GLOBEMISSION

Final Report

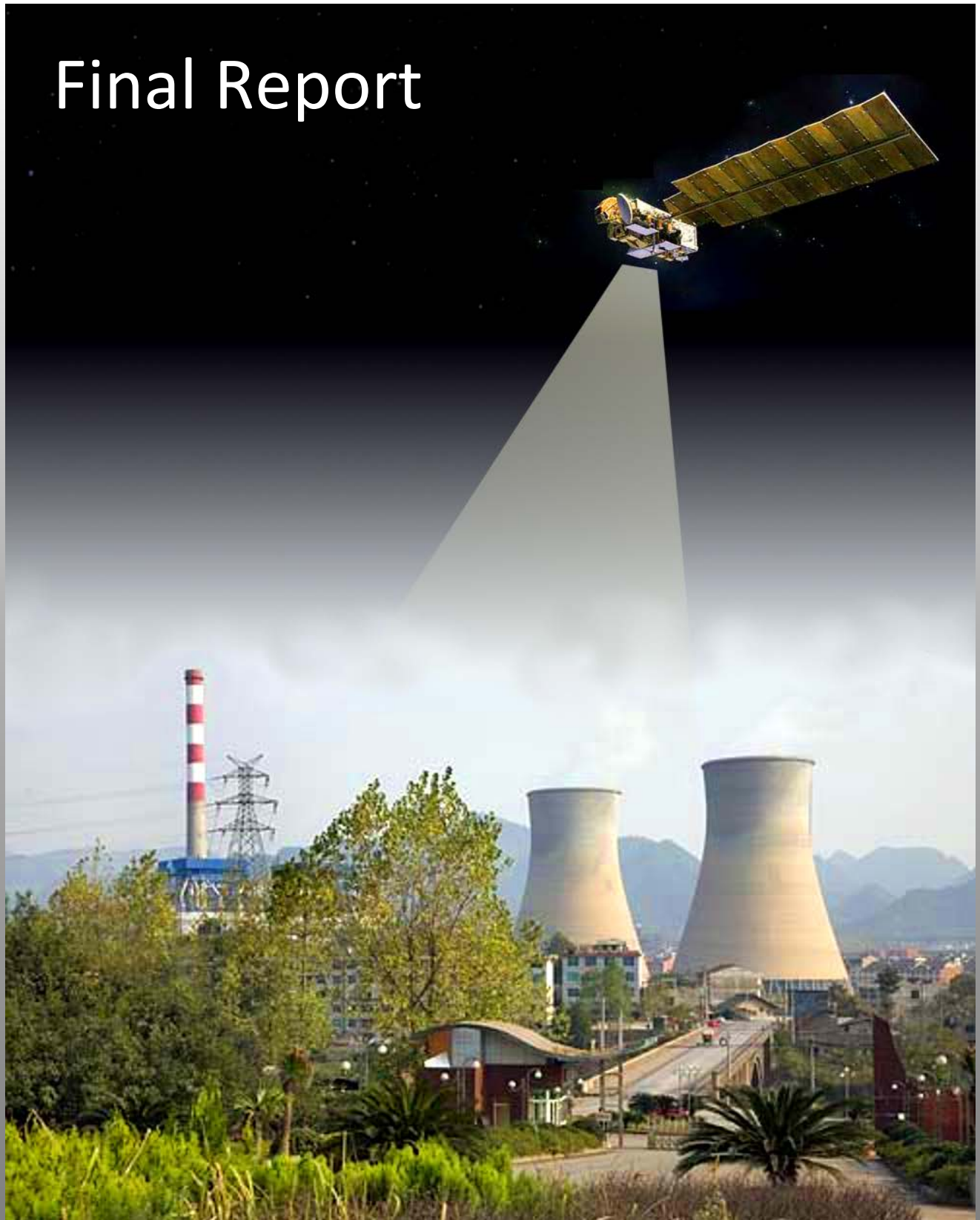


Table of Contents

1 Executive Summary

GlobEmission: quantifying the sources of air pollution from space

At the origin of all air quality issues are the emissions of pollutants. Emission inventories provide essential information on magnitude, type of activity, time evolution and the spatial coverage of the emissions. These inventories are developed for use by the policy makers in order to evaluate progress towards emission abatement measures, and decide on future strategies, and for use in scientific applications as input in urban, regional, continental or global scale models. Unfortunately, traditional emission inventories are often inaccurate or outdated. Within the GlobEmission project (part of Data User Element programme of ESA) we develop new emission estimates from satellite observations of air constituents. The main advantage of these emission estimates are the **spatial consistency**, **high temporal resolution** and **the rapid availability** of these estimates to the user.

Based on the requirements of our dedicated users the following services have been developed in GlobEmission so far:

- Global biogenic emissions of isoprene
- Global emissions related to forest-fires
- Regional anthropogenic VOC emissions (China)
- Regional emissions of NO_x and SO_2 (China, South Africa, India, Middle East)
- European emission estimates of NO_x and SO_2
- Regional aerosol-related emissions

The space-based emission inventories from GlobEmission offer:

- Spatial consistency and high temporal resolution
- Comparison between regions using the same method and satellite instrument
- Identification of weaknesses in existing inventories
- Monitoring of emission changes, trends and new emission spots
- Fast updates and rapid availability to users
- Easy access via the web-portal: www.globemission.eu

The methods used in GlobEmission are state-of-the-art, and have resulted in numerous publications and a good reputation for the consortium in this field.

The GlobEmission products are used worldwide, and for many users it is the only reliable information on the emissions in their area. The group of GlobEmission product users keeps growing steadily. At this moment, the main dedicated users (those who use the data and provide feedback to the project) are:

- European Environmental Agency
- LATMOS, France
- Satellite Environment Center of the Chinese Ministry of Environmental Protection
- Indian Institute of Tropical Meteorology

- South African National Space Agency and South African Weather Service
- National Institute for Environmental Studies, Japan
- Qatar Environmental & Energy Research Institute
- Inha University, Korea
- Shanghai Meteorological Service, China

The GlobEmission project started at October 2011 and its current phase continued until April 2016. Workshops and User Consultation meetings were organized in November 2012 (The Bilt, Netherlands), December 2013 (Frascati, Italy) and November 2015 (Doha, Qatar), where users were familiarized with the GlobEmission products, and the consortium received important feedback.

GlobEmission is a consortium of KNMI (The Netherlands), BIRA-IASB (Belgium), FMI (Finland), TNO (The Netherlands), and VITO (Belgium).

2 Introduction to GlobEmission Services

Emissions of pollutants to the ambient environment are at the origin of atmospheric pollution issues. Emission inventories provide important information on magnitude, type of activity, time evolution and the spatial coverage of the estimated emissions. These inventories are developed for use in scientific applications as input in urban, regional, continental or global scale models, and for use by policy makers in order to evaluate progress towards emission abatement measures, and decide on future strategies.

Within the GlobEmission project (part of Data User Element programme of ESA) emission estimates are developed from satellite observations of air constituents. The main advantage of these emission estimates are the spatial consistency, high temporal resolution and the rapid availability of these estimates to the user. Based on the requirements of several dedicated users the following services have been developed:

