The global economic cycle and satellite-derived NO$_2$ trends over shipping lanes

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[1] In recent years, space-borne spectrometers have been used to detect shipping emissions of nitrogen oxides. Driven by economic growth, these emissions have been increasing for several decades, yet in few studies it has been attempted to detect trends in ship emitted NO$_2$ from space. Here a method is presented that enhances the shipping signal in satellite measurements of NO$_2$, which makes it possible to detect non-linear trends on a monthly to yearly basis. The method removes variations in NO$_2$ measurements over shipping lanes that are not related to shipping and that obscure shipping trends. With this method we could detect non-linear trends in NO$_2$ over major shipping lanes in the Mediterranean Sea, the Red Sea, the Indian Ocean and the South Chinese Sea. The shipping signal displays a large increase of 62–109% between 2003 and the summer of 2008 and a sharp decline of 12–36% afterwards, corresponding to the global economic recession of 2008-2009. These two trends are detected over all four shipping lanes by several space-borne spectrometers. Because of high correlations between satellite data mutually and between satellite data, shipping statistics and international trade volumes, we conclude that the detected trends are caused by actual changes in shipping emissions. This study therefore shows that it is possible to detect short-term economic fluctuations in satellite measurements of NO$_2$ over major shipping lanes. Citation: de Ruyter de Wildt, M., H. Eskes, and K. F. Boersma (2012), The global economic cycle and satellite-derived NO$_2$ trends over shipping lanes, Geophys. Res. Lett., 39, L01802, doi:10.1029/2011GL049541.

1. Introduction

[2] Anthropogenic emissions of greenhouse gases and other trace gases into the atmosphere, caused by the combustion of fossil fuels, are directly related to human activities and the global economy [e.g., Raupach et al., 2007]. This is also the case for shipping, as over the last 30 years a clear relation has been observed between fuel consumption by ships and seaborne trade in ton-miles [e.g., Endresen et al., 2007]. As the global economy expanded during recent decades, both the global seaborne trade volume and the world fleet fuel consumption displayed an average rising trend of more than 3% per year [Eyring et al., 2010]. The increase in international shipping emissions has been made possible by the near-absence of legislation, which contrasts with the situation over land in Europe and North America. There, the increase in economic activity has been compensated by legislation that reduces emissions. The exact level of emissions by ships is not known and estimates of global emission totals from shipping differ significantly [Eyring et al., 2010].

[3] One way to reduce the uncertainty in the level of shipping emissions is to use data from space-borne spectrometers, which can measure vertical column densities of several trace gases. Of importance for detecting shipping emissions are satellite measurements of NO$_2$, which clearly display several major international shipping lanes [e.g., Beirle et al., 2004; Richter et al., 2004; Franke et al., 2009; Marmer et al., 2009]. These studies have shown that quantitative information about NO$_2$ concentrations from shipping can be derived from satellite data.

[4] It is also possible to detect trends in NO$_2$ with satellite measurements, as has been done in a number of studies [see Richter, 2009]. However, most of these studies are primarily concerned with continental emissions and in very few studies trends in NO$_2$ concentrations from shipping have been detected. Franke et al. [2009] made multi-annual linear regressions of monthly values of tropospheric NO$_2$ over a shipping lane in the Indian Ocean. They found an apparent increase in NO$_2$ columns between early SCIAMACHY measurements and more recent GOME-2 measurements. Konovalov et al. [2008] derived linear trends in NO$_2$ from satellite data over Europe and found a decadal increase in shipping emissions over the Mediterranean Sea.

[5] In this study, we describe a method to derive non-linear trends in NO$_2$ over shipping lanes, based on monthly data. This method removes noise and enhances the relatively weak shipping signal, so that changes over shipping lanes can be derived with a temporal resolution of one month. The method is applied to some major international shipping lanes that are clearly visible in the data from several satellite sensors [e.g., Beirle et al., 2004; Richter et al., 2004; Franke et al., 2009; Marmer et al., 2009]. These shipping lanes are located in the Mediterranean Sea, the Red Sea, the Indian Ocean east of Sri Lanka and the South Chinese Sea east of Malaysia. It is not the purpose of this study to estimate NO$_x$ emissions quantitatively, but to detect short-term trends in NO$_2$. The high temporal resolution of the inferred trends allows a detailed comparison between derived NO$_2$ concentrations and statistics on shipping and trade during the economic crisis of 2008 and 2009. This comparison may help to improve our understanding of the relation between shipping emissions and economic activity.

