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AIRBORNE LOAD OF NITROGEN TO EUROPEAN SEAS

DEPOZYCJA AZOTU Z ATMOSFERY DO MÓRZ EUROPEJSKICH

Summary: Atmospheric deposition of nitrogen is an important source of nutrients to the sea, accounting for approximately 30% of the total nitrogen load, which in addition includes input from the rivers and direct discharges. The excess of nutrients in the sea water is causing eutrophication which is a common problem for the European seas. Therefore, atmospheric nitrogen deposition to the seas has been monitored since 1980s, with the help of measurements only at the beginning and with the help of models later on and at present. The results of the Unified EMEP model are presented for the period 1995-2005. Computed annual wet and dry depositions of oxidized and reduced nitrogen to the Baltic Sea, to the North Sea, to the Mediterranean Sea and to the Black Sea are analysed, as well as the main emission sources responsible for the deposition. In addition, some indications concerning future scenarios for the airborne load of nitrogen to European seas are given.

Keywords: nitrogen, deposition, European seas, eutrophication

Introduction

Water and air pollution entering the European seas are responsible for many environmental problems. One of them is eutrophication. In the 1800s, water in the European seas was relatively clear. Since then, environment in the seas has changed into mostly eutrophic. Nitrogen and phosphorus are among the main growth limiting nutrients and as such do not pose any direct hazards to marine organisms. However, a significant nutrient load can cause eutrophication, a condition in an aquatic ecosystem where high nutrient concentrations stimulate growth of algae which leads to imbalanced functioning of the system [1]. The eutrophication is a problem for all European Seas at present, but it is more significant for relatively shallow water seas, first of all for the Baltic Sea [2] with an average depth of 55 m. The North Sea [3] is also strongly affected by the eutrophication, because it is only slightly larger than the Baltic Sea and slightly deeper with an average depth 94 m. The problem of eutrophication is mostly limited to the costal regions of other European seas such as the Mediterranean Sea [4] and the Black Sea [5] which are relatively deep.

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In this study we considered the four European Seas mentioned above, which are the subjects of international conventions: 1) The Baltic Sea - HELCOM Convention [1], 2) The North Sea - a part of the area under the OSPAR Convention [6], 3) The Mediterranean Sea - Barcelona Convention [7], and the Black Sea - The Bucharest Convention [5]. The areas, average depths and the maximum depths of the selected seas are given in Table 1.

Table 1

Comparison of the surface, average depth and maximum depth of the selected European seas

Sea	Surface [km^2]	Average depth [m]	Maximum depth [m]
Baltic Sea	377 000	55	459
North Sea	570 000	94	660
Mediterranean Sea	2 500 000	1 500	5 267
Black Sea	436 000	1 240	2 206

The Baltic Sea has the smallest area and is very shallow compared to the other seas (maximum depth of 459 m). The North Sea is slightly larger than the Baltic Sea and also relatively shallow (maximum depth 660 m). The Black Sea is not large either in this context, smaller than the North Sea and larger than the Baltic Sea, but relatively deep with the maximum depth 2206 m. On the other hand, the Mediterranean Sea is much larger, approximately 5-6 times larger than the other selected seas and is relatively deep with the average depth 1500 m and maximum depth of 5267 m.

Because of eutrophication, monitoring of nitrogen load to European seas is an important issue. Estimation of the load can, to some extent, be done using the results of measurements, but mainly using dispersion models. Monitoring and estimation of air pollution contribution to the European seas has been performed in the framework of the Co-operative Programme for **M**onitoring and **E**valuation of the Long-range Transmission of Air pollutants in **E**urope (EMEP) **p**rogramme [8] for more than two decades. The main objective of the EMEP programme is to regularly provide Governments and subsidiary bodies under the **C**onvention on **L**ong-**R**ange **T**ransboundary **A**ir **P**ollution (CLRTAP) [9] with qualified scientific information to support the development and further evaluation of the international protocols on emission reductions negotiated within the Convention [9].

Within the EMEP programme depositions of nitrogen compounds into the EMEP area of interest have been calculated since the 1980's. However, computations of nitrogen depositions to European land and seas performed with the Unified EMEP model, with a consistent set of meteorology and emissions, are only available from 1995. Therefore, here we consider the period 1995-2005, for which annual depositions are available for each year.

There has been a close cooperation between EMEP and two conventions: the HELCOM convention and the OSPAR convention since 1990's. Within this cooperation, nitrogen depositions to different sub-regions of the Baltic Sea [10] and sub-regions of the OSPAR Convention waters [11] have been evaluated. In all computations, the EMEP model was the main tool for evaluating the depositions. Also in this study, the Unified EMEP model was used for all computations of nitrogen depositions. Therefore, a short description of the Unified EMEP model is given in the next chapter.

The Unified EMEP model

The Unified EMEP model is an Eulerian model that has been developed at EMEP/MSC-W (Meteorological Synthesizing Centre - West of EMEP) for simulating atmospheric transport and deposition of acidifying and eutrophying compounds as well as photo-oxidants in Europe. The model has been documented in EMEP Status Report 2003, Part I [12] and updates of the model have been described in EMEP Status Reports 2004 [13], 2005 [14], 2006 [15] and 2007 [16]. Here we only give a short description of the basic features of the model. Model details and its applications can be also found on the EMEP web site [9].

The model domain covers Europe and the Atlantic Ocean (Fig. 1). The model grid (of the size 170×133) has a horizontal resolution of 50 km at 60^{o} N, which is consistent with the resolution of emission data reported to CLRTAP. In the vertical, the model has 20 sigma layers reaching up to 100 hPa. Approximately 10 of these layers are placed below 2 km to obtain high resolution of the boundary layer which is of special importance to the long range transport of air pollution.

