Helmholtz-University Young Investigators Group

SeaKLIM

Impact of Ship Emissions on Atmosphere and Climate

-

Comparison to Other Transport Modes

Veronika Eyring (DLR-IPA), Klaus Franke (UniB-IUP),
Axel Lauer (DLR-IPA) and Mathias Schreier (UniB-IUP)

Helmholtz Centre:	Deutsches Zentrum für Luft- und Raumfahrt e.V. Institut für Physik der Atmosphäre (DLR-IPA)
Cooperating University:	Universität Bremen Institut für Umweltphysik und Fernerkundung (UniB-IUP)

Contact:
Dr. Veronika Eyring

DLR, Institut für Physik der Atmosphäre
Phone: 0049-8153-28-2533
Email: **Veronika.Eyring@dlr.de**

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Contents

1 Scientific Goals and Reference to the Helmholtz Program 3
2 Executive Summary 4
3 Scientific Results 6
3.1 Introduction 6
3.2 Emission Inventories 6
3.2.1 Historical Fuel Consumption and Emissions 6
3.2.2 Future Emission Scenarios 7
3.3 Impact on Regional and Global Chemistry 8
3.3.1 Near-Field Dispersion and Chemical Dilution 8
3.3.2 Large-Scale Chemistry Effects 9
3.4 Impact on Aerosols and Clouds 12
3.4.1 Ship Tracks 12
3.4.2 Impact on Aerosols and Large-Scale Clouds 14
3.5 Radiative Forcing 18
3.6 Outlook 19
3.6.1 Open Science Questions 19
3.6.2 Future Activities and Projects 20
4 SeaKLIM Publications 21
4.1 Peer-Reviewed 21
4.2 Submitted 21
4.3 In Preparation 21
4.4 Invited Talks 22
4.5 Proceedings etc. 22
4.6 Other Talks and Poster Presentation 22

1 Scientific Goals and Reference to the Helmholtz Program

The aim of the SeaKLIM group is to quantify the impact of gaseous and particulate emissions from international shipping on the chemical composition of the atmosphere and on climate.

The main aim is approached through the following objectives:

i. To establish consistent ship emission inventories for all gaseous and particulate emissions for the past and present-day and to develop plausible scenarios for the future.
ii. To assess the impact of shipping on the chemical composition of the atmosphere.
iii. To assess the impact of shipping on aerosols and clouds.
iv. To assess the impact of shipping on climate.
v. To synthesise the results on shipping with other transport modes (aviation, road traffic).

To reach these objectives, the work is divided into six main tasks. Four scientists who form the core team of SeaKLIM are working on these tasks (see Table 1).

The group is supported and well linked with other research fields of the two host institutes DLR-IPA and UniB-IUP (see Section 6) and contributes to reach the scientific and programmatic goals to understand physical and chemical processes in the troposphere and stratosphere. In particular, the need for an optimal combination between global observations and models to improve our understanding of these processes is central in both institutes, which is well established in SeaKLIM.

With the aim of the SeaKLIM group to quantify the impact of ship emissions it is also well localised in the Helmholtz Association linking into the research fields ‘Transport and Space’. The 'Transport' programme plays a particularly important role in the Helmholtz Association, because ever-growing volumes of transport place a great burden on the environment and it is therefore seen as an important political-strategic field. SeaKLIM contributes to help answering the questions how the impact on the chemical composition of the atmosphere and on climate from pollutant emissions by international shipping can be reduced. Clear information on the climate impact will allow the shipping industry to incorporate, with greater confidence, environmental considerations into their design and development work.

Table 1: The SeaKLIM Team. Two SeaKLIM members work each at DLR-IPA and UniB-IUP. The PhD students at UniB-IUP are supervised by Dr. Veronika Eyring and Dr. Heinrich Bovensmann (UniB-IUP). Since 1 July 2006 the team is supported by Ludovic Joxe (Master Student) working on the analysis of temporal ship track development from Meteosat-8 satellite data.

Institute	Name	Scientific Tasks	Position	Contract Period in SeaKLIM
DLR-IPA	Dr. Veronika Eyring	(1) Development of emission inventories for international shipping for the past and the future. (2) Global modelling of the impact of shipping on the chemical composition of the atmosphere.	Team Leader	1 January 2004 - 31 December 2006
DLR-IPA	Dr. Axel Lauer	(3) Global modelling of the impact of emissions from shipping on aerosols and clouds.	Post doc	1 August 2004 - 31 March 2007
UniB-IUP	Klaus Franke	(4) Boxmodel studies on dilution and chemical transformation of ship plumes. (5) Retrieval of tropospheric trace gas concentrations from satellite data along the main shipping routes.	PhD Student	1 October 2004 - 30 September 2007
UniB-IUP	Mathias Schreier	(6) Remote sensing of ship tracks using satellite data.	PhD Student	1 April 2004 - 31 March 2007

2 Executive Summary

With emissions of international shipping taking place both in coastal areas and open oceans their impact on the atmosphere through contribution to ozone formation and the aerosol direct and indirect effect can be significant. However, large uncertainties about the emission budget from international shipping and their impacts on atmospheric chemistry and climate characterised the situation at the time SeaKLIM started, which needed to be explored using models and observations. In SeaKLIM the following main results have been achieved:

Historical Emissions from Shipping and Expected Future Changes

- Over the past decades, the world merchant fleet, fuel consumption and emissions from international shipping have substantially increased. Our results suggest a fuel consumption increase from 64.5 million metric tons (Mt) in 1950 to 280 Mt in the year 2001. This corresponds to 187 (5.4) Tg CO_2 (NO_x) in 1950, and 813 (21.4) Tg CO_2 (NO_x) in 2001. Although shipping contributes only with 16% to the total fuel consumption of all traffic related sources today, the ocean-going fleet emits about 9.2 (0.8) times NO_x and about 80 (2.7) times SO_2 compared to aviation (road traffic).
- Emission scenario calculations up to the year 2050 show that if no control measures are taken beyond existing national and international regulations, NO_x emissions might increase up to a value higher than present day global road transport by 2050 (38.8 Tg (NO_2)/yr). If the sulphur content remains at present day levels a doubling of ship SO_2 emissions can be expected. However, given the air quality issue of shipping emissions, further emission reductions of total NO_x and SO_2 emissions are likely. It could be shown that using aggressive NO_x emission reduction technologies, a significant decrease down to 15% of today's NO_x emissions could be reached until 2050 despite a growing fleet.

Regional Dilution and Processing

- Box model studies with emission data from a large container ship imply that large scale models overestimate the ship-induced ozone production if emissions are instantaneously diluted into large grid-boxes. This shows the importance to parameterise subgrid processes in global models. At noon, the differences between the plume and the global model approach in the ship induced ozone changes are largest. The global model approach overestimates the plume model results by up to a factor of three, depending on emission time and source strength.
- A method to derive effective ship emissions has been developed for a particular case. It is shown that this method is able to account for the neglect of subgrid processes for different emission times, emission strength and sizes of the large scale box, which cannot be resolved by global models.

Large-scale Effects of Ship Emissions on the Chemical Composition of the Atmosphere

- Evidence for the importance of ship emissions comes from satellite observations by SCIAMACHY that clearly show enhanced tropospheric NO_2 columns along the major international shipping routes in the Red Sea and over the Indian Ocean.
- The global impact of shipping on chemistry as well as associated uncertainties are quantified from an ensemble of state-of-the-art atmospheric chemistry models for present-day conditions and for two future ship emission scenarios for the year 2030. Large increases in tropospheric ozone column are found over the Atlantic and even stronger over the Indian Ocean (1 DU in 2000 and up to 1.8 DU in 2030). If all other emissions vary according to the IPCC SRES A2 scenario, shipping contributes with 3% to increases in ozone burden until 2030 and with 4.5% to increases in sulphate. However, if land-based emissions decrease but ship emissions continue to grow, shipping will significantly counteract the benefits derived from land-based emission reductions.

Impact on Aerosols and Clouds

- The perturbation of a cloud layer by ship-generated aerosol changes the cloud reflectivity and is identified by elongated structures in satellite images, known as ship tracks. Compared to the surrounding cloud a significant increase in droplet number concentration and optical thickness as well as a decrease in effective radius is found within the ship tracks. A global distribution of ship tracks derived from one year of AATSR data shows high spatial and temporal variability with highest occurrence of ship tracks westward of North America and the southwest coast of Africa.
- Simulations with the global model system ECHAM5/MADE show that emissions from shipping significantly increase the cloud droplet number concentration of low maritime water clouds. Whereas the cloud liquid water content remains nearly unchanged, effective radii of cloud droplets decrease, leading to cloud optical thickness increase up to 5-10%. Shipping contributes with 3.6% to the total sulphate burden and 0.4% to the total black carbon burden in 2000. In addition to changes in aerosol chemical composition, shipping increases the aerosol number concentration, e.g. above the Atlantic up to 25% in the size range of the accumulation mode (> 0.1 μm). The total aerosol optical thickness above the Indian Ocean and the Gulf of Mexico increases by 8-10%, above the other major shipping routes by 2-4%.
- Overall, the changes in cloud microphysical properties due to ship emissions result in a change of the global annual top of the atmosphere (TOA) net cloud forcing of –0.59 W/m^2 (indirect aerosol effect). Furthermore, changes in aerosol optical thickness caused by shipping induced modification of aerosol particle number concentration and chemical composition lead to a change of the net TOA clear sky radiation of about –0.036 W/m^2 on global annual average (direct aerosol effect). However, according to the definition of radiative forcing (RF), these changes in net radiation cannot directly be translated into RFs.

Radiative Forcing

- In 2000, the contributions to the total RF from shipping as calculated with a climate response model are 43 mW/m^2 for CO_2, 28.3 mW/m^2 for O_3, -10.9 mW/m^2 for CH_4, -22.2 mW/m^2 from direct effect of SO_4, and 2.5 mW/m^2 for black carbon. The RF from ship tracks estimated from a global ship track distribution derived from one year of AATSR data is small (-0.12 mWm^{-2}), but might affect the climate locally.
- In the future, the RF from shipping CO_2 is expected to increase. All other RF contributions strongly depend on the technology applied in the fleet. If the sulphur content of the fuel is reduced, the positive contributions from CO_2 and O_3 will remain, whereas the effect on aerosols and clouds will strongly decrease. RF from shipping O_3 can be reduced by equipping the fleet with NO_x reduction technologies, but this would also reduce the negative RF from CH_4.

Outlook

The scientific goals of the SeaKLIM group have been reached in general. For global modelling aspects the major future challenge lies in the parameterisation of subgrid processes both for gaseous and particulate emissions. Further measurements and modelling studies are needed to understand plume processes. Current uncertainties of global modelling studies on the effects of emissions from shipping on aerosols and clouds are expected to be much higher than in the case of the ozone change studies. Reduction in measurement uncertainties through use of long-term averages and data from more instruments combined with better constraints on land-based sources and higher spatial resolution in the models should facilitate a comparison between global models and satellite data in the future.

3 Scientific Results

3.1 Introduction

Seagoing ships emit exhaust gases and particles into the marine boundary layer contributing significantly to the total budget of anthropogenic emissions (see Table 2). Emissions of nitrogen oxides and other ozone precursors from shipping lead to tropospheric ozone formation and perturb the hydroxyl radical (OH) concentrations, and hence the lifetime of methane (CH_4), which changes the Earth's radiation budget as ozone and methane are greenhouse gases. In addition to NO_x, shipping contributes significantly to global SO_2 emissions as the average sulphur content of the fuel burned in marine diesel engines of 2.4% is high compared to other transport sectors (EPA, 2002).

