

Assessing methane emissions from global spaceborne observations

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Introduction

In the past two centuries, atmospheric methane (CH_4) concentrations have more than doubled. Despite the about 200 times smaller atmospheric burden of methane compared to carbon dioxide (CO_2) this increase constitutes about 20% of the anthropogenic climate forcing by greenhouse gases ($0.48 \pm 0.05 \text{ Wm}^{-2}$; IPCC 4th assessment report, 2007), because on a per molecule basis methane is a much more effective greenhouse gas than CO_2 . Remarkably, the methane growth rate has decreased markedly since the early 1990s, and global concentration levels have remained relatively constant since 1999 (Figure 1). The possible causes of this leveling off are subject of intense scientific debate^{1,2,3}.

An obvious explanation would be that the total global methane emissions have been more or less constant since the end of the 1980s (apart from some anomalous years such as 1993 and 1998), and that the chemical sinks have reached equilibrium with the sources during the 1990s. However, even if this would be true most important questions remain. Assumed

anthropogenic emission reductions by improved agricultural practices and waste treatment may be counteracted by increased emissions from fossil fuel production and consumption. Climate changes and land-use changes, e.g., tropical deforestation, are likely to change the natural emissions, though possibly with different signs. The lifetime of methane in the atmosphere is controlled by oxidation, mainly in chemical reaction with the hydroxyl radical (OH) which correlates strongly with solar ultraviolet radiation⁴, modulated by overhead ozone (O_3) and clouds. OH levels may get enhanced by increases in water vapour, tropospheric ozone and nitrogen oxides (NO_x), but reduced by increases in carbon monoxide (CO) and methane itself. Recent redistributions of anthropogenic emissions, mainly from Europe and N-America to Asia, may also affect the methane trend. Therefore, in order to answer

Anthropogenic sources (in Tg/year)		Natural sources (in Tg/year)		Sinks (in Tg/year)	
Fossil (coal/oil/gas)	102	Wetlands	145	Tropospheric OH	523
Rice	80	Termites	20	Soils	30
Burning	45	Ocean	15	Stratospheric	40
Animals	98	Geologic	18		
Waste	70	Plants	?		
Totals	395		198		593

Table 1. The global methane budget. Methane sources and sinks estimates⁵. A new, so far unaccounted, plant source has been reported recently¹⁰. A closed global budget has been assumed (no trend). Anthropogenic emissions (about two-third) are reasonably well constrained by the combination of pre-industrial methane concentration levels from ice cores and bottom-up estimates based on socio-economic statistics of anthropogenic activities. Natural sources (about one third) are much more uncertain. These emissions vary considerably in time and space and available ground-based measurements are sparse, albeit precise, and hardly representative for larger scales. Oxidation, mainly in chemical reaction with OH radicals, leads to an atmospheric lifetime of 8.7 ± 1.3 years (IPCC 4th assessment report).

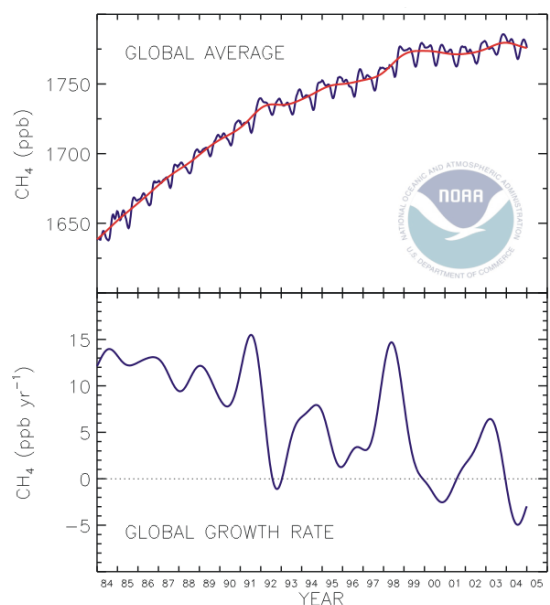


Figure 1. The decrease in the methane growth rate. Top: Global average methane mixing ratios (blue line) determined from the NOAA/GMD cooperative air sampling network (since 1984). The red line represents the long term trend. Bottom: Global average growth rate for methane. Source: Dr. Ed Dlugokencky, NOAA/ESRL; <http://www.esrl.noaa.gov/gmd/>.

