

climate changes spatial planning

Climate scenarios

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Contents

Summary

Summary in Dutch

Aërosolen zijn de grootste onbekende factor in de stralingsforcering van de aarde. Het meest belangrijke effect lijkt het Aërosol Indirect Effect (AIE) dat op verschillende wijzen de vorming en dynamica van wolken beïnvloedt. Wolken ontstaan door condensatie van waterdamp op aërosolen. Het aantal antropogene aërosoldeeltjes is in onze regio veel hoger dan het aantal natuurlijke deeltjes. Daardoor worden meer wolkendruppels gevormd, die meer zonlicht reflecteren en extra koelend werken. Dit is in het kort het zgn. eerste AIE. In het project is een aërosol-wolkenmodule ontwikkeld voor het regionale klimaatmodel RACMO om de respons van het (regionale) klimaat op het eerste AIE te berekenen. De antropogene aërosolen die voor de wolkenvorming van belang zijn ontstaan in de atmosfeer. De aerosol concentraties (sulfaat, nitraat) werden met een separaat chemisch model (LOTOS-EUROS) berekend. Het aantal wolkendruppels werd afgeleid uit deze concentraties d.m.v. bestaande parameterisaties voor de aërosol-wolken interactie. Het blijkt dat verschillende parameterisaties een onderling verschil geven dat even groot is als het regionale AIE zelf, hetgeen de onzekerheid in deze schattingen onderstreept.

In Nederland en omgeving is ammoniumnitraat de belangrijkste component van aërosolen. Dit is een product van de emissies van de landbouw en het verkeer. In het project is experimenteel onderzoek verricht naar het belang van ammoniumnitraat voor de wolkenvorming. Dit gebeurde in een speciale grote wolkenkamer waarin metingen konden geschieden met de in dit project ontwikkelde (prototype) multipurpose aerosol meet-instrument, de MARGA-sizer. De lokale aërosol-component ammoniumnitraat blijkt over Nederland van even groot belang in het AIE als de sulfaat-aërosolen waarmee in IPCC berekeningen doorgaans rekening wordt gehouden.

Summary

The magnitude of the regional first Aerosol Indirect forcing Effect (AIE) was addressed. This is the increase in reflectivity of clouds due to manmade aerosol. Two approaches were followed: 1) modelling using generic knowledge on the interaction of aerosol and cloud, and 2) an experimental study on the importance of a specific regional aerosol, viz. ammonium nitrate.

1) The Chemical Transport Model LOTOS-EUROS provided the aerosol field of anthropogenic sulphate and natural sea salt for Europe. Four different parameterisations were used to convert these concentration fields into fields of the number of Cloud Condensation Nuclei, which in turn was used to determine the cloud droplet effective radius. Different parameterisations gave rise to differences of up to 5 W m^{-2} in estimates for the AIE for Europe. An aerosol-cloud module was developed for the regional climate model RACMO2. The module was tested in an offline radiation module with a comprehensive set of measurements on cloud and aerosol parameters and surface radiative fluxes obtained at the meteo-tower of Cabauw.

2) The importance of the regional aerosol in cloud formation was studied. This was done in a large cloud chamber that allowed the use of a novel aerosol detection instrument developed in the project. It was found that the compound ammonium nitrate plays a major role in the cloud formation. Its origins are traffic and manure from agricultural origin. It has become the most abundant regional aerosol type and appears to be as active as the better known sulphate aerosol. This forms the basis of the parameterisation of its cloud forming properties.

Extended summary

Aerosol is the term used for small particles suspended in the air. These particles reflect solar light. The most important but least quantified effect is the Aerosol Indirect Effect (AIE) via clouds. The processes responsible for the first AIE can be summarized as follows: Clouds are formed by condensation of water on aerosols. The number of manmade aerosol particles in our region is much larger than the number of natural particles. Therefore clouds contain more droplets and reflect more solar energy and hence result in cooling of the regional climate. This project assessed the regional impact of manmade aerosol emissions by following two approaches.

1) Modelling based on a generic parameterisation of the interaction of aerosols and clouds;
2) Experimentally testing of the cloud forming properties of the regional aerosol.

1) Modelling formation and cloud effects of the regional aerosols

Only a limited number of particles serve as nuclei for cloud formation. These are mostly formed in the atmosphere, a complex process that is difficult to capture in General Circulation Models (GCMs). The approach often used in climate modelling (and also used here) is to separate the modelling of the aerosol formation process and the meteorological impacts of the aerosol fields.

Aerosol emission and distribution

A Chemical Transport Model CTM (LOTOS-EUROS) provided the aerosol field of anthropogenic sulphate and natural sea salt over Europe. For these components parameterisations were available to convert mass concentrations to number concentrations of Cloud Condensation Nuclei (CCN) using empirical relations (parameterisations). In a sensitivity study four parameterisations were compared with respect to the surface shortwave radiation flux. It was shown that differences of up to -5 W m^{-2} resulted, which is of the order of the uncertainty in the AIE.

Effective radius in RACMO

A key parameter describing the cloud radiative properties is the “effective radius” (Reff); it is an important property that influences the reflectivity of clouds and the formation of precipitation. It is inversely related to the number of CCN (assuming constant liquid water content). The effective radius plays a key role in the link between CCN and cloud reflectivity in the regional climate model RACMO2. An off-line interactive test run of one month was performed in project CS6 in which meteorological data from RACMO were used to force LOTOS-EUROS, while in turn aerosol data from LOTOS-EUROS were used to force the aerosol-cloud module in RACMO.

2) Experimental determination of the regional aerosol composition

The local farming sector is, together with traffic, considered to be a major source of manmade aerosol known as ammonium-nitrate, which has currently become the most abundant regional aerosol type.

The farming sector also produces aerosol-carbon. The role of ammonium nitrate and carbon in the regional aerosol-cloud interactions is largely unknown, and measurements were conducted to determine the importance of these contributions. The cloud forming properties were investigated via measurements in a large cloud chamber that allowed the use of aerosol detection equipment specifically designed for this. The measurements were made in collaboration with the CS2 field campaign at the CESAR Observatory Site at Cabauw. The experiments showed that ammonium nitrate is preferentially present in those aerosol particles that serve as cloud condensation nuclei in polluted local air masses. The data obtained at Cabauw showed that ammonium nitrate is present as a local CCN component in the relevant aerosol particle size range over a longer period of time than, and of comparable importance to, (ammonium) sulphate.

