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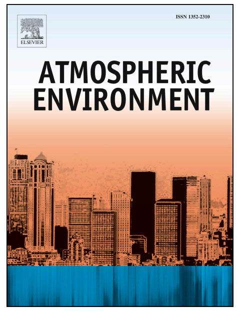

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PII: S1352-2310(14)00950-9

DOI: 10.1016/j.atmosenv.2014.11.071

Reference: AEA 13452

To appear in: *Atmospheric Environment*

Received Date: 14 July 2014

Revised Date: 21 November 2014

Accepted Date: 23 November 2014

Please cite this article as: Djambazov, G., Pericleous, K., Modelled Atmospheric Contribution to Nitrogen Eutrophication in the English Channel and the Southern North Sea, *Atmospheric Environment* (2015), doi: 10.1016/j.atmosenv.2014.11.071.

Modelled Atmospheric Contribution to Nitrogen Eutrophication in the English Channel and the Southern North Sea

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Abstract

Eutrophication of the coastal waters results in algal blooms which may be harmful to the marine ecosystem and coastal economy. The main sources of nutrients are the rivers but an unquantified amount of nitrogen is also transported from ground sources via the atmosphere and deposited to the sea directly by rain and turbulent diffusion. A Lagrangian Particle Dispersion (LPD) model based on the open source code FLEXPART (http://flexpart.eu) is described that quantifies the dissolved nitrogen coming from the air in the English Channel and Southern North Sea (the '2Seas' geographical region). The model uses meteorological records, emissions data and LPD computations to simulate the motion and deposition of nitrogen compounds. The emission sources contributing to the deposition are individually identified, and calculated concentrations are compared with ground measurements in selected locations. The highest calculated atmospheric depositions to the sea in the considered region are found to be along the Belgium-Netherlands coast.

Keywords: atmospheric transport; pollutants; eutrophication; Lagrangian particle dispersion

1. Introduction

Nutrient enrichment of estuaries and coastal waters by human activities causes phytoplankton and algae to grow more than it would do otherwise (e.g. Peierls, 1991; Anderson, 2002). Provided adequate light is available, phosphorus and nitrogen are the nutrients that limit phytoplankton growth in aquatic systems, and primary production in estuaries and coastal waters is thought to be limited by nitrogen availability (Anderson, 2002). In contrast, freshwater phytoplankton tends to be limited by phosphorus availability, although the extent and severity of nitrogen limitation remains open to question (Hecky, 1988; Boynton, 1982; Nedwell, 2002) and in situations where light penetration is poor as in turbid estuarine and coastal waters, even high nutrient concentrations may not lead to significant algal growth. As a societal problem, eutrophication and consequent algal overgrowth has several undesirable socioeconomic and environmental consequences. The additional growth does not enter the marine food chain and by decaying depletes the water of oxygen and thus causes harm to marine life. Another side effect of the decay is unsightly foam on the beaches, which affects tourism and dependant commercial activities.

Groundwater transport constitutes the main source of eutrophicants and therefore the main target of regulative corrective measures (Anderson, 2002). Nevertheless, atmospheric deposition is also significant adding from 300 to 1000 mg Nm^{-2} yr^{-1} to coastal waters in biologically active forms NO_x, NH_3/NH_4^+, and in dissolved organic nitrogen (Paerl, 1997). Atmospheric tracer-based model results show that atmospheric deposition accounts for 6% of the external nitrogen inputs in the North Sea (Troost, 2013). This percentage however is shown to vary strongly with region. For example, in the OSPAR area NL-O2 (OSPAR, 2013), 16% of the total nitrogen originates from atmospheric deposition. Furthermore, model

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results show that primary production rates are disproportionately affected by atmospheric deposition, possibly due to a change in the carbon-to-nitrogen ratio (Troost, 2013). Budgeting approaches (Spokes, 2005) suggest that the atmosphere can in some situations provide enough nitrogen to produce a large increase in phytoplankton growth. The modelled regional and temporal variation reflects the highly episodic nature of atmospheric deposition and the strong gradients away from source regions.

A parallel study in the Baltic Sea shows that atmospheric deposition, primarily from burning fossil fuels (land based and shipping), accounts for 25 % of nitrogen input (WRI, 2014). Even more significant atmospheric contributions were found in Chesapeake Bay, U.S (up to 30% of all nitrogen inputs) and in some other areas in the U.S. North Atlantic, where atmospheric deposition of nitrogen can exceed riverine nitrogen inputs to coastal areas (Spokes, 2005). It is evident from these observations, that the atmospheric contribution is an essential part of any inventory of nutrients leading to algal growth.

As stated above, the nutrients phytoplankton species need are inorganic compounds of nitrogen, phosphorus and silicon. Of these only nitrogen-bearing compounds such as nitrogen oxides and ammonia, being gases, can be airborne in significant quantities. While in some cases of blooming phytoplankton the availability of phosphorus may be the growth-limiting factor (Ly, 2014), nitrogen may still play a part for some species. So a model of the atmospheric input of eutrophicants is a valuable tool in the study, prediction and prevention of harmful algal blooms.

This paper is an illustration of how the three main components of such a model – weather data, emissions data and computer simulations – can be combined into a working tool for quantitative estimates of the atmospheric inputs.

2. Lagrangian Transport Computer Model

Emitted nitrogen-containing gases are carried and dispersed by the wind before being deposited to the ground or sea. A publically available, open source software package FLEXPART (Stohl, 2005) implementing the Lagrangian Particle Dispersion method is used in this study. It can simulate the movement of pollutants in the atmosphere and includes also algorithms for determining the rates of their deposition onto various surfaces (e.g. Plainiotis 2005a, 2005b, 2010). In the model, each of the traced ‘particles’ is assumed to be carrying a certain quantity of the investigated substance. Concentrations are calculated after dispersion by atmospheric turbulence is taken into account. From the concentrations, using specific deposition properties of each traced gas, deposited quantities are calculated on a user-prescribed grid.

