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1. Summary

Regulating transport emissions requires comprehensive knowledge of the present day fuel consumption and emissions, their potential future evolution, and mitigation options. With emissions of international shipping taking place both in coastal areas and open oceans, their impact on air quality and climate can be significant. Large uncertainties about the emission budget and atmospheric impacts from international shipping characterised the situation at the time SeaKLIM started. A variety of important results have been achieved by the group. For example, SeaKLIM showed that shipping emitted around 800 Tg carbon dioxide (CO_2) and contributed around 2.7% to all anthropogenic CO_2 emissions in 2000 (1 Tg = 10^{12} g). For comparison, aviation and road transport contributed around 2.2% and 14%, respectively. Other comparisons suggest that shipping accounted for around 15% of all global anthropogenic nitrogen oxides (NO_x) emissions and for around 8% of sulphur dioxide (SO_2) emissions in 2000. These relatively high contributions result because most marine engines operate at high temperatures and pressures without effective NO_x emission reduction technologies and because of the high average sulphur content (2.4%-2.7%) of marine fuels. SeaKLIM also showed that if anthropogenic emissions from the land surface are reduced, then the poorly regulated ship emissions could take on an even greater importance in the future. To address questions on the geographical distribution of ship emissions, SeaKLIM has developed the first global bottom-up ship emission algorithm where emissions are calculated from actual ship movements. This algorithm is now regularly used in follow-up projects to provide policy-relevant emission calculations for a variety of different allocation criteria.

One of the major findings in terms of climate impacts was that the potential of particle emissions and their precursors from shipping to modify the microphysical and optical properties of clouds (the so-called “indirect aerosol effect”) is significant and more important than previously recognised. Of all anthropogenic sources, ship-stack effluents provide the clearest demonstration of the indirect aerosol effect. Curves of larger reflectance in cloud fields were observed in satellite imagery and identified as ship tracks. Evidence for the importance of ship emissions on atmospheric composition was found in satellite observations by SCIAMACHY that clearly showed 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 have been 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. These studies have been complemented by studies to address the question of near-field mixing of the emissions. It was shown that treatment of these processes is necessary if global models are not to overestimate the impact of ship emissions on ozone. SeaKLIM developed a module that parameterizes gas-phase chemistry in ship plumes and successfully included it in the global atmospheric chemistry model that is run by DLR. At a local and regional-scale, it was shown that ocean-going ships impact human health through the formation and transport of ground-level ozone, sulphur emissions and particulate matter. In harbour cities, ship emissions are in many cases a dominant source of urban air pollution. Furthermore, emissions of ozone precursors, particles and sulphur from ships may be transported over several hundreds of kilometres, and thus can contribute to air quality problems on land, even if they are emitted at sea.

Overall, the SeaKLIM group carried out an extensive research programme on the impact of ship emissions on atmospheric composition, climate, and human health and regularly reported on these results at the Marine Environment Protection Committee (MEPC) meetings of the International Maritime Organization (IMO). The SeaKLIM results contributed significantly to the increasing attention of environmental and health effects caused by shipping. Shipping has now been recognized as a growing problem and an intense dialogue on how to best reduce emissions from ships has started between policymakers, industry, and scientists.

2. Work Report

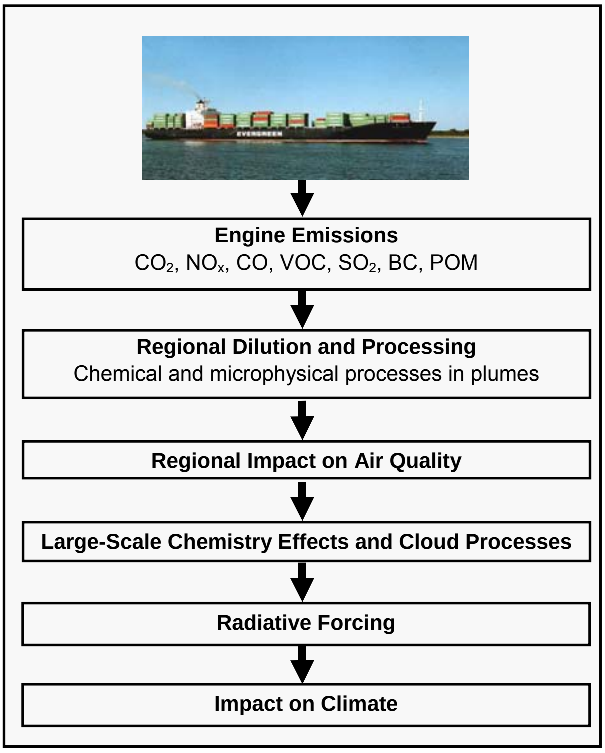
a) State-of-the-art when SeaKLIM started