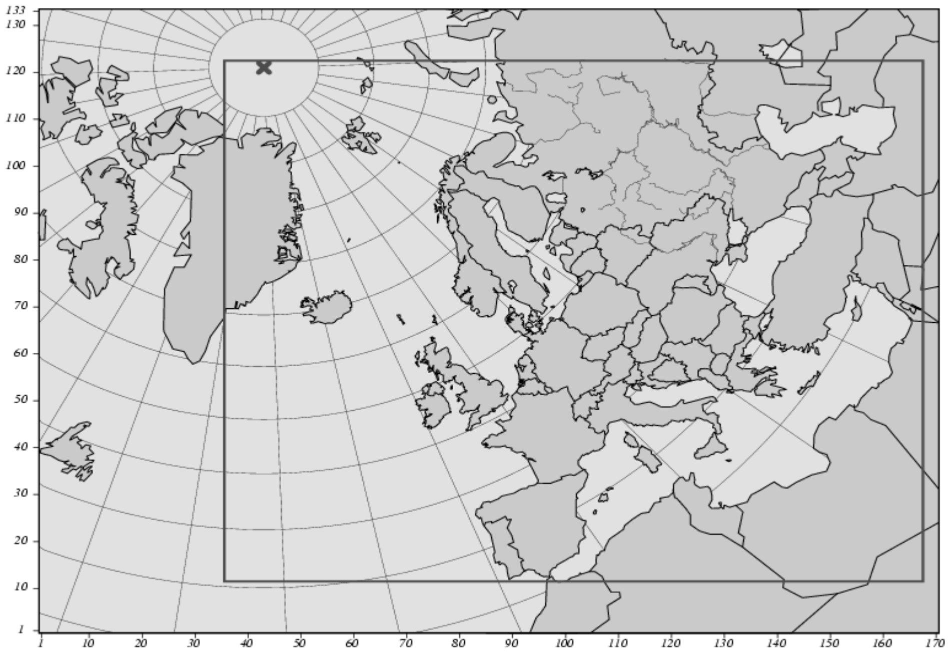

Fig. 1. Computational domain of the Unified EMEP model. The official EMEP area is included within the internal frame and the results of routine model applications are also provided in this area

The Unified EMEP model uses 3-hourly resolution meteorological data from the PARLAM-PS model, a dedicated version of the HIRLAM (*High Resolution Limited Area Model*) Numerical Weather Prediction model [17].

The emissions consist of gridded national annual emissions of sulphur dioxide, nitrogen oxides, ammonia, non-methane **v**olatile **o**rganic **c**ompounds (VOC) and carbon monoxide. They are available in each of the 50 × 50 km^2 model grid. These emissions are distributed temporally according to monthly and daily factors derived from data provided by the University of Stuttgart (GER).

Concentrations of 71 species are computed in the latest version of the Unified EMEP model (56 are advected, 15 are short-lived and not advected). The sulphur and nitrogen chemistry is coupled to the photo-chemistry, which allows a more sophisticated description of *eg* the oxidation of sulphur dioxide to sulphate.

Dry deposition is calculated using the resistance analogy and is a function of the pollutant type, meteorological conditions and surface properties. Parameterization of wet deposition processes includes both in-cloud and sub-cloud scavenging of gases and particles using scavenging coefficients.

The EMEP model has been thoroughly validated. Fagerli et al. [18] presented an extensive evaluation of the acidifying and eutrophying components for the years 1980, 1985, 1990 and 1995 to 2000. In Fagerli et al. [19], a comparison of observations and modelled results for 2001 was conducted, and in Fagerli [20] results for 2002 with an updated EMEP Unified model, version 2.0, was presented. This version differed slightly from the 2003 version, as described in Fagerli [20], however the main conclusions on the model performance were the same. In 2004, 2005 and 2006 the model results were presented for the years 2002, 2003 and 2004, respectively Fagerli [21], Fagerli et al. [22], Fagerli and Hjellbrekke [23]. It has been shown that the EMEP model performance is rather homogeneous over the years (Fagerli et al. [18]), but depends on geographical coverage and quality of the measurement data. The EMEP model has also been validated for nitrogen compounds in Simpson et al. [24] and for dry and wet deposition of sulphur, and wet depositions for nitrogen in Simpson et al. [25], with measurements outside the EMEP network. Calculated trends of total nitrate (HNO_3 and NO_3^-) and ammonia + ammonium in air and precipitation have been evaluated by Fagerli and Aas [26] and they show in general good correspondence with the observations.

Nitrogen emissions

Atmospheric nitrogen depositions to European seas originate from different nitrogen emission sources located in the official EMEP domain. In this chapter we focus on annual total emissions of nitrogen oxides and annual total emissions of ammonia from each EMEP countrie and ship traffic on European Seas, which serve as the emission input to model calculations. National nitrogen emissions are routinely provided every year to MSC/W by all EMEP Contracting Parties. The missing and uncertain emissions are revised and evaluated by experts and then distributed in the computational domain of the Unified EMEP model shown in Figure 1. Maps of annual emissions of oxidized and reduced nitrogen for the year 2005 [27] are shown in Figure 2 in the official EMEP domain.

The areas with maximum emissions of nitrogen oxides are located close to the North Sea, in UK, Belgium, Netherlands and Germany. The main sources of these emissions are mainly related to transportation and to a less extend to combustion. An important source of nitrogen oxides emissions from the international ship traffic can also be clearly recognized in Figure 3. Among EMEP sources, the Russian Federation, Mediterranean Sea, United Kingdom, Germany and Spain are the largest emitters of nitrogen oxides with 3093, 1810, 1627, 1443 and 1405 Gg NO_2 per year, respectively.

Agriculture is a dominating source of ammonia emissions into the atmosphere and this fact is reflected in the spatial distribution of ammonia emissions shown in Figure 2. Contrary to nitrogen oxides emissions, ammonia emissions originate on land only. The maxima of ammonia emissions in 2005 are located in Belgium, Netherlands, Northern France and Northern Italy. Among EMEP sources, France, the Russian Federation, Germany, Ukraine and Kazakhstan are the largest emitters of ammonia with 735, 621, 619, 550 and 537 Gg NH_3 per year, respectively.