Main results / conclusions are:

- An aerosol cloud module was developed and incorporated into RACMO linking aerosol concentrations to cloud reflective properties.
- The aerosol-fields generated by LOTOS-EUROS have been interactively coupled with RACMO.
- The regional manmade aerosol-component (ammonium) nitrate appears to be of equal importance to the magnitude of the 1st AIE as the component sulphate which is normally considered by IPCC.
- A new (prototype) multi-monitoring aerosol instrument was developed for measuring ammonium nitrate and water soluble organic carbon.

1. Introduction

The project CS4 was initiated to investigate the role of aerosols in the regional climate system, concentrating on the Netherlands and surroundings. Aerosols are the small suspended particles in the air with a typical size of 1 micrometer. In contrast to greenhouse gases the aerosols are relatively short-lived and thus their influence on the radiation balance is spatially confined to their source region.
The third assessment report of the IPCC (2001) claims that the most important uncertainty in quantifying future warming is the role of aerosols; in particular their effects on cloud formation and evolution, the so-called aerosol indirect effect (AIE). In this project it was investigated what the impact of the aerosol indirect effect in the European domain is. A second research question concerned the identification of the aerosol component that is of greatest importance in influencing the magnitude of the AIE in our region.
The approach followed here was to assess the AIE as traditionally modelled with sulphate as the key anthropogenic forcing component. Simultaneously the cloud forming properties of local aerosol was analysed in an experimental approach. As these two lines of research followed a parallel time path, a third [and obvious follow-on] task – the integration of the findings of the experiments with the modelling study – was not executed within the time frame of this project.
Before we address the two research strategies in chapter 2 and 3, we briefly describe the Aerosol Indirect Effect.

1.1 Aerosol Indirect Effect

The best estimate of the global first Aerosol Indirect Effect (AIE) is, at present, that it partly offsets the greenhouse warming by a forcing of -0.7 W m^{-2}, with an uncertainty that is as large as its absolute value [IPCC AR4]. The uncertainty is reflected by a lack of agreement between Global Climate Models results, caused by differences in their development and individual choices in linking aerosols to cloud reflective properties. The qualification 'first' refers to the phenomenon that the reflectivity of clouds increases with the number of particles.
The processes and events leading from manmade emissions to aerosol in the atmosphere and subsequently to a radiative forcing are very complex. It is at present not possible to determine to what extent the representation of the AIE in GCMs is realistic. Our approach was to develop and test an aerosol parameterisation to be used in a regional climate model. Testing of the performance of this parameterisation is taking place in project CS6. It is anticipated that the high spatial resolution of this model enables an assessment of the impact of the AIE on the regional/local climate.

2. The Modelling Work

2.1 Introduction

Only a limited number of particles serve as nuclei for cloud formation. They are mostly formed in the atmosphere by complex processes that are difficult to capture in GCMs. The approach most often used in climate modelling [and also applied here] is the detailed modelling of the aerosol formation in a separate model.

2.2 Aerosol fields

We used the operational 3D chemistry transport LOTOS-EUROS model [Schaap et al., 2008] to calculate sulphate, nitrate and sea-salt aerosol distributions over Europe for the years 2000-2007. As input LOTOS-EUROS uses meteorology obtained from the Regional Atmospheric Climate Model – RACMO [van Meijgaard et al., 2008]. The modelling domain and horizontal spatial resolution were comparable to that of RACMO. Couplers were developed to map the high vertical resolution atmospheric profiles from RACMO (40 layers) onto the coarser mesh (5 layers) employed by LOTOS-EUROS and to project the aerosol information from LOTOS-EUROS back on the RACMO vertical grid. The aerosol concentrations were sampled at an hourly resolution.

LOTOS-EUROS simulates the aerosol distributions taking into account emission, transport, chemical production, destruction and deposition of aerosols. The components modelled are those that appear in the parameterisations that existed at the time the approach was started (non-sea salt sulphate and sea salt; see section 2.3). In figure 1 the modelled annual mean concentration fields of sulphate and sea salt at the surface are given for 2002. Sulphate concentrations are highest in south-eastern Europe. Sea salt concentrations (presented as sodium) are highest over the open ocean. Comparison with observations showed satisfactory results, in line with earlier studies, indicating that coupling to the new meteorological source was successful.

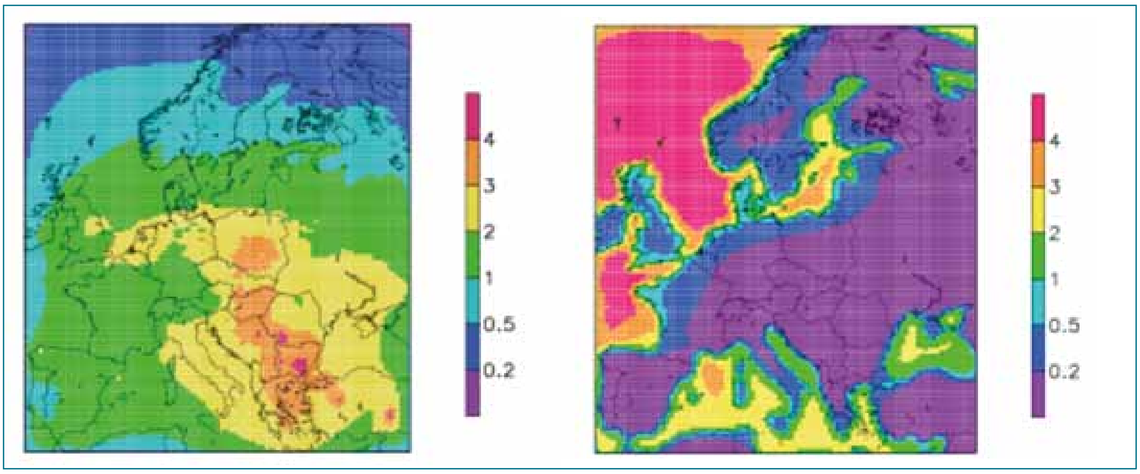

Figure 1.
Annual mean distribution (μg/m3) for 2002 of (left) sulphate and (right) sodium representing sea salt.