2.1 *FLEXPART Equations*

2.1.1 Particle trajectory calculations

The trajectory equation (Stohl, 1998)

$$\frac{d\boldsymbol{X}}{dt} = \boldsymbol{v}[\boldsymbol{X}(t)]$$

with $\boldsymbol{X}$ the position vector, $\boldsymbol{v}$ the particle velocity, t the time and Δt the time step is integrated using the “zero acceleration” scheme

$$\boldsymbol{X}(t + \Delta t) = \boldsymbol{X}(\boldsymbol{t}) + \boldsymbol{v}(\boldsymbol{X}, t)\Delta t.$$

The wind vector $\boldsymbol{v} = \overline{\boldsymbol{v}} + \boldsymbol{v}_t + \boldsymbol{v}_m$ is composed of the grid-scale wind $\boldsymbol{v}$, the turbulent wind fluctuations $\boldsymbol{v}_t$ and the mesoscale wind fluctuations $\boldsymbol{v}_m$ (Stohl, 2005).

Turbulent motions are represented assuming a Markov process based on the Langevin equation (Thomson, 1987) for each turbulent wind component $\boldsymbol{v}_{t_i}$, $i = 1 \dots 3$. The formulation includes a drift term and a diffusion term which are functions of the position, the turbulent velocity and time. Cross-correlations between the different turbulent wind components are not taken into account, since they have little effect for long-range dispersion (Uliasz, 1994).

Mesoscale motions (sub-grid motions which are not turbulent in nature) need to be taken into account since they can accelerate the growth of a dispersing plume. Updrafts in convective clouds that occur in conjunction with downdrafts within the clouds and compensating subsidence in the cloud-free surroundings are modelled by a convective parameterization scheme.

2.1.2 Wet deposition

Based on the humidity and temperature from the meteorological input data, the occurrence of clouds is calculated. After that separately in-cloud and below-cloud ‘scavenging’ of the transported substances are computed in the form of an exponential decay process for the particle mass *m*:

$m(t + \Delta t) = m(t)e^{-\Lambda \Delta t}$.

For gases the *in-cloud* scavenging coefficient Λ [s^{-1}] is

$$\Lambda = \frac{I}{Hc_{eff}}$$

where I [mm/h] is the precipitation rate, H is the height over which scavenging takes place and c_{eff} is effective cloud liquid water content.

The *below-cloud* scavenging coefficient is $\Lambda = AI^B$ where both A and B are empirical parameters specific for each modelled gas. Sub-grid variability of the precipitation is also taken into account for the wet deposition via the meteorological data for ‘total cloud cover’, ‘large scale precipitation’ and ‘convective precipitation’ (Stohl, 2005).

2.1.3 Dry deposition

The downward flux due to dry deposition F_C of a species with concentration C at height z is described by a deposition velocity

$v_d(z) = -F_C/C(z)$.

For *gases* the deposition velocity is represented as the inverse of the sum of the following ‘resistances’

$$|v_d(z)| = [r_a(z) + r_b + r_c]^{-1}$$

where r_a is the aerodynamic resistance between z and the surface, r_b is the quasilaminar sublayer resistance, and r_c is the bulk surface resistance. These are calculated from the atmospheric boundary layer properties contained in the meteorological input data and from the land-use surface data within FLEXPART.

2.2 *Required input data*

The FLEXPART algorithm needs 3-dimensional, time-dependent meteorological and emissions data as input for the investigated geographical region and time period. The weather data include wind velocities, humidity, temperature, pressure, sunshine, precipitation and turbulence in the atmospheric boundary layer. The emissions inputs are in the form of a list of 4-dimensional space-time 'boxes' corresponding to the grid cells on which the emissions data are available.

3. Weather Data

Past records of the main meteorological variables for the whole world or for a chosen region can be obtained free of charge from at least two sites: the US National Centers for Environmental Prediction (NCEP, 2014) and the European Centre for Medium-Range Weather Forecasts (ECMWF, 2014). Since this work is sponsored by a European project (ISECA, 2014), preference was given to the latter, also because FLEXPART contains a direct interface to the ECMWF data. The recommended frequency of weather records for best accuracy in FLEXPART is one every 3 hours; however both analyses are available in 6-hour periods and, bearing in mind that the eutrophication simulations should cover many weeks and months, the 6-hour interval was assumed.

The best spatial resolution for publicly available weather records is on a regular grid with 0.75 degree spacing in the ERA-Interim reanalysis (ECMWF, 2014). Vertically, the resolution of this dataset is 60 levels covering the troposphere and the lower stratosphere where atmospheric transport occurs. Choosing a suitable domain covering Western Europe helps keep these data files to a manageable size (about 2 megabytes, unzipped, for each 3D record). Avoiding too wide a region means less downloading time for the weather data. The selected geographical area contains the English Channel and the southern part of the North Sea which is the object of the present study and includes the surrounding land masses, i.e. the '2Seas' Region (INTERREG, 2014). Bearing in mind that nitrogen oxides will be one of the main species whose transport needs to be modelled, the domain is extended eastwards to include the heavily industrialised western Germany (12^{o} E). A similar span is chosen to the west of the Dover Straights (9^{o} W) and the south and north boundaries are chosen to include most of France and Britain (44^{o} N to 57^{o} N). All the data are in binary format and a decoding software package (GRIB_API) is freely and publicly available from ECMWF for use in FLEXPART (e.g. Plainiotis, 2010).

