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Cross-references

Stratospheric Ozone

TRACE GASES, TROPOSPHERE - DETECTION FROM SPACE

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Introduction

The increase of human activity over the last 100 years has resulted in an enormous increase in atmospheric

concentrations of various gases of anthropogenic origin, polluting the atmosphere and changing climate on Earth. The detection of the stratospheric ozone hole raised awareness that human activities can lead to dramatic changes in atmospheric composition, with large consequences for life on Earth. The satellite maps of air pollution and greenhouse gases in the troposphere (this is the lower 10–16 km of the atmosphere) over the last 5–10 years made people realize that our lifestyle does not only influence the ozone layer but also our daily living environment and the air we breathe.

Trace gases in the troposphere

The atmosphere consists of nitrogen (78 %) and oxygen (21 %), with only a minor contribution from other gases (1 %), which are called trace gases due to their low abundance. Although their abundance is low, trace gases play a key role in climate change and air quality. Ozone (O_3) is one of the most abundant minor trace gases. Ozone resides mainly in the stratosphere – the so-called ozone layer – protecting us from the harmful ultraviolet radiation from the Sun because it efficiently absorbs this high-energy radiation. Ozone also plays an important role in the troposphere, where it is a greenhouse gas as well as an air pollutant. Other important tropospheric trace gases are carbon dioxide (CO_2), water vapor (H_2O), methane (CH_4), nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), NH_3 and VOCs (volatile organic compounds) like formaldehyde ($HCHO$). CO_2 and H_2O are important greenhouse gases. H_2O plays a major role in the hydrological cycle and is the gas that in reaction with O_3 forms the highly reactive radical OH. OH is the key species in cleansing the atmosphere of pollutants. All other mentioned gases play a role as greenhouse gas or air pollutant and/or as a precursor for a greenhouse gas, aerosols, or air pollutant. For example, NO_2 is an air pollutant and an important precursor for the greenhouse gas ozone and aerosols, as the air pollutant SO_2 is also an important precursor for aerosols. Other nongaseous atmospheric constituents that are of paramount importance for climate change and air pollution are aerosols and clouds.

The trace gases CO_2 , CH_4 , NO_2 , SO_2 , $HCHO$, NH_3 and CO , which can be observed from space and are increasing due to human activities, will therefore be the focus of this entry. H_2O is a natural gas and will therefore not be considered. OH in the troposphere is undetectable from space.

History of detection of trace gases from space

In the early 1970s, the first measurements of (stratospheric) ozone were made from space by the SBUV satellite instrument (Hilsenrath et al., 1995), later followed by the TOMS instrument (McPeters et al., 1996). These were the first measurements of the chemical composition of the atmosphere from space. In addition to stratospheric ozone, TOMS also observed SO_2 from volcanic eruptions. GOES was used to retrieve aerosol optical depth (Fraser et al., 1984). Fishman et al. (1987) used ozone columns from

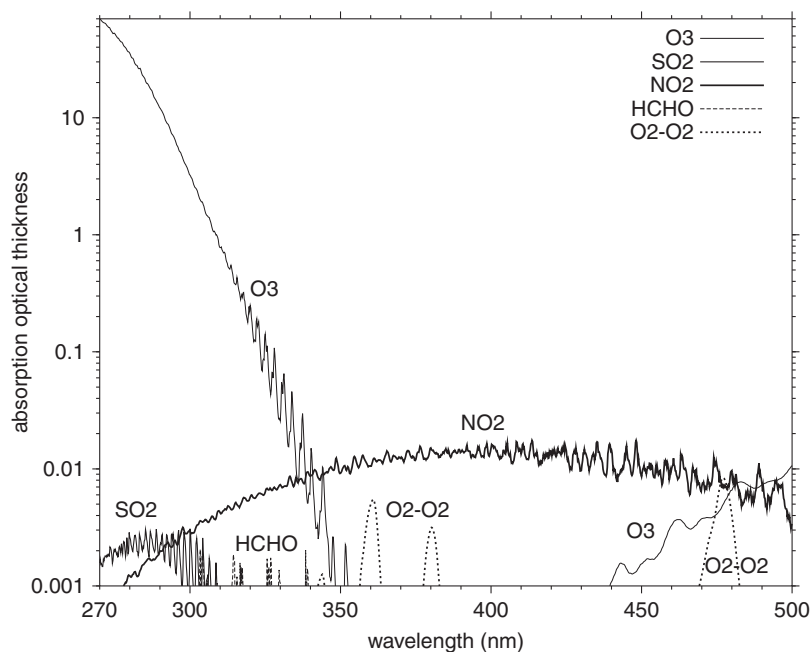
TOMS to investigate an episode with ozone smog over the eastern United States. An important step forward was made with the launch of the GOME instrument in 1995 (Burrows et al., 1999), which could measure several of the minor trace gases using the backscatter technique. This instrument was followed by SCIAMACHY (2002, Bovensmann et al., 1999), OMI (2004, Levelt et al., 2006), and GOME-2 (2006, Callies et al., 2000). Apart from the solar backscatter technique, measurements of tropospheric trace gases can also be made in the thermal infrared. MOPITT (1999, Deeter, 2009), AIRS (2002, Aumann et al., 2003), TES (2004, Beer, 2006), and IASI (2007, Blumstein et al., 2004) are instruments that use this wavelength range.

