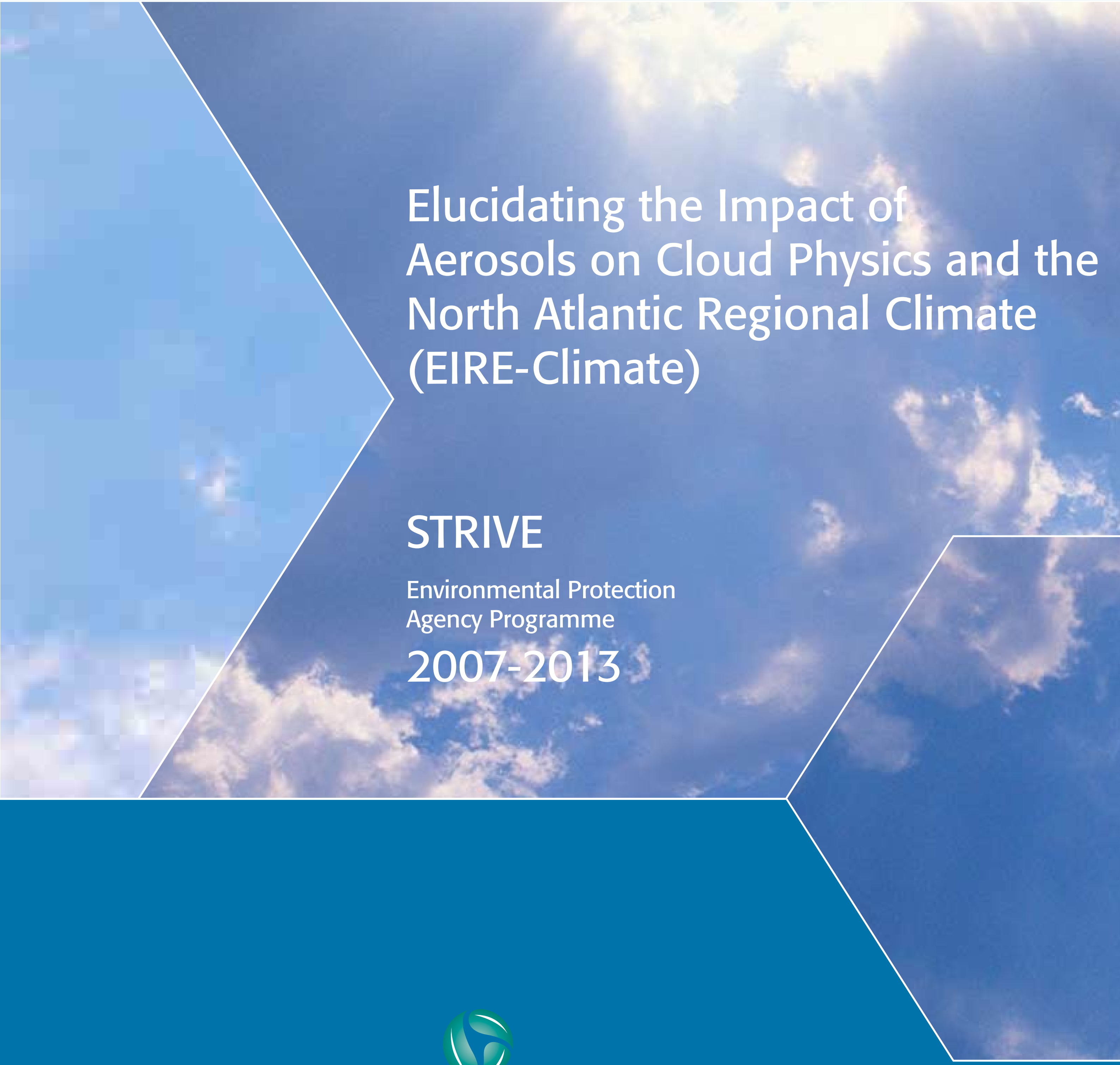
National Development Plan 2007 - 2013

Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

STRIVE

Report Series No.52



Elucidating the Impact of Aerosols on Cloud Physics and the North Atlantic Regional Climate (EIRE-Climate)

STRIVE

Environmental Protection
Agency Programme

2007-2013

SSTI
Strategy for Science, Technology and Innovation

Comhshaol, Oidhreacht agus Rialtas Áitiúil
Environment, Heritage and Local Government

Environmental Protection Agency

The Environmental Protection Agency (EPA) is a statutory body responsible for protecting the environment in Ireland. We regulate and police activities that might otherwise cause pollution. We ensure there is solid information on environmental trends so that necessary actions are taken. Our priorities are protecting the Irish environment and ensuring that development is sustainable.

The EPA is an independent public body established in July 1993 under the Environmental Protection Agency Act, 1992. Its sponsor in Government is the Department of the Environment, Heritage and Local Government.

OUR RESPONSIBILITIES

LICENSING

We license the following to ensure that their emissions do not endanger human health or harm the environment:

- waste facilities (e.g., landfills, incinerators, waste transfer stations);
- large scale industrial activities (e.g., pharmaceutical manufacturing, cement manufacturing, power plants);
- intensive agriculture;
- the contained use and controlled release of Genetically Modified Organisms (GMOs);
- large petrol storage facilities.
- Waste water discharges

NATIONAL ENVIRONMENTAL ENFORCEMENT

- Conducting over 2,000 audits and inspections of EPA licensed facilities every year.
- Overseeing local authorities' environmental protection responsibilities in the areas of - air, noise, waste, waste-water and water quality.
- Working with local authorities and the Gardaí to stamp out illegal waste activity by co-ordinating a national enforcement network, targeting offenders, conducting investigations and overseeing remediation.
- Prosecuting those who flout environmental law and damage the environment as a result of their actions.

MONITORING, ANALYSING AND REPORTING ON THE ENVIRONMENT

- Monitoring air quality and the quality of rivers, lakes, tidal waters and ground waters; measuring water levels and river flows.
- Independent reporting to inform decision making by national and local government.

REGULATING IRELAND'S GREENHOUSE GAS EMISSIONS

- Quantifying Ireland's emissions of greenhouse gases in the context of our Kyoto commitments.
- Implementing the Emissions Trading Directive, involving over 100 companies who are major generators of carbon dioxide in Ireland.

ENVIRONMENTAL RESEARCH AND DEVELOPMENT

- Co-ordinating research on environmental issues (including air and water quality, climate change, biodiversity, environmental technologies).

STRATEGIC ENVIRONMENTAL ASSESSMENT

- Assessing the impact of plans and programmes on the Irish environment (such as waste management and development plans).

ENVIRONMENTAL PLANNING, EDUCATION AND GUIDANCE

- Providing guidance to the public and to industry on various environmental topics (including licence applications, waste prevention and environmental regulations).
- Generating greater environmental awareness (through environmental television programmes and primary and secondary schools' resource packs).

PROACTIVE WASTE MANAGEMENT

- Promoting waste prevention and minimisation projects through the co-ordination of the National Waste Prevention Programme, including input into the implementation of Producer Responsibility Initiatives.
- Enforcing Regulations such as Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) and substances that deplete the ozone layer.
- Developing a National Hazardous Waste Management Plan to prevent and manage hazardous waste.

MANAGEMENT AND STRUCTURE OF THE EPA

The organisation is managed by a full time Board, consisting of a Director General and four Directors.

The work of the EPA is carried out across four offices:

- Office of Climate, Licensing and Resource Use
- Office of Environmental Enforcement
- Office of Environmental Assessment
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet several times a year to discuss issues of concern and offer advice to the Board.

EPA STRIVE Programme 2007–2013

Elucidating the Impact of Aerosols on Cloud Physics and the North Atlantic Regional Climate (EIRE-Climate)

(2008-FS-29-M1)

STRIVE Report

Prepared for the Environmental Protection Agency

by

National University of Ireland, Galway

Authors:

Robert J. Flanagan and Colin D. O'Dowd

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co.Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

ACKNOWLEDGEMENTS

This report is published as part of the Science, Technology, Research and Innovation for the Environment (STRIVE) Programme 2007–2013. The programme is financed by the Irish Government under the National Development Plan 2007–2013. It is administered on behalf of the Department of the Environment, Heritage and Local Government by the Environmental Protection Agency which has the statutory function of coordinating and promoting environmental research.

DISCLAIMER

Although every effort has been made to ensure the accuracy of the material contained in this publication, complete accuracy cannot be guaranteed. Neither the Environmental Protection Agency nor the authors accept any responsibility whatsoever for loss or damage occasioned or claimed to have been occasioned, in part or in full, as a consequence of any person acting, or refraining from acting, as a result of a matter contained in this publication. All or part of this publication may be reproduced without further permission, provided the source is acknowledged.

The EPA STRIVE Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

EPA STRIVE PROGRAMME 2007–2013

Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-84095-352-7 **Online version**
Price: Free

Details of Project Partners

Robert J. Flanagan
School of Physics and Centre for Climate and Air Pollution Studies
Environmental Change Institute
National University of Ireland, Galway
University Road
Galway
Ireland
Tel.: +353-91-51267
Email: robert.flanagan@nuigalway.ie

Colin D. O'Dowd
School of Physics and Centre for Climate and Air Pollution Studies
Environmental Change Institute
National University of Ireland, Galway
University Road
Galway
Ireland
Tel.: +353-91-493306
Email: colin.odowd@nuigalway.ie

Table of Contents

Acknowledgements **ii**

Disclaimer **ii**

Details of Project Partners **iii**

Executive Summary **vii**

1 Introduction **1**

- 1.1 Objectives 1

2 The Science of Climate Change **2**

- 2.1 The Earth’s Radiation Balance 3
- 2.2 The Greenhouse Effect 3
- 2.3 Atmospheric Aerosols and Climate Change 3
- 2.4 Links between Air Quality and Climate Change 5
- 2.5 Cloud Droplet Formation 6
- 2.6 Climate Modelling 6

3 The REMOTE Regional Climate model **9**

- 3.1 The M7 Aerosol Microphysics Module 10

4 Modelling Cloud Droplet Activation **12**

- 4.1 Aerosol–Cloud Chemistry Process Model 12
- 4.2 The Nenes Cloud Droplet Activation Parameterisation 14
- 4.3 Implementation of the Parameterisation in REMOTE 14
- 4.4 Sample Parameterisation Output 15

5 Model Simulations **17**

- 5.1 Aerosol Number Concentration 18
- 5.2 Cloud Droplet Number Concentration 18
- 5.3 Droplet Effective Radius 20

6 Conclusions **21**

7 Ongoing Work and Recommendations **22**

References **23**

Research Outputs – Publications **25**

Acronyms and Annotations **26**

Executive Summary

Aerosols affect the Earth's climate through their interaction with clouds by acting as sites on which cloud droplets can form. These interactions alter the cloud's microphysics and lifetime. This effect is of critical importance as clouds perform a major role in maintaining the Earth's radiation balance primarily by reflecting sunlight back into space and absorbing the infrared radiation emitted by the Earth. The number and size of droplets are the key factors influencing how much radiation clouds reflect back into space.

A cloud droplet activation parameterisation has been implemented in the REMOTE (REgional MOdel with Tracer Extension) regional climate model. The parameterisation provides a robust computationally efficient treatment of aerosol cloud interactions. There are large uncertainties in the indirect effect due to the complex aerosol–cloud interactions involved. REMOTE, including the newly implemented cloud droplet nucleation scheme, provides a useful tool to study the indirect effect of aerosols.

REMOTE (Langmann, 2000) is a three-dimensional high-resolution regional climate model (RCM). The dynamics are based on the regional weather forecast model system of the German Weather Service, while physical parameterisations are based on the ECHAM4 (European Centre Hamburg Model 4). The aerosol dynamics are based on the modal aerosol model M7 (Vignati et al., 2004). It includes RADM2 (Regional Acid Deposition Model 2) chemistry and is driven by the European Centre for Medium Range Weather Forecasting (ECMWF) analysis data every six hours at lower and lateral boundaries. The model covers a domain of the north-east Atlantic Ocean and most of Europe. A combined organic–inorganic sea-spray source function has been incorporated into the model and the model now also includes a treatment of aerosol deposition. It has been shown that organic matter is highly significant in the marine environment and the combined organic–inorganic sea-spray source function provides useful input for the RCM.

The months of January and June 2003 were chosen as case studies for model simulations. Using these two months, the effect of increased levels of organic matter during summertime compared to wintertime can be evaluated.

For both months droplet effective radius is larger over the ocean than the continent. The average droplet effective radii within an area (M1) off the west coast of Ireland are 11.39 μm and 11.59 μm for January and June, respectively. This area M1 was chosen as being representative of north-east Atlantic marine conditions. Within the M1 area around Ireland, the average cloud droplet number concentration (CDNC) for January was 41.2 cm^{-3} and the average CDNC for June was 23.8 cm^{-3}. The average wind speeds for January and June were 8.8 ms^{-1} and 6.1 ms^{-1}, respectively.

The addition of this cloud droplet activation parameterisation makes REMOTE one of the most advanced regional climate models available worldwide, and, along with other developments taking place, will help REMOTE to provide detailed climate predictions for Europe and the north Atlantic with particular reference to Ireland. Some other developments taking place with REMOTE include treatments of ozone deposition, coastal nucleation and secondary organic aerosols. The model will be used for long-term simulations based on the Intergovernmental Panel on Climate Change's (IPCC) AR5 (Fifth Assessment Report) emission scenarios, and will also be used to study air quality and links between air quality and climate change. The inclusion of the aerosol–cloud interaction parameterisation makes the model particularly suitable for studying precipitation trends for Ireland and the rest of Europe.

1 Introduction

Aerosols affect the Earth's climate through their interaction with clouds by acting as sites on which cloud droplets can form. These interactions alter cloud microphysics and lifetime. This effect is of critical importance as clouds perform a major role in maintaining the Earth's radiation balance primarily by reflecting sunlight back into space and absorbing the infrared radiation emitted by the Earth.

The number and size of droplets are the key factors influencing how much solar radiation clouds reflect directly back into space and also how much infrared radiation emitted by the Earth they absorb. Aerosols act as the nuclei on which cloud droplets form. How well aerosols function as cloud condensation nuclei (CCN) depends on their size and chemical composition. If the number of CCN increases, this will lead to an increase in cloud droplet number and, since there is a limited amount of liquid water available, this will lead to the droplets being of smaller size. As well as impacting on climate, the smaller droplet size will also impact on air quality, as precipitation is one of the key processes for the removal of pollutants from the atmosphere through wet deposition.