A number of atmospheric model studies quantifying the impact of ship emissions on the chemical composition of the atmosphere and on climate were available at the time when SeaKLIM started. Historical emission inventories and possible future scenarios did not exist. All the studies therefore focused on present-day conditions and used a global fuel consumption of about 150 million metric tons (Mt or Tg) per year derived from energy statistics (Corbett and Fischbeck, 1997; Corbett et al., 1999; Olivier et al., 2001). However, estimates of the fuel consumption calculated with an activity-based approach suggested higher fuel consumption of 289 Mt (Corbett and Köhler, 2003). Even though model studies used the lower total fuel consumption, it was shown that models overestimate the observed NO_x distribution for example over the Atlantic (Lawrence and Crutzen, 1999; Kasibhatla et al., 2000; Davis et al., 2001; Endresen et al., 2003), but underestimated SO_2 observations (Davis et al., 2001). There were first indications that this discrepancy could be reduced by accounting for ship plume dispersion in global models (Kasibhatla et al., 2000; Davis et al., 2001; Song et al., 2003; von Glasow et al., 2003). However, there was no clear consensus on the effective global emissions from ships.

In addition to the impact on tropospheric chemistry, particle emissions from ships also change the microphysical properties of low clouds. This is the so-called indirect aerosol-effect, which has been observed in satellite data in many studies (e.g., Conover, 1966; Twomey et al., 1968; Radke et al., 1989). Particles and their precursors from ship emissions are able to act as cloud condensation nuclei (CCN) in the water-vapour saturated environment of the maritime cloud or can change the surface tension due to their solubility. Amount and size of these particles depend on the fuel and also the kind of combustion, but can possibly result in a higher cloud droplet concentration (Twomey et al., 1968; Twomey, 1974) and consequently in a change of reflectivity of the maritime cloud. Measurements in the Monterey Ship Track Experiment confirmed this hypothesis (e.g., Durkee et al., 2000; Hobbs et al. 2000). These measurements also confirmed the role of emitted particles as CCNs and especially the importance of SO_2. The higher droplet concentration leads to an increased scattering, resulting in larger reflectances. In addition, aerosols from shipping might also change cloud cover and precipitation formation efficiency. However, at the time when SeaKLIM started, the potential global influence of aerosols on clouds had been only roughly estimated (Capaldo et al. 1999) and no detailed model studies assessing the overall indirect effect due to shipping were available. Also, the global distributions as well as radiative forcings from ship tracks were unknown.

SeaKLIM could contribute to fill important gaps discussed above. The following sections summarise the main scientific results that have been achieved within SeaKLIM.

3.2 Emission Inventories

3.2.1 Historical Fuel Consumption and Emissions

Ship number and average engine statistics have been used to calculate total fuel consumption, greenhouse gas and air pollutant emissions of seagoing ships for the time period 1950 to 2001. The inventory is a bottom-up analysis using fuel consumption and fleet numbers for the total civilian and military fleet including auxiliary engines at the end of 2001. Trend estimates for fuel consumption, CO_2, NO_x and other emissions for the time between 1950 and 2001 have been calculated using ship number statistics and average engine statistics. Our estimate for total fuel consumption and global emissions for the year 2001 is similar to previous activity-based studies. However, compared to

earlier studies, a detailed speciation of non-methane hydrocarbons (NMHCs) and particulate matter is given and carbon monoxide emissions are calculated explicitly. Our results suggest a fuel consumption of approximately 280 million metric tons (Mt) for the year 2001 and 64.5 Mt in 1950. This corresponds to 187 (5.4) Tg CO_2 (NO_x) in 1950, and 813 (21.4) Tg CO_2 (NO_x) in 2001. Although shipping contributes only about 16% to the total fuel consumption of all traffic related sources (Aviation: 207 Mt, International Shipping: 280 Mt, Road Traffic: 1320 Mt), ship emissions significantly contribute to emissions of pollutants from all transport modes (see Figure 1), particularly because there have been no strict international emission regulations in the past as for road traffic and aviation. Table 2 gives an overview of the relative contribution of the three individual transport modes to the total anthropogenic emissions.

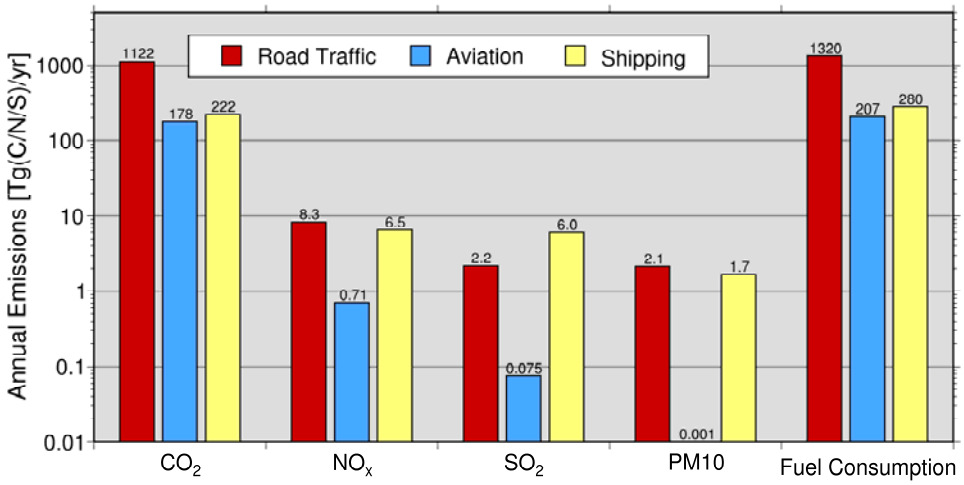

Figure 1: Transport-related annual emissions of CO_2 in Tg (C), NO_x in Tg (N), SO_2 in Tg (S) and PM_{10} in Tg (PM) and the fuel consumption in Mt estimated for the year 2000 (from Eyring et al., 2005a).

3.2.2 Future Emission Scenarios

To address possible future development, several scenarios until 2050 have been investigated. The scenarios are based on some very strict assumptions on future ship traffic demands and technological improvements.

Table 2: Relative contribution of road traffic, shipping (Eyring et al., 2005a) and aircraft to total annual anthropogenic emissions for the year 2000 (EDGAR 32FT2000, Olivier et al., 2005).

	CO_2	CH_4	CO	NO_x	NMVOC	SO_2
Road Traffic	14.1%	0.3%	17.2%	20.6%	17.8%	2.4%
Shipping	2.7%	16.1%	12.2%	15.4%	1.8%	7.8%
Aircraft	2.2%	0.0%	16.4%	1.7%	0.3%	0.1%

The four future ship traffic demand scenarios are mainly determined by the economic growth, which follows the IPCC SRES storylines (IPCC, 2000). The resulting fuel consumption is projected through extrapolations of historical trends in economic growth, total seaborne trade and number of ships, as well as the average installed engine power per ship. The scenario calculations indicate that the demand for ship transport will continue to increase in the future. For the future technology scenarios we assume a diesel-only fleet in 2020 resulting in fuel consumption between 382 and 409 million metric tons (Mt). For 2050 one technology scenario assumes that 25% of the fuel consumed by a diesel-only fleet can be saved by applying future alternative propulsion plants, resulting in a fuel consumption that varies between 402 and 543 Mt. The other scenario is a business-as-usual scenario for a diesel-only fleet even in 2050 and gives an estimate between 536 and 725 Mt.

The today's fleet-average emission factors of the most important ship exhausts from Eyring et al. (2005a) are used to calculate emission scenarios for the future. These calculations up to the year 2050 show that if no control measures are taken beyond existing IMO regulations, NO_x emissions might increase to a value higher than present day global road transport. If the sulphur content remains at present day levels a doubling of SO_2 emissions can be expected. However, given the air quality issue of shipping emissions, further emission reductions of NO_x and SO_2 are to be expected.

Using aggressive NO_x emission reduction a significant decrease up to 85% of today's NO_x emissions can be reached until 2050, in spite of the larger fleet. CO_2 emissions are suggested to further increase by about 35% under the same "clean" scenario due to the direct connection between fuel consumption and CO_2 emissions. Figure 2 shows the possible range of future NO_x and CO_2 emissions.

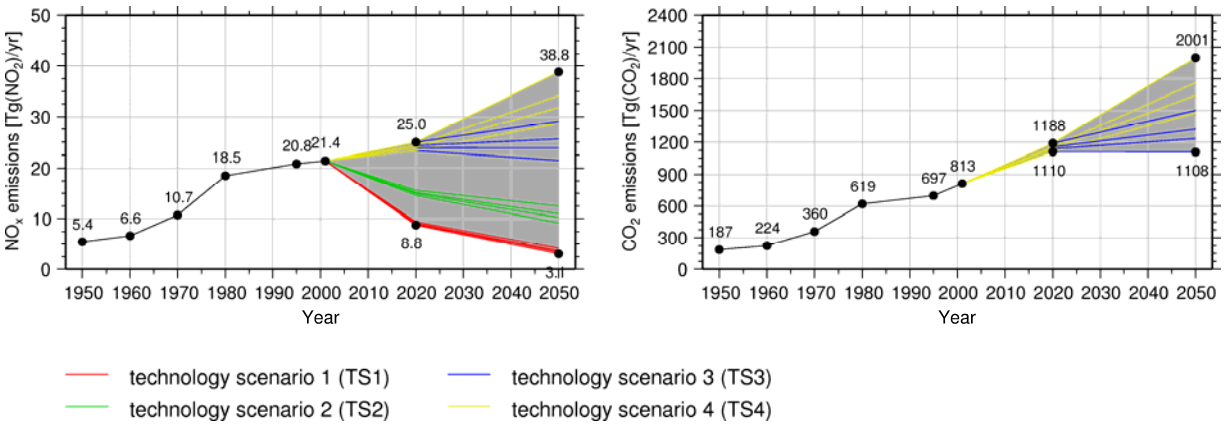

Figure 2: Possible range of future NO_x and CO_2 emissions according to the four different technology scenarios (TS1-4) and the four different ship traffic demand scenarios (DS1-4). Results for the technology scenario 1 (TS1) are shown for different ship traffic demand scenarios (DS1-4) with red lines, those for TS2 with green lines, for TS3 with blue lines, and for TS4 with yellow lines.

As a result an entirely consistent set of emission inventories from 1950 to 2050 suitable as input for global chemistry models has been provided by the SeaKLIM group (Eyring et al., 2005a,b).

3.3 Impact on Regional and Global Chemistry

3.3.1 Near-Field Dispersion and Chemical Dilution

The chemical production of ozone by ship emissions from a single ship is simulated with two different modelling approaches during the first days after emission. While both techniques use the same photochemical box model to solve the chemical equations, the parameterisation of the dilution of the exhaust into the background air is different. One approach uses a Gaussian plume model to take the expansion of a plume into account (hereafter: 'Plume Dispersion' (PD)). The other one disperses the emissions instantaneously over a large-scale model box like a regional or global model would do (hereafter: 'Instantaneous Dilution' (ID)). In a case study both approaches are applied to ship emissions of 145 mol(NO_x)/s, which where emitted at noon of May 8th into background air taken from Chen et al. (2005). The ship emissions were calculated from the fuel consumption of a large container ship, the Clifford Maersk (H. Schlager, pers. comm.). The calculations where performed until the time t_{ref} when the PD-box has grown to the size of the ID box. The height was limited by the height of the marine boundary layer. 60 km was chosen as maximum width of horizontal plume expansion and size of the ID box.

