Sensing the Troposphere from Space

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ABSTRACT

The growth of human population and the industrialisation in the 19th and 20th century has led to dramatic changes in the Earth System. The chemical composition of the lowest part of the atmosphere, the troposphere, is changing as a result of human activities. The Earth has entered the “Anthropocene” epoch, where the activities of humans play a key role in air quality and climate change. The rapid development of megacities (see Figure 1) and the strong development in the Asian countries are clear examples of rapid changes that affected the atmosphere in the last decades and will continue to do so in the future.

For understanding climate change and air quality, global changes in the chemical composition of the troposphere need to be taken into account/addressed. Especially the global inventory of emission sources play a key role in understanding and modelling the troposphere in relation to climate change and air pollution. Also regional and long-range transport of pollution, as well as the rapid development of pollution levels during the day, are important for understanding air quality and climate change and their interaction

Atmospheric measurements from space started in the 70th’s with US sensors SBUV[1] and TOMS[2], focussing on the ozone layer residing in the higher layers in the atmosphere. Sensing the lower atmospheric layers from space is a recent development in satellite remote sensing, where SCIAMACHY[[3]] on board ESA’s ENVISAT), OMI[4] on board NASA’s EOS-Aura) and GOME-2[5] (on board METOP-1) instruments play a leading role. Unprecedented measurements from space from OMI reveal tropospheric pollution maps on a daily basis with urban scale resolution. Measurements from Thermal Infrared instruments like MOPITT [6], AIRS[7] , IASI[[8]] and TES[[9]] also provide unique information on the troposphere, providing tropospheric profile information.

In this paper an overview will be given of satellite measurements from space of the chemical composition of the troposphere and their role in climate change and air pollution. Also challenges and future developments for tropospheric measurements from space will be discussed, including the Dutch initiative satellite instrument (TROPOMI) for detection of the tropospheric composition.

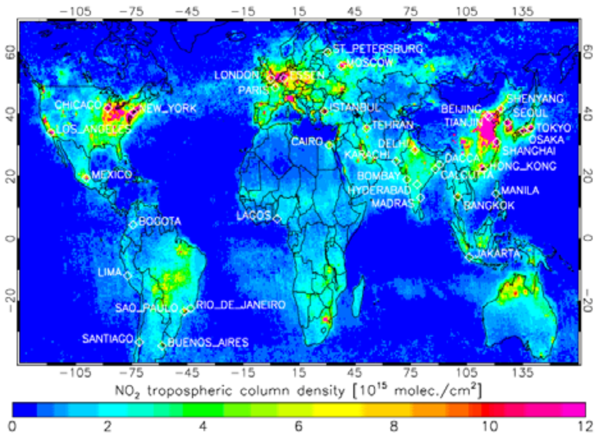

Figure 1. *Cities with over 5 millions inhabitants as reported by the UN for 1995, superimposed on measurements of tropospheric NO_2 from OMI on EOS-Aura for the month October 2004. The development of these megacities will have a major impact on future air quality (Ronald van der A, KNMI)*

SCIENTIFIC THEMES IN THE TROPOSPHERE

In the last 15 years satellite instruments and retrieval techniques improved, enabling tropospheric measurements with considerable improved accuracy from space (see Figure 2). Current measurements clearly show the unique capability of satellite measurements to obtain globall coverage and consistent quality of tropospheric measurements worldwide. The composition of the troposphere plays a major role in air quality and climate change. Tropospheric satellite measurements therefore provide essential information to contribute to the understanding of air quality and climate change. Important scientific themes satellite data can contribute to are:

Air Quality and Tropospheric Composition on a Global, Regional and Urban Scale

Local air pollution is determined, not only by local sources and sinks, but also by long-range transport of pollutants. Therefore, in order to have a full picture and an in depth understanding of air pollution, both local and global observations are needed. Satellite

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measurements can quantify (inter-)continental transport and dispersion of pollution plumes, important information on the non-local contribution to air pollution is obtained. The long-range transport of pollution itself is mainly determined by the export of pollutants from the boundary layer into the free troposphere. Satellite measurements will improve the estimates of pollution export into the free troposphere through profile information on CO and O_3, and by detecting areas with elevated aerosol layers in the low troposphere.

Emission Estimates of Trace Gases and Aerosols

For a proper understanding of air quality and tropospheric composition in general it is needed to quantify the strength, distribution and variability of emissions of NO_x, CO, aerosols, SO_2, CH_4 and volatile organic compounds, and to identify the contribution of the different source categories, such as fossil fuel burning, agriculture, and natural emissions such as lightning.

Tropospheric Composition Changes and their Connection with Climate

Tropospheric satellite measurements contribute to understanding climate change by their detection of greenhouse gases (like CH_4) and aerosols, which both have a direct radiative effect on climate. Satellites also measure precursors (especially NO_2, SO_2, CO and VOCs) of radiatively active constituents, including CO_2, O_3 and secondary aerosols.