Given the significance of the aerosol indirect effects, it is important to include an accurate representation of aerosol–cloud interactions in climate models. However, it is too computationally intensive to model in complete detail these complex interactions in global or regional climate models. Therefore, a cloud droplet nucleation parameterisation has been implemented in REMOTE (REgional MOdel with Tracer Extension)[1]. This parameterisation provides a computationally efficient description of the activation of CCN into cloud droplets. There are large uncertainties in the indirect effect due to the complex aerosol–cloud interactions involved. REMOTE, including the newly implemented cloud droplet nucleation scheme, provides a useful tool for studying the indirect effects of aerosols.

1.1 Objectives

The objectives of this project as set out in the original proposal are given below:

1. To develop a state-of-the-art organic–inorganic aerosol–cloud chemistry process model;
2. To elucidate the role of organic compounds on cloud formation;
3. To develop multi-component aerosol–cloud chemistry parameterisations for use in regional climate models (RCMs) and global climate models (GCMs);
4. To implement the above parameterisations in a RCM and make them available to the wider climate modelling community;
5. To evaluate the effect of different aerosol species on the regional north Atlantic and western European climate with particular reference to Ireland.

In addition to the goals and objectives outlined above, this model will continue to be a useful tool for Irish environmental studies. The model will also be used to study aerosol growth resulting from heterogeneous chemistry and its impact on air quality, as aerosols are known to have a significant impact on air quality and human health (e.g. IPCC, 2001; Dockery and Pope, 1994). It is our intention that this model would be further utilised and developed by future researchers in order to better understand, protect and predict our sensitive climate.

---

[1] REMOTE (Langmann, 2000) is a three-dimensional high-resolution regional climate model (RCM).

2 The Science of Climate Change

Eleven of the last 12 years (1995–2006) have been among the 12 warmest years on Earth in the instrumental record of global surface temperature (since 1850). It has become clear that human activities, primarily through the emission of greenhouse gases, are responsible for this temperature change. Figure 2.1 shows the increasing temperature trend and gives model predictions based on different emission scenarios (IPCC, 2000). The B1 scenario is a future with a high level of environmental and social consciousness combined with a globally coherent approach to a more sustainable development. The A1 scenarios are for cases of rapid and successful economic development, in which regional average incomes per capita converge – current distinctions between 'poor' and 'rich' countries eventually dissolve. Full details of the scenarios can be found in Nakićenović and Swart (2000) and at: http://www.ipcc.ch/.

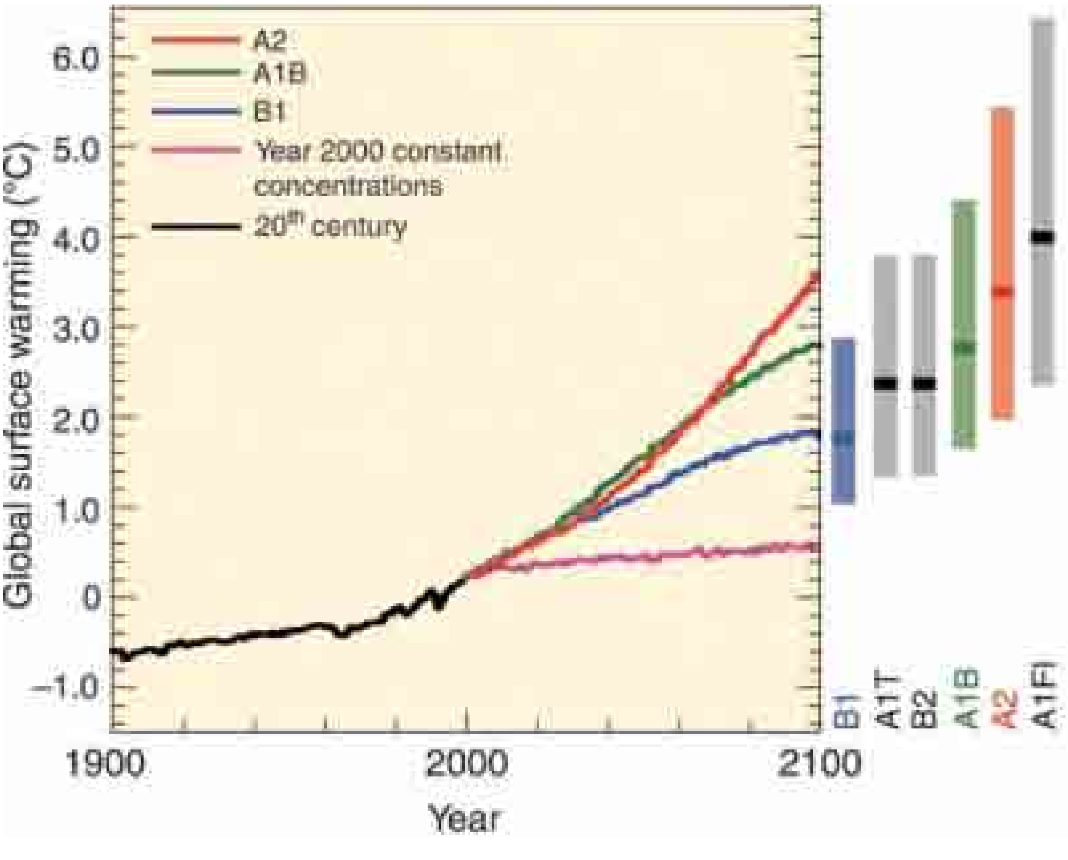


Figure 2.1. Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the emission scenarios, shown as continuations of the 20th century simulations. The B1 scenario describes a world more integrated, and more ecologically friendly than present day. A1T represents a future reliant on non-fossil fuel energy sources. B2 represents a world of increased concern for environmental and social sustainability. A1B represents a future where there is a balance across all fuel sources. The A2 scenario represents a more divided world and A1FI represents a fossil intensive future. The pink line is for the experiment where concentrations were held constant at year 2000 values. For a full explanation of the scenarios see Nakićenović and Swart (2000). (From IPPC, 2007.)

2.1 The Earth's Radiation Balance

Life on Earth as we know it is maintained because the delicate balance between the amount of energy the Earth absorbs from the sun and what is re-emitted results in temperatures near the surface which are favourable for life. Clouds, atmospheric gases such as water vapour and carbon dioxide (CO_2) and aerosols all play an important role in maintaining this balance. However, human activities have changed the concentration and distribution of some of these variables and this has led to enhanced global warming. As defined by the Intergovernmental Panel on Climate Change (IPCC), 'radiative forcing' is a measure of how the energy balance of the Earth's atmosphere system is influenced when factors that affect climate are altered relative to pre-industrial times. The term radiative forcing is used to denote an externally imposed perturbation in the radiative energy budget of the Earth's climate system, which may lead to changes in climate parameters. The radiative forcing of the surface–troposphere system due to the perturbation or the introduction of an agent (say, a change in greenhouse-gas concentrations) is defined as the change in net (down minus up) irradiance (solar plus long-wave in Wm^{-2}) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values. The anthropogenic influence on the various radiative forcing components is given in Fig. 2.2.

2.2 The Greenhouse Effect

The greenhouse effect is the heating of the Earth due to the presence of greenhouse gases. It is named this way because of a similar effect produced by the glass panes of a greenhouse. Shorter-wavelength solar radiation from the sun passes through the Earth's atmosphere, then is absorbed by the surface of the Earth, causing it to warm. Part of the absorbed energy is then re-radiated back to the atmosphere as long-wave infrared radiation. Little of this long-wave radiation escapes directly back into space; the atmosphere is not completely transparent to these wavelengths. The greenhouse gases selectively transmit the infrared wavelengths, whilst absorbing others. The greenhouse gases absorb these waves and re-emit some of the waves downward, leading to a higher energy density in the lower atmosphere causing the lower atmosphere to warm. Three of the most important anthropogenic greenhouse gases are CO_2, methane (CH_4) and nitrous oxide (N_2O). Carbon dioxide is released into the atmosphere by a large number of sources, including the burning of solid waste, wood and wood products, and fossil fuels (oil, natural gas and coal). Methane also has a wide variety of sources, including organic waste decomposition under anaerobic conditions, for example, in landfills or in connection with enteric fermentation in animals, especially ruminants. Methane emissions also occur during the production and transport of fossil fuels. Nitrous oxide emissions occur during various agricultural and industrial processes, and when solid waste or fossil fuels are burned. The atmospheric concentration of greenhouse gases has been increasing since the beginning of the industrial age due to human activities. The global atmospheric concentration of CO_2 has increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005 (Solomon et al., 2007). Measurements of CO_2 concentrations at the Mace Head Atmospheric Research Station agree well with these values. The radiative forcing estimates and ranges in 2005 for anthropogenic CO_2, CH_4 and N_2O are given in Fig. 2.2. The estimated radiative forcing due to these gases is estimated to be between +2.07 and +2.53 Wm^{-2}. Their impact on climate is relatively well understood and there is high confidence associated with the values.

2.3 Atmospheric Aerosols and Climate Change

Aerosols are ubiquitous in our atmosphere and are present from both natural and anthropogenic sources. Around 75% of all aerosols found in the Earth's atmosphere come from natural sources. The most important of these natural components are sea spray, soil and rock debris (dust), products of volcanic emissions, smoke from forest fires, and solid and liquid particles formed by chemical reactions in the atmosphere. The remaining atmospheric aerosols result from human actions. Some, such as the aerosols released from spray-can products, go directly to form aerosols in the atmosphere. Others undergo chemical changes similar to those associated with natural products. For example, oxides of nitrogen and sulphur produced during the combustion of fossil fuels may be converted to liquid or solid nitrates and sulphates, which are then incorporated into atmospheric aerosols.

Aerosols may be emitted directly (primary aerosols) or they can be formed in the atmosphere by gas-to-particle conversion (secondary aerosols). Natural sources include sea spray, dust and volcanoes. The main source of anthropogenic aerosols is fossil fuel combustion. Gas-to-particle conversion (nucleation and new particle formation) has been observed in many different locations such as the coastal environment (O'Dowd et al., 2002a), street canyons (Voigtländer et al., 2006), boreal forests (Kulmala et al., 2004), Finnish Lapland (Vehkamäki et al., 2004) and Antarctica (Koponen et al., 2003). It is a complex and very important process that is not yet fully understood.

Aerosol size distributions (i.e. how the concentration varies with size) are usually described by a combination of log-normal modes, which can vary in size and composition. Each of these modes has a defined modal diameter and geometric standard deviation. The nucleation mode has a modal diameter of less than 0.01 µm, the Aitken mode between 0.01 and 0.1 µm, the accumulation mode between 0.1 and 1 µm and the coarse mode >1 µm. These modes can differ in composition and solubility. For instance, the mode could consist of sea salt or dust particles, and it could be soluble, insoluble or partially soluble.

The main processes describing aerosol particle formation and growth are nucleation, condensation and coagulation. Nucleation occurs when gas molecules aggregate and change phase to a liquid or a solid to form a new small aerosol particle or a cluster on an existing particle surface. Condensation occurs when a gas diffuses to and sticks to the surface of a particle and changes state to a liquid. Evaporation occurs when a liquid molecule on a particle surface changes state to a gas and diffuses away from the surface. Coagulation occurs when two aerosol particles collide and coalesce (stick together) to form a third larger particle. Aerosol particles have been shown to have a net cooling effect on the Earth (Houghton et al., 2001). Their impact is usually divided into two separate effects: the direct aerosol effect and the indirect aerosol effect.

2.3.1 The Direct Aerosol Effect

The direct effect is the mechanism by which aerosols scatter and absorb short-wave and long-wave radiation, thereby altering the radiative balance of the Earth's atmosphere system. Sulphate, fossil fuel organic carbon, fossil fuel black carbon (BC), mineral dust (≈20% anthropogenic) and biomass burning produce aerosols, and all have been identified as having a significant anthropogenic component and exerting a significant direct radiative forcing (Solomon et al., 2007). These aerosols often form haze layers which block incoming solar radiation. As can be seen from Fig. 2.2 it has a net cooling effect. The IPCC (Solomon et al., 2007) has estimated that the global radiative forcing due to the direct effect is –0.5 ±0.4 Wm^{-2} with medium to low level of scientific understanding. It is clear that there is still a large uncertainty of the magnitude of this effect, but understanding has improved since the IPCC's Third Assessment Report in 2001 (Houghton et al., 2001) where there was a very low level of scientific understanding.

2.3.2 The Indirect Aerosol Effect

Aerosols also affect the Earth's climate through their interaction with clouds by acting as sites on which cloud droplets can form. These interactions alter the clouds' microphysics and atmospheric lifetimes. A cloud's lifetime is influenced by evaporation and precipitation processes (i.e. it either evaporates or is removed by precipitation). This effect is of critical importance as clouds perform a major role in maintaining the Earth's radiation balance, primarily by reflecting sunlight back into space and absorbing the infrared radiation emitted by the Earth.

The number and size of droplets are the key factors influencing how much radiation clouds reflect back into space. Aerosols act as the nuclei on which cloud droplets form. How well aerosols act as cloud condensation nuclei depends on their size and chemical composition. If the number of cloud condensation nuclei increases, this will lead to an increase in cloud droplet number, and, since there is a limited amount of liquid water available, this will lead to the droplets being of smaller size. This increases the cloud's albedo, leading to a further cooling effect, and is known as the first indirect effect. Drizzle suppression occurs when the droplets are smaller in size, which can increase the lifetime of the cloud. This is known as the second indirect effect. As well as impacting on climate, this will also impact on air quality as precipitation is one of the key processes for the removal of pollutants from the atmosphere through wet deposition. There are large uncertainties in the indirect effect due to the complex aerosol–cloud interactions involved. The estimated magnitude of the indirect effect and level of uncertainty are given in Fig. 2.2.

