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Atmosphere


Fig.1

Composition of the atmosphere

After the first soundings of the upper layers of the atmosphere with ODIN, which celebrated its 15th year in orbit this year, and with GOMOS/Envisat and other satellites, notably to gain a better understanding of the formation of the ozone hole in the stratosphere and of polar stratospheric clouds (PSCs), and subsequently of exchanges between the troposphere and stratosphere, space instruments are today capable of sensing at lower altitudes in the troposphere using ever-more-innovative technologies to obtain better and more precise signals.

For example, the IASI program that CNES is leading jointly with Eumetsat has been delivering data on atmospheric composition in the troposphere since 2006, detecting an impressive array of trace species. The latest IASI conference in Antibes, France, in early April 2016 highlighted the wealth of results for research into air pollution from industrial emissions, large fires and volcanoes. With the current program scheduled to extend to at least 15 years and continuity assured for another 15 years after that from the IASI New Generation project, the long record of data will be a key asset in keeping track of our changing climate through monitoring of essential climate variables (ECVs).

The next challenge is to sound the atmosphere near Earth's surface to gain new insights into exchanges between the atmosphere and land surfaces and oceans. The latest report from the International Panel on Climate Change (IPCC) shows that if greenhouse gas emissions continue at their current rate or increase, temperatures could rise an additional 2 °C, seriously impacting the climate system over the course of the 21st century in ways that will far exceed the consequences seen over the previous century. In addition to such climate perturbations, we can expect major modifications to the carbon cycle that could further fuel the greenhouse effect and climate change.

For all of these reasons, CNES and its partners are pursuing MERLIN and MICROCARB, two innovative projects to measure atmospheric concentrations of the two main greenhouse gases responsible for global warming.

The first, MERLIN (MEthane Remote sensing LIdar missioN), aims to tell us more about methane fluxes, notably in key regions of the globe like the Arctic, Eurasia and tropical land surfaces, which today are not covered or only sparsely so. Analysis of ice cores highlights the significant impact of human activities on current levels of methane, which have reached a

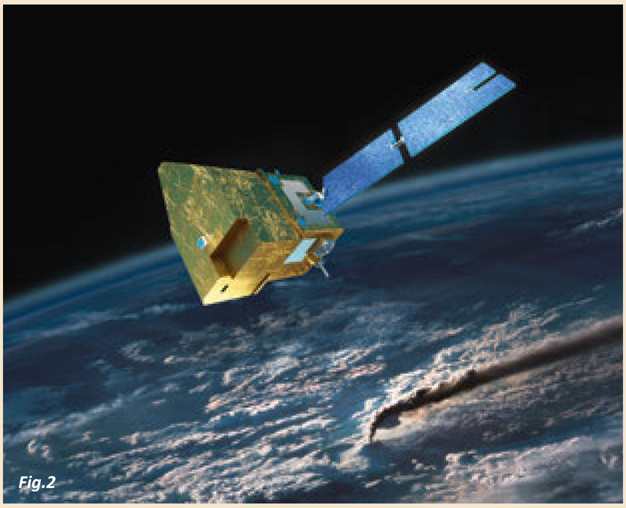
Fig.2

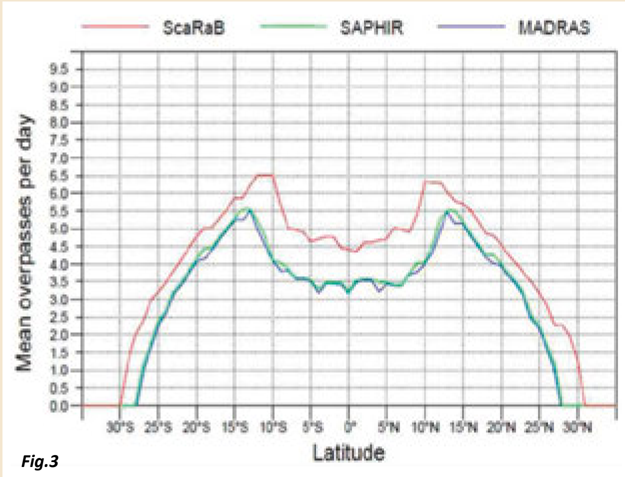

Fig.3


Fig.4

Fig. 1: The MicroCarb and Merlin missions are also intended to measure the concentration of atmospheric CO_2, the main greenhouse gas contributing to climate change.

Fig. 2: Artist's view of Microcarb built around the Myriade bus.

Fig. 3: Mean number of measurements per day as a function of observation latitude for each of the instruments on the Megha-Tropiques mission (from Roca et al. 2015). *© NASA/JPL Caltech, 2011*

Fig. 4: Artist's view of the Megha-Tropiques satellite. This French-Indian mission was designed to study the water cycle and energy exchanges in the tropics. Megha-Tropiques will therefore contribute to a better understanding of the climate processes responsible for hurricane formation and monsoon variability. *© CNES/PHOTON/REGY Michel, 2011