In addition to these promised fields also those for the component nitrate were modelled for the indicated years. The results are provided in the figures 2a (sulphate) and b (nitrate).

Figure 2a shows the yearly averaged sulphate concentrations as calculated by the LOTOS-EUROS model for the years 2000, 2003, 2005 and 2007. Although the aerosol distributions ca vary considerable over time at daily time scales,, the annually averaged fiels from year to year do not vary much. High sulphate values are found over south-eastern Europe where largest emissions of SO2 are found.

Figure 2b shows the yearly averaged nitrate concentrations as calculated by the LOTOS-EUROS model for the years 2000, 2003, 2005 and 2007. Again, it can be seen that the yearly averaged field is not very different for the different years. Highest nitrate values are found over the Benelux and the Po valley. These are regions with a high population/traffic and industry density.

The emissions of the components that give rise to the formation of the nitrate and sulphate were kept constant to the emissions in the year 2000.

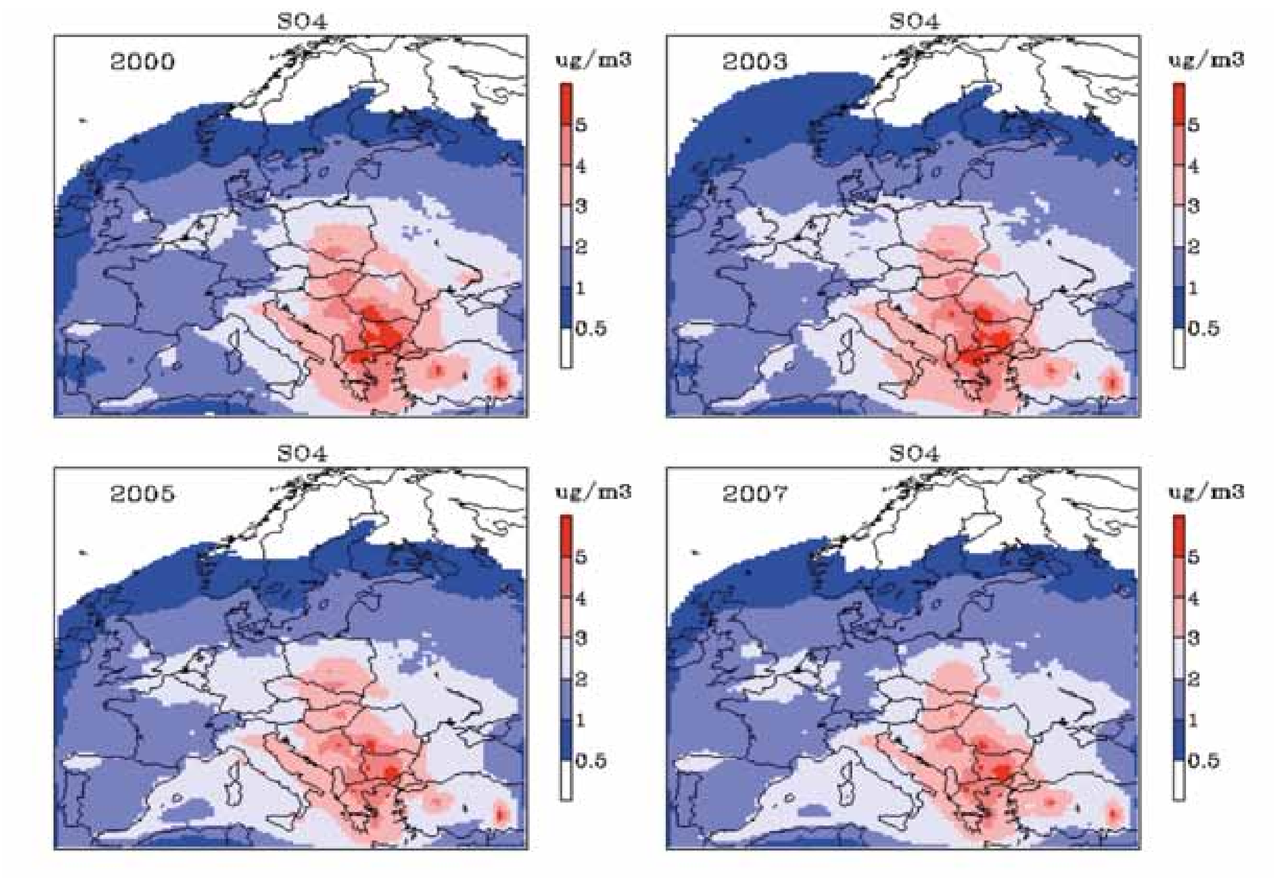

Figure 2a.
Yearly averaged SO4 concentrations over Europe for the years 2000, 2003, 2005 and 2007.