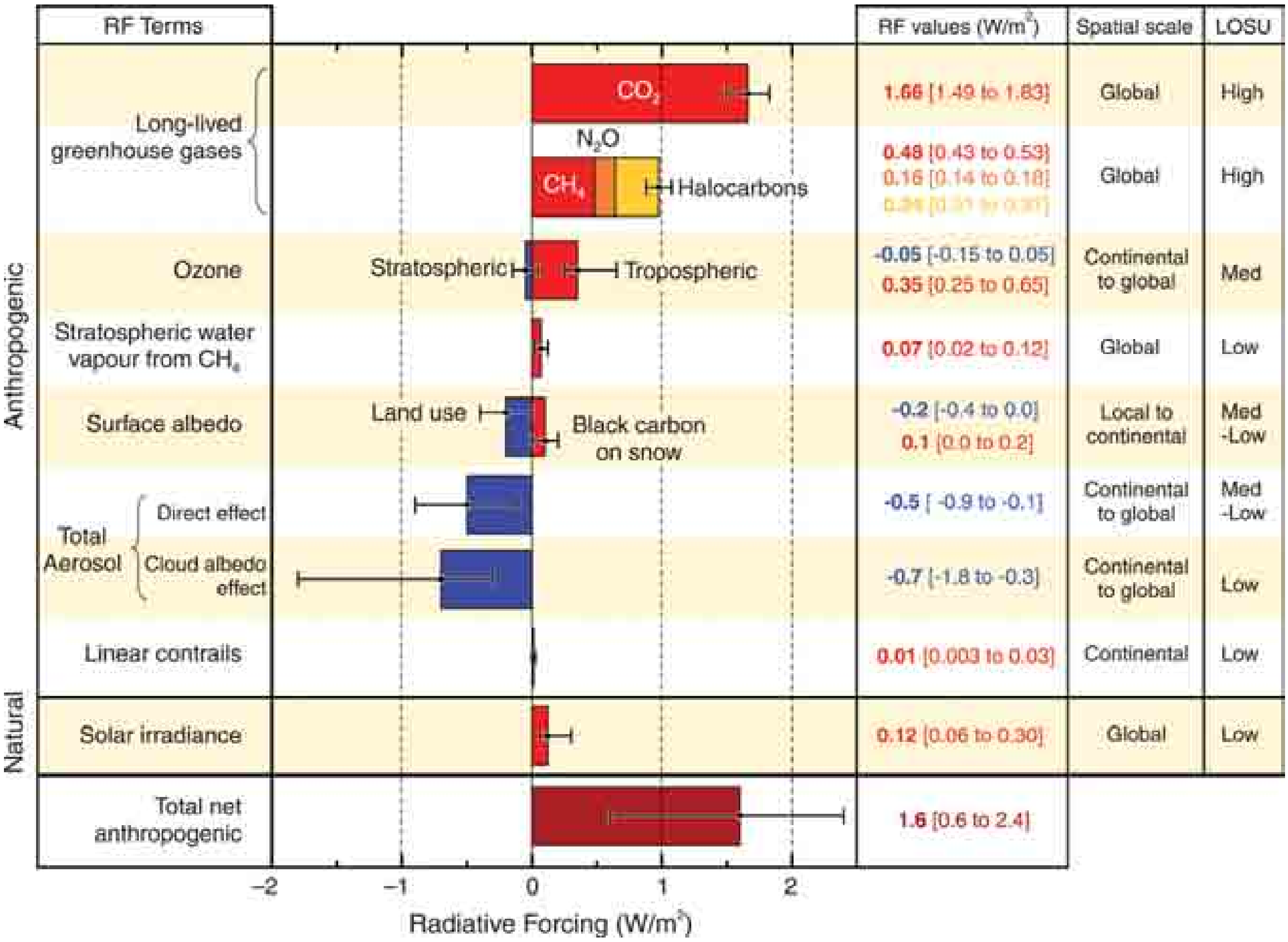


Figure 2.2. Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. (Taken from Solomon et al., 2007.)

Its magnitude is estimated as –0.7 Wm^{-2} with a large uncertainty range from –1.1 Wm^{-2} to –0.4 Wm^{-2}. It is clear that this is a major component of the Earth's radiation balance. In order to be able to provide better climate predictions further research is required in this area. As the model used in this study is able to provide high spatial resolution simulations of the European region, it will be able to identify regional impacts that might be missed by global models using lower resolutions. For example, the influence of topographical features could be examined. Also, as the model contains detailed gas-phase chemistry, aerosol microphysics and aerosol–cloud interactions it will be able to study the links between climate change and air quality. Some of these links are given in the following section.

2.4 Links between Air Quality and Climate Change

There are many complex links between climate change and air quality. These include effects related to chemistry via changes in temperature or water vapour concentration. This is due to the fact that the types of reaction and rates of reactions taking place in the atmosphere are influenced by the temperature and humidity. For example, in cloud droplet formation, if water vapour concentration is increased, larger cloud droplets will be formed. The larger droplets have larger surface areas on which heterogeneous chemical reactions can take place and thus will influence the atmospheric lifetimes of reactive gases such as sulphur dioxide

(SO_2). Other links include emissions (e.g. biogenic volatile organic compounds [VOCs], lightning and soil NO_x, wetland methane and wild fires) and atmospheric dynamics (e.g. convective mixing, precipitation, stratosphere–troposphere exchange and boundary layer ventilation). Natural emissions of aerosols and gases will also be affected by climate change due to, for example, an increase in the frequency of lightning and wild fires. The most significant removal mechanism for long-range transport of particulate matter (PM) is wet removal, and the frequency of rainfall is more important than the total amount of rainfall to determine such removal. The time between precipitation events determines the lifetime of an aerosol in the free troposphere. One key question for future impact analysis of PM is to determine how precipitation is changing with climate.

2.5 Cloud Droplet Formation

Cloud droplets are formed when an air parcel cools due to adiabatic expansion or radiative loss of heat. The model presented here simulates a rising air parcel and its cooling due to adiabatic expansion. The decrease in temperature decreases the saturation vapour pressure of water and increases the saturation ratio of water in the air parcel as the saturation ratio *S* and is given by:

$$S = \frac{\rho_w}{\rho_{sw}} ,$$

where ρ_w is the partial pressure and ρ_{sw} is the saturation vapour pressure. Homogenous nucleation of water vapour requires very high saturation ratios and this would present a large barrier for cloud droplet formation. However, atmospheric aerosols provide surfaces onto which water can condense. This condensation requires much lower saturation ratios and is the primary mechanism that leads to cloud droplet formation.

Traditionally, Köhler theory has been used to describe the formation of cloud droplets (see e.g. Seinfeld and Pandis, 1998). The saturation ratio of water vapour over the droplet surface is given by

$$S = \frac{\rho_w}{\rho_{sw}} = f_w X_w \exp \frac{2\sigma v_w}{RTr} ,$$

where p_w is the partial pressure, p_{sw} is the saturation vapour pressure, f_w is the activity coefficient, X_w is the mole fraction, v_w is the molar volume of water, σ is the surface tension of the solution, R is the gas constant, T is the temperature, and r is the radius of the droplet. Figure 2.3 shows Köhler curves for sodium chloride (NaCl) and ammonium sulphate ($(NH_4)SO_4$) particles of various dry diameters (D_d). Once a particle reaches the critical size (D_c) it grows spontaneously due to the condensation of water vapour. This process is known as the activation of an aerosol particle to a cloud droplet. The critical supersaturation (S_c) required for activation depends on the size and composition of the particle and can be calculated using Köhler theory. As the droplet grows and more water condenses, this removes water vapour from the gas phase and also releases latent heat. This results in a reduction in the rate of increase of the water saturation ratio and eventually the saturation ratio begins to decrease. Depending on conditions, some droplets might grow large enough to form precipitation, but usually the droplets evaporate at the top of the cloud. An average cloud droplet has a diameter of 0.02 mm, whereas an average rain droplet has a diameter of 2 mm. As can be seen in the figure, for a given size, NaCl has a lower critical supersaturation than $(NH_4)SO_4$ and thus forms cloud droplet more easily. The difference in the chemical properties of different types of aerosol is one of the key factors affecting cloud formation.

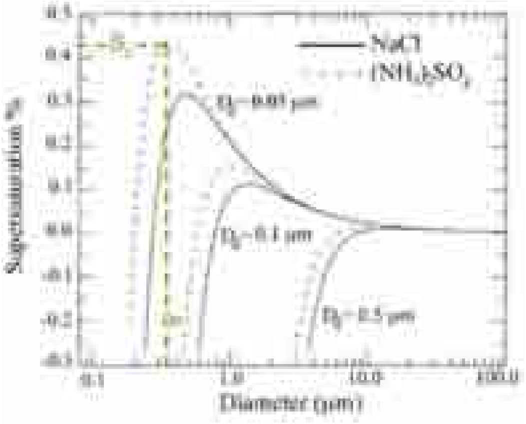


Figure 2.3. Ammonium sulphate and sodium chloride Köhler curves.

2.6 Climate Modelling

In general terms, a climate model could be defined as a mathematical representation of the climate system based on physical, biological and chemical principles. The equations derived from these laws are so complex that they must be solved numerically (e.g. Goosse et al., 2009).

As a consequence, climate models provide a solution that is discrete in space and time, meaning that the results obtained represent averages over regions, each

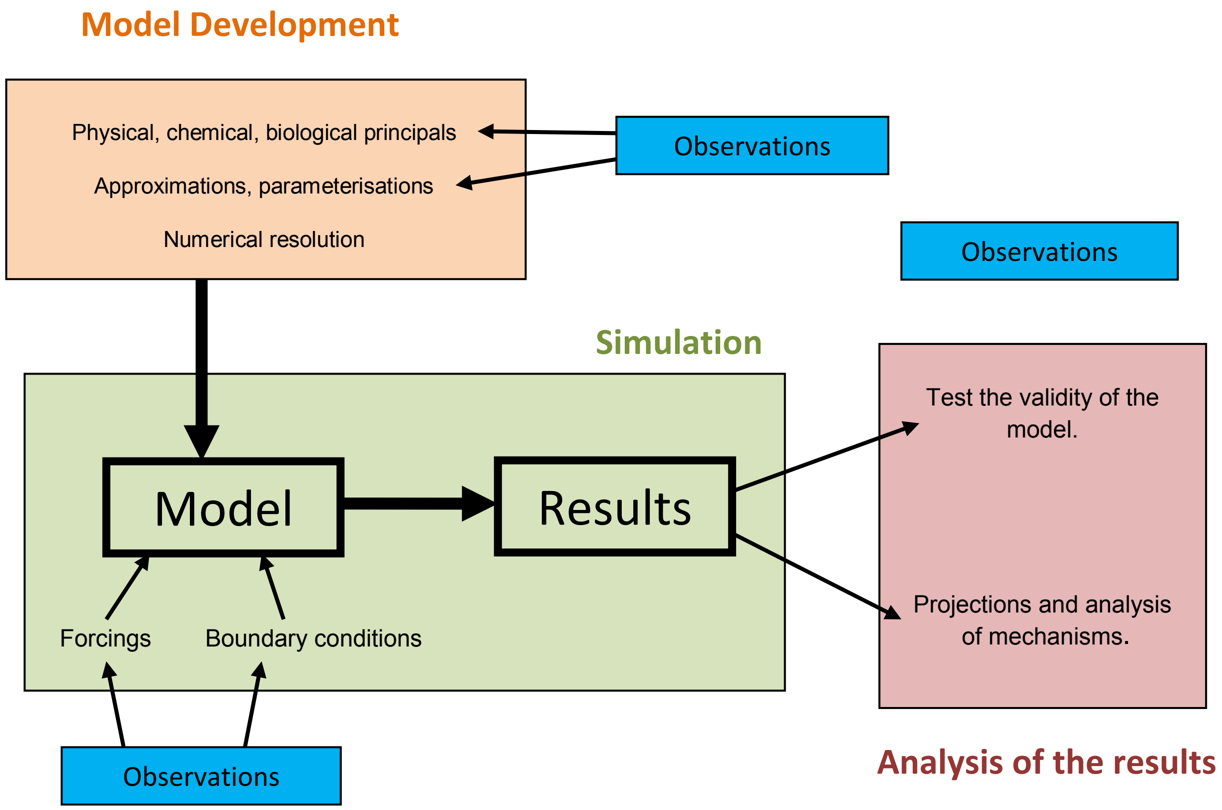


Figure 2.4. Schematic representation of the development and use of a climate model.

of whose size depends on model resolution, and over specific time steps. For instance, some models provide only globally or zonally averaged values, while others have a numerical grid whose spatial resolution could be less than 100 km. The time step could be between minutes and several years, depending on the process studied.

Despite the increase in sophistication of global and regional climate models in recent years, and the increase in computing power available, the numerical grids are still much too coarse to represent small-scale processes such as turbulence in the atmospheric and oceanic boundary layers, the interactions of the circulation with small-scale topography features, thunderstorms, cloud microphysics processes, etc. Furthermore, many processes are still not sufficiently well known to include their detailed behaviour in models. As a consequence, parameterisations have to be designed, based on empirical evidence and/or on theoretical arguments, to estimate the large-scale influence of those processes not included explicitly in the model. Because these parameterisations reproduce only the first-order effects and are usually not valid for all possible conditions, they are often a source of considerable uncertainty in models.

In addition to the physical, biological and chemical process information included in the model equations, climate models require some inputs derived from observations or other model studies as these observations are crucial links between the model and the real atmosphere. Model inputs are separated into boundary conditions (which are generally fixed during the course of the simulation) and external forcings, such as the changes in solar irradiance, which drive the changes in climate. Boundary conditions and external forcings sometimes differ, depending on the model. The external forcing in one model could be a key state variable of another, that is, simulated within the model itself. For instance, the changes in CO_2 concentration could be prescribed in some models, while it is directly computed in those models that include a representation of the carbon cycle. Furthermore, a fixed boundary in some models, like the ice-sheet topography, can evolve interactively in a model designed to study climate variations on a longer time scale.

In this framework, some data are required as inputs during the simulation. However, the importance of data is probably even greater during the development phase of the model, as they provide essential information on the properties of the system that is being modelled. In addition, large numbers of observations are needed to test the validity of the models in order to gain confidence in the conclusions derived from their results. Figure 2.4 gives a schematic representation of a climate model and how observations feed into each aspect of its development and use.

Many climate models have been developed to perform climate projections, that is, to simulate and understand climate changes in response to the emission of greenhouse gases and aerosols. In addition, models can be formidable tools to improve our knowledge of the most important characteristics of the climate system and of the causes of climate variations. Obviously, climatologists cannot perform experiments on the real climate system to identify the role of a particular process clearly or to test a hypothesis. However, this can be done in the virtual world of climate models. For highly non-linear systems, the design of such tests, often called sensitivity experiments, has to be very carefully planned. However, in simple experiments, neglecting a process or an element of the modelled system (e.g. the influence of the increase in CO_2 concentration on the radiative properties of the atmosphere) can often provide a first estimate of the role of this process or this element in the system. That is, it is often very valuable to perform simple experiments to gain a first-order insight into the processes before progressing to more detailed and computationally expensive modelling.