All instruments that have been observing tropospheric trace gases were on board satellites in a Sun-synchronous orbit, providing at most one (backscatter techniques) or two (thermal infrared) measurements at the same local time per day.

Retrievals and validation

What can be detected from space on tropospheric trace gases? Since the species of interest reside in the troposphere, and the instruments are orbiting the Earth at around 500–800 km altitude, observing in nadir, it is quite a challenge to detect the minor constituents in the lower 10–15 km of the atmosphere from space. There are basically two methods used to measure the troposphere, both based on passive remote sensing techniques: the solar backscatter technique and the thermal infrared technique. In the solar backscatter technique, the instrument measures the solar radiation that has been absorbed and scattered by the atmosphere. This so-called Earth radiance spectrum contains the specific absorption features of the molecules of interest (due to electronic-vibrational-rotational transitions in the molecule, see Figure 1). In the thermal infrared technique, the thermal emission of the Earth-atmosphere system is measured, revealing the specific absorption features of the trace gases (see Figure 2). Due to the specific spectroscopic “fingerprint” of the molecule, it is possible to determine the trace gas concentration, using very sensitive detectors and optimally designed optical instruments. The solar backscatter instruments usually provide tropospheric columns of the trace gases. The technique has the advantage to be sensitive to the surface, since the atmosphere is transparent in the visible wavelength range. With the thermal infrared technique, also some vertical information can be obtained, approximately two layers in the troposphere, but the sensitivity to the surface is less so that accurate total column amounts are more challenging.

The retrieval of tropospheric trace gas concentrations from satellite measurements is a so-called ill-posed problem. For ill-posed problems, the information from the measurement is not enough to derive all unknowns independently. This means that to retrieve trace gas concentrations from satellite measurements, assumptions have to be



Trace Gases, Troposphere - Detection from Space, Figure 1 Total absorption optical thickness for tropospheric trace gases in the UV–vis wavelength range, as calculated for a mid-latitude atmosphere in summer. Note that a logarithmic scale is used, thus the absorption by ozone decreases by six orders of magnitude in the wavelength range from 270 to 360 nm (Image courtesy: P. Stammes (KNMI)).

made on, for example, the reflectivity of the surface and the approximate vertical distribution of the trace gas. One of the most widely used retrieval techniques is optimal estimation (Rodgers, 2000). For the solar backscatter technique, also differential optical absorption spectroscopy (DOAS) retrieval is widely used (Platt, 1994).

Satellite measurements of tropospheric trace gases are hampered by clouds that reflect radiation to space, effectively screening the gas concentrations in the most polluted layer below the clouds. For fully clouded scenes algorithms are therefore fundamentally limited to retrieving above-cloud concentrations. But in situations with partial cloud cover, radiance signals still contain information on trace gas concentrations in the lowest layers, and tropospheric column retrievals are possible. By reducing the size of the ground pixel, the probability of encountering a completely cloud-free pixel increases. Therefore, recent developments have focused on limiting the pixel size, thereby increasing the amount of measurement samples in order to obtain more cloud-free observations while retaining global coverage.

