.2	50.6
01/08/2003	09:00:00	20.2	19.3	24.3	52.3	49.9	42	25.5	53.1
01/08/2003	10:00:00	20.4	19	24	42.9	42.4	37.4	22.6	50.4
01/08/2003	11:00:00	21.7	18.3	23	44.6	45.5		18.6	44.3
01/08/2003	12:00:00	26.7	18	25.8	41.2	33.9	22.9	17.9	28.1
01/08/2003	13:00:00	24.3	18.3	25.8	52.3	31.3	23.9	19.3	40.1
01/08/2003	14:00:00		21.3	25	47.7	40.9	30.1	20	54.6
01/08/2003	15:00:00	17.7	22	28.5	59.1	44.8	25.4	18.5	43.3
01/08/2003	16:00:00	15.8	20.8	28.5	60.3	34.9	25.7	16.9	63.6
01/08/2003	17:00:00	16.2	15	26.3	51.8	35.4	22.6	16.3	33
01/08/2003	18:00:00	16.1	14.3	22	48.9	36.1	24.8	19.4	39.6
01/08/2003	19:00:00	14.3	15	19.3	52	40.4	27.1	17.8	45.3
01/08/2003	20:00:00	17.5	11.5	17	54.5	38	25.4	12.5	53.8
01/08/2003	21:00:00	15.5	14.3	21	34.4	29.1	13.4	12	37.2
01/08/2003	22:00:00	16.1	14	18.3	23.3	22.3	11.7	14	30.8
01/08/2003	23:00:00	16.3	12.8	13	31.7	31.3	19.8	13.7	36.9
02/08/2003	00:00:00	11.2	10.5	14.5	32.7	37.3	13.1	16.7	36.9
02/08/2003	01:00:00	8.1	8.3	14.5	37.8	34.6	15.7	17.2	36.2
02/08/2003	02:00:00	9	8.8	15	42.4	48.7	12	12.7	34.3
02/08/2003	03:00:00	11.1	7.5	15	47	37.8	10.3	11.5	32.8
02/08/2003	04:00:00	14.1	9	15	37.1	34.4	11.8	12.5	36.5

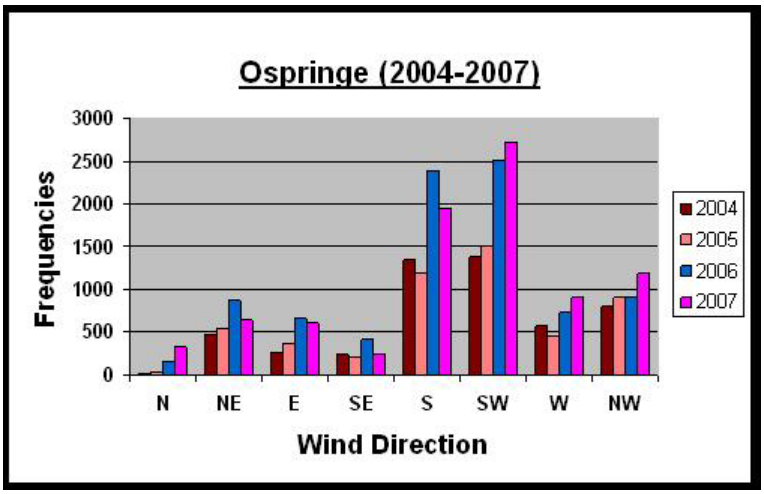
Appendix J: Example of the query created to link the tables

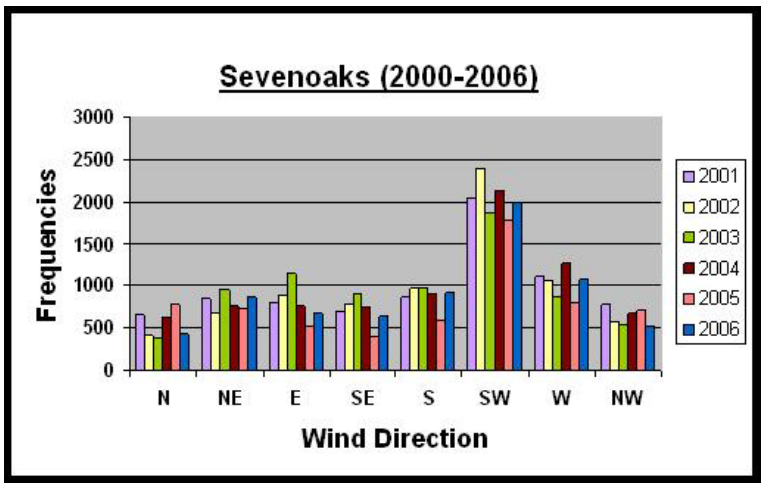


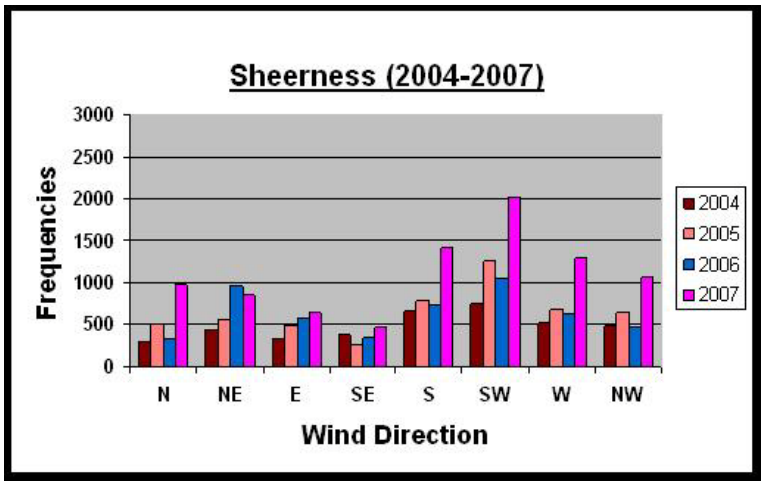
Appendix K: Two examples of the plots for every specific location over the years

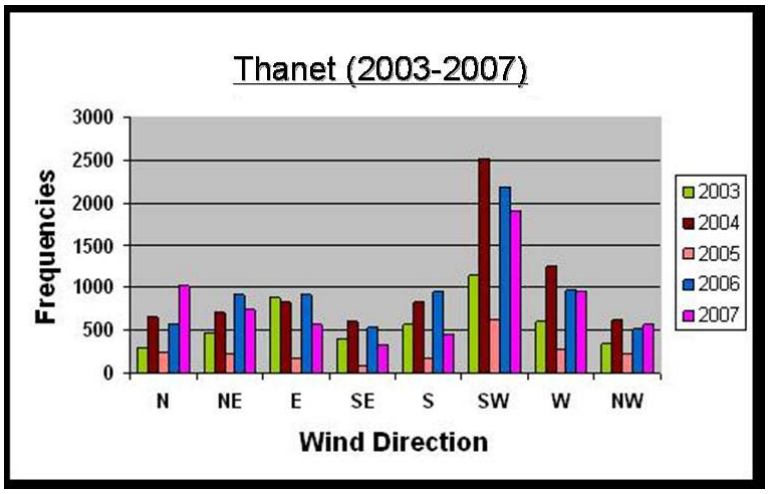







Sevenoaks (2000-2006)
Frequencies
3000
2500
2000
1500
1000
500
0
N
NE
E
SE
S
SW
W
NW
Wind Direction
2001
2002
2003
2004
2005
2006


Sheerness (2004-2007)
Frequencies
3000
2500
2000
1500
1000
500
0
N
NE
E
SE
S
SW
W
NW
Wind Direction
2004
2005
2006
2007


Thanet (2003-2007)
Frequencies
3000
2500
2000
1500
1000
500
0
N
NE
E
SE
S
SW
W
NW
Wind Direction
2003
2004
2005
2006
2007

Appendix L: Matrixes showing correlation between sites from 2000-2008

2000	Chatham	Dartford 1 (St. Clements)	Dover	Folkestone	Gravesham (A2)	Gravesham (Northfleet)	Lower Stoke	Luton	Maidstone (Detling)
Chatham									
Dartford 1 (St. Clements)	0.545								
Dover	0.533	0.611							
Folkestone	0.524	0.473	0.608						
Gravesham (A2)	0.635	0.703	0.576	0.503					
Gravesham (Northfleet)	0.456	0.532	0.553	0.415	0.537				
Lower Stoke	0.574	0.520	0.532	0.536	0.596	0.447			
Luton	0.669	0.544	0.685	0.489	0.553	0.460	0.616		
Maidstone (Detling)	0.686	0.596	0.575	0.633	0.658	0.544	0.705	0.653	
Maidstone (Fairmeadow)	0.589	0.687	0.456	0.578	0.459	0.528	0.688	0.625	0.587

2001	Canterbury	Chatham	Dartford St Clements	Dover	Folkestone	Gravesham (A2)	Gravesham (Northfleet)	Lower Stoke	Luton	Maidstone (Detling)
Chatham	0.731									
Dartford 1 (St. Clements)	0.619	0.688								
Dover	0.620	0.567	0.525							
Folkestone	0.743	0.589	0.548	0.695						
Gravesham A2	0.643	0.715	0.741	0.500	0.560					
Gravesham Northfleet	0.429	0.422	0.404	0.398	0.305	0.361				
Lower Stoke	0.612	0.728	0.516	0.446	0.522	0.560	0.333			
Luton	0.467	0.795	0.398	0.427	0.366	0.424	0.234	0.344		
Detling	0.782	0.748	0.631	0.575	0.707	0.682	0.409	0.646	0.462	
Maidstone (Fairmeadow)	0.861	0.764	0.784	0.680	0.756	0.754	0.623	0.859	0.835	0.887

2002	Ashford Roadsite	Canterbury	Chatham	Dartford 1 (St. Clements)	Dover	Folkestone	Gravesham (A2)	Gravesham (Northfleet)	Lower Stoke	Luton	Maidstone (Detling)
Canterbury	0.718										
Chatham	0.674	0.699									
Dartford 1 (St. Clements)	0.531	0.496	0.577								
Dover	0.590	0.680	0.542	0.460							
Folkestone	0.663	0.767	0.565	0.438	0.731						
Gravesham (A2)	0.609	0.600	0.628	0.660	0.485	0.517					
Gravesham (Northfleet)	0.357	0.448	0.442	0.441	0.405	0.385	0.490				
Lower Stoke	0.557	0.658	0.577	0.503	0.492	0.549	0.606	0.411			
Luton	0.615	0.681	0.714	0.520	0.530	0.572	0.584	0.420	0.586		
Maidstone (Detling)	0.296	0.362	0.243	0.247	0.321	0.315	0.284	0.215	0.257	0.273	
Maidstone (Fairmeadow)	0.508	0.589	0.637	0.569	0.485	0.559	0.771	0.578	0.587	0.754	0.499

2003	Ashford Roadsite	Canterbury	Chatham	Dartford 1 (St. Clements)	Dartford 2 (Town Centre)	Dartford 3 (Bean Interchange)	Dover	Folkestone	Gravesham (A2)	Gravesham (Northfleet)	Lower Stoke	Luton	Maidstone (Detling)
Canterbury	0.770												
Chatham	0.726	0.710											
Dartford 1 (St. Clements)	0.693	0.622	0.672										
Dartford 2 (Town Centre)	0.678	0.670	0.682	0.846									
Dartford 3 (Bean Interchange)	0.663	0.627	0.688	0.833	0.817								
Dover	0.577	0.595	0.517	0.509	0.501	0.475							
Folkestone	0.772	0.775	0.638	0.626	0.658	0.625	0.655						
Gravesham (A2)	0.659	0.614	0.648	0.781	0.762	0.819	0.439	0.597					
Gravesham (Northfleet)	0.459	0.548	0.493	0.643	0.719	0.641	0.444	0.536	0.568				
Lower Stoke	0.649	0.680	0.677	0.617	0.618	0.617	0.487	0.661	0.571	0.509			
Luton	0.745	0.761	0.811	0.711	0.741	0.724	0.664	0.710	0.678	0.584	0.701		
Maidstone (Detling)	0.481	0.511	0.473	0.434	0.456	0.440	0.391	0.504	0.403	0.386	0.470	0.507	
Maidstone (Fairmeadow)	0.237	0.244	0.359	0.215	0.275	0.230	0.186	0.218	0.711	0.589	0.598	0.619	0.620

2004	Ashford	Canterbury	Chatham	Dartford 3 (Bean Interchange)	Dover	Folkestone	Gravesham (A2)	Gravesham (Northfleet)	Lower Stoke	Luton	Maidstone (Detling)
Canterbury	0.710										
Chatham	0.665	0.625									
Dartford 3 (Bean Interchange)	0.608	0.556	0.690								
Dover	0.576	0.606	0.495	0.437							
Folkestone	0.658	0.721	0.485	0.469	0.702						
Gravesham (A2)	0.538	0.556	0.571	0.665	0.390	0.450					
Gravesham (Northfleet)	0.241	0.363	0.322	0.442	0.345	0.298	0.323				
Lower Stoke	0.226	0.239	0.170	0.200	0.264	0.253	0.186	0.192			
Luton	0.279	0.286	0.217	0.271	0.286	0.285	0.228	0.236	0.697		
Maidstone (Detling)	0.223	0.190	0.245	0.227	0.217	0.125	0.174	0.203	0.487	0.638	
Maidstone (Fairmeadow)	0.187	0.197	0.150	0.178	0.214	0.198	0.148	0.165	0.643	0.670	0.491