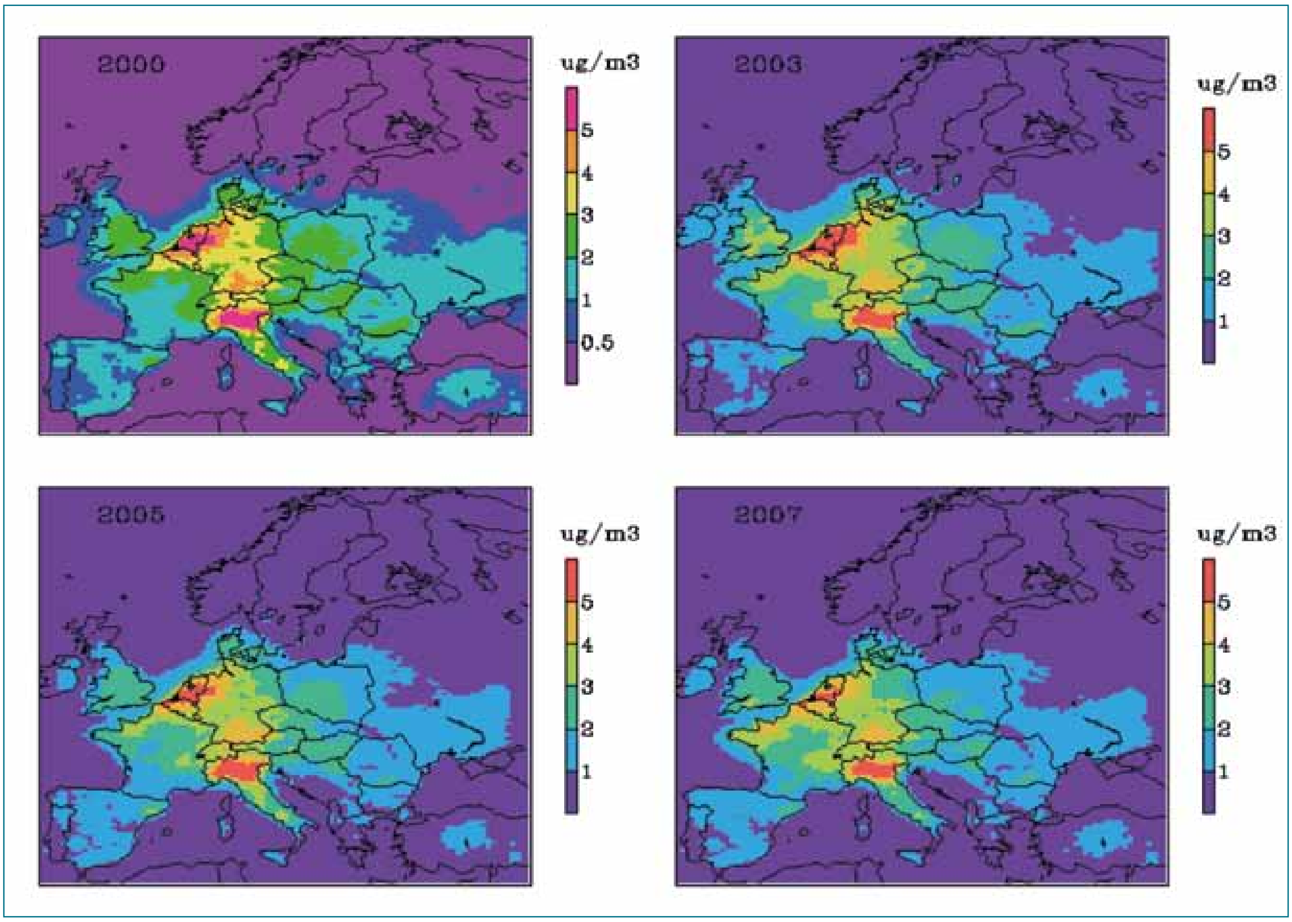

Figure 2b.
Annual average concentrations of NITRATE in Europe for the same years.

2.3 CCN-fields from aerosol-fields

Fundamental in determining the radiative forcing is the choice of the parameterisation converting aerosol mass concentrations into number concentrations of Cloud Condensation Nuclei (CCN). The maximum impact of a specific parameterization on the radiative forcing is determined under the following conditions: excluding the effects of turbulence intensity and vertical velocity; with a tunable parameter for obtaining realistic and stable output; and assuming a continuous stratocumulus layer with a fixed cloud albedo of 0.5. This simplification allows an evaluation without the involvement of complex GCM simulations.

The Boucher-Lohmann parameterization (BL) was chosen to serve as reference. Three other parameterizations used in current state-of-the art GCMs were included in the comparison. This led to the differences in irradiance of up to 60 W m^{-2} for the different parameterisations (figure 3). Therefore, we confined ourselves to the calculation of differences of the impact of the parameterizations on the calculation of the radiative forcing.

These large differences are strongly affected by the imposed simplifications in the assumed cloud structure. A more realistic picture would be the use of a cloud cover of 30% together with varying cloud albedo values, e.g., due to the presence of cirrus cloud. This results in an order of magnitude reduction in sensitivity, still yielding differences of up to -5 W m^{-2} (see calculations in the Appendix). This uncertainty, due to differences in the CCN–parameterizations, is of the same order as the uncertainty in the AIE itself for this region [IPCC-TAR WG1, fig. 6.7h]

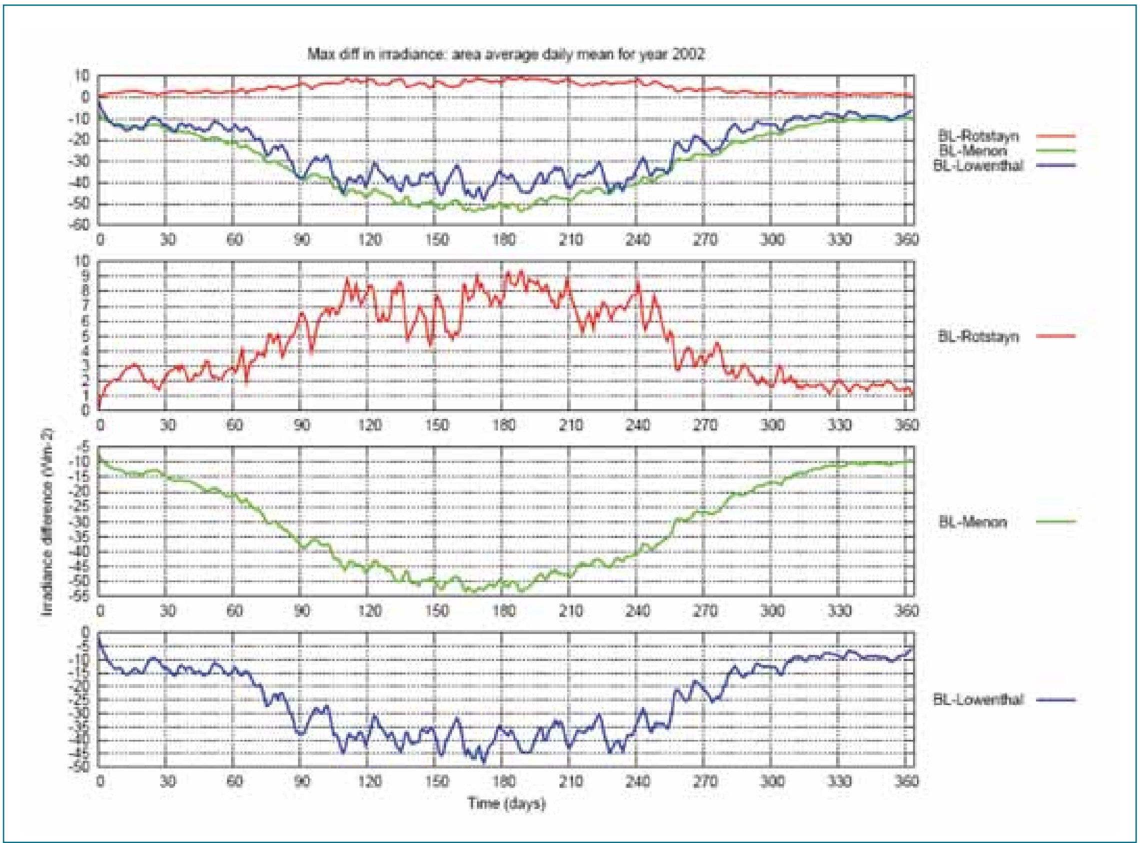

Figure 3.