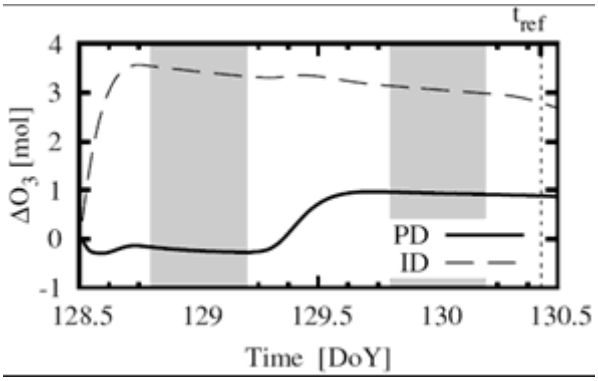

Figure 3: Temporal development of ship induced ozone change. Shown is the ozone change integrated over the boxes of one calculation with plume dispersion (PD) and one with instantaneous dispersion (ID).

Comparison of both approaches show significant differences in ship induced ozone production. The different box sizes lead to different NO_x-concentrations. The small PD box with high concentrations of NO_x lies in a regime where ozone production is hydrocarbon limited and additional NO_x results in ozone destruction. On the other hand in the ID box the ozone chemistry is in the NO_x-limited regime where additional NO_x produces ozone. The resulting ozone development can be seen in Figure 3. For the PD case at the reference time t_{ref} a total of 3 mol ozone has been produced, while in the ID box about 1 mol is produced. Therefore, for this

particular case with emissions from a large container ship, global models overestimate the ozone response by a factor of three.

In a following study a method to correct for this overestimation in global models is tested. The method follows Petry et al. (1998), who investigated the same problem for aircraft emissions. The core idea of this approach is to adjust the emissions for the ID approach in a way that at the reference time t_{ref} the calculations end up at values approximately that of a corresponding PD simulation. For the above described situation it is possible to correct the ozone production for an ID calculation. This can be seen in Figure 4.

The differences in ozone production and therefore the effective emissions are expected to depend on a variety of parameters, e.g. background conditions, time of release, and emission strength. To study these dependences, sensitivity studies have been conducted. Figure 4 shows ship induced ozone concentration changes in the different boxes ID and PD as a function of time of the emissions released into the marine boundary layer (MBL). A dependence of ozone production on release time can be seen for both the PD and the ID calculations. However, while the ozone produced for the PD calculations reaches its maximum at 3 in the morning with 0.82 nmol/mol and the minimum at noon with 0.46 nmol/mol, the ozone production calculated with the ID model reaches its maximum at noon with 1.5 nmol/mol and minimum at 6 in the evening with 0.63 nmol/mol. This is due to the different times after emission when ozone production takes place. In the ID case ozone production directly starts after the emissions while in PD calculations the production of ozone occurs mainly on the second day. The relative difference between the approaches is highest at noon, when in the ID box 3.2 times as much ozone as in the PD box is simulated. It is smallest at 21 LT, when ID simulates 1.2 times as much ozone than PD. Additionally, for all calculations shown the capability to correct the ID cases with effective emissions was tested. It can be seen that these calculations (EF) give approximately the same ozone production as the PD runs.

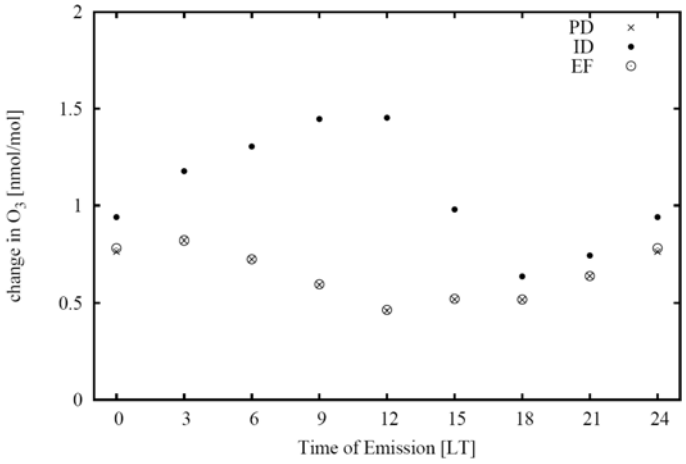

Figure 4: Ship induced ozone change at reference time t_{ref} as a function of time of the emissions release into the MBL. Shown are results for three calculations: with plume dispersion (PD), instantaneous dispersion without effective emissions (ID) and instantaneous dispersion with effective emissions (EF).

A similar study was made for the dependence on emission strength. Here the emissions from the first run (emissions of 145 mol/s at noon) are varied in ten steps from 14.5 mol/s up to 145 mol/s. For the ID case the ozone production at t_{ref} is nearly linear in respect to emission strength. It ranges from 0.17 nmol/mol for an emission of 14.5mol/s up to 1.5 nmol/mol at 145 mol/s. In the PD case the ship induced ozone concentration change ranges from 0.11 nmol/mol at 14.5 mol/s to 0.46 nmol/mol at 145 mol/s and show no linear dependence on emission strength. The relative difference between the two approaches also increases with increasing emission strength. At 14.5 mol/s 1.6 times as much ozone is produced in the ID case as in the PD case, at 145 mol/s it is 3.2 times as much.

Overall the results highlight the importance of plume chemistry. Further details on this study are summarised in Franke et al. (2006).

3.3.2 Large-Scale Chemistry Effects

Evidence for the importance of large-scale chemistry effects due to international shipping comes from satellite observations from SCIAMACHY (Richter et al., 2004) that show enhanced tropospheric NO_2 columns along the major international shipping routes in the Red Sea and over the Indian Ocean (Figure 5).

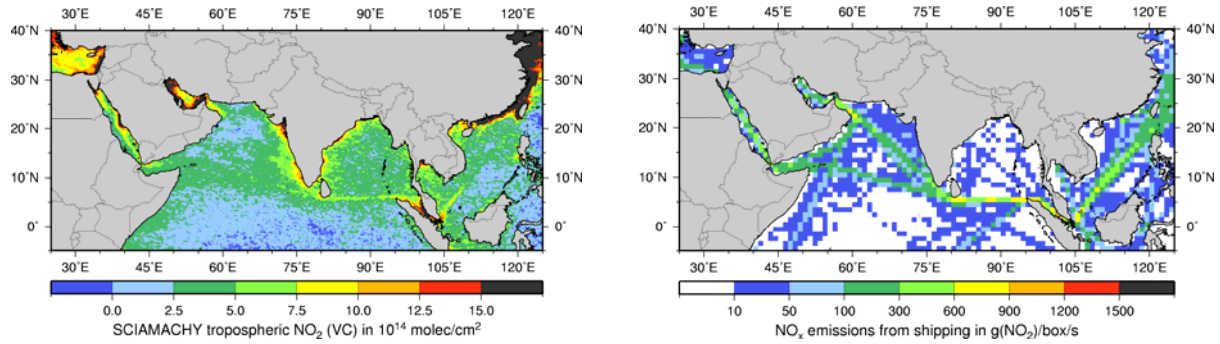

Figure 5: NO_x signatures of shipping in the Red Sea and Indian Ocean. Left: Tropospheric NO_2 columns derived from SCIAMACHY data from August 2002 to April 2004. Right: Estimated distribution of NO_x emissions by shipping in the same region (from Richter et al., 2004).

Large scale effects on chemistry are also assessed with the help of coupled chemistry-climate models (CCMs). As parameterisations for subgrid processes are not yet available, the model simulations presented here have been run without accounting for subgrid plume chemistry.

3.3.2.1 PHOTOCOMP-ACCENT-IPCC Study

The global impact of shipping on atmospheric chemistry and radiative forcing as well as the associated uncertainties have been quantified using an ensemble of ten state-of-the-art atmospheric chemistry models and a pre-defined set of emission data. The analysis is performed for present-day conditions (year 2000) and for two future ship emission scenarios. The main characteristics of the participating models (CHASER-CTM, FRSGC/UCI, GMI/CCM3, GMI/DAO, LMDz/ INCA, MATCH-MPIC, STOCHEM-HadAM3, STOCHEM- HadGEM, TM4, and UIO_CTM2) are summarised in Eyring et al. (2006a), their Table 1 and are described in detail in the cited literature.

Two of the five simulations have been defined as part of the wider PHOTOCOMP-ACCENT-IPCC study (Stevenson et al., 2006; van Noije et al., 2006; Shindell et al., 2006; Dentener et al., 2006a,b): a year 2000 base case (S1) and a year 2030 emissions case (S4) where all other anthropogenic sources (except biomass burning emissions, which remain fixed at year 2000 levels) vary according to IPCC SRES A2 broadly representing a 'pessimistic' future situation. As noted in Stevenson et al. (2006) in the S4 simulation emissions from ships were included at year 2000 levels by mistake. For the shipping study, an additional model simulation for 2030 (S4s) has been designed to assess the impact of shipping if emission growth remains unabated. Ship emissions in S4s are based on a 'Constant Growth Scenario' in which emission factors are unchanged and emissions increase with an annual growth rate of 2.2% between 2000 and 2030. In the S4s scenario emissions from shipping increase to 5.95 Tg(N) for NO_x and 7.36 Tg(S) for SO_2 in 2030. In addition to the S1 and S4 simulations, two sensitivity simulations have been defined that use identical conditions to S1 or S4/S4s except that ship emissions are excluded. The year 2000 and 2030 experiments without ship emissions are denoted as S1w and S4w. The difference between the simulation with and without ship emissions are used to quantify the impact of shipping on NO_2, O_3, and sulphate distributions.

The first key question addressed in this study is how NO_x and SO_2 emissions from international shipping might influence atmospheric chemistry in the next three decades if these emissions increase unabated. The models show future increases in NO_x and ozone burden which scale almost linearly with increases in NO_x emission totals. For the same ship emission totals but higher emissions from other sources a slightly smaller response is found. Changes in the annual mean near-surface level reach 5.5 nmol/mol over the Atlantic (Figure 6b) and increase up to 7.4 nmol/mol in the S4s scenario in 2030 (Figure 6h). Over Northern Europe where there are high levels of NO_x, and relatively low levels of insolation (even in summer), the increase in NO_x from shipping decreases, rather than increases, ozone levels. This is due to reduction in oxidant levels as OH is removed by the reaction $NO_2 + OH \rightarrow HNO_3$, and in winter to direct titration of ozone by NO_2. This effect can clearly be seen over the Baltic and the North Sea. The effect is stronger in the 2030 scenarios due to the increased

background level of NO_x in Northern Europe, with shipping decreasing ozone by 3 nmol/mol in the S4s scenario. The impact on the ozone decreases rapidly with height (Figure 6a,d,g). The most pronounced changes in tropospheric ozone columns are found over the Indian Ocean (1.16 DU in 2000 and 1.72 DU in 2030), related to the higher tropopause there and to more effective transport of ozone from the boundary into the upper troposphere. A second peak is simulated over the Atlantic. Over Europe, the increase in ship emissions under the 'Constant Growth Scenario' will enhance the positive trend in NO_2 over land up to 2030. In addition, efforts to lower European sulphate levels through reductions in SO_2 emissions from anthropogenic sources on land will be partly counteracted by the rise in ship emissions. The results discussed above are calculated under the assumption that all other emissions follow the IPCC SRES A2 scenario. However, if future ground based emissions follow a more stringent scenario, the relative importance of ship emissions becomes larger. The second key issue of this work is to examine the range of results given by the individual models compared to the ensemble mean. Uncertainties in the different model approaches in the simulated ozone contributions from ships are found to be significantly smaller than estimated uncertainties stemming from the ship emission inventory, mainly the ship emission totals, the neglect of ship plume dispersion, and the distribution of the emissions over the globe. The results are summarised in Eyring et al. (2006a).

