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Impact of ship emission on the Bay of Bengal pollution and climate

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Abstract

Seagoing ships play an important role in the transport sector of economy. However, seagoing ships pollute the clean marine environment and contribute significantly to the total anthropogenic emissions from the transportation sector. Key compounds emitted from shipping are carbon dioxide, nitrogen oxides, carbon monoxide, volatile organic compounds, sulphur dioxide and particulate matter such as sulphate, organic carbon, black carbon and ash into the atmosphere. Ship traffic is currently growing by about 3 percent globally which is leading to considerable increase of long-lived greenhouse gas concentrations in the atmosphere. In this study, we analysed the multi-year satellite data to derive a global distribution of ship emissions and their radiative forcing. We constrained the analysis to shipping corridor over Bay of Bengal by separating 'clean' from 'polluted' oceanic regions based on the location of shipping routes. The enhanced NO_2 emissions in the shipping lane are reducing the surface reaching solar radiation by ~1 W/m^2 during the solar noon hours and heating the lower troposphere by 0.05 K. As ship emissions are released in regions with frequent low marine clouds in an otherwise clean environment, the possible impact of ship emissions on Cloud Condensation Nuclei (CCN) are examined. CCN efficiency varied from 0.56 $\pm$ 0.06 over relatively pristine location to 0.17 $\pm$ 0.1 over polluted shipping corridor. The effects seen here may have significant implications for climate mitigation strategies.

1. Introduction:

Over the last 30 years a sudden increase in the amount of freight transport by international shipping is observed (*Eyring et al*., 2009). Emissions from international shipping contribute significantly to the total budget of anthropogenic emissions from the transportation sector (*Eyring et al.*, 2005). The total emissions of particles and their precursors are even higher than those from road-traffic because of the high sulphur content of the fuel burned in marine diesel engines today. The principal gaseous and particle emissions from ships include CO_2, H_2O, NO_x, SO_x, CO, unburned hydrocarbons, and particulate matter. While all these components do have an impact on the atmosphere and on climate (*Capaldo et al.*, 1999), in this paper we concentrate on NO_2 since no significant measures of NO_x-reductions have been introduced.

The absorption of incoming solar and outgoing terrestrial radiation by trace gases is one of the key factors in the Earth's radiative budget and plays a leading role in climate change (*Hansen et al.*, 2007). Carbon dioxide (CO_2) is the largest anthropogenic climate forcing gas, but other trace gases are also important including methane (CH_4), tropospheric ozone (O_3), nitrous oxide (N_2O), and halocarbons such as chlorofluorocarbons (CFCs) (*Forster et al*., 2007). Little attention has been paid to nitrogen dioxide (NO_2), because its effect on the global radiative budget, particularly the radiative forcing, is small. However, on a local scale, enhanced NO_2 in polluted areas can change the partitioning of absorbed solar radiation between the atmosphere and surface. *Lawrence and Crutzen*, (1999) reported that the plumes from fossil-fuel burning ship contribute to more than 10% of global NO_x production and in heavily traversed ocean regions ship emissions lead to more than 100-fold increase in surface NO_x concentrations. Being a greenhouse gas NO_2 contributes considerably to local radiative forcing (*Solomon et al.*, 1999). Moreover, NO_2 absorbs incoming solar radiation at ultraviolet and visible wavelengths (300–650 nm). Thus it produces atmospheric heating in the troposphere and contributes to dimming (reduction of solar radiation) at the surface.

In addition, emissions of aerosols and their precursors by ships result in a high amount of additional cloud condensation nuclei and can possibly lead to a change of the optical and microphysical properties of clouds (*Durkee et al.*, 2000).The primary objective of this study is to analyse the trends in ship induced NO_x emission and their radiative forcing using

satellite data. The shipping lane between Sri Lanka and Indonesia in the Bay of Bengal has been selected as a suitable region for study since it is a heavily traversed narrow track.