At the time when the SeaKLIM group was established, large uncertainties existed in the calculation of ship emissions and their impacts on atmospheric composition and climate. A number of atmospheric model studies quantifying the impact of ship emissions on the chemical composition of the atmosphere and on climate were available. 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 method available that could be used to parameterize ship plume chemistry in global models.

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 for a specific region [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 the 'Radiative Forcing' (RF)[1] from ship tracks were unknown and detection of enhanced concentrations of trace gases along main shipping routes by satellite measurements were unknown. The goal of the SeaKLIM group was to quantify the impact of gaseous and particulate emissions from international shipping on atmospheric composition and on climate.

b) Progress of Work

The chain of impact from ship emissions on atmospheric composition and climate is complex and is schematically illustrated on the right. To study the relevant processes from the exhaust of vessels to climate change, a variety of studies using models on different scales combined with observations were applied in SeaKLIM in different work packages (WP). Table 1 gives an overview of the WP in SeaKLIM Phase I (2004-2006) and II (2007-2010). Some of the Phase I WP continued into Phase II. The key milestones of the project have all been reached. Means of verification for the milestones in each WP are given in the last column of Table 1 mostly in the form of references to peer-reviewed SeaKLIM publications (see reference list in Section 6). The work plan has not been changed except that two subtasks of WP 1 of Phase II, namely 'Microphysical Box Model Development' and 'Box Model Studies on Microphysical Changes in Ship Plumes', have been replaced with work in a different and newly emerging area. The reason for this change is briefly stated below.



The *Lauer et al.* [2007] SeaKLIM study indicated that the cooling due to altered clouds far outweighs the warming effects from greenhouse gases such as CO_2 or ozone (O_3) from shipping, overall causing a negative present-day radiative forcing. In collaboration with US scientists, additional SeaKLIM work demonstrated that PM emissions from ocean-going ships could cause premature mortalities from cardiopulmonary disease and lung cancer [*Corbett et al.*, 2007]. Current efforts to reduce sulphur and other pollutants from shipping may modify this. Assessing new policy scenarios was therefore one of the major foci in WP 1 Phase II. In our new work we assessed the impact of a 2012 "*No Control*" scenario with three emissions control scenarios on aerosol burdens and the Earth's radiation budget [*Lauer et al.*, 2009] and a related paper evaluates potential health benefits from reducing ship emissions [*Winebrake et al.*, 2009].

[1]RF in units of W/m^2 is a common metric to quantify climate impacts from different sources, since there is an approximately linear relationship between global mean radiative forcing and change in global mean surface temperature. A positive RF implies warming whereas negative RF implies cooling to present-day climate. RF refers to the change in the earth-atmosphere energy balance since the pre-industrial period. If the atmosphere is subject to a positive radiative forcing from, for example, the addition of a greenhouse gas such as CO_2, the atmosphere attempts to re-establish a radiative equilibrium, resulting in a warming of the atmosphere.

The financial plan was not changed, except that SeaKLIM finished only in June 2010 rather than in March 2009. This extension has been requested because (a) at the time when the SeaKLIM group was approved shortly before its official start in January 2004, it took until October to fill all positions with appropriate candidates, and (b) the Phd students and Postdocs who left the group during the five years to continue their work in other research institutions or in the industry had to be replaced, which also caused a delay. This change did not result in any additional costs.

Table 1: Work packages and means of verification for milestones.

