Impact of ship emissions on cloud properties over coastal areas

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[1] Although land based emissions in Europe are decreasing, ship emissions continue to grow. The main emissions from ships can modulate cloud properties of coastal areas and are of direct relevance to the earth radiation budget. In this context, satellite data from AVHRR onboard NOAA-14 are evaluated for six years (1997–02) in order to assess impact of ship emissions on cloud properties over coastal areas. Study area was chosen in such a way that it includes the English Channel and top three polluting harbours in Europe. Results present first evidence of possible impact of ship emissions on both cloud albedo and cloud top temperature over coastal areas using long-term satellite measurements. Increase in cloud albedo (with corresponding decrease in cloud top temperature) and higher variability are observed over coastal areas. This effect is more pronounced for areas over and around harbours and the English Channel. It also confirms indirect aerosol effects. **Citation:** Devasthale, A., O. Krüger, and H. Graßl (2006), Impact of ship emissions on cloud properties over coastal areas, *Geophys. Res. Lett.*, *33*, L02811, doi:10.1029/2005GL024470.

1. Introduction

[2] The principal emissions from ships include exhaust gases, hydrocarbons and particulate matter and are one of the least regulated sources of air pollution. Ship traffic is currently growing by about 3 percent globally [*Corbett et al.*, 1999] and according to an International Maritime Organization study [*International Maritime Organization*, 2000], global ship traffic density share reaches 85 percent in the northern hemisphere. Several global inventories for the energy/fuel consumed by shipping are available [*Corbett et al.*, 1999; *Corbett and Köhler*, 2003; *Endresen et al.*, 2003]. The most recent global inventory [*Eyring et al.*, 2005] estimates a fuel consumption of approximately 280 million metric tonnes (*Mt*) for the year 2001 compared to 64.5*Mt* in 1950. A growing number of studies show that ship emissions could have an impact on radiative climate forcing, tropospheric photochemistry and climate [*Capaldo et al.*, 1999; *Lawrence and Crutzen*, 1999; *Beirle et al.*, 2004; *Richter et al.*, 2004].

[3] The ship emissions like other sources of air pollution influence cloud microphysical properties (known as indirect aerosol effects) as they can be additional sources of cloud condensation nuclei (CCN) upon which cloud droplets form. They lead to an increase in cloud droplet number concentration and decrease in effective radius resulting in enhanced cloud albedo (referred as first indirect aerosol effect or Twomey effect [*Twomey*, 1977]). Another important indirect effect relevant to ship emissions is the "thermal effect" which influence cloud top temperature. An increase in CCN will lead to the smaller droplets with less coalescence efficiency. This will suppress or delay the formation of large droplets, subsequently delaying the downdraft and precipitation. In such case the updrafts might dominate the downdrafts due to release of latent heat of condensation. Therefore clouds near the pollution sources will be lifted up reducing cloud top temperatures [*Devasthale et al.*, 2005; *Koren et al.*, 2005; *Pincus and Baker*, 1994; *Teller and Levin*, 2005].

[4] Clouds play a key role in the Earth's Radiation Budget and thus even a small change in cloud properties could affect radiation budget and regional climate. But there are only few studies that point out importance of possible impact of ship emissions on clouds and most of them so far are limited to studying microphysical properties of clouds or changes in CCN and/or restricted to smaller episodes [*Ferek et al.*, 1998; *Durkee et al.*, 2000; *Hobbs et al.*, 2000; *Hudson et al.*, 2000; *Noone et al.*, 2000]. In this context, satellite data for six years from NOAA-14 are evaluated to assess the possible impact of these ship emissions on cloud properties over coastal areas in Europe. The study area is chosen in such a way that it covers English Channel and Europe's top three polluting harbours, namely Rotterdam (Netherlands), Antwerp (Belgium) and Milford Haven (United Kingdom) [*Entec UK Ltd*, 2002].

2. Evaluation of Cloud Properties

[5] A brief description about satellite data, its pre-processing (i.e., calibration, atmospheric correction and cloud detection), and its analysis is given in this section. We analyzed Global Area Coverage (GAC) level 1B data from the Advanced Very High Resolution Radiometer (AVHRR) onboard NOAA-14 satellite for the period of six years from 1997 to 2002 at 4 km resolution. Rigorous quality control is applied to the data to make sure that no erroneous or contaminated pixels are being used in the analysis.