2005	Ashford	Canterbury	Chatham	Dartford 1 (St Clements)	Dartford 2 (Town Centre)	Dartford 3 (Bean Interchange)	Dover	Folkestone	Gravesham (A2)	Gravesham (Northfleet)	Lower Stoke	Luton	Maidstone (Detling)	Maidstone (Fairmeadow)	Swale (Ospringe)	Swale (Sheerness)
Canterbury	0.640															
Chatham	0.716	0.606														
Dartford 1(St. Clements)	0.426	0.438	0.575													
Dartford 2 (Town Centre)	0.552	0.502	0.638	0.809												
Dartford 3 (Bean Intercahnge)	0.652	0.559	0.756	0.382	0.682											
Dover	0.613	0.595	0.582	0.496	0.513	0.489										
Folkestone	0.689	0.650	0.559	0.491	0.561	0.424	0.716									
Gravesham (A2)	0.511	0.434	0.547	0.507	0.584	0.736	0.423	0.461								
Gravesham (Northfleet)	0.420	0.488	0.538	0.578	0.728	0.563	0.528	0.498	0.491							
Lower Stoke	0.160	0.179	0.179	0.186	0.183	0.216	0.245	0.195	0.146	0.194						
Luton	0.283	0.295	0.294	0.256	0.317	0.281	0.313	0.281	0.210	0.301	0.461					
Maidstone (Detling)	0.228	0.187	0.229	0.073	0.267	0.142	0.227	0.186	0.143	0.217	0.309	0.592				
Maidstone (Fairmeadow)	0.266	0.245	0.313	0.316	0.300	0.260	0.295	0.250	0.203	0.264	0.373	0.682	0.336			
(Swale Ospringe)	0.305	0.298	0.337	0.240	0.340	0.274	0.363	0.275	0.232	0.316	0.223	0.675	0.563	0.569		
(Swale Sheerness)	0.217	0.199	0.229	0.171	0.220	0.262	0.253	0.191	0.156	0.219	0.345	0.520	0.414	0.412	0.447	
Thanet (Ramsgate)	0.278	0.447	0.304	0.044	0.274	0.214	0.146	0.216	0.221	0.325	0.322	0.058	0.412	0.146	0.107	0.170

2006	Ashford	Canterbury	Chatham	Dartford 1 (St Clements)	Dartford 2 (Town Centre)	Dartford 3 (Bean Interchange)	Dover	Folkestone	Gravesham (A2)	Gravesham (Northfleet)	Lower Stoke	Luton	Maidstone (Detling)	Maidstone (Fairmeadow)	Swale (Ospringe)	Swale (Sheerness)
Canterbury	0.730															
Chatham	0.712	0.716														
Dartford 1(St. Clements)	0.597	0.498	0.572													
Dartford 2 (Town Centre)	0.442	0.471	0.521	0.486												
Dartford 3 (Bean Intercahnge)	0.311	0.300	0.331	0.305	0.248											
Dover	0.531	0.586	0.536	0.422	0.349	0.217										
Folkestone	0.616	0.679	0.566	0.412	0.384	0.242	0.598									
Gravesham (A2)	0.594	0.588	0.634	0.624	0.519	0.332	0.411	0.443								
Gravesham (Northfleet)	0.417	0.548	0.531	0.467	0.547	0.241	0.481	0.421	0.539							
Lower Stoke	0.619	0.685	0.657	0.510	0.424	0.269	0.509	0.554	0.560	0.540						
Luton	0.423	0.457	0.491	0.332	0.310	0.170	0.305	0.557	0.354	0.334	0.444					
Maidstone (Detling)	0.402	0.442	0.415	0.293	0.280	0.158	0.320	0.365	0.330	0.325	0.413	0.272				
Maidstone (Fairmeadow)	0.741	0.681	0.760	0.565	0.550	0.282	0.486	0.484	0.582	0.518	0.588	0.454	0.389			
(Swale Ospringe)	0.641	0.715	0.704	0.484	0.483	0.255	0.558	0.358	0.530	0.533	0.614	0.404	0.404	0.665		
(Swale Sheerness)	0.458	0.508	0.481	0.269	0.253	0.195	0.288	0.589	0.404	0.301	0.486	0.275	0.270	0.401	0.377	
Thanet (Ramsgate)	0.572	0.673	0.517	0.498	0.393	0.226	0.587	0.425	0.569	0.535	0.569	0.319	0.350	0.465	0.561	0.362

2007	Ashford	Canterbury	Chatham	Dartford 1 (St Clements)	Dartford 2 (Town Centre)	Dartford 3 (Bean Interchange)	Dover	Folkestone	Gravesham (A2)	Gravesham (Northfleet)	Lower Stoke	Luton	Maidstone (Detling)	Maidstone (Fairmeadow)	Swale (Ospringe)	Swale (Sheerness)
Canterbury	0.685															
Chatham	0.589	0.334														
Dartford 1(St. Clements)	0.702	0.325	0.572													
Dartford 2 (Town Centre)	0.459	0.518	0.521	0.486												
Dartford 3 (Bean Intercahnge)	0.453	0.540	0.331	0.305	0.248											
Dover	0.531	0.533	0.536	0.422	0.349	0.217										
Folkestone	0.688	0.443	0.566	0.412	0.384	0.242	0.598									
Gravesham (A2)	0.590	0.421	0.634	0.624	0.519	0.332	0.411	0.443								
Gravesham (Northfleet)	0.426	0.557	0.531	0.467	0.547	0.241	0.481	0.421	0.539							
Lower Stoke	0.684	0.358	0.657	0.510	0.424	0.269	0.509	0.554	0.560	0.540						
Luton	0.436	0.365	0.491	0.332	0.310	0.170	0.305	0.557	0.354	0.334	0.444					
Maidstone (Detling)	0.520	0.484	0.415	0.293	0.280	0.158	0.320	0.365	0.330	0.325	0.413	0.272				
Maidstone (Fairmeadow)	0.678	0.554	0.760	0.565	0.550	0.282	0.486	0.484	0.582	0.518	0.588	0.454	0.389			
(Swale Ospringe)	0.641	0.715	0.704	0.484	0.483	0.255	0.558	0.358	0.530	0.533	0.614	0.404	0.404	0.665		
(Swale Sheerness)	0.489	0.588	0.481	0.269	0.253	0.195	0.288	0.589	0.404	0.301	0.486	0.275	0.270	0.401	0.377	
Thanet (Ramsgate)	0.572	0.673	0.517	0.498	0.393	0.226	0.587	0.283	0.569	0.535	0.569	0.319	0.350	0.465	0.561	0.362

2008	Ashford	Canterbury	Chatham	Dartford 1 (St Clements)	Dartford 2 (Town Centre)	Dartford 3 (Bean Interchange)	Dover	Folkestone	Gravesham (A2)	Gravesham (Northfleet)	Lower Stoke	Luton	Maidstone (Detling)	Maidstone (Fairmeadow)	Swale (Ospringe)	Swale (Sheerness)
Canterbury	0.237															
Chatham	0.244	0.286														
Dartford 1(St. Clements)	0.197	0.270	0.488													
Dartford 2 (Town Centre)	0.215	0.285	0.455	0.413												
Dartford 3 (Bean Intercahnge)	0.275	0.215	0.256	0.404	0.334											
Dover	0.230	0.290	0.462	0.270	0.325	0.486										
Folkestone	0.186	0.277	0.557	0.350	0.518	0.509	0.685									
Gravesham (A2)	0.218	0.307	0.558	0.377	0.540	0.558	0.539	0.585								
Gravesham (Northfleet)	0.711	0.261	0.496	0.561	0.533	0.288	0.354	0.421	0.652							
Lower Stoke	0.563	0.503	0.692	0.481	0.390	0.269	0.443	0.554	0.332	0.483						
Luton	0.589	0.186	0.491	0.389	0.301	0.587	0.330	0.557	0.426	0.486	0.422					
Maidstone (Detling)	0.619	0.266	0.399	0.598	0.535	0.687	0.582	0.365	0.369	0.550	0.293					
Maidstone (Fairmeadow)	0.620	0.684	0.601	0.411	0.463	0.282	0.560	0.484	0.457	0.424	0.590	0.305	0.332			
(Swale Ospringe)	0.295	0.623	0.610	0.305	0.354	0.255	0.867	0.358	0.241	0.253	0.490	0.412	0.565	0.674		
(Swale Sheerness)	0.033	0.549	0.583	0.320	0.000	0.195	0.568	0.589	0.170	0.393	0.587	0.624	0.510	0.590	0.269	
Thanet (Ramsgate)	0.358	0.444	0.383	0.588	0.456	0.226	0.790	0.584	0.158	0.598	0.602	0.467	0.484	0.426	0.498	0.589

Appendix M: A table showing the seasonality results

Site/Year	2000		2001		2002		2003		2004		2005		2006		2007		2008	
Season	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Ashford	--	--	--	--	19.20	**20.81**	22.21	**22.66**	**19.60**	19.55	**21.06**	19.74	**22.63**	22.10	**21.15**	18.38	**22.37**	14.68
Canterbury	--	--	**19.55**	19.25	16.73	**17.75**	19.53	**20.40**	16.36	**16.86**	15.10	**18.19**	17.88	**18.58**	**15.98**	15.03	**19.31**	17.33
Chatham	18.25	**20.11**	--	--	19	**21.31**	18.1	**23.20**	18.85	**19.90**	**20.71**	20.48	**22.57**	21.70	**19.17**	16.75	**21.21**	17.52
Dover	--	--	**29.43**	28.64	24.63	**26.54**	29.80	**33.78**	22.67	**27.32**	23.90	**26.95**	26.08	**29.98**	**25.16**	24.17	**28.57**	24.30
Folkestone	16.7	**18.2**	17.6	**19.2**	13.9	**17.09**	**20.8**	20.4	15.1	**16.9**	17	**17.8**	16.6	**18.69**	**18.40**	15.40	**20.4**	15.81
Lower Stoke	16.2	**19.77**	17.15	**17.9**	14	**17.53**	--	21.52	15.2	**16.75**	16	**19**	15.4	**18.8**	15.66	**17.34**	18.1	**18.7**
Luton	14.5	--	--	--	14.87	**15.67**	--	19.51	14.17	**14.25**	**17.37**	15.57	16.64	**18.23**	15.29	**15.48**	**15.08**	14.56
Maidstone (Detling)	13.17	**16.37**	15.3	**17.25**	13.77	**20.20**	15.24	**20.68**	13.07	**15.38**	13.95	**16.21**	15.97	**17.77**	14.22	**15.42**	13.31	**15.24**
Maidstone (Fairmeadow)	**24.34**	22.64	**25.19**	23.37	**22.27**	20.76	**25.26**	25.09	**24.23**	20.30	**23.12**	21.90	**27.42**	24.42	**22.67**	19.63	**27.58**	19.15
Swale (Ospringe)	--	--	--	--	--	--	--	--	17.95	**19.04**	17.49	**18.12**	19.73	**20.34**	17.12	**17.26**	**18.40**	17.06
Swale (Sheerness)	--	--	--	--	--	--	--	--	20.35	**23.61**	18.84	**19.98**	20.22	**22.66**	**25.41**	20.51	**24.32**	24.14
Thanet (Ramsgate)	--	--	--	--	--	--	--	--	**34.03**	32.18	**30.07**	28.67	**32.37**	31.16	31.08	**33.4**	34.37	**35.64**

Appendix N: High levels of pollution (monthly tables)

Ashford	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
2000	No available data for this period											
2001												
2002	2*	3*	10*	10*	2	1*	2	5	6	4	5*	2
2003	1	8	7	4	1	1	2	8	6	3	7	4
2004	0	4	4	1	2	0	1*	1	6	1	5	8
2005	2	6	11	3	0	1	0	2	2	2	4	6
2006	2	3	4	3	0	2	4	0	3	4	4*	2
2007	4	6	14*	6*	4*	1	0	0	2	4	5	3
2008	4*	9	0	0	1	0	0	1	0	0	0	0

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Canterbury	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
2000	No available data for this period											
2001	5	0	1	0	1	1	1	3	0	1	3	2
2002	1	0	1	5	2	0	2	3	2	3	3	3
2003	0	8	8	6	0	4	1	8	8*	0	3	2
2004	0	1	0	0	1	5	1	1	1	1	3	3
2005	0	1	1	1	1	12*	5	2	3	2	0	0
2006	2	1	0	0	1	1	5*	0	4	1	3*	0
2007	0	0	8*	4	2	0	0	0	5*	1	3*	4*
2008	3*	6	3	6	7	0	5	3*	4*	11*	2*	1

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Chatham	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
2000	5	3	5	0	0	4*	0	3*	2	0	**2***	0
2001	6*	1	4	0	4	3	4	4	0	2	**8***	0
2002	5	3	6	5	0	0	3	5	2	0	**2**	3
2003	5	5	0	7*	0	1	2	8	3	2*	**9***	3
2004	2	4	8*	3	2	0	1	3	2	1	**6***	6
2005	2	9	0	3	0	2	2	1	4	7	6	3
2006	4	6*	2	1	4	2	6	0	2	2	3*	2
2007	1	3	7*	2	0	1	0	0	1	3	5*	6
2008	3*	7	2*	3	3	3	1	2*	1	0	2	1