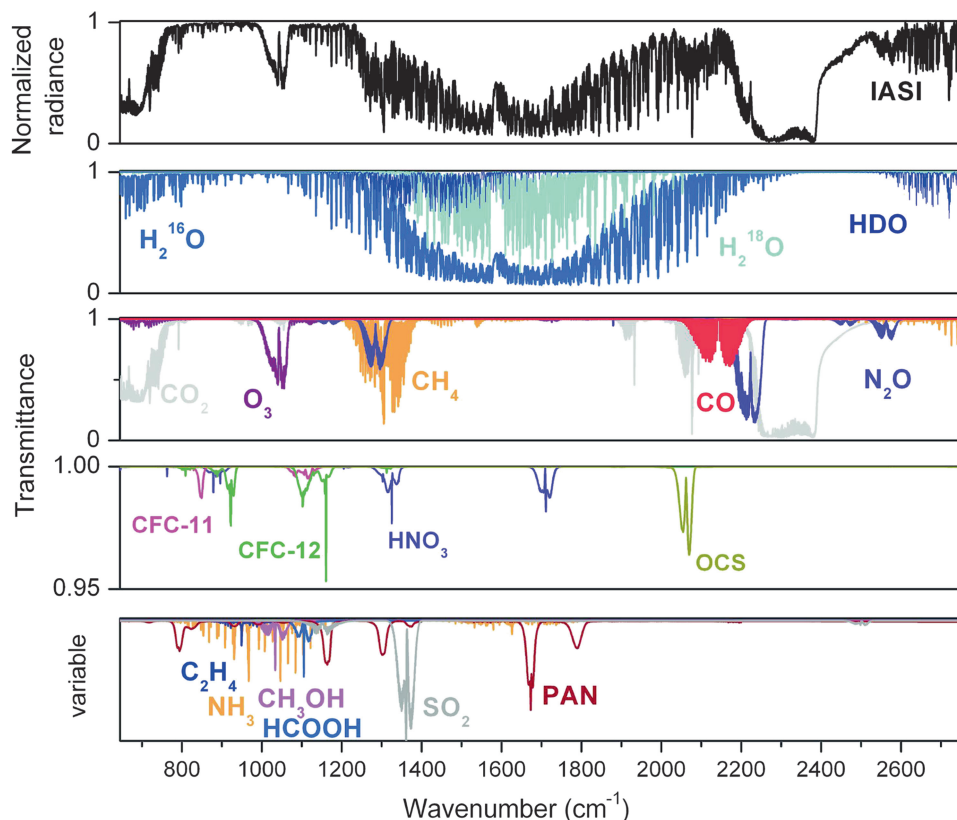
In order to check their accuracy, satellite measurements are validated by comparisons with ground-based and aircraft measurements and atmospheric models. Ground-based and aircraft campaigns are often performed for validation for specific atmospheric conditions and are thus limited in scope. Networks of ground-based instruments of known quality are thus a valuable tool for validation of satellite measurements over the whole mission lifetime.

Extensive networks exist only for a limited set of trace gases (for instance, ozone and CO_2). For other trace gases, like NO_2 , SO_2 , and HCHO , the development of consistent ground-based networks is much called for, but only starting.

The advantages of satellite observations

The capability of satellite instruments to measure the tropospheric pollution first became apparent by measurements of GOME on NO_2 (Leue et al., 2001) and MOPITT on CO (Edwards et al., 2004). These instruments enabled for the first time global measurements of pollutants in the troposphere in the form of maps of monthly or yearly averaged concentrations. Up to that point, only models provided such information, and independent data to validate these models was sparse. SCIAMACHY extended the measurements of the troposphere to greenhouse gases like methane (Frankenberg et al., 2005). The GOSAT satellite (Hamazaki et al., 2004) was launched in 2009 is dedicated to measure CH_4 and CO_2 with very high accuracy. Recent results suggest that GOSAT CO_2 retrievals are useful to constrain surface fluxes of CO_2 (Butz et al., 2011). In 2014 NASA's OCO satellite (Crisp et al., 2004) will be launched dedicated to measure CO_2 .

Because of its small pixels and daily global coverage, OMI provides much more measurements of the troposphere than previous instruments were able to. Instead of monthly averaged maps, OMI is able to provide daily maps. In Figure 3, four consecutive frames are shown of



Trace Gases, Troposphere - Detection from Space, Figure 2 IASI-normalized radiance spectrum (*top panel*, recorded by IASI/MetOp, over west of Australia, on December 20, 2006) and transmittance simulated molecular contributions to identify the main absorbing gases (*middle panels*) and the weaker (*bottom panel*) (From Clerbaux et al., 2009).