Full three-dimensional values are obtained for temperature, eastward and northward wind velocity components, vertical velocity and humidity. Two-dimensional (surface) data are needed for atmospheric pressure, terrain height, solar radiation, cloud cover, precipitation, heat flux, horizontal components of turbulent stress and dew-point temperature. The three-dimensional variables were downloaded in three groups (due to server file size limitations), one month worth of data at a time, and the 2D surface variables appear in two other groups (analysis and 12-hour forecasts, for some accumulated variables) also in monthly files. Decoding, de-accumulation (of precipitation and boundary turbulence data) and regrouping were carried out to form the 6-hourly records needed by FLEXPART. Figure 1 illustrates the vertical and temporal (during one month) profile of the wind data at one point of the grid located in the English Channel. In total, two full years (2009 and 2011) of meteorological records were downloaded and pre-processed for use with FLEXPART. Refinement of the horizontal resolution of the weather data was tested with the publicly available software package (WRF, 2014) but this was considered unnecessary for eutrophication studies and is not presented here.

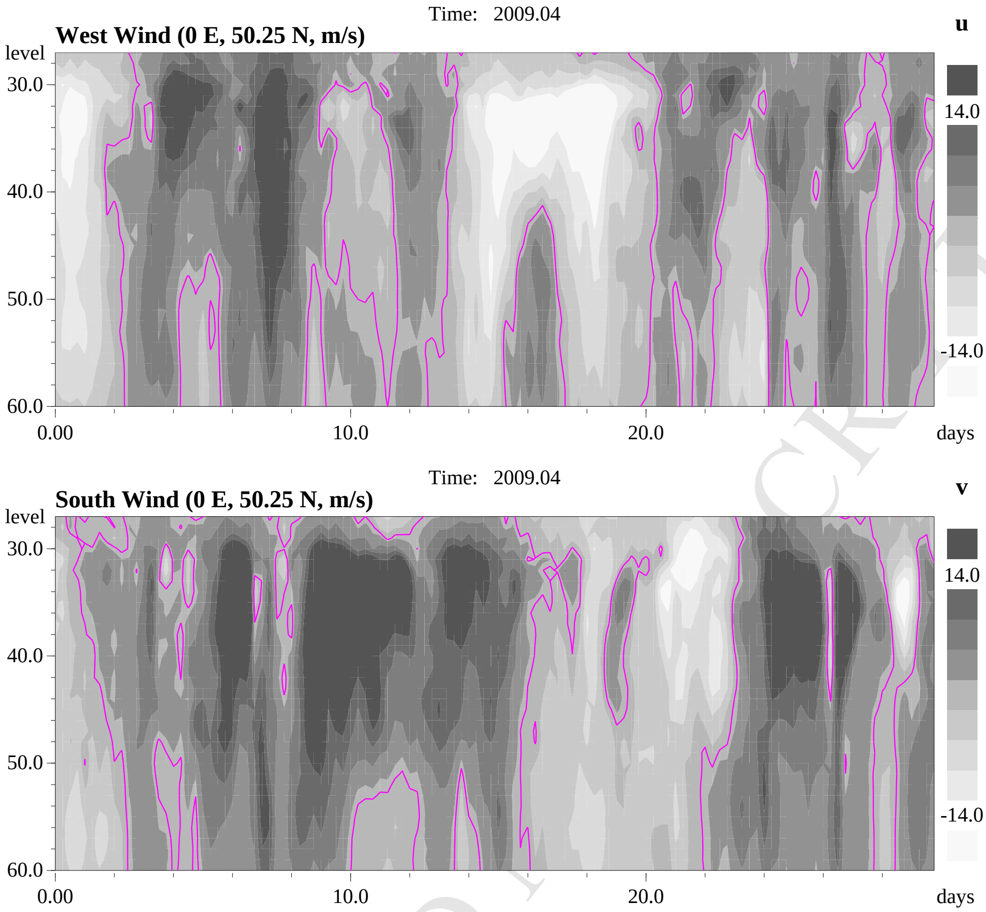

Figure 1. Wind components (u – eastward, v – northward) sample vertical record in April 2009 for 0°E, 50.25°W. The strongest winds at around model level 37 form the jet stream; level 60 is the ground.

4. Emissions

4. 1 *Coarse-Grid EMEP Data*

The European Monitoring and Evaluation Programme (EMEP) maintain a website (WebDab, 2014) with *freely* available gridded emissions data for the main air pollutants including nitrogen oxides and ammonia. Yearly emitted quantities (Figure 2) are currently offered on a 50 km by 50km grid (EMEP, 2014) and a new fine grid with 0.1 degree resolution (CEIP, 2015) is planned from 2015 onwards. The data are compiled from the yearly reports of the participating countries and can be very useful for atmospheric transport eutrophication modelling. One can see in Figure 2 that the highest nitrogen oxides emissions are around cities and industrial areas while the highest ammonia emissions are in agricultural areas. In this study proprietary fine-grid data were available (see next subsection) and they were used in place of the EMEP emissions.

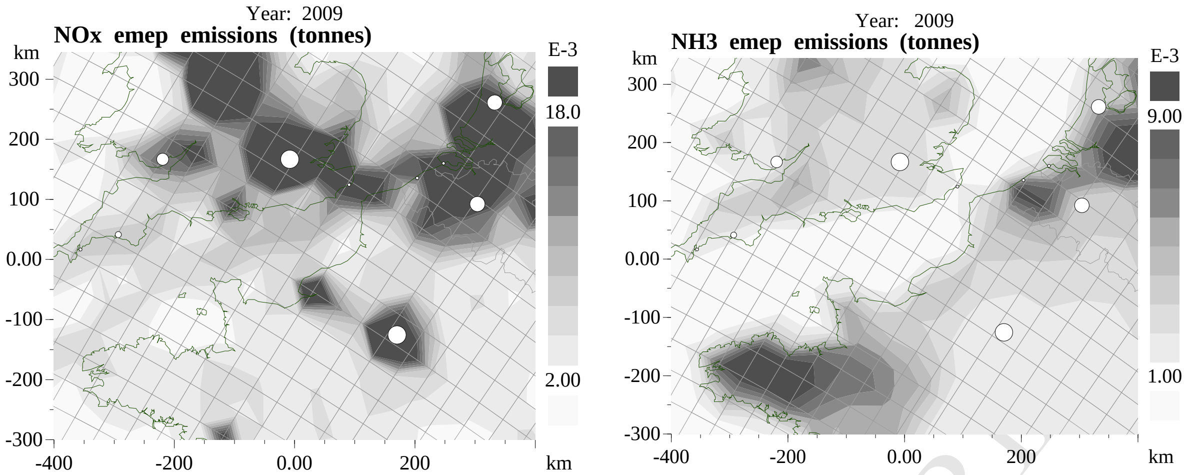

Figure 2. Emission of nitrogen oxides (left) and ammonia (right) as used in EMEP models (tonnes/year) in 2009. The white circles here and below show the cities of Cardiff, London, Paris, Brussels and Amsterdam.