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Dartford 1	January	February	March	April	May	June	July	August	September	October	November	December
2000	17*	26*	26*	20*	19*	23*	16*	20*	23*	27*	24*	18*
2001	27*	25*	26*	19*	25*	23*	10*	22*	17*	29*	23*	17*
2002	28*	23*	30*	25*	26*	8*	20*	24*	22*	20*	20*	21*
2003	17*	24*	29*	22*	21*	21*	17*	19*	23*	18*	19*	15*
2004	17	22*	28*	26*	26*	26*	28*	28*	27*	31*	24*	24*
2005	18*	19*	26*	28*	24*	26*	25*	24*	27*	29*	26*	22*
2006	24*	21*	23*	17*	19*	22*	25*	18*	25*	29*	26*	19*
2007	14*	21*	25*	27*	25*	26*	27*	25*	24*	31*	23*	22*
2008	27*	28*	19*	25*	26*	19*	22*	24*	26*	15*	16*	21*

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Dartford 1 Over 100UM	January	February	March	April	May	June	July	August	September	October	November	December
2000	5*	9	11*	3	9	7	4	3	2	10*	9	4
2001	9	9	8	4*	8	5	5*	8*	5	8	11*	9
2002	12	7*	11*	10*	9	2*	7*	8	11*	7*	14*	6
2003	5	18*	25*	11*	6	3	2	9*	9	3	7	5
2004	0	8	4*	13*	8	2	6*	10	10*	6	12*	9
2005	3	8	18*	13	4	8*	2	8*	11*	15	8*	5
2006	5	4	4	2*	7*	5	5	0	2	6	11*	3
2007	1	8*	15*	13*	3	3	5	1	1	17*	9	7
2008	5	15	4	6	15	2*	4	2	6	1	3	5

Note: *Annual concentrations over 100 µg/ m^{-3}

Dartford 2	January	February	March	April	May	June	July	August	September	October	November	December
2000	No available data for this period											
2001												
2002												
2003	14*	22*	26*	26*	10*	18*	14*	23*	26*	22*	19*	17*
2004	11*	25*	24*	18*	23*	14*	14*	23*	19*	26*	25*	25*
2005	19*	21*	29*	25*	22*	23*	21*	18*	29*	27*	22*	18*
2006	22*	24*	17*	9*	14*	17*	18*	9	17*	27*	15*	6
2007	9*	16*	23*	28*	15	14*	7	10	12	27*	24*	16*
2008	14*	21*	6	15*	25*	13*	8*	7*	19*	10*	6*	17*

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Dartford 2	January	February	March	April	May	June	July	August	September	October	November	December
2000	No available data for this period											
2001												
2002												
2003	1	12*	13*	9*	1*	2	2	10	7	4	8	4
2004	6*	0	10*	6*	2	1	5	6	6	2	5*	10
2005	7	2*	19	10	4*	4	1	4	9*	7	1	5
2006	8	4	2	2	3	3*	4*	0	3	3	4*	0
2007	9	4*	10	5	0	1	0	0	0	4	5	6*
2008	2	5	0	1	4	2	3	1	2	1	2	3

Note: *Annual concentrations over 100 µg/ m^{-3}

Dartford 3	January	February	March	April	May	June	July	August	September	October	November	December
2000	No available data for this period											
2001												
2002												
2003	14*	22*	24*	23*	18*	26*	23*	20*	21*	18*	17*	18*
2004	11*	18*	19*	18*	19*	12*	20*	20*	15*	22	25*	25*
2005	16*	20*	2	--	--	--	--	--	--	--	19*	21*
2006	18*	18*	19*	13	12*	20*	25*	11*	19*	18*	19*	13*
2007	12*	18*	22*	22*	11*	17*	14	16	11	24*	16*	14*
2008	15*	24*	11*	17*	20*	9	13*	19*	17*	5	8	17*

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Dartford 3	January	February	March	April	May	June	July	August	September	October	November	December
2000	No available data for this period											
2001												
2002												
2003	1	7	14	9	2	5*	2	10*	3	1	3	2*
2004	2	2	7*	3	2	0	3	6	2	0	10*	8
2005	1	6*	0	--	--	--	--	--	--	--	2	3
2006	3	6*	7	0	3	2	12	0	3	2	4	0
2007	2	3	10*	5	2	1	0	0	0	2	4*	1
2008	1	4	4	1	2	0	3*	4*	4	0	0	1

Note: *Annual concentrations over 100 µg/ m^{-3}

Dover	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
2000	No available data for this period											
2001	6*	10	14*	5	13	7	11	9	1	6	6*	3
2002	5	1	10	11	8	4	6	11	5	7	5	7
2003	5	16*	14*	12	5	15*	7	12*	11	8	6	4
2004	3	5	8*	10	9	4	6*	10*	7	1	2*	5
2005	1	6	6*	8	1	8*	14	5*	9	7	2	1
2006	7	4	10	7	9*	8	16*	5	10	7	4*	1
2007	2	5	9*	6	7	9	9	7	3	4	2*	5
2008	3*	11*	1	1	10	8	7	6	2	0	3*	3

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Folkestone	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
2000	1	0	4*	0	5	1	2	1	0	0	2*	0
2001	3	1	0	0	1	2	1	2	0	1	3	0
2002	0	1	3	2	1	0	1	3	1	0	2	2
2003	0	4	3	3	0	0	0	6	1	1	2*	0
2004	0	1	0	0	0	0	1	0	3	0	3*	3
2005	1	0	1	1	0	2	0	1	1	2	2	2
2006	1	1	0	0	3	2	3	0	3	1	3*	0
2007	0	2	7*	1	0	0	0	0	0	0	3	2
2008	3	4	0	0	0	0	1	0	0	0	0	0

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Gravesham A2	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
2000	27*	26*	30*	23*	24*	30*	27*	29*	25*	17	22*	20
2001	18*	18*	21*	14*	18*	20*	22*	20*	16	26*	20*	15
2002	8*	4	29*	22*	21*	16	20*	27*	23*	25*	26*	18*
2003	14*	27*	25*	27*	20*	29*	28*	21*	24*	21*	21*	18*
2004	13*	25*	24*	27*	16*	18*	26*	22*	21*	11	25*	6
2005	20*	19*	19*	15*	16*	16*	11*	19*	22*	18*	24*	22*
2006	22*	24*	19*	18*	20*	16*	21*	20*	19*	18*	23*	15*
2007	23*	20*	26*	23*	27*	24*	28*	19*	26*	12*	14*	23*
2008	12*	18*	22*	22*	11*	17*	14	16	11	24*	16*	14*

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Gravesham A2 100	January	February	March	April	May	June	July	August	September	October	November	December
2000	6	3	12	1	13	12	7	4	3	0	1*	0
2001	5*	3	3	1	3	1	3	6	0	1*	1*	0
2002	2	0	6	4*	2	0	4*	5	1	4*	6*	2*
2003	1	2	2*	2	3	1	2	2	4	5	1*	8*
2004	5*	5	4*	1	6	2	6*	2*	2	0	2*	0
2005	4	1	9	1	6	3	1	1*	2	1*	4*	10*
2006	0	4	11	2	4	2	2*	2*	9	8	3*	4*
2007	3	2	6*	3*	2*	2	8	9*	2	1	4*	6
2008	2	3	2*	5	4	2	0	0	0	1	3*	0

Note: *Annual concentrations over 100 µg/ m^{-3}

Gravesham Northfleet	January	February	March	April	May	June	July	August	September	October	November	December
2000	23*	21*	27*	21*	24*	24*	26*	21*	26*	12*	15*	24*
2001	14*	22*	26*	25*	15*	17*	14*	23*	24*	18*	14*	20*
2002	12*	25*	24*	18*	23*	14*	14*	21*	18*	10*	16*	17*
2003	22*	24*	18*	11*	14*	17*	18*	9*	17*	27*	15*	8*
2004	9*	16*	23*	28*	14*	15*	7*	10*	12*	27*	21*	16*
2005	21*	22*	22*	23*	13*	18*	8*	20*	25*	22*	22*	18*
2006	20*	19*	18*	15*	16*	16*	9*	19*	21*	18*	24*	22*
2007	18*	26*	22*	19*	19*	22*	22*	23*	23*	16*	9*	23*
2008	13*	21*	8	15*	25*	21*	13*	8*	7*	19*	7*	16*

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Gravesham Northfleet	January	February	March	April	May	June	July	August	September	October	November	December
2000	4*	2	16*	3*	14*	10	10*	8*	2	1	3*	8*
2001	4*	7*	5	6	11*	7	9	9	3	8	4	2
2002	1	5	9*	10	2	6	4	8	8	5	6	10*
2003	2	4	8*	11	14*	2*	6	5	1	2	5	8*
2004	6	6	6*	2	3	5	7*	3	5	7*	2	16*
2005	3*	2*	12*	3	4	6	8*	2	5	3	2*	13*
2006	4	18*	8*	5	6	4*	9*	1	8*	11*	4*	2
2007	8*	10	2*	9*	3	2	2*	13*	20*	6*	9*	3
2008	3*	11*	8	5	5	8	1	8*	7*	1	7*	6*

Note: *Annual concentrations over 100 µg/ m^{-3}

Lower Stoke	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
2000	0	0	5	0	3	1	5*	11*	1	0	3*	0
2001	5	0	0	0	2*	0	1	4	2	1	2*	0
2002	0	0	1	2	2	0	6	8*	0	0	0	0
2003	0	0	4	5	2	2	1	12*	7*	1	4	1
2004	0	0	1	0	1	0	4*	1	4	1	2*	2
2005	0	0	0	0	1	3	8*	7	1*	3	3	0
2006	0	1	0	0	0	1	8	2*	3*	2	2	0
2007	0	1	6	2	0	1	5	4*	2	2	3	2
2008	2*	2	1	0	6	1	9	6*	5	0	0	0

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Luton	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
2000	2*	1	5*	2	4*	1	0	0	0	0	0	1
2001	5	2	3	3*	0	0	0	0	0	2	4*	3
2002	1	0	2*	2*	2	3	3	2	2	3	2	0
2003	0	0	5	6	0	0	0	9	0	2*	4*	1
2004	0	0	0	1	0	0	0	3	1	0	3*	1
2005	0	2	2	1	0	0	0	4	3	2	3	1
2006	1	3	1	3*	2	0	2	0	3	2	3	1
2007	1	1	8	3	1	1	0	2	0	7	4	4
2008	0	3	0	0	3	0	4*	1	1	1	2	2

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Maidstone (Detling)	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
2000	0	0	3	0	1	0	0	0	0	0	1	0
2001	2	1	0	0	0	2*	0	1	0	2	1	0
2002	0	0	0	1	1	1	4	2	1	0	0	0
2003	0	1	3	3	0	1	5	6	2	0	0	0
2004	0	1	0	0	0	0	2*	2*	0	0	1	1
2005	0	0	0	1	2	1	1	2*	0	0	1*	0
2006	0	1	0	1	0	0	1	0	2	1*	2*	0
2007	0	0	2	1	0	1	5	3	0	2	1*	0
2008	0	1	2	1	0	0	3	4	1	0	0	1

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Maidstone (Fairmeadow)	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
2000	9	5*	12*	3	9	4	4*	1	2	1	6*	4
2001	8*	6	5*	0	2	4	7	5	2	6	9*	4
2002	5	0	6	8	2	0	3	5	5	4	4*	6
2003	4	14*	15	10*	4	5*	4	11	11	7	10*	9
2004	3	10*	14*	8	5	1	2	1	3	5	8*	5
2005	4	7	14	4	0	3	1	4	2	7	11	6
2006	11	11	9*	5	4	2	8	2	4	4	8*	3
2007	3	10	14*	3	2	1	0	0	0	8	10*	9
2008	6	12	2	1	3	0	1	0	2	2	1	5

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Swale (Ospringe)	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
2000	No available data for this period											
2001												
2002												
2003												
2004	1	2	4	1	0	0	1	2	1	1	4	5
2005	1	4*	8*	1	0	2	1	3	4	3	2	0
2006	5	5	4	1	3*	3	7	0	5	3	3	2
2007	0	2	9*	3	2	0	1	1	0	4	1	4
2008	6	10	4	0	5	1	1	--	--	--	--	--

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Swale (Sheermess)	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
2000	No available data for this period											
2001												
2002												
2003												
2004	10	6	8	8	5	14*	14	8	17	6	5	6
2005	3	5	8	8*	8*	6	7*	9	11*	4	4	1
2006	1	4	7*	11	6	10	7	8	9	4	6*	5
2007	13	8	20	11	5	6	14	6	9	5	15*	13
2008	11	12*	13*	10	0	11*	13	13	7*	15	11*	3