OMI measurements. The figure clearly shows the Sunday dip in NO_2 concentration due to reduction of traffic during the weekend resulting in less NO_2 emissions.

These instruments clearly showed the unique capability of satellite measurements to obtain global coverage and consistent quality of the measurements. For instance, ground-based networks for most of the tropospheric trace gases are sparse and the quality of the data is sometimes station dependent.

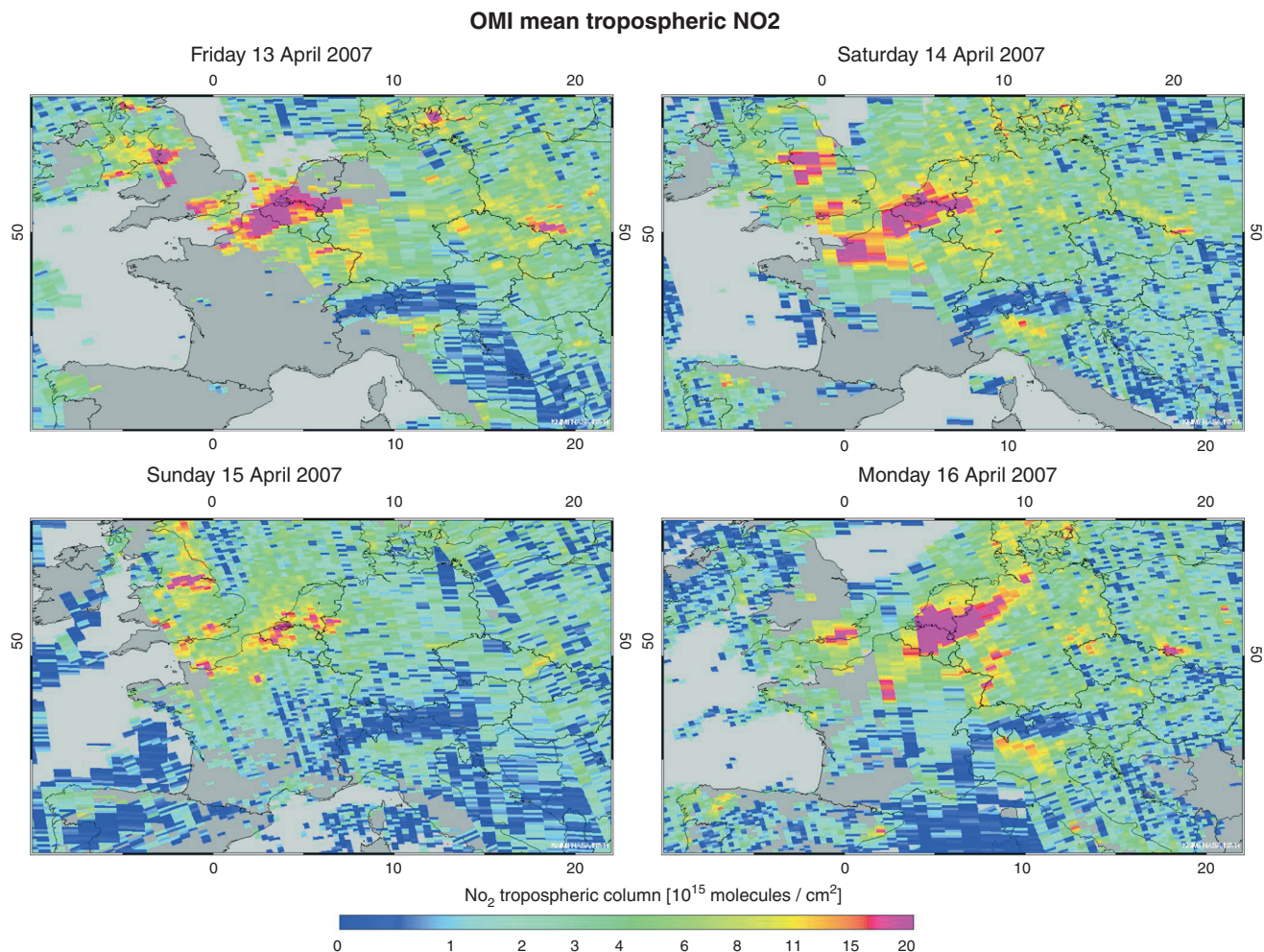
The chemistry of the troposphere is complex and involves many trace gases and chemical reactions. Combining the observations of trace gases from satellite instruments is therefore a great advantage. The added value of satellite observations of key species is illustrated in Figure 4. This figure shows the prominent global impact of human activities on the composition of the troposphere. Figure 4 shows satellite maps of concentrations of NO_2 , CO , CH_4 , HCHO , and particulate matter. Also shown is a map of the population density. The sources for NO_2 and CO are fossil fuel combustion by power plants, industry, and traffic. For CH_4 , important sources are wetlands (including rice agriculture), energy, livestock, landfills and waste, and biomass burning. Formaldehyde sources include biogenic emissions, as