Table 1: List of services and their status

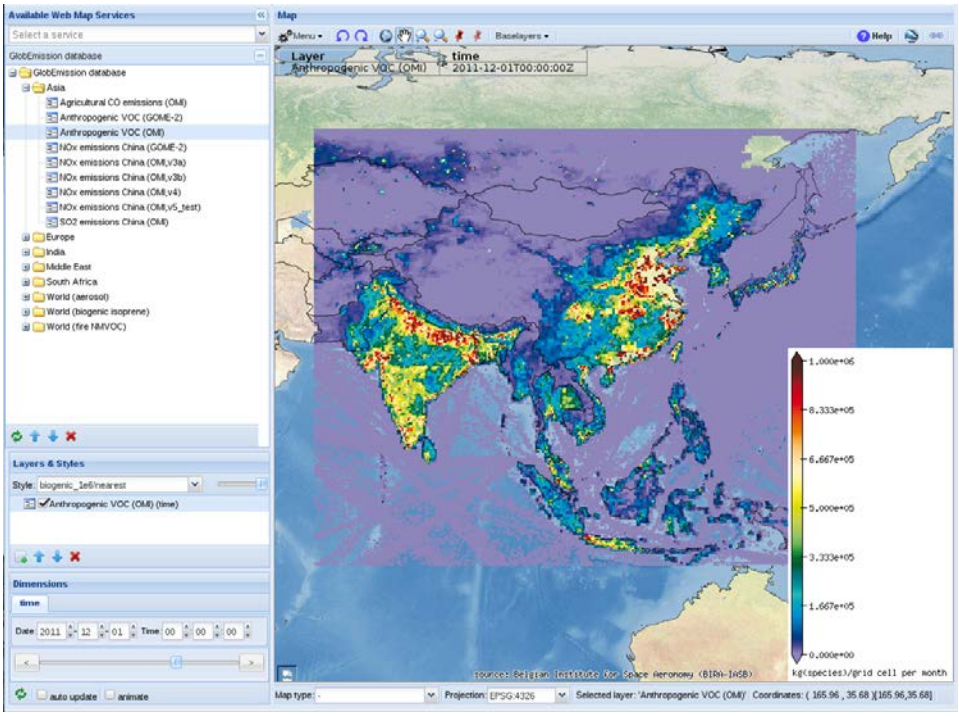
Service	Time period	Spatial resolution
Global products		
Global biogenic emissions for isoprene (OMI-based)	2005-2014	0.5°x0.5°
Global emissions for fire-related NMVOC (OMI-based)	2005-2014	0.5°x0.5°
Global biogenic emissions for isoprene (GOME2-based)	2007-2011	0.5°x0.5°
Global emissions for fire-related NMVOC (GOME2-based)	2007-2011	0.5°x0.5°
Global emissions for wild fire related species	2001-2010	0.5°x0.5°
Regional products		
European anthropogenic emission for PM2.5 and PM10	2008	0.5°x0.5°
Regional emissions for NOx for East China and Middle East	2007-2014	0.25° x 0.25°
Regional emissions for NOx for South Africa	2009-2011	0.25° x 0.25°
Regional emissions for NOx for India	2007-2008	0.25° x 0.25°
Downscaling of South African emissions	2009-2011	0.01° x 0.01°
Anthropogenic NMVOC for East Asia (OMI-based)	2005-2014	0.25° x 0.25°

Anthropogenic NMVOC for East Asia (GOME2-based)	2007-2011	0.25° x 0.25°
Agricultural waste burning emissions for East China (OMI-based)	2005-2012	0.25° x 0.25°
NOx emission trend service for Europe	2005-2010	0.25° x 0.5°
Downscaled regional emissions for Qatar	2010-2011	0.01° x 0.01°

Dissemination

The web portal **http://www.globemission.eu** contains all emission data from the project. All data is freely available without registration. The data sets can be previewed interactively and downloaded. Documentation about the user requirements, the product specification, the algorithm description and the product validation is included on the web-site.

There are about 400 unique visitors to the portal per month. Most visitors are from European countries, the United States and China.



Example of online visualisation of a GlobEmission emission data set at http://www.globemission.eu

3 Project highlights

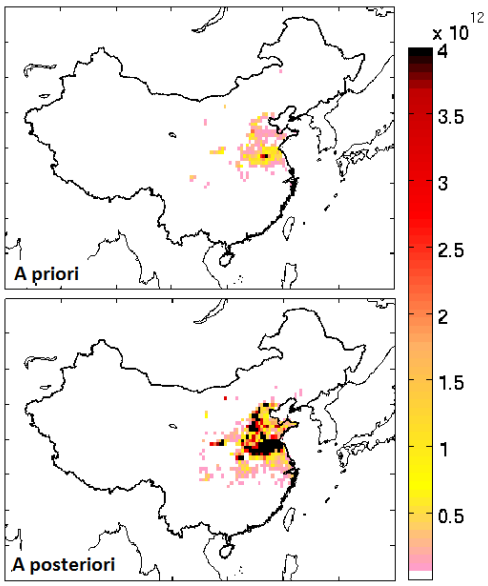
3.1 Post harvest crop burning in China

Product: Biogenic Emissions

User: Ministry of Environmental Protection, China

Due to its rapid population growth and economic development, China suffers from increasingly poor air quality, which is associated to industrial and residential anthropogenic emissions. However, the North China Plain is also one of the most important wheat producing regions of the world, with agricultural residue burning being a common practice after the harvest season. This source of pollution was only recently recognized to contribute to the poor air quality in eastern China during the post-harvest period occurring in June every year.

The Chinese authorities need a reliable quantification of the emissions generated by these agricultural fires in order to properly evaluate the causes of bad air quality and decide on future policies. The most recent inventory based on statistical information for crop residue burning in this region was published in 2012 and refers to the year 2006 (Huang et al. 2012). The long-term record of OMI satellite observations of formaldehyde offers an unparalleled opportunity to evaluate the strength of crop residue burning, but also to detect its interannual variability. For this purpose, we use an inverse modelling approach in which formaldehyde abundances from space are used to constrain the emissions of volatile organic compounds in this region. As part of the GlobEmission project researchers from BIRA-IASB (Belgium) developed a satellite-based emission inventory covering the period 2005 to 2012.



Emissions from agricultural burning in the North China Plain (in kg/grid/year) averaged over 2005-2012. Upper panel: the emissions according to the bottom-up inventory of Huang et al. (2012). Lower panel: the emissions according to the GlobEmission product based on OMI formaldehyde observations.

The OMI observations suggest that current emission inventories over this region are largely underestimated, by at least a factor of 2 to 3 with respect to the bottom-up estimate of Huang et al. (2012), and by a factor of 5-10 or even higher with respect to other bottom-up emission inventories for fires in this region. Although the Chinese government enacted regulations prohibiting field burning, this practice remains common and therefore space observations are valuable for detecting the evolution and successfulness of regulation policies. Model simulations show that the agricultural residue burning in June leads to important increases of other pollutants such as surface ozone, carbon monoxide, and fine aerosol concentrations. The researchers of BIRA-IASB conclude that targeted actions are urgently needed towards changes in agricultural management practices, in order to improve the air quality in this densely populated region of China.