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

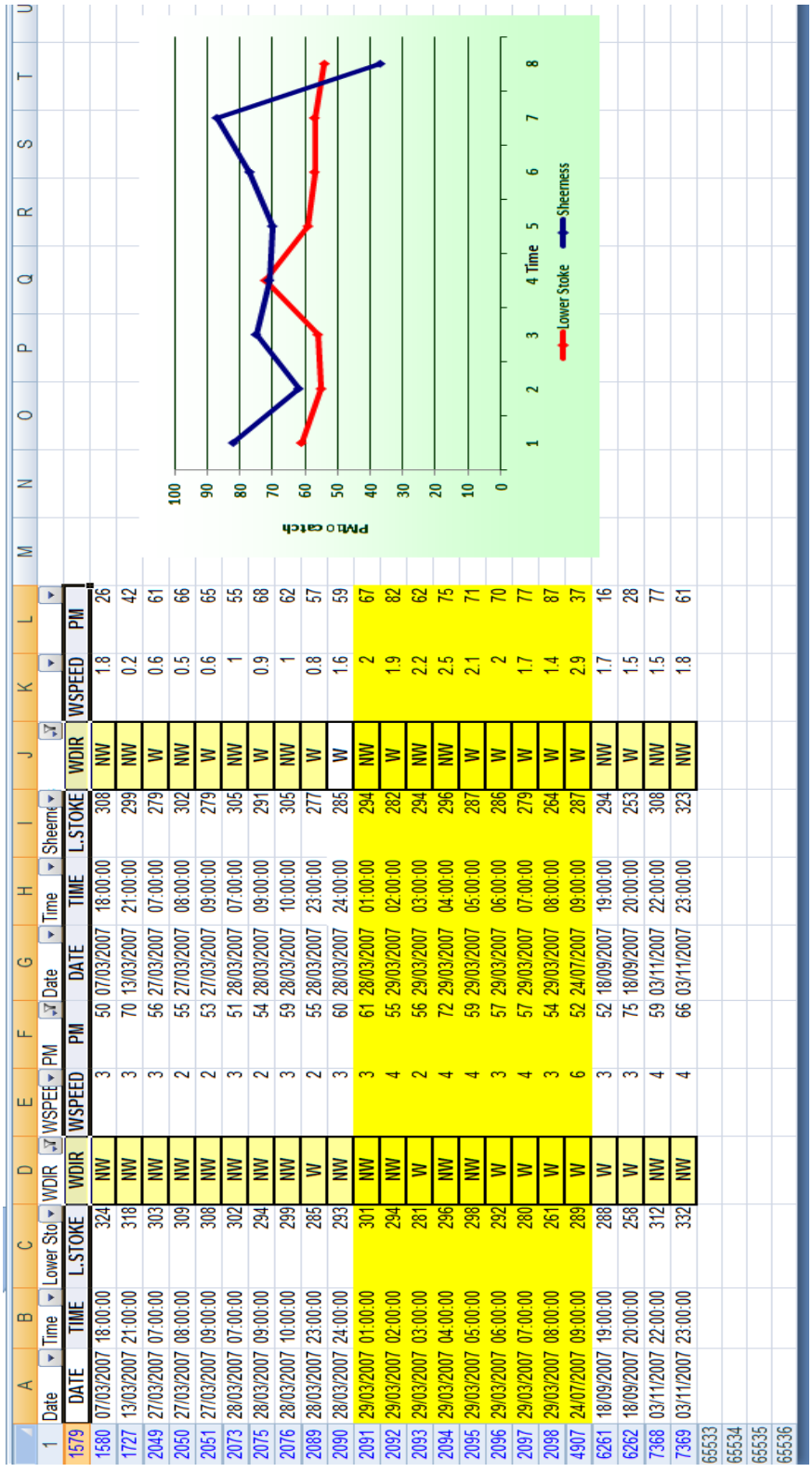
Thanet	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
2000	No available data for this period											
2001												
2002												
2003												
2004	8	13	17	13	14*	8	15	21	12	3	10*	5
2005	4	11*	12	13	6	8	14	10*	13*	11*	5	1
2006	9	11	16	10	7	15	22*	9	23*	13	12*	9*
2007	10	12*	9	11	17	16	20	21	20	18	13*	10
2008	13	19*	9	15*	26	18	16	23*	21	12*	18*	13*

Note: *Annual concentrations over the recommended 40 µg/ m^{-3}

Appendix O: Distance between sites in kilometres

	Ashford	Canterbury	Chatham	Dartford	Dover	Folkestone	Gravesham	Lower Stoke	Luton	Maidstone	Detling	Sevenoaks
Ashford												
Canterbury	22.1											
Chatham	39	45.5										
Dartford	56.5	65	22.1									
Dover	35.7	24.7	68.2	87.7								
Folkestone	29.2	22.7	61.7	81.2	13							
Gravesham	50.7	55.2	16.2	12.3	78	71.5						
Lower Stoke	42.2	39	13	31.2	61.7	58.5	20					
Luton	39	43.5	6.5	19.5	61.7	58.5	16.2	19.5				
Maidstone	32.5	41.6	14.3	32.5	55.2	48.7	21.4	20.8	9.7			
Detling	29.2	40.8	13	29.2	58.5	52	26	16.2	6.5	6.5		
Sevenoaks	52	58.5	29.2	19.5	81.2	71.5	22	35.7	22.7	19.5	29.2	
Ospringe	11	9.3	14.8	29.5	37	20.6	21.5	12	17.5	15.19	13	29.3
Sheerness	37.7	30.55	22.7	39	55.2	52	29.2	19.7	25	26	19.5	42.2
Thanet	25.1	12.9	35	75	16	20	41.1	31.5	38.5	36.2	34	85

Appendix P: Example of filtering pollution trajectories



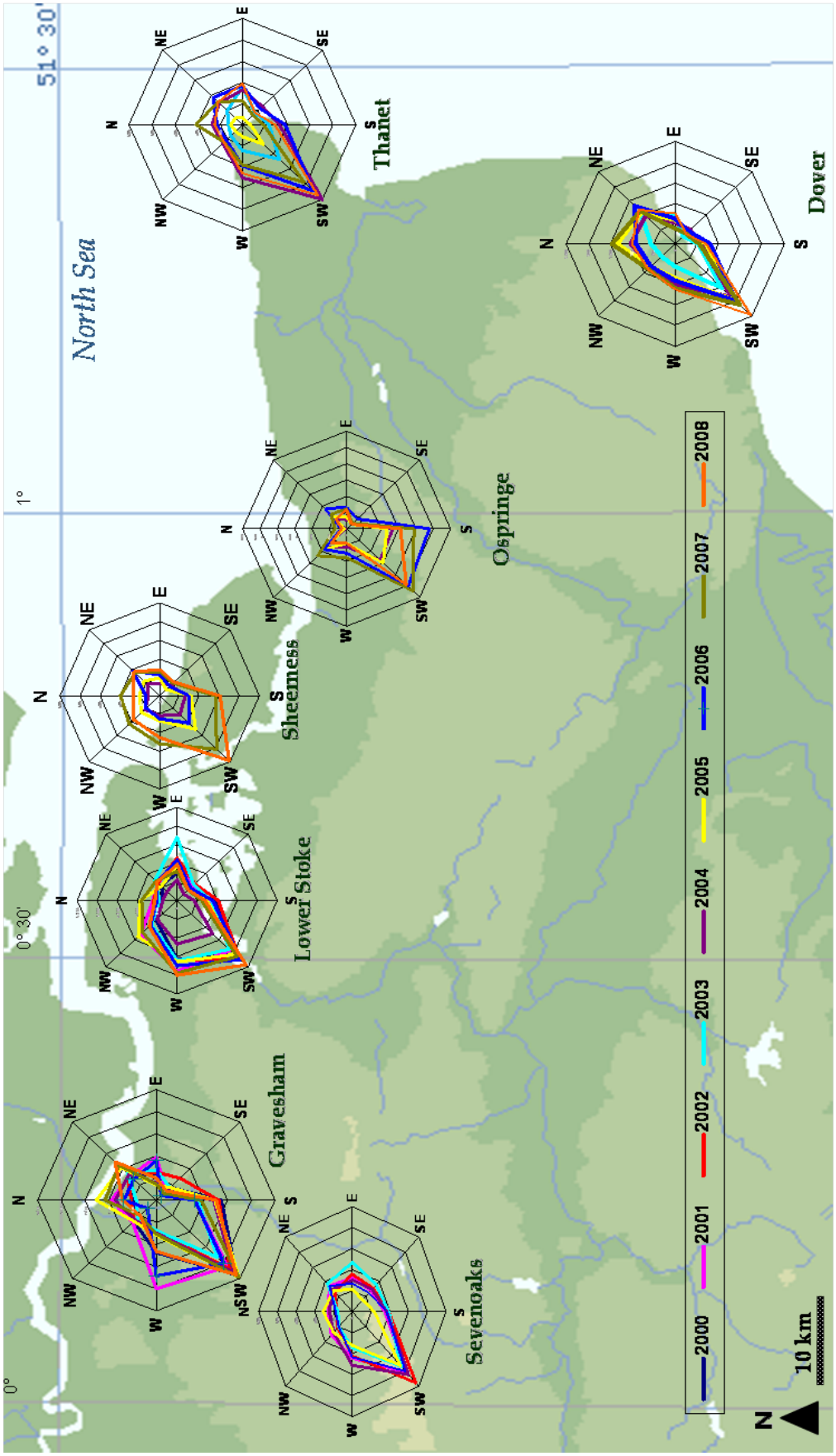
	A	B	C	D	E	F	G	H	I	J	K	L
1	Date	Time	Lower Sto	WDIR	WSPEE	PM	Date	Time	Sheern			
1579	DATE	TIME	L.STOKE	WDIR	WSPEED	PM	DATE	TIME	L.STOKE	WDIR	WSPEED	PM
1580	07/03/2007	18:00:00	324	NW	3	50	07/03/2007	18:00:00	308	NW	1.8	26
1727	13/03/2007	21:00:00	318	NW	3	70	13/03/2007	21:00:00	299	NW	0.2	42
2049	27/03/2007	07:00:00	303	NW	3	56	27/03/2007	07:00:00	279	W	0.6	61
2050	27/03/2007	08:00:00	309	NW	2	55	27/03/2007	08:00:00	302	NW	0.5	66
2051	27/03/2007	09:00:00	308	NW	2	53	27/03/2007	09:00:00	279	W	0.6	65
2073	28/03/2007	07:00:00	302	NW	3	51	28/03/2007	07:00:00	305	NW	1	55
2075	28/03/2007	09:00:00	294	NW	2	54	28/03/2007	09:00:00	291	W	0.9	68
2076	28/03/2007	10:00:00	299	NW	3	59	28/03/2007	10:00:00	305	NW	1	62
2089	28/03/2007	23:00:00	285	W	2	55	28/03/2007	23:00:00	277	W	0.8	57
2090	28/03/2007	24:00:00	293	NW	3	60	28/03/2007	24:00:00	285	W	1.6	59
2091	29/03/2007	01:00:00	301	NW	3	61	28/03/2007	01:00:00	294	NW	2	67
2092	29/03/2007	02:00:00	294	NW	4	55	29/03/2007	02:00:00	282	W	1.9	82
2093	29/03/2007	03:00:00	281	W	2	56	29/03/2007	03:00:00	294	NW	2.2	62
2094	29/03/2007	04:00:00	296	NW	4	72	29/03/2007	04:00:00	296	NW	2.5	75
2095	29/03/2007	05:00:00	298	NW	4	59	29/03/2007	05:00:00	287	W	2.1	71
2096	29/03/2007	06:00:00	292	W	3	57	29/03/2007	06:00:00	286	W	2	70
2097	29/03/2007	07:00:00	280	W	4	57	29/03/2007	07:00:00	279	W	1.7	77
2098	29/03/2007	08:00:00	261	W	3	54	29/03/2007	08:00:00	264	W	1.4	87
4907	24/07/2007	09:00:00	289	W	6	52	24/07/2007	09:00:00	287	W	2.9	37
6261	18/09/2007	19:00:00	288	W	3	52	18/09/2007	19:00:00	294	NW	1.7	16
6262	18/09/2007	20:00:00	258	W	3	75	18/09/2007	20:00:00	253	W	1.5	28
7368	03/11/2007	22:00:00	312	NW	4	59	03/11/2007	22:00:00	308	NW	1.5	77
7369	03/11/2007	23:00:00	332	NW	4	66	03/11/2007	23:00:00	323	NW	1.8	61
65533												
65534												
65535												
65536												