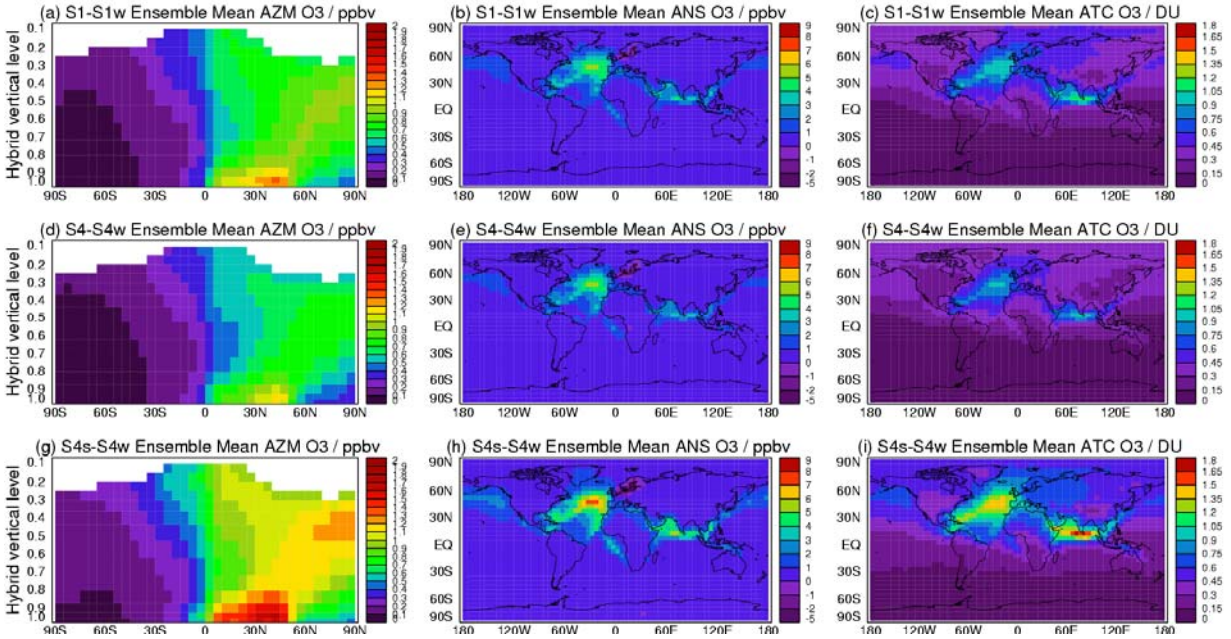

Figure 6: Modelled ensemble mean ozone change between (a-c) S1 (year 2000) and S1w (year 2000 without ship emissions), (d-f) S4 (year 2030) and S4w (year 2030 without ship emissions), and (g-i) S4s (year 2030) and S4w. Figure 5a, 5d, and 5g are zonal mean changes (nmol/mol), Figures 5b, 5e, and 5h are near-surface ozone changes (nmol/mol) and Figure 5c, 5f, and 5i are tropospheric ozone column changes (DU).

3.3.2.2 First Simulations with ECHAM5/MESSy

First simulations were performed with ECHAM5/MESSy and the detailed chemistry module MECCA (Sander et al., 2005) taking into account NO_x-HO_x-CH_4-CO-O_3 as well as NMHC chemistry. Time-slice experiments are used to examine the response to specific changes in forcing, in this case emissions from international shipping. We have so far carried out two time-slice experiments with fixed boundary conditions for the year 2000, one with and one without ship emissions. The model's horizontal resolution in these two simulations was T42 with 31 vertical layers and an upper boundary centered at 10 hPa. Ship emissions are taken from Eyring et al. (2005a), whereas all other emissions are prescribed according to EDGAR3.2 Fast Track (Oliver et al., 2005). The climatological mean consists of the first three simulated years for each run. Three years are not expected to provide full statistical significance, thus the results presented here are preliminary. Figure 7 displays absolute and relative changes in near-surface NO_2 and O_3 distributions. Due to the short lifetime of NO_2 in the boundary layer, near-surface changes in NO_2 follow closely the main shipping routes, but the dispersion is a few hundred kilometres, which is partly due to the coarse resolution of the model, but also

transport. Maximum changes in the annual mean reach up to 1 nmol/mol. Largest relative changes of more than 80% are found over the remote Atlantic and along the major shipping lanes, where background levels are small and NO_x emissions from ships are the dominant source. In contrast to the absolute changes, the relative changes in NO_x are small over strongly polluted areas along the West Coast of Europe, the Baltic Sea and the Mediterranean Sea. Most pronounced changes in near-surface ozone up to 9 nmol/mol are simulated over wide areas of the Atlantic, the Western and Northern Pacific and the Indian Ocean. Due to the longer lifetime of ozone compared to NO_2 in the boundary layer, ozone changes are less tightly located to the main shipping lanes compared to NO_2 changes, and affect larger areas. Non-linear effects of ozone photochemistry are significant. For example, over the Baltic and the North Sea, where background NO_2 levels are relatively high, changes in ozone are comparatively small, whereas they are substantial over more remote areas. The global pattern of the response due to shipping agrees well with results presented in Endresen et al. (2003) who used the same vessel traffic densities. However, the response is higher than in Endresen et al. (2003) due to differences in the emission totals between the two studies.

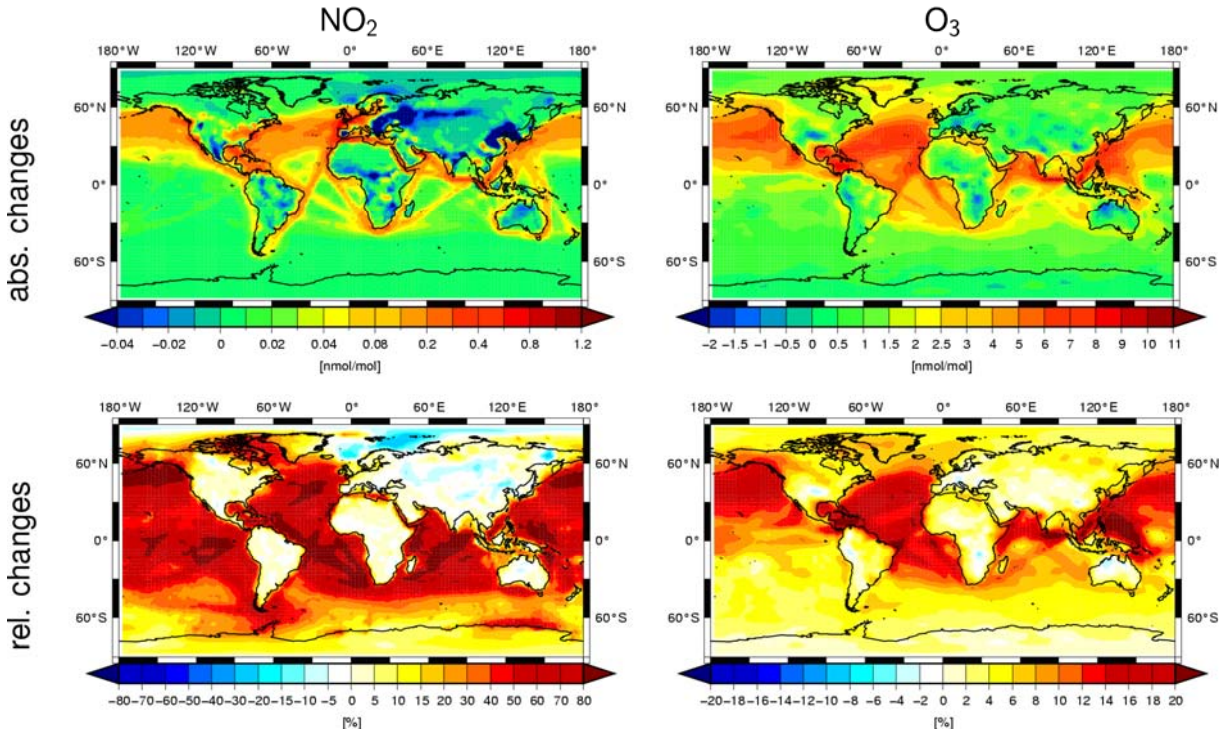

Figure 7: Absolute and relative changes in annual mean near-surface NO_2 (left column) and ozone (right column) between the ECHAM7MESSy simulation with and without ship emissions. The 1st row shows absolute changes in nmol/mol and the second row shows relative changes in %.

3.4 Impact on Aerosols and Clouds

3.4.1 Ship Tracks

One of the aims of SeaKLIM is the quantification of the impact of ship emissions on clouds and the resulting changes in the radiation budget. Here, we analyse visible anthropogenic cloud modifications over the ocean via satellite data (so called „ship tracks“). Ship tracks are often seen in low marine clouds as elongated structures of changes in backscattered solar flux over the ocean with an obvious anthropogenic origin. They develop particularly because of the high SO_2 emissions due to the high sulphur content of the fuel burned by ships. These sulphuric emissions result in a change of cloud droplet number concentration and thus affect the droplet size distribution. A decrease in droplet size and an increase in droplet number concentration (Figure 8a,b) affects the reflectivity of the cloud resulting in ship tracks observable in satellite data.

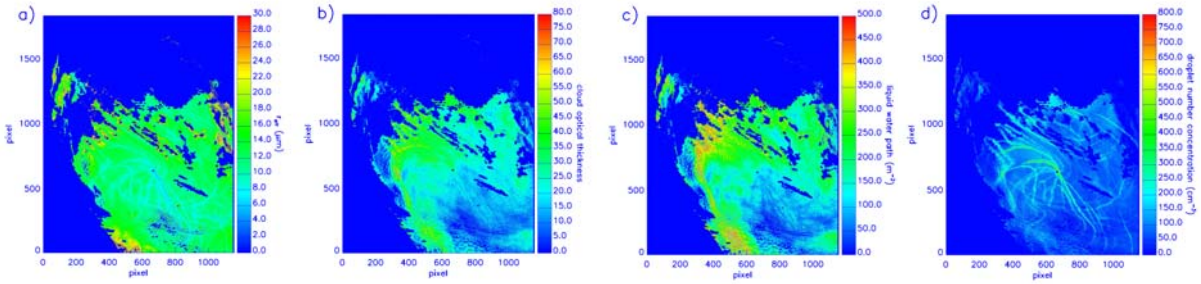

Figure 8: Cloud properties from a MODIS scene from 10th February, 2003 on the west coast of North America. a) effective radius, b) cloud optical thickness, c) liquid water path , d) droplet number concentration.

To estimate the effect of ship emissions on the radiation budget of clouds, an analysis for a satellite scene from MODIS (MODerate resolution Imaging Spectrometer) on the satellite Terra was performed in an accurate way via cloud optical properties. The cloud optical thickness (Figure 8a) and the effective radius (Figure 8b) were calculated for a satellite scene via a semi-analytical approach (Kokhanovsky et al, 2003) combined with a look-up-table-approach derived by libRadtran (Mayer and Kylling, 2005), to estimate the changes of the cloud optical properties. These values can also be used to calculate secondary cloud properties, e.g. the liquid water path (Figure 8c) and the droplet number concentration (Figure 8d) and to compute the local radiative forcing via radiative transfer calculations (Schreier et al., 2006a).