3 The REMOTE Regional Climate model

The regional model (REMO) is based in the dynamical part on the regional weather forecast model system EM/DM (Europa-Modell/Deutschland-Modell) of the German Weather Service (Majewski, 1991). It includes the physical parameterisation package of the global model ECHAM4 (Roeckner et al., 1996). This allows a consistent model chain of the driving global climate model and the regional model to be applied for climate simulations. Additionally, the REMO can be forced by analysis data at its lateral boundaries. This allows a comparison of model results with observations to improve the model. Alternatively, the REMO can help to interpret field experiments as it fills the gaps in observational data. The REMOTE used in this work contains all the features of the REMO listed above but also includes many extra features. The main extra features of REMOTE are the detailed gas-phase chemistry and the M7 aerosol microphysics module (see Section 3.1). A more detailed description of REMOTE is given in the following paragraphs.

The regional three-dimensional online climate chemistry aerosol model REMOTE (Langmann, 2000; Marmer and Langmann, 2007) is one of the few regional climate models that determines the physical, photochemical and aerosol state of the model atmosphere at every model time step, thus offering the possibility of considering trace species effects on climate (e.g. Langmann, 2007). Model simulation is made of the release into the atmosphere of gas-phase and aerosol-phase species, which then undergo transport processes (horizontal and vertical advection) (Smolarkiewitz, 1983), transport in convective clouds (Tiedtke, 1989) and vertical turbulent diffusion (Mellor and Yamada, 1974), and are removed from the atmosphere by sedimentation, and dry and wet deposition.

The total number of transported trace species in REMOTE is 63, with 38 of these participating in photochemical transformations (Langmann, 2000). Photochemical production and loss in REMOTE is determined by the RADM2 chemical scheme (Stockwell et al., 1990). There are 163 chemical reactions in the gas phase, including a wide range of hydrocarbon degradation reactions. Photolysis rates are calculated as described by Madronich (1986) and Chang et al. (1987). Aqueous-phase chemistry processes are implemented according to Walcek and Taylor (1986). Sulphate production in the aqueous phase is determined, dependent on pH, via oxidation by hydrogen peroxide (H_2O_2), ozone (O_3), methylhydrogenperoxide, or peroxyacetic acid and catalysed by Fe^{3+} and Mn^{2+}. Cloud water pH is determined by solving iteratively an ion balance which is continuously maintained (Walcek and Taylor, 1986). Nitrate (NO_3) and ammonium (NH_4^+) are not yet considered in the M7 version applied here; however, M7 is flexible enough to be extended to more components. Nitrate aerosols are expected to become more important in the future atmosphere due to an increase in nitrate precursor emissions and the decline of $(NH_4)_2SO_4$ aerosols in many regions of the Earth (Bauer et al., 2007).

Anthropogenic emissions of SO_x, NO_x, ammonia (NH_3), carbon monoxide (CO), VOCs and PM2.5 (particulate matter with an aerodynamic diameter of up to 2.5 µm) obtained from the EMEP emission inventory (http://www.ceip.at/) are prescribed as monthly fluxes as described in Marmer and Langmann (2007). NO_x emissions are split into NO (96%) and NO_2 (4%) emissions. Total VOC emissions are split into VOC classes according to Memmesheimer et al. (1991). For primary anthropogenic aerosol emissions, number mean radius and number concentration of the respective size mode is related to the mass concentration based on Stier et al. (2005). Chemical speciation of PM2.5 emissions into primary organic carbon (POC) and BC is based on Andersson-Skold and Simpson (2001). We assume that 96% of the SO_x is being released as SO_2 and 4% as sulphate, from which 50% is attributed to the accumulation and coarse modes, respectively (Seinfeld and Pandis 1998). Black carbon emissions are assumed insoluble and POC emissions soluble. Secondary organic aerosol formation is not considered in the current study. In addition to anthropogenic emissions, terrestrial biogenic terpene and isoprene emissions from forests are considered, based on Guenther et al. (1991, 1993). For coarse mode sea salt, the same approach as described in Stier et al. (2005) is used, with a table look-up for wind speeds of between 1 and 40 m/s. The net accumulation sea-spray flux is based on Geever et al. (2005) and is used as an organic–inorganic source function for the mixture of POC and sea-salt aerosols. Recent measurements at the Mace Head station on the Atlantic coast of Ireland (O'Dowd et al., 2004; Yoon et al., 2007) have shown that POC contributes a considerable fraction to sea-spray aerosol mass during periods of increased biological activity of the ocean. Further details are given in O'Dowd et al. (2008). For the current application of REMOTE over Europe, mineral dust emissions have not been considered. Dry deposition fluxes for gaseous compounds are determined after Wesley (1989). For aerosol particles, the same size-dependent parameterisations as in the ECHAM5-HAM model (Stier et al., 2005, where HAM stands for Hamburg Aerosol Model) are used for dry deposition and sedimentation, which are based on Ganzeveld et al. (1998) and Seinfeld and Pandis (1998). Wet deposition is computed according to Walcek and Taylor (1986) by integrating the product of the grid-averaged precipitation rate and the mean cloud-water concentration which is determined from cloud base (the first layer above the surface containing more than 0.001 g/kg liquid water) to cloud top (the highest level exceeding an amount of 0.001 g/kg liquid water) for fair weather clouds, and from the surface to cloud top for raining clouds. Scavenging efficiencies are based on Kasper-Giebl et al. (2000), distinguishing between soluble and insoluble aerosols, dependent on cloud liquid-water content. In-cloud produced sulphate is distributed to the available pre-existing accumulation mode and coarse mode aerosol particles according to the respective number concentration (Stier et al., 2005).

REMOTE is applied with a time step of 5 min in 0.5° horizontal resolution, and 20 vertical layers of increasing thickness between the Earth's surface and the 10 hPa pressure level, using terrain following hybrid pressure-sigma coordinates. The prognostic equations are solved on an Arakawa C-grid (Mesinger and Arakawa, 1976). The height of the lowest layer with prognostic trace species concentration is approximately 40 m, dependent on surface pressure. The model domain covers Europe and the north-east Atlantic Ocean. REMOTE is initialised at the first time step using meteorological analysis data of the European Centre for Medium Range Weather Forecast (ECMWF), which are updated at the lateral boundaries every six hours and are used for nudging the model in the outer eight grid cells. Trace species concentrations at the lateral boundaries are prescribed (Langmann, 2000) and held constant throughout the simulation period. Here we analyse results for January and June 2003, to take into account the seasonal variability of meteorological conditions, emissions and photochemistry. Beside the standard model simulation, four sensitivity studies have been conducted: for June 2003: (a) a day–night variability has been introduced for the anthropogenic emissions, (b) biogenic emissions have been increased by a factor of five, (c) forest-fire emissions have been taken into account, and (d) a sensitivity study with the aerosol bulk mass approach has been out carried for January and June 2003.

3.1 The M7 Aerosol Microphysics Module

For the determination of aerosol dynamics and thermodynamics in REMOTE, the M7 module was implemented, which is described in detail in Vignati et al. (2004) and Stier et al. (2005). The aerosol dynamical processes in M7 include nucleation, coagulation and condensation. The aerosol size spectrum is represented by the superposition of seven log-normal distributions subdivided into soluble and insoluble coarse, accumulation and Aitken modes, and an additional soluble nucleation mode (Table 3.1). The

Table 3.1. Modal structure and properties of M7. Ni denotes the aerosol number of mode i, M_i^j denotes the mass of component j in mode i, and r the dry radius.

Modes in M7	Soluble/Mixed	Insoluble
Nucleation	**Mode 1**	
r<0.005 µm	N_1, $M_1^{SO_4}$	
Aitken	**Mode 2**	**Mode 5**
0.005 µm<r<0.05 µm	N_2, $M_2^{SO_4}$, M_2^{BC}, M_2^{OC}	N_5, M_5^{OC}, M_5^{OC}
Accumulation	**Mode 3**	**Mode 6**
0.05 µm<r<0.5 µm	N_3, $M_3^{SO_4}$, M_3^{BC}, M_3^{OC}, M_3^{SS}, M_3^{DU}	N_6, M_6^{DU}
Coarse	**Mode 4**	**Mode 7**
0.5 µm<r	N_4, $M_4^{SO_4}$, M_4^{BC}, M_4^{OC}, M_4^{SS}, M_4^{DU}	N_7, M_7^{DU}

five aerosol components considered in M7 are sulphate (SO_4), black carbon (BC), organic carbon (OC), sea salt (SS) and mineral dust (DU). These components have either negligible or low solubility or are treated as an internal mixture of insoluble and soluble compounds. Mixed particles are formed from insoluble particles by coagulation and condensation. Each mode can be described by three moments: aerosol number N, number median radius r, and standard deviation σ. Standard deviations are prescribed in M7 (Vignati et al., 2004) so that the median radius of each mode can be calculated from the corresponding aerosol number and aerosol mass, which are transported as 25 tracers (Table 3.1).

4 Modelling Cloud Droplet Activation

The main aim of this project was to implement a cloud droplet activation parameterisation in a RCM. Originally it was thought appropriate to base the parameterisation on the results of ensemble simulations of an aerosol–cloud process model. An aerosol–cloud process model simulates in detail the activation of CCN in a rising air parcel. The process model was developed and it included a treatment of a limited number of organic species. However, during the development process it became clear that a parameterisation based on this method would always be limited by the number and type of the simulations used in the ensemble (i.e. if the conditions deviate significantly from the ensemble, runs such a parameterisation would not be reliable). A more general description was required, and after a detailed review of the literature it was decided that the most suitable approach was to use a parameterisation based on the work of Nenes and Seinfeld (2003). This allowed simulation of cloud droplet activation for a large variety of aerosol types and environmental conditions and is computationally efficient. While some other parameterisations exist, this was considered most suitable for the project as it interacts well with the M7 module already included in the RCM.

4.1 Aerosol–Cloud Chemistry Process Model

The model developed is a size-resolved droplet physico-chemical model linked to a Lagrangian parcel framework and is used to study sulphate production in clouds. It simulates complex chemical and physical reactions in a rising air parcel. The model is centred on two main modules. A thermodynamic equilibrium module based on Pitzer thermodynamics calculates the equilibrium of the aqueous aerosol solution droplets. A mass and heat flux module calculates the condensation and evaporation of condensable vapours onto the droplet. The results from these modules, plus adiabatic variables (temperature, pressure, etc.) and chemical reactions, are fed into an ordinary differential equation (ODE) solver. There is a high temporal resolution iteration process to converge on a solution, and the output is written to file and the iteration process starts again for the next time step. A simplified schematic of the process model is given in Fig. 4.1. This model can simulate the cloud processing of a variety of types of aerosol. As an example, the number size distributions of ammonium sulphate and sodium chloride aerosol particles before and after a cloud cycle are given in Fig. 4,2, It can be seen that after the cloud cycle the larger aerosols particles have grown to become cloud droplets while the smallest sizes have not grown.

The mass flux of the condensable species during droplet growth or evaporation is calculated using:

$$I_j^{[p]} = \frac{dm}{dt} = -\frac{4\pi a^{[p]} M_j D_{\mathrm{mix}j}\left(T_\infty\right) p}{RT_\infty} \ln\left(\frac{p - p_{a_j^{[p]}}\left(T_{a^{[p]}}\right)}{p - p_\infty\left(T_{a^{[p]}}\right)}\right),$$

where superscript [p] refers to the particle, $a^{[p]}$ is the radius of the particle, M_j is the molar mass of species j, R is the molar gas constant, T_∞ is the temperature far away from the particle (i.e. the temperature of the surrounding air), p_{∞_j} is the partial pressure of species j in the gas phase and $p_{a_j^{[p]}}$ is the vapour pressure of j just above the particle surface. The effective binary diffusivity $D_{\mathrm{mix}j}$ is the diffusivity of species j in a gas mixture and it can be calculated using, for example, Blanck's law (Reid et al., 1987). The curvature of a small particle increases the vapour pressure of substance j over the particle surface and is described by the Kelvin equation:

$$p_{a_j^{[p]}} = p^0_{a_j^{[p]}} \exp\left(\frac{2\sigma^{[p]} v_j^{[p]}}{a^{[p]} RT_{a^{[p]}}}\right),$$

where $p^0_{a_j^{[p]}}$ is the vapour pressure of species j above a flat solution surface, $\sigma^{[p]}$ is the surface tension at equilibrium and $v_j^{[p]}$ is the partial molar volume of species j. The heat flux due to the condensation/ evaporation is calculated using:

$$\frac{dT_{a^{[p]}}}{dt} = \frac{1}{m^{[p]} c_p^{[p]}} \left[\begin{array}{c} \sum_{j=1}^{n} \hbar_j^{[p]}\left(T_{a^{[p]}}\right) I_j^{[p]} - 2\pi a^{[p]}\left(K_a - K_\infty\right)\left(T_{a^{[p]}} + T_\infty\right) \\ + F_a\left(T_{a^{[1]}}, t_f\right) - 4\pi a^{[p]^2} \sigma_{\mathrm{SB}} \varepsilon^{[p]}\left(T^4_{\sigma^{[p]}} + T^4_\infty\right) \end{array}\right],$$

where $m^{[p]}$ is the mass of the particle, $c_p^{[p]}$ is the specific heat capacity of the mixture, K_a is the thermal conductivity of the gas at temperature T_a, K_∞ is the thermal conductivity of the gas at temperature T_∞, t_f is the freezing time and σ_{SB} is the Stefan–Boltzmann