Appendix Q: BVST battery swap records

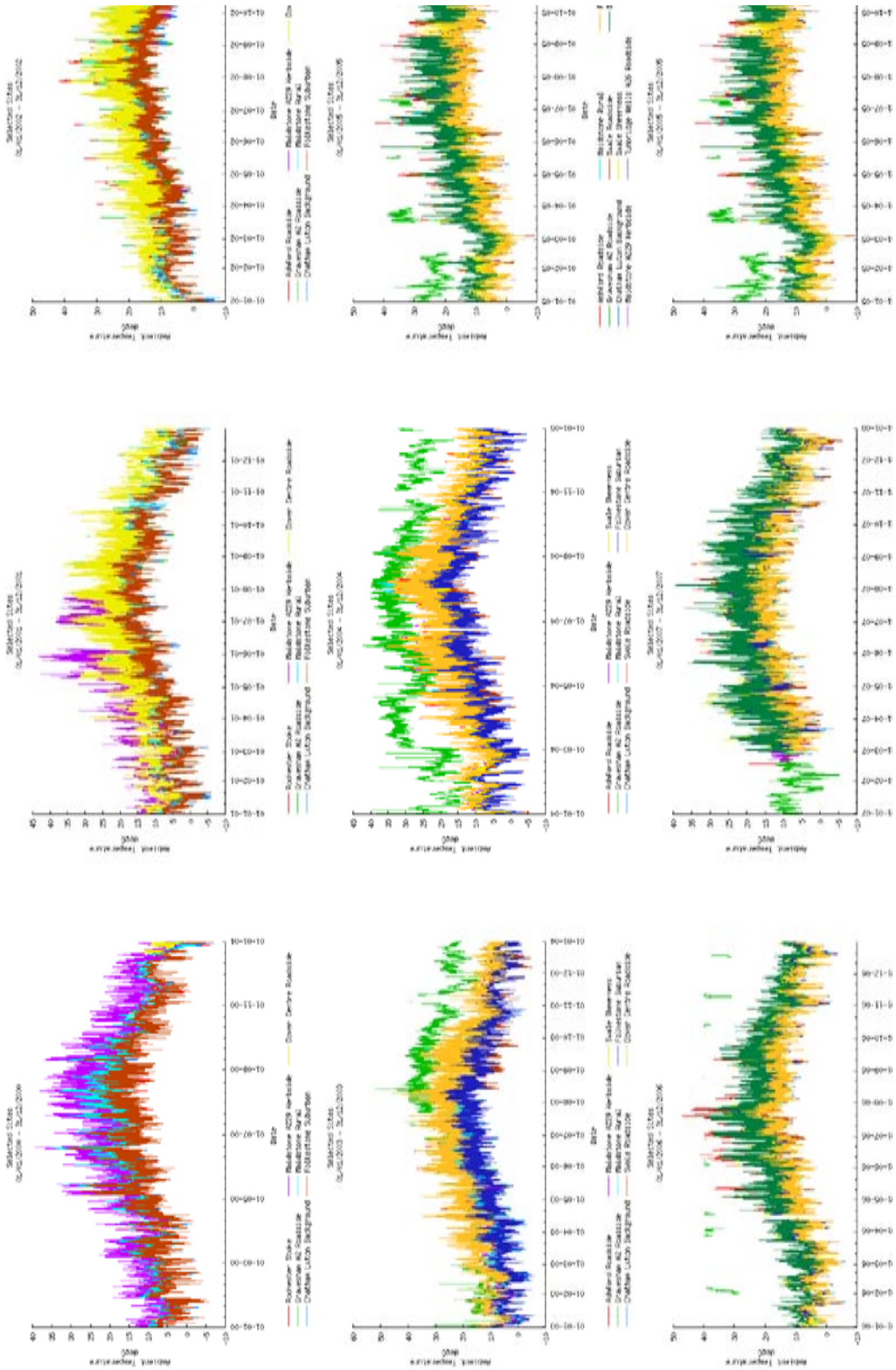
Date	Time	Date	Time
21/07/05	11:00	**22/03/06**	9:20
28/07/05	9:20	**29/03/03**	9:45
04/08/05	9:15	**05/04/06**	11:00
11/08/05	9:20	**12/04/06**	9:30
18/08/05	10:20	**19/04/06**	12:00
25/08/05	9:00	**26/04/06**	11:00
01/09/05	9:30	**02/05/06**	12:00
08/09/05	9:55	**09/05/06**	9:00
20/09/05	18:00	**16/05/06**	11:00
29/09/05	8:00	**23/05/06**	12:00
04/10/05	11:20	**30/05/06**	9:00
10/10/05	9:30	**06/05/06**	11:00
18/10/05	8:20	**13/05/06**	10:00
25/10/05	10:00	**20/05/06**	12:00
01/11/05	10:10	**30/05/06**	9:00
08/11/05	10:30	**07/06/06**	10:00
15/11/05	10:30	**14/06/06**	11:00
22/11/05	11:00	**21/06/06**	9:00
29/11/05	11:00	**28/06/06**	10:00
06/12/05	10:00	**05/07/06**	9:30
13/12/05	10:10	**12/07/06**	10:00
20/12/05	12:00	**19/07/06**	11:00
29/12/05	12:10*	**26/07/06**	9:00
03/01/06	10:30	**02/08/06**	12:00
10/01/06	12:00	**09/08/06**	9:30
17/01/06	8:00	**16/08/06**	11:15
26/01/06	10:30*	**23/08/06**	12:30
01/02/06	14:15	**30/08/06**	9:45
08/02/06	10:00	**06/09/06**	11:00
15/02/06	10:00	**14/09/06**	16:15
22/02/06	10:30	**22/09/06**	07:55
01/03/06	12:00	**29/09/06**	07:55
08/03/06	9:00	**06/10/06**	07:30
15/03/05	11:00		

***Trap wasn't running**

Appendix R: Map showing wind roses with data available for all studied sites



Appendix S: Examples of Temperature profiles and WDIR comparison



Appendix T: Sea breezes tables showing east and northeast occurrences for of all studied years.

Lower Stoke site sea breeze study 2000

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	1	--	**6**	**9**	**11**	**5**	**9**	**6**	6	2	3	6
10.00-18.00	5	--	**8**	**8**	**22**	**8**	**3**	**5**	5	4	4	7
18.00-00.00	--	--	**5**	**4**	**14**	**7**	**2**	**3**	4	--	2	4

Lower Stoke site sea breeze study 2001

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	5	3	**9**	**3**	**16**	**5**	**8**	**5**	--	3	1	2
10.00-18.00	5	3	**9**	**6**	**20**	**6**	**8**	**9**	4	5	4	3
18.00-00.00	3	4	**3**	**2**	**13**	**3**	**5**	**5**	1	3	4	3

Lower Stoke site sea breeze study 2002

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	5	--	**8**	**2**	**6**	**3**	**8**	**5**	11	10	5	7
10.00-18.00	4	5	**11**	**7**	**9**	**2**	**13**	**8**	20	6	2	8
18.00-00.00	3	4	**8**	--	**9**	**2**	**3**	**6**	12	4	1	5

Lower Stoke site sea breeze study 2003

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	4	12	**11**	**11**	**4**	**12**	**6**	**9**	4	6	3	6
10.00-18.00	3	11	**12**	**14**	**5**	**9**	**5**	**11**	18	2	6	6
18.00-00.00	5	7	**5**	**7**	**3**	**6**	**7**	**6**	9	6	1	6

Lower Stoke site sea breeze study 2004

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	2	4	**5**	**10**	**6**	**1**	**5**	**7**	4	3	6	6
10.00-18.00	3	6	**10**	**13**	**11**	**4**	**4**	**4**	3	3	5	7
18.00-00.00	2	--	**3**	**4**	**4**	**2**	**4**	**5**	1	5	4	3

Lower Stoke site sea breeze study 2005

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	--	3	**5**	**6**	**5**	**12**	**7**	**4**	4	4	--	--
10.00-18.00	3	8	**12**	**12**	**11**	**19**	**10**	**8**	9	10	--	2
18.00-00.00	1	2	**9**	**11**	**7**	**10**	**8**	**5**	7	5	1	2

Lower Stoke site sea breeze study 2006

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	2	4	**6**	**2**	**3**	**6**	**10**	--	1	2	--	--
10.00-18.00	2	5	**9**	**5**	**5**	**17**	**10**	**5**	4	6	--	1
18.00-00.00	--	3	**7**	**2**	**2**	**9**	**11**	**1**	3	5	--	2

Lower Stoke site sea breeze study 2007

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	5	13	**8**	**6**	**5**	**14**	**12**	**11**	7	7	6	--
10.00-18.00	4	12	**19**	**9**	**5**	**5**	**7**	**5**	9	10	5	--
18.00-00.00	1	10	**8**	**15**	**6**	**12**	**8**	**10**	1	8	4	--

Lower Stoke site sea breeze study 2008

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	5	8	**6**	**6**	**10**	**5**	**5**	**4**	4	7	10	--
10.00-18.00	5	4	**7**	**10**	**12**	**2**	**4**	**3**	3	4	2	--
18.00-00.00	2	6	**5**	**5**	**9**	**1**	**4**	**7**	2	5	6	--

Gravesham site sea breeze study 2000

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	3	--	**3**	**8**	**12**	**5**	**9**	**6**	8	3	6	6
10.00-18.00	3	--	**10**	**14**	**12**	**10**	**13**	**7**	3	4	2	--
18.00-00.00	1	--	**4**	**6**	**8**	**3**	**3**	**3**	2	3	3	3

Gravesham site sea breeze study 2001

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	9	4	**12**	**3**	**10**	**7**	**7**	**5**	4	5	3	6
10.00-18.00	6	13	**7**	**6**	**22**	**7**	**14**	**5**	8	1	5	12
18.00-00.00	5	3	**5**	**4**	**13**	**4**	**8**	**4**	3	3	3	8

Gravesham site sea breeze study 2002

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	4	3	**9**	**11**	**3**	**14**	**8**	**10**	8	12	12	10
10.00-18.00	4	6	**7**	**9**	**9**	**14**	**12**	**12**	13	14	4	14
18.00-00.00	5	2	**6**	**8**	**8**	**10**	**7**	**6**	8	11	9	8

Gravesham site sea breeze study 2003

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	3	6	**No data available**	**14**	**6**	**9**	10	9	10	14	**No data available**	
10.00-18.00	4	5		**7**	**8**	**13**	22	8	4	9		
18.00-00.00	2	4		**6**	**7**	**16**	3	2	4	8		

Gravesham site sea breeze study 2004

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	2	1	**4**	**9**	**1**	**4**	**3**	**4**	1	3	8	3
10.00-18.00	1	5	**10**	**9**	**8**	**3**	**1**	**6**	1	3	3	8
18.00-00.00	1	3	**6**	**4**	**13**	**2**	**5**	**8**	1	3	2	5

Gravesham site sea breeze study 2005

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	2	1	**2**	**5**	**5**	**9**	**3**	**3**	11	8	8	8
10.00-18.00	0	1	**5**	**8**	**8**	**10**	**5**	**5**	14	7	10	4
18.00-00.00	1	--	7	**3**	**2**	**7**	**8**	**3**	**8**	14	16	3

Gravesham site sea breeze study 2006

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	--	13	**6**	**8**	**8**	**10**	**8**	**17**	16	10	15	8
10.00-18.00	--	10	**9**	**5**	**6**	**4**	**8**	**6**	8	11	8	5
18.00-00.00	--	10	**8**	**11**	**5**	**12**	**8**	**15**	4	4	7	7

Gravesham site sea breeze study 2007

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	--	9	**16**	**5**	**2**	**6**	**9**	**5**	1	9	1	9
10.00-18.00	--	8	**12**	**5**	**15**	**7**	**12**	**7**	6	3	1	15
18.00-00.00	--	4	**7**	**7**	**9**	**8**	**8**	**8**	2	3	--	6

Gravesham site sea breeze study 2008

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	6	--	**9**	**6**	**4**	**2**	**9**	**13**	2	8	11	4
10.00-18.00	5	3	**11**	**8**	**6**	**3**	**10**	**7**	5	7	3	5
18.00-00.00	5	3	**11**	**9**	**6**	**3**	**7**	**2**	6	5	5	1

Dover site sea breeze study 2003

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	4	5	**6**	**4**	**4**	**10**	**8**	**5**	10	5	4	1
10.00-18.00	4	4	**5**	**3**	**4**	**7**	**7**	**8**	13	11	8	2
18.00-00.00	2	4	**2**	**2**	**2**	**8**	**5**	**15**	3	5	3	3

Dover site sea breeze study 2004

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	2	1	**7**	**10**	**12**	**8**	**3**	**9**	5	2	2	--
10.00-18.00	2	--	**7**	**16**	**16**	**8**	**11**	**2**	5	3	6	--
18.00-00.00	1	--	**5**	**6**	**8**	**3**	**6**	**4**	5	2	6	--

Dover site sea breeze study 2005

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	--	6	**7**	**5**	**3**	**5**	**1**	**3**	3	12	--	--
10.00-18.00	3	7	**8**	**6**	**5**	**8**	**8**	**14**	9	6	2	--
18.00-00.00	--	5	**4**	**3**	**3**	**4**	**2**	**6**	4	5	--	--

Dover site sea breeze study 2006

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	3	3	**5**	**2**	**3**	**12**	**3**	**7**	2	3	2	--
10.00-18.00	5	4	**4**	**7**	**14**	**10**	**8**	**6**	6	3	2	2
18.00-00.00	5	2	**5**	**2**	**2**	**2**	**3**	**2**	2	2	1	--

Dover site sea breeze study 2007

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	9	1	**2**	**3**	**8**	**4**	**3**	**3**	1	9	1	--
10.00-18.00	4	1	--	**4**	**8**	**4**	**2**	**7**	8	6	2	--
18.00-00.00	4	1	**1**	**1**	**2**	**5**	**5**	**1**	2	4	3	--

Dover site sea breeze study 2008

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	1	4	**1**	**4**	**2**	**5**	**4**	**7**	4	2	5	1
10.00-18.00	1	9	**5**	**9**	**3**	**7**	**6**	**4**	3	3	7	--
18.00-00.00	1	6	**2**	**3**	**1**	**1**	**3**	**3**	2	3	4	--

Sevenoaks site sea breeze study 2001

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	--	--	**7**	**4**	**11**	**8**	**4**	**2**	2	1	1	2
10.00-18.00	--	--	**8**	**5**	**16**	**4**	**6**	**5**	3	2	--	2
18.00-00.00	--	--	**2**	**1**	**8**	**6**	**2**	**4**	1	--	--	1

Sevenoaks site sea breeze study 2002

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	3	3	**7**	**1**	**4**	**4**	**7**	**4**	7	--	3	4
10.00-18.00	2	4	**7**	**5**	**8**	**5**	**3**	**7**	2	--	1	1
18.00-00.00	1	2	**5**	**2**	**7**	**2**	**3**	**5**	1	--	1	2

Sevenoaks site sea breeze study 2003

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	1	6	**9**	**7**	**2**	**7**	**2**	**5**	1	--	1	4
10.00-18.00	2	7	**5**	**11**	**2**	**2**	**4**	**4**	1	2	5	2
18.00-00.00	--	5	**5**	**3**	**3**	**4**	**1**	**2**	--	4	1	--

Sevenoaks site sea breeze study 2004

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	2	2	**7**	**8**	**8**	**2**	**4**	**8**	4	4	2	0
10.00-18.00	4	5	**9**	**9**	**5**	**6**	**7**	**7**	2	4	1	1
18.00-00.00	1	2	**2**	**4**	**2**	**2**	**3**	**5**	--	2	--	1