SeaKLIM PHASE I (2004-2006) WPs		
WP	Title of WP	Means of verification for milestones in this WP
1	Coordination	SeaKLIM annual reports
2	Model development	*Lauer et al.* [2005]; *Franke et al*. [2008]
3	Ship emission inventories	*Eyring et al*. [2005a,b]; *Paxian et al.* [2010]
4	Remote Sensing of ship induced changes in chemical species and ship tracks	*Richter et al.* [2004]; *Schreier et al.* [2006]
5	Impact of ship emissions on atmospheric composition	*Eyring et al.* [2007a]
6	Numerical Modelling of the Ship-induced Indirect Aerosol Effect	*Lauer et al.* [2007]
7	Ship-induced radiative forcing	*Eyring et al.* [2007a], *Lauer et al*. [2007]
8	Prognostic studies	*Eyring et al*. [2007a]
9	Comparison to other anthropogenic and natural emissions	*Eyring et al.* [2005a]
10	Publications	In total, the SeaKLIM group members achieved 146 publications between 2004 and 2010 (see Section 3)
SeaKLIM PHASE II (2007-2010) WPs		
WP	Title of WP	Means of verification for milestones in this WP
1	Numerical Modelling of the Ship-induced Indirect Aerosol Effect	*Corbett et al*. [2007]; *Lauer et al*. [2009]; *Winebrake et al.* [2009]
2	Satellite Study of the Ship-induced Indirect Aerosol Effect	*Schreier* [2007] *Schreier et al.* [2007], *Schreier et al.* [2009]
3	Effective Emissions in Global Models	*Franke* [2008]; *Franke et al.* [2009]; *Dall'Amico and Jöckel*, in prep. [2010]
4	Satellite Simulator for Global Model Evaluation with ENVISAT Data	*Khlystova et al*., in prep. [2010]
5	Synthesis of the Results	*Eyring* [2008]; *Eyring et al*. [2010a]
6	Coordination	SeaKLIM annual reports

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[2]The EMAC model is a numerical chemistry and climate simulation system that includes sub-models describing tropospheric and middle atmosphere processes and their interaction with oceans, land and human influences [*Jöckel et al*., 2006]. It uses the first version of the Modular Earth Submodel System (MESSy1) to link multi-institutional computer codes. The core atmospheric model is the 5th generation European Centre Hamburg general circulation model (ECHAM5, *Roeckner et al*. [2006]).

[3]The Dobson Unit (DU) is the most common unit for measuring ozone concentration. 1 DU is the number of molecules of ozone that would be required to create a layer of pure ozone 0.01 millimeters thick at a temperature of 0 degrees Celsius and a pressure of 1 atmosphere (the air pressure at the surface of the Earth).

[4]The aerosol dynamics module MADE [*Lauer et al.*, 2005] represents the aerosol size-distribution by three log-normally distributed modes with constant standard deviation. Aerosol components considered are sulphate (SO_4), ammonium (NH_4), nitrate (NO_3), black carbon (BC), particulate organic matter (POM), sea salt, mineral dust and aerosol liquid water.

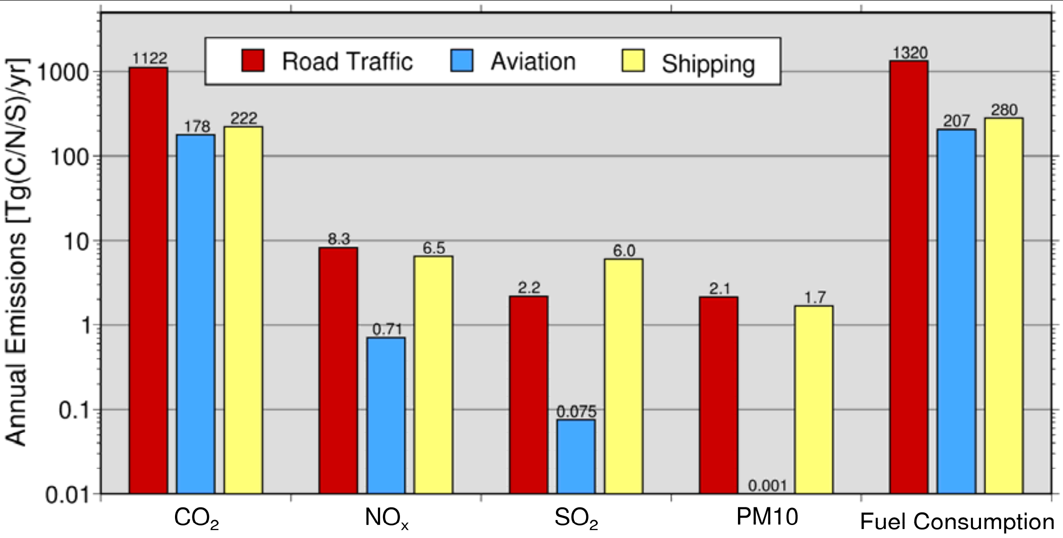

Figure 1: Transport-related annual emissions of CO_2 in Tg (C), NO_x in Tg (N), SO_2 in Tg (S) and PM_{10} in Tg and the fuel consumption in Mt estimated for the year 2000. From *Eyring et al.* [2010a].

c) Summary of Results

A variety of important results have been achieved by the SeaKLIM group, which are briefly summarized below. More detailed information can be found in the cited literature.