2. Satellite Data

[6] We use NO$_2$ measurements from four different sensors: GOME, SCIAMACHY, OMI and GOME-2 (see Table 1). These sensors have been in operation during periods that
partly overlap and combined, the entire period from 1996 till present is covered. The temporal overlap also means that data from different sensors can be cross-validated. Such a cross-validation, however, is hindered somewhat by different properties of the datasets. First, the spatial resolution of GOME, the only instrument that covers the period 1996–2003, is 320 km across the satellite track (WNE-ESE). This is insufficient to detect all shipping lanes, which typically have a width of about 100 km [Franke et al., 2009]. Only in the along-track direction (NNE-SSW), the resolution of GOME is high enough, and the more a shipping lane is oriented perpendicular to this direction, the more likely it will be detected by GOME. The other sensors have higher spatial resolutions and can resolve the width of all major shipping lanes.

Second difference between the various data sets is the acquisition time of the data. All data from GOME, SCIAMACHY and GOME-2 were acquired in the morning, whereas OMI data were acquired a few hours later in the early afternoon. This has consequences for the observed NO$_2$ density, because the NO$_2$ concentration exhibits a daily cycle. Therefore, OMI will normally detect lower NO$_2$ densities than the other three instruments [Boersma et al., 2008; Vinken, 2008]. Finally, Table 1 shows that OMI has the highest repeat time, which is beneficial for the detection of weak anthropogenic signals. When more images are available during a certain period, more noise is suppressed in the average image over that period.

The spectra that are measured by these space-borne spectrometers can be converted into the total number of NO$_2$ molecules in a vertical column of the troposphere. This was done for all four instruments in a similar way. First, total slant columns were derived with the DOAS technique. This was done for GOME, SCIAMACHY and GOME-2 by the Belgian Institute for Space Aeronomy (BIRA-IASB) and for OMI by the Royal Netherlands Meteorological Institute (KNMI) and NASA. Then, tropospheric vertical column densities (TVCDs) of NO$_2$ were derived with the combined modeling/retrieval/assimilation approach of KNMI [Boersma et al., 2004, 2007]. Absolute errors are primarily introduced by the second processing step [Boersma et al., 2004], which is similar for all instruments.

Average TVCD values over the area of interest are shown in Figure 1a. Of importance for this study is the intercontinental network of shipping lanes south of the Eurasian continent. This network is visible in the Mediterranean Sea, the Red Sea, the Indian Ocean and in the South Chinese Sea. It is detected by all used instruments, although the spatial resolution of GOME is too low to detect all parts of it. These international shipping lanes are narrow and well defined, because they represent the shortest way around the landmasses. Also, the emitted NO$_2$ is concentrated along the shipping lanes because NO$_2$ has a relatively short lifetime. The visibility of the shipping lanes is further enhanced because the atmosphere above the surrounding waters is mostly pristine. Close to populated regions on land, it is more difficult to detect shipping signals clearly, because there they intermingle with land-based emissions.

### 3. Method

Because of variable conditions, satellite measurements of the TVCD display large fluctuations in time. In order to reveal trends in the shipping signal that are obscured by these variations, the data were processed in the following way. First we defined a section of each studied shipping lane, as well as nearby areas well separated from the shipping lanes where NO$_2$ concentrations are much lower (see Figure 1a). It is assumed that these adjacent regions are not measurably affected by shipping lane. This assumption is valid because the atmosphere above the surrounding waters is mostly pristine. Close to populated regions on land, it is more difficult to detect shipping signals clearly, because there they intermingle with land-based emissions.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Satellite</th>
<th>Retrieval Algorithm</th>
<th>Period of Operation</th>
<th>Horizontal Resolution* (km)</th>
<th>Local Equator Crossing Time (During Daylight)</th>
<th>Global Coverage Time (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOME</td>
<td>ERS-2</td>
<td>TM4NO2A v1.04</td>
<td>1996 - 2003</td>
<td>40 320</td>
<td>10:30 (desc.)</td>
<td>3</td>
</tr>
<tr>
<td>SCIAMACHY</td>
<td>Envisat</td>
<td>TM4NO2A v1.10</td>
<td>2002 - present</td>
<td>30 120</td>
<td>10:00 (desc.)</td>
<td>6</td>
</tr>
<tr>
<td>OMI</td>
<td>EOS-aurora</td>
<td>DOMINO v1.02</td>
<td>2004 - present</td>
<td>13 24</td>
<td>13:38 (asc.)</td>
<td>1</td>
</tr>
<tr>
<td>GOME-2</td>
<td>MetOp-A</td>
<td>TM4NO2A v1.10</td>
<td>2007 - present</td>
<td>40 80</td>
<td>09:30 (desc.)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

*For GOME, SCIAMACHY and GOME-2 the exact directions are NNE-SSW and NW-ENE; for OMI the exact directions are NNW-SSE and WSW-ENE.
fluctuations. Similar fluctuations are present in the annual running mean of TVCD$_{bg}$, but here no basic rising trend is present. Subtraction of TVCD$_{bg}$ from TVCD$_{tot}$ yields TVCD$_{ship}$, in which the fluctuations are removed and the trend becomes much more pronounced.