4.2 *Fine Grid*

As part of the (ISECA, 2014) project, one of the partners - the Flemish Institute for Technological Research (VITO) – provided its refined database to be included in the simulations whose results are presented here. The fine grid of this database is 7x7 km. Emissions time profiles were also provided representing the daily, weekly and seasonal cycles. The fine-gridded data are derived from the country-reported totals and from information about what is where on the ground using a unique algorithm (Maes et al., 2009). In order to highlight the local contribution to local eutrophication, only sources within the ISECA target region (-6 to 7^{o}E, 48 to 54^{o}N) are included in the simulations. The emitted quantities are classified in the database in categories (SNAP sectors) according to the Standard Nomenclature for Atmospheric Pollutants (SNAP, 2014). Figure 3 shows the overall quantities emitted in the ISECA region for each sector for the years selected in the database.

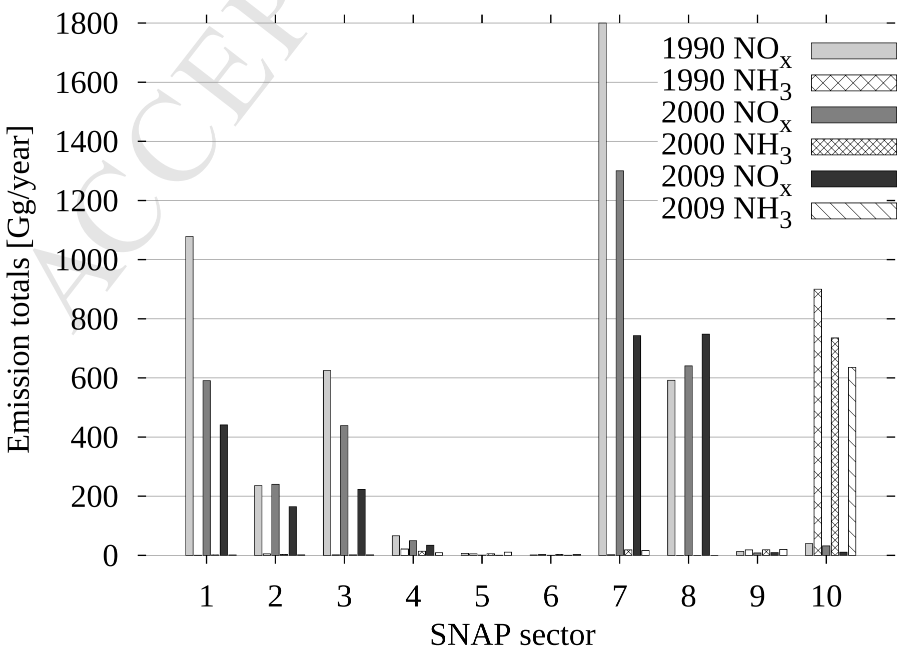

Figure 3. Fine grid emissions totals (Gg/year) for each Standard Nomenclature for Atmospheric Pollutants (SNAP) sector in the ISECA target region for representative years 1990, 2000 and 2009

It can be seen the main contributors in this geographical region are ‘Combustion in energy and transformation industries’ (SNAP sector 1), ‘Non-industrial combustion plants’ (SNAP sector 2), ‘Combustion in manufacturing industry’ (SNAP sector 3), ‘Road transport’ (SNAP sector 7), ‘Other mobile sources and machinery’ (SNAP sector 8) and ‘Agriculture’ for ammonia (SNAP sector 10). These are the data sources used to obtain the results presented in Section 6. Most nitrogen oxides and ammonia emissions exhibit downward trends over the years; the only exception is SNAP sector 8 which includes shipping through the Dover Straights which is on the increase.

5. Model Validation

The concentrations calculated by FLEXPART at a number of prescribed receptor points on the ground can be used to check the simulation results against available measurements.
The publicly available European Air Quality Database (AirBase, 2014) maintained by the European Environment Agency was used to obtain measurement data for nitrogen oxides concentrations from selected observation sites for the year 2009. (That is the latest year for which fine-grid emissions data were available within the ISECA project.) A denser network of measuring stations (KentAir, 2014) at various locations in Kent, UK also offers free data for that region but AirBase was chosen for the validation because it includes stations from different countries under the same format. Out of the many monitoring stations in the dataset, a few suburban and rural sites (located near the coast in the target region) were selected (Table 1) because the others, indicated in the database as being situated by roads, would show local variations that are not represented in the model.

