Global distribution of ship tracks from one year of AATSR-data

M. Schreier*, H. Bovensmann
Institute of Environmental Research, University of Bremen, 28359 Bremen, Germany

H. Mannstein, V. Eyring
DLR - Institut für Physik der Atmosphäre, Oberpfaffenhofen, 82234 Wessling, Germany

Keywords: ship tracks, radiative forcing

ABSTRACT: 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. As ship tracks indicate a pollution of the clean marine environment and also affect the radiation budget below and above the cloud, it is important to investigate their radiative and climate impact. In this study we use satellite data to examine the effects of ship tracks on a particular scene as well as on the global scale. The cloud optical and microphysical properties are derived using a semi-analytical retrieval technique combined with a look-up-table approach. Within the ship tracks a significant change in the droplet number concentration, the effective radius and the optical thickness are found compared to the unaffected cloud. The resulting cloud properties are used to calculate the radiation budget below and above the cloud. Local impacts are shown for a selected scene from MODIS on Terra. The mean reflectance at top of atmosphere (TOA) is increased by 40.8 Wm^{-2}. For a particular scene chosen close to the West Coast of North America on 10th February 2003, ship emissions increase the backscattered solar radiation at TOA by 2.0Wm^{-2}, corresponding to a negative radiative forcing (RF). 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, but small RF on the global scale.

1 INTRODUCTION

Emissions from ships significantly contribute to the total budget of anthropogenic emissions. The principal exhaust gas emissions from ships include CO_2, NO_x, SO_x, CO, hydrocarbons, and particulate matter (Eyring et al., 2005). Compared to other transport modes, the sulphur content of the fuel burned in marine diesel engines and the total amount of SO_x emissions is high. The average sulphur fuel content of today's world-merchant shipping fleet is 2.4% resulting into a large amount of SO_2 and particulate matter emission totals (EPA, 2000).

The SO_2 and particle emissions from ships change the physical 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). The natural number of cloud condensation nuclei is limited and reflected in larger droplets and a smaller droplet number concentration in low-level stratiform clouds over the ocean compared to continental clouds. In case of injection of additional aerosols, the changes of the aerosol concentration and amount result in a change in the droplet number concentration within the cloud (Facchini et al., 1999), depending on the solubility and size of the injected aerosol particles. 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 the solubility. Especially the high sulphur content of the fuel may be an important factor for the modification of clouds, because the resulting SO_x is able to act as CCN. Amount and size of these particles depends on the fuel and also the kind of combustion, but can possibly result in a higher droplet concentration (Twomey et al., 1968;

* *Corresponding author:* Mathias Schreier, Institute of Environmental Research, University of Bremen, 28359 Bremen. Email: schreier@iup.physik.uni-bremen.de

Twomey, 1974) and consequently in a change of reflectivity of the maritime cloud. The increased reflectivity is even higher in the near infrared, because here, the ratio of absorption to scattering is strongly depending on the droplet size (Coakley et al., 1987; Kokhanovsky et al., 2004). In this study the modification of clouds and the influence of the ship exhaust on the radiation budget of a given scene are examined. Full details can be found in Schreier et al. (2006) and only a brief summary is presented here. Satellite data are also used to retrieve cloud properties and their modifications due to ship emissions on the global scale.

2 METHODS

2.1 *Cloud properties retrieval*

A new algorithm has been developed that combines the semi-analytical cloud retrieval algorithm SACURA (Kokhanovsky et al., 2003) and look-up-tables (LUTs) for thin clouds calculated with the libRadtran radiative transfer package (Mayer and Kylling, 2005). An advantage of the new algorithm is that it can be applied to different satellite instruments with channels in the near infrared (e.g. Terra-MODIS, AATSR).

The optical and microphysical parameters of the cloud were derived from the 0.9 µm and 1.6 µm channels for MODIS and AATSR. 1.6 µm was selected because the smaller absorption of liquid water enables more accurate results for the SACURA-retrieval. The two cloud retrieval algorithms - SACURA and LUTs - are different, but both derive the cloud optical thickness and also the effective radius r_{eff}, defined by the ratio of the third to second moment of the particle size distribution and therefore indicating a change of the ratio of volume to surface in the particle size distribution.

The columnar droplet number concentration for both retrievals is calculated via effective radius and cloud optical thickness by assuming a gamma droplet size distribution with a coefficient of variance of 0.37. Calculations of droplets per volume (N) were performed using a hypothetical vertical homogeneous cloud of a thickness 500 m, which is a reasonable value for low marine stratiform clouds.