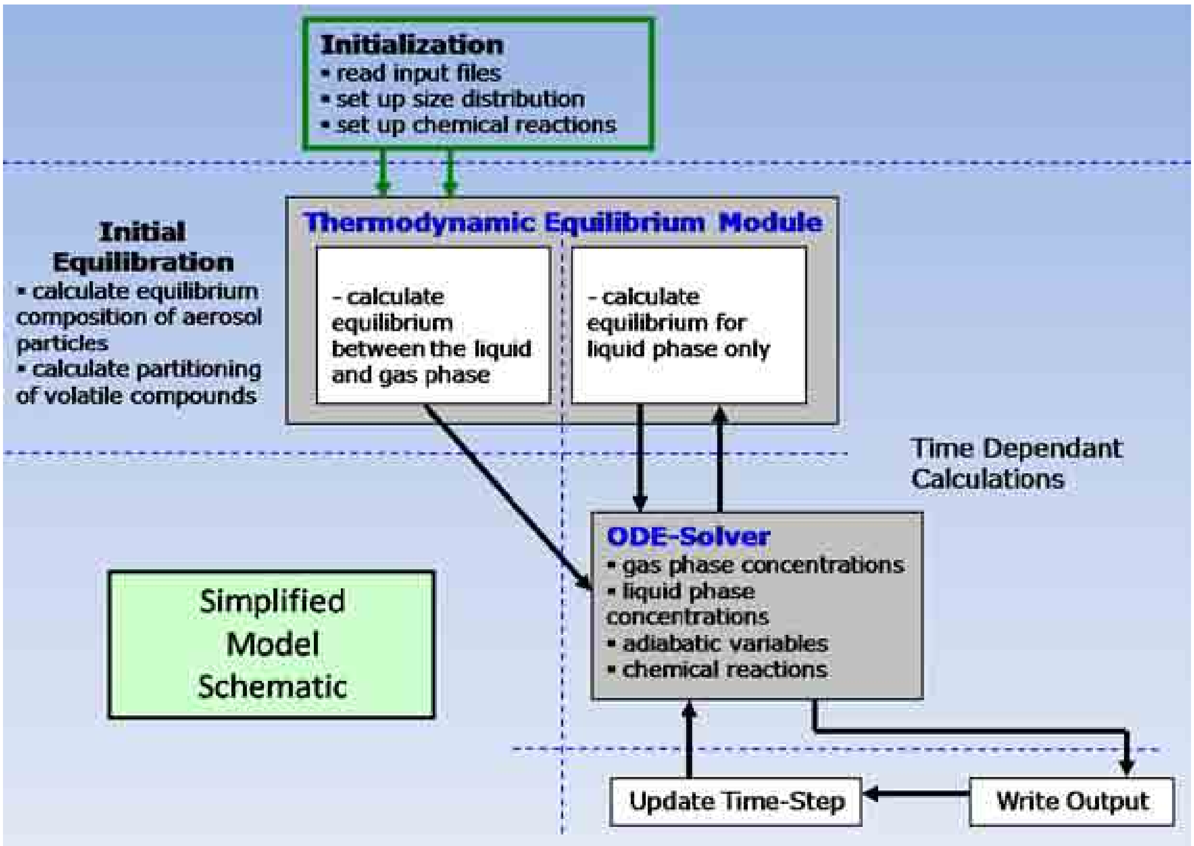


Figure 4.1. A simplified schematic of the aerosol–cloud chemistry process model.

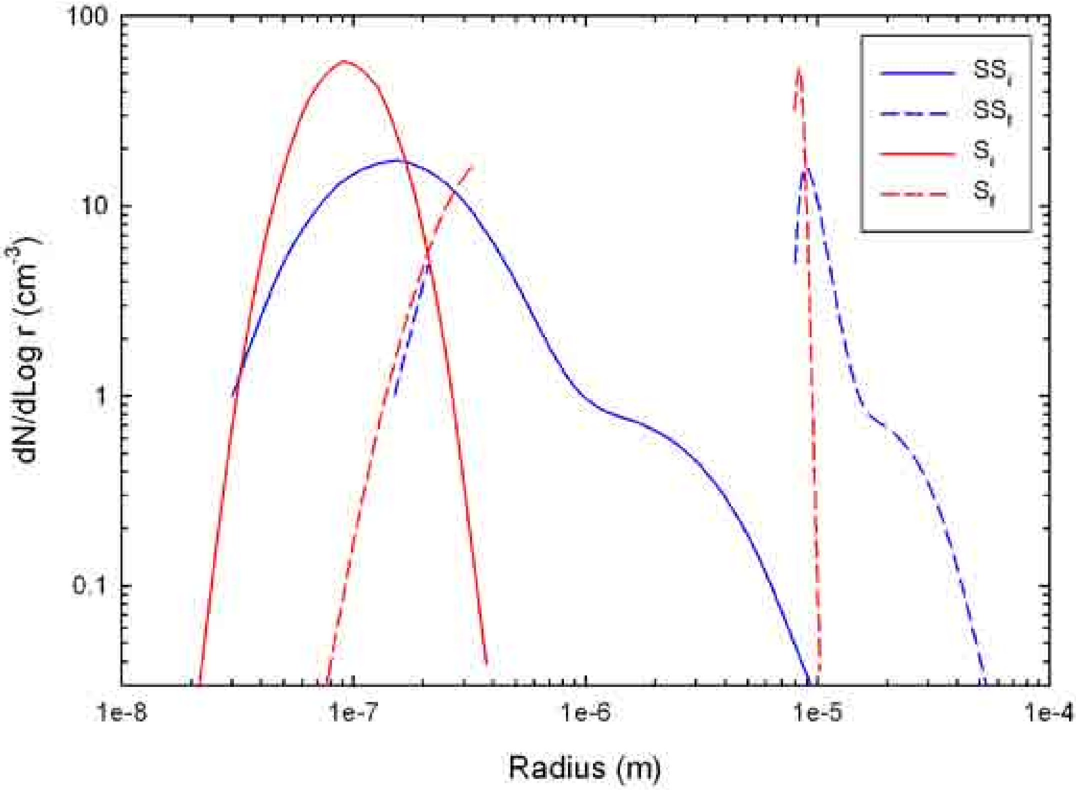


Figure 4.2. Sulphate (S) and sea-salt (SS) aerosol distributions before (left) and after (right) a cloud cycle. Here the subscripts *i* and *f* stand for initial and final, respectively. dN/dlog r is the number of particles per cm^3 of air in the size range log r to (log r + dlog r) where r refers to particle radius.

constant. For complete details of the mass and heat flux module, see Hienola et al. (2001).

4.2 The Nenes Cloud Droplet Activation Parameterisation

A number of cloud droplet activation parameterisations have been developed. The one used here is based on the work of Nenes and Seinfeld (2003). The work of Fountoukis et al. (2005) further enhanced its suitability as they have now adapted it to allow for the more realistic log-normal representation of the aerosol distribution and have included a size-dependent mass transfer coefficient for the growth of water droplets to accommodate the effect of size and organic films on the droplet growth rate. Fountoukis et al. (2005) have shown that the parameterisation compared very well with detailed cloud parcel model simulations over a large range of aerosol size distributions and velocities, and was proven to work well for a variety of aerosol activation conditions. The cloud parcel model had been previously evaluated with in-situ data.

Pressure, temperature, updraft velocity and aerosol characteristics are input into the cloud droplet nucleation scheme. For each mode *i*, with geometric mean diameter *g*, the critical supersaturation $s_{g,i}$ of a particle with diameter $D_{g,i}$ is calculated using:

$$s_{g,i} = \sqrt{\frac{4A^3\rho_w M_s}{27v\rho_s M_{wD_{g,i}^3}}},$$

where ρ_w is the density of water and ρ_s is the solute density, M_s is the solute molecular weight, M_w is the molecular weight of water and *v* is the number of ions resulting from the dissociation of one molecule of solute. For a full description of the parameters and the algorithm, see Fountoukis et al. (2005).

If the maximum parcel supersaturation $s_{\max}$ is known, the activated droplet number N_d can be calculated using:

$$N_d = F^s(s_{\max}) = \sum_{i=1}^{n_m}\frac{N_i}{2}erfc\left[\frac{2\ln(s_{g,i}/s_{\max})}{3\sqrt{2}\ln\sigma_i}\right],$$

where N_i is the aerosol number concentration, F_s is the concentration of particles with saturation ratio greater than the critical supersaturation, *erfc* is the mathematical error function and σ_i is the standard deviation of mode *i*. $s_{\max}$ is calculated using the bisection iteration method. This scheme provides a flexible approach to simulate the activation of a variety of aerosol types.

The parameterisation based on the work by Nenes et al. (2003) is implemented in the model. The first step of implementation was to implement it in the stand-alone M7 box model and then to conduct a full implementation in REMOTE. This two-step implementation provides more rigorous testing and will produce two different usable models. As this parameterisation is based mainly on first principles rather than an ensemble of empirical data. It is a much more flexible approach to the problem than a parameterisation based on ensemble process model runs. An overview of the algorithm used in the parameterisation is given in Fig. 4.3.

4.3 Implementation of the Parameterisation in REMOTE

As the Nenes parameterisation is modal, it is well suited to take output from the M7 aerosol dynamics module. Total modal particle number concentration, modal diameter, densities, soluble mass fraction and molar mass for each of the aerosol modes are fed into the Nenes parameterisation. These data, updraft velocity and other environmental variables are used by the scheme to calculate the total cloud droplet number concentration. The code of REMOTE was modified to accommodate the new scheme, and new output files were created for post-processing the results. The model code was modified so that if a better parameterisation becomes available in the future it can be easily implemented. Another advantage of this parameterisation is that it is similar to the approach being taken by global climate-model developers. The harmonising of the physics between regional and global climate models is desirable as it enables modules and routines that are developed and tested in the less computationally intensive regional climate models to be more easily implemented in the global climate models.

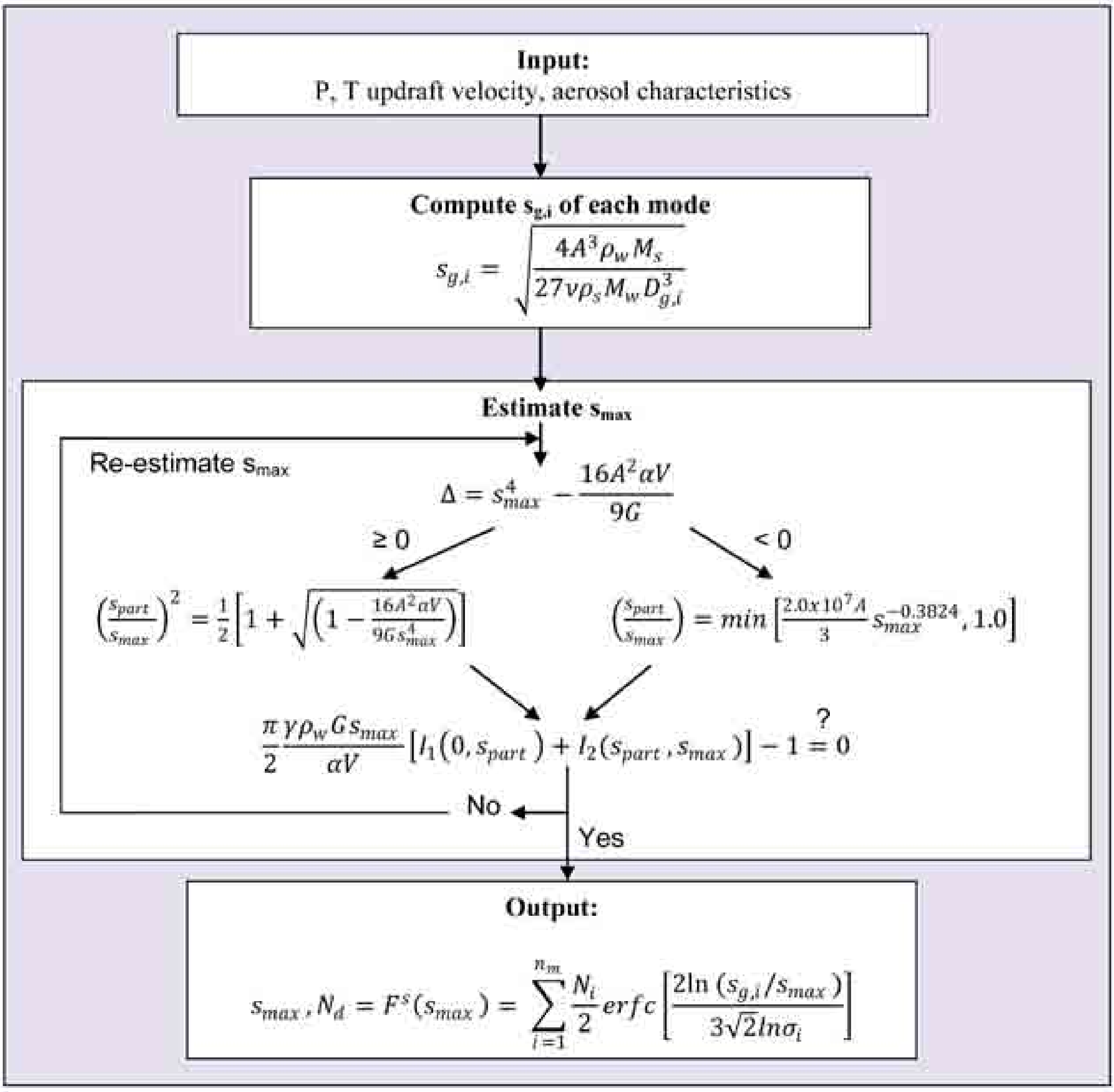


Figure 4.3. An overview of the algorithm used in the parameterisation (adapted from Fountoukis et al., 2005).

4.4 Sample Parameterisation Output

Figure 4.4 gives some sample output of the Nenes parameterisation for marine conditions. The parameterisation is tested at different updraft velocities. The blue line gives the cloud droplet number, the green line gives the percentage of CCN activated and the red line gives the maximum supersaturation for different values of updraft velocity. As is expected, as updraft velocity increases, activated fraction and cloud droplet number also increase. Table 4.1 gives sample output from the parameterisation for different environmental conditions.