Table 1. Monitoring stations and model statistics

Station Code	Town/Place	Pollutant	Station Type	East deg	North deg	Height m	RMSE, normalised	Bias, normalised	Correl. coeff.
BETN012	Moerkerke	NO_x	suburban	3.36	51.26	3	0.68	-0.26	0.79
BETN029	Veurne	NO_x	rural	2.58	51.02	2	0.76	-0.31	0.72
FR10007	St. Pol-Mer	NO_2	suburban	2.34	51.03	3	1.06	0.78	0.77
FR10012	Mardyck	NO_2	industrial	2.25	51.02	4	1.1	0.77	0.67
FR10025	Sangatte	NO_2	suburban	1.77	50.95	2	0.99	0.33	0.64
FR10029	Cappelle	NO_2	urban	2.36	51.00	2	1.13	0.88	0.77
FR10032	Outreau	NO_2	suburban	1.58	50.69	54	0.72	-0.14	0.76
GB0038R	Lullington	NO_x	rural	0.18	50.79	125	1.03	0.12	0.61
GB0617A	Rochester	NO_x	rural	0.63	51.46	14	1.27	0.70	0.71
GB0737A	Canterbury	NO_x	urban	1.10	51.27	35	0.84	-0.36	0.66
NL00235	Huijbergen	NO_x	rural	4.36	51.44	18	0.77	-0.04	0.64
NL00301	Zierikzee	NO_x	rural	3.92	51.64	-1	0.63	-0.19	0.83
NL00437	Westmaas	NO_x	rural	4.45	51.79	-1	0.62	-0.18	0.81

The statistical quantities indicating the modelling quality (Thunis, 2012) for the whole of 2009 and shown in Table 1 for comparison of the model calculations with station measurements are the following: *RMSE, normalised* – root mean square error divided by the standard deviation (SD) of the observations; *Bias, normalised* – mean bias of the model divided by observations SD; *Corel. coeff.* – Pearson correlation coefficient of daily model results and measured data. The model calculations are for total nitrogen oxides (NO_x)

expressed as NO_2. However the French stations in the table report only the concentrations of NO_2, hence the positive bias of the model results.

It should be noted, that the model does not include far-away sources. For example, if nitrogen oxides emitted to the west of the 2Seas target region are carried by the wind and some atmospheric process (e.g. rain) causes the deposition of substantial amounts within the region, this will not be picked up by the current model. This explains the predominantly negative bias for stations reporting NO_x.

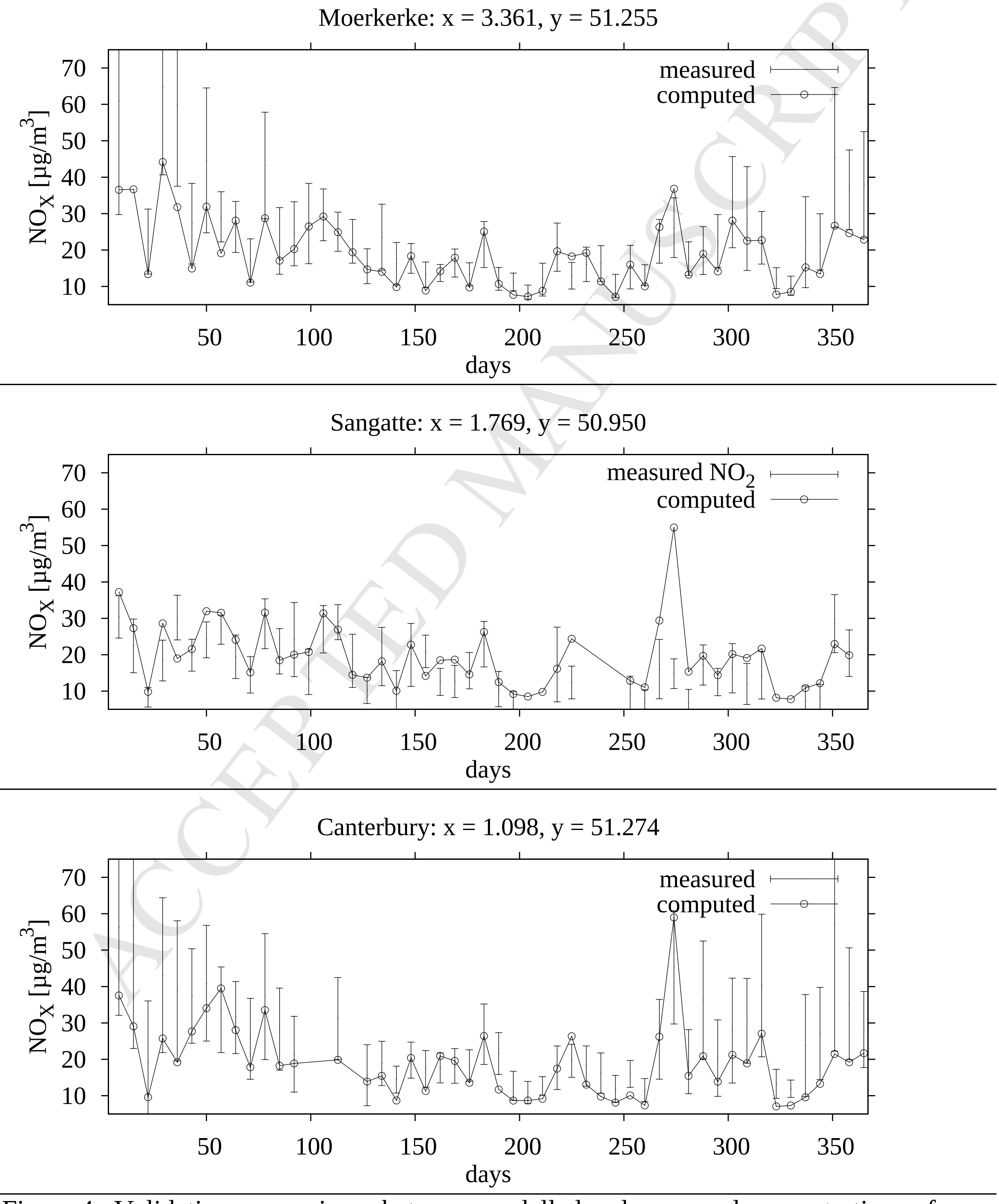

Figure 4. Validation comparisons between modelled and measured concentrations of nitrogen oxides (weekly averages at selected stations) in 2009

The comparison in Figure 4 shows weekly concentration averages of nitrogen oxides (as NO_2, in micrograms per cubic metre) at some of the monitoring stations from Table 1. The error-bars of the measured quantities represent the standard deviation of the observations calculated within each weekly average from the reported hourly measurements. The corresponding calculated values are the means of 7 daily results output by Flexpart which are themselves daily concentration averages.