well as biomass burning and fossil fuel burning. Most of the particulate matter is formed in the atmosphere from the trace gases.

Research themes and operational applications

Measurements of tropospheric trace gases are important for air quality monitoring and forecasting. Especially, observations of longer-lived trace gases such as CO have proven useful in analyzing the impact of distant sources to local air pollution levels (e.g., Gloudemans et al., 2009). Air quality prediction systems increasingly use satellite observations to improve their forecasting capability.

Satellites provide top-down constraints on emission inventories, which traditionally rely on rapidly outdated bottom-up estimates, and generally go unchecked by measurements. As a result of the unique global character of satellite data and their consistency (one retrieval algorithm for all measurements), satellite measurements provide an exceptional tool for checking emission databases. Examples include Lamsal et al. (2011) who combined a top-down approach with a bottom-up a priori inventory to produce an optimal a posteriori inventory for NO_x emissions. Mijling et al. (2012) recently applied a new



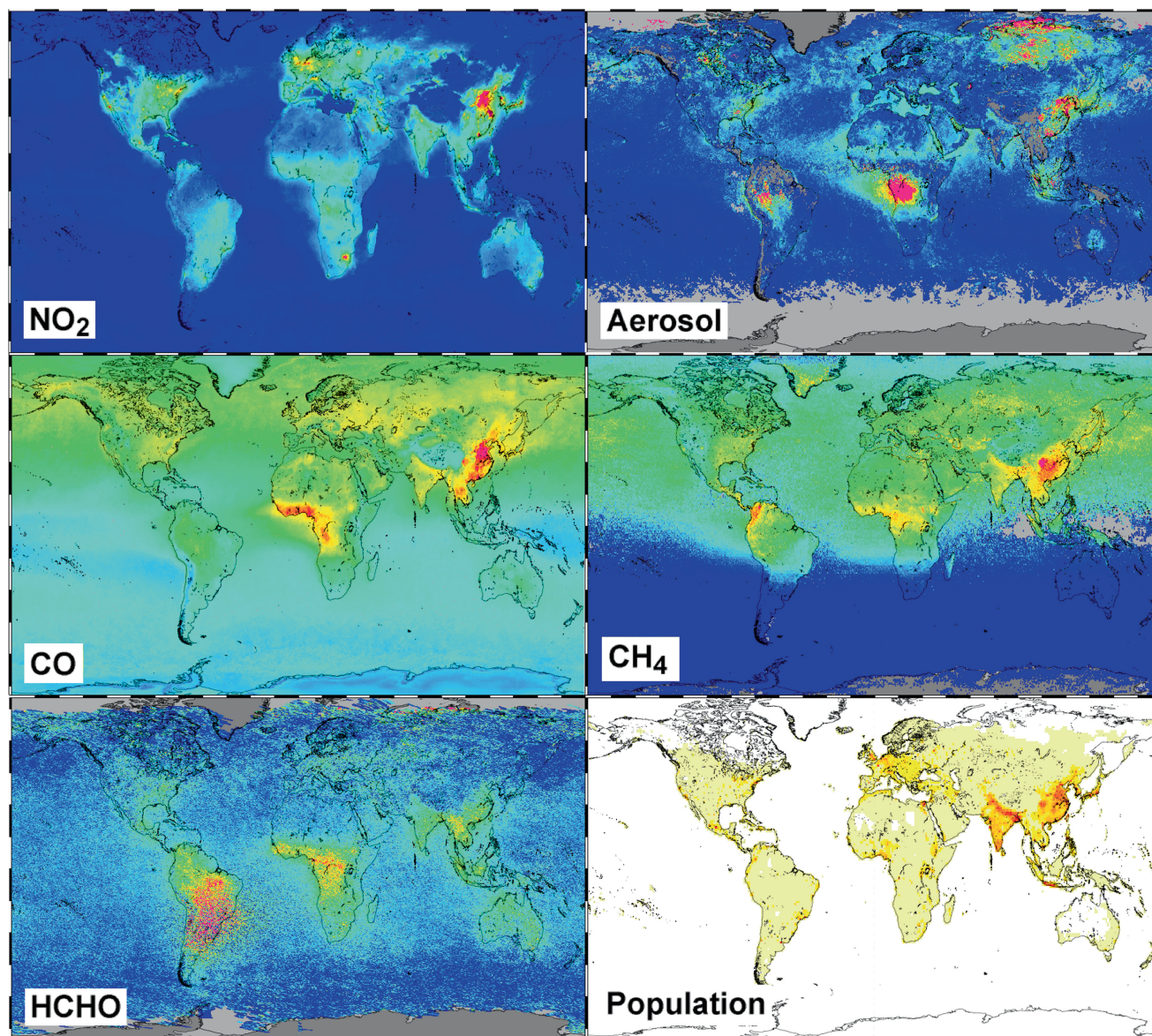
Trace Gases, Troposphere - Detection from Space, Figure 3 Four consecutive frames of OMI tropospheric NO₂ measurements. The figure clearly shows the Sunday dip in NO₂ concentration due to reduction of traffic resulting in less NO₂ emissions (Image courtesy: R. Noordhoek (KNMI); data courtesy: KNMI/NASA/NSO and www.temis.nl).