Ship emission calculations. The SeaKLIM work showed that emissions of exhaust gases and particles from seagoing ships contribute significantly to the total emissions from the transportation sector [*Eyring et al.*, 2005a], thereby affecting atmospheric composition, climate as well as regional air quality and human health [e.g., *Eyring et al.*, 2010a]. Key compounds emitted are CO_2, NO_x, SO_2, carbon monoxide (CO), volatile organic compounds (VOC), black carbon (BC) and particulate organic matter (POM). Shipping emitted around 800 Tg CO_2 and contributed around 2.7% to all anthropogenic CO_2 emissions in 2000 (1 Tg = 10^{12} g), see Figure 1. For comparison, aviation and road transport contributed around 2.2% and 14%, respectively. Other comparisons suggest that shipping accounted for around 15% of all global anthropogenic nitrogen oxides (NO_x) emissions and for around 8% of sulfur dioxide (SO_2) emissions in 2000. The relatively high contribution results because most marine engines operate at high temperatures and pressures without effective NO_x emission reduction technologies and because of the high average sulfur content (2.4%-2.7%) of marine fuels. *Eyring et al.* [2005a] also showed that over the past decades, the world merchant fleet, fuel consumption and emissions from international shipping have substantially increased. The results suggest a fuel consumption increase from 64.5 million metric tons (Mt) in the year 1950 to 280 Mt in 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. Emission scenario calculations up to the year 2050 indicate 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 [*Eyring et al.*, 2005b]. Future scenarios for geographically resolved ship emission inventories were calculated with the newly developed SeaKLIM bottom-up algorithm [*Paxian et al.*, 2010]. With the expected Arctic sea ice decline, the algorithm projected that the fuel consumption on Arctic polar routes could increase by factors of up to 9 and 13 until 2050 on the Northeast and Northwest Passage, respectively. The SeaKLIM bottom-up algorithm has also been used to produce policy-relevant information on market based instruments, in particular to study how a global maritime emissions trading system could impact the shipping sector as well as individual countries or regions [*Faber et al*., 2009; 2010]. These calculations revealed for example a significant share of global CO_2 ship emissions on voyages to and from Europe.

Regional Dilution and Processing. The majority of emissions from shipping are injected into the atmosphere in form of coherent plumes, often in relatively pristine parts of the atmosphere. To assess the impact of shipping on the atmospheric composition with the help of global models, the emission totals are distributed over the globe with spatial proxies of global ship traffic and are instantaneously spread onto large inventory grid boxes (e.g., 1° longitude x 1° degree latitude), without accounting for dispersion, transformation and loss processes on the sub-grid scale. It is recognised now that subgrid-scale processes should be accounted for in global models with a resolution of several hundred kilometres because of nonlinearities in atmospheric processes. To study plume processes, a box model was developed within SeaKLIM. The box model studies with emission data from a large container ship confirmed that large scale models overestimate the ship-induced ozone production if emissions are instantaneously diluted into large grid-boxes [*Franke et al*., 2008]. 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. In the second phase of SeaKLIM one major focus therefore was to develop a parameterization that accounts for subgrid scale processes in global models. A submodel (PLUMEGAS) for the ECHAM/MESSy Atmospheric Chemistry (EMAC)[2] model was developed, that parameterises gas-phase chemistry in exhaust-gas plumes and the effect of PLUMEGAS on simplified tracers in global simulations with EMAC was assessed [*Dall'Amico and Jöckel*, 2010].