[6] Firstly, calibration of the solar and the thermal channels of the AVHRR is performed as done by *Rao and Chen* [1999] and *Kidwell* [1998]. This takes into account the degradation of the AVHRR sensor in space. The thermal channels are found to be stable for the trend analysis [*Devasthale et al.*, 2005]. We used new radiance based method for the nonlinearity correction of the thermal channels as described by *Sullivan* [1999]. Secondly, the reflectances from solar channels are corrected for the Rayleigh scattering and ozone absorption using the data from Total Ozone Monitoring Spectrometer (TOMS). Details of atmospheric correction procedure are given by *James and Kalluri* [1994]. The corrections for eccentricity

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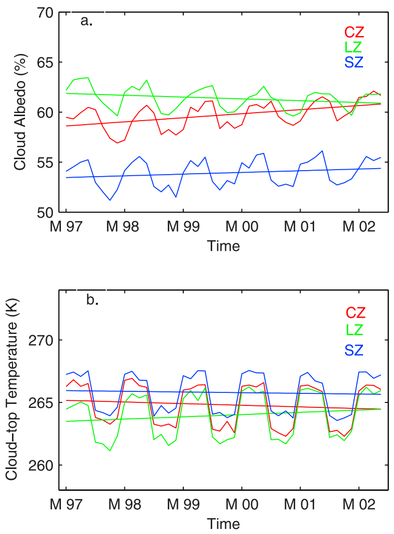

Figure 1. Observed changes (a) in cloud albedo and (b) in cloud top temperature from May 1997 (denoted by M 97 and so on) till August 2002 (monthly averages, in cycles of summer and winter) over the study area. Increase in cloud albedo and decrease in CTT over coastal zone (CZ), and vice versa for land zone (LZ) suggest possible impact of ship emissions.

of the earth and solar illumination are also applied. In the third step, these corrected reflectances and brightness temperatures along with other parameters are given as input to the cloud detection algorithm. We implemented the known CLAVR-1 (Clouds from AVHRR Phase 1) [*Stowe et al.*, 1999] algorithm for detection of cloudy pixels and cloud type. And finally, monthly mean cloud albedos and cloud top temperatures are computed using AVHRR channel 2 reflectances and channel 4 brightness temperatures for cloudy pixels respectively. The trends in these properties are discussed in the Section 3. To assess the variability, coefficient of variation and its spatial pattern for the six summer and winter seasons are analyzed. Only low level clouds are analysed since they are most likely to show an impact from ship emissions.

[7] Calibrated reflectances and brightness temperatures are validated using Pathfinder AVHRR Land (PAL) data set [*James and Kalluri*, 1994] and Moderate Resolution Imaging Spectroradiometer (MODIS) [*King et al.*, 1992]. Correlation of our cloud albedos and cloud top temperatures with both PAL and MODIS data sets is better than 0.90. Details are given by *Devasthale et al.* [2005].

3. Results and Discussions

[8] Cloud albedo and cloud top temperature are evaluated in this case study. Summer (May, June, July and August) and winter (November, December, January and February) seasons from 1997 to 2002 are analysed. The study area (lower left and upper right coordinates are 48.0N, 7.0W and 55.0N, 5.0E) is divided into 3 zones, namely coastal zone (CZ), sea zone (SZ) and land zone (LZ). The CZ is approximately 50 km area on either side of the coast line (defined by the 1 km resolution land/sea mask). The area landward is categorized as LZ and seaward as SZ. CZ covers areas around major sea ports in southern United Kingdom (England, Wales), Netherlands, Belgium and northern France, while LZ covers the inland parts of these countries. SZ covers the parts of open waters of North Sea and north-east Atlantic ocean. The idea was to separate the CZ from LZ and SZ so as to analyse the cloud properties of all the three zones individually, since this 100 km area along the coast is most likely affected by ship emissions due to high ship traffic density and shipping activities like harbouring.