2.2 *Estimating impact on the radiation field*

The derived optical parameters were used to estimate changes in solar radiation for the areas below and above the cloud as well as the thermal outgoing radiation by radiative transfer calculations. Optical thickness and the effective radius have been applied to create look-up-tables for the solar flux via the radiative transfer code libRadtran (Mayer and Kylling, 2005), by using the built in k-distribution by Kato et al. (1999) to calculate integrated solar irradiance with the solver disort2 (Stamnes et al., 1988) for the wavelength range of 0.24 µm to 4.6 µm. The down-welling irradiance at the surface and the up-welling flux at TOA were calculated for the mid-latitude winter atmosphere. The different distributions of cloud optical properties were considered by using these look-up-tables to calculate the solar flux for every pixel and taking into account the local solar zenith angle. The cloud top height was chosen to be 1000 m and the cloud-bottom height was 500 m. The optical properties of the clouds were calculated according to Mie theory. The mean values for all low-cloud-pixels, ship-track-pixels and no-track-pixels were determined, to estimate the impact of ship tracks on both, the solar radiation at the surface and the backscattered radiation at TOA.

3 ANALYSIS OF SHIP A TRACK SCENE

A particular and adequate satellite scene from Terra-MODIS (King et al., 1995) was selected to show local impacts. The scene from 10th February 2003, close to the West Coast of North America (153°W to 120°W and 40° N to 60° N), exhibits a number of anomalous cloud lines in the stratiform clouds over the ocean.

3.1 *Cloud properties*

The cloud retrieval algorithm (section 2) was used to calculate optical and microphysical parameters of low clouds (Fig. 1). A significant decrease of the average effective radius from 12 µm to 6 μm is visible across the ship-track-pixels (Fig. 1a). The optical thickness of unpolluted clouds is about 20 to 30 and is increasing in the track up to 45 and higher (Fig. 1b). Also the change in the droplet number concentration from around 100 cm^{-3} up to 800 cm^{-3} is substantial (Fig. 1c). Table 1 summarizes the mean values of the various parameters for all low-cloud-pixels, ship-track-pixels and no-ship-track-pixels. The decrease in the effective radius from 13.2 to 10.1 μm for the area is evident and also an increase in cloud optical thickness from 20.7 up to 34.6 is observed. There is also an obvious increase of droplet number concentration from 79 to 210 cm^{-3}.

Table 1. Mean values of cloud parameters for all low-cloud-pixels, ship-track-pixels and no-ship-track-pixels..

	Low-cloud-pixels	No-ship-track-pixels	Ship-track-pixels
Effective radius (μm)	13.0	13.2	10.1
Optical thickness	21.4	20.7	34.6
Droplet number (cm^{-3})	85	79	210