Average values of maximum differences in irradiance for 2002 on the whole LOTOS-EUROS domain, relative to the reference simulation BL (the 'Boucher-Lohmann' parameterization). Top panel shows all three parameterisations, relative to the reference, while bottom three panels show them individually on a different scale.

2.4 Aerosol cloud module for RACMO

In RACMO the reflection of solar light by clouds is calculated via the effective radius parameter $r_{e.}$ This size parameter is inversely related to the number of cloud droplets (CCN). A stand-alone version of the RACMO radiation module was used to construct an aerosol – cloud module in which r_e could be varied as function of the number CCN that was imported from the LOTOS-EUROS model. This module was used in an offline model study with a comprehensive set of measurements [de Martino et al., 2008]. Input consisted of detailed atmospheric information observed at the Cabauw site together with hourly data on the aerosol components that are used in the CCN-parameterisation. The same parameterizations as discussed in section 2.3 (figure 3) were tested. The output parameter is the solar radiation received at the ground, which was compared with the measured radiation. From the sensitivity tests it was evident that it is possible to achieve a reasonably good comparison with data. (which obviously depends on the parameterization chosen as these vary wildly). However, the number of degrees of freedom in the model is so large that it overshadows the differences arising from the use of different CCN-parameterizations. Therefore a quantitative estimate of the AEI could not be made. Though the first evaluation study was not conclusive because of insufficient statistics, the parameterisation of Menon was found to be in closest agreement with the Cabauw data, and has the advantage that it can be easily extended to include other components like the regional nitrate (see chapter 3). We continue to use this parameterization.

2.5 Interactive combination of aerosol field and climate model

The coupling technique proposed and used so far has been to ingest the aerosol fields from LOTOS-EUROS into RACMO and derive the cloud reflective properties, the so-called One-Way Coupling. More appropriate and physically realistic is a Two-Way coupling whereby the resulting output from RACMO is used to drive the LOTOS-EUROS meteorology. Although not originally planned in CS4, a start was made to implement this Two-Way coupling using three-hourly output from RACMO. The implementation of this 'handshaking' is complex due to a different vertical resolution between the two models and the need to develop software enabling running the two models in parallel. At the time of writing of this report a test version of the Two-Way Coupled LOTOS-EUROS/RACMO is complete and a first modelling exercise of the full scheme for a single month is being implemented. The test run for this one month of Two-Way Coupling is performed and reported under project CS6. Clearly, a Two-Way Coupling interactive climate / aerosol transport models is preferred and should be pursued in follow-up projects.

3. Relevance of ammonium nitrate in the regional AIE

3.1 Introduction

In the modelling workpackage it was assumed that the compound sulphate is the leading constituent in the aerosol particles that serve as cloud condensation nuclei. In the region of the Netherlands another compound, namely ammonium nitrate, is present in high concentrations as well, but its role in the cloud condensation process is largely unknown. Its origins are traffic and agricultural application of manure. The farming sector also produces aerosol-carbon.
The cloud forming properties were examined by measurements in a large cloud chamber that allowed the use of equipment for aerosol measurements designed for this task. Ammonium nitrate is semi-volatile and thus requires special measurement instrumentation. Experiments were performed to analyse cloud formation under conditions leading to the formation of the most relevant cloud types.

3.2 Cloud chamber

The cloud forming properties of nitrate were analysed in the ECN cloud-chamber. The cloud-chamber is operated at supersaturation simulating local marine stratocumulus, the most important type of clouds for the AIE. The chamber is situated at the North-Sea coast of the Netherlands. Arriving air masses range from clean arctic to polluted continental, depending on wind direction. Ambient air was ingested into the CCN chamber and the number of droplets formed was determined. Aerosol spectra were measured both at the entrance and exit of the chamber. The difference in aerosol number is theoretically equal to the number of cloud droplets formed. In addition nitrate, sulphate and ammonium concentrations were measured at the entry and exit points of the chamber. Here the instrument described in section 3.3 is used.
In the Netherlands nitrate dominates in "polluted air" while sulphate dominates in "clean air" [Weijers et al., 2011]. The high nitrate (NO_3) concentrations in the nights of August 2nd and 4th

characterise "polluted" periods (fig. 3). In less polluted periods sulphate (SO_4) is the dominant aerosol component. However, there is no difference in the number of cloud droplets formed, suggesting that both compounds are effective as CCN . This indicates that (manmade) nitrate is at *least* as important as sulphate for the regional CCN budget and thus for the AIE.