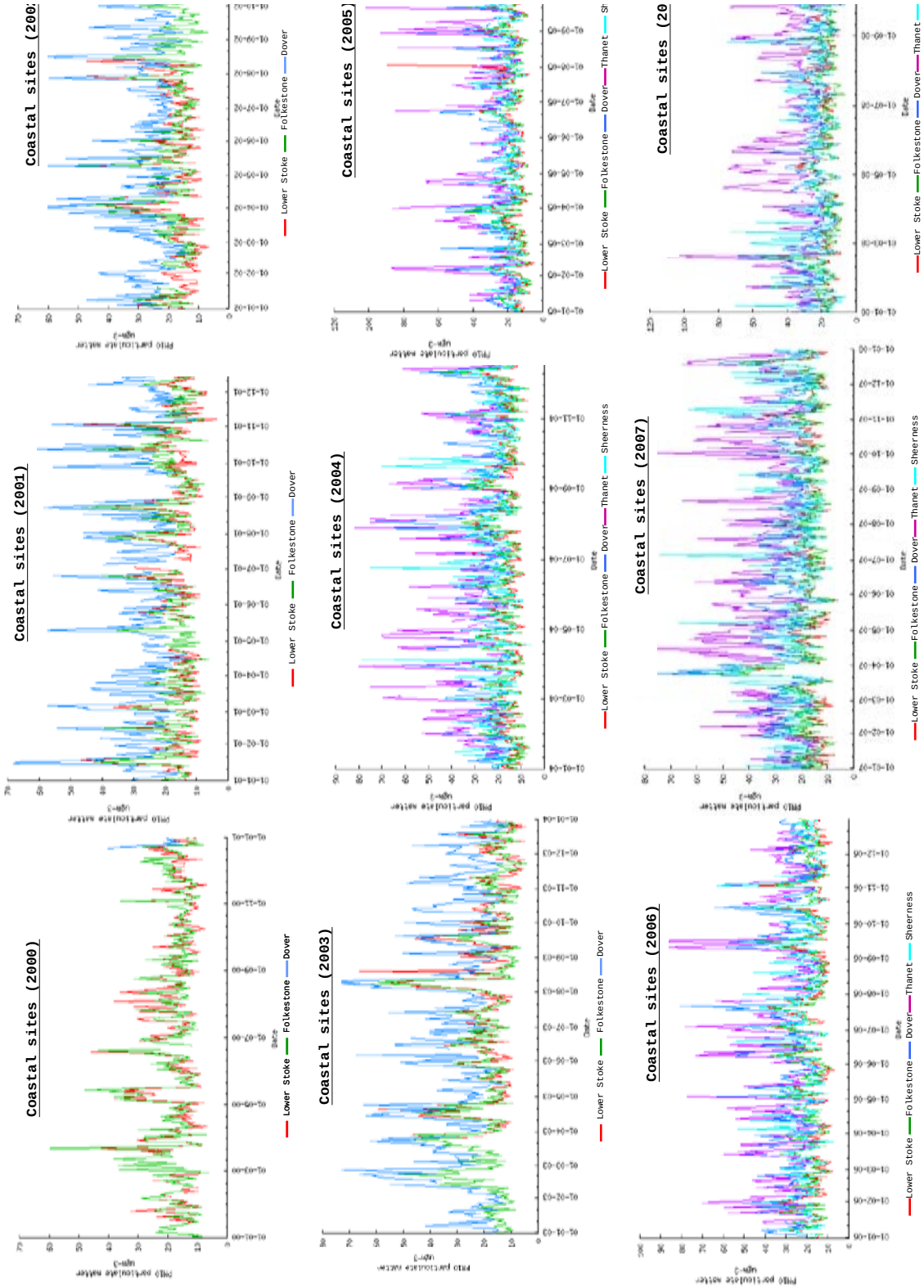
Sevenoaks site sea breeze study 2005

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	--	1	**3**	**2**	**2**	**1**	**4**	**3**	2	--	--	--
10.00-18.00	2	--	**2**	**5**	**6**	**8**	**7**	**2**	3	--	--	--
18.00-00.00	1	--	**5**	**7**	**8**	**4**	**3**	**2**	1	--	--	--

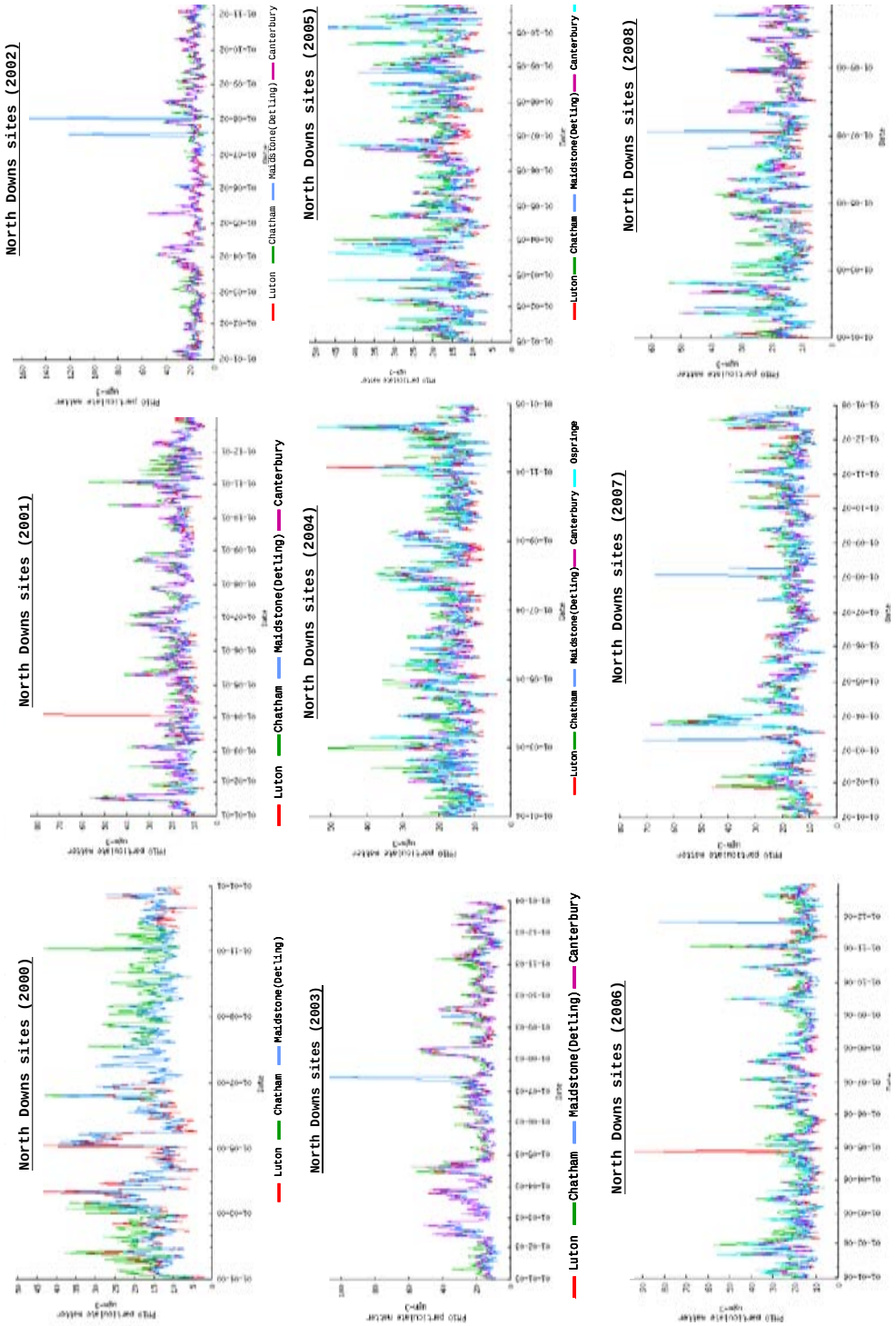
Sevenoaks site sea breeze study 2006

Time of the day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00.00-9.00	1	2	**4**	**3**	**5**	**3**	**2**	**3**	1	1	--	--
10.00-18.00	3	8	**9**	**8**	**5**	**6**	**7**	**5**	6	1	1	2
18.00-00.00	2	1	**2**	**3**	**4**	**2**	**1**	**1**	--	1	1	--