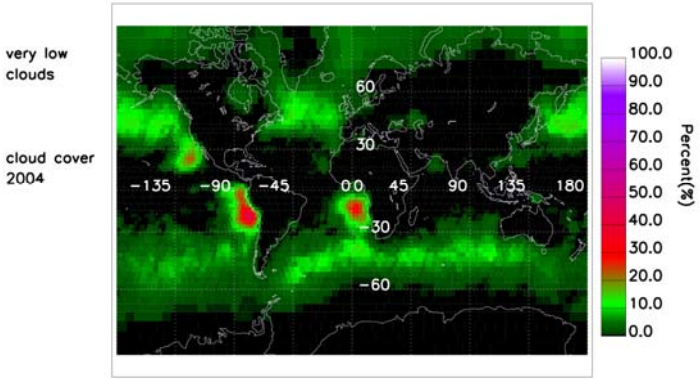

Figure 9: Global coverage of low-level marine boundary layer clouds from AATSR data of 2004.

The results show an increase of backscattered solar flux between unaffected marine stratus clouds and ship tracks up to 71 Wm^{-2} depending on the solar zenith angle and resulted in an overall loss of 3 Wm^{-2} due to ship tracks for the entire satellite scene. This shows that local effects of ship tracks are not negligible.

In the following analysis, the data from the instrument AATSR (Advanced Along Track Scanning Radiometer) on Envisat for the whole year 2004 was used to obtain a global ship track distribution and to estimate the radiative forcing due to ship tracks. The first step of this analysis was to retrieve low clouds over the ocean which are susceptible for ship emissions and thus for the development of ship tracks. According to Durkee et al. (2000), ship tracks occur only in very low clouds in the marine boundary layer and thus several restrictions like terrain height, cloud top temperature and amount of clouds in the satellite data were used, to derive a global amount of very low clouds in 2004 (Figure 9). High occurrence of very low clouds is found over the west coast of South America, South-West Africa and North America, resulting from the cold ocean currents along the coast in these regions. Between 30°S and 60°S low clouds results from an inversion over the ocean due to subsidence by global circulation. The belt is similar in the Northern Hemisphere but interrupted by continental landmasses.

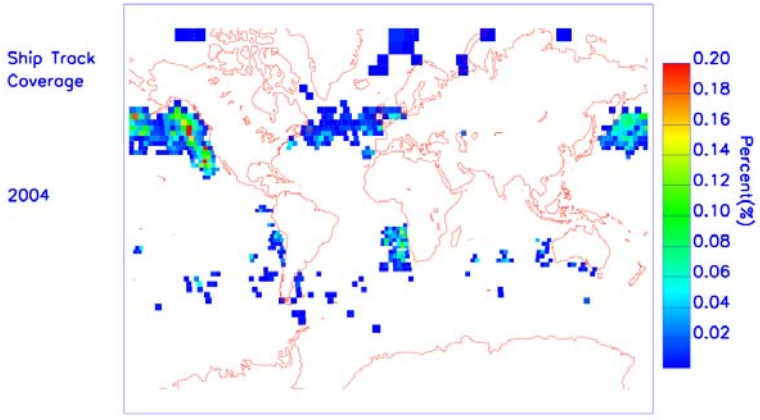

Figure 10: Global coverage of ship tracks derived from AATSR data of 2004.

The examined cloud scenes showed a large variety in size and radiative behaviour, ranging from slight changes

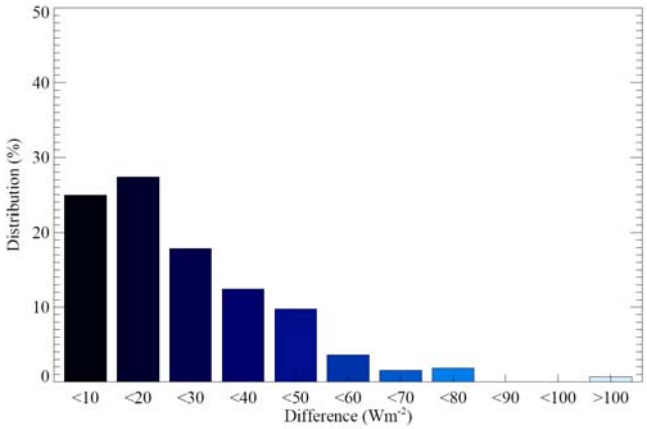

Figure 11: Distribution of the increased backscattered radiative flux by ship tracks compared to the environment.

in reflectivity of an already existing cloud to the development of thick clouds in almost cloud free conditions. The differences in size were taken into account by extracting ship tracks via visual classification. Figure 10 shows the resulting global coverage of ship tracks. Areas of high occurrence differ from the global coverage of low clouds. As a combination of low clouds and ship traffic, ship tracks are more concentrated in certain areas. The most important area for the development of ship tracks in the Northern Hemisphere is the Northern Pacific, mainly the west coast of North America. Large areas over the Northern Atlantic are also covered with ship tracks, but the coverage is only small compared to the other areas. For the Southern Hemisphere, the most important area is the west coast of South West Africa. The remaining occurrence of ship tracks in the southern part of the world is small. To take into account also the variety in radiative behaviour, each forcing was calculated individually for every cloud pixel by calculating the cloud optical properties (effective radius and cloud optical thickness) and recalculating the difference of solar backscattered radiative flux between the ship track and the surrounding area, taking into account the solar zenith angles of the area (Figure 11). The increased backscattering of the ship tracks shows a high variety ranging from 0 to 80 Wm^{-2}. There are also ship tracks with values above 100 Wm^{-2} resulting from ship tracks developing in almost cloud free conditions, but the frequency of occurrence is only small.

Table 2: Seasonal variation of global, northern and southern hemispheric RFs from ship tracks.

Season (Northern Hemisphere)	RF (mWm^{-2}) Global	RF (mWm^{-2}) Northern Hemisphere	RF (mWm^{-2}) Southern Hemisphere
Winter	-0.02	-0.03	-0.01
Spring	-0.13	-0.25	-0.01
Summer	-0.32	-0.56	-0.08
Autumn	-0.02	-0.02	-0.02
Year	**-0.12**	**-0.21**	**-0.03**

The RF was derived by multiplying individual backscattered radiative flux per area with the amount of ship tracks per area and the value of (-1), because the increased backscattering results in a cooling and thus in a negative RF. This does not match the definition of RF exactly (see section 3.5), but because the perturbation is small the derived values should be quite similar to RFs. The average values derived from the satellite analysis are shown in Table 2. The global mean RF from ship tracks for the year 2004 is only -0.12 mWm^{-2}, but shows a large seasonal and spatial variability. Ship tracks mainly occur in the northern hemispheric spring and summer where RFs are largest, whereas only small RFs are observed elsewhere. The RFs due to ship tracks in the Northern Hemisphere are much higher than in the Southern Hemisphere. This results from the high amount of ship tracks in the northern Pacific compared to the remaining parts of the world (see Figure 10). The results are summarised in Schreier et al. (2006a,b).

3.4.2 Impact on Aerosols and Large-Scale Clouds

Two model simulations have been performed with the model system ECHAM5/MADE (extended from Lauer et al. (2005, 2006)) for present-day conditions (year 2000) in order to assess the impact of emissions from international shipping on aerosols and clouds. Both model experiments have identical setup. The simulations cover the period 1998 to 2004 applying the nudging technique using ECMWF data for input. Emissions of trace gases such as NO_x and SO_2 as well as emissions of particulate matter from shipping (Eyring et al., 2005a; Dentener et al., 2006b) have only been consid-

ered in the first model run, whereas these have been switched off in the second one. The impact of shipping is calculated from the differences between both model experiments.

Impact of Emission from Shipping on Clouds

The results of the SeaKLIM model runs show that the impact of shipping on clouds is limited to the lower troposphere ranging from the surface up to about 1.5 km. Thus, the largest potential impact of emissions from shipping on clouds has to be expected in regions with major shipping lanes and a high amount of low clouds. Such regions are found in particular at the west coast of the United States and Africa and over the north-eastern Atlantic (see Figure 9).

The model simulations show only a weak increase in cloud liquid water content in the tropical and subtropical lower troposphere in the Northern Hemisphere of about 15-20 μg/m^3 (about 3%). However, these changes due to shipping are not statistically significant. As expected, the cloud ice water content remains unchanged due to shipping, because the impact of shipping is limited to the lowermost troposphere in the region 40°S to 60°N where warm clouds are predominant. In contrast, the cloud droplet number concentration (CDNC) is significantly increased due to emissions from shipping. Maximum changes of the CDNC amount to about 50 cm^{-3} above the main shipping routes in the northern Atlantic and the Indian Ocean at an altitude of about 500 m. In the Pacific, the annual mean changes of CDNC amount to about 30 cm^{-3}. The relative contribution of shipping is about 20-25%. The zonal annual average shows maximum changes due to shipping between 20°N and 40°N of about 25 cm^{-3} (15%). Overall, the impact on CDNC due to shipping is limited to the lowermost 1.5 km. This shipping induced increase in CDNC results from the increase in aerosol particles that can be activated, which is a consequence of the increase in aerosol number concentration in the accumulation mode (> 0.1 μm) and the increase in of soluble aerosol compounds.

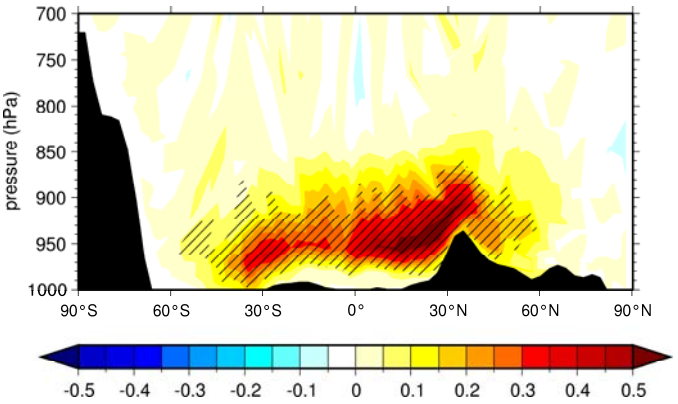

Figure 12: Climatological annual mean (1999-2004) of zonally averaged changes in cloud optical thickness (0.28-0.69 mm) due to shipping. Hatched areas show significant differences.

As a consequence of only slightly increased liquid water content of low clouds in conjunction with a significant increase in CDNC, the effective radii of the cloud droplets decrease. The model results show a maximum decrease of cloud effective radii on zonal annual average of 0.2-0.25 μm (-5%) at an altitude around 500 m. The higher number concentration of smaller cloud droplets scatter light more effectively than clouds with a similar liquid water content but lower CDNC. Thus, the optical thickness (solar spectrum) of the clouds affected by shipping increases. The model simulations suggest a significant increase in cloud optical thickness up to about 5-10% on zonal annual average (see Figure 12). Maximum increases in cloud optical thickness up to 10% are simulated above the northern Atlantic and the Pacific Ocean westward of the United States. Cloud optical thickness also increases in the thermal spectrum, maximum changes simulated amount up to 10% in the northern Atlantic. However, these changes are not statistically significant. As expected, ice clouds are not influenced by emissions from shipping: ice water content, ice crystal number concentration and effective radii of ice clouds remain unchanged.

The model results show, that the changes in microphysical properties of low water clouds due to shipping do not affect precipitation: no significant change in the geographical distribution or the amount of precipitation has been found. In contrast, the global annual mean total cloud cover slightly increases by about 0.1 percentage points. Again, this results from changes due to shipping in the regions westward of the United States and Africa as well as above the north-eastern Atlantic. This increase in total cloud cover is similar to the effect of contrails amounting 0.1% (Marquart, 2003).