[9] Results (Figure 1) indicate that there are changes in cloud properties (monthly averages) over CZ. The cloud albedo over CZ is increasing, while cloud albedo over LZ shows a decrease. On the other hand, the cloud top temperatures (CTTs) over CZ are decreasing and increasing over LZ. Such behaviour of cloud albedo and CTT over CZ and LZ can be explained by decreasing air pollution over land and increasing ship emissions. The slight increase in cloud albedo and decrease in CTT over SZ could be due to a weakening but still with less ship traffic detectable influence of these emissions over sea areas. The first indirect aerosol effect, the Twomey effect, seems to exist for CZ and LZ in the solar spectral range and also the “thermal effect”.

[10] To validate this interpretation, firstly, we analysed the aerosol optical thickness data (at 670 nm) from Aerosol Robotic Network (AERONET, Level 2.0 quality assured and manually inspected) and European Monitoring and Evaluation Programme Expert Emissions (EMEP-EE) [*Vestreng et al.*, 2004]. There are two AERONET stations that fall into our study area and have a record of aerosol optical thickness for more than 3 years. Fortunately, one falls into LZ (station at Lille, France) and the other is close to CZ (station at The Hague, Netherlands). The EMEP-EE for the UK, Belgium, Netherlands, France, North Sea and north-east Atlantic ocean are also analyzed. The SO_x emissions from EMEP-EE for all countries (shown in Figure 2) and aerosol optical thickness for the station (Lille) in LZ confirm decreasing trend in air pollution. A similar decreasing trend from EMEP-EE for all the main pollutants is seen over these countries. But the station (The Hague) closest to the CZ and EMEP-EE for sea areas show an almost constant or slightly increasing trend (in the case of the north-east Atlantic Ocean).

[11] To validate further, since the impact of ship emissions could be more localised, four smaller regions in the study area are selected and trends in cloud properties are observed there (see Figure 3 for observed trends in cloud

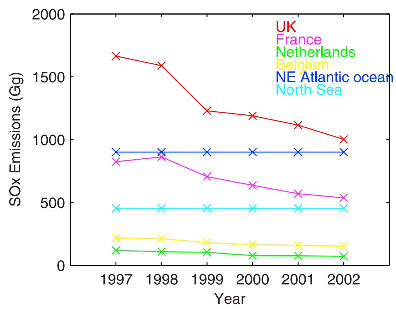

Figure 2. EMEP-EE data confirm the decreasing pollution over land and almost constant or slightly increasing trend for the sea areas [*Vestreng et al.*, 2004].

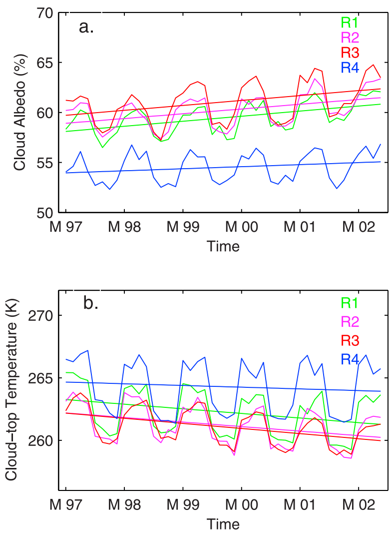

Figure 3. Trend observed in (a) cloud albedo and (b) CTTs for 4 regions from May 1997 till August 2002 (monthly averages, in cycles of summer and winter) covering 3 harbour areas (R1, R3), the English Channel (R2) and a relatively remote ocean region (R4) clearly confirms the influence of ship emissions.

albedo and CTTs and Figure 4 for four selected regions). Region 1 covers an area in and around harbour Milford Haven, region 2 part of the English Channel, region 3 areas in and around the harbours Rotterdam and Antwerp and region 4 is chosen in the open ocean, away from the coast. Regions 1, 2 and 3 show a sharp increase in cloud albedo and decrease in CTTs compared to region 4. Rotterdam is the most polluting harbour followed by Antwerp and Milford Haven. For example, estimated annual emissions of SO_2 from Rotterdam are 3.7 kT, followed by 2.2 kT for both Antwerp and Milford Haven for the year 2000 [*Entec UK Ltd*, 2002]. The English channel is the busiest sea route for almost all types of ships and about 90 percent of all ship emissions in the North Sea originate from within 90 km from the coast line (Ship Emissions Abatement and Trading February 2005 newsletter, available at http://www.seaat.org). Also EMEP estimates that the contribution of secondary inorganic particles formed from ship emissions in western European coastal areas varies between 20–30 percent.