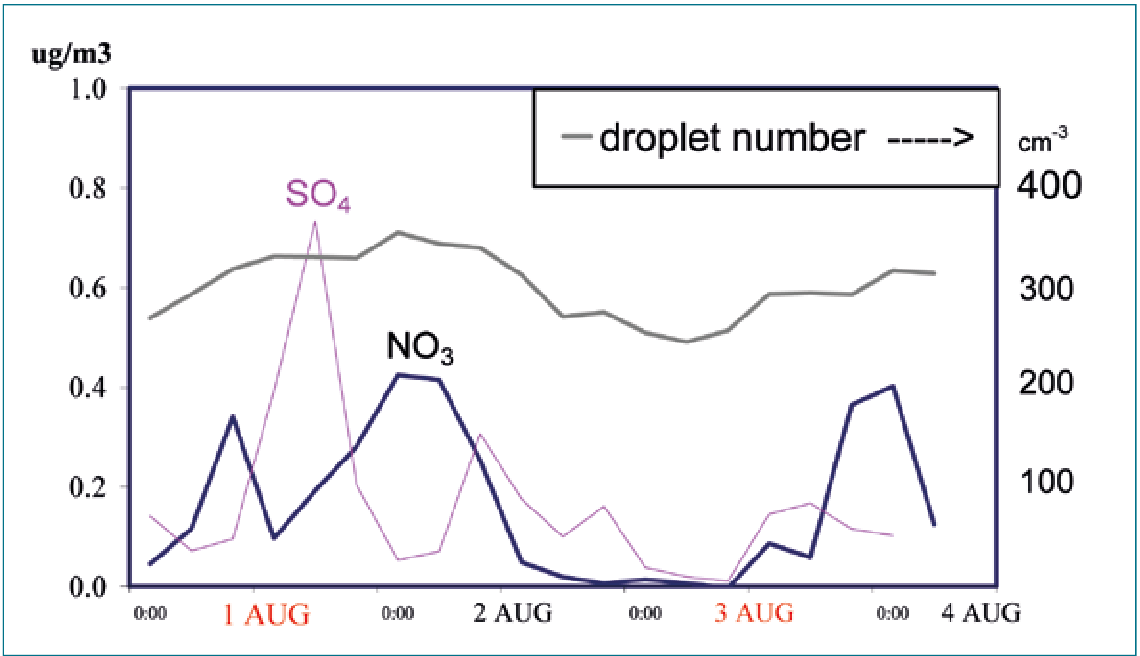

Figure 4.
Concentration of nitrate and sulphate in the aerosol-fraction of the CCN and the resulting cloud droplet concentration, in the cloud chamber during the indicated period in 2008.

3.3 Multi-monitoring instrument for aerosol characterisation

For the representative measurement of the semi-volatile compound ammonium nitrate a prototype instrument, the "MARGA-sizer", was developed. The instrument was (also) deployed at the Cabauw site in the year 2008 (in project CS2). The analysis of the data is carried out in project CS4. The CCN concentrations in the size-range that dominates the most numerous CCN numbers is presented in figure 5. To emphasize the importance of nitrate also the concentration of sulphate in the same size-range is shown. It is seen that generally the concentration of nitrate highly exceeds that of sulphate.

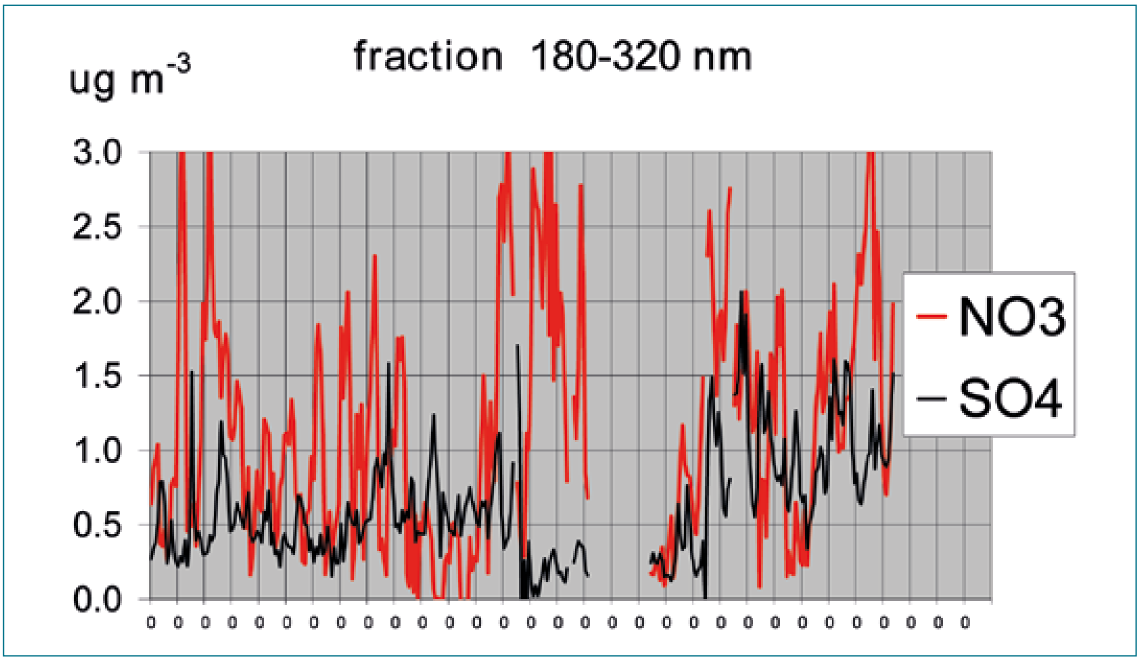

Figure 5.
Concentrations of sulphate and nitrate in a typical CCN size-range during the month of May 2008 at the CESAR-site of Cabauw, in the centre of the Netherlands.

A provision was made in the experiment to measure the concentration of Water Soluble Organic Carbon. A first measuring campaign was carried out with simultaneous operation of another instrument measuring the total content of Organic Carbon. Results for the total amounts from the two instruments agreed fairly well. Approximately half of the Organic Carbon is water soluble, implying that it is present in concentrations that are comparable to those of sulphate.
The concentration of oxalate was measured separately. It is the most abundant and most ideal organic CCN-component. However it is present at a concentration that is a few percent of that of sulphate. This means that it is not an important CCN-substance.

3.4 Contribution of natural/biogenic sources

The effect of the combined radiative forcing due to anthropogenic and natural aerosols is not additional but proportional. This means that the levels of natural aerosols determine for a large part the magnitude of the AIE. In north-western Europe and most notably the Netherlands the most important natural aerosol components are sea salt and organic matter. Whereas the natural contribution by sea salt is obvious and reasonably well constrained, the contribution of natural organic matter to the aerosol budget is uncertain. The uncertainty is caused by the limited insight into the relative abundance of aerosol components and an unclear comprehension on the formation pathways of secondary organic aerosol. Here, we use a high and a low estimate for the natural fraction of organic matter, i.e. 25 and 50%. The natural contributions to mineral dust and sulphate/nitrate/ammonium are estimated to be low (~20%) and very low (~5%), respectively. Sea salt, mineral dust and a small part of the natural Organic Matter contribute mostly to the coarse aerosol fraction, whereas the secondary inorganic aerosol and carbonaceous aerosol dominate the fine aerosol mode. Hence, it is likely that the natural fine mode aerosol has a significantly different CCN activity than the present day fine mode aerosol that is dominated by (manmade) sulphate/nitrate/ammonium. Quantitative figures on the number of CCN associated with these compounds are only available for sulphate, as discussed in section 2.3.