inversion technique to use daily satellite observations for fast updates of emission estimates at high spatial resolution (25×25 km²) for eastern Asia. VOC emissions were first derived from GOME retrievals of HCHO over North America using an inversion based on the relationship between HCHO columns and VOC emissions scaled by their HCHO yields (Palmer et al., 2003). Important developments include simultaneous multispecies inversions to infer CO and NO_x emissions from MOPITT and GOME information (Müller and Stavrou, 2005), and recently, Beirle et al. (2011) estimated megacity NO_x emissions and lifetimes directly from the decay-with-distance of NO₂ concentrations downwind of megacities.

The satellite data can also be used to evaluate models. Comparison of air quality models – traditionally focusing on the lower troposphere – to satellite measurements, for instance, has shown the need to accurately represent the free troposphere in these models (Blond et al., 2007).

Using SCIAMACHY NO₂ columns, Bertram et al. (2005) were able to improve the model description of microbial soil NO_x emissions that depend on humidity, fertilizer application, and temperature.

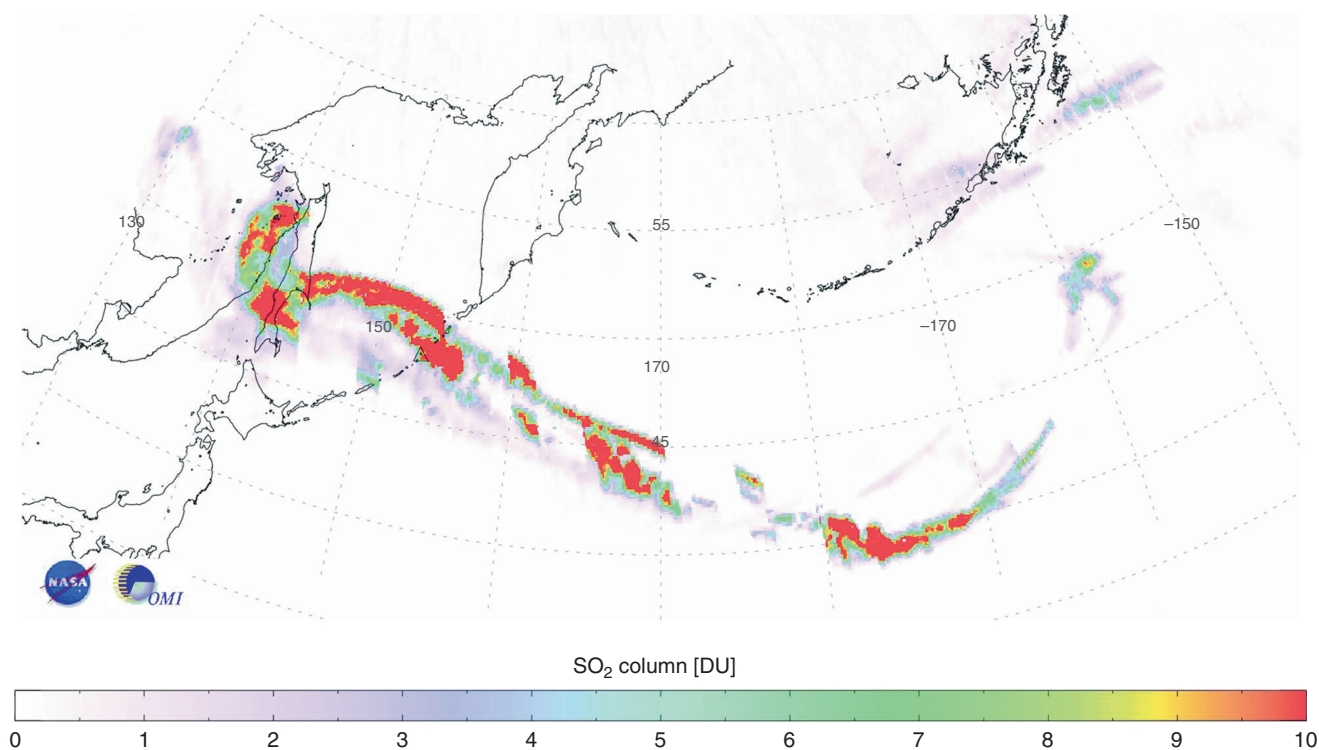
Satellite data are also very suitable to extend our knowledge on the atmospheric composition by analyzing the long-term records. Richter et al. (2005) showed the increase of NO₂ pollution over eastern Asia over the last 10 years. Van der A et al. (2008) extended this work and analyzed spatially resolved trends in NO₂ concentrations for the entire globe. Recently, Castellanos and Boersma (2012) showed that reductions in NO₂ concentrations over Europe reflect a combination of environmental policy and economic activity. Especially the 2008–2009 global economic recession triggered a distinct change in anthropogenic activity in Europe, indicated by sharp downturns in grossdomestic product and industrial production, and, consequently, in air pollution.