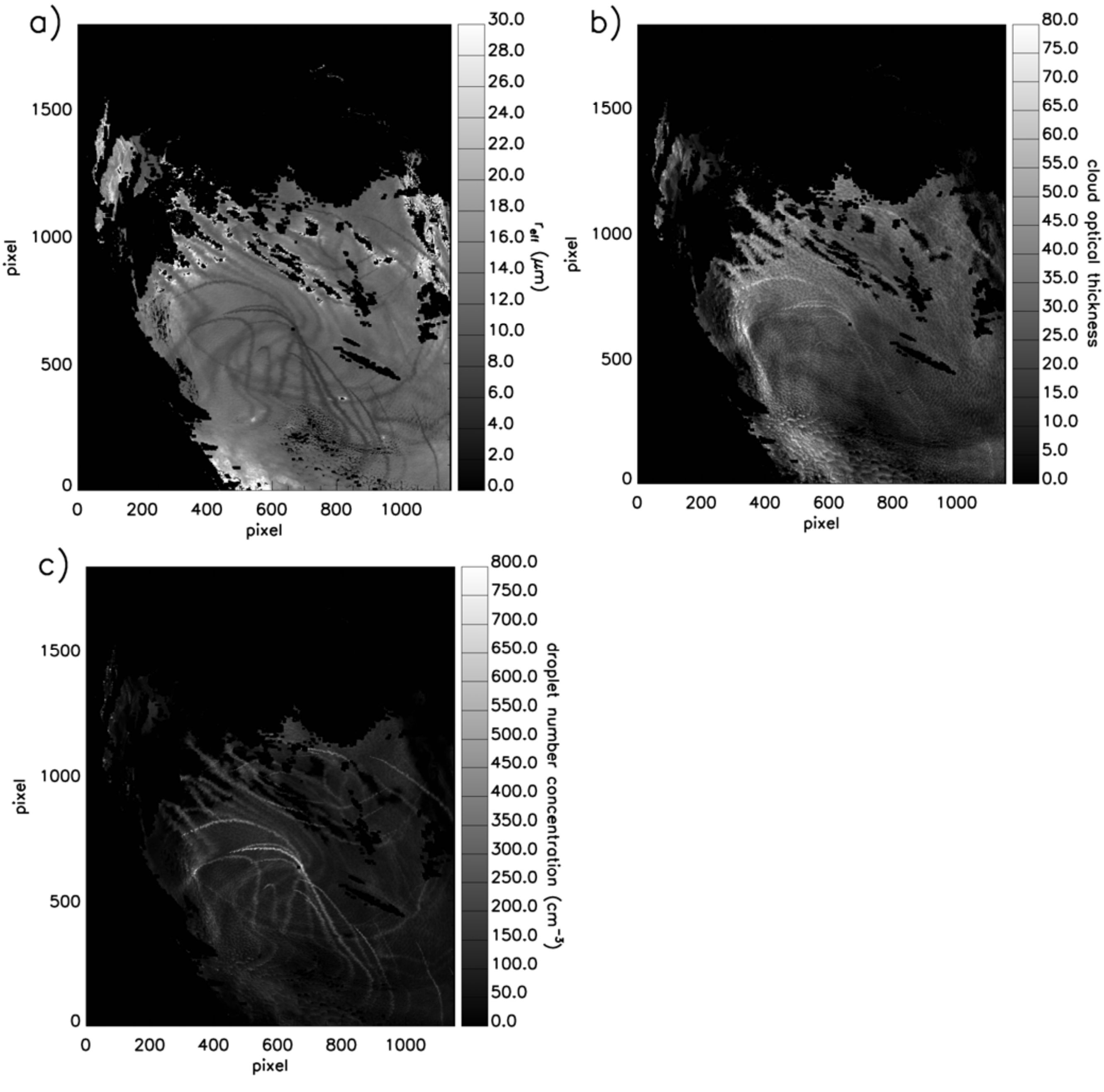

Figure 1: Effective radius (a), cloud optical thickness (b) and concentration of particles (c) (cm−3) derived from the MODIS channels 2 and 6 for the analysed scene. From Schreier et al. (2006).

3.2 *Radiative Effects*

To separate the impact of changes in cloud parameters from ship tracks on the radiation field without the uncertainties represented by the solar zenith angle variations, radiative transfer calculations were performed assuming a mean solar zenith angle of 63° for all pixels. The calculated values now only depend on the cloud optical properties, as the influence of a varying solar zenith angle has been eliminated.

Assuming a constant solar zenith angle, at TOA, ship-track-pixels reflect $40.8 Wm^{-2}$ more than the no-ship-track-pixels. The amount of ship-track-pixels in the scene is 6.7%. The net radiative effect of the change in cloud properties due to ships for the particular scene is estimated by calculating the difference of the absolute radiation values between all low-cloud-pixels ($E_{low-cloud}$) and the no-ship-track-pixels ($E_{no-ship-track}$). According to these values, the solar radiation at the surface is reduced on average by $2.1 Wm^{-2}$ by the ship emissions and additional $2.0 Wm^{-2}$ are reflected back at TOA.

4 GLOBAL DISTRIBUTION OF SHIP TRACKS

The global distribution of ship tracks is derived from data of the AATSR (Advanced Along Track Scanning Radiometer) instrument aboard the European ENVISAT satellite for the year 2004.

To select scenes dominated by low clouds over ocean, we applied the following criteria: (1) excluding clouds over land via the terrain height, (2) distinguish between ocean and clouds by the reflectance of a channel in the short wavelength and (3) estimation of cloud top height with the help of the 11µm channel. The remaining scenes include 'very low clouds', which were further examined and the scenes that included ship tracks were used to estimate the global coverage of ship tracks with a resolution similar to the International Cloud and Climate Project was calculated.

The results show highest occurrence of ship-tracks over the Northern Pacific and the Northern Atlantic (up to 0.2%). A comparable high amount of ship-tracks is also found at the Western Coast of Africa and in the Northern Atlantic. In addition to large regional variations, large seasonal variations have been found, with most ship-tracks occurring in springtime and in summer, and only few in wintertime and autumn.

Calculation of the increased backscattering compared to the surrounding for fixed solar zenith angle show most values are around $40 Wm^{-2}$. This indicates an increased cooling of the atmosphere on regional scale. On global scale, the estimations for radiative forcings show values smaller than -1 mWm^{-2}, which is small compared to other radiative forcings.