4. Results

4.1. Trends in the Satellite-Derived Shipping Signal

With the procedure above, regional variations in NO$_2$ concentration are suppressed and underlying trends that are similar for all regions emerge (see Figure 3). For the period until 2002 only GOME data are available, but, as mentioned in section 2, these cannot resolve shipping lanes with an orientation close to NNE-SSW. This is the case for the shipping lane in the South Chinese Sea. Over the Red Sea and over the Indian Ocean, TVCD$_{ship}$ is also rather low (below 0.3 10$^{15}$ molec./cm$^2$), but a slight rising trend seems present. The strongest signal is detected over the Mediterranean Sea, but there the results may be biased because of the proximity of land-based sources of NO$_x$ and the large size of the GOME pixels.

Figure 1. NO$_2$ TVCDs over the study area, detected by SCIAMACHY. (a) Average values between January 2007 and December 2008. Indicated are the four studied shipping lanes and their respective background regions: the Mediterranean Sea (1), the Red Sea (2), the Indian Ocean (3) and the South Chinese Sea (4). (b) Difference between the periods January 2007 – December 2008 and July 2002 – July 2004. The arrows indicate the increase in NO$_2$ over the four studied shipping lanes.
[14] A more pronounced increase in TVCD\textsubscript{\text{ship}} occurred over all regions between 2003 and 2008, for which period data from SCIAMACHY and OMI are available. This increase is confirmed by the difference image in Figure 1b. The four selected shipping lanes are visible as narrow bands where the NO\textsubscript{2} concentration has increased.

[15] During the summer of 2008 the positive trend reversed and a strong decline commenced. Figure 3 shows that this trend reversal is consistently detected over all four shipping lanes and by all three instruments that were operational at the time. The decline is smallest in the OMI data, which seems to be caused by the late overpass-time of OMI, when the NO\textsubscript{2} concentration is low. Relatively, however, all three instruments detect decreases of a similar magnitude between the summers of 2008 and 2009. Over the entire period 2003–2010, temporal correlations between different instruments and regions are mostly high with an average correlation coefficient of 0.71. This is the case for measurements by one instrument over different areas, as well as for measurements over one area by different instruments.

4.2. Comparison With Economic Data

[16] The observed fall in NO\textsubscript{2} concentrations coincides with the global economic recession of 2008 and 2009, when international trade collapsed [Baldwin, 2009]. To investigate this concurrence, we compared monthly values of the annual running means of TVCD\textsubscript{\text{ship}} with statistical data on international shipping and trade volumes. Monthly values of shipped cargo volume were obtained for the Suez Canal [Suez Canal Authority, 2011]. We also used monthly international trade volumes, which were obtained from the Netherlands Bureau for Economic Policy Analysis (CPB) (CPB, World trade monitor: January 2011, http://www.cpb.nl/en/number/world-trade-monitor-january-2011). Regions in the CPB data set that are relevant for this study are: the countries of the Euro area, Asia (Japan excluded) and Japan. It makes sense to use these data, as 80 to 90% of the global

Figure 2. Intermediate and final results of the retrieval method. Results are shown for the South Chinese Sea and were measured by SCIAMACHY.

Figure 3. Annual running means of NO\textsubscript{2} TVCD\textsubscript{\text{ship}}, measured by four different sensors over four different shipping lanes. The shaded bands indicate the standard error in each annual mean value.
Trade volume is transported by ships [Eyring et al., 2010]. Also, although the CPB data only partly represent shipping traffic along the studied shipping lanes, they complement the Suez Canal data. First, they are valid for a much larger area and, second, they can be viewed as an independent source of information that links satellite data and shipping volumes to the regional and global economy. All shipping and trade data were indexed with respect to the year 2000 and averaged over twelve months in the same way as the satellite data.