Trace Gases, Troposphere - Detection from Space, Figure 4 Global concentration maps. *Color scale* concentrations range from red, via yellow and green, to blue, which represents very high, high, medium, and low values, respectively. For population (*lower right*) white represents small, and dark brown, red represents large population numbers. From top-left to bottom-right: (a) OMI tropospheric column NO_2 , average for 2007, (b) POLDER/PARASOL (Tanré et al., 2011) fine-mode aerosol optical thickness, June–August 2006, (c) MOPITT CO average mixing ratio between 0–2 km and 7 km altitude, 7 year average (2000–2007), (d) SCIAMACHY methane column- averaged mixing ratio, Jan 2003 – Oct 2005, (e) SCIAMACHY formaldehyde, average for year 2004, (f) World population map from the Center for International Earth Science Information Network (CIESIN), Columbia University, and Centro Internacional de Agricultura Tropical. (Image courtesy Henk Eskes, KNMI and http://esamultimedia.esa.int/docs/SP1313-6_TRAQ.pdf).

For air quality prediction, usually data assimilation systems are used, where satellite data and ground-based data are integrated with the model data in order to improve the forecast. This technique is only effective when the data are available within a few hours of measurement, also called near real time (NRT). Nowadays, measurements from most backscatter instruments can be obtained within this time frame (e.g., Boersma

et al., 2007). In the thermal infrared, the IASI instrument is also delivering in NRT. The NRT SO_2 measurements from volcanoes are used for aviation control, relaying aircraft after a volcanic outburst. Figure 5 shows a SO_2 plume from a volcanic outburst as observed by OMI in June 2009. The observations clearly indicate the locations that should be avoided by intercontinental flights.