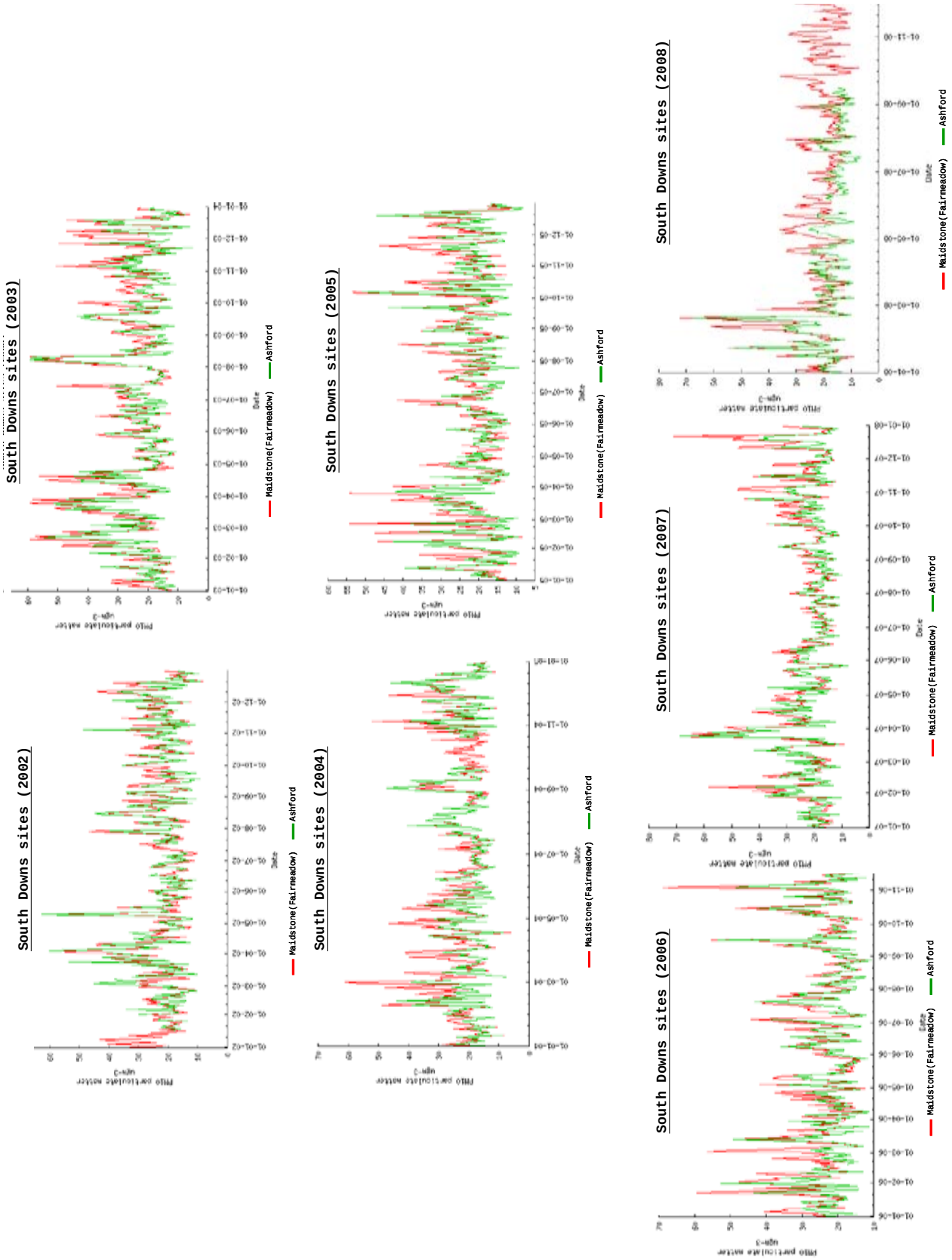
Appendix U: Coastal sites



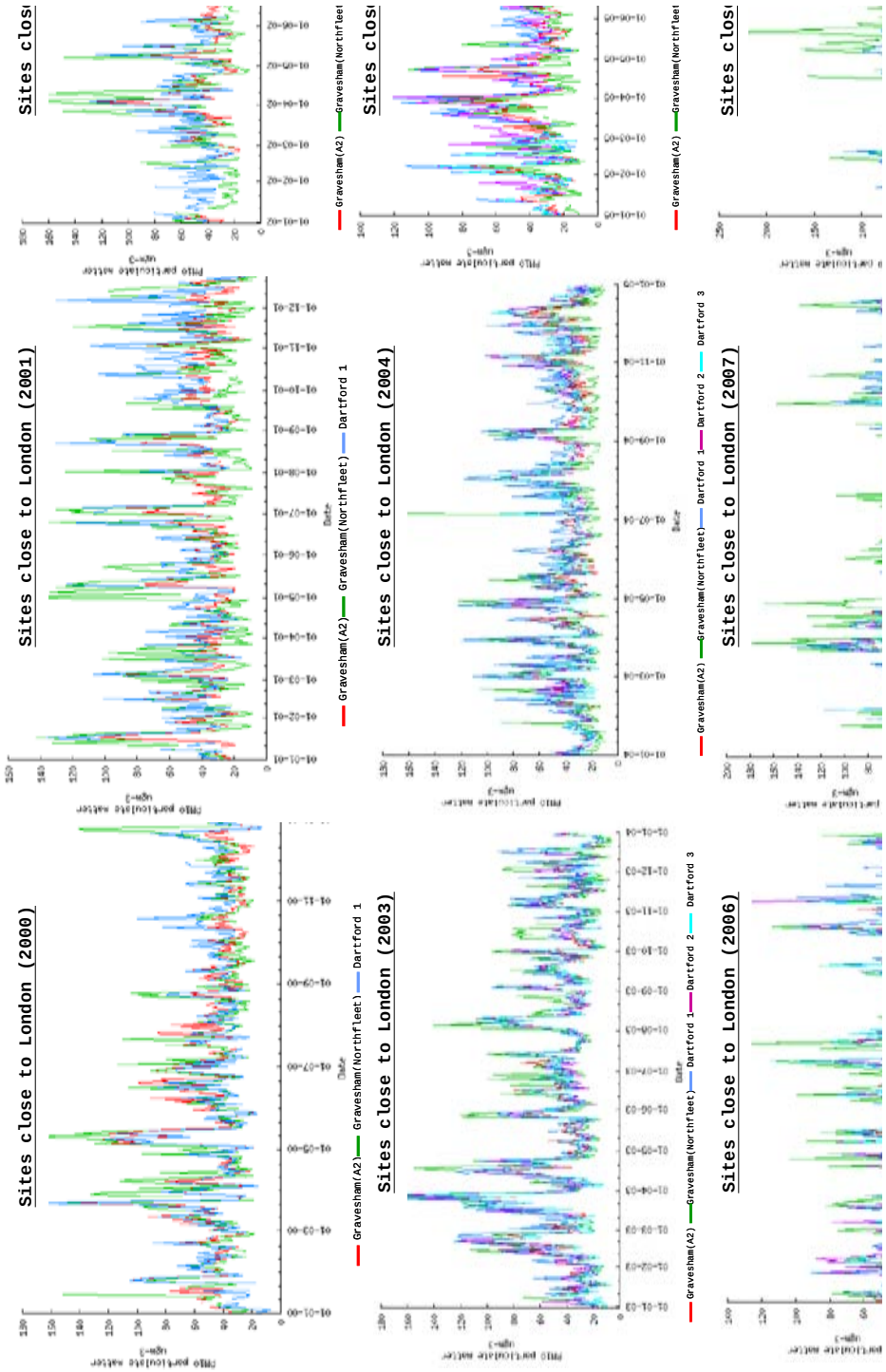
Appendix V: North Downs



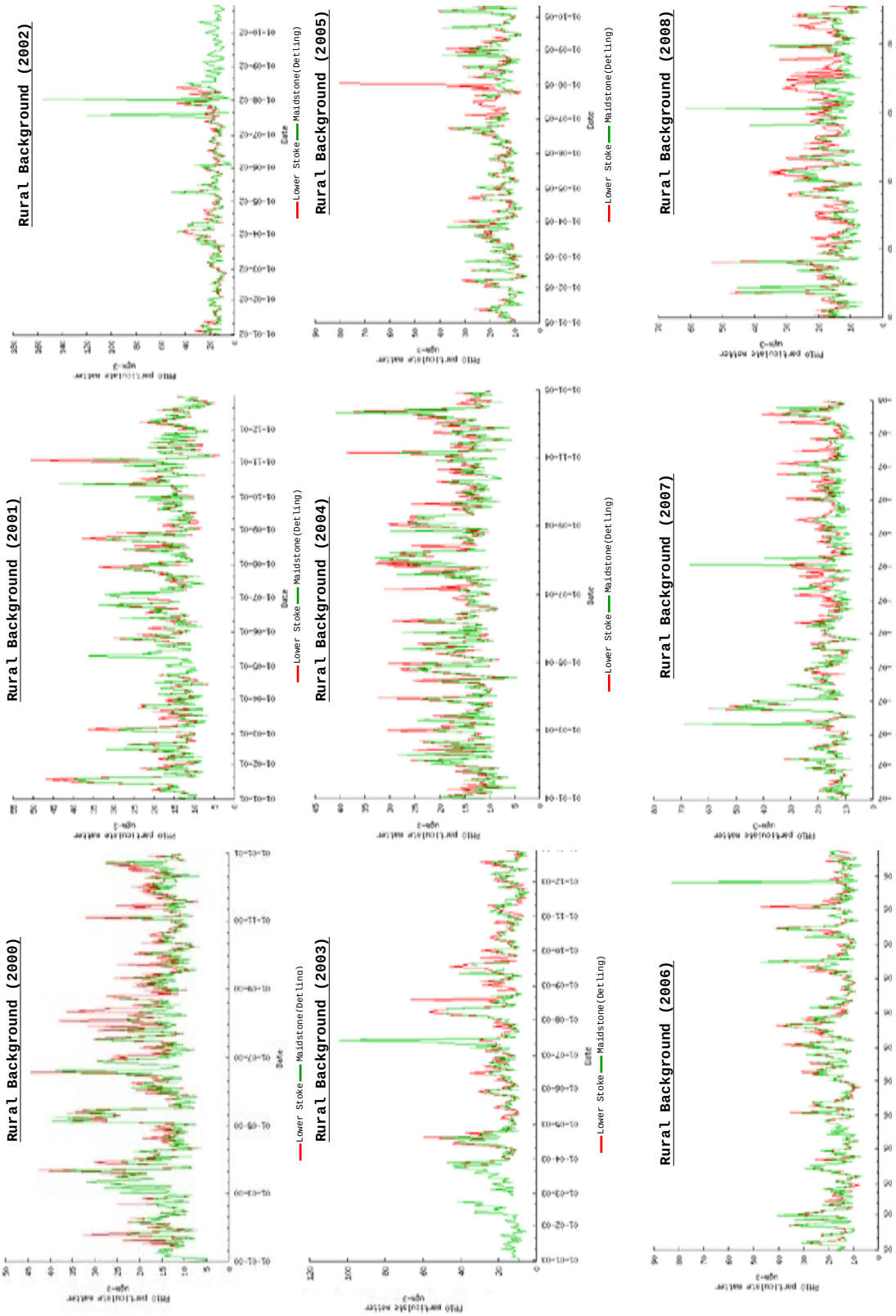
Appendix W: South Downs



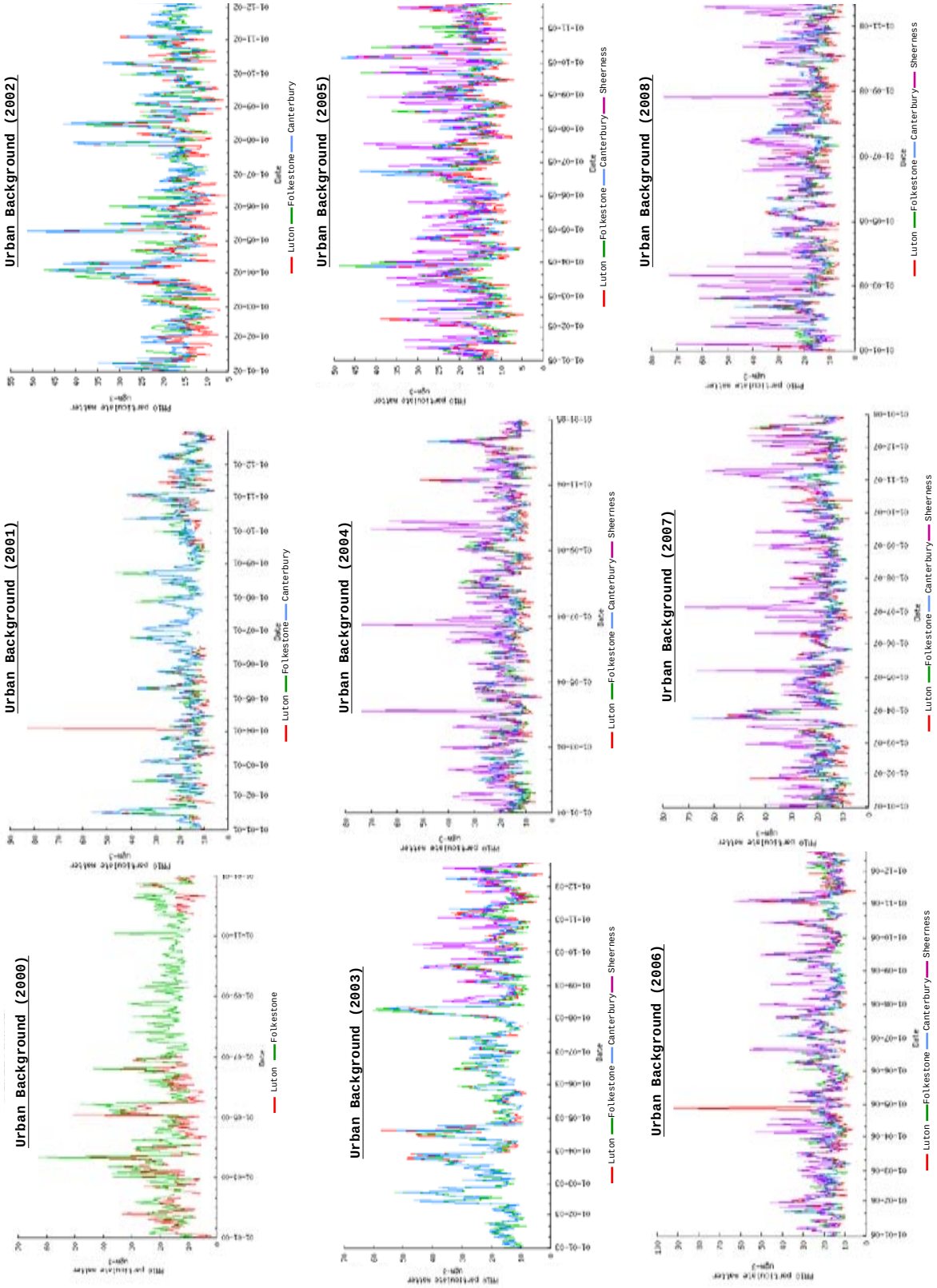
Appendix X: Sites close to London



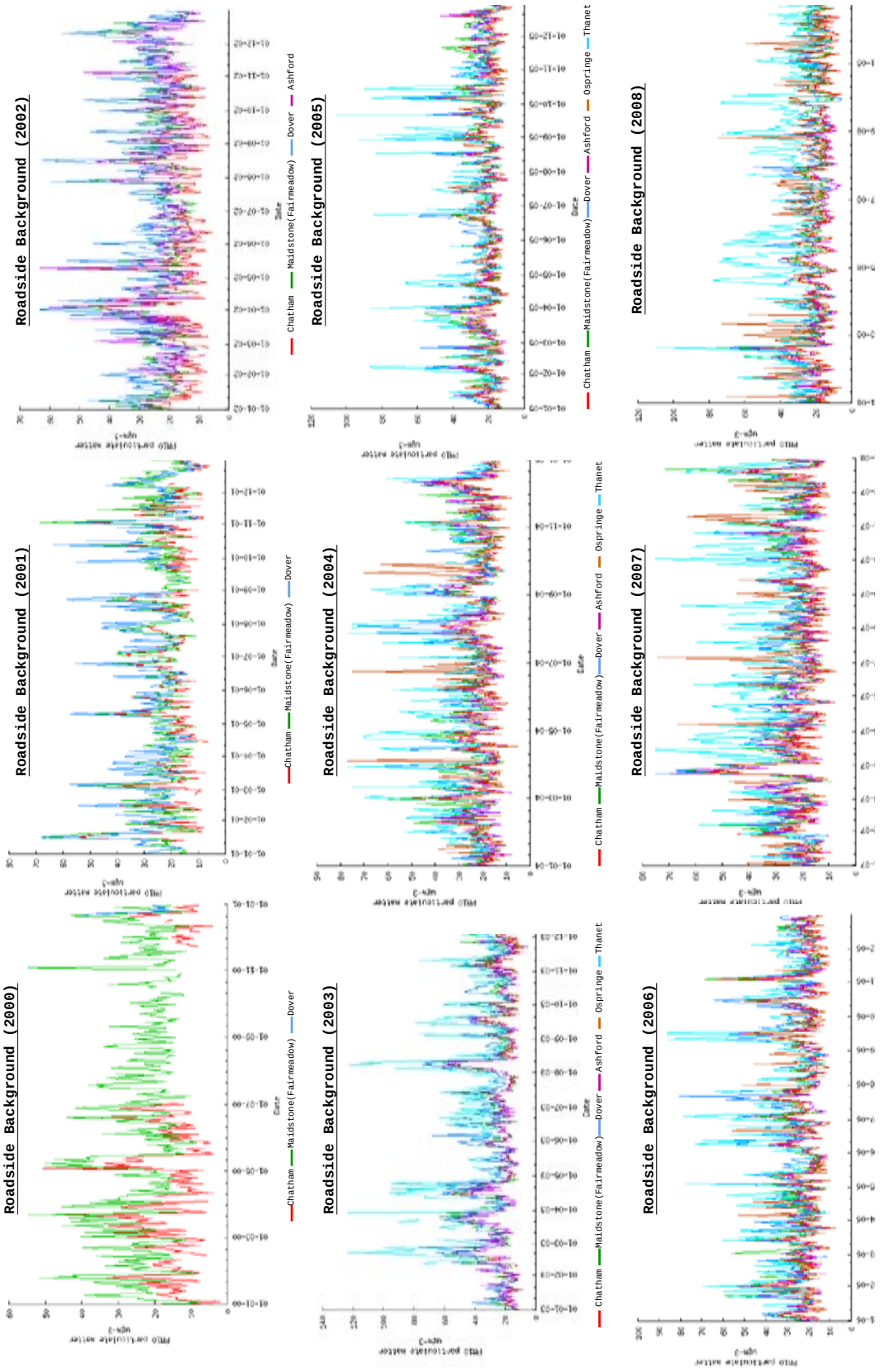
Appendix Y: Rural background



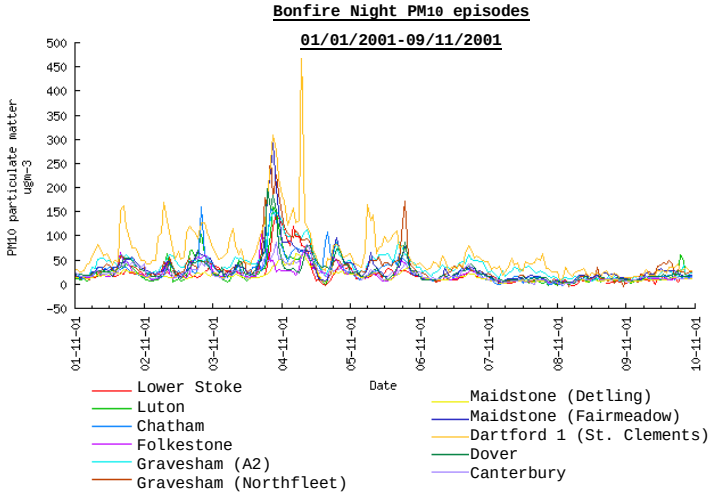
Appendix Z: Urban background

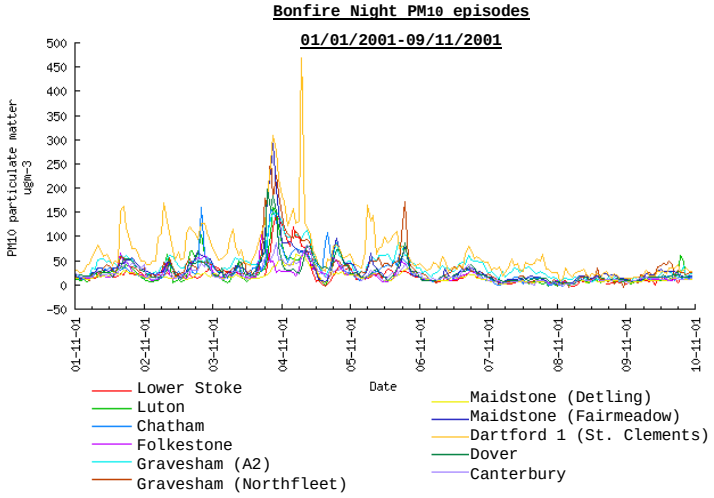


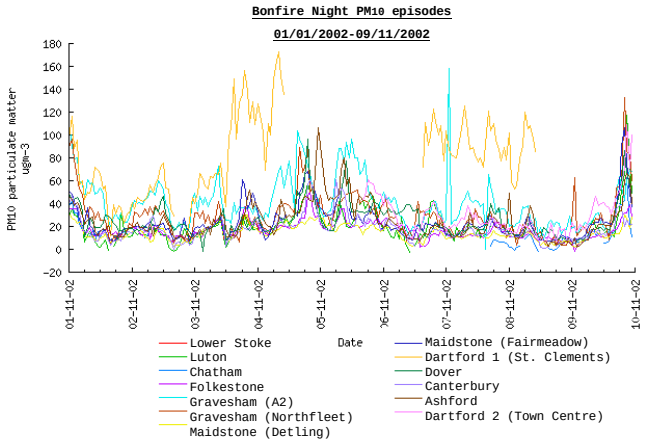
Appendix AA: Roadside background

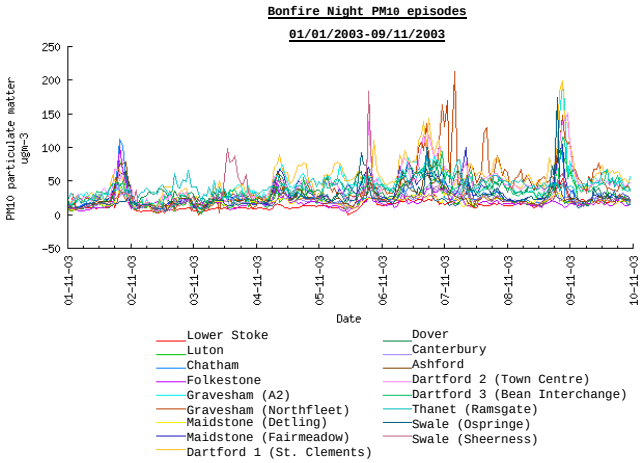


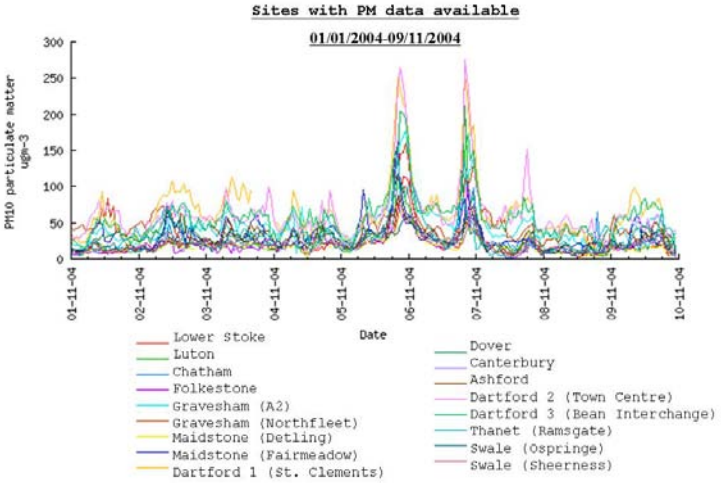
Appendix AB: Bonfire Night (2000-2008)

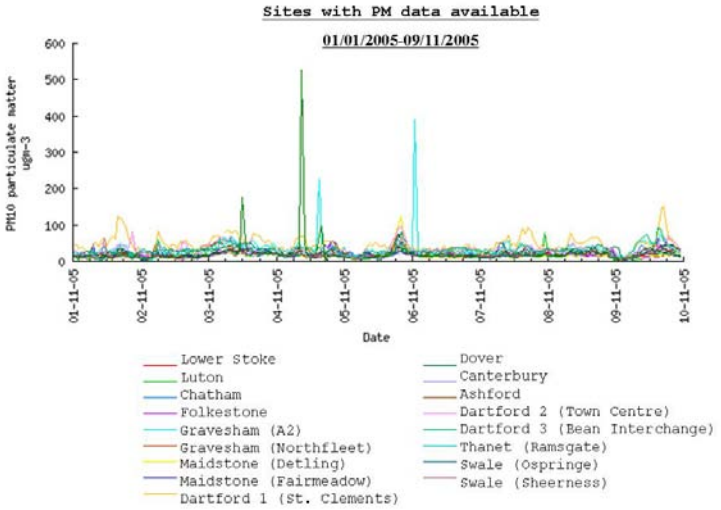


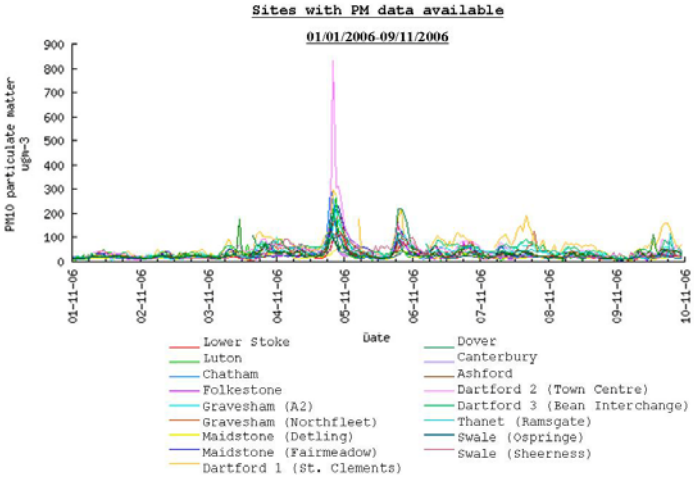


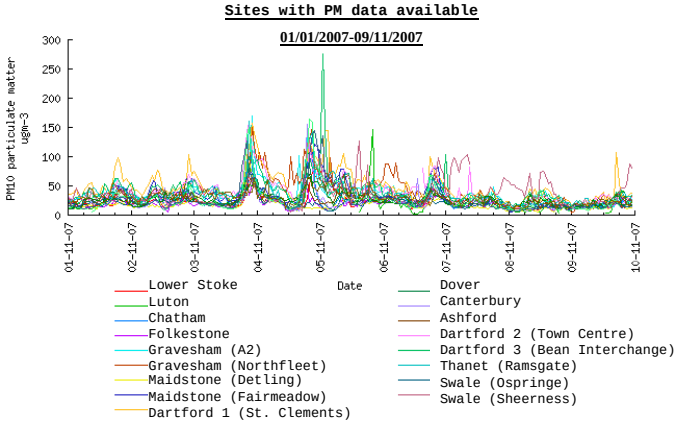


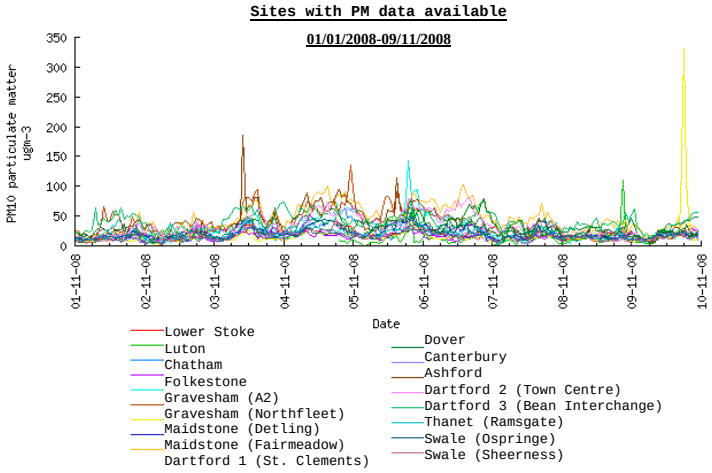

Bonfire Night PM10 episodes
01/01/2003-09/11/2003
PM10 particulate matter ugm-3
Date
Lower Stoke
Luton
Chatham
Folkestone
Gravesham (A2)
Gravesham (Northfleet)
Maidstone (Detling)
Maidstone (Fairmeadow)
Dartford 1 (St. Clements)
Dover
Canterbury
Ashford
Dartford 2 (Town Centre)
Dartford 3 (Bean Interchange)
Thanet (Ramsgate)
Swale (Ospringe)
Swale (Sheerness)


Sites with PM data available
01/01/2004-09/11/2004
PM10 particulate matter ugm-3
Date
Lower Stoke
Luton
Chatham
Folkestone
Gravesham (A2)
Gravesham (Northfleet)
Maidstone (Detling)
Maidstone (Fairmeadow)
Dartford 1 (St. Clements)
Dover
Canterbury
Ashford
Dartford 2 (Town Centre)
Dartford 3 (Bean Interchange)