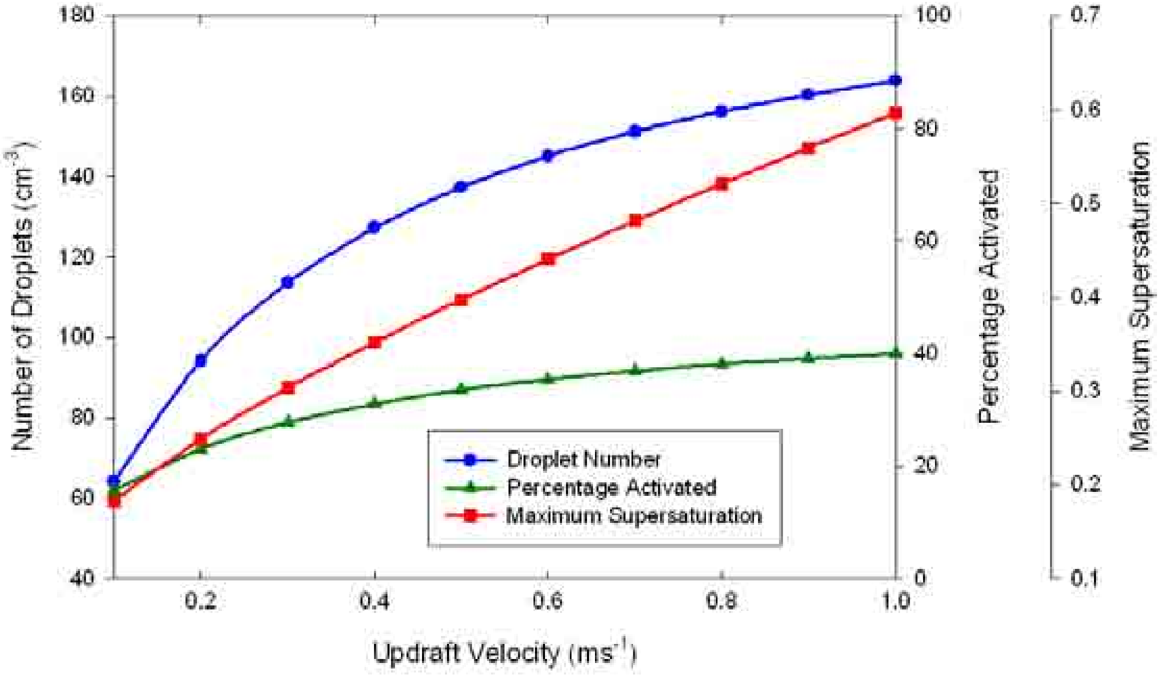


Figure 4.4. Sample output from the cloud droplet activation parameterisation. The blue line gives the cloud droplet number, the green line gives the percentage of cloud condensation nuclei activated and the red line gives the maximum supersaturation for different values of updraft velocity.

Table 4.1. Sample output from the cloud droplet activation parameterisation for different environments.

Marine (north Atlantic) aerosol	
Updraft (m/s) = 0.0500	Updraft (m/s) = 1.0000
S_{max} (%) = 0.1411	S_{max} (%) = 0.5985
N_{drop} (# cm^{-3}) = 40.004	N_{drop} (# cm^{-3}) = 162.994
Activation fraction (%) = 9.762	Activation fraction (%) = 39.774
Continental aerosol	
Updraft (m/s) = 0.0500	Updraft (m/s) = 1.000
S_{max} (%) = 0.0887	S_{max} (%) = 0.3719
N_{drop} (# cm^{-3}) = 97.459	N_{drop} (# cm^{-3}) = 440.024
Activation fraction (%) = 5.412	Activation fraction (%) = 24.436
Marine (south oceans) aerosol	
Updraft (m/s) = 0.0500	Updraft (m/s) = 1.0000
S_{max} (%) = 0.1968	S_{max} (%) = 0.9021
N_{drop} (# cm^{-3}) = 19.331	N_{drop} (# cm^{-3}) = 71.360
Activation fraction (%) = 5.046	Activation fraction (%) = 18.627

5 Model Simulations

The main focus of this work is to study the effect of marine aerosols on climate. Sea-spray emissions are described by the inorganic–organic sea-spray source function of O'Dowd et al. (2006). Sea-spray emissions can be switched on and off to facilitate the evaluation of their effect on cloud physics and climate. The months of January and June 2003 were chosen as case studies for the model simulations. These months were chosen due to the availability of input data. Using these two months, the effect of increased levels of organic matter during summertime compared to wintertime can be evaluated. REMOTE (see, e.g. Langmann 2000), including the cloud droplet nucleation scheme described, was used for the simulations. Figure 5.1 gives the modelled mean temperatures for January a nd June 2003 at the 1.2 km vertical level. Figure 5.2 gives the mean temperatures for the same months but at the 4.5 km level. Figure 5.3 gives the mean aerosol concentration again for the same months at the 1.2 km level. To study marine aerosols in more detail, an area covering mostly open ocean was defined and is marked in Fig. 5.4 with black dashed lines. This area will be referred to as area M1.

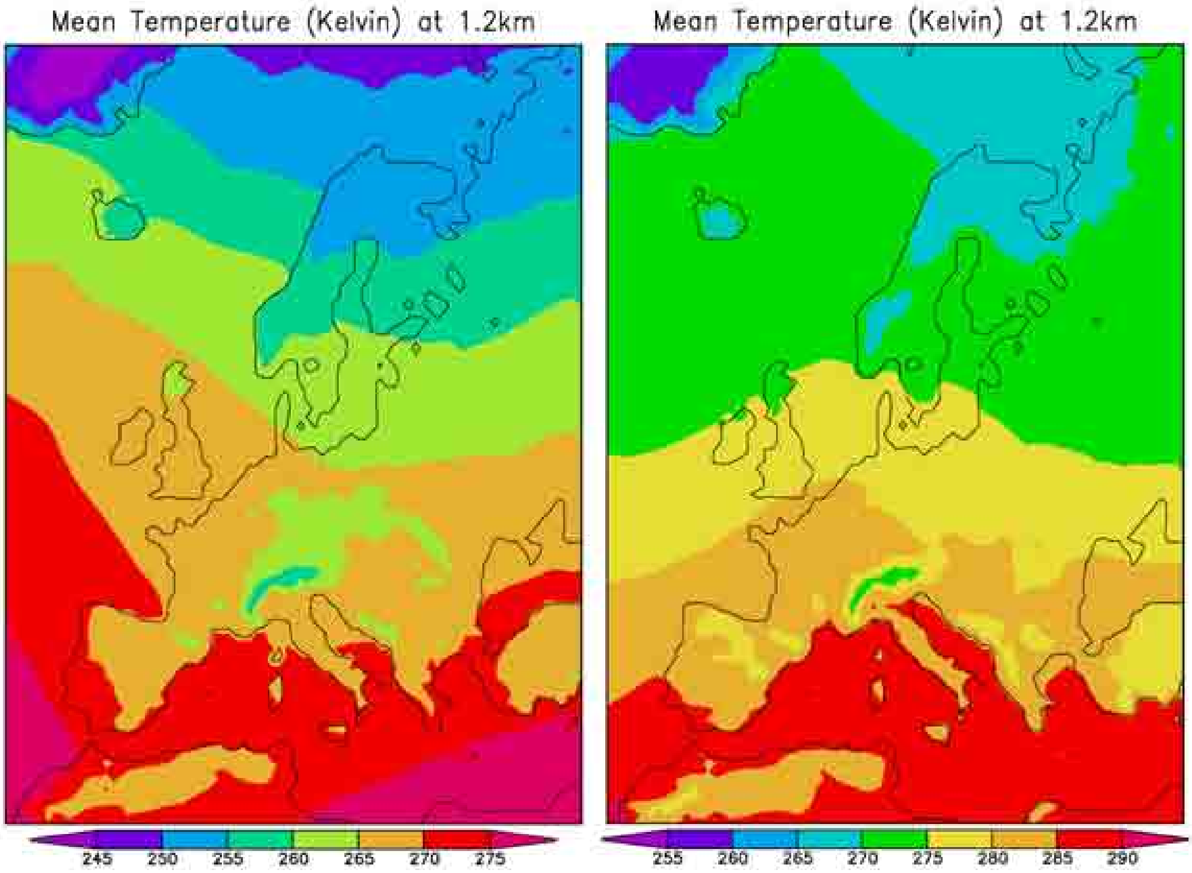


Figure 5.1. Modelled temperatures for January (left) and June (right) 2003 at 1.2 km.

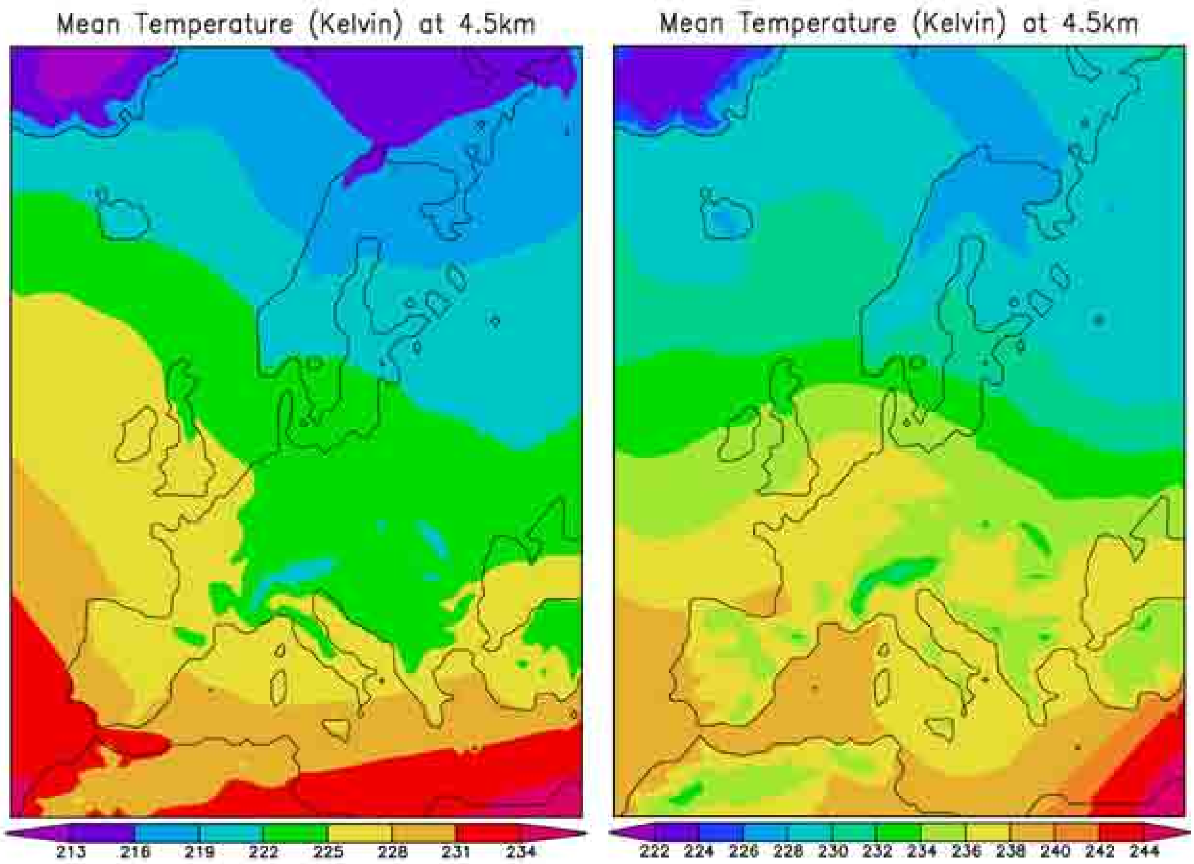


Figure 5.2. Modelled temperatures for January (left) and June 2003 (right) at 4.5 km.

5.1 Aerosol Number Concentration

Figure 5.3 presents modelled average aerosol particle number concentrations for Europe and the north Atlantic for the months of January and June 2003. As would be expected, there are higher aerosol concentrations over the continent for both months. The Mediterranean region is particularly polluted. It should be noted that this is an average concentration at 1.2 km. Aerosol concentrations at the surface would be considerably larger as not all aerosols are mixed throughout the atmosphere. The larger particles especially do not usually exist in large concentrations far from the surface as they do not mix well into the upper layers and are deposited to the surface quickly. It is possible to plot each aerosol mode available in the M7 microphysics module separately if further details on the spatial distribution of different types of aerosol or different sizes are required.

5.2 Cloud Droplet Number Concentration

Figure 5.4 presents modelled average cloud droplet number concentrations (CDNC) for Europe and the north Atlantic for the months of January and June 2003. Cloud droplet number concentrations are higher over the ocean for the winter month of January, while there is a lower CDNC over the continent. Within the M1 area the average CDNC for January was 41.2 cm^{-3} and the average CDNC for June was 23.8 cm^{-3}. The average wind speeds for January and June were 8.8 ms^{-1} and 6.1 ms^{-1}, respectively. This CDNC data can be fed into an offline radiative transfer scheme to study the effect of aerosols on the Earth's radiation balance. An offline radiative transfer scheme has been obtained and the scheme is currently being tested with the output from the cloud droplet nucleation scheme.

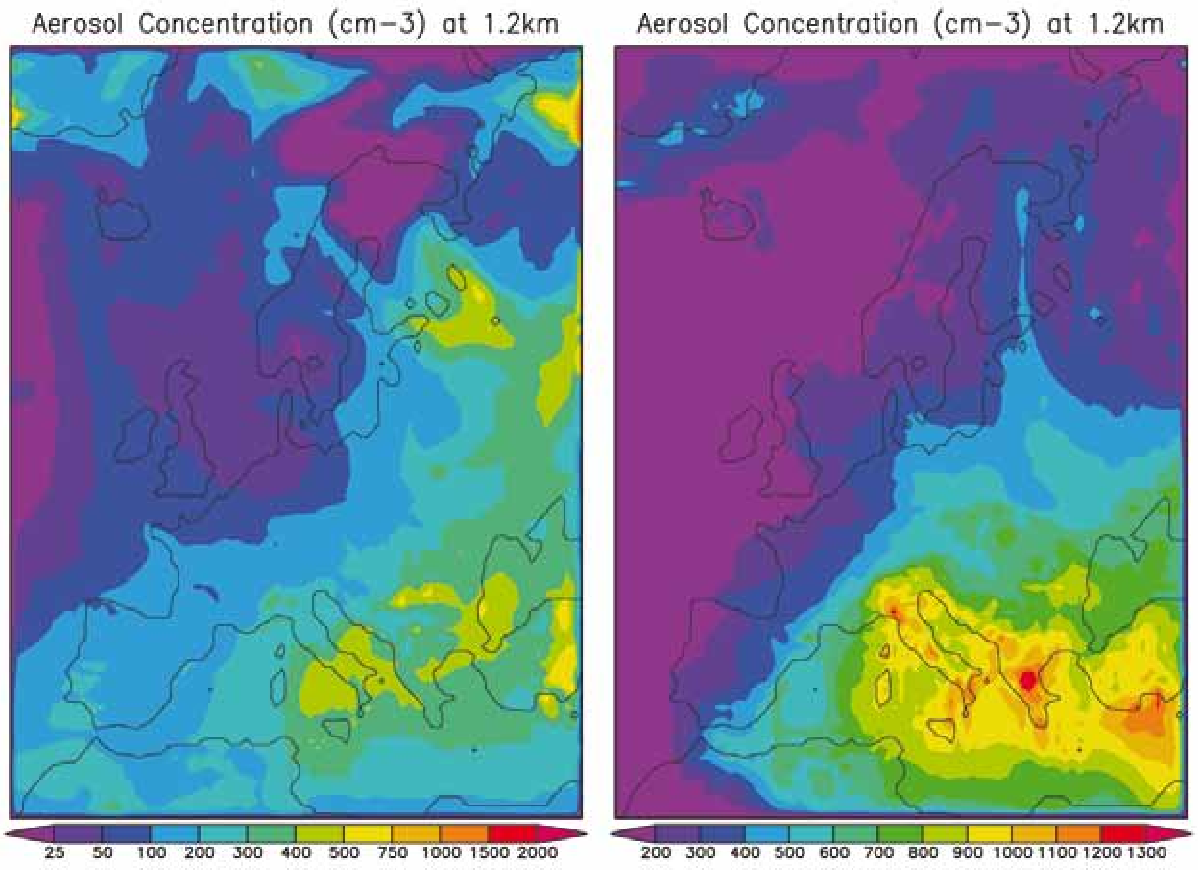


Figure 5.3. Modelled aerosol number concentrations for January (left) and June (right) 2003 at 1.2 km.