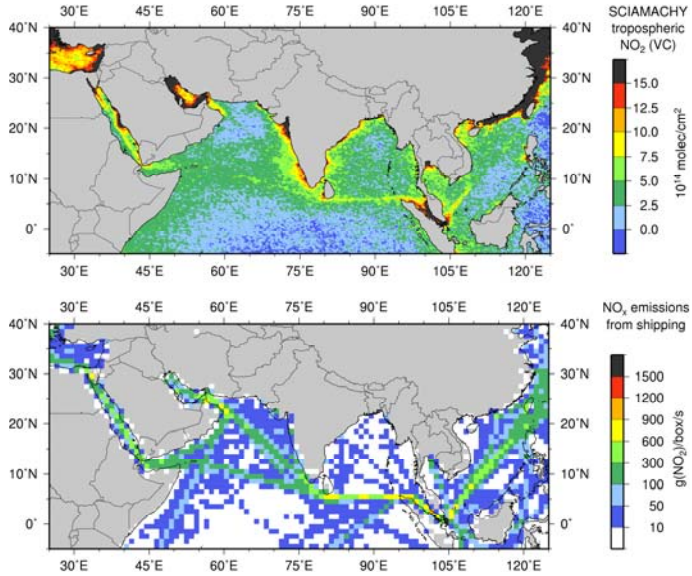

Figure 2. NO_x signatures of shipping in the Red Sea and Indian Ocean. Upper panel: Tropospheric NO_2 columns derived from SCIAMACHY data from August 2002 to April 2004. Lower panel: Estimated distribution of NO_x emissions by shipping in the same region. From *Richter et*

Large-scale Effects of Ship Emissions on Atmospheric Composition. 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 (*Richter et al.* [2004], see also Figure 2). The global impact of shipping on chemistry as well as associated uncertainties were 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 were found over the Atlantic and even stronger over the Indian Ocean (1 DU[3] in 2000 and up to 1.8 DU in 2030). If all other emissions vary according to the IPCC SRES A2 scenario, shipping would contribute 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 [*Eyring et al.*, 2007a]. It was demonstrated that satellite data of tropospheric NO_2 is able to independently document the increase in ship emissions for example in the Indian Ocean [*Franke et al.*, 2009].

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 could be found within the ship tracks (*Schreier et al*. [2006], see Figure 3). A global distribution of ship tracks derived from one year of AATSR data showed high spatial and temporal variability with highest occurrence of ship tracks westward of North America and the southwest coast of Africa [*Schreier et al.*, 2007]. Simulations with the global model system EMAC/MADE[4] also showed that emissions from shipping significantly increase the cloud droplet number concentration of low maritime water clouds [*Lauer et al.*, 2007]. Whereas the cloud liquid water content remained nearly unchanged, effective radii of cloud droplets decreased, 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 increased by 8-10%, above the other major shipping routes by 2-4%.

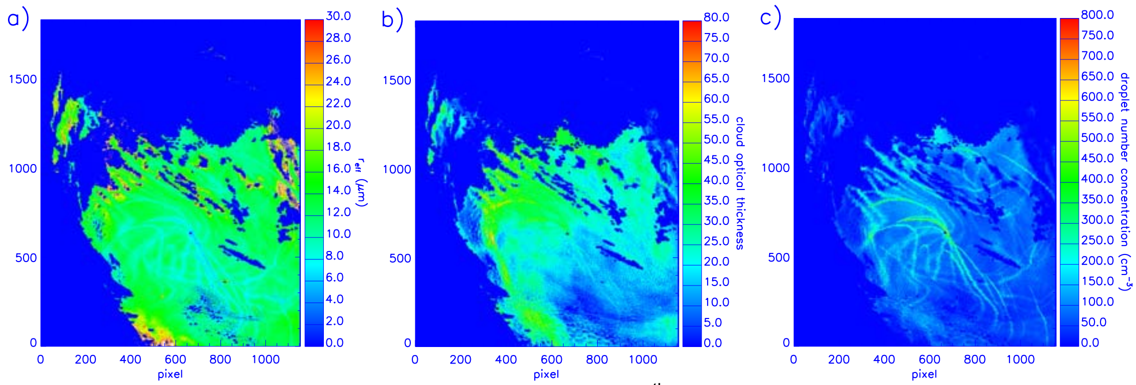

Figure 3. Cloud properties from a MODIS scene from 10th February 2003 on the west coast of North America. a) effective radius, b) cloud optical thickness, c) droplet number concentration. From *Schreier et al.* [2006].