4. Conclusions / synthesis, recommendations, outlook

The main achievements of the CS4 project are:

- An aerosol-cloud module was developed and incorporated in the regional climate model RACMO linking the aerosol concentrations to cloud nucleating properties and hence to the cloud reflective properties.
- Over Europe the uncertainty in the first AIE was about 5 Wm^{-2}, about the size of the value of the first AIE itself. This precluded a determination of the absolute value of the AIE.
- The sulphate and sea-salt aerosol-fields generated by LOTOS-EUROS have been interactively coupled with RACMO.
- A new (prototype) multi-monitoring aerosol instrument was developed for measuring ammonium nitrate and water soluble organic carbon. Further evaluations including comparisons with other ways of measurement are underway.
- The regional manmade aerosol-component (ammonium) nitrate appears to be of equal importance to the magnitude of the first AIE as the component sulphate, routinely considered by IPCC.

The above results provide an outlook for many other initiatives, some of which are already in progress:

- Including nitrate in the RACMO and LOTOS-EUROS model combination. Preparation for this has indeed been started. The development of highly integrated meteorological/chemical transport models is also further developing. This will allow future studies addressing the regional effects of this type of manmade aerosol, locally emitted.
- The experimental knowledge gained in the cloud chamber is being used to evaluate the feasibility of geo-engineering practices involving the addition of artificially produced aerosol into clouds
- The cloud-chamber will continue to be helpful in formulating new theories on cloud formation and aerosol-cloud interactions, and to assist in developing or calibrating new instruments. The chamber has been used to calibrate the CCN-counter that was acquired in another project (CS2)
- The integration of the detection-system of the MARGA-sizer for the various aerosol components in size-classes. This initiative is in progress.

5. Literature

De Martino, G., B. van Ulft, H. ten Brink, M. Schaap, E. van Meijgaard and R. Boers (2008) An aerosol-cloud module for inclusion in the KNMI regional climate model RACMO2. KNMI publication: WR-2008-05, 11/2008.

De Martino, G., R. Boers, M. Schaap and H.M. ten Brink, (2006), Comparative study of cloud droplet number concentration parameterizations for use in regional climate models. EGU general Assembly, 2/4/2006-7/4/2006, Vienna, Austria.

Schaap, M., van Loon, M., ten Brink, H.M., Dentener, F.D., Builtjes, P.J.H. (2004), Secondary inorganic aerosol simulations for Europe with special attention to nitrate, Atmos. Phys. Chem., 4, 857-874

Schaap, M., Timmermans, R.M.A., Sauter, F.J., Roemer, M., Velders, G.J.M., Boersen, G.A.C., Beck, J.P., and Builtjes, P.J.H. (2008). The LOTOS-EUROS model: description, validation and latest developments, Int. J. Environment and Pollution, Vol. 32 (2), 270-289

Brink, H.M. ten, R. Otjes, P. Jongejan, G. Kos (2009) Monitoring of the ratio of nitrate to sulphate in size-segregated submicron aerosol in the Netherlands, Atmospheric Research, 92, 270-276.,

Brink, H.M. ten R. Otjes, P. Jongejan (2009) Nitrate and the regional Indirect Aerosol Effect. European Aerosol conference 2009, Karlsruhe, 6-11 September

Brink, H.M. ten, R. Otjes, P. Jongejan, G. Kos (2007). On the importance of nitrate as IAE-agent in western Europe. AGU Fall-meeting, San Francisco, 10-14 December.

Brink, H.M. ten, R. Otjes, P. Jongejan, J. Slanina. (2007). An instrument for semi-continuous monitoring of the size-distribution of ammonium nitrate aerosol. Atmosph. Environ., 41, 2768–2779

Meijgaard, E. van, L.H. van Ulft, W.J. van de Berg, F.C. Bosveld, B.J.J.M. van den Hurk, G. Lenderink, A.P. Siebesma, 2008: The KNMI regional atmospheric climate model RACMO, version 2.1. KNMI Technical Report 302, 43 pp. Available from KNMI, Postbus 201, 3730 AE, De Bilt, The Netherlands. http://www.knmi.nl/bibliotheek/knmipubTR/TR302.pdf

Weijers, E.P., Schaap, M., Nguyen, L., Matthijsen, J., Denier Van Der Gon, H.A.C., Ten Brink, H.M., Hoogerbrugge, R. Anthropogenic and natural constituents in particulate matter in the Netherlands (2011) Atmospheric Chemistry and Physics, 11 (5), pp. 2281-2294.

Appendix:
Sensitivity study of AIE in Europe as function of CCN parameterisation

A first estimate was made of the first AIE. The interest was on differences between the radiative forcings associated with a range of CCN-parameterizations. Details of the approach can be found in De Martino et al (2008). The albedo calculated by the different parameterisations is mutually compared with the Boucher-Lohmann parameterization acting as reference In the case of conservative scattering, one gets an expression of the albedo, A, as combination of the scattering and the total optical depth, τ:

$$A = \frac{\gamma\tau}{1+\gamma\tau} \qquad (1)$$

γ is a scattering constant of order 0.15.

Now, the optical depth can be expressed as function of the cloud condensation nuclei number, N_d:

$$\tau = \frac{3}{2}\frac{LWC \cdot \Delta z}{r_e},$$

with

$$r_e \cong \left(\frac{3}{4\pi}\frac{LWC}{\rho N_d}\right)^{1/3}$$

LWC, is the liquid water content; r_e effective droplet radius; ρ the density; and Δz the cloud thickness.