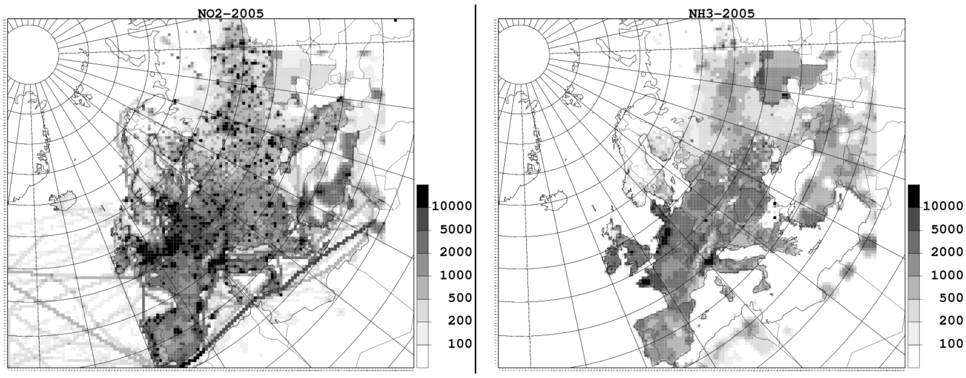

Fig. 2. Spatial distribution of: annual 2005 nitrogen oxides emissions. (Mg NO_2 per year and per grid) and annual 2005 ammonia emissions (Mg NH_3 per year and per grid), in the official EMEP domain

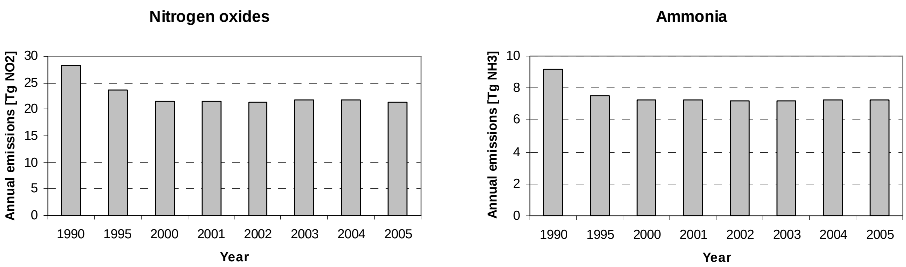

Fig. 3. Annual total nitrogen oxides and ammonia emissions from the entire EMEP area for the years 1990, 1995-2005

Time series of annual national total emissions of nitrogen oxides and ammonia from the entire EMEP domain, as presented in the EMEP Status Report 2007 [17], are shown in Figure 3 for the years 1990, 1995-2005. Emissions of both nitrogen oxides and ammonia show a similar pattern in time. There is a visible (more than 20%) reduction of emissions in the period 1990-1995 and then emissions remain on the same level, changing slightly from one year to another.

An additional and very important source of atmospheric NO_x emissions to the European seas is the international ship traffic. Official data for 2005 give 343, 739, 1810 and 90 Gg NO_x (as NO_2) annual emissions from the international ship traffic on the Baltic Sea, on the North Sea, on the Mediterranean Sea and on the Black Sea, respectively. Compared with emissions from the EMEP countries, which already include emissions from the local costal zone ship traffic, emissions of nitrogen oxides from the international ship traffic show a different temporal pattern. Endresen [27] reports a 1.6% per year increase in fuel consumption from shipping between 1996 and 2000. In the model calculations we have assumed a 2.5% increase per year, the same as in EEB [28]. Nitrogen oxides emissions from the international ship traffic on the selected European seas have increased more than 40% in the period 1995-2000.

Calculated depositions

Emission inventories described in the previous chapter were used in the Unified EMEP model runs for the period 1995-2004. Annual total depositions of dry, oxidized, wet oxidized, dry reduced and wet reduced nitrogen to four selected European seas were calculated for each year of the considered 11-year period. Oxidized nitrogen deposition calculated in nitrogen units consists of the sum of peroxyacetyl nitrate (PAN), NO_2, HNO_3 and aerosol nitrate (ammonium nitrate + coarse nitrate) deposition. Deposition of reduced nitrogen includes deposition of NH_3 and aerosol ammonium (ammonium sulphate + ammonium nitrate).

The maps with spatial distributions of calculated depositions of oxidized and reduced nitrogen into the Baltic Sea in 2005 in the EMEP grid system are shown in Figure 4.

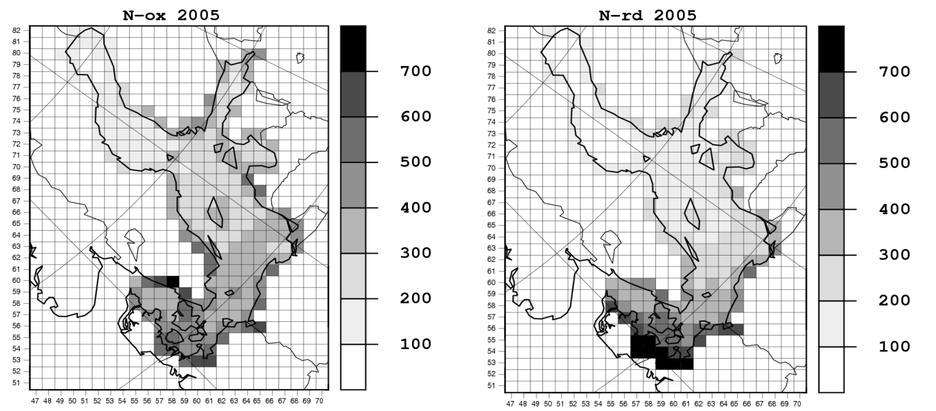

Fig. 4. Maps of annual 2005 nitrogen deposition to the Baltic Sea. Deposition of oxidized nitrogen on the left and deposition of reduced nitrogen on the right. Units: mg N m^{-2} yr^{-1}

The maximum of oxidized nitrogen deposition is located in the coastal grid on the Swedish coast. The maximum of reduced nitrogen deposition is also located in the coastal grid, but on the Danish coast. In general depositions of both oxidized and reduced nitrogen to the Baltic Sea are largest near to the coast and decreases towards the open sea. The deposition field tend to decrease in the direction from the South-West to the North-East.

The maps with spatial distributions of calculated depositions of oxidized and reduced nitrogen into the North Sea in 2005 are shown in Figure 5. The maximum of oxidized nitrogen deposition to the North Sea is located in the coastal grid on the Belgium coast. The maximum of reduced nitrogen deposition is located in the coastal grid, on the French coast. As for the Baltic Sea, depositions of both oxidized and reduced nitrogen to the North Sea are largest near to the coast and decrease towards the open sea. There is also a decreasing pattern in the direction from the South to the North.