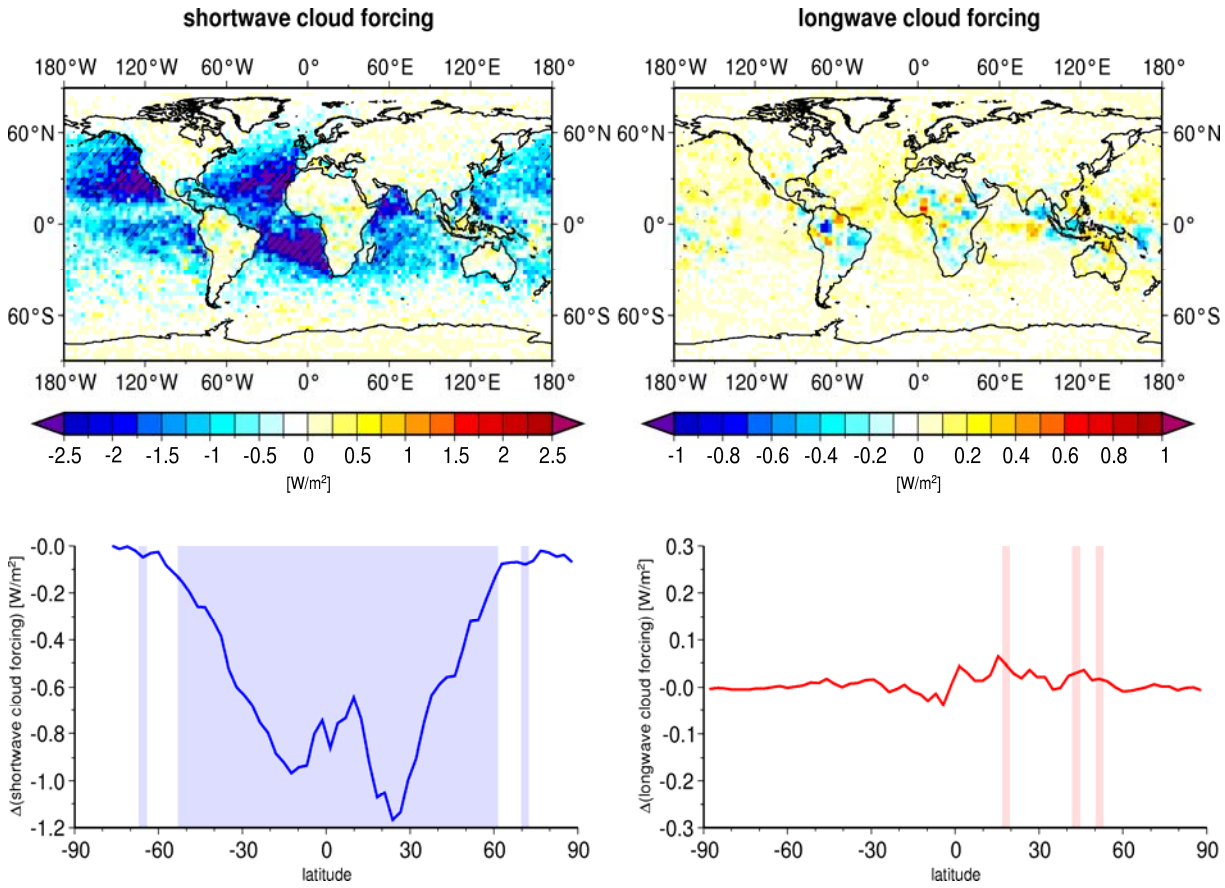

Figure 13: Climatological annual mean (1999-2004) of changes in shortwave (left) and longwave (right) cloud forcing at TOA due to shipping. Upper row shows the geographical distribution, lower row zonal averages. Hatched areas (upper row) and light-red/light-blue shaded areas (lower row) show significant differences.

Overall, the impact of emissions from shipping on clouds results in changes of the Earth's energy budget by altering the cloud forcing at the top of the atmosphere (TOA). Figure 13 shows the climatological annual mean (1999-2004) of changes in solar (shortwave) and thermal (longwave) TOA cloud forcing due to shipping. Changes in shortwave cloud forcing up to –3 to –4 W/m^2 are simulated above the northern Atlantic and the Pacific, and up to –5 W/m^2 westward of Africa. The global annual average of changes in shortwave cloud forcing amount to about –0.6 W/m^2. In contrast, no significant change in longwave cloud forcing due to shipping is simulated by the model. Thus, the change in net cloud forcing amounts to about –0.59 W/m^2 on global annual average.

A first sensitivity experiment with a fuel sulphur content of 0% shows that about 75% of these changes in cloud forcing are caused by sulphur emissions (SO_2 and SO_4). Compared to other model studies focusing on the total anthropogenic effect of aerosols on clouds, the change in cloud forcing due to shipping obtained in this study has to be regarded as high. It should be noted, that there are still many uncertainties in modelling the indirect aerosol effect. Key properties of question are in particular aerosol size-distribution and aerosol activation (Lohmann and Feichter, 2005; Penner et al., 2006).

Impact of Emission from Shipping on Aerosols

Emissions from shipping also impact on the chemical composition of aerosol particles, the aerosol size-distribution and thus aerosol optical thickness and direct aerosol forcing. In addition, these changes impact on the ability of aerosol particles to act as cloud condensation nuclei.

Table 3 Global total burden of aerosol compounds considered in the ECHAM5/MADE study and contribution from shipping.

Compound	Atmospheric Burden [Tg]	Contribution of Shipping [%]
SO_4	1.531 Tg	3.6%
NH_4	0.366 Tg	1.4%
NO_3	0.146 Tg	0.2%
H_2O	17.881 Tg	1.0%
BC	0.119 Tg	0.4%
POM	1.040 Tg	0.1%
Sea Salt	3.588 Tg	n.a.
Mineral Dust	9.042 Tg	n.a.

In the near surface layer above the Atlantic Ocean, ship emissions increase the annual average total dry particle mass concentration in the Aitken mode (< 0.1 μm)from 0.2 μg/m^3 to 0.24 μg/m^3 and in the accumulation mode (> 0.1 μm) from 2.0 μg/m^3 to 2.4 μg/m^3. In both submicrometer modes, the relative contribution of sulphate increases (in the Aitken mode from 51% to 57% and in the accumulation mode from 30% to 37%). This increase is caused particularly by the ships' SO_2 emissions. In the accumulation mode, also the contribution of ammonium (6.2% to 7.7%) and of nitrate (4.5% to 5.1%) increases due to emissions from shipping. Although ships also emit BC and POM, the relative contribution of soot over the Atlantic to particle mass concentration decreases due to the strong increase in the contribution of SO_4, NH_4 and NO_3. On global annual average, shipping contributes about 3.6% to the total sulphate burden. Due to NO_x emissions, also aerosol nitrate increases (0.2%). Because of the increase in SO_4 and NO_3, additional NH_3 can go into the aerosol phase increasing the NH_4 concentration. The relative contribution of NH_4 related to emissions from shipping amounts to 1.4% of the global annual average NH_4 burden. Table 3 gives an overview of all individual aerosol components considered in this study.

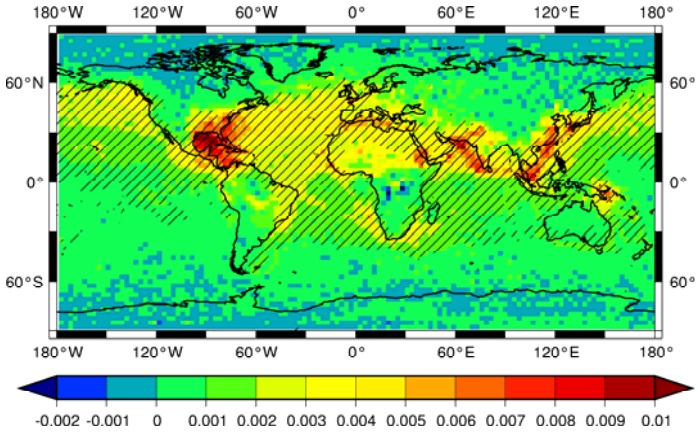

Figure 14: Climatological annual mean (1999-2004) of changes in total aerosol optical thickness at 550 nm due to shipping. Hatched areas show significant differences.

In addition to gaseous emissions, ship engines also release primary particles. Both emissions types affect the aerosol size-distribution. Over the Atlantic, emissions from shipping increase the annual average aerosol number concentration in the Aitken mode from about 500 particles per cm^3 to 970 cm^{-3} and in the accumulation mode from 350 cm^{-3} to 440 cm^{-3}. The increase in Aitken mode particle number concentration is a direct result of the emissions, the increase of accumulation mode particles is a consequence of Aitken particles growing into the size range of the accumulation mode by condensation of sulphuric acid vapour and by coagulation. As a result of the small primary particles emitted by ships (d=0.03 μm), the average dry geometric mean diameter of the Aitken mode decreases from 0.05 μm without ship emissions to 0.04 μm with ship emissions. In contrast, the geometric mean diameter of the accumulation mode is hardly influenced by ship emissions and remains at about 0.09 μm. For a given average particle diameter, the number of aerosol particles that can be activated to cloud droplets is roughly proportional to the accumulation mode number concentration. Thus, the increase in accumulation mode number concentration and the increase of soluble aerosol compounds (sulphate, nitrate, ammonium) leads to an increase in CDNC.

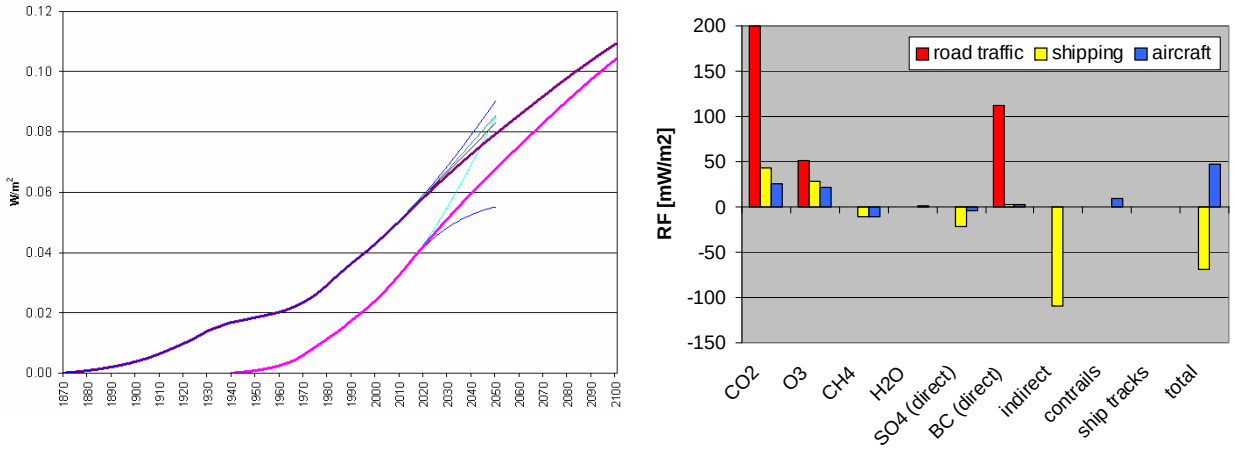

Figure 15: Left: Transient changes in RFs from shipping CO_2 to aviation throughout 2100 (from Eyring et al., 2006b). Right: RFs from transport-related emissions in [mW/m^2] for 2000.