The graphs (Figure 4) and the correlations (Table 1) show that the computed results generally exhibit the right trends and are in the right range of values. Overall, the model accuracy is acceptable for the stated purpose of showing the contribution of the local sources to the eutrophication in the chosen target region.

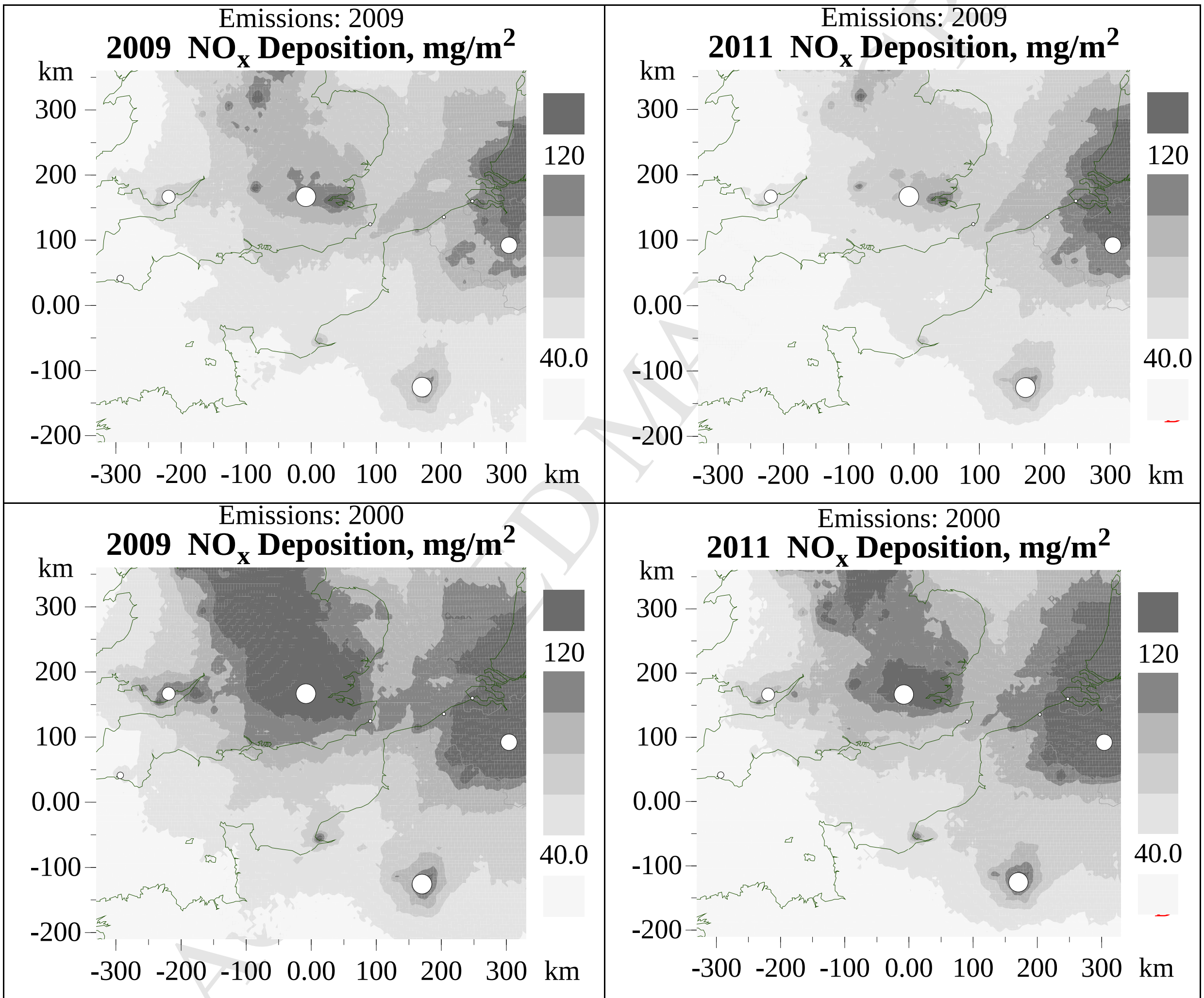

Figure 5. Nitrogen oxides modelled scenarios in the 2Seas region

6. Computed Depositions

The results of the computer modelling of the transport by air of nitrogen oxides and ammonia from their sources to the coastal waters in the 2Seas region are presented here. The computer model uses weather data and emissions data to calculate the transport and deposition of these nitrogen containing gases. The examples provided are for emissions in 2000 and 2009 and historical weather data for 2009 and 2011. All four combinations between these emission and simulation years are included, so that comparisons can be made and the effect of both the emissions and the weather can be demonstrated. As mentioned previously, only sources in the ISECA chosen window (-6 to7°E, 48 to 54°N) are included in the simulations - to highlight the local contribution to local eutrophication. In Figures 5 and 7 total annual deposited quantities are shown for nitrogen oxides and ammonia. Figure 6 presents the 2009 NO_x deposits which are only due to shipping and other mobile machinery, excluding road transport (SNAP sector 8).