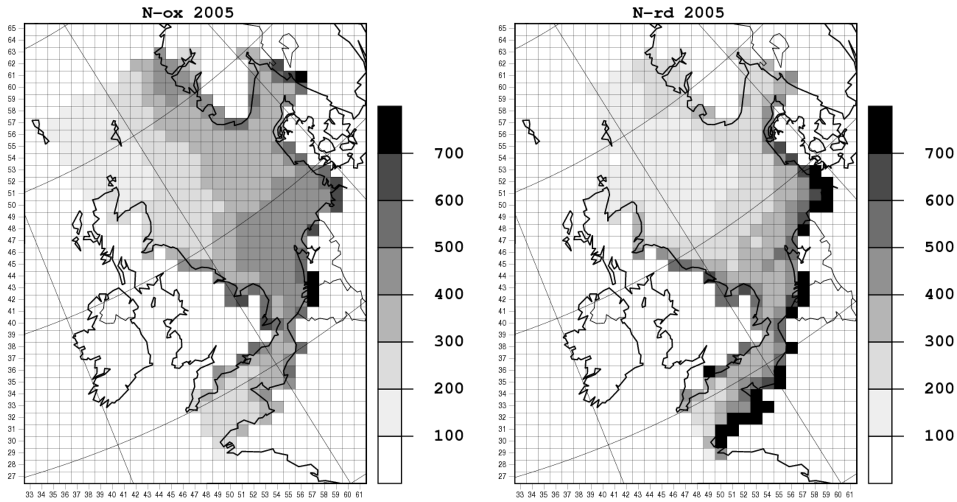

Fig. 5. Maps of annual 2005 nitrogen deposition to the North Sea. Deposition of oxidized nitrogen on the left and deposition of reduced nitrogen on the right. Units: mg N m^{-2} yr^{-1}

The maps with spatial distributions of calculated depositions of oxidized and reduced nitrogen into the Mediterranean Sea in 2005 are shown in Figure 6. The maximum of oxidized nitrogen deposition to the Mediterranean Sea is located in the coastal grid on the Italian coast. The maximum of reduced nitrogen deposition is also located in the coastal grid, and also on the Italian coast. For both, depositions of oxidized and reduced nitrogen to the Mediterranean Sea, there is a clear decreasing pattern in the direction from the North to the South, reflecting closely the regional emission pattern for nitrogen oxides and ammonia.

The maps with spatial distributions of calculated depositions of oxidized and reduced nitrogen into the Black Sea in 2005 are shown in Figure 7. The maximum of oxidized nitrogen deposition to the Black Sea is located in the coastal grid on the Bulgarian cost. The maximum of reduced nitrogen deposition is also located in the coastal grid on the Bulgarian coast. For both depositions of oxidized and reduced nitrogen to the Black Sea there is a decreasing pattern in the direction from the West to the East, with the exception of some coastal grids located in the East, where the depositions of reduced nitrogen are relatively high.

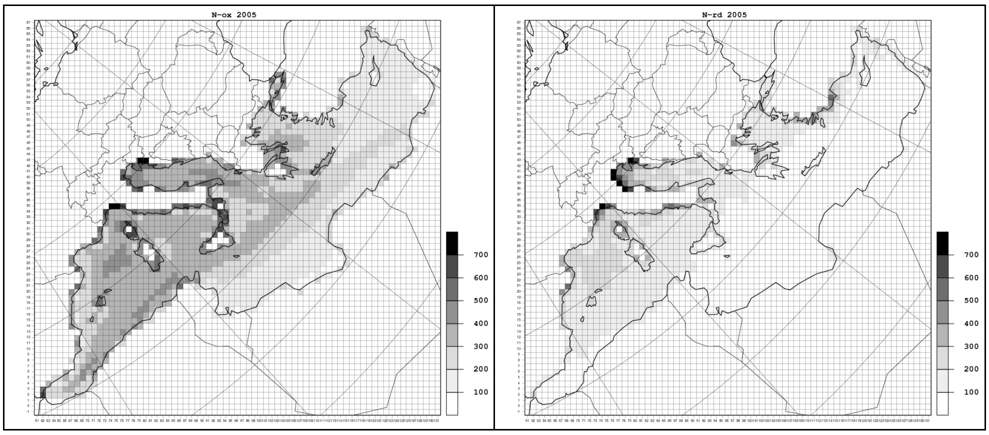

Fig. 6. Maps of annual 2005 nitrogen deposition to Mediterranean Sea. Deposition of oxidized nitrogen on the left and deposition of reduced nitrogen on the right. Units: mg N m^{-2} yr^{-1}

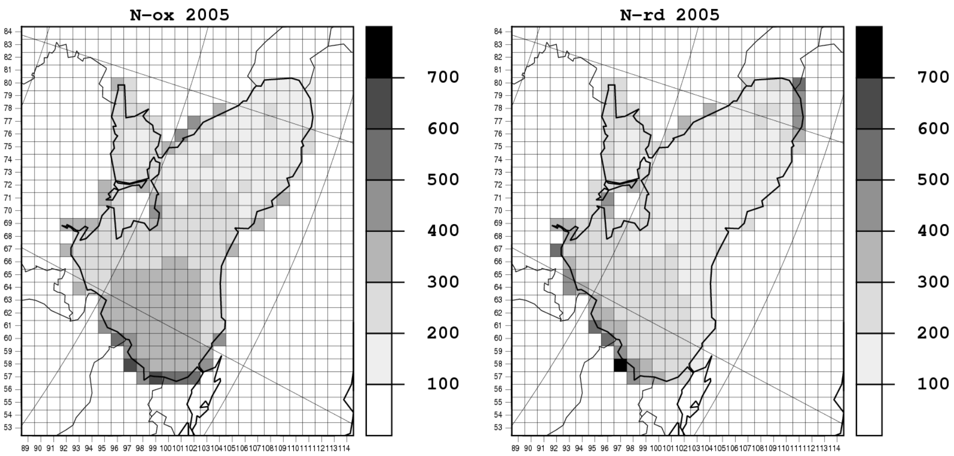

Fig. 7. Maps of annual 2005 nitrogen deposition to the Black Sea. Deposition of oxidized nitrogen on the left and deposition of reduced nitrogen on the right. Units: mg N m^{-2} yr^{-1}

For all considered seas, the gradient of reduced nitrogen deposition is steeper than the gradient of oxidized nitrogen deposition, because only the emission sources located on the land contribute to reduced nitrogen deposition into the sea. Also for all the seas, the gradients in calculated deposition fields of oxidized and reduced nitrogen follow the gradients in input emission fields of nitrogen oxides and ammonia in 2005.