Figure 14 shows the changes in annual average aerosol optical thickness (AOT) at 550 nm due to emissions from shipping. Above the main shipping lanes, AOT increases by about 0.003-0.004 (2-4%), above the Indian Ocean and the Gulf of Mexico AOT increases up to 0.01 (10%). The main contribution is caused by increases in sulphate, nitrate and associated ammonium and, in particular, due to increase in associated aerosol liquid water. Changes in BC and POM contribute only negligible to the changes in total AOT, as the amount emitted by ships is only very small compared to other aerosol sources (see Table 3).

The changes in AOT also impact the radiation fluxes in the atmosphere (direct aerosol effect). Maximum annual average changes in TOA shortwave clearsky fluxes amount to –0.25 W/m^2 in the Gulf of Mexico and the Indian Ocean, about –0.15 W/m^2 above the northern Atlantic and about –0.1 W/m^2 above the Pacific. The global annual average change in TOA shortwave flux due to aerosols from shipping amounts to –0.038 W/m^2. Again, the main contribution (about 75%) is caused by sulphur emissions increasing the aerosol sulphate, ammonium and water content. In contrast to the shortwave flux, no significant change is calculated for the longwave TOA clearsky flux (global annual average +0.002 W/m^2). The net change in TOA clearsky fluxes due to aerosol related emissions from shipping amounts to –0.036 W/m^2.

3.5 Radiative Forcing

The radiative forcing of the surface-troposphere system due to the perturbation in or the introduction of an agent (say, a change in greenhouse gas concentrations) is 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 (IPCC, 2001). A linear climate response model (Lim et al., 2006) is applied to estimate RFs from shipping in 2000 and to compare transient changes in RFs from shipping CO_2 to aviation throughout 2100. Using ship emissions from Eyring et al. (2005a,b) and aviation emissions from IPCC (1999), the predicted RFs from shipping CO_2 are higher until 2050 for all except the Fe1 aviation scenario, which reaches a similar value of 0.084 Wm^{-2} in 2050 (Figure 15, left).

Table 4: RFs from transport-related emissions of CO_2, O_3, CH_4, SO_4 (direct), BC (direct), indirect effect, contrails, ship tracks and total in [mW/m^2]. The given values include SeaKLIM results, but also results from other studies (see footnotes). For uncertainties it is referred to the cited literature.

	CO_2	O_3	CH_4	H_2O	SO_4 (direct)	BC (direct)	indirect	Contrails	Ship tracks	Contrail cirrus	Total
Road Traffic	118[1]	51[2]	-8[1]	~0	-12	64-160[3]	-22[1]	-	-	-	
Shipping	43.2[4]	28.3[4]	-10.9[4]	~0	-22.2[4]	2.5[4]	-110[5]	-	-0.12[6]	-	-69.2
Aircraft	25.3[7]	21.9[7]	-10.4[7]	2[7]	-3.5[7]	2.5[7]	?	10[7]	-	10-80[8]	47.8[7]

[1] Approximate numbers from http://www.pa.op.dlr.de/tac/restricted/presentations/Fuglestvedt_ClimateImpacts_oral_060628.pdf
[2] Niemeyer et al. (2006) [3] Schultz et al. (2004) [4] Eyring et al. (2006b) [5] Capaldo et al. (1999)
[6] Schreier et al. (2006) [7] Sausen et al. (2005) w/o cirrus [8] Stordal et al. (2005)

A summary of the various contributions to the RFs from shipping, aviation and road transport is given in Figure 15 (right) and Table 4. Compared to aviation (~ 22 mW/m^2; Sausen et al., 2005) tropospheric ozone forcing from shipping is of similar magnitude in 2000, despite the much higher NO_x emissions from ships (Eyring et al., 2005a). This can be understood because peak changes in ozone due to shipping occur close to the surface, whereas changes in ozone due to aviation peak in the upper troposphere (Grewe et al., 2002). The net radiative forcing is most sensitive to NO_x emissions at altitudes of about 8-12 km because of longer NO_x and O_3 lifetimes, and colder temperatures compared to the surface (Lacis et al., 1990; Brasseur et al., 1998). Ship NO_x reduces the CH_4 lifetime by 0.13 years in 2000 (Eyring et al., 2006a), introducing a negative radiative forcing that partly counteracts the positive ozone RF.

3.6 Outlook

3.6.1 Open Science Questions

With the work summarised in the previous sections and in the executive summary, SeaKLIM gave answers to important questions regarding the impact of ship emissions on chemistry and climate. Nevertheless, further work is needed to reach a complete synthesis of the results. In the remaining time of SeaKLIM a more thorough comparison of the impacts of shipping to impacts from aviation and road traffic as well as to other anthropogenic and natural emissions is planned and some of the processes need to be further investigated.

It has been shown that plume processes are important and the developed method is suitable to parameterise subgrid processes. However, so far the results are based on one given background environment.

- The step from a case study to a suitable parameterisation of subgrid processes in global models has to be made for both gaseous as well as particulate emissions. To reach this, more measurements and model studies are needed to understand plume processes.
- A comparison of the box model results with airborne measurements is planned to analyse data of exhaust plumes from large container ships. A model approach with multiple ships could be evaluated by a comparison of ship emission inventories and satellite data of NO_2.

The comparison of global models with satellite measurements of tropospheric NO_2 columns is currently limited by the coarse spatial resolution of the models, the uncertainty in the measurements and the difficulty to separate ship emissions from other even stronger emission sources. Unambiguous detection of NO_2 ship emissions in satellite data is currently only available for the region of the Red Sea and the Indian Ocean, where shipping routes are close to the costal area.

- Reduction in measurement uncertainties through the use of long-term averages and data from more instruments (e.g. OMI and GOME-2) combined with better constraints on land-based sources and higher spatial resolution in the models should facilitate such a comparison in the future.

Uncertainties in the simulated ozone contributions from ships for different model approaches are found to be significantly smaller than estimated uncertainties stemming from the ship emission inventory. This reflects that the net ozone change from ship emissions under relatively clean conditions in global models is rather similar and suggests that the atmospheric models used here are suitable tools to study these effects. Current uncertainties of global modelling studies on the effects of emissions from shipping on aerosols and clouds are expected to be much higher than in the case of the ozone change studies. In particular the indirect aerosol effect depends crucially on simulated key properties such as the aerosol size-distribution and the activation of aerosol particles in clouds. Minor changes of these properties can have a significant impact on the simulated indirect effect. Furthermore, changes in cloud properties such as cloud liquid water content, cloud cover and precipitation formation due to ship emissions impact on atmospheric chemistry via wet deposition and changes in scavenging efficiency. Changes in atmospheric chemistry such as ozone or OH concentrations result in a feedback on aerosols e.g. via modified oxidation rates of SO_2. For the global modelling aspects the major future challenges lie in:

- The parameterisation of physical and chemical subgrid processes taking place during the dilution time of the ship plume into the scale of a global model grid box. This applies to both, gaseous and particulate emissions.
- Further model development in particular on the representation of aerosol size-distribution, aerosol activation, aerosol-cloud interaction and extension of feedback mechanisms.
- Additional measurement data e.g. of the size-distribution and composition of particles emitted by ships are required to reduce current uncertainties in global model studies.

Ship tracks are only the obvious stage of the indirect aerosol effect. An analysis of the global distribution of ship tracks and an estimation of their influence on the radiation budget was done via data from the instrument AATSR on board the European satellite ENVISAT. However, the polar orbit of ENVISAT limits the knowledge about the development of ship tracks over time. There is also a high discrepancy between the measured radiative forcing of ship tracks for 2004 and the estimated radiative forcing due to the total indirect aerosol effect calculated by model simulations. Concerning ship tracks, the following major issues arise for future work:

- Further development of the ship-track-mask algorithm is needed to improve its detection efficiency for use with a larger amount of AATSR-data or even on instruments with higher coverage like MODIS on Terra and Aqua.
- An investigation via geostationary satellites like Meteosat-8 offers the opportunity to analyse the temporal and spatial development of ship tracks for a better estimate of the influence on marine boundary layer clouds. In addition, the possible temporal influence on coastal areas and higher level clouds could be investigated.
- Satellite data of marine boundary layer clouds offer the possibility to compare the cloud optical properties of different areas with low vessel traffic density with areas of high vessel traffic density or high ship track density. If there is a high influence from ship emissions, a clear difference should be observable. This can be used to estimate the radiative effect.

The SeaKLIM group will further work on the open science questions summarised above, and therewith continuously contributing to reach the scientific and programmatic goals of both host institutes.

3.6.2 Future Activities and Projects

Two dissertations will be finished in the remaining time of SeaKLIM and a habilitation is planned:

- Dissertation by Mathias Schreier: ‘Remote Sensing of Ship Tracks Using Satellite Data’.
- Dissertation by Klaus Franke: ‘Parameterisation of Ship Plume Processes in Global Models.’
- Dr. Veronika Eyring plans a habilitation on the topic ‘Assessment of the impact of ship emissions on the atmosphere and climate’ in the first half of 2007.

In addition several projects related to the SeaKLIM topic will be kicked off in the near future:

- The ‘European Assessment of Transport Impacts on Climate Change and Ozone Depletion: 2009’ will provide assessments of the emissions of single transport sectors, viz. of aviation, shipping, and road and rail traffic and an assessment on metrics that describe, quantify, and compare in a fair way the effects of the transport emissions in the atmosphere. Within ATTICA, Dr. Veronika Eyring will co-ordinate and lead the ship emission assessment together with Prof. Dr. Ivar Isaksen (University of Oslo, Norway).
- Within BIOCLEAN (‘Reducing the emissions of gaseous and particulate emissions from large diesel engines for navigation and stationary application through alternative fuels’) measurements at the engine test beds as well as global modelling studies are planned to quantify impacts on chemistry and climate for different alternative fuels.
- In addition the SeaKLIM group plans to apply for a two year extension (SeaKLIM Phase II: 1 January 2007 to 31 December 2008). In case of a positive evaluation through DLR on 8 September 2006, the proposal will be submitted to the Helmholtz Society by the end of September 2006. The proposal will be evaluated by the Helmholtz Society in November 2006.

4 SeaKLIM Publications

4.1 Peer-Reviewed[1]

Eyring, V., H.W. Köhler, J. van Aardenne, and **A. Lauer:** Emissions from International Shipping: 1. The last 50 Years. *J. Geophys. Res*., 110, (10.1029/2004JD005619), 2005a.

Eyring, V., H. W. Köhler, **A. Lauer,** and B. Lemper: Emissions From International Shipping: 2. Impact of Future Technologies on Scenarios Until 2050. *J. Geophys. Res*., 110, (10.1029/2004JD005620), 2005b.

Kinne, S., M. Schulz, C. Textor, S. Guibert, Y. Balkanski, S. E. Bauer, T. Berntsen, T. F. Berglen, O. Boucher, M. Chin, W. Collins, F. Dentener, T. Diehl, R. Easter, J. Feichter, D. Fillmore, S. Ghan, P. Ginoux, S. Gong, A. Grini, J. Hendricks, M. Herzog, L. Horowitz, I. Isaksen, T. Iversen, A. Kirkevåg, S. Kloster, D. Koch, J. E. Kristjansson, M. Krol, **A. Lauer**, J. F. Lamarque, G. Lesins, X. Liu, U. Lohmann, V. Montanaro, G. Myhre, J. Penner, G. Pitari, S. Reddy, O. Seland, P. Stier, T. Takemura, and X. Tie: An AeroCom initial assessment - optical properties in aerosol component modules of global models, *Atmos. Chem. Phys.*, 6, 1815-1834, 2006.