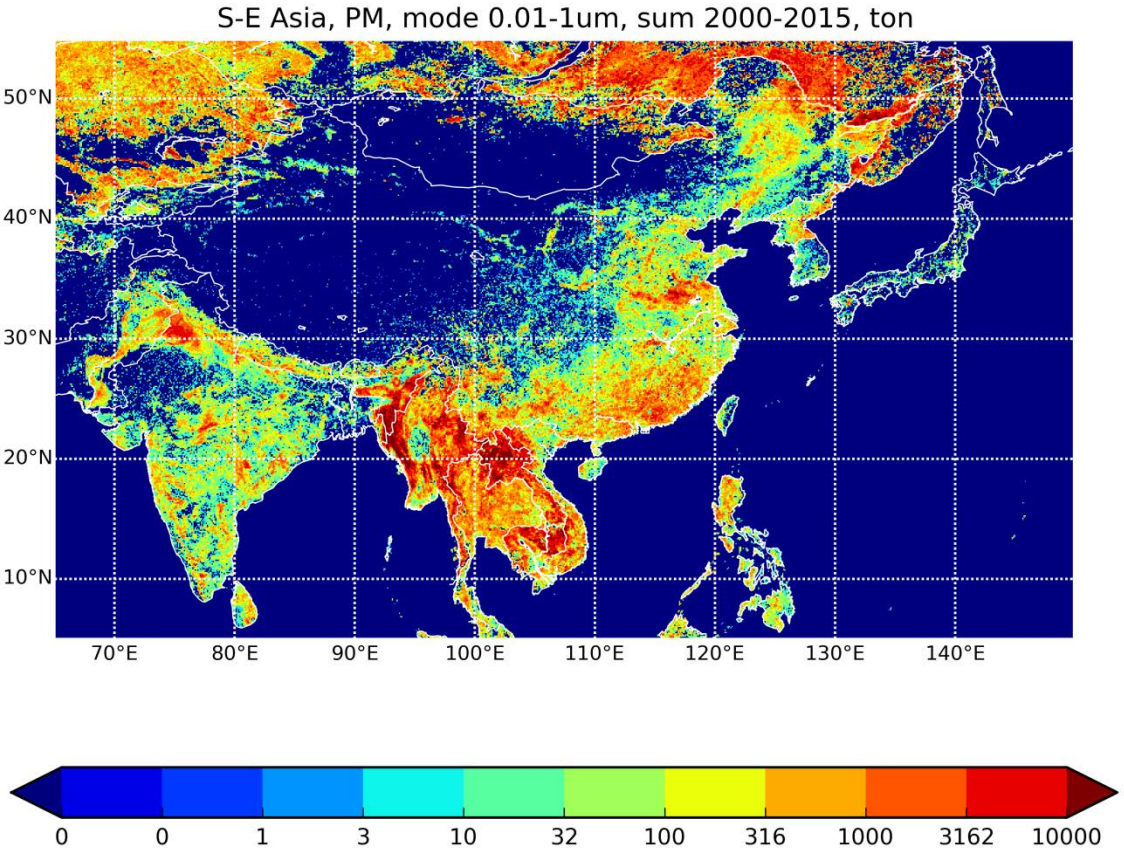
3.2 Wild-land fires

Product: Fire Emissions

User: LATMOS, France

Vegetation fires are among the highly varying sources of atmospheric pollution in the region. The 16-years-long IS4FIRES v.2.0 reanalysis released as the final fire product of GlobEmission based on active-fire records of MODIS instrument, showed that both intensity and location of the fires vary strongly for different regions and season. For the Asia region, shown below, strong differences can be seen in the fire distribution reflecting the state of national legislation and law-enforcement, as well as agriculture policy.

The inter-annual variability at a global scale is about 25%, with the main peaks associated with the fire season in Northern Hemisphere (late-spring-early-summer and late-summer).



Spatial distribution of the total particulate matter (PM) emission from vegetation fires, sum over 2002-2015 for Asia, IS4FIRES v.2.0. Unit: [ton PM]

3.3 NOx emissions from power plants in South Africa

Product: Regional NOx Emissions

User: South African Weather Service, South Africa

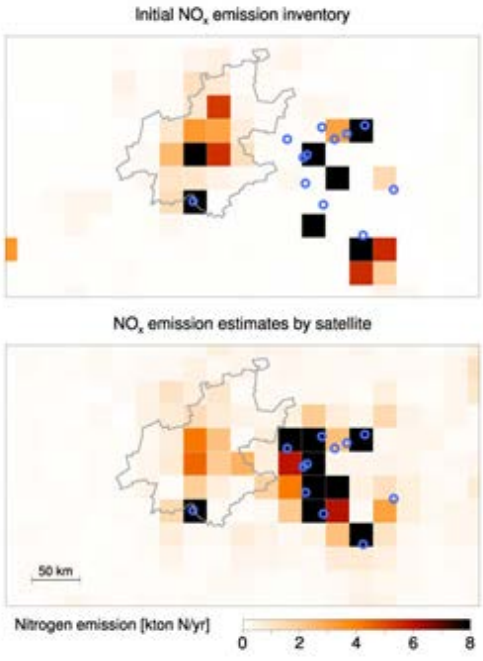
South African Weather Service

South Africa's economy is rapidly growing. From 2002 to 2012, its gross domestic product grew by about 270 billion US dollars. Unfortunately, a strong economy often leads to high levels of air pollutants – which can influence regional air quality and can have an impact on global climate change. Over the industrialised Highveld region, satellites show concentrations of the air pollutant NO_2 comparable to those observed in Europe, eastern North America and south-east Asia. With such high levels of air pollution, it is important to monitor the emissions that cause them.

Emission inventories are used to describe the location and magnitude of emissions from various origins, such as traffic, forest fires or industry. These inventories are then used for atmospheric models, as well as by policy makers to evaluate the effectiveness of air quality improvement initiatives and decide on future strategies. Emission inventories are usually compiled from statistical data, but are limited by the lack of continuity. Furthermore, events such as forest fires or extreme weather are not taken into account. In addition, economic developments directly affect atmospheric composition but are not accounted for by common emission inventories.

Earth observation satellite observations, however, can provide consistent data on atmospheric composition for improved emissions inventories. For a closer look, ESA began the GlobEmission project to focus on emissions for specific regions: China, India, Europe, Middle East and South Africa. "We use state-of-the-art satellite measurements and computer models to calculate the measured air pollutant concentrations back to their origins," said Dr Ronald van der A, leader of the GlobEmission project. "The advantages of these emission estimates are their spatial consistency and high temporal resolution. Above all, they are rapidly available because there is no more need to wait for the newest release of statistical data."

At KNMI, Dr Bas Mijling works on improving regional emission estimates using NO_2 observations from the OMI satellite instrument. He was surprised to see such a large difference between the estimated emissions values for South Africa's Highveld region and actual values from the satellites. "The old inventory was especially wrong about the location and strength of emissions by power plants and heavy industry. Using satellite data, however, we can correct their location and update their emission to actual values".



NO_x emissions for the South African Highveld region. The grey outline indicates the Gauteng province. Blue circles indicate the location of coal-fired power plants. The upper panel shows the emission strength of the initial emission inventory. The lower panel shows the emission estimates from OMI. The use of satellite data improves the identification of

3.4 European NOx emission trends to check national emission reporting

Product: European NOx Emission Trends

User: European Environmental Agency, Denmark

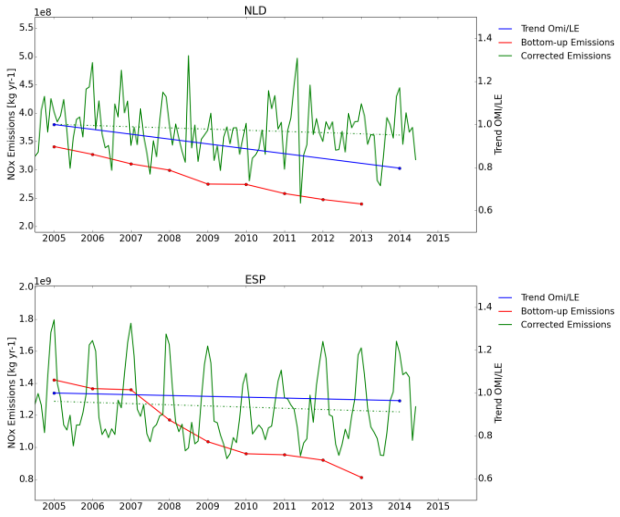
In Europe air quality improved across the region due to effective emission reduction over the past decades. However, air pollutant concentrations are still too high, and air quality problems persist. Air quality standards and emission limits for important air pollutants such as nitrogen oxides are exceeded in densely populated areas where a significant proportion of Europe's population live. Reducing air pollution therefore remains important.

To assess progress and compliance with policy commitments independent information on the environment is needed. The European Environmental Agency is coordinating the reporting of official emission inventory data for the EU to international conventions for both air pollution and climate change. The emissions also serve as input to air quality modelling activities, including near real time forecasting.

The reported emissions in the inventories are bottom-up, i.e. activities per sector are combined with emission factors. To improve emission knowledge for Europe and its surrounding countries, remote sensing data is used to estimate emissions in the GlobEmission project. This independent emission estimates allow for improved verification of national emission inventory data and for improved emission inventory data for use in air quality model applications

To estimate emissions from satellite observation the emissions in a state-of-art air quality model are adjusted so that calculated concentrations agree with satellite observations within their estimated uncertainties. In this way we contribute retrospectively to improving the quality of emission inventory data submitted to the European commission and EEA and we facilitate the verification of national emission inventory data.

Another great advantage of estimating emission from satellite observations is that more recent data is available than in national emission inventory data. This allows for more timely evaluation of measures or compliance with limit values. Because of the higher spatial and temporal details it is possible to view inter-annual variability and intra-annual variability. For the situations where the emission inventory and satellite-based emissions differ, the seasonal information helps to identify responsible sources.



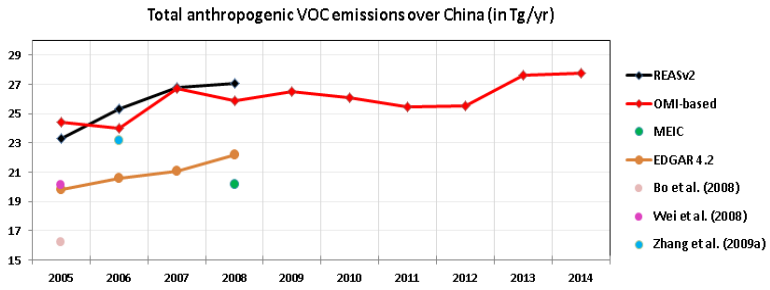
NO_x emissions for the Netherlands (top) and Spain (bottom). Reported emission (red line) are steadily declining. For the Netherlands the reported trend in emissions reduction is confirmed by satellite based emissions (green; trend in blue). For Spain the reported emissions are not confirmed. Apparently the emission reduction measures are nullified by new or other increased emissions.