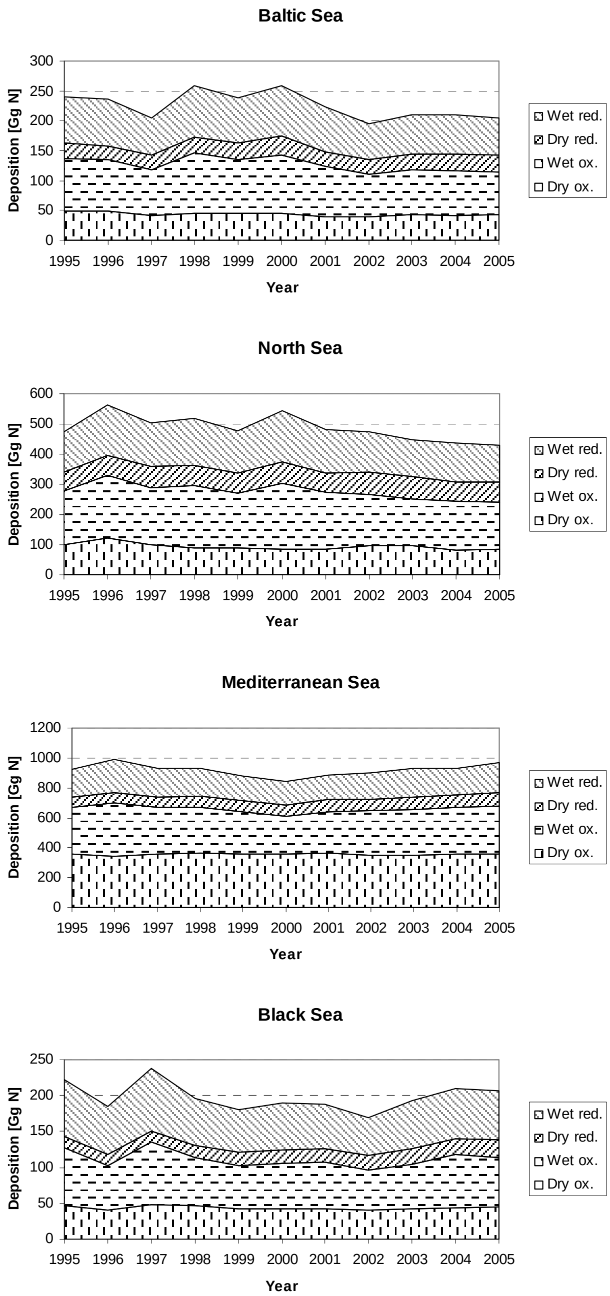

Fig. 8. Time series of annual atmospheric load of nitrogen to the European seas in the period 1995-2005. Dry oxidized, wet oxidized, dry reduced, wet reduced and total annual nitrogen deposition are shown

Similar calculations, as for the year 2005, have been performed with the EMEP model for all the years of the period 1995-2005. Annual total depositions of dry oxidized, wet oxidized, dry reduced and wet reduced nitrogen have been calculated for each sea. The results are shown in Figure 9. Total nitrogen deposition to the European seas shown in Figure 8 is the sum of four depositions: dry oxidized, wet oxidized, dry reduced and wet reduced.

Total nitrogen deposition to the Baltic Sea decreased by 18% from 240 Gg N in 1995 to 204 Gg N in 2005. However, the decrease is not monotonic and the maximum of the total deposition (259 Gg N) occurred in 1999. The most significant decrease in the considered period can be noticed for wet deposition of nitrogen: 25% for oxidized and 24% for reduced. It means that the local nitrogen emission sources have likely become more important in 2005, since the wet deposition is the main contribution pathway for the distant sources.

A smaller (12%) reduction occurred for the deposition of dry oxidized nitrogen and for the deposition of dry reduced nitrogen an increase of 5% can be noticed between the years 1995 and 2005. For all the years, the contribution of wet deposition to the total nitrogen deposition into the Baltic Sea (65%) is significantly larger than the contribution of dry deposition (35% in 2005). Also for the entire period, the contribution of oxidized deposition to the total nitrogen deposition (56% in 2005) is larger than the contribution of reduced deposition (44% in 2005).

Total nitrogen deposition to the North Sea decreased by 11% from 476 Gg N in 1995 to 430 Gg N in 2005. The maximum of total deposition occurred in 1996 - 543 Gg N. A clear drop of total nitrogen deposition to the North Sea is visible after the year 2000. The most significant decrease in the considered period can be noticed for the oxidized deposition of nitrogen: 19% for dry and 14% for wet. For all the years, the contribution of wet deposition to the total nitrogen deposition into the North Sea (65%) is larger than the contribution of dry deposition (35% in 2005). Also for the entire period, the contribution of oxidized deposition to the total nitrogen deposition (56% in 2005) is larger than the contribution of reduced deposition (44% in 2005).

Compared with the Baltic Sea and with the North Sea, the pattern of total nitrogen deposition to the Mediterranean Sea is different. Total nitrogen deposition to the Mediterranean Sea increased by 4% from 924 Gg N in 1995 to 965 Gg N in 2005. The maximum of total deposition occurred in 1996 - 990 Gg N. A steady increase of all types of nitrogen deposition to the Mediterranean Sea is visible after the year 2000. The most significant increase in the considered period can be noticed for the dry reduced deposition - 24%, followed by the wet reduced, wet oxidized and dry oxidized deposition, with 6, 2 and 1%, respectively. For all the years, the contribution of oxidized nitrogen deposition to the total nitrogen deposition into Mediterranean Sea (71% in 2005) is significantly larger than the contribution of the reduced nitrogen deposition (21% in 2005). Contribution of wet deposition to the total nitrogen deposition (54% in 2005) is slightly larger than the contribution of dry deposition (46% in 2005).