2. Data and Methodology:

In this study, tropospheric NO_2 columns retrieved by GOME, SCIAMACHY and OMI sensors on board the satellites have been used to identify the ship tracks over Bay of Bengal. GOME (Global Ozone Monitoring Experiment) is a nadir-viewing spectrometer that measures earthshine radiance and solar irradiance in ultraviolet-visible range (240 – 790 nm) and was launched on-board the second European Remote Sensing Satellite (ERS-2) on April 21, 1995. It has a spatial resolution varying from 40 X 320 km^2 to 80 X 960 km^2, spectral resolution of 0.2 - 0.4 nm and achieves global coverage in 3 days after 43 orbits (*Burrows et al*., 1999; *Boersma et al.,* 2004). SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY) is a passive remote sensing spectrometer launched on-board ENVISAT which was operational from March, 2002 to April, 2012. It measures sunlight transmitted, reflected and scattered by the earth's atmosphere or surface in ultraviolet-visible and near-infrared region (240 – 2380 nm) with spectral resolution of 0.2 - 1.5 nm and horizontal resolution of 60 X 30 km^2 for nadir viewing pixels. It can make both limb and nadir measurements and global coverage is achieved in 6 days at the equator and more frequently at higher altitudes (*Boersma et al.*, 2004; *Bovensmann et al.*, 1999; *Zyrichidou et al.*, 2009). The Dutch-Finnish OMI (Ozone Monitoring Instrument) on-board NASA's EOS Aura satellite was launched onto a Sun-synchronous polar orbit on July 15, 2004 with an equator crossing time of 13:30 local time. OMI is a nadir-viewing imaging spectrometer which measures direct and atmosphere-backscattered sunlight in the ultraviolet-visible range (270 - 500 nm) using two two-dimensional CCD detectors. With its swath width of 2600 km it can achieve daily global coverage with a spectral resolution of 0.5 nm and spatial resolution of 13 km along track and 24 km to 128 km in across track (*Boersma et al.*, 2007; *Levelt et al.,* 2006a).

The datasets used in this study are GOME (April 1996 - June 2003), SCIAMACHY (July 2003 – March 2012) and OMI (April 2012 – December 2014). The OMI satellite data sets have been rescaled to match the coarser resolution of GOME and SCIAMACHY data. Monthly means were calculated on a grid of 0.25^0 x 0.25^0. In order to understand the consistency among the measurements from the three sensors, the comparison of monthly

mean tropospheric columnar NO_2 densities over Bay of Bengal region are shown in Figure 1. The tropospheric columnar NO_2 retrieved from GOME and SCIAMACHY agree within 0.01 x 10^{15} molecules/cm^2 (Fig 1a). The maximum difference of 0.038 x 10^{15} molecules/cm^2 (Fig 1b) was seen between SCIMACHY and OMI. It is important to note that the OMI equator crossing time is 13:30 local time, as opposed to SCIAMACHY's equator crossing time of 10:00 local time. The relative offset noted between the three satellite's data values could be due to the different equator crossing time of each of the satellites and different temporal sampling rates of each sensor (*Zyrichidou et al*., 2009). Taking into account of these reasons, we have examined the 19 year inventory of tropospheric NO_2 emissions combining the data from the three sensors. Linear regression has been used to study the trend in NO_2 values.

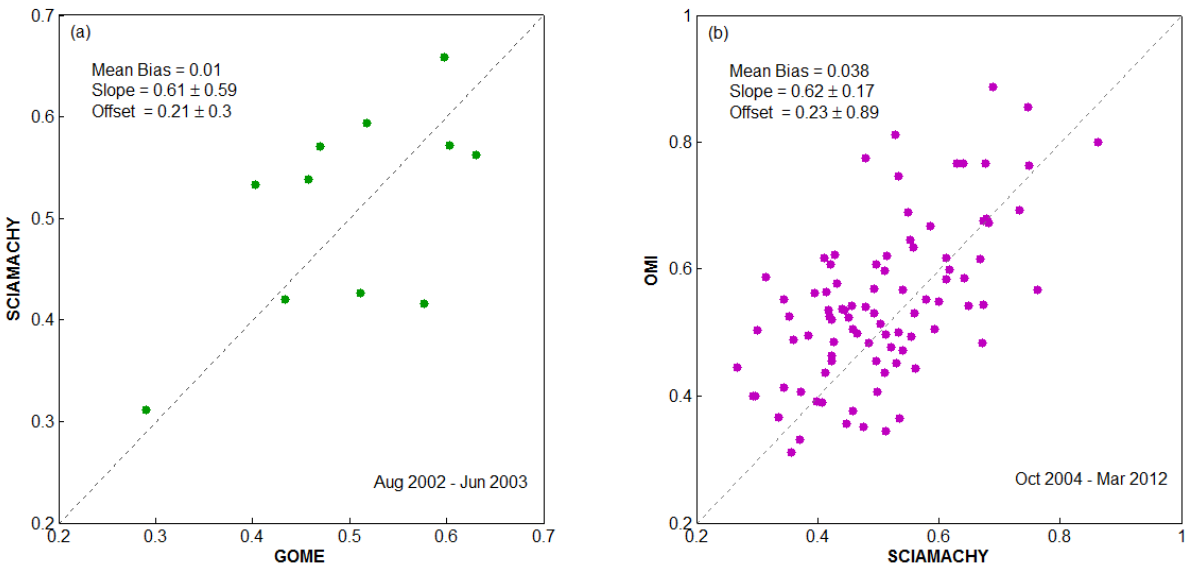

Figure 1: Scatter plot of the comparison of tropospheric columnar NO_2 (x 10^{15} molecules/cm^2) retrieved by (a) GOME and SCIAMACHY and (b) SCIAMACHY and OMI with all available common data. The dashed line corresponds to perfect agreement.