The generic difference of albedo between the one as computed using the expression for N_d by BL and the albedo as computed using one of the other expressions can be thus be written as:

$$\partial A = A_{BL} - A_{other} = \frac{\gamma\tau_{BL}}{1+\gamma\tau_{BL}} - \frac{\gamma\tau_{other}}{1+\gamma\tau_{other}} \quad (2)$$

Assuming that $\tau_{other} = \tau_{BL} + \partial\tau$, after Taylor expansion and other substitutions one gets:

$$\partial A = A_{BL} - A_{other} = A(1-A)\frac{1}{3}\frac{\partial N}{N}, \text{ with } \partial N = \frac{N_{BL} - N_{other}}{N_{BL}} \quad (3)$$

Equation (3) is well known in the literature describing the AIE, and is often used to simplify the sensitivity of albedo to changes in the droplet number concentration. However, it is equally valid for the calculations in this paper where we consider variations in droplet concentration due to differences in parameterization. The term *A*(1-*A*) has a maximum for A=0.5, and for this value of A this term is equal to 0.25. This means that the maximum difference of albedo as function of the cloud condensation nuclei number can be expressed using

$$\partial A = \frac{1}{12}\frac{N_{BL} - N_{other}}{N_{other}} \quad (4)$$

Equation (4) has been computed for all the different parameterizations of Nd on each point of the LOTOS-EUROS domain. Figure A1 shows the monthly averages of the resulting values for August 2000, which demonstrate large geographic differences between the different parameterisations.

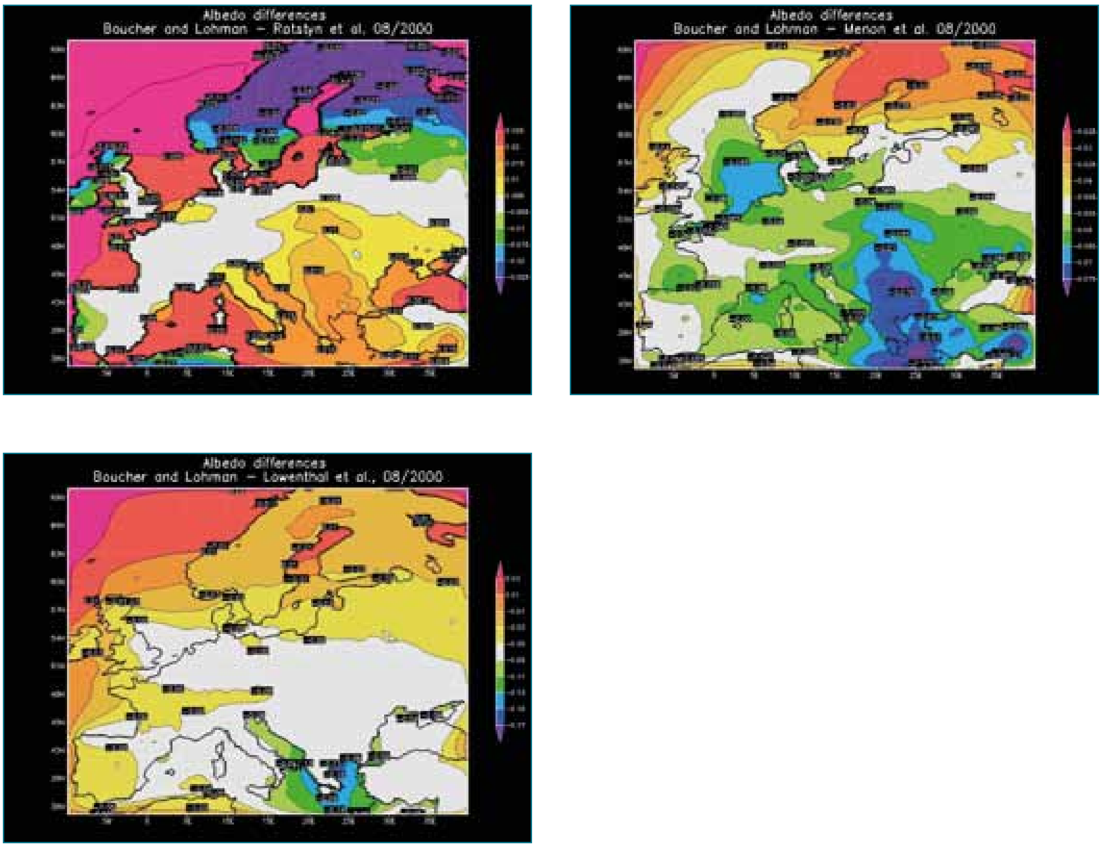

Figure A1.
Geographical variability of the differences between $N^{1/3}$ parameters.

To summarize the picture for a whole year, daily averages have been computed, starting from the hourly data (see figure 3 of the main text). Using the (fairly unrealistic) assumptions of a year-round stratocumulus deck at all regions, a strong radiative effect of 60 W m-2 has been calculated. More realistic assumptions on the cloud cover types and their albedo values reduce this value to 5.4 W m^{-2} (see main text). Clearly more precise results may be obtained from an extended evaluation of the satellite cloud climatology over Europe, and / or calculations using a regional climate model. However, the essential point is here to note that the uncertainty in albedo calculations that are just due to changes in the CCN – parameterizations is at least of the order of the uncertainty in the AIE as typically been stated in the literature and the IPCC documents.

Climate changes Spatial Planning

Climate change is one of the major environmental issues of this century. The Netherlands are expected to face climate change impacts on all land- and water related sectors. Therefore water management and spatial planning have to take climate change into account. The research programme 'Climate changes Spatial Planning', that ran from 2004 to 2011, aimed to create applied knowledge to support society to take the right decisions and measures to reduce the adverse impacts of climate change. It focused on enhancing joint learning between scientists and practitioners in the fields of spatial planning, nature, agriculture, and water- and flood risk management. Under the programme five themes were developed: climate scenarios; mitigation; adaptation; integration and communication. Of all scientific research projects synthesis reports were produced. This report is part of the Climate scenarios series.

Climate scenarios

The projects in this field are designed to obtain high quality climate information and scenarios relevant for the Netherlands. The projects both focus on an improved monitoring and modelling of regional climate variability, and at the construction of tailored climate change scenarios suitable for exploring spatial adaptation options, such as flood retention areas or coastal defense. In all fields special attention is devoted to extreme climate conditions. The climate scenarios are designed and developed jointly with a number of key stakeholders.

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