[17] Shipping and trade volumes are shown in Figure 4, together with the NO$_2$ data from GOME and SCIAMACHY, the two instruments that have been operational for the longest time. To facilitate the comparison, the satellite data in this figure have been averaged over the four shipping lanes. Correlations between the satellite data and the shipping and trade volumes are mostly high. On average, the correlation of SCIAMACHY, OMI and GOME-2 data over the Mediterranean Sea and the Red Sea with the shipped volume through the Suez Canal is 0.78. For the same three instruments, the average correlation with trade data for the Euro area and Japan is 0.77. These results suggest a direct relationship between observed NO$_2$ concentrations and shipped cargo volume. However, some of the correlations that we find are rather low. This is the case for most GOME data, probably due to the low spatial resolution of this instrument. Some low correlations are also found for the Asian trade volume, which is probably due to the fact that the CPB data only partially represent shipping along the studied shipping lanes.

[18] In general, however, satellite data, shipping volume and trade volumes follow the same trends: before 2003, the trade volumes increased modestly with some small perturbations. During this period the GOME data also display a very slight increase. From 2003 till 2008 there was robust economic growth and international shipping volumes increased. According to the United Nations Conference on Trade And Development (UNCTAD), worldwide seaborne trade increased with 39% between 2002 and 2008 [United Nations Conference on Trade and Development, 2009]. Between June 2003 and June 2008, transported volume through the Suez Canal increased with 64% and the CPB data display increases in trade volume of 23 to 84%. During the same period, TVCD$_{\text{ship}}$ values that are detected by SCIAMACHY also increased strongly over all studied shipping lanes, with increases ranging from 92 to 121%.

[19] During the economic recession that began in the summer of 2008, international trade declined strongly. The trade data in Figure 4 show that shipping and trade volumes peaked during the summer of 2008, after which a decline of 11% to 25% set in. Interestingly, the average satellite signal over the four regions peaks at exactly the same moment and displays equally substantial declines afterwards, ranging from 12% to 36%.

5. Discussion and Conclusions

[20] For several major international shipping lanes that are visible in satellite measurements of NO$_2$ densities, a trend analysis over a number of years was performed. Over these shipping lanes the NO$_2$ signal is not as strong as over many continental regions, but they are often situated against a
pristine background. Because of this, it is possible to remove background variations from the shipping signal and to make underlying trends more apparent. This is possible for data from several space borne instruments, including GOME, SCIAMACHY, OMI and GOME-2. The instrument per excellence is one of the older instruments, SCIAMACHY. It combines a long time series with an adequate spatial resolution and an early overpass time at 10:00 AM, when the diurnal cycle of NO\(_2\) is still in a relatively high phase.

[21] The detection of trends in shipping emissions is especially possible for well-defined shipping lanes that are situated in relative pristine areas and where low average cloudiness allows ample sampling. This is the case for the shipping lanes that have been studied here: the Mediterranean Sea, the Red Sea, the Indian Ocean and the South Chinese Sea. Over regions with variable weather, frequent clouds and/or large continental emission sources nearby, detection of shipping signals and especially trends therein is more difficult. For example, some of the most busy ship traffic in the world is found in the North Sea and along the European margin of the Atlantic Ocean, but with the method described in this study no trends could be detected there.

[22] Similar general trends and temporal variations could be detected in most time series, independent of the instrument and the region: an increase in NO\(_2\) densities between the summers of 2003 and 2008 and a decrease between the summers of 2008 and 2009. Correspondingly, temporal correlations between different regions and different instruments are mostly high with an average value of 0.71. The emergence of the same temporal trends in most of the time series demonstrates the effectiveness of the method to separate the background signal, which depends on local conditions, from the shipping signal, which has a more intercontinental signature.

[23] The satellite-derived NO\(_2\) column densities also correlate well with statistics on shipping and international trade volumes: the average correlation between SCIAMACHY, OMI and GOME-2 data over the Mediterranean Sea and the Red Sea with shipping volumes through the Suez Canal is 0.78. High correlations are also found when the satellite data over all studied shipping lanes are compared with trade data for the Euro area and Japan. Between the summers of 2003 and 2008, shipping volume through the Suez Canal, international trade volumes and values of TVCD\(_{\text{ship}}\) all increased, respectively with 64%, 23–84% and 92–121%. The economic crisis of 2008 and 2009 is also clearly visible in all data sets, with declines of 25%, 11–22% and 12–36%, respectively. Indeed, the severity of this recession and the strong decline in international trade and shipping emissions make the period between 2000 and 2010 par excellence suitable for detecting non-linear trends in NO\(_2\). Because of the high correlations between satellite data mutually and between satellite data, shipping statistics and international trade volumes, we conclude that the detected trends are caused by actual changes in shipping emissions. This means that it is possible to detect in satellite observations of NO\(_2\), on a monthly to annual time scale, the economic cycle of boom and bust in shipping.

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