[12] Finally, the spatial pattern of variability confirm the areas where cloud properties show the above-mentioned trends. Coefficient of variation (using six years of data) for cloud top temperatures for both summer and winter seasons are analysed. Values of coefficient of variation will be higher for regions where ship emissions are influencing CTTs due to decrease in mean CTT values in such regions compared to remote regions. The result for only summer season is shown in Figure 4. High variability is seen for CTTs over these harbours and the coastal areas. All the aspects above do point to a possible impact of these emissions on cloud properties. Both cloud albedo and cloud top temperatures are influenced around harbours and coastal zones. Apart from increased SO_2, NO_x emissions from ships lead to the increased aerosol production rates and cloud reflectivities as speculated by *Lawrence and Crutzen* [1999]. *Capaldo et al.* [1999] estimate the change in global radiative cloud forcing due to ships up to -0.16 W/m^2 for the Northern Hemisphere. Our results support and complement these studies. All the trends and variability observed in cloud properties because of ship emissions are also in line with the findings of *Krüger and Graßl* [2002] and *Devasthale et al.* [2005], where changes in cloud albedo and cloud top temperatures are studied as a function of air pollution over Europe.

[13] There could be two sources of error in the analysis. Firstly, error induced in cloud top temperatures by not applying water vapour correction above clouds. Water vapour absorption although important for land surface temperatures, is generally small over clouds. Our analysis using radiative transfer code Streamer [*Key and Schweiger*, 1998] and MODIS Level 3 water vapour data product shows that for the chosen study area, resultant error induced in cloud top temperatures by not applying water vapour correction would be less than 0.5K for thick low clouds. This error would even be less for the winter season. Second one is the impact of orbital drift of NOAA-14 on our analysis, if at all present. However, the error induced because of orbital drift in our study should be small because higher latitudes owing to curvature of the earth have smaller daily solar zenith angle changes resulting in smaller time rates of change [*Privette et al.*, 1995]. Further, this effect would even be smaller for winter season. Since we analysed the winter and summer seasons seperately and found similar thermal signatures in our study, this confirms the observed trends. The total error in our study remains well below 1 K for CTTs. The trends observed in CTTs for polluted regions clearly surmount this error and hence are not spurious.

4. Conclusion

[14] An evaluation of six years of satellite measurements suggests an influence of ship emissions on cloud albedo and cloud top temperatures over coastal areas. The increase in ship emissions lead to the increased cloud albedo and decreased cloud top temperatures over costal waters and harbours. Higher variability is observed in cloud top temperatures. It also confirms indirect aerosol effects in the visible and the thermal spectral range. Ship emissions need particular attention in assessing the cloud properties over coastal areas and could even be significant as shown in this

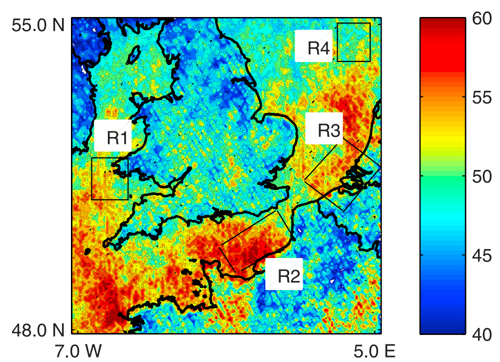

Figure 4. Coefficient of variation (in thousands) of CTTs over study area and four regions. High variability can be easily seen over harbours Milford Haven (R1), Rotterdam and Antwerp (R3), English Channel (R2) and coastal areas.

letter. This would directly have an impact on the climate of coastal areas. Various studies combining ship emission inventories, precise chemical transport models and remote sensing information at higher resolution from recent more sophisticated sensors like MODIS, Medium Resolution Imaging Spectrometer (MERIS), the SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY) etc could give more insight in this context and are important to quantify such an impact on the regional and global scales.

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