In order to understand the impact of NO_2 on the radiation budget, the calculations are performed with the MODTRAN (short for MODerate resolution radiative TRANsfer program) code (*Berk et al.*, 1998). The clear-sky (i.e., cloud-free condition) calculations are performed with MODTRAN5 code, which is the latest version of the radiative transfer code. The code simulates fluxes at mid-ultraviolet to visible to far-infrared bands to cover the solar

spectrum from 0.2 to 100.0 μm. Broadband integration in the shortwave region (0.2–4.0 μm) is used for estimation of fluxes at multiple altitudes (incoming and reflected), atmospheric solar absorption and heating rates. Correlated k-distributions are used to incorporate gaseous absorption by water vapour, ozone, oxygen, carbon dioxide etc. (see MODTRAN manual for more details, *Berk et al*., 1998). The model accounts for all multiple scattering and absorption by individual aerosol species, cloud droplets, air molecules, and reflections from the surface. The underlying surface is considered to be oceanic surface. The oceanic surface albedos were calculated according to *Briegleb et al.* (1986) and were incorporated in the code. The diurnal time averaging is performed by integration over the solar zenith angle. The model profile uses 33 atmospheric layers with a vertical resolution of 1 km from the surface to 25 km, 2 km from 25 to 30 km, 5 km from 30 to 40 km and 10km, 20km, 30km from 40 to 50 km, 50 to 70 km and 70 to 100 km respectively. The top of the atmosphere solar flux is from *Kurucz et al* (1992). Vertical profiles of meteorological parameters and gaseous concentrations were taken from the tropical standard atmosphere. Simulated fluxes were calculated by varying tropospheric columnar NO_2 amount using temporally relevant data. In this paper, we compute the net atmospheric heating due to tropospheric NO_2 with an emphasis on polluted shipping lane.

3. Results and Discussions

3.1 Enhancement of NO_2 in shipping corridor

Fig 2 shows the annual mean tropospheric columnar NO_2 amounts over Bay of Bengal in 1996 (from GOME measurements) and in 2014 (from OMI measurements). The large expanse of NO_2 values near the east coastline of India (and west of China) is due to the continental outflow of pollution. For instance in the Chennai region, tropospheric NO_2 increased by ~17% since 1996. Moreover, it can be clearly noted that in comparison to the 1996 image the shipping lane along ~5^0N has become more prominent and elevated in magnitude in the 2014 image. The shipping lane is identified by the region having NO_2 of about 1×10^{15} molecules/cm^2 in comparison to the surrounding region, where values of around 0.2×10^{15} molecules/cm^2 are found. This can be attributed to the increase in NO_2 due to ship emissions. The width of the shipping lane is approximately 1^0 in latitude (~110 km).

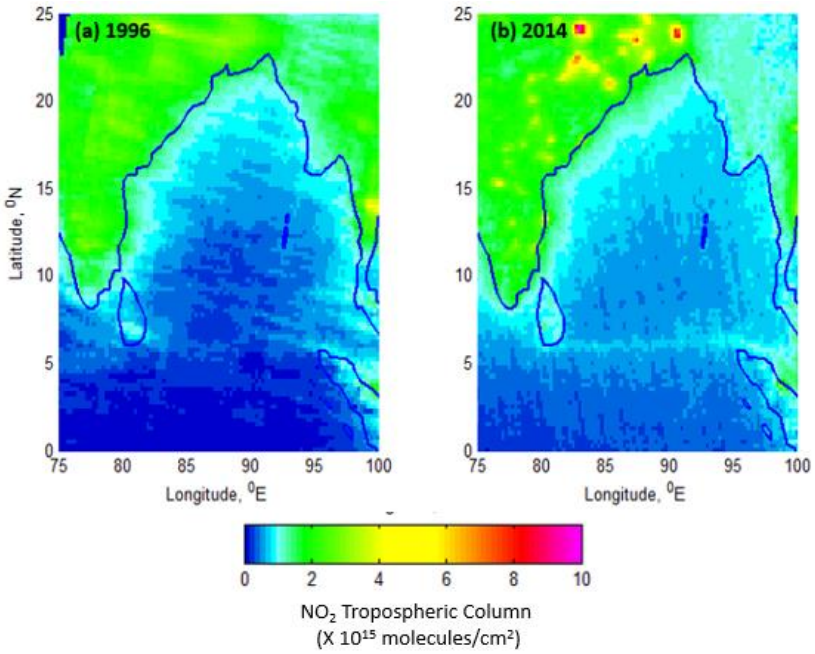

Figure 2: NO_2 signature of shipping in the Bay of Bengal. Annual mean tropospheric NO_2 retrieved by (a) GOME for the year 1996 and (b) OMI for the year 2014. A discernible rise in NO_2 concentration levels can be observed in the shipping lane at ~5^0N.