Total nitrogen deposition to the Black Sea decreased by 7% from 222 Gg N in 1995 to 207 Gg N in 2005. The maximum of total deposition 237 Gg N, occurred in 1997. The line of total nitrogen deposition to the Black Sea oscillates around 200 Gg N level, but increases after the year 2002. Three types of nitrogen deposition to the Black Sea decreased and one increased from the year 1995 to 2005.

A significant increase in the considered period can be noticed for the dry deposition of reduced nitrogen - 33%, as in the case of Mediterranean Sea. The wet oxidized, wet reduced and dry oxidized depositions decreased in this period by 6, 2 and 1%, respectively. For all the years, the contribution of oxidized nitrogen deposition to the total nitrogen deposition into Mediterranean Sea (67%) is again significantly larger than the contribution of the reduced nitrogen deposition (23% in 2005). Also, the contribution of wet deposition to the total nitrogen deposition (55% in 2005) is larger than the contribution of dry deposition (45% in 2005).

It should be mentioned that the changes in calculated depositions for different years are not only result of changes in the emission, but also changes in meteorological conditions for each year. The inter-annual variability of the meteorological conditions affecting atmospheric transport and deposition of pollutants is large. Since we consider only 11 years, and the reductions in emissions are about on the same level as the deposition changes due to meteorological variability, it is difficult to judge whether we can really observe a downward trend or not in the considered period.

In order to compare the annual nitrogen load to different seas, we have also calculated annual deposition fluxes to the European sea which are shown in Figure 9.

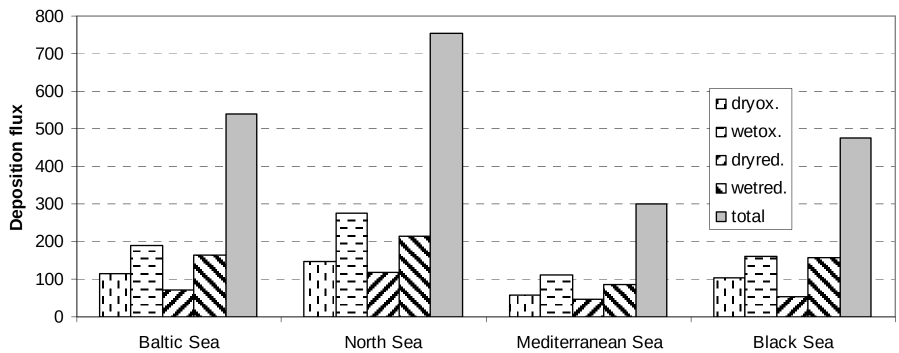

Fig. 9. Comparison of average annual nitrogen deposition fluxes into selected European seas in the year 2005. Units: mg N m^{-2} yr^{-1}

The largest deposition flux of total nitrogen (754 mg N m^{-2} yr^{-1}) can be observed for the North Sea. The Baltic Sea (540 mg N m^{-2} yr^{-1}) is next on the list, followed by the Black Sea (474 mg N m^{-2} yr^{-1}) and by the Mediterranean Sea with the lowest deposition flux of total nitrogen in 2005 (302 mg N m^{-2} yr^{-1}). The differences in total deposition fluxes between the European seas are rather large with the total deposition flux into the North Sea being more than twice of the deposition flux into the Mediterranean Sea. However, the structure of the deposition fluxes is similar for all cases discussed. Wet deposition flux is higher than the dry deposition flux for all of them. Also for all the seas, the deposition flux of oxidized nitrogen is higher than the deposition flux of reduced nitrogen.

Main contributors to nitrogen deposition in 2005

One of the advantages of the Unified EMEP model is a possibility of computing the so-called source-receptor or blame matrices indicating how much of nitrogen emitted from each source is deposited in the selected receptor area. Such blame matrices have been latest computed for the year 2005 [16] and the results for considered European seas are presented in Figure 10.

Only five emission sources with the largest contribution to oxidized and reduced nitrogen deposition are taken into account in Figure 10. However, for all selected seas, the first five sources in the ranking contribute more than 50% to the deposition.

The main contributors to oxidized nitrogen deposition into the Baltic Sea in 2005 are: international ship traffic on the Baltic Sea, Germany and Poland. In this case, international ship traffic is the most important source of the deposition, mainly from the Baltic Sea, but there is also a significant contribution from the North Sea, which is a distant source for the Baltic Sea. Another distant source is the UK as a fourth in the ranking. The main contributors to reduced nitrogen deposition into the Baltic Sea in 2005 are: Germany, Poland and Denmark. The major sources are Parties to the HELSINKI Commission and are located around the Baltic Sea. This means, that the local sources play an important role in oxidized nitrogen deposition to the Baltic Sea.

The main sources contributing to oxidized nitrogen deposition into the North Sea in 2005 are: the UK, international ship traffic on the North Sea and France. Also in this case, the international ship traffic is high in the ranking, as a second most important source. The remaining large contributors belong to the Contracting Parties to the OSPAR Commission and are located at the North Sea cost. The main contributors to reduced nitrogen deposition into the North Sea in 2005 are: France, the UK and Germany. All of these countries are Parties to the OSPAR Commission. The first five sources together contribute to 82% of the reduced nitrogen deposition to the North Sea.

The main contributors to oxidized nitrogen deposition into the Mediterranean Sea in 2005 are: international ship traffic on the Mediterranean Sea, Italy and Spain. Again, the international ship traffic on the Mediterranean Sea is the most important source of the deposition. The next four sources belong to the countries located along the cost of the Mediterranean Sea. The first five sources together are responsible for 70% of oxidized nitrogen deposition to the Mediterranean Sea. The main contributors to reduced nitrogen deposition into the Mediterranean Sea in 2005 are: Italy, France and Turkey. All of these sources are located around the Mediterranean Sea. The first five sources together contribute to 70% of the reduced nitrogen deposition.

The main contributors to oxidized nitrogen deposition into the Black Sea in 2005 are: Russia, Turkey and Ukraine. The international ship traffic on the Black Sea is still among five major contributors, but compared with other European seas it is slightly less important. Major sources belong to the countries located along the coast of the Black Sea. The first five sources together are responsible for 67% of the oxidized nitrogen deposition to the Black Sea. The main contributors to reduced nitrogen deposition into the Black Sea in 2005 are: Ukraine, Turkey and Russia. The first five sources together contribute to 70% of the reduced nitrogen deposition.