Trace Gases, Troposphere - Detection from Space, Figure 5 The image shows average column sulfur dioxide concentrations between 11 and 17 June 2009, based on data from OMI. The high SO_2 amounts originate from an eruption of the Sarychev Volcano (Kuril Islands, northeast of Japan) on June 12, 2009 (Images like these are used to redirect aircrafts. Image courtesy: S. Carn (Michigan Technology University)).

Future

To improve the measurements of the tropospheric trace gases, smaller ground pixels are essential to reduce cloud contamination and obtain highly resolved information on suburban scales. New instruments will target at a $5 \times 5 \text{ km}^2$ spatial resolution. In 2015 the TROPOMI instrument will be launched on ESA's sentinel-5 precursor (Veefkind et al., 2012) with a spatial resolution of $7 \times 7 \text{ km}^2$. From 2020 onward this instrument will be followed by ESA's sentinel 5 instrument on METOP-SG as part of the EU Copernicus program (Ingmann et al., 2012). Special cloud-observing capabilities are in development so that extra cloud information can be measured and the accuracy of the trace gas retrievals for partly cloudy pixels can be improved. By developing combined retrieval techniques that take advantage of backscatter as well as the thermal infrared spectral measurements, vertical profiles of tropospheric trace gases with more than two pieces of information in the troposphere are anticipated. Such combined techniques can be used when both instruments are located on the same satellite. Adding a dedicated aerosol instrument to such a platform would allow for simultaneous observations of all anthropogenic influences on the troposphere for the first time. The METOP-SG satellite is expected to have this combination of instruments on board (Berger et al., 2012).

Apart from a Sun-synchronous orbit, also non-Sun-synchronous as well as geostationary orbits could be used. The Sun-synchronous orbit will provide full global measurements with one or two observations a day. From the geostationary orbit, hourly observations can be made for a relatively small part of the world (e.g., Europe or North America). The non-Sun-synchronous-inclined orbit (see e.g., http://esamultimedia.esa.int/docs/SP1313-6_TRAQ.pdf) combines global coverage (apart from the polar regions) and frequent measurements (about five per day). Two to three of these non-Sun-synchronous satellites are needed to provide high temporal measurements throughout the year for the whole globe, except the poles. Which orbit to use is dependent on the specific scientific or operational purposes of the satellite. For climate observations, the global coverage of the measurements is of paramount importance. For regional air quality, the high temporal sampling is more important than global coverage. In the timeframe 2017-2020 three geostationary missions are planned: the Sentinel 4 (Ingmann et al., 2012) as part of the EU Copernicus programme over Europe, the South Korean GEMS (Kim et al., 2012) over Southeast Asia, and the U.S. TEMPO (Fishman et al., 2012) over North America. These instrument form a constellation of geostationary air quality missions, can be linked to the Low-Earth-Missions like the sentinel 5 precursor and

METOP-SG that provide the global coverage and thus interconnect the regional missions.

Summary

In the last 15 years, observing trace gases in the troposphere from space has been a tremendously fast developing field. Sophisticated retrieval techniques have been developed in order to obtain tropospheric trace gas concentrations, and these techniques have been validated successfully. Satellite instruments now provide daily observations of the chemical composition of the troposphere with spatial detail as fine as urban scale. Satellite observations have been successfully used to provide constraints on emissions of pollutants, to evaluate and improve atmospheric models, and to identify trends in air pollution. In the future, pixel sizes will even decrease further, and combined measurements from backscatter and thermal infrared will provide better vertical profiles in the troposphere.

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TRAFFICABILITY OF DESERT TERRAINS

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Definition

Trafficability (of desert terrains): The ability to traverse a surface in a cart vehicle.

The trafficability of desert terrain is controlled by soil strength, surface roughness, and the propensity for a surface to generate dust (dust loading) that would obscure vision or impair engine performance. This entry focuses on the most important and treacherous factor in desert trafficability, soil strength. Surface roughness and dust loading are mentioned in context with specific terrain types. Finally, methods for remotely estimating these factors are briefly discussed. Perhaps the most difficult to recognize, and likely the most important factor for trafficability in desert terrains, is soil strength, which itself is dependent upon several factors that can be measured or estimated: soil moisture, grain (or clast) size, and composition. It is the combination of soil strength and vehicle footprint (the area over which the weight of the vehicle is distributed) that dominates a surface's trafficability.

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