Lauer, A., J. Hendricks, I. Ackermann, B. Schell, H. Hass, and S. Metzger: Simulating aerosol microphysics with the ECHAM/MADE GCM - Part I: Model description and comparison with observations, *Atmos. Chem. Phys*., 5, 3251-3276, SRef-ID: 1680-7324/acp/2005-5-3251, 2005.

Richter, A., **V. Eyring**, J. P. Burrows, **H. Bovensmann, A. Lauer**, B. Sierk, and P. J. Crutzen, Satellite measurements of NO_2 from international shipping emissions, *Geophys. Res. Lett.*, 31, L23110, doi:10.1029/2004GL020822, 2004.

Schwarz, J. P., R.S. Gao, D.W. Fahey, D.S. Thomson, L.A. Watts, J.C. Wilson, J.M. Reeves, D.G. Baumgardner, G.L. Kok, S.H. Chung, M. Schulz, J. Hendricks, **A. Lauer**, B. Kärcher, J.G. Slowik, K.H. Rosenlof, T.L. Thompson, A.O. Langford, M. Loewenstein, and K.C. Aikin: Single-particle measurements of midlatitude black carbon and lightscattering aerosols from the boundary layer to the lower stratosphere, *J. Geophys. Res.*, accepted, 2006.

Textor, C., M. Schulz, S. Guibert, S. Kinne, Y. Balkanski, S. Bauer, T. Berntsen, T. Berglen, O. Boucher, M. Chin, F. Dentener, T. Diehl, R. Easter, H. Feichter, D. Fillmore, S. Ghan, P. Ginoux, S. Gong, A. Grini, J. Hendricks, L. Horowitz, P. Huang, I. Isaksen, T. Iversen, S. Kloster, D. Koch, A. Kirkevåg, J. E. Kristjansson, M. Krol, **A. Lauer**, J. F. Lamarque, X. Liu, V. Montanaro, G. Myhre, J. Penner, G. Pitari, S. Reddy, Ø. Seland, P. Stier, T. Takemura, and X. Tie: Analysis and quantification of the diversities of aerosol life cycles within AeroCom, *Atmos. Chem. Phys.*, 6, 1777-1813, 2006.

4.2 Submitted

Eyring, V., D.S. Stevenson, **A. Lauer**, F.J. Dentener, T. Butler, W.J. Collins, K. Ellingsen, M. Gauss, D.A. Hauglustaine, I.S.A. Isaksen, M.G. Lawrence, A. Richter, J.M. Rodriguez, M. Sanderson, S.E. Strahan, K. Sudo, S. Szopa, T.P.C. van Noije, and O. Wild: Multi-model simulations of the impact of international shipping on atmospheric chemistry and climate in 2000 and 2030, *Atmos. Chem. Phys. Discuss.*, submitted, 2006a.

Lauer, A., and J. Hendricks: Simulating aerosol microphysics with the ECHAM/MADE GCM - Part II: Results from a first multi-annual integration, *Atmos. Chem. Phys. Discuss.*, submitted, 2006.

Schreier, M., A. A. Kokhanovsky, **V. Eyring**, L. Bugliaro, H. Mannstein, B. Mayer, H. Bovensmann, and J. P. Burrows: Impact of ship emissions on the microphysical, optical and radiative properties of marine stratus: a case study, *Atmos. Chem. Phys. Discuss.*, 6, 1023-1071, 2006a.

4.3 In Preparation

Eyring, V., D.S. Lee, L. Lim, and R. Sausen: A comparison of shipping and aviation to CO_2 forcing and climate response until 2100 using a simple climate model, *Climatic Change,* in preparation, 2006b.

Franke, K., V. Eyring, R. Sander, J. Hendricks, **A. Lauer**, and R. Sausen: Ozone produced in Ship Plumes: A comparison of small and large scale models leading to Effective Emission Indices, J. *Geophys. Res.*, in preparation, 2006.

Schreier, M., H. Mannstein, and **V. Eyring**: Global Distribution of Ship Tracks from 1-year of AATSR-Data, *J. Geophys. Res.*, in preparation, 2006b.

[1] Authors from the SeaKLIM are written in bold

4.4 Invited Talks

Eyring, V.: Impact of Ship Emissions on Climate and Compliance with Future Emission Regulations through Technological Improvements, Marine Propulsion Conference 2004, Amsterdam, The Netherlands, 28-29 April, 2004.

Eyring, V.: Impact of traffic emissions on climate and atmospheric chemistry, University of Toronto, Canada, 30 July, 2004.

Eyring, V.: Impact of traffic emissions on climate and atmospheric chemistry, Canadian Centre for Climate Modelling and Analysis, Victoria, Canada, 11 August, 2004.

Eyring, V.: Impact of ship emissions on climate and atmospheric chemistry, NOAA Chemical Sciences Division Seminar, Boulder, Colorado, USA, 14 October, 2005.

Eyring V., and H.W. Köhler: Past, Present-Day and Forecasting Inventories for International Shipping and Potential Impact on Climate: Co-operation between Industry and Academia, Marine & Power Emissions Conference 2005, London, UK, 29 November, 2005.

4.5 Proceedings etc.

Bovensmann, H., V. Eyring, K. Franke, A. Lauer, M. Schreier, A. Richter, and J. P. Burrows: Emissions of international shipping as seen by satellites, Proceedings of the ESA Atmospheric Science Conference, Frascati, Italy, 8-12 May, 2006.

Eyring V., V. Grewe, R. Sausen, A. Petzold, H. Schlager, and U. Schumann: Impact of ship emissions on climate and compliance with future emission regulations through technological improvements, Proceedings of the *Marine Propulsion Conference*, Amsterdam, The Netherlands, 28-29 April, 2004.

Eyring V., and H.W. Köhler: Past, Present-Day and Forecasting Inventories for International Shipping and Potential Impact on Climate: Co-operation between Industry and Academia, Proceedings of the Marine & Power Emissions Conference 2005, London, UK, 153-161, 29 November, 2005.

Eyring, V., and H.W. Köhler: The impact of ship emissions on climate, The Motor Ship, p.32-34, April, 2005.

Lauer, A., and J. Hendricks: The role of aerosol dynamics in the global atmospheric aerosol budget: Simulations with ECHAM4/MADE. Proceedings of the European Aerosol Conference, Budapest, HU, 6-10 September 2004, *Journal of Aerosol Science*, 1197-1198, 2004.

Lauer, A.: Untersuchung von Größenverteilung und Zusammensetzung des troposphärischen Aerosols mit einem globalen Zirkulationsmodell, DLR-Forschungsbericht 2005-17, DLR Oberpfaffenhofen, Wessling, Germany, ISSN 1434-8454, 2005.

4.6 Other Talks and Poster Presentation

Bovensmann H., V. Eyring, K. Franke, A. Lauer, M. Schreier, A. Richter, and J.P. Burrow: Emissions of international shipping as seen by satellites (Talk), 31st International Symposium on Remote Sensing of the Environment Saint Petersburg, Russia, 20-24 June, 2005.

Eyring, V., H. Bovensmann, and A. Richter: Einfluss von Schiffsemissionen auf Atmosphäre und Klima (Invited talk presented by H. Bovensmann), UBA / GAUSS Workshop Schadstoffemissionen großer Schiffsdieselmotoren, Bremen, 12 May, 2004.

Eyring, V.: Verkehrsemissionen und Klima, Physikalisches Kolloquium der Universität Bremen, 3 June, 2004.

Eyring, V.: Einfluss von Schiffsemissionen auf Atmosphäre und Klima: Ergebnisse der Nachwuchsgruppe SeaKLIM, Institutsseminar des Instituts für Physik der Atmoshphäre (Talk), DLR Oberpfaffenhofen, 4 July, 2005.

Eyring, V., Köhler, H.W., Aardenne, J. van, **Lauer, A.**, Lemper, B.: Emissions From International Shipping Over the Last 50 Years and Future Scenarios Until 2050. 1st international conference on Harbours and Air Quality (Talk), Genova, I, 15-17 June, 2005.

Eyring, V., D.S. Stevenson, **A. Lauer**, F.J. Dentener, T. Butler, W.J. Collins, K. Ellingsen, M. Gauss, D.A. Hauglustaine, I.S.A. Isaksen, M.G. Lawrence, A. Richter, J.M. Rodriguez, M. Sanderson, S.E. Strahan, K. Sudo, S. Szopa, T.P.C. van Noije, and O. Wild: Multi-model simulations of the impact of international shipping on atmospheric chemistry and climate in 2000 and 2030 (Poster), EGU, Wien, Austria, 2-7 April, 2006.

Eyring, V., D.S. Stevenson, **A. Lauer**, F.J. Dentener, T. Butler, W.J. Collins, K. Ellingsen, M. Gauss, D.A. Hauglustaine, I.S.A. Isaksen, M.G. Lawrence, A. Richter, J.M. Rodriguez, M. Sanderson, S.E. Strahan, K. Sudo, S. Szopa, T.P.C. van Noije, and O. Wild: Multi-model simulations of the impact of international shipping on atmospheric chemistry and climate in 2000 and 2030 (Talk), International Conference on Transport, Atmosphere and Climate, Oxford, UK, 26-29 June, 2006.

Franke, K, V. Eyring, H. Bovensmann, and J.P. Burrows: Modellierung der chemischen Entwicklung von Schiffsemissionen (Poster), 69. Jahrestagung der Deutschen Physikalischen Gesellschaft (DPG), Berlin, 4-9 March, 2005.

Franke, K., **V. Eyring**, R. Sander, J. Hendricks, **A. Lauer**, **H. Bovensmann**, and R. Sausen: Ship emissions in the marine boundary layer: Ozone production and effective emissions (Poster), International Conference on Transport, Atmosphere and Climate, Oxford, UK, 26-29 June, 2006.

Lauer, A.: Simulation des troposphärischen Aerosols mit ECHAM4/MADE unter besonderer Berücksichtigung der Russemissionen des Straßenverkehrs, Gemeinsames Seminar des Instituts für Meteorologie, Fachbereich Geowissenschaften, FU Berlin, November, 2005.

Lauer, A.: Simulation des troposphärischen Aerosols mit ECHAM4/MADE unter besonderer Berücksichtigung der Russemissionen des Straßenverkehrs (Talk), Institutsseminar des Instituts für Physik der Atmosphäre, DLR Oberpfaffenhofen, 19 January, 2004.

Lauer, A., and J. Hendricks: The global model system ECHAM/MADE (Poster), 4th AeroCom workshop, Oslo, Norway, 15-17 June, 2005.

Sausen R., and **Eyring, V.**: An introduction to QUANTIFY (Invited talk presented by V. Eyring), Aeronautics Days 2006, Sustainable Solutions for New Horizons, Vienna, Austria, 19-21 June, 2006.

Schreier, M.: Ship Tracks – Cloud modifications by ship emissions (Talk), Seminar on Physics and Chemistry of the Atmosphere, Institute of Envrionmental Physics, Bremen, Germany, 9 June, 2006.

Schreier, M., H. Mannstein, **V. Eyring,** and **H. Bovensmann**: Global Distribution of ship tracks from one year of AATSR data. (Talk), International Conference on Transport, Atmosphere and Climate, Oxford, UK, 26-29 June, 2006.

Schreier, M., V. Eyring, and **H. Bovensmann**: Modifications of cloud properties due to ship emissions – quantitative analysis of changes in solar irradiance and backscattered light (Poster), EGU, Wien, Austria, 25-29 April, 2006.

Schreier, M., **H. Bovensmann**, **V. Eyring**, A. Kokhanovsky, and J.P. Burrows: Cloud-modifications by ship emissions derived from remote sensing data (Poster), EGU, Vienna, Austria, 25-29 April, 2005.