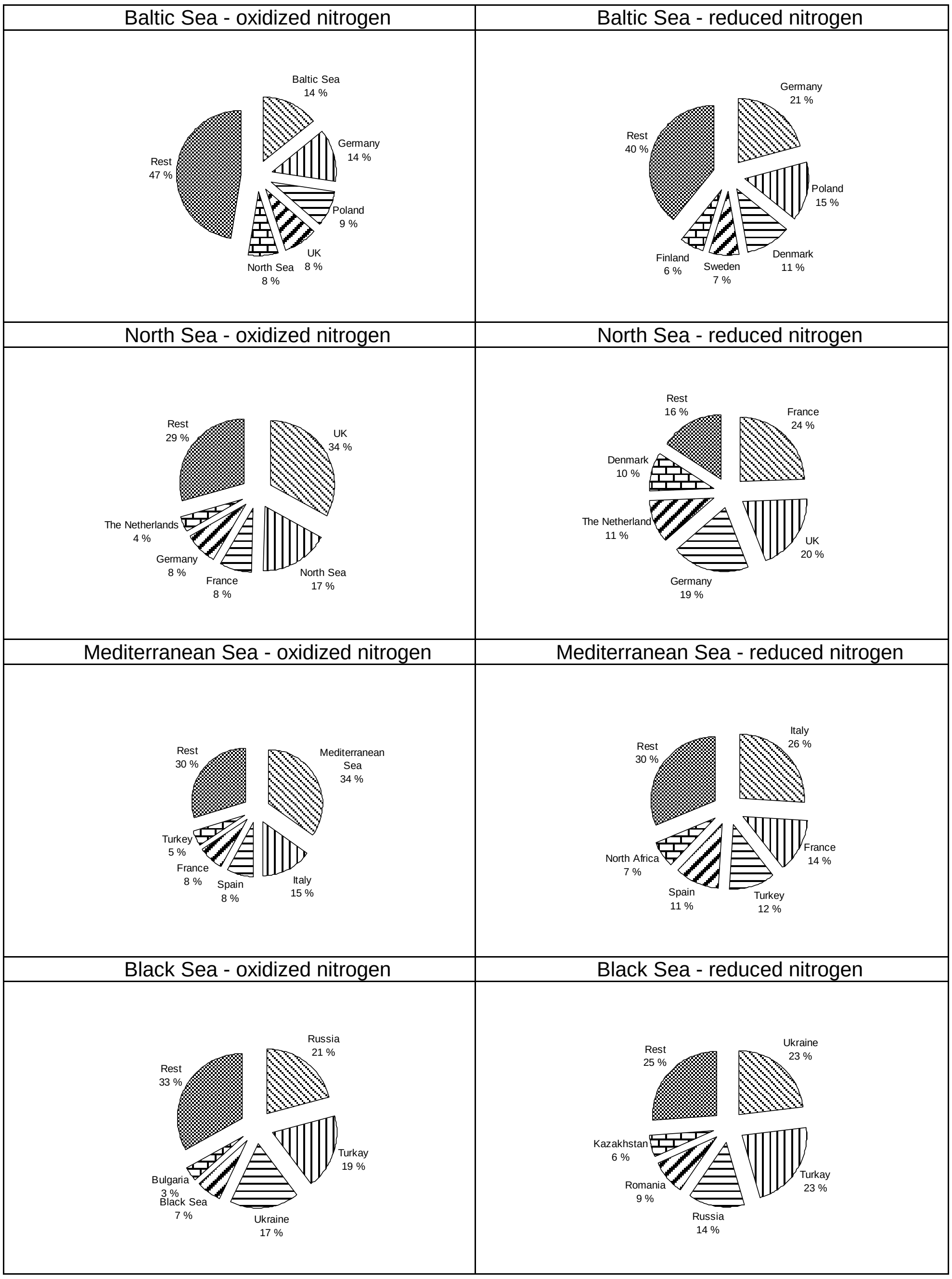

Fig. 10. Main emission sources contributing to annual nitrogen (oxidized and reduced) deposition into European seas in the year 2005

Estimation of the future nitrogen depositions to European seas

The Unified EMEP model has been used for evaluation of nitrogen depositions and source allocation budgets in the year 2010 [13]. The so-called “Current Legislation” (CLE) emission scenario for 2010 was used in the model runs for 2010, together with the meteorological fields from the year 2000. The CLE emissions were developed at the International Institute for Applied Systems Analysis (IIASA) as emissions achieved by the foreseen implementation of current standards in each country as estimated by the RAINS model. The results for oxidized, reduced and total nitrogen deposition in 2010 are presented in Figure 11. For comparison calculated nitrogen depositions for 2005 are also shown in Figure 11.

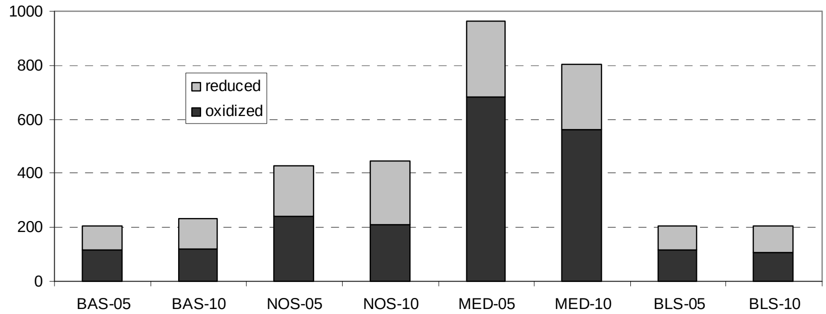

Fig. 11. Comparison of oxidized, reduced and total nitrogen deposition to selected European seas in the years 2005 and 2010. The acronyms have following meanings: BAS - Baltic Sea, NOS - North Sea, MED - Mediterranean Sea, BLS - Black Sea, 05 - deposition in the year 2005 and 10 - projected deposition in the year 2010

In case of the Baltic Sea, total deposition of nitrogen in 2010 is higher (15%) than the total deposition in 2005, mainly because of larger increase of reduced nitrogen deposition and smaller increase of oxidized nitrogen deposition.