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the question on how global methane concentrations will develop in the coming decades better insight is required in the global methane budget. Table 1 summarizes current estimates⁵⁾ for the most important terms in the global methane budget. Anthropogenic source estimates are mainly based on socio-economic statistics.

Since the launch of ESA's environmental satellite ENVISAT in 2002, with onboard the German-Dutch-Belgian instrument SCIAMACHY, methane observations are being made using spaceborne shortwave infrared absorption spectroscopy that allow the global detection of spatial and temporal variations in atmospheric methane concentrations including variations near the surface. These observations enable identification of emission distributions, which is particularly worthwhile over tropical land regions that are poorly sampled by existing surface networks. This was the subject of a paper by Frankenberg et al., in cooperation with KNMI, which appeared in Science

in 2005. Here the main findings of this paper are highlighted.

SCIAMACHY methane observations

Methane not only absorbs thermal radiation from the Earth system causing radiative forcing, but also solar radiation in the near-infrared. Hence, it can be measured by means of differential optical absorption spectroscopy (DOAS). The SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartography) instrument onboard ESA's European environmental research satellite ENVISAT records the intensity of solar radiation, reflected from the Earth's surface or the atmosphere, in more than 8000 spectral channels between 240-2390 nm. ENVISAT operates in a nearly polar, sun-synchronous orbit at an altitude of 800 km, crossing the equator at 10:00 AM local time. In nadir mode the instrument points down almost perpendicular to the Earth's surface, detecting reflected sunlight. The spatial extent of the ground pixels of the near-infrared spectrometers is 60 km (East-West) by 30 km (North-South). Global coverage is achieved every six days. The SCIAMACHY column-averaged dry volume mixing ratio (VMR) of CH₄ is derived from the ratio of the retrieved CH₄ and CO₂ vertical columns, multiplied by a constant global and annual mean CO₂ column-averaged VMR of 370 ppm. The measured CO₂ vertical column is used as a proxy for the changes in the light path by orography, (partial) cloud cover and aerosols. A minor retrieval bias is introduced because the CO₂ column-averaged VMR varies globally and seasonally over a range (minimum to maximum) of about 11 ppmv or 3%. Using a lower threshold for the CO₂ vertical column, measurements can be discarded exhibiting substantial cloud cover at altitudes significantly above the ground. Details on the retrieval, data selections and error estimates are described elsewhere^{6,7,8)}.

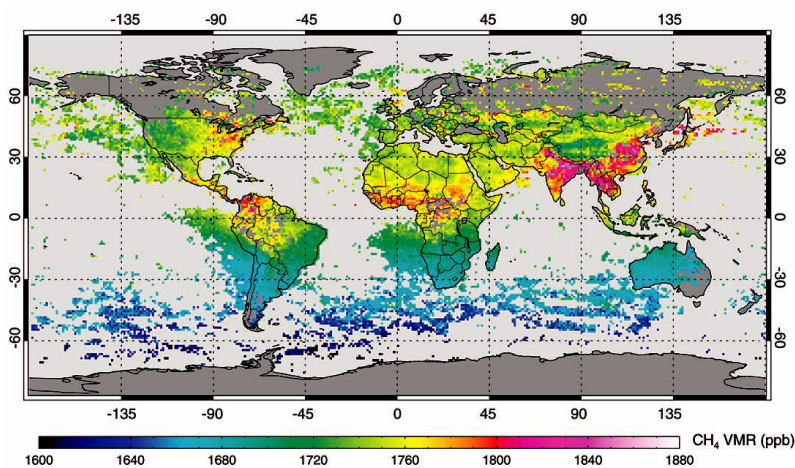


Figure 2. The unequal global distribution of atmospheric methane showing, amongst others, significant sources of methane over Asia. The figure is based on SCIAMACHY measurements of column-averaged methane volume mixing-ratios (VMR) in units of parts per billion (ppb). The measurements are averaged over the time period of August through November 2003 on a 1°x1° horizontal grid. At least 5 measurements (up to 150) are taken for each grid cell. Only few observations are available over the ocean, since low ocean reflectivity substantially reduces the quality of the retrieval leading, in turn, to unreliable measurements that are discarded. Occasionally, sun glint or clouds at low altitudes allow measurement over the ocean.