Thanet (Ramsgate)
Swale (Ospringe)
Swale (Sheerness)


Sites with PM data available
01/01/2005-09/11/2005
PM10 particulate matter ugm-3
Date
Lower Stoke
Luton
Chatham
Folkestone
Gravesham (A2)
Gravesham (Northfleet)
Maidstone (Detling)
Maidstone (Fairmeadow)
Dartford 1 (St. Clements)
Dover
Canterbury
Ashford
Dartford 2 (Town Centre)
Dartford 3 (Bean Interchange)
Thanet (Ramsgate)
Swale (Ospringe)
Swale (Sheerness)


Sites with PM data available
01/01/2006-09/11/2006
PM10 particulate matter ugm-3
Date
Lower Stoke
Luton
Chatham
Folkestone
Gravesham (A2)
Gravesham (Northfleet)
Maidstone (Detling)
Maidstone (Fairmeadow)
Dartford 1 (St. Clements)
Dover
Canterbury
Ashford
Dartford 2 (Town Centre)
Dartford 3 (Bean Interchange)
Thanet (Ramsgate)
Swale (Ospringe)
Swale (Sheerness)


Sites with PM data available
01/01/2007-09/11/2007
PM10 particulate matter ugm-3
Date
Lower Stoke
Luton
Chatham
Folkestone
Gravesham (A2)
Gravesham (Northfleet)
Maidstone (Detling)
Maidstone (Fairmeadow)
Dartford 1 (St. Clements)
Dover
Canterbury
Ashford
Dartford 2 (Town Centre)
Dartford 3 (Bean Interchange)
Thanet (Ramsgate)
Swale (Ospringe)
Swale (Sheerness)


Sites with PM data available
01/01/2008-09/11/2008
PM10 particulate matter ugm-3
Date
Lower Stoke
Luton
Chatham
Folkestone
Gravesham (A2)
Gravesham (Northfleet)
Maidstone (Detling)
Maidstone (Fairmeadow)
Dartford 1 (St. Clements)
Dover
Canterbury
Ashford
Dartford 2 (Town Centre)
Dartford 3 (Bean Interchange)
Thanet (Ramsgate)
Swale (Ospringe)
Swale (Sheerness)