3.5 Anthropogenic VOC emissions in China

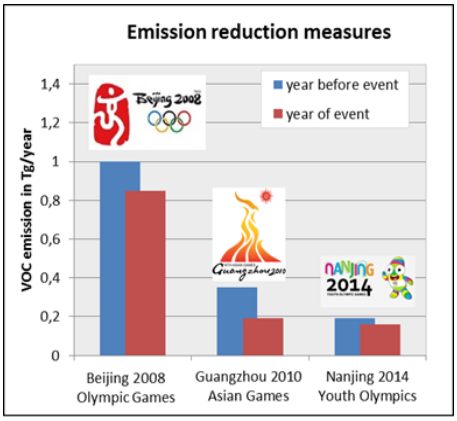
Product: Anthropogenic VOC Emissions

User: National Institute for Environmental Studies (NIES), Japan

Volatile organic compounds (VOCs) have a profound impact on air quality and even on climate, owing to their influence on OH levels and the methane lifetime and to their role as precursors of ozone and secondary organic aerosols, leading to the formation of smog and haze. The accurate estimation of their fluxes is therefore of great importance. The Chinese government integrated VOC prevention and control in 2015, and before any other city, Beijing included VOCs in its emission control targets in 2013. However, in order to evaluate the effectiveness of emission reduction measures, the VOC emissions need first to be quantified. Currently used bottom-up emission inventories do not provide emission estimates for recent years, and rely on activity data and emission factors that are highly uncertain and often outdated. At BIRA-IASB (Belgium), 10 years of formaldehyde (HCHO) observations by the OMI satellite were used to provide space-based VOC emission estimates over China. The inverse modelling technique was used. The space-based emissions are a unique way to obtain emission estimates for recent years. It also provides valuable feedback to the scientific community developing the bottom-up inventories.



As part of the GlobEmission project and in response to the user requirements by NIES, a space-based anthropogenic VOC inventory is developed for the years between 2005 and 2014 based on formaldehyde observations from OMI. The top-down emissions are generally higher than in bottom-up REASv2 inventory (developed by NIES), with the strongest updates (up to 80%) derived in Northeast provinces, moderate positive emission updates in the Beijing region (up to 10-30%), and in the rapidly developing Chengdu-Chongqing region in southwest China (up to 40%). An important reduction of the emissions is found in Shanghai (up to 50%), and along the Yangtze river (20%), whereas moderate flux decreases (ca. 20%) are deduced in the Guangzhou region. The total inferred anthropogenic VOC emissions in China are close to the bottom-up inventory, but the OMI observations suggest higher emissions in Northern China and lower emissions in Southern China.



Thanks to the availability of space-based emission estimates for recent years, it is possible to quantify the impact on air quality of emission control measures implemented during short-term events. Indeed, the significant reduction in satellite-based VOC emissions during the 2008 Olympic Games in Beijing (14%), the 2010 Asiatic games in Guangzhou (46%) and the 2014 Youth Olympics in Nanjing (15%) compared to the bottom-up emission estimate of the previous year, is a tangible quantification of the efficiency of emission restrictions.

3.6 Global isoprene emissions

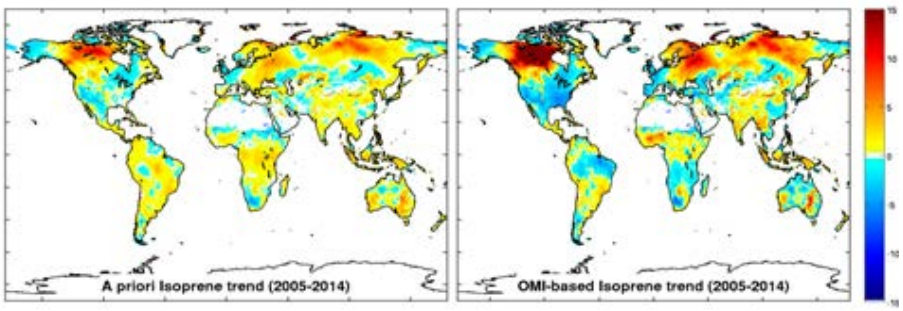
Product: Isoprene Emissions

User: LATMOS (Laboratoire Atmosphères, Milieux, Observations Spatiales)

Natural emission from vegetation is the dominant source of volatile organic compounds (VOCs) in the atmosphere. The global annual flux is estimated at ca. 1000 Tg VOC, with isoprene accounting for half of this emission. Despite a general consensus on the isoprene emission patterns, bottom-up isoprene emission fluxes come, however, with large uncertainties (factor of 2 to 5), associated with the strong variability of emission factors and the extrapolation of sparse measurements to larger scales. Isoprene has a strong impact on air quality and climate. It leads to secondary organic aerosol formation, and in polluted, high NOx environments, it contributes to tropospheric ozone formation. An accurate quantification of isoprene emissions is therefore important for the Earth system. The bottom-up community therefore welcomes satellite-based emission estimates in order to narrow down the uncertainties of this source.

Formaldehyde (HCHO) is a high-yield secondary product in the oxidation of isoprene and space borne HCHO observations can be used to constrain the global isoprene fluxes in an inverse modelling framework. As part of the GlobEmission project and in response to the LATMOS user requirements, the researchers of BIRA-IASB (Belgium) derived multi-year daily and monthly isoprene emissions using formaldehyde observations retrieved from the OMI instrument.

The OMI column abundances suggest significant reductions of isoprene fluxes in tropical ecosystems (Amazonia and Northern Africa), increased fluxes over Eurasia, especially during heat waves in summer (e.g. western Russia in 2010), and large isoprene emission increases over semi-arid and desert areas, indicating that the soil moisture parameterization of the bottom-up inventory leads to overly decreased isoprene fluxes. Based on the inverse modelling results, BIRA-IASB results highlight that in boreal regions the satellite-based emission estimates show a stronger temperature response compared to the bottom-up inventory, likely reflecting forest expansion and the warming trend. These findings are consistent with a recent experimental evidence reporting an emission response to temperature considerably higher in the Arctic than at mid-latitudes (Kramshøj et al., Nature Geosci. 2016).



Global isoprene emission trends over 2005-2014 (in %/year). Left : trends obtained using the bottom-up emission model MEGAN-MOHYCAN. Right : trends obtained using the GlobEmission isoprene product based on OMI formaldehyde observations.

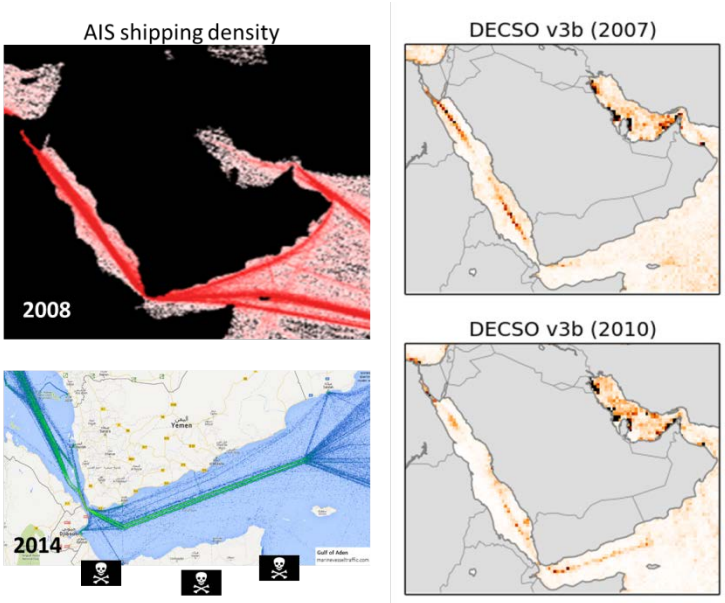
3.7 Somalian pirates modify international shipping lanes

Product: NO_x emissions

User: Qatar Environmental & Energy Research Institute

The Middle East is a region with strong emissions of air pollutants of anthropogenic origin. However, it is hard to make a reliable emission inventory for this region based on statistical information, since it is often unavailable or outdated by rapid socio-economic changes.

The Arabian Peninsula is surrounded by important international shipping lanes, dominated by container ships and oil tankers. These ships concentrate in a narrow shipping lane in the Red Sea, connecting the Suez Canal with the Gulf of Aden. International ships usually emit large quantities of air pollutants, due to the lack of emission regulations in international waters. Nitrogen dioxide produced in shipping lanes can be detected by space-based instruments like OMI. Usually ships take the shortest route from their origin to their destination. However, since 2008 pirates have attacked hundreds of vessels in the Arabian Sea and the Indian Ocean. News agencies report that the rate of attacks in January and February 2009 was about 10 times higher than during the same period in 2008 and there had been almost daily attacks in March and April. Shipping companies reacted to this incidents by choosing new routes, at a greater distance from the Somali and Yemen coast, where most of the pirates are based.



The left panels show the ship density around the Arabian Peninsula based on transponder information of the individual ships (AIS). The right panels show the NOx emissions derived from OMI observations.

Using the DECSO algorithm and the tropospheric NO2 columns by OMI, we calculate the NOx emissions from the observed plumes for a long time series spanning 2007 to 2014. As can be seen in the figures, there is a clear shift in emission patterns, which is caused by the new location of international shipping lanes in the Gulf of Aden.

3.8 PM emissions from MODIS

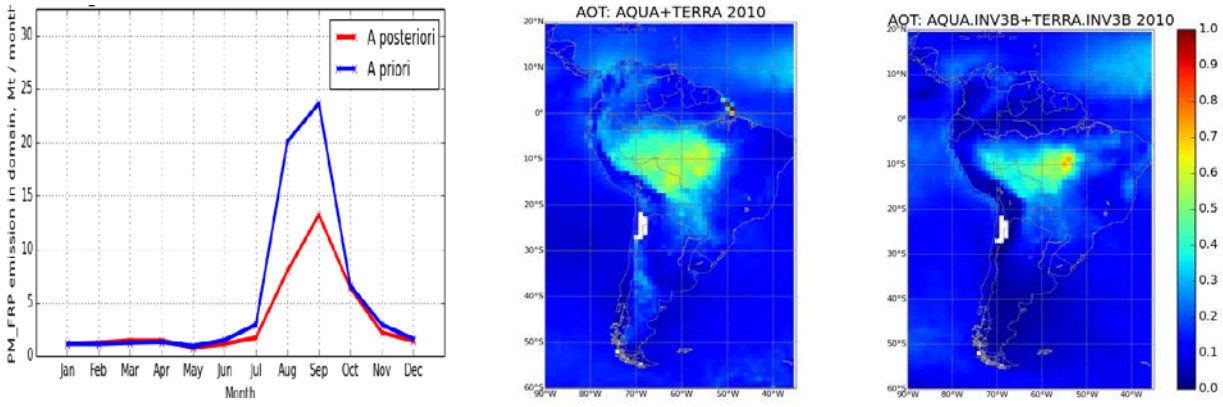
Product: Aerosol Emissions

User: Coming soon

Atmospheric aerosols constitute a significant uncertainty in the understanding of climate system. At the same time, they have been recognized as a major health hazard across the world. However, due to the diversity of sources of aerosol emission, bottom-up modelling of the atmospheric aerosol budget has proven to be a difficult task.

The GlobEmission project aims to address this difficulty by employing data from the MODIS instrument onboard the Aqua and Terra satellites. With the help of a state-of-art chemistry transport model, the observed aerosol features can be attributed to individual aerosol components of either anthropogenic or natural origin. Then, the emission fluxes for each component are optimized to match the observed aerosol distribution.

Some of the most important aerosol sources globally, such as desert dust and wildfire emissions, remain also the most poorly quantified. These emissions typically occur in remote areas, which makes satellite observations the only effective means to monitor them. For example, the Saharan dust emissions for 2010 were refined to be about 70% lower after assimilating the satellite data. New satellite products capable of aerosol retrieval over bright surfaces are expected to further improve the quantification of dust emissions.



The aerosol optical thickness from MODIS are used as input for the dispersion model, resulting in improved agreement between the simulated (right panel) and observed (middle panel) and aerosol loading in the South America during 2010. The main emission source is found to be wildfires, whose total aerosol emission is reduced by almost a factor of two during the period from July to September, 2010.

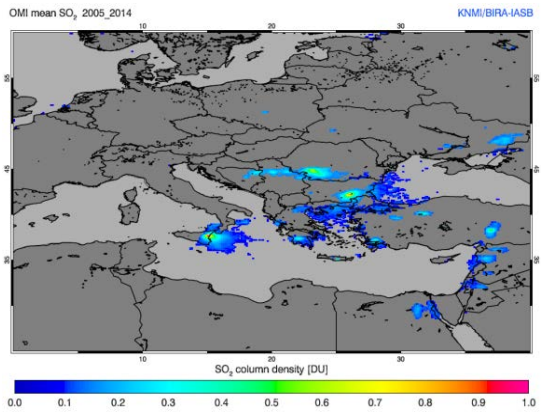
For the wildfire emissions, our approach combines both satellite based aerosol and fire radiative power observations with dispersion modelling. The fire radiative power observations provide an accurate spatial and temporal distribution for the fire emissions, while assimilation of aerosol products subsequently corrects for local variations in the emission factors.

3.9 SO_2 emission point source detection

Product: SO_2 Emissions

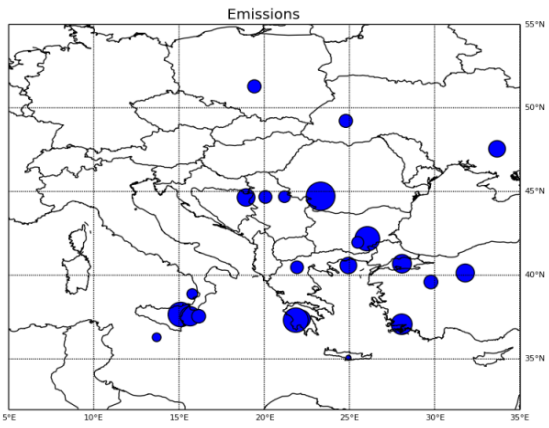
User: Indian Institute of Tropical Meteorology

SO_2 in the air is bad for health, leads to acid rain and is a precursor of greenhouse gases. Emission sources of SO_2 are volcanic activity, fossil-fuel power plants, heavy industry and smelters and shipping. Most SO_2 in the air (99%) is of anthropogenic origin. Shipping emissions are hard to detect from satellite because of the dilution of SO_2 along the ship lane. The other sources, however, are non-moving point sources and their emission strength and location are derived with a new algorithm from the satellite observations. In this product we use a simple plume model in combination with meteorological information of the European Centre of Medium-range Weather Forecasts (ECMWF) to fit the satellite observations. The observations we use are from the OMI instrument on board of the AURA satellite. The OMI instrument provide measurements at a resolution of about 25 to 60 km. These observations are available since 2004, which allow us to provide trend analysis.



Average SO_2 as measured by the OMI satellite instrument during 2005 to 2014.

For GlobEmission, SO_2 point sources have been derived for the regions of India, South-Africa, the Middle East and Europe. In India and South Africa the biggest sources are big thermal power plants, mining activities and heavy industry. The figures show the results for Europe. The satellite observations over Europe indicate that most sources are located in the South East of Europe. With our method, we have identified 19 strong SO_2 sources of in Europe. Except for the Etna eruptions, all the 18 other sources are related to coal-firing power plants. The power plants are usually also located next to a coal mine. The biggest sources of SO_2 emissions in Europe are the power plants of Rovinari in Romania, Megalopolis in Greece, and the Maritza complex in Bulgaria. These three locations together emit about one third of the total SO_2 emissions derived for Europe.



Derived point sources of SO_2 emissions. The emission strength of the source is indicated by the size of the blue dots.

3.10 Down-scaled Emission Estimates of NO_x

Product: Regional NO_x emissions

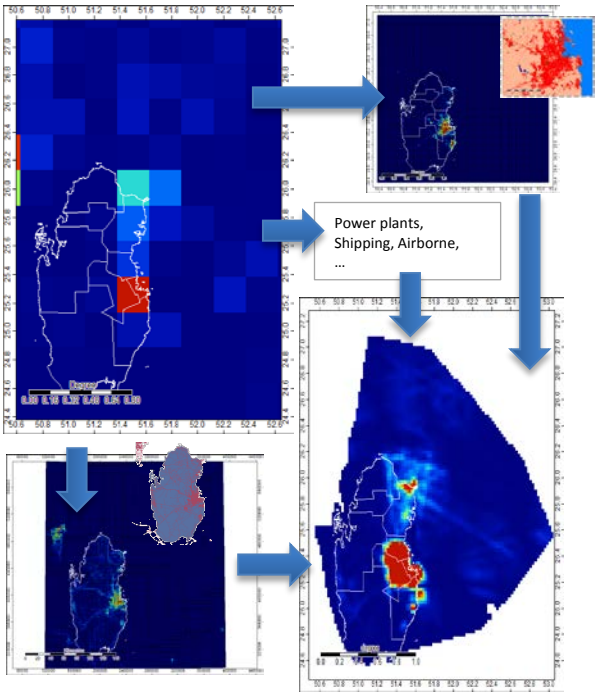
User: Qatar Environmental & Energy Research Institute

Many areas around the Middle East, including Qatar, have experienced substantial development over the past few decades. In Qatar, there is a challenging task to strike a balance between rapid economic growth, social development and environmental protection. In addition to its thriving natural gas based industries, the country is expanding massively due to an urgent need to infrastructure capacity, which has raised a concern about the ability of the atmosphere to process pollutants and safely remove them.

In an attempt to address the deteriorating air quality, intensive activities have already been witnessed. However, to support efforts to meet Air Quality Standards, more research is needed. The GlobEmission project, providing emission estimates that are suitable for air quality modelling (rapidly available, spatially consistent, high temporal resolution), supports Qatar's efforts to amend the local air quality, meet the standards and reduce the health risk from air pollution.

Within the project VITO developed and demonstrated algorithms for downscaling coarse resolution emission estimates from remote sensing data to a spatial scale suitable for national air quality assessment studies. This task is directly in line with the core business strategy of VITO's atmospheric modelling team: (i) to provide the tools and expertise for emerging and rapidly growing regions to shape air quality modelling capacities, and (ii) to provide high-resolution emission maps to end-users, allowing detailed air quality assessments for their regions. These emission maps are therefore valuable to regions with limited or no air quality modelling capabilities.

At VITO, Dr Nele Veldeman and Dr Bino Maiheu work on improving national and local emission estimates using regional NO_2 emission estimates provided by GlobEmission project partners, KNMI in particular. Within the project, first a downscaling methodology, resulting in high resolution emission maps for South Africa, was developed. Consequently, the methodology was adapted and applied in Qatar. Currently, they are working on a generalization of the methodology allowing for a more generic application of the algorithm. This would significantly add to the end-user relevance of the GlobEmission results and methods. Indeed, given such a more generic methodology the downscaled emission estimates could be made available at a modest additional cost.

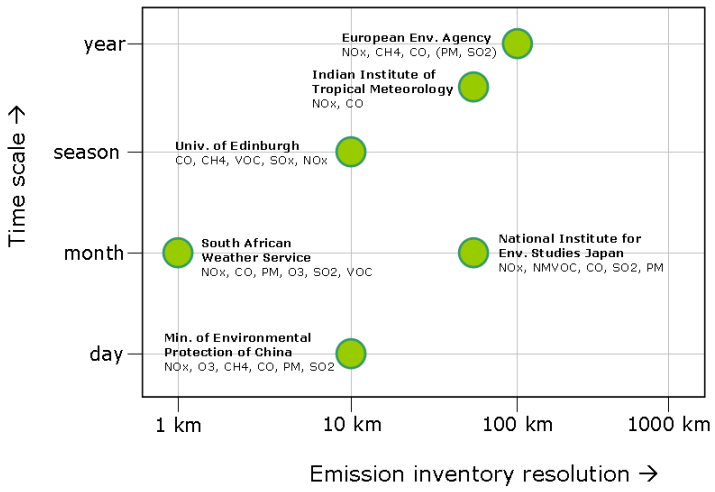


Downscaling of NO_x emissions for Qatar. The upper left corner shows the regional NO_x emission estimates (KNMI). The upper right and lower left corner show the downscaled NO_x emissions from respectively industrial/ residential sources and traffic sources, based on relevant proxy data (urbanization & road network). Together with downscaled maps for emissions from e.g. power plants and shipping, they constitute the high resolution NO_x emission map.

4 User feedback and service assessment

4.1 Dedicated users and their requirements

Committed End-User	**Requirements**
European Environment Agency	Service Usage: Verification of Emission Inventories (EU) Species: NO_x, CH_4, CO, and if possible PM, and SO_2 Accuracy needed: better than 50%
University of Edinburgh	Service Usage: Derivation of Forest Fire Emissions Species: CO, CH_4, VOC, sulphur compounds and NO_x Accuracy needed: better than 30%
Ministry of Environmental Protection of China	Service Usage: Air Pollution Emission Monitoring in China, new emission inventory Species: NO_x, O3, CH_4, CO, PM, and SO_2 Accuracy needed: better than 80%
Indian Institute of Tropical Meteorology	Service Usage: Derivation of a Top-down Emission Inventory for India Species: NO_x, and CO Accuracy needed: better than 50%
South African Weather Service	Service Usage: Derivation of new Regional Emission Inventories for South Africa Species: NO_x, CO, PM, O_3, SO_2, VOCs Accuracy needed: better than50%
National Institute for Environmental Studies Japan	Service Usage: Verification/Up-date of Asian Emission Inventories Species: NO_x, NMVOC, CO, SO_2, and PM Accuracy needed: better than 30-50% for SO_2 and NO_x, and better than 50-100% for other species such as NMVOC, CO, and aerosols
LATMOS	Service Usage: global biogenic isoprene emissions
MPI-Hamburg	Service Usage: Emissions from forest fires, use in global modelling (ECHAM)
Faculty of Earth and Life Sciences, VU University Amsterdam	Service Usage: Emissions from forest fires, in particular for comparison with bottom-up emission estimates Species: aerosols, VOC
Environmental & Energy Research Institute, Qatar	Service Usage: air quality modelling and scientific research Species: aerosols, dust, NOx, SO2
Inha University, Korea	Service Usage: Korean Air quality forecasts and emission inventory Species: aerosols, NOx, SO2
Shanghai Meteorological Service, China	Service Usage: Operational air quality modelling for the West coast of China. Species: NO_x



Requirements on spatial resolution and temporal resolution

4.2 Service assessment

For each of the GlobEmission users its service assessment is summarized below. This assessment is based on received service assessment forms and/or presentations during the user workshops in November 2012. When available, they are updated with the 2016 assessments, from the Qatar workshop and/or assessment forms.

4.2.1 European Environment Agency

The European Environment Agency (EEA) has provided written feedback on the European Emissions. EEA did not participate in the workshop.

The EEA user requirements are closely connected to the EEA task 'to provide sound, independent information on the environment'. EEA does not specify its requirements in terms of temporal or spatial resolution, accuracy, etc. Rather EEA emphasizes national emission inventories on the level of the member states. EEA explains its interest in obtaining improved emission knowledge for Europe and its surrounding countries based on remote sensing data in terms of their application.

Assessment 2012 For the assessment of the GlobEmission services in view of their requirements, EEA has developed a set of 7 criteria which are applied to the GlobEmission services for NOx and PM. EEA concludes at first that GlobEmission European emission products were currently not usable for the EEA tasks. More information should be provided and data should be presented in a different format which better suits EEA. They expressed their hope that in a next version of products will be more complete and provide more information that meets the user requirements such as national emission inventory by sector and for a series of years. EEA is willing to support the further development of GlobEmission and is looking forward to updated products on the GlobEmission website. Suggestions for further improvement:

- Ensure a good description of the data available and the methods and dataset that

have been used

- Improve quality control before putting products online
- Take note of the criteria applied by the EEA in evaluating the GlobEmission dataset and try to ensure that the GlobEmission products meets these criteria by being complete and in a format that enables easy comparison by the users. Consider changing the dissemination of data in other formats than netcdf, for example tables with emissions data by country, or csv file products.

It is noted, that after the first User Workshop, no other feedback has been received from EEA. This should be followed up. No assessment was provided in 2016

4.2.2 Satellite Environmental Centre – Ministry of Environmental protection

MEP has evaluated the GlobEmission service on NOx emission data in East China. The purpose is to monitor effects of emission reductions. The feedback provided in the Service Assessment forms of 2012, 2013 and 2016. A presentation on the "preliminary validation of emission data in some areas in China" was given by Dr. Li during the November 2012 workshop and another presentation was given during the December 2013 workshop by Huiquin Mao. The GlobEmission product used was OMI NOx data to investigate its relation with bottom-up estimates of emission data. In the second presentation GOME-2 NOx data were used as a substitute of the bottom-up inventory because its use in an air quality model results in better correlation with observations.

MEP is very positive about the service. However, in the presentation differences between the MEP UR and the GlobEmission service were indicated. These include the products (species) provided and assessed (e.g. PM10, PM2.5, O3, SO2, etc.); the required spatial resolution cannot be achieved (instrument limitation); temporal resolution of 1 day is available although the provider recommends to use monthly averages to reduce noise.

MEP would like to see services for a larger region covering all China. They would also like to obtain more species, such as those available for Europe, in particular PM2.5, and O3, but also PM10, SO2, CO2, etc. There is a need for technical training on the efficient use of the data and some more background on how the data are generated, their accuracy etc. MEP also would like to see more flexibility on the website as regards selecting data products, extension to recent years (after 2011), and better temporal and spatial resolution.

Assessment 2016 (through user assessment form). The product used is PM2.5 emitted by forest fires which, together with GFAS and a bottom-up product, are used to find yearly and monthly emission tendencies. The data are easy to download in an easy to use format (netcdf). MEP concludes that there are different tendencies between the Globemission and other products which is illustrated with figures. This makes it hard to use for policy related to regulated straw burning. More validation to improve the emission estimates is needed. MEP would also like to see more recent data (2011- 2016) and would also like to use near-real time for operational work. Also, MEP would like to add a product addressing the variable use of land use and land cover types to the fire products, as well as VOC fire products.

4.2.3 Indian Institute of Tropical Meteorology

No direct feedback on the GlobEmission service over India has been provided by Indian Institute of Tropical Meteorology (IITM). The service includes NO2 data from OMI which have been used to constrain NOx emission estimates using WRF-Chem model simulations. This work was presented during both workshops by Dr. S.D. Ghude from IITM, and in the 2015 user workshop by Dr. Prakash ,also IITM.

Assessment 2016 (participation of Dr. Prakash in the 2015 user consultation meeting). Driver for the use of Globemission NO2 data is that surface O3 production in most parts of India is NOx limited, simulated surface O3 will highly depend on choice of the NOx emission inventory, and large uncertainties in NOx emission inventories could inhibit a better understanding of surface O3 pollution and reliable assessment of ozone budget over the Indian region. NOx emissions have been increasing rapidly over India. WRF-Chem simulations are used with different NOx emission inventories, including Globemission data. In comparison with OMI-derived NO2 columns, the bottom-up emissions results in column concentrations which are too high, whereas simulations using top-down emissions perform better and may represent accurate spatial distribution of surface O3 in India than the simulation with any other bottom-up emissions

4.2.4 National Institute for Environmental Studies & Asia Center for Air Pollution Research

National Institute for Environmental Studies (NIES) & Asia Center for Air Pollution Research (ACAP) has provided a service assessment form in November 2013 and Dr. Kurokawa (ACAP) & Dr. Ohara (NIES) provided a presented their work during both workshops: “Emission of air pollutants and greenhouse gases over Asia region during 2000-2008: Regional Emission Inventory in Asia (REAS) version 2” and “REAS version 2 and comparison with GlobEmission products”, respectively. REAS is a bottom-up inventory and the methodology was presented during the November 2012 workshop. The inventory includes a range of trace gases (SO2, NOx, CO, NMVOC, NH3, CH4, N2O, CO2) as well as PM2.5, PM10, BC (Black Carbon) and OC (Organic Carbon). Temporal trends for the period 2000-2008 show an increase for all species except SO2 which appears to decrease slightly after 2006. REAS NOx emissions were compared with GlobEmission products (GOME2 and OMI) and REAS NOx emissions are much higher. In his presentation Dr. Kurokawa indicated that the following products which currently are not indicated in the GlobEmission service would be useful for improving REAS and also for modelers:

- SO_2 emissions from Asia and volcanoes
- NO_x and aerosol emissions from Southeast Asia
- Information for weekly and diurnal variations
- Other species (Ex. NH_3 monthly emissions)

In their feedback, NIES / ACAP provide an assessment of the use of GlobEmission products NOx and NMVOC for comparison with REAS over China for the years 2007 and 2008. The results were reported in Japanese meetings and projects funded by the Japanese Ministry of Environment. In their assessment, NIES / ACAP indicate that GlobEmission provides a unique data set for satellite-based data. However, they would like to obtain data for NOx and NMVOC

for other Asian regions than China and India (e.g. over Japan), and also other species. Further they would like to obtain information for specific emission sources such as large power and industrial plants, road transport, agricultural activities (especially monthly variation), etc. They would also like to see better data descriptions rather than references to research articles. They found the website very user friendly but would like to see simpler data formats than netcdf. Also they would like to see information on uncertainties and on the validation of the products. Further they would like an email alert when new data sets become available.

Assessment 2016 (a presentation prepared by Kurokawa and Ohara was presented on their behalf in the 2015 user consultation meeting). Two conclusions from this presentation are:

- GlobEmission is the unique project for bottom-up EI researchers which provides both top-down data sets and opportunities of collaboration with top-down researchers. More close relationship is favorable to create more reliable EI.
- Satellite-derived data of many kind of species in whole Asian region in addition to China and India are valuable for developers of Asian Emission Inventories.

4.2.5 MPI-Hamburg

MPI-Hamburg joined during the project and Dr. Khlystova attended the November 2012 workshop with a presentation on “Satellite fire products for use in global models”. MPI-H uses satellite data with the Earth System Model (ESM) ECHAM6. In particular emission ratio (ER) information is used. In her presentation, Dr. Khlystova provided a short list of requirements for a better satellite ER. However, an assessment of the GlobEmission service for this purpose was not yet provided. User requirements have also been provided in a document. During the December 2013 Dr. Khlystova could attend only briefly due to other commitments, and presented “Emission Ratios from SCIAMACHY”, but she provided a written service assessment (Annex 8) afterward which reflects opinions from the MPI-Hamburg Fire Modeling Group. They ask for a completely new product which is being worked on. However, there is no immediate need for the product yet because also the model work is still underway.

MPI wants to extend its satellite data driven fire algorithm by adding satellite-based information - global fire emissions factors. The products available from GlobEmission seem to be suitable for the compilation of such factors values. However, because no global estimates do exist for now, these values need to be compiled for the first time. For global models, the satellite-based emissions factors are of crucial importance. With their help it will be possible to substitute currently used constant single-site values in the model. As soon as emission factors will become available from the GlobEmission project, they will be integrated into the JSBACH fire model together with other satellite measured fire parameters, such as burned area. The use of several fire parameters from satellite measurements in the model is expected to increase the level of confidence for modelled fire emission, making the models results comparable to some independent measurements.

Since the GlobEmission EF products are not yet available, MPI cannot assess them. However, MPI’s preliminary feedback, based on our independent estimates based on SCIAMACHY total column, shows that the satellite values of emission factors are generally useful for our model. The main benefit from the GlobEmission project for MPI is the general availability of data as well as well-organized data access, supported by relevant information about the products

status, and direct links to the original literature references, where the detailed information can quickly be found. Visualization tools look attractive for MPI as a user.

No assessment was provided in 2016.

4.2.6 VU University Amsterdam

VU University Amsterdam is part of the GFED team and evaluates the GlobEmission global CO wildfire emissions. VU (Thijs van Leeuwen) participated in both workshops and presented comparisons between GlobEmission and bottom-up estimated (*Global Fire Emissions Database:* GFED) wild fire emissions, in particular for CO. They also returned a service assessment form. In general, differences between the GFED bottom-up and GlobEmission fire estimates are due to a use of burned area estimates on the one hand (GFED), and active fire data (GlobEmission) on the other. These different datasets were likely to be the cause of the differences in emissions found for Temperate North America, South America and Indonesia.

VU has provided critics but is in general slightly positive about the GlobEmission service and provides suggestions. Would like to see the service extended and advices to focus on South America: very important (on a global scale) from a biomass burning emissions perspective, but also as an anthropogenic source (Sao Paulo region). High-resolution emission estimates for South America, more specifically the deforestation regions on the southern edges of the Amazon rainforest.

No assessment was provided in 2016.

4.2.7 LATMOS

LATMOS (Laboratoire Atmosphères, Milieux, Observations Spatiales) is interested in Global Emissions World – biogenic isoprene. Katerina Zemankova attended the workshop (presentation “Evaluation of the MEGAN-MACC emission inventory of biogenic VOCs”) and provided feedback via the service assessment form of 2016. LATMOS focuses on the creation and evaluation of emission datasets. The global totals of isoprene vary within a factor of 2. Confrontation of emissions with any kind of measurement is therefore needed. Surface measurements of isoprene fluxes are limited in space and time. They provide valuable but usually only short-term information on a local scale. Satellite observations offer better temporal and spatial coverage. Application of formaldehyde satellite retrievals in the model inversion system together with the chemical transport model IMAGESv2 is a sophisticated and efficient way to improve the emission estimates. Even though this indirect method holds its own uncertainties, it is a powerful tool to constrain the biogenic and biomass burning emissions.

LATMOS uses global emission estimates of isoprene for the full time period for which data are available (2007 – 2012), in netCDF format. Information on the dataset was obtained from the Project validation Report version 2, the Algorithm Theoretical Baseline Document and through personal communication with Jenny Stavrakou to clarify details about the dataset.

GlobEmission isoprene emissions were used in an evaluation of our bottom-up emission inventory (MEGAN-MACC). GlobEmission data (top-down) and 4 bottom-up emission datasets were compared in order to address differences in modelling approaches and uncertainties in isoprene estimates. This comparison of different methods to emission calculation helped

LATMOS to learn more about the accuracy and uncertainties of the emission inventories. Use of satellite observations in estimation of biogenic VOC emissions through an inversion using the chemical transport model IMAGESv2 is an up-to-date scientific approach and can efficiently serve to diminish emission uncertainties.

Presentation of the data on the GlobeEmission webpage is clear and easy to follow, files are easily accessible. The mapping tool is a nice feature to display and examine the data.

Assessment 2016 (through user assessment form and a presentation prepared by Sindelarova et al. was presented on her behalf in the 2015 user consultation meeting). Globemission isoprene emissions were used for 2005-2013, information on the data sets was obtained through the PVR and through personal contact with the provider, Jenny Stavrakou (BIRA). The data set provided a valuable alternative to bottom-up inventories. MOZART model runs with Globemission isoprene input data proved to have best agreement with measurements. Data and format are easy to use, presentation on website is clear, files easily accessible. Mapping tool is a nice feature. Suggestion to add the publication as global attribute to the netcdf file.

Value statement: Adopting the top-down approach and constraining the emissions with satellite observations has proven to increase the quality of emission data. The GlobEmission dataset generally showed the best performance among the isoprene inventories used.

Isoprene emissions are dependent on meteorological conditions and can significantly vary from year to year. Keeping the development of GlobEmission isoprene dataset during the coming years would be of high importance and a valuable contribution to the emission and atmospheric chemistry modelling community.

A conclusion from the 2015 user consultation workshop: BISA-top-down inventory created within the GlobEmission project represents an important approach to emission estimation. Constraining emissions with observations are an opportunity to decrease emission uncertainty which is generally very high. Further development of ‘top-down’ inventories would be a great contribution to emission community.

4.2.8 Inha University, Korea

Assessment 2016 (through user assessment form and participation of Dr. SeogYeon Cho in the 2015 user consultation meeting). Globemission data sets (NOx and HCHO are mentioned and the extension to PM is recommended: the presentation in the 2015 user consultation focused first on PM10, which exceeds the norm frequently in Korea, then on NO2 and HCHO) are used for updating bottom-up emissions and validation of seasonal variability. NOx emissions were validated against Korean data bases and HCHO emissions in East Asia are used to test an air quality forecasting model for its ability to reproduce O3 concentrations in Korea. Furthermore, Globemission provides data for North Korea for which no other data are available.

The Globemission data is rated as high quality and have proven to be very helpful in the work described above. Continuation of satellite derived emissions is recommended.

4.2.9 Shanghai Meteorological Service, China

Assessment 2016 (through user assessment form; a presentation prepared by Ying Xie was presented on her behalf in the 2015 user consultation meeting). They would like to use Globemission data (e.g. NOx) in the regional air quality model and compare the results with those using conventional bottom-up estimates. More species would be needed in the East Asia domain, in particular PM2.5, and larger spatial coverage would be useful. The presentation in the 2015 user consultation meeting had a strong focus on PM2.5, underpinning the need for PM emission data.

5 Project outlook

Since emission estimation based on satellite observations is a relatively new development, the GlobEmission project is far from finished. There are several general directions to go for in future activities, which will be briefly described in this section. Further improvement of the state-of-the-art algorithms is still very important. Besides algorithm development the assessment of the quality of the current algorithms will be especially important to indicate to existing and new users how valuable the emission estimates are. Future activities can also consist of developments of new products. For instance estimates of new species could be included, or adding new regions satisfying the needs of the users.

In a follow-up of the GlobEmission project, the quality of all current products can be further improved. For example, the development of the DECSO algorithm for NOx inversion is currently in progress, the relation between aerosol and PM is under investigation, new SO2 inversion methods are studied, and the downscaled inventories of South Africa and the Middle East can be improved. Another essential progress is the development of a regional high-resolution model based on the IMAGESv2 global model. This is planned in order to take best advantage of future enhanced-resolution satellite observation systems (e.g. TROPOMI) , and will allow us to provide both global and regional products using the same model core. Besides the new possibilities to derive high-resolution satellite-based emission estimates over target regions, like the Middle East, China, or India, this will also facilitate validation efforts, often hindered by the limited representativity of global model predictions at specific measurement locations.

For most users it is very interesting to extend the current emission data sets in time to an up-to-date inventory.

Besides the algorithm itself, the quality of the emission data is largely determined by the satellite data that is used. Therefore, aspects as filtering the data or improving the error assessment of the satellite data are important in improving the quality. Also, new satellite products with a superior spatial resolution will become available soon. In this respect, incorporating new satellite data from Sentinel 3 and in the near-future S5p is a logical step forward for the GlobEmission algorithms.

To assess the impact of all those improvements extensive validation activities are needed to inform the users about the accuracy of the provided emission data. Validation shall mainly take place by comparing model output using new emission data with ground-based observations or to compare it to existing bottom-up inventories.

There are many possibilities for extending the range of emission products. In a follow-up of this phase of GlobEmission we could include regional dust emissions (e.g. for the Middle East), ammonia, black and organic carbon from fires, as well as global carbon monoxide and methanol emissions. Experimental, but highly innovative, would be the inclusion of methane emission at a high spatial resolution.

One can also think about setting up new specific services for gas flaring or for shipping emissions. With generalised downscaling techniques, which have been developed under GlobEmission, we can provide emission products on an even higher spatial resolution.

New regions for the emissions products will largely depend on the wishes of the (new) users. One can think about monitoring forest fire emissions in the Amazon region, the Indo-Gangetic Plain for crop residue burning, or Russia for air quality and fire emissions.

6 Further reading

User Requirements Document (http://www.globemission.eu/docs/GE_URD_02_01.pdf)

Product Specification Document (http://www.globemission.eu/docs/GE_PSD_02_00.pdf)

Algorithm Theoretical Baseline Document (http://www.globemission.eu/docs/GE_ATBD_03_04.pdf)

System Specification Document (http://www.globemission.eu/internal/docs/GE_SSD_03_00.pdf)

Input Output Data Definitions (http://www.globemission.eu/internal/docs/GE_IODD_04.pdf)

Product Validation Report (http://www.globemission.eu/docs/GE_PVR_04.pdf)

Service Assessment Report (http://www.globemission.eu/internal/docs/GE_SAR_02.pdf)