A resulting subset of SCIAMACHY column-averaged methane concentrations for the time period from August to November 2003 is shown in Figure 2. In comparison to surface concentrations column-averaged methane concentrations exhibit less variation and are slightly lower due to reduced methane concentrations in the stratosphere. The latitudinal gradient is clearly seen. It is strongest across the Inter-Tropical Convergence Zone (ITCZ). Strong regional methane enhance-

Unexpectedly high methane concentrations over tropical rainforests reveal that emission inventories considerably underestimate methane sources in these regions during the time period of investigation

ments are observed over the Gangetic plains of India, South-East Asia and parts of China. According to emission inventories, these regional sources in this time period can be attributed to rice cultivation, and, to a lesser extent, to domestic cattle (ruminants). Wetlands presumably cause the observed high abundances in central Africa and Manchuria in China. Fossil fuel production can be associated with enhanced methane over the industrialised Yellow-river basin in China and the Appalachian basin (coal mining) in the

eastern USA. Waste-treatment related emissions are likely to contribute in populated areas.

Unexpectedly high methane concentrations over tropical rain forests

To further substantiate the interpretation of the observations these were compared with methane concentration fields simulated using the global chemistry-transport model TM₃ that takes current emission inventories into account⁹. In Figure 3 the upper panel shows the modelled fields and the lower panel shows the absolute differences with the SCIAMACHY observations. Modelled enhancements in the USA and Asia as well as the north-south gradient strongly resemble SCIAMACHY observations in magnitude and spatial extent. Some of the observed enhancements can be traced to long-range transport, e.g. over the Pacific, east of Japan. While the general agreement between the measurements and the model is very good, there are discrepancies in India and in the tropics (Figure 3, lower panel). The measured lower abundances over India probably indicate that the applied rice emissions in the model (amounting to 80 Tg/year) are an overestimation.

In the tropics SCIAMACHY observations are up to 4% (70 ppb) higher than predicted by the model. This can be explained either by tropical methane emissions not considered in the model, a regional CO₂ depression relative to the annual global mean, or a combination of both. It was found that the discrepancy cannot be attributed to a retrieval error dependent on solar zenith angle, light-path changes or albedo. Also a model bias, such as an underestimation of the stratospheric methane abundances or large errors in the modelled distribution of OH radicals, could be excluded. Although CO₂ flux estimates in the tropical landmasses are uncertain, the required depression in the CO₂ column of 3-4% would be of an improbably high magnitude. Hence, it was concluded that tropical CH₄ sources in the model have been underestimated.

A strong spatial correlation was found between the tropical discrepancies and the presence of broadleaf evergreen forest. Model simulations indicate that an additional tropical source of around 30 Tg over the considered time period (August-November) is needed if the discrepancy is fully to be assigned to methane