Impacts on human health. A study led by scientists from the US in collaboration with the SeaKLIM group indicated that shipping-related PM emissions were responsible for around 60,000 cardiopulmonary and lung cancer deaths annually, with most deaths occurring near coastlines in Europe, East Asia, and South Asia in 2000 [*Corbett et al.*, 2007]. This number was bounded by a range of 20,000 to 104,000 premature deaths when considering the uncertainties due to emission inventories and models used in this study. Compared to previous estimates, these shipping-related deaths account for 3-8% of the total number of worldwide deaths related to atmospheric particles and is in the order of SO_2 contributions from the shipping sector. A follow up study showed that by 2012 control scenarios would reduce premature deaths by ~44,000 if the sulphur content in the fuel is limited to 0.1% within 200 nautical miles (370 km) of coastal areas and be reduced by ~41,000 if the sulphur content is reduced globally to 0.5% [*Winebrake et al.*, 2009].

Radiative Forcing. In addition to the impact on atmospheric composition and health, ship emissions have an impact on climate. 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. Ship tracks can change the radiation budget on a local scale, but are short lived and cover a very small fraction of the globe so that their radiative effect on the global scale is negligible (–0.4 to –0.6 mW/m^2 ±40%; *Schreier et al.* [2007]). Simulations with the global model EMAC/MADE on the other hand showed a high impact of gaseous and particulate emissions from ocean-going ships on maritime clouds [*Lauer et al.*, 2007]. The additional aerosol particles brighten the clouds above the oceans, which then are able to reflect more sunlight back into space. Although the uncertainties associated with this study are still high, the model results clearly indicate that the cooling due to altered clouds far outweighs the warming effects from greenhouse gases such as CO_2 or ozone from shipping, overall causing a negative radiative forcing today. The indirect aerosol effect of ships on climate was found to be far larger than previously estimated, contributing up to 39% to the total indirect effect of anthropogenic aerosols. This contribution is high because ship emissions are released in regions with frequent low marine clouds in an otherwise clean environment. In addition, the potential impact of particulate matter on the radiation budget is larger over the dark ocean surface than over polluted regions over land. A summary of the RF contributions for shipping is displayed in Figure 4 for the year 2000 [*Eyring et al.*, 2010a]. 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 and on the sulphur content of the fuel [*Fuglestvedt et al.*, 2010].

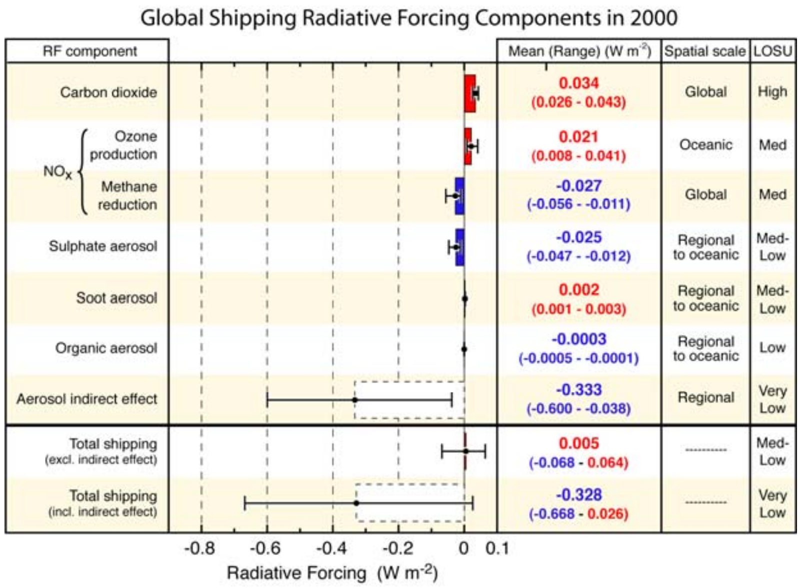

Figure 4. Annual mean RF due to ship emissions in Wm^{-2} for 2000. The boxes show the mean of the lower and upper estimate reported in the literature and the whiskers show the range of literature values given by the highest and lowest estimate. The typical geographical extent of the RF and the level of scientific understanding (LOSU) is given in addition. From *Eyring et al.* [2010a].