5 CONCLUSIONS

On the basis of a particular satellite scene it has been shown that ship emissions modify existing clouds on a regional scale by decreasing the effective radius, while they increase droplet concentration and optical thickness (Schreier et al., 2006). The results agree with the theory and experiment (Öström et al., 2000; Hobbs et al., 2000): Low clouds of the maritime boundary layer have less cloud condensation nuclei than clouds over land; in consequence, this results in larger droplet radii for similar water content and dispersion of droplet size distributions. Injection of aerosols and their pre-cursors by ships results in more CCNs causing the mean droplet radius to decrease and the droplet number concentration to increase. The derived parameters were used to calculate changes in the radiative energy budget below and above the cloud. The mean values show an increase of $40.8 Wm^{-2}$ at TOA. If the whole low-cloud area with 6.7% ship-track-pixels is taken into account, an increase of $2.0 Wm^{-2}$ in backscattered solar radiation was found, when assuming a constant solar zenith angle of 63° for the scene. Full details of this study can be found in Schreier et al. (2006).

The global distribution of ship tracks shows high occurrence over the Northern Pacific and the West Coast of Africa. A first estimate of the global impact of ship tracks result in only small radiative forcings compared to other ship-induced RFs. However, due to large seasonal and spatial variations ship tracks can impact the climate locally.

REFERENCES

Coakley Jr., J.A., P.A. Durkee, K. Nielsen, J.P. Taylor, S. Platnick, B.A. Albrecht, D. Babb, F.L. Chang, W.R. Tahnk, C.S. Bretherton, P.V. Hobbs, 2000: The Appearance and Disappearance of Ship Tracks an Large Spatial Scales, *J. Atmos. Sci.*, 57 , 2765-2778.

Conover, J.H., 1966: Anomalous Cloud Lines, J. Atmos. Sci., 23, 778-785.

EPA, 2000: United States Environmental Protection Agency Air and Radiation, Analysis of Commercial Marine Vessels Emissions and Fuel , *EPA420-R-00-002*.

Eyring, V., H.W. Köhler, J. van Aardenne, and A. Lauer, 2005: Emissions from international shipping: 1. The last 50 years, *J. Geophys. Res.*, 110, D17305.

Facchini, M.C., M. Mircea, S. Fuzzi, R.J. Charlson, 1999: Cloud albedo enhancement by surface-active organic solutes in growing droplets, *Nature*, 401, 257-259.

Hobbs, P.V., T.J. Garrett, R.J. Ferek, S.R. Strader, D.A. Hegg, G.M. Frick, W.A. Hoppel, R.F. Gasparovic, L.M. Russell, D.W. Johnson, C. O´Dowd, P.A. Durkee, K.E. Nielsen, G. Innis, 2000: Emissions from Ships with their respect to clouds, *J. Atmos. Sci.*, 57, 2570-2590

Kato, S., T.P.Ackermann, J.H. Mather, E.E. Clothiaux, 1999: The k-distribution method and correlated-k approximation for a shortwave radiative transfer model, *J. Quant. Spectrosc. Radiat. Trans.*, 62, 109-121.

Kokhanovsky, A.A., V.V. Rozanov, E.P. Zege, H. Bovensmann, J.P. Burrows,2003: A semi-analytical cloud retrieval algorithm using backscattered radiation in 0.4-2.4 micrometers spectral range, *J. Geophys. Res.*, 108(D1), 4008.

Kokhanovsky, A., 2004: Optical properties of terrestrial clouds, *Earth Science Reviews*, 64, 189-241.

Mayer, B., A. Kylling, 2005: Technical note: The libRadtran software package for radiative transfer calculations, description and examples of use, *Atmos. Chem. Phys.*, 5, 1855-1877.

Öström, E., K.J. Noone, R.A. Pockalny, 2000: Cloud Droplet Residual Particle Microphysics in Marine Stratocumulus Clouds Observed during the Monterey Area Ship Track Experiment, *J. Atmos. Sci.*, 57, 2671-2683.

Radke, L.F., J.A. Coakley Jr., M.D. King, 1989: Direct and Remote Sensing Observations of the Effects of Ships on Clouds, *Science*, 346, 1146-1149.

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

Stamnes, K., S.C. Tsay, W. Wiscombe, K. Jayaweera, 1988: Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scatteringand emitting layered media, *Appl. Opt.*, 27, 2502-2509.

Twomey, S., H.B. Howell, T.A. Wojciechowski, 1968: Comments on Anomalous cloud lines, J. Atmos. Sci., 25, 333-334.

Twomey, S., 1974: Pollution and the planetary albedo, *Atmosph. Environ.*, 8, 1251-1256.