Introduction
Satellite observations of atmospheric constituents have many applications in the area of climate research, air quality monitoring and aviation safety. Here, we will focus on the satellite observations of two important trace gases, NO$_2$ and SO$_2$. Applications are air quality monitoring and support to aviation control.

Nitrogen oxides (NO$_x$, the collective name for NO and NO$_2$) play an important role in atmospheric chemistry and in the climate system as precursor of tropospheric ozone, an important greenhouse gas. The most important source of NO$_x$ is the combustion of fossil fuels, mainly by traffic and large power plants. Other important contributors are the burning of biomass, soil emissions and lightning. Close to the earth surface the lifetime of NO$_x$ is short (a few hours). Therefore, NO$_2$ concentrations will be highest close to the source. Nitrogen oxides affect the health of humans and animals. They irritate the lungs and lead to lower resistance to respiratory infections such as influenza. Frequent exposure to high concentrations may cause acute respiratory illness. Another serious problem caused by nitrogen oxides is the formation of aerosols and tropospheric ozone (i.e. smog), which has also harmful health effects. In addition, increasing tropospheric ozone affects climate.

Sulphur dioxide, SO$_2$, enters the atmosphere as a result of natural phenomena as well as anthropogenic activities, e.g. combustion of fossil fuels, oxidation of organic material in soils, volcanic eruptions, and biomass burning. Coal burning is by far the largest man-made source of SO$_2$ (about 50%), with oil burning accounting for a further 25 to 30%. Sulphur dioxide reacts on the surface of a variety of airborne solid particles, is soluble in water and can be oxidised within airborne water droplets, producing sulphuric acid. This acidic pollution can be transported by wind over large distances, and is deposited as acid rain. Changes in the abundance of SO$_2$ have an impact on atmospheric chemistry and hence on the climate. Consequently, global observations of SO$_2$ are important for atmospheric and climate research. Volcanic eruptions are important sources of ash and SO$_2$ in the atmosphere, which may have an impact on air traffic. Near-real time retrieval of SO$_2$ concentrations enables monitoring of such events and assists in aviation control. Off-line retrieval, on the other hand, is more suitable for monitoring anthropogenic pollution aspects.

Tropospheric nitrogen dioxide

Satellite observations
Satellite instruments (such as GOME, SCIAMACHY and OMI) use spectroscopy to retrieve atmospheric trace gas concentrations in the atmosphere. By comparing the measured spectrum of the backscattered light from the Earth’s atmosphere with a reference spectrum, the column density of nitrogen dioxide along the light path can be determined. The NO$_2$ stratospheric column is deduced from a chemistry-transport model assimilation run of the NO$_2$ column data. Subsequently, the assimilated stratospheric column is subtracted from the retrieved total column, resulting in a tropospheric column. Information about the global tropospheric NO$_2$ columns is publicly available on the TEMIS (Tropospheric Emission Monitoring Internet service) website http://www.temis.nl. TEMIS is a service, led by the KNMI, that provides tropospheric data from satellites freely to a wide range of users and applications. More details about the satellite observations and the retrieval technique can be found in several publications$^{1,4,9}$.

NO$_2$ has been monitored by satellite since 1995 with GOME, since 2002 with SCIAMACHY, and since 2004 with the OMI instrument; the latter two instruments having the advantage of a high spatial resolution. In Figure 1 the mean tropospheric NO$_2$ is shown as measured by OMI in the period May 2006 till February 2007. Clearly visible are the industrial regions in China, Europe, South-Africa and the USA. The yearly averaged NO$_2$ column for 2005 measured with SCIAMACHY zoomed-in over China can be seen in Figure 2. It shows high concentrations of NO$_2$ above highly populated regions like Beijing, Shanghai, Hong Kong and South Korea. It can also be seen that the satellite detects the emissions around the Yellow river (Huang He). Over the sparsely populated western
part of China, low NO\textsubscript{2} concentrations are observed, except over the large city Urumqi in the Northwest.

**Air quality monitoring**

Blond and co-authors\textsuperscript{4} have shown that SCIAMACHY provides detailed information on the nitrogen dioxide content in the planetary boundary layer. The cloud free satellite observations were compared with surface measurements and simulations over Western Europe performed with the regional air-quality model CHIMERE (shown in Figure 3). The model has a resolution of 50 km, similar to the satellite observations. CHIMERE seems to underestimates surface NO\textsubscript{2} concentrations for urban and suburban stations but this is mainly attributed to the low representativeness of point observations. No such bias is found for rural locations. The yearly-average SCIAMACHY and CHIMERE spatial distributions of NO\textsubscript{2} show a high degree of quantitative agreement over rural and urban sites: a bias of 5\% (relative to the retrievals) and a correlation coefficient of 0.87 ($n=2003$). The consistency of both SCIAMACHY and CHIMERE outputs over sites where surface measurements are available gives confidence in evaluations of the model over large areas not covered by surface observations. The NO\textsubscript{2} columns show a high daily variability. Still, the daily NO\textsubscript{2} pollution plumes observed by SCIAMACHY are often well described by CHIMERE both in extent and in location. This result demonstrates the capabilities of a satellite instrument such as SCIAMACHY to accurately monitor the NO\textsubscript{2} concentrations over large areas on a regular basis. It provides evidence that present and future satellite missions, in combination with a regional air quality model and surface data, will contribute to improve quantitative air quality analyses at a continental scale.