Satellite Simulator. To facilitate a consistent comparison between observed and simulated atmospheric species, a Satellite Simulator (SATSIM) tool has been developed [*Khlystova et al.*, in prep., 2010]. The SATSIM tool was designed for a consistent comparison of atmospheric trace gases measured by SCIAMACHY and MOPITT with those simulated by the EMAC model. Due to its flexible construction, the tool can be extended to include other satellite instruments in future work (including different satellite geometries) and it can also be used for the evaluation of different chemistry-climate models (CCMs). The SATSIM tool can also be used for the comparison of different space-based instruments precision independent of their retrieval procedures. The tool can be called from a Unix shell script or alternatively can be started by the Windows Interface Application.

d) Sustainability and Open Science Questions

Sustainability. The scientific goals of the SeaKLIM group have been reached. With the SeaKLIM work summarised in Section 2c, a variety of important results have been achieved that brought the importance of ship emissions and the projected future increases to the attention of the international policy and science community. For example, the SeaKLIM studies supported the Health and Environment sub-group of the International Maritime Organization (IMO) Cross Government/Industry Group that is evaluating the effects of the different options proposed under the revision of Annex VI to the MARPOL Convention which addresses the control of air pollution from ships. In the meantime, the Marine Environment Protection Committee (MEPC) of the IMO adopted NO_x regulations and progressive reduction in SO_2 emissions from ships, with the global cap (a fuel sulphur content limit) initially reduced from the current 4.5 to 3.5% by 2012, to be followed by progressive reduction to 0.5% by 2020, subject to a feasibility review by 2018. In addition, the sulphur limits in emission control areas will be reduced from the current level of 1.5 to 1% in 2010, and further to 0.1% in 2015. The head of the SeaKLIM group has supported the 2nd IMO GHG Study that was written by a team of international researchers [*Buhaug et al*., 2008; 2009]. As a member of the German IMO delegation, Veronika Eyring also serves as an adviser in the area of climate impacts caused by ship emissions. This adviser role will last beyond the SeaKLIM period.

Another area of emerging policy-relevant research which will continue beyond the SeaKLIM time is the application of the SeaKLIM bottom-up ship emission algorithm that can calculate ship emissions for a variety of different allocation criteria [*Paxian et al.,* 2010]. Existing top-down approaches do not allow the allocation of emissions to countries as they calculate energy use and emission totals without respect to location by means of quantifying the worldwide fuel consumption by power production first and then multiplying the consumption by emission factors [*Corbett and Köhler*, 2003; *Endresen et al.,* 2003, 2007; *Eyring et al*., 2005a; *Buhaug et al*., 2009]. Therefore, a bottom-up method is needed where fuel use and emissions are directly estimated within a spatial context and can be linked to ship movement data. The SeaKLIM algorithm is the first global bottom-up approach that has been developed worldwide. Under the lead of CE Delft, the SeaKLIM group has supported the study *'Technical support for European action to reducing Greenhouse Gas Emissions from international maritime transport'* commissioned by the European Commission and the study '*A Global Maritime Emissions Trading System, Design and Impacts on the Shipping Sector, Countries and Regions*' funded by the Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety). In both studies policy-relevant information was derived that assessed how market based instruments could impact the shipping sector as well as individual countries or regions [*Faber et al*., 2009; 2010]. The collaboration with CE Delft has been continued beyond the SeaKLIM time in a study commissioned by the UK Committee on Climate Change. In this new study the SeaKLIM algorithm is used to calculate UK emissions. These emission calculations form the baseline of a simplified model (also developed as part of this project) that will be used to project UK emissions for a variety of different assumptions on relevant parameters (e.g., global domestic product and technology options). Since the SeaKLIM algorithm is unique, it is expected that other projects will follow.

The SeaKLIM group also responded to the new emerging question of the use of biofuels for shipping. The group has successfully contributed to BIOCLEAN, a collaboration project between DLR, MAN B&W and the Ökö-Institut that was funded by the BMBF. The use of biofuels for stationary power generation or propulsion in shipping gains increasing importance in the framework of CO_2 reductions and the use of energy from renewable sources. The knowledge on emission characteristics of various biofuels and resulting climate impacts however was very limited. BIOCLEAN considered the quantification of all key climate-active exhaust constituents as a very important task not only for fossil fuels but also for fuels from renewable sources. BIOCLEAN provided decision guidance and guidance on technological realisation for a world-wide use of fuels from renewable sources in the investigated applications of large diesel engines. Further research and collaboration projects in this area, also with the industry, can be expected.