For the purpose of quantitative analysis, we have considered the region between 82^0E to 95^0E and 4.5^0N to 6.5^0N which contains the shipping track from Sri Lanka to Sumatra. Figure 3 shows the annual mean variation of tropospheric NO_2 over the above mentioned region. Linear regression over 8 years of GOME measurements in the shipping region yields a slope of (0.06 ± 0.2) $\times 10^{14}$ molecules/cm^2/yr. For the11 years of SCIAMACHY measurements the regression gives a slope of (0.05 ± 0.08) $\times$ 10^{14} molecules/cm^2/yr. Whereas for the 2 years of OMI measurements the regression yields a slope of (0.3 ± 0.7) x 10^{14} molecules/cm^2/yr. The rise in NO_2 values over the time period covered by GOME measurements (1996-2002), SCIAMACHY observations (2002-2012) and OMI observations (2012-2014) is 13%, 26% and 27% respectively. When we carry out the linear regression for the entire data (i.e., 1996-2014), the polluted shipping lane show an increase of NO_2 concentrations with a slope of (0.08 $\pm$ 0.04) x 10^{14} molecules/cm^2/year. Since there are no oceanic sources of NO_2 over this region, the observed increase in tropospheric NO_2 values due to commercial ships at 5^0N is significantly high.

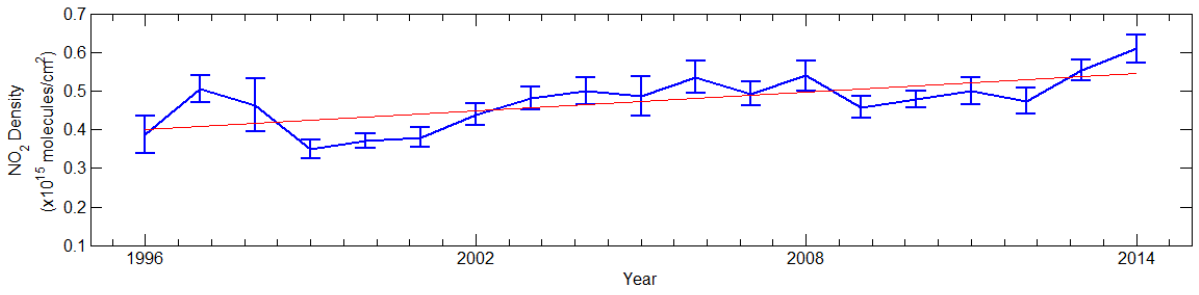

Figure 3: Time series analysis NO_2 concentrations for the shipping corridor over Bay of Bengal from the satellite observations of GOME, SCIMACHY and OMI.

3.2 Dimming due to NO_2

Dimming (i.e., a reduction in surface reaching solar radiation) has been reported over the last several decades primarily due to aerosol direct and indirect effects (e.g., *Stanhill and Cohen.*, 2001). Various estimates of dimming have been reported, and they vary with location (*Liepert et al.*, 2002). *Ramanathan and Ramana* (2005) estimated a reduction of surface reaching solar radiation due to aerosols from about 5% to 10% of Top of Atmosphere (TOA) insolation over the variety of polluted regions around the world.

NO_2 absorbs solar radiation at ultraviolet and visible wavelengths and Fig 2 shows clear enhancement of tropospheric NO_2 in the shipping lane. Using the MODTRAN radiative transfer code, the net surface reaching solar radiation with NO_2 and without NO_2 is estimated in the shipping lane (6^0N and 86^0E) over the Bay of Bengal. The NO_2 radiative forcing at the surface is the effect of NO_2 on the net short-wave radiative fluxes and is defined as the difference between the clear-sky net shortwave radiative flux with and without NO_2 atmosphere. In the radiative transfer model, NO_2 columnar amounts are fixed as per the OMI gridded monthly mean value (i.e., the value near 13:30 local time). The calculated diurnal variation of NO_2 radiative forcing at the surface is plotted in Fig.4. The reduction in the surface reaching irradiance by NO_2 is close to -0.8 ± 0.2 W/m^2 during the solar noon time in the shipping lane over the Bay of Bengal. Therefore, NO_2 is contributing to the observed global dimming and may be of importance locally in radiative forcing.