**Trends in tropospheric NO\textsubscript{x} emissions**

The combined measurement series of both GOME and SCIAMACHY almost span a decade, which allows for a trend analysis of NO\textsubscript{2} concentrations. To do so, the averaged monthly tropospheric NO\textsubscript{2} columns are fitted with a linear model that also includes a sinus to represent the seasonal variation of NO\textsubscript{2}. The seasonal variation for anthropogenic NO\textsubscript{2} is mainly determined by the changing day-length over the year. In absence of sunlight NO\textsubscript{2} has a longer lifetime in the atmosphere, which explains that the NO\textsubscript{2} columns are on average higher during wintertime. By applying the model to each grid cell a spatial distribution of the fit parameters is calculated. Furthermore the precision of the trend is calculated. It can be concluded that the 10 years long NO\textsubscript{2} dataset from GOME and SCIAMACHY can be used for significant trend analysis in most parts of the world. In highly populated and industrialised areas the trend is large enough to be significant. For instance Shanghai had a yearly increase of tropospheric NO\textsubscript{2} of about 29\% since 1996. Figure 4 shows the derived annual growth in the tropospheric NO\textsubscript{2} columns from this analysis.
The largest trend is found in Eastern China, where the economic growth is one of the fastest of the world. The fastest growing city with respect to both economy and tropospheric NO$_2$ is Shanghai. It is interesting to note that the growth in the region around Hong Kong is less than for other regions with a high economical activity. This is probably due to the already high level of economic activity in 1996 when our trend study started, and to a package of measures against air pollution in Hong Kong over the last years. Further results of this trend study are published by Van der A and co-authors.\textsuperscript{5}

**Global implications**

The fast growing emissions in China lead locally to rapidly increasing NO$_2$ concentrations, which affects the local ozone concentrations. Clearly these large increases will have severe consequences for the local air quality, but even effects on global scale can be expected, because the lifetime of tropospheric ozone is much larger than the lifetime of NO$_2$. Therefore, ozone can be transported over large distances by the wind. Using a chemical transport model the change in ozone due to increasing emissions in China can be calculated. Figure 5 shows increasing ozone concentrations in the Northern hemisphere caused by the growing Chinese emissions in the period 1997-2005. In this period of eight years the global averaged tropospheric ozone column has increased with 0.54\%\textsuperscript{6}. The largest growth in tropospheric ozone we find in a plume reaching from China to the East along the direction of the prevailing winds. From the figure we conclude that the tropospheric ozone concentrations in the entire Northern hemisphere are increased due to the growing emissions in China. These increases seem small, but are still important. In Europe, the air pollution has been increased as a result of intercontinental transport. In addition, since ozone is a strong greenhouse gas, the effects on climate change cannot be neglected.
Volcanic eruptions may eject large amounts of ash (aerosols) and trace gases such as SO$_2$ into the atmosphere. These ejecta can have considerable impact on the safety of air traffic and on human health. Ground-based monitoring is carried out at only a limited number of volcanoes: most volcanoes, in particular remote ones, are not monitored on a regular basis. Global observations of SO$_2$ and aerosols derived from satellite measurements in near-real-time may therefore provide useful complementary information to assess possible impacts of volcanic eruptions on air traffic control and public safety. Observations of SO$_2$ are performed with UV-VIS satellite instruments such as GOME, SCIAMACHY and OMI. The technique used to retrieve the SO$_2$ column is called Differential Optical Absorption Spectroscopy (DOAS). Volcanic emissions and strong pollution events are clearly detected with this approach, which makes it very suitable for use in a near-real-time service, with an automatic warning system for exceptional SO$_2$ emission levels. Within the ESA projects TEMIS and PROMOTE this system provides information to the London and Toulouse VAAC (Volcanic Ash Advisory Centre), which issues warnings to the airline companies in case of observed volcanic ash or SO$_2$ clouds. The London and Toulouse VAAC are responsible for the air traffic in Europe, Africa and part of Asia.

**Figure 5.** The difference in ground-level ozone caused by the increase of Chinese NO$_x$ emissions between 1997 and 2005.

**Figure 6.** OMI observations of SO$_2$ from the eruption of the Manam volcano in New Guinea on 27 January 2005 (source: NASA).

Shanghai had a yearly increase of tropospheric NO$_2$ of about 29% since 1996

**Volcanic eruptions**

A decade of satellite observations of nitrogen dioxide in the atmosphere has been used to derive trends in anthropogenic emissions in China. As expected the nitrogen dioxide concentration is growing most rapidly in Eastern China, where the economic growth is largest. By feeding the derived trends to a global chemical transport model of the atmosphere the effects on the concentrations of world-wide tropospheric ozone can be determined. According to the model the background concentration of ozone has increased in the entire northern hemisphere as a result of the growing emissions in China. Another trace gas observed by satellites is SO$_2$, which occurs in large quantities in areas with large air pollution or with volcanic eruptions. Observation of these volcanic eruptions in near-real time helps the Volcanic Ash Advisory Centres in warning airline companies for potentially dangerous areas.

**Conclusions**

Figure 6 shows the OMI observations of SO$_2$ from the eruption of the Manam volcano in New Guinea on 27 January 2005.