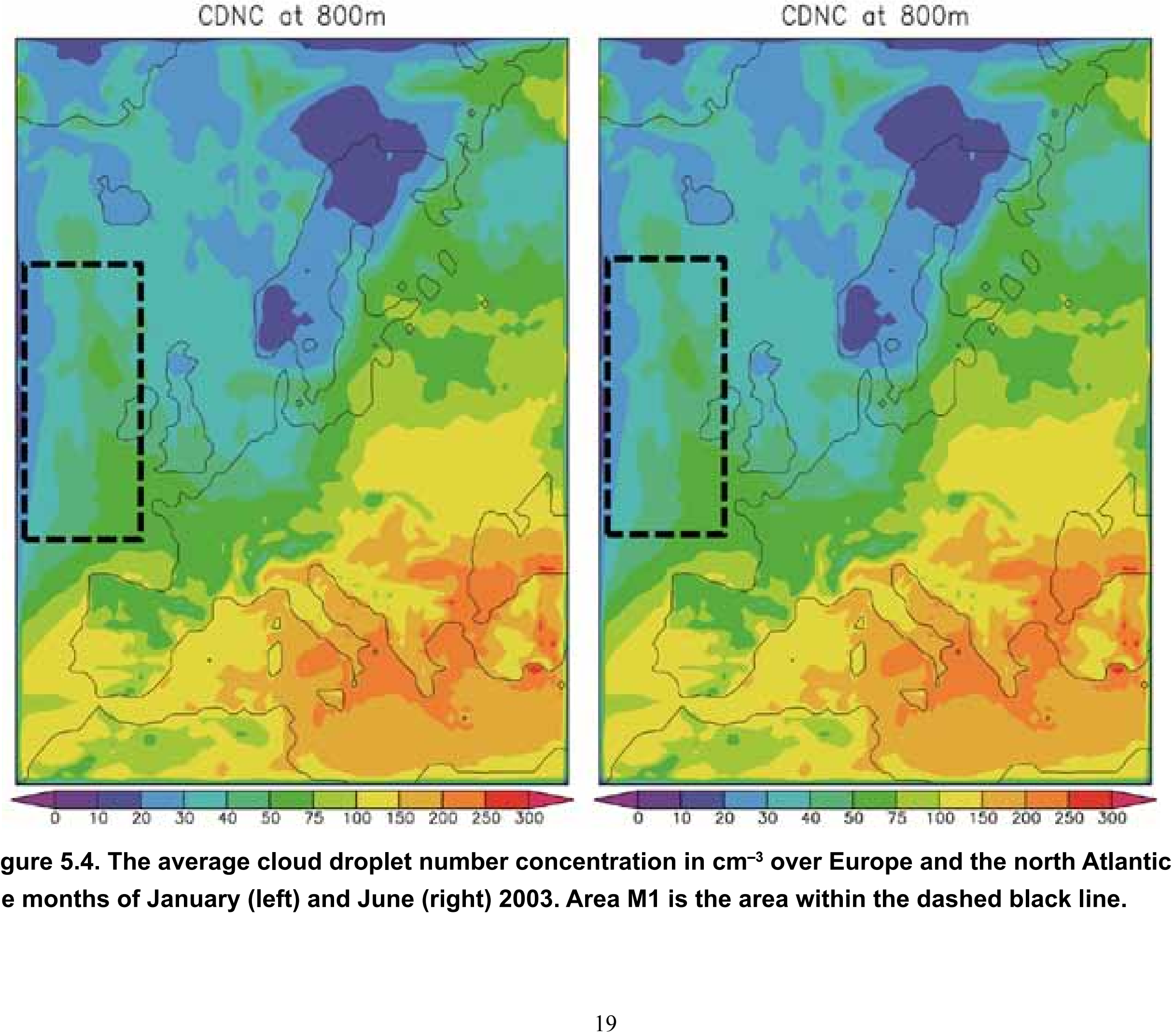


Figure 5.4. The average cloud droplet number concentration in cm^{-3} over Europe and the north Atlantic for the months of January (left) and June (right) 2003. Area M1 is the area within the dashed black line.

5.3 Droplet Effective Radius

Cloud droplet effective radius r_e, is a key variable that is used in the radiative transfer calculations of liquid water clouds. The droplet effective radius is related to droplet number concentration by the expression:

$$r_e = \left(\frac{3LWC}{4\pi\kappa N_{tot}}\right)^{1/3},$$

where *LWC* is the liquid water content, ρ is the density of water, N_{tot} is the droplet concentration and κ is a constant that depends on maritime (0.80) or continental (0.67) clouds (see, e.g. Wyser, 1998).

Figure 5.5 presents modelled average droplet effective radius for Europe and the north Atlantic for the months of January and June 2003. For both months, droplet effective radius is larger over the oceans than the continent. The average droplet effective radii within area M1 (dashed-line box) are 11.39 µm and 11.59 µm for January and June, respectively. Again, the average wind speeds for January and June were 8.8 ms^{-1} and 6.1 ms^{-1}, respectively. These values are in good agreement with other studies and, as with the cloud droplet number concentration data, are currently being used in conjunction with an offline radiative transfer module to study the effect of the different types of aerosol on the Earth's radiation balance.

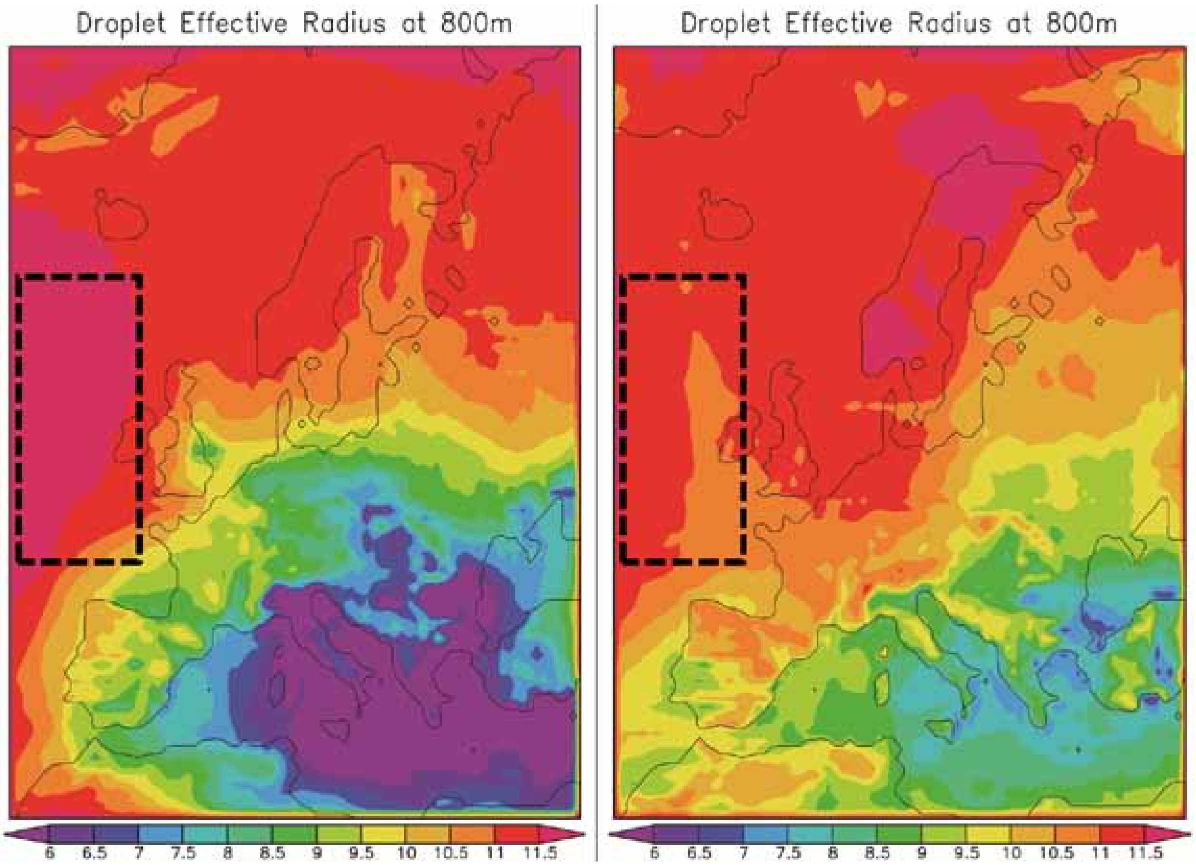


Figure 5.5. The average droplet effective radius in µm over Europe and the north Atlantic for the months of January (left) and June (right) 2003. Area M1 is the area within the dashed black line.

6 Conclusions

In line with the objectives of the project, an aerosol–cloud droplet activation parameterisation has been implemented in a regional climate model. This scheme takes output from the M7 aerosol dynamics module and calculates cloud droplet number concentration. This parameterisation provides a computationally efficient description of the activation of cloud condensation nuclei into cloud droplets. The months of January and June 2003 were chosen as case studies for the model simulations. Using these two months, the effect of increased levels of organic matter during summertime compared to wintertime can be evaluated.

For both months droplet effective radius is larger over the oceans than the continent. The average droplet effective radii within an area surrounding Ireland are 11.39 µm and 11.59 µm for January and June, respectively. Within the M1 area around Ireland, the average CDNC for January was 41.2 cm^{-3} and the average CDNC for June was 23.8 cm^{-3}. Again the average wind speeds for January and June were 8.8 ms^{-1} and 6.1 ms^{-1}, respectively.

In order to gain a better insight into the effect of aerosols on climate, it is necessary to perform longer-term simulations. The necessary boundary data which will enable these long-term simulations to be performed has now been secured.

REMOTE is currently one of most advanced regional climate models available worldwide and is under continuing development, and this cloud droplet activation scheme will help provide detailed climate predictions for Ireland and the rest of Europe.

7 Ongoing Work and Recommendations

The current work presents a major advance in the capabilities of the REMOTE regional climate model. It is recommended that in the future the regional climate model undergoes further development to ensure that it continues to represent the state of the art and provides the best climate predictions for Ireland. In particular, it is recommended that an interactive online radiative transfer scheme be implemented in the regional climate model. This would provide valuable feedback between the aerosol processes and their radiative effects. This will enable the simulation of the crucial radiative forcing component of the various aerosol species.

It is also clear that it is advisable to continue investment in environmental measurements and monitoring. These data provide crucial model inputs and also validation resources. It is clear that marine aerosols have a very significant impact on clouds and thus climate. Given the current status of the model and the considerable expertise and experience gained in marine aerosol and climate modelling research, it is advisable that investment is continued so that Ireland remains a leader in this field.

To take full advantage of the current advances, it is necessary to perform long-term simulations to study the effect of aerosols on climate. The required global boundary condition data has now become available and long-term simulations are currently being prepared. While it is important to continue to develop models, it is also important that enough resources and time are invested in the use of these models and the interpretation of model results.

References

Bauer, S. E., D. Koch, N. Unger, S. M. Metzger, D. T. Shindell and D. G. Streets. Nitrate aerosols today and in 2030: a global simulation including aerosols and tropospheric ozone, *Atmos. Chem. Phys.*, 7, 5043–5059, 2007.

Cavalli, F., M. C. Facchini, S. Decesari, M. Mircea, L. Emblico, S. Fuzzi, D. Ceburnis, Y. Y. J., C. D. ODowd, J.-P. Putaud and A. Dell'Acqua. A. Advances in characterization of size resolved organic matter in marine aerosol over the north atlantic, *J. Geophys. Res.*, 109, doi:0.1029/2004JD0051377, 2004.

Chang, J. S., R. A. Bros, I. S. A. Isaksen, S. Madronich, P. Middleton, W. R. Stockwell and C. J. Walcek, C. A three-dimensional Eulerian acid deposition model: physical concepts and formulation, *J. Geophys. Res.*, 92, 1481–14700, 1987.

Flanagan, R.J., Kulmala, M. and O'Dowd, C. D. The effect of nitric acid on heterogeneous sulphate production in maritime stratiform clouds. Proceedings of the European Aerosol Conference, 6–10 September, Budapest, Hungary, 2004, *Journal of Aerosol Science*, 35, Supplement 1, 297–298, 2004.

Fountoukis, C. and A. Nenes. Continued development of a cloud droplet formation parameterization for global climate models, *J. Geophys. Res.,* 110, D11212, doi:10.1029/2004JD005591, 2005.

Ganzeveld, L., J. Lelieveld and G.-J. Roelofs. Dry deposition parameterization of sulfur oxides in a chemistry and general circulation model, *J. Geophys. Res.,* 103, 5679–5694, 1998.

Geever, M., C. D. O'Dowd, S. van Ekeren, R. Flanagan, E. D. Nilsson, G. de Leeuw and U. Rannik. Sub-micron sea-spray fluxes, *Geophys. Res. Lett.*, 32, L15810, doi:10.1029/2005GL023081, 2005.

Goosse H., P.Y. Barriat, W. Lefebvre, M.F. Loutre and V. Zunz, Introduction to climate and climate modelling. Online textbook available at http://www.climate.be/textbook, 2009.

Hienola, J., M. Kulmala, and A. Laaksonen. Model studies on the effect of nitric acid vapour on cirrus cloud activation, *Atmos. Res.*, 65(3–4), 235–250, doi:10.1016/S0169-8095(02)00151-5, 2003a.

Houghton, J., Y. Ding, D. Griggs, and M. Noguer (Eds.). Climate change 2001: The scientific basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, UK, 2001.