A specific challenging research topic is the connection between air quality and climate. Due to a changing climate, air pollution levels will raise. At the same time, air pollutants are often radiative active, or a precursor for a radiative active constituent, and thus also have a direct impact on climate.

SATELLITE MEASUREMENTS OF TRACE GASES AND AEROSOLS

In the early seventies the first measurements of (stratospheric) ozone were made from space by the SBUV satellite instrument, later followed by the TOMS instrument. In addition to stratospheric ozone, TOMS also observed SO_2 from volcanic eruptions. An important step forward was made with the launch of the GOME instrument in 1995, which could measure several of the minor trace gases using the backscatter technique. This instrument was followed by SCIAMACHY (2002), OMI (2004) and GOME-2 (2006). Apart from the Solar backscatter technique, measurements of tropospheric trace gases can also be made in the thermal infrared. MOPITT (1999), AIRS (2002), TES (2004) and IASI (2007) 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.

Satellite observations of aerosols can be done using passive and active techniques. A state-of-the-art passive instrument like POLDER can measure aerosol optical depth, aerosol type and aerosol size. CALIPSO is dedicated lidar instrument, providing amongst others aerosol altitude. The geostationary instrument SEVIRI provides aerosol measurements for several times a day.

There are basically two methods used to measure trace gases in 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. 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 this visible wavelength range. In the thermal infrared technique the thermal emission of the Earth-atmosphere system is measured, revealing the specific absorption features of the trace gases. With the thermal infrared technique 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. One of the most wide used retrieval techniques is Optimal Estimation[10]] For the solar backscatter technique also Differential Optical Absorption Spectroscopy (DOAS)[11] retrieval is much used.

NEW DEVELOPMENTS IN MEASURING THE TROPOSPHERE FROM SPACE

In order to address the scientific themes related to the troposphere new instruments have to improve in horizontal and vertical resolution, diurnal information, amount of collocated measurements and cloud-, and surface albedo detection capabilities. These improvements will be shortly addressed below.

Using more detailed cloud-, and surface albedo information, the accuracy of trace gas retrievals in the troposphere can be improved. 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. Also for obtaining highly resolved information on sub-urban scales for improving emission data bases and understanding regional air quality small pixels are important. New instruments target 5 x 5 km2 spatial resolution. Special cloud observing capabilities will be added 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 infra red spectral