In addition to the projects that have been outlined above, at DLR the SeaKLIM work will be continued for example as part of the DLR project 'Verkehrsentwicklung und Umwelt (VEU)' and as part of the the project TRANPSHORM, that is funded by the European Commission under the 7th Framework and will assess transport related air pollution and health impacts. At the University of Bremen, the remote sensing activities of ship emission impacts on the marine troposphere will be continued. Focus of the future work will be, based on the experience gained in *Franke et al.* [2009], to improve techniques to derive trends in ship emissions from available long term satellite data sets (GOME, SCIAMACHY, GOME-2 spanning already 15 years). In addition, the work will focus on using higher spatial resolution remote sensing techniques (ground/ship-based, EOS-AURA, Sentinel 5P) to estimate the impact of ship emissions on troposheric composition along European and German coast lines. This work and other ongoing research efforts will continue to inform policymakers and will help to further implementation of needed emission reduction and mitigation strategies.

Open Science Questions. For global modelling aspects the major future challenge lies in further assessing 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. Evaluation of the global models' response to ship emissions is still at a preliminary stage and is currently limited by the coarse spatial resolution of the models, the uncertainty in the measurements, the lack of sufficient in situ measurements over the ocean, and the difficulty to separate ship emissions from other even stronger emission sources close to land. Additional in situ measurements inside single ship plumes, but also in the corridor of the shipping lanes are needed and the set up of a measurement network onboard ships similar to MOZAIC (Measurements of OZone and water vapour by in-service AIrbus airCraft) or CARIBIC (Civil Aircraft for Global Measurement of Trace Gases and Aerosols in the Tropopause Region) onboard civil aircrafts would be desirable. Unambiguous detection of ship emissions in satellite data is currently only available for the region of the Red Sea and the Indian Ocean [*Richter et al.*, 2004], where shipping routes are close to the coastal area. Reduction in measurement uncertainties through 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 a comparison between global models and satellite data in the future.

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. Further model development, focusing in particular on the representation of aerosol size-distribution, aerosol activation, aerosol-cloud interaction and extension of feedback mechanisms, is needed in addition to extended measurement data (e.g. of the size-distribution and composition of particles emitted by ships) to reduce current uncertainties in global model studies. For a better evaluation of clouds in the model, satellite simulators like the CFMIP Observational Simulator Package (COSP) should be used. COSP facilitates the exploitation of A Train data in numerical models and allows simulating the signal that CloudSat/CALIPSO would see in a model-generated world.

e) Application Potential

As summarized in the previous sections, the SeaKLIM group provided high quality research that has found direct input into IMO work and contributed to the justification that further national and international regulations are needed to reduce the impact of ship emissions on atmospheric composition and climate. The studies showed that ship emissions have a significant impact on atmospheric composition and climate already today, and if unabated, could lead to severe problems in terms of impacts on air quality and human health. With these studies SeaKLIM made a significant contribution to also raise the profile of this topic in the scientific community. A variety of other groups have started new research in this field.

One of the major findings of the SeaKLIM group in terms of climate impacts was that the potential of particle emissions or their precursors from shipping to modify the microphysical and optical properties of clouds (the so-called "indirect aerosol effect") is significant and more important than previously recognised. The studies also showed that a large fraction of ship emissions occurs within 400 km of coastlines, and cause air quality problems in coastal areas and harbours with heavy traffic. The long range transport of ship emissions motivated the Task Force on Hemispheric Transport of Air Pollution (TF HTAP) working under the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP) to include ship emissions among sources relevant for the intercontinental transport of air pollution. The ship emission inventories developed by the SeaKLIM group are now also part of a new set of emission inventories that is used in chemistry-climate modelling studies in support of the IPCC Fifth Assessment Report [*Lamarque et al.*, 2010].

The remote sensing techniques and interpretation methods that use satellite data on trace gas concentrations to get an additional and independent constrain on ship emissions are founding the basis for potential future GMES services on space based verification of emissions using the new generation of high spatial resolution atmospheric satellite sensors Sentinel 5 Precursor, Sentinel 4 (geostationary) and Sentinel 5.

3. List of Publications from SeaKLIM Members (2004-2010)

■ <u>*Peer-reviewed*</u>

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[1] **Eyring, V.**, I. S. A. Isaksen, T. Berntsen, W. J. Collins, J. J. Corbett, O. Endresen, R. G. Grainger, J. Moldanova, H. Schlager, and D. S. Stevenson, Transport impacts on atmosphere and climate: Shipping, *Atm. Env.*, 44, 4735 – 4771, doi:10.1016/j.atmosenv.2009.04.059, 2010a.

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