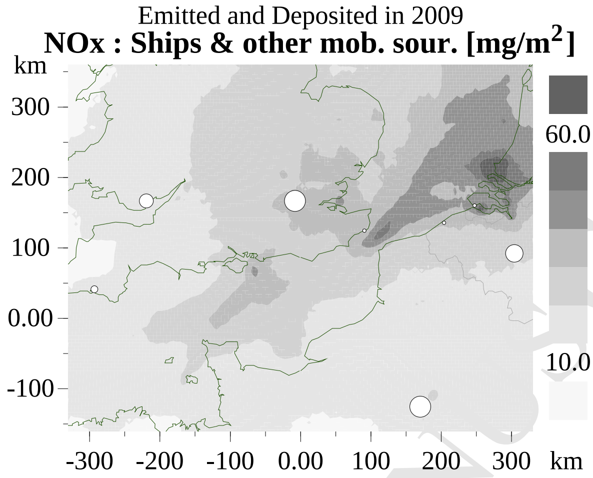

Figure 6. Modelled 2009 nitrogen oxides deposits from shipping and other (non-road) mobile emitters (SNAP sector 8)

7. Analysis and Discussion

The significantly higher NO_x emissions in 2000 compared to 2009 (Figure 3) result in visible increase in the computed depositions in Figure 5, while for ammonia the difference in both emissions and depositions (Figure 7) is much smaller. However, the deposited amounts of ammonia are 7.5 times higher than the corresponding NO_x depositions. This can be explained with the fact that ammonia is a hydrophilic compound, i.e. the Henry's law constant (FLEXPART, 2014) for ammonia is many times higher than the corresponding one for nitrogen oxides.

In Figure 6, showing the deposition map for SNAP sector 8, the busiest shipping routes through the narrow Strait of Dover as well as the seaborne traffic surrounding the port areas of Antwerp and Rotterdam dominate deposition and become visible on the contour plot. The high deposition rate is due first to the fact that shipping is the main pollutant within SNAP sector 8 and, second, as the smoke of the ships engines is dragged by the ship's wake over the sea surface, it has greater chance to react with the water directly while inland emissions undergo a longer cycle of transport to the clouds and deposition with the rain.

The influence of the weather on the atmospheric deposition of nitrogen nutrients can be seen by comparing the left and right halves of Figures 5 and 7: 2011 was drier than 2009 (illustrated in Figure 8 showing actual recorded rainfall in three UK locations) which results in lower deposits, especially of NO_x. Most pronounced are the differences in nitrogen oxides depositions over England where the 2011 quantities are on average with 20 mg/m^2 lower than in 2009. The quantities emitted within the model domain but not deposited there are transported by the wind across the domain boundaries.

The model set-up is operational; new meteorological data can be freely downloaded and further simulations can be done with either free or proprietary emissions data as needed. It is quite possible to run the model with emissions data available from previous years (e.g. from EMEP) and with current meteorological data – in this way estimates can be made of the atmospheric input (e.g. during the winter months) which can help predict the occurrence of potentially harmful algal blooms in the spring.