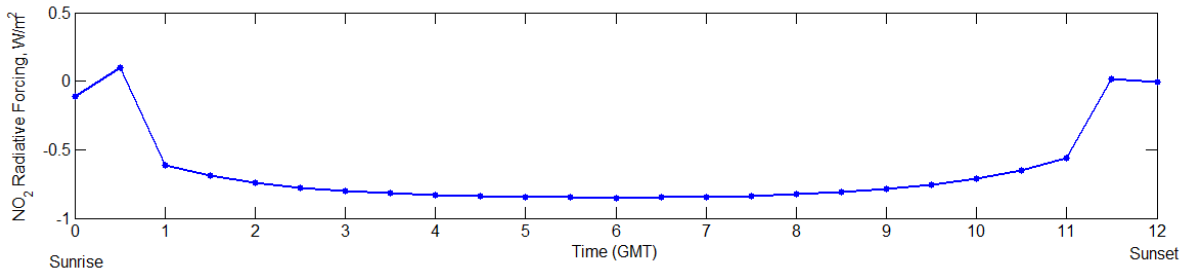

Figure 4: Diurnal variations of tropospheric NO_2 radiative forcing at the surface over the polluted shipping region in the Bay of Bengal.

3.3 Diurnal mean Atmospheric heating due to NO_2:

The 24-hour mean atmospheric heating in the shortwave region (0.2 – 4.0 μm) from surface to 16 km altitudes with NO_2 and without NO_2 atmosphere is calculated using the MODTRAN radiative transfer code. The increase in NO_2 concentrations during the 19 year period is almost 2 x 10^{14} molecules/cm^2. The vertical profiles of net atmospheric heating rates for the respective atmospheres are computed at different zenith angles and are converted into 24-hour mean (i.e., diurnal mean) values. The radiative transfer computations show that the diurnal mean atmospheric heating for the lower atmosphere in the shortwave region due to the increased tropospheric NO_2 concentration in the study area for the 19 year period (from 1996 to 2014) is close to 0.05 $\pm$ 0.02 K for clear sky conditions. Ship emitted NO_2 may reside in the atmospheric boundary layer (i.e., ~1 km above the ocean surface), which may heat the lower atmosphere further.

4. Conclusions

The distinct line of NO_2 in the ocean identified in the satellite image clearly coincides with the ship routes from Sri Lanka to Indonesia. In this study, ship emissions of NO_2 in the Bay of Bengal have been analysed with the help of measurements from GOME (April 1996 - June 2003), SCIAMACHY (July 2003 - March 2012) and OMI (April 2012 – December 2014).The shipping route from India to Indonesia can be detected in satellite data with an enhancement in tropospheric NO_2 of about 2 × 10^{14} molecules/cm^2 (~50% increase). Linear regression has been used to study the trend in tropospheric NO_2 within the measurement

period from GOME, SCIAMACHY and OMI measurements. From the trend analysis statistically significant increase in NO_2 was identified.

The radiative impact of tropospheric columnar NO_2 is calculated using MODTRAN radiative transfer code. Our calculations of the surface irradiance reduction by NO_2 is ~1 W/m^2 during the solar noon hours during clear sky conditions. Therefore, NO_2 is important locally in radiative forcing, but the trace gas may not be contributing significantly to the observed global dimming. The contribution to net atmospheric heating by the increased tropospheric NO_2 is 0.05 K. Although the MODTRAN calculated flux values have uncertainties (due to uncertainties in the NO_2 satellite observations and model calculations), the result highlights the contribution of ship emissions to the radiative forcing in marine boundary layer over the Bay of Bengal.

In addition, our group carried out direct measurements of cloud condensation nuclei (CCN) over Bay of Bengal region during summer 2012. CCN concentrations over polluted shipping regions are about one order of magnitude greater than over their remote counter parts. CCN efficiency varied from 0.56 $\pm$ 0.06 over relatively pristine location to 0.17 $\pm$ 0.1 over polluted shipping corridor. The seaborne trade in South Asia grew by an average of 5 - 6% per year in recent times [*Streets et al*., 2000]. There are efforts to decrease sulphur emissions from ships [*Capaldo et al*., 1999; *Streets et al*., 2000], and the data presented in this study suggest that such reductions should be accompanied by reductions in NO_2 also. The complexity of myriad nonlinear effects resulting from anthropogenic emissions from commercial ships over southern Bay of Bengal is an area worthy of study.

Acknowledgments

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