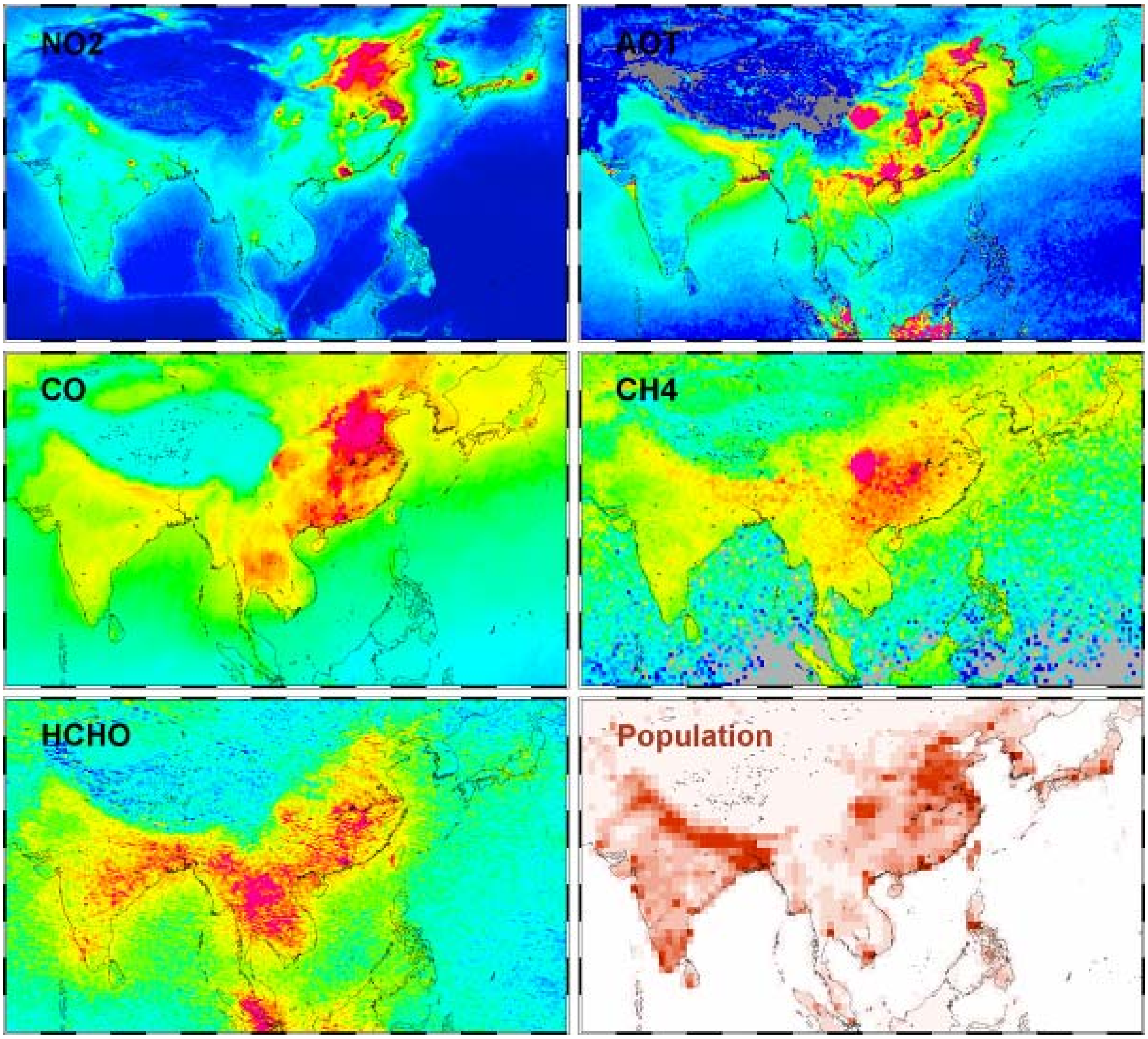

Figure 2. *Tropospheric concentrations of key species over Asia, originating from several instruments. Colour scale concentrations range from red, via yellow and green, to blue, which represent very high, high, medium and low values, respectively. For population (lower right) white represent small, and dark brown-red represent large population numbers. The NO2 map presents OMI measurements averaged over 2007. Note that major shipping routes are clearly visible. The AOT map shows the Aerosol optical depth, averaged over March 2005 to May 2008, derived from PARASOL fine mode measurements. The CO map shows MOPITT measurements averaged over 2000 till 2007. The CH_4 map is obtained from observations by SCIAMACHY, averaged over January 2003 till October 2007. The Formaldehyde (HCHO) map is also obtained from observations by SCIAMACHY, averaged over 2003 till 2007. The Center for International Earth Science Information Network (CIESIN), Columbia University; and Centro Internacional de Agricultura Tropical, is acknowledged for the population number data, available at http://sedac.ciesin.columbia.edu/gpw. Image courtesy: H. Eskes, KNMI*

measurements, vertical profiles of tropospheric trace gases with more than two pieces of information in the troposphere, are anticipated. These 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.

Apart from a sun-synchronous orbit, also non-sun synchronous as well as geostationary orbits could be used. The sun-synchronous will provide full global measurements with 1 or 2 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 combines global coverage (apart from the polar regions) and frequent measurements (about 5 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.

Collocated measurements of more trace gases and aerosols at the same time will help understanding the complex chemistry in the troposphere.

TROPOMI

TROPOMI (Tropospheric Ozone Monitoring Instrument) is a satellite instrument for remote sensing of the Earth's atmosphere. Its primary goal is to be sensitive in the troposphere down to the boundary layer/Earth's surface in order to quantify emissions and transport of anthropogenic and natural trace gases and aerosols, which impact air quality and climate.

TROPOMI will measure the main tropospheric pollutants (O_3, NO_2, CO, formaldehyde (HCHO) and SO_2) and two major climate gases (tropospheric O_3 and methane (CH_4)). In addition, it will measure important parameters of aerosols (aerosol scattering, absorption and type identification), which play a key role in climate change as well as in tropospheric pollution. The main instrument requirements for the TROPOMI instrument have been derived to fulfill the user requirements for the above-mentioned species.

TROPOMI measures in the UV/VIS wavelength range (270 to 490 nm) like OMI, adding two bands, one in the near infrared (710-790 nm) for dedicated cloud detection, and one in the short wave infrared (around 2300nm) for CO and methane. The instrument targets 7 x 7 km2 pixel size in all channels, obtaining daily global coverage at the same time. TROPOMI will be launched on ESA's precursor sentinel 5 in 2014 in an afternoon orbit in loose formation with NPP.NPOESS.

TROPOMI is a Dutch initiative building upon the successes of SCIAMACHY and OMI. This new instrument combines all good things of the previous instruments and improves on most specifications. Notably improved are horizontal resolution and the accuracy of the tropospheric columns, due to improved cloud and surface albedo characterization capabilities. By combining with the GOME-2 instrument on board ESA's ERS-2, also diurnal information can be obtained. The instrument is designed by TNO and Dutch Space in The Netherlands, who were also involved to great extent in TROPOMI's predecessors (OMI on NASA's EOS-Aura, launched in 2004; SCIAMACHY on ESA-ENVISAT, launched in 2002; GOME[12] on ESA-ERS-2, launched in 1995 and EUMETSAT MetOp, launched in 2006.

CONCLUSIONS

In the last decade a rapid development took place in sensing the troposphere from space, enabling measurements of tropospheric columns and first tropospheric profile retrievals. In future developments will focus on limiting the horizontal pixel size, improving the vertical information by combined retrieval techniques, and by improving cloud detection and correction algorithms.

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