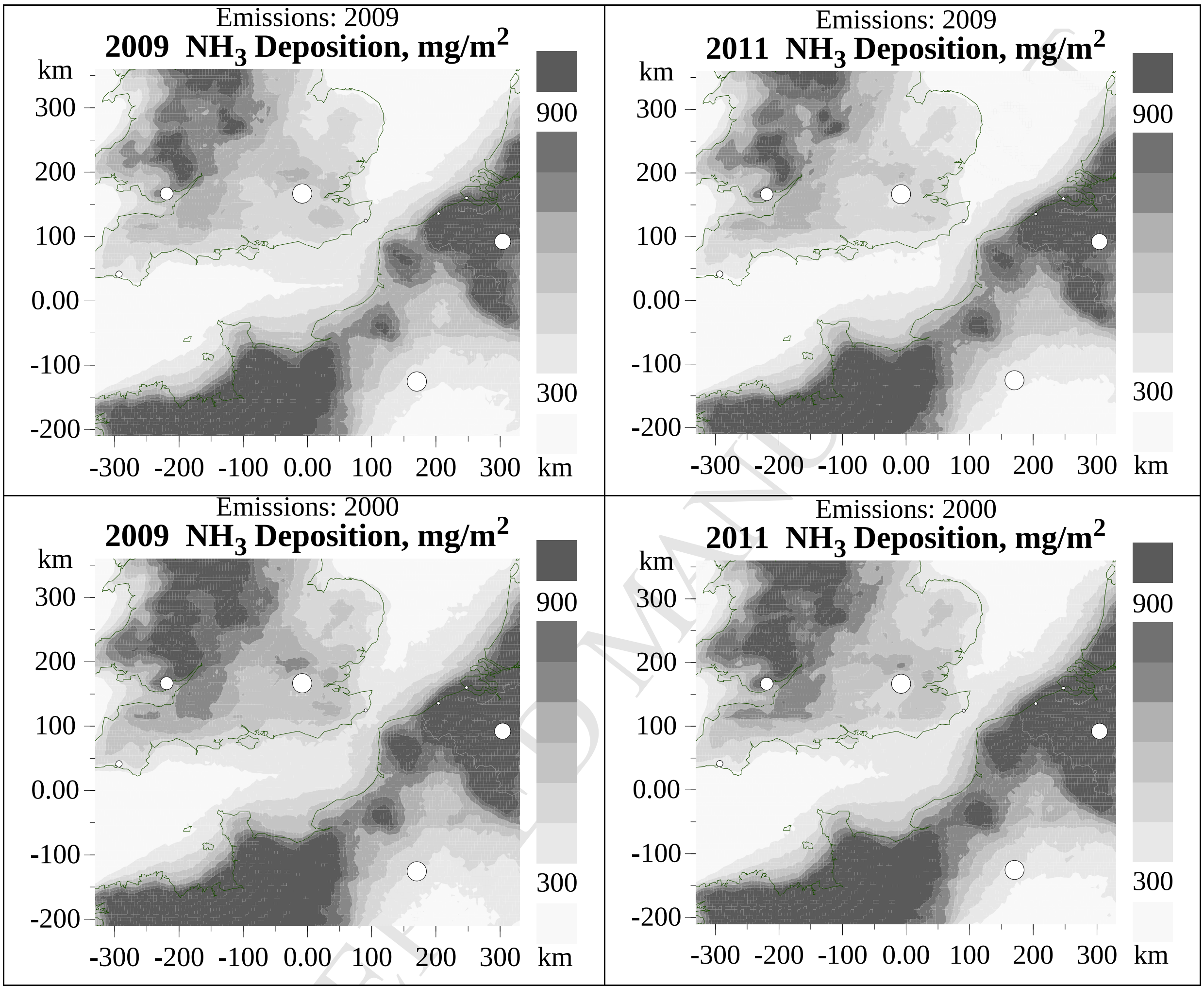

Figure 7. Ammonia modelled scenarios in the 2Seas region

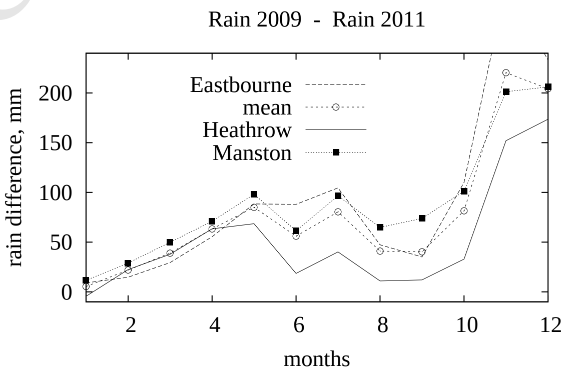

Figure 8. Difference in monthly rainfall over south-east England between 2009 and 2011, source: (Met Office, 2014)

The simulation results can be used in a number of ways to highlight various aspects of the problem of coastal waters eutrophication: The combined contribution all SNAP sectors from the sources in the chosen region can be displayed graphically (as in Figures 5, 7) or numerically for the areas of interest. The effect of any of the SNAP sectors can be traced individually (as in Figure 6). The emitted quantities which have not been deposited within the target domain but are transported through its boundaries are recorded over the duration of the simulation and can be analysed. The effect of the weather can be investigated by running the same emissions with meteorological data from two or more different years (as in Figures 5 and 7).

The presented results show that, of all seas in the investigated region, the coastal areas of Belgium and the Netherlands receive the highest depositions of both NO_x and ammonia. These atmospheric deposits are in addition to the riverine inputs as shown by other models (Vermaat, 2012; Shutler, 2011; Lacroix, 2007). Those models, backed by satellite observations, indicate the waters near the continental coast (French, Belgian and Dutch) of the eastern English Channel and the southern North Sea as usually having the highest concentrations of chlorophyll-*a* which means those are the zones with the most severe eutrophication in the 2Seas region. So the atmospheric depositions contribute to making that eutrophication even worse.

Further improvement of the model is possible in the following ways. The meteorological time-step can be reduced from 6 hours to the recommended 3 hours (Stohl, 2005). In the ERA-Interim dataset (ECMWF, 2014), 3-hourly records are available as short-term (12-hour) forecasts run twice daily. Although this shorter time-step is more appropriate for tracing single pollution events, the enhanced accuracy may be useful for estimating the atmospheric input of nutrients to the sea water in the days and weeks immediately preceding an algal bloom (e.g. in April; Lacroix, 2007). Around critical emitting areas, e.g. Brittany in France where significant quantities of ammonia is released by agriculture (Figure 2, right), it may be appropriate to refine the resolution of the weather information with the help of a numerical weather prediction package (WRF, 2014). In such a way the tendency of ammonia to be deposited nearer to the source will be better resolved and the estimate of this route of eutrophication of the surrounding seas will become more accurate. In one or two years, when emissions data with the improved spatial resolution of 0.1 degrees become freely available (CEIP, 2015), the model can be adjusted to provide better estimates (with or without WRF weather refinement) of the local polluters' contribution to the local eutrophication in selected regions. Then comparisons can be made with the trans-boundary pollution calculated and reported by EMEP thus helping local policy decisions.

8. Conclusions

A model of the atmospheric transport of pollutants responsible for eutrophication has been constructed, which couples the effects of pollution emitting sources within the area of interest, with weather dynamics. A Lagrangian Particle Dispersion approach is used (the code FLEXPART) to model atmospheric transport and deposition. With emissions databases which contain information about the types of pollutant sources (e.g. SNAP sectors) the model can distinguish between the various emission sources highlighting their contribution to the deposited quantities. In this way the effect of different industrial sectors and agriculture on airborne eutrophication can be estimated. A discretisation that employs coarse-grid weather data and fine-grid emissions data shows that: (a) Ammonia is responsible for the largest share of nitrogen deposits from the atmosphere. This can be explained with the fact that, being more soluble, ammonia is deposited more easily and nearer the sources. Overall, agriculture contributes more (in the form of ammonia) than all the local NO_x sources. (b) In contrast, nitrogen oxide emissions are more likely to leave the region and be deposited elsewhere. (Far-away emissions which may be carried by the wind and be deposited in the 2Seas region are not part of these simulations.) (c) Heavy nutrient load from the atmosphere to the coastal waters of Belgium and the Netherlands is observed in the considered model scenarios.

When used with near real-time weather data (freely available from ECMWF) the presented model can, in conjunction with other models for the riverine input of nutrients, be used to forecast algal blooms in the eastern English Channel and the southern North Sea. Alternatively, retrospective calculations with historical weather records can help analyse and understand the mechanisms and evolution of the atmospheric part of the eutrophication phenomenon.

Acknowledgments

This work forms part of the project ISECA, Part-financed by ERDF through the Interreg IV A 2-Seas Programme "Investing in your Future"

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Weather data, emissions data and Lagrangian computations form the numerical model.

Deposition maps in a target geographical region are produced and compared.

Individual polluting industrial or transport sectors can be traced.

Atmospheric deposition of nitrogen eutrophicants increases in wet weather.

Heaviest atmospheric deposition adds to high riverine input in some coastal regions.