Deposition of oxidized nitrogen to the North Sea in 2010 is smaller in 2010 than in 2005, but on the other hand, the deposition of reduced nitrogen is higher. These contrary effects sum up in slightly increased (3%) total nitrogen deposition to the North Sea in 2010. Total nitrogen deposition to the Mediterranean Sea in 2010 is lower (17%) in 2010 than in 2005. This is achieved by a significant reduction of oxidized nitrogen deposition and slightly lower decrease of reduced nitrogen deposition in 2010.

In case of the Black Sea, total nitrogen deposition remains on the same level in 2010 and 2005. However, there is an increase in the reduced nitrogen deposition and at the same time decrease in oxidized nitrogen deposition in 2010.

As discussed depositions in the year 2010 were computed based on meteorology from the year 2000. We do not know the meteorology for the year 2010, but we know that it varies significantly from one year to another. Some experiments performed with the different meteorological years [10, 19] and the same emissions have indicated a large uncertainty, up to 60% in the computed depositions for specific grid cells, which is associated with the uncertain meteorological conditions in the future estimations of the deposition. This uncertainty should be taken into account when using the results presented above.

Conclusions

The nitrogen loads to European seas were calculated for each year of the period 1995-2005 using the Unified EMEP model. The EMEP model was also used for estimating the future nitrogen depositions in the year 2010. Atmospheric emissions of nitrogen oxides and ammonia, as well as meteorological data were the main input for the EMEP model runs.

Four kinds of nitrogen depositions have been calculated with the Unified EMEP model for the period 1995-2005: oxidized dry, oxidized wet, reduced dry and reduced wet. In addition, oxidized (wet plus dry), reduced (dry plus wet), dry (oxidized plus reduced), wet (oxidized plus reduced) and total deposition have been also calculated. Calculated total nitrogen load to the Baltic Sea, the North Sea, the Mediterranean Sea and the Black Sea in the year 2005 was 204, 430, 965 and 207 Gg N per year, respectively. Calculated total deposition the Baltic Sea, North Sea and Mediterranean Sea has decreased from 1995 to 2005 by 18, 11 and 7%, respectively. Total nitrogen deposition to the Mediterranean Sea has increased by 4%. Note, however, that the differences between these two years are strongly affected by the specific meteorology in those years. For all the years wet deposition was larger than dry depositions and deposition of oxidized nitrogen was larger than the deposition of reduced nitrogen for all considered seas.

It should be mentioned that the changes in calculated depositions for different years are not only result of changes in the emission, but also changes in meteorological conditions for different years. The inter-annual variability of the meteorological conditions affecting atmospheric transport and deposition of pollutants is large. Since we consider only 11 years, and the reductions in emissions are about on the same level as the deposition changes due to meteorological variability, it is difficult to judge whether we can really observe a downward trend or not in the considered period.

In order to compare the annual nitrogen load to different seas, we have also calculated annual deposition fluxes to the European seas. The deposition fluxes of total nitrogen for the Baltic Sea, North Sea, Mediterranean Sea and the Black sea were 540, 754, 302, and 474 mg N m^{-2} yr^{-1}, respectively. It means that the North Sea is relatively most polluted followed by the Baltic Sea, the Black Sea and the Mediterranean Sea. The differences in total deposition fluxes between the European seas are rather large with the total deposition flux into the North Sea being more than twice of the deposition flux into the Mediterranean Sea. However, the structure of the deposition fluxes is similar for all the seas. Wet deposition flux is higher than the dry deposition flux and the deposition flux of oxidized nitrogen is higher than the deposition flux of reduced nitrogen.

Using the Unified EMEP model we have been able to determine the main emission sources contributing to nitrogen load into selected European Seas. The largest contributors to oxidized nitrogen load into the Baltic Sea, North Sea, Mediterranean Sea and the Black sea in the year 2005 are: international ship traffic on the Baltic Sea (14%), the UK (34%), international ship traffic on the Mediterranean Sea (34%) and the Russian

Federation (21%), respectively. The number one contributors to reduced nitrogen load into the Baltic Sea, North Sea, Mediterranean Sea and the Black sea in the year 2005 are: Germany (21%), France (24%), Italy (26%) and Ukraine (23%).

Model estimation of future nitrogen depositions in the year 2010 indicates an increase of total nitrogen load to the Baltic Sea (15%) and to the North Sea (3%), and the same deposition level for the Black Sea, compared with the year 2005. Computed total nitrogen load to the Black Sea remains on the same level in 2010 as in 2005, whereas total nitrogen load to the Mediterranean Sea is 17% lower in 2010. Due to unknown meteorological conditions in 2010 the computed depositions for the year 2010 represent a year with average meteorological conditions, which should be taken into account in the applications of these results. Furthermore, the differences between those two years are affected by the specific meteorological conditions in 2005.

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DEPOZYCJA AZOTU Z ATMOSFERY DO MÓRZ EUROPEJSKICH

Streszczenie: Atmosferyczna depozycja azotu jest ważnym źródłem składników odżywczych w morzach, odpowiedzialnym za około 30% całkowitego ładunku azotu, który dodatkowo obejmuje również wkład rzek i źródeł bezpośrednich. Nadmiar składników odżywczych w wodzie morskiej powoduje eutrofizację, która stanowi powszechny problem dla mórz europejskich. Dlatego atmosferyczna depozycja azotu do mórz jest monitorowana od lat osiemdziesiątych, początkowo za pomocą pomiarów, a następnie i aż do chwili obecnej przy pomocy modeli. Rezultaty zunifikowanego modelu EMEP przedstawiono dla lat 1995-2005. Przeanalizowano obliczone roczne, mokre i suche depozycje azotu utlenionego i zredukowanego do Morza Bałtyckiego, Morza Północnego, Morza Śródziemnego i Morza Czarnego, a także najważniejsze źródła emisji odpowiedzialne za depozycję. Ponadto w pracy wskazano na możliwe scenariusze atmosferycznych ładunków azotu do mórz europejskich w przyszłości.

Słowa kluczowe: depozycja azotu, morza europejskie, eutrofikacja