Kasper-Giebl, A., A. Koch, R. Hitzenberger and H. Puxbaum Scavenging efficiency of aerosol carbon and sulfate in supercooled clouds at Mt. Sonnblick (3106ma.s.l, Austria), *J. Atmos. Chem.*, 35, 33–46, 2000.

Koponen, I., R. Virkkula, A. Hillamo, V.-M. Kerminen, and M. Kulmala. Number size distributions and concentrations of the continental summer aerosols in Queen Maud Land, Antarctica, *J. Geophys. Res.*, 108(D18), 4587, doi:10.1029/2003JD003614, 2003.

Langmann, B. Numerical modelling of regional scale transport and photochemistry directly together with meteorological processes, *Atmos. Environ.*, 34, 3585–3598, 2000.

Langmann, B. A model study of the smoke-haze influence on clouds and warm precipitation formation in Indonesia 1997/1998, *Atmos. Environ.*, 41, 6838–6852, doi:10.1016/j.atmosenv.2007.04.050, 2007.

Madronich, S. Photodissociation in the atmosphere. I: Actinic flux and the effect of ground reflections and clouds, *J. Geophys. Res.*, 92, 9740–9752, 1987.

Majewski, D. The Europa Model of the Deutscher Wetterdienst, *Seminar Proceedings ECMWF*, 2, 147–191, 1991.

Marmer E. and Langmann, B.: Aerosol modelling over Europe Part I: Inter-annual variability of aerosol distribution, *J. Geophys. Res.*, 112, D23S15, doi:10.1029/2006JD008113, 2007.

Mellor, B. and T. Yamada. A hierarchy of turbulence closure models for planetary boundary layers, *J. Atmos. Sci.*, 31, 1791–1806, 1974.

Mesinger, F. and A. Arakawa. Numerical methods used in atmospheric models. *GARP Public. Ser.*, 17, 1–64, 1976.

McFiggans, G., P. Artaxo, U. Baltensperger, H. Coe, M. C. Facchini, G. Feingold, S. Fuzzi, M. Gysel, A. Laaksonen, U. Lohmann, T. F. Mentel, D. M. Murphy, C. D. O'Dowd, J. R. Snider, and E. Weingartner. The effect of physical and chemical aerosol properties on warm cloud droplet activation, *Atmos. Chem. and Phys.*, 6(9), 2593–2649, 2006.

Nakiećnović, N. and R. Swart (Eds.). Special report on emissions scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Geophysical Monograph Series, Cambridge University Press, UK and New York, 2000.

Nenes, A., and J. H. Seinfeld. Parameterization of cloud droplet formation in global climate models, *J. Geophys. Res.*, 108(D14), 4415, doi:10.1029/2002JD002911, 2003.

O'Dowd, C. D., K. Hameri, J. Makela, M. Vakeva, P. Aalto, G. de Leeuw, G. J. Kunz, E. Becker, H. C. Hansson, A. G. Allen, R. M. Harrison, H. Berresheim, M. Geever, S. G. Jennings, and M. Kulmala. Coastal new particle formation: Environmental conditions and aerosol physicochemical characteristics during nucleation bursts, *J. Geophys. Res.*, 107(D19), 8107, doi: 10.1029/2000JD000206, 2002a.

O'Dowd, C. D., J. A. Lowe, N. Clegg, S. L. Clegg and M. H. Smith. Modelling heterogeneous sulphate production in maritime stratiform clouds, *J. Geophys. Res*. 105, 7143–7160, 2000.

O'Dowd, C. D., M. C. Facchini, F. Cavalli, D. Ceburnis, M. Mircea, S. Decesari, S. Fuzzi, Y. J. Yoon and J. P. Putaud. Biogenically-driven organic contribution to marine aerosol, *Nature*, doi:10.1038/nature02959, 2004.

O'Dowd, C. D. and G. de Leeuw. Marine aerosol production: a review of the current knowledge, *Philosophical Transactions (A) of the Royal Society*, 365(1856), 1753–1774, doi:10.1098/rsta.2007.2043, 2007.

O'Dowd, C. D., B. Langmann, S. Varghese, C. Scannell, D. Ceburnis, and M. C. Facchini., A combined organic–inorganic sea-spray source function, *Geophys. Res. Letts.*, 35, L01801, doi:10.1029/2007GL030331, 2008.

Roeckner, E., K. Arpe, L. Bengtsson, M. Christoph, M. Claussen, L. Dumenil, M. Esch, M. Giorgetta, U. Schlese, and U. Schulzweida. The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate, MPI-Report No. 218, Max Planck Institute for Meteorology, Hamburg, Germany, 1996.

Seinfeld, J. H., and S. N. Pandis. Atmospheric Chemistry and Physics: From Air Pollution to Climate Change, Wiley, New York, 1998.

Simpson, D., W. Winiwarter, G. Boerjesson, S. Cinderby, A. Ferreiro, A. Guenther, C. N. Hewitt, R. Janson, M. A. K. Khalil, S. Owen, T. E. Pierce, H. Puxbaum, M. Shearer, U. Skiba, R. Steinbrecher, L. Tarrason and M. G. Oequist. Inventorying emissions from nature in Europe, *J. Geophys. Res.*, 104, 8113–8152, 1999.

Smolarkiewitz, P. K. A simple positive definite advection scheme with small implicit diffusion, *Mon. Weather Rev.*, 111, 479–486, 1983.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (Eds.). Climate change 2007: The Physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, 2007

Stier, P., J. Feichter, S. Kinne, S. Kloster, E. Vignati, J. Wilson, L. Ganzeveld, I. Tegen, M. Werner, Y. Balkanski, M. Schulz, O. Boucher, A. Minikin and A. Petzold. The aerosol climate model ECHAM5-HAM, *Atmos. Chem. Phys.*, 5, 1125–1156, 2005.

Stockwell, W. R., P. Middleton, J. S. Chang and X. Tang. The second generation regional acid deposition model: chemical mechanism for regional air quality modelling, *J. Geophys. Res.*, 95, 16343–16367, 1990.

Tiedtke, M. A comprehensive mass flux scheme for cumulus parameterization in large-scale models, *Mon. Weather Rev.*, 117, 1778–1800, 1989.

Vehkamäki, H., M. Dal Maso, T. Hussein, R. Flanagan, A. Hyvärinen, J. Lauros, J. Merikanto, P. Mnkknen, M. Pihlatie, K. Salminen, L. Sogacheva, T. Thum, T. M. Ruuskanen, P. Keronen, P. P. Aalto, P. Hari, K. E. J. Lehtinen, U. Rannik, and M. Kulmala. Atmospheric particle formation events at värriö measurement station in Finnish Lapland 1998–2002, *Atmos. Chem. and Phys.*, 4, 2015–2023, 2004.

Vignati, E., J. Wilson and P. Stier. M7: An efficient size-resolved aerosol microphysics module for large-scale aerosol transport models, *J. Geophys. Res.,* 109, D22202, doi:10.1029/2003JD004485, 2004.

Voigtländer, J., T. Tuch, W. Birmili, and A. Wiedensohler. Correlation between traffic density and particle size distribution in a street canyon and the dependence on wind direction, *Atmos. Chem. Phys.*, 6, 4275–4286, 2006.

Wyser, K. The effective radius in large-scale models: Impact of aerosols and coalescence, *Atmospheric Research*, 49, Issue 3, 213–234, doi: 10.1016/S0169-8095(98)00081-7, 1998.

Walcek, C. J. and G. R. Taylor. A theoretical method for computing vertical distributions of acidity and sulfate production within cumulus clouds, *J. Atmos. Sci.*, 43, 339–355, 1986.

Walcek, C. J., R. A. Brost, J. S. Chang and M. L. Wesley. SO_2, Sulfate and HNO_3 deposition velocities computed using regional land use and meteorological data, *Atmos. Environ.*, 20, 946–964, 1986.

Yoon, Y. J., D. Ceburnis, F. Cavalli, O. Jourdan, J. P. Putaud, M. C. Facchini, S. Decesari, S. Fuzzi, S. G. Jennings and C. O'Dowd.: Seasonal characteristics of the physico-chemical properties of North Atlantc marine aerosols, *J. Geophys. Res.*, 112, D04206, doi:10.1029/2005JD007044, 2007.

Research Outputs – Publications

Flanagan R. J. and C. D. O'Dowd, A modelling study of the effect of increasing background ozone on PM production in clouds. Proceedings of the 17th International Conference on Nucleation and Atmospheric Aerosols, 13–17 August, Galway, Ireland, 2007.

Varghese, S., R. Flanagan, B. Langmann and C. D. O'Dowd, Influence of marine aerosols on cloud droplet number concentration over the north-east Atlantic: Current problems in atmospheric radiation. Proceedings of the International Radiation Symposium (IRC/IAMAS) Foz do Iguaçu, Brazil, 3–8 August 2008, Series: AIP Conference Proceedings, Vol. 1100, Nakajima, Teruyuki; Yamasoe, Marcia Akemi (Eds.), 2009, 696pp.

Flanagan, R., S. Varghese, B. Langmann, A. Nenes, and C. O'Dowd, Aerosol–cloud interactions in the REMOTE regional climate model. Proceedings of the 18th International Conference on Nucleation and Atmospheric Aerosols, 10–14 August, Prague, Czech Republic, 2009.

Flanagan, R. J., S. Varghese, B. Langmann and C. D. O'Dowd, Evaluation of aerosol–cloud interaction parameterizations in the REMOTE regional climate model. In preparation, to be submitted to *J. Geophys. Res*.

Flanagan, R. J., S. Varghese, B. Langmann and C. D. O'Dowd, Th effect of aerosols on cloud droplet number concentration and effective radius over Europe. In preparation, to be submitted to *J. Geophys. Res*.

Acronyms and Annotations

BC	Cloud condensation nuclei
CDNC	Cloud droplet number concentration
DM	Deutschland-Modell
DU	Mineral dust
ECHAM4	European Centre Hamburg Model 4
ECMWF	European Centre for Medium Range Weather Forecasting
EM	Europa-Modell
EMEP	European Monitoring and Evaluation Programme
GCM	Global Climate Model
HAM	Hamburg aerosol model
IPCC	Intergovernmental Panel on Climate Change
LWC	Liquid water content
OC	Organic carbon
ODE	Ordinary differential equation
PM	Particulate matter
POC	Primary organic carbon
RADM2	Regional Acid Deposition Model 2
RCM	Regional climate model
REMO	Regional model
REMOTE	Regional model with tracer extension
SRES	Special report on emission scenarios
SS	Sea salt
VOC	Volatile organic carbon

An Ghníomhaireacht um Chaomhnú Comhshaoil

Is í an Gníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlachta reachtúil a chosnaíonn an comhshaol do mhuintir na tíre go léir. Rialaímid agus déanaimid maoirsiú ar ghníomhaíochtaí a d'fhéadfadh truailliú a chruthú murach sin. Cinntímid go bhfuil eolas cruinn ann ar threochtaí comhshaoil ionas go nglactar aon chéim is gá. Is iad na príomh-nithe a bhfuilimid gníomhach leo ná comhshaol na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil agus Rialtais Áitiúil a dhéanann urraíocht uirthi.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaol i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistrithe dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh., déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreail.
- Scardadh dramhuisce

FEIDHMIÚ COMHSHAOIL NÁISIÚNTA

- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain.
- Maoirsiú freagrachtaí cosanta comhshaoil údarás áitiúla thar sé earnáil - aer, fuaim, dramhaíl, dramhuisce agus caighdeán uisce.
- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí comhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaol mar thoradh ar a ngníomhaíochtaí.

MONATÓIREACHT, ANAILÍS AGUS TUAIRISCIÚ AR AN GCOMHSHAOL

- Monatóireacht ar chaighdeán aeir agus caighdeáin aibhneacha, locha, uiscí taoide agus uiscí talaimh; leibhéil agus sruth aibhneacha a thomhas.
- Tuairisciú neamhspleách chun cabhrú le rialtais náisiúnta agus áitiúla cinntí a dhéanamh.

RIALÚ ASTUITHE GÁIS CEAPTHA TEASA NA HÉIREANN

- Cainníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdéan aeir agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

MEASÚNÚ STRAITÉISEACH COMHSHAOIL

- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaol na hÉireann (cosúil le pleananna bainistíochta dramhaíola agus forbartha).

PLEANÁIL, OIDEACHAS AGUS TREOIR CHOMHSHAOIL

- Treoir a thabhairt don phobal agus do thionscal ar cheisteanna comhshaoil éagsúla (m.sh., iarratais ar cheadúnais, seachaint dramhaíola agus rialacháin chomhshaoil).
- Eolas níos fearr ar an gcomhshaol a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózóin.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Ghníomhaireacht i 1993 chun comhshaol na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstiúrthóir agus ceithre Stiúrthóir.

Tá obair na Gníomhaireachta ar siúl trí ceithre Oifig:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig um Fhorfheidhmiúchán Comhshaoil
- An Oifig um Measúnacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáide

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.

National Development Plan 2007 - 2013

Science, Technology, Research and Innovation for the Environment (STRIVE) 2007-2013

The Science, Technology, Research and Innovation for the Environment (STRIVE) programme covers the period 2007 to 2013.

The programme comprises three key measures: Sustainable Development, Cleaner Production and Environmental Technologies, and A Healthy Environment; together with two supporting measures: EPA Environmental Research Centre (ERC) and Capacity & Capability Building. The seven principal thematic areas for the programme are Climate Change; Waste, Resource Management and Chemicals; Water Quality and the Aquatic Environment; Air Quality, Atmospheric Deposition and Noise; Impacts on Biodiversity; Soils and Land-use; and Socio-economic Considerations. In addition, other emerging issues will be addressed as the need arises.

The funding for the programme (approximately €100 million) comes from the Environmental Research Sub-Programme of the National Development Plan (NDP), the Inter-Departmental Committee for the Strategy for Science, Technology and Innovation (IDC-SSTI); and EPA core funding and co-funding by economic sectors.

The EPA has a statutory role to co-ordinate environmental research in Ireland and is organising and administering the STRIVE programme on behalf of the Department of the Environment, Heritage and Local Government.

epa
Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

ENVIRONMENTAL PROTECTION AGENCY
PO Box 3000, Johnstown Castle Estate, Co. Wexford, Ireland
t 053 916 0600 f 053 916 0699
LoCall 1890 33 55 99
e info@epa.ie w http://www.epa.ie

SSTI
Strategy for Science, Technology and Innovation

Comhshaol, Oidhreacht agus Rialtas Áitiúil
Environment, Heritage and Local Government