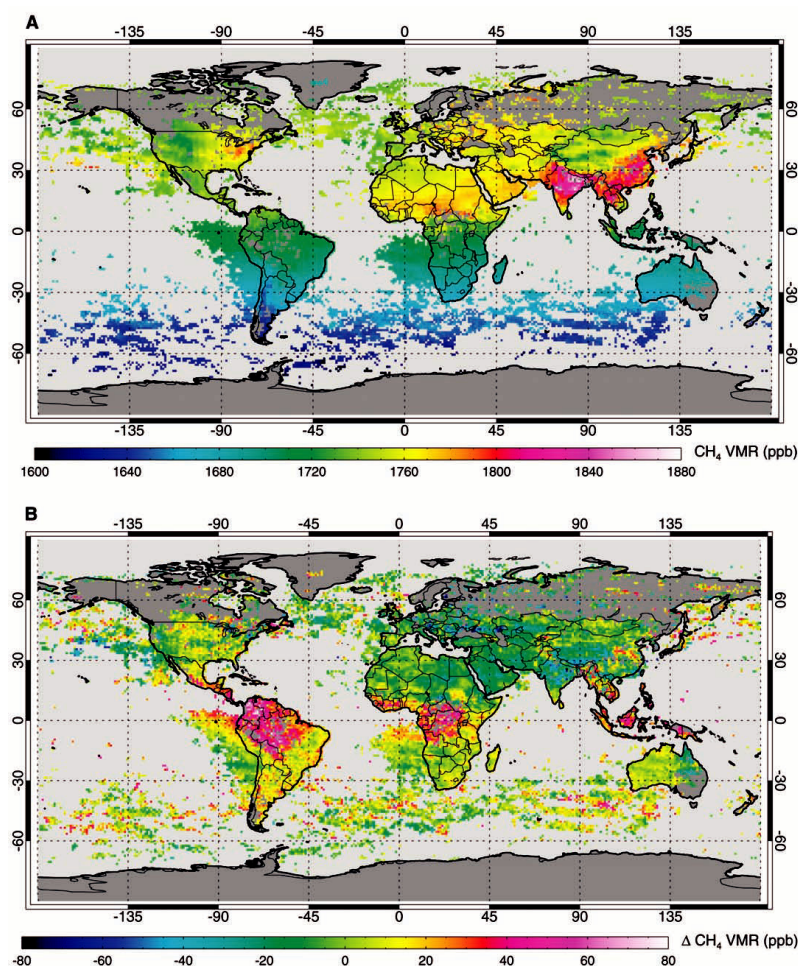


Figure 3. The sources of methane in tropical areas have been systematically underestimated. This conclusion could be drawn from simulation of the SCIAMACHY methane observations with a model (upper panel). The red and purple areas in the lower panel show where most important differences with the model (our current understanding) are found. Units as in Figure 2.

sources. For comparison: the tropical source in our model is 45 Tg. An additional methane source of 30 Tg in four months is large but can be accommodated by the uncertainties in the global budget (Table 1). It is important to note that surface methane observations are not in disagreement with an additional tropical source. Methane emitted in the tropics is generally rapidly uplifted by convection, so that the surface stations, which are located at remote ocean sites, are only to a limited extent sensitive to these emissions.

What are potential candidates for the enhanced tropical source? Wetlands, biomass burning, termites, cattle breeding in pastures? Or maybe a hitherto unknown methane source that might be directly related to the broadleaf evergreen forest? Recently, a hitherto unknown plant source was reported¹⁰⁾. Termites constitute a significant but poorly constrained tropical methane source. Tropical fires are characterized by a molar CH₄/CO₂ ratio that is more than twice the ratio of their respective background concentrations. Hence, the SCIAMACHY observations are sensitive to these fires. Wetland emissions, in particular in the Amazon Basin, appear to be underestimated in the TM₃ model. However, the investigated period coincides with the dry season in most of the tropics, when wetland emissions are supposed to be lowest. In the dry season unaccounted biomass burning can contribute to the discrepancy. Further validation measurements and process-based investigations for the considered season in the evergreen forests of tropical South America, Africa and Indonesia are needed to conclude which source

type(s) is/are responsible for the discrepancies between the observations and model simulations over these areas.

Conclusion and Outlook

In conclusion, SCIAMACHY methane observations have become available which show large-scale patterns of anthropogenic and natural methane emissions. Unexpectedly high methane concentrations over tropical rainforests reveal that emission inventories considerably underestimate methane sources in these regions during the time period of investigation (August–November 2003).

Without improved understanding of the relative contributing factors to the trend in methane over the past decades it is hard to make predictions for the future. Several counteracting effects are likely to mask future changes in anthropogenic sources, natural sources, and chemical lifetime, similar as has been suggested for the recent past^{9,11)}. Methane concentration scenarios in climate assessments so far have been based on IPCC/SRES anthropogenic methane emission scenarios, such as presented in Figure 4. However, there is no doubt that future methane concentrations will as much depend on changes in natural emissions and chemical lifetime.

The EU project HYMN (2006–2009), lead by KNMI, will further contribute to our understanding of the methane budget, variability, and trend. Improved methane emission distributions can be expected from inverse modelling^{12,13)}. Within HYMN 4D-var data assimilation techniques will be applied to better constrain methane sources based on the SCIAMACHY data record. The framework of the global climate model EC Earth will allow better studying of the chemistry-climate interactions for methane. These include direct forcing, feedbacks via natural sources and OH, and impacts on stratospheric water and the ozone layer.

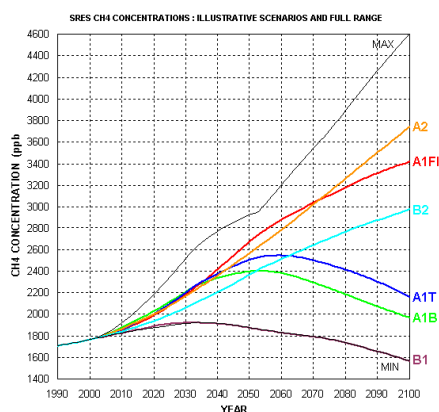


Figure 4. Illustrative CH₄ concentrations in the 21st century for the six groups of IPCC/SRES emission scenarios applied in the 3rd and 4th IPCC assessment reports; <http://www.ipcc.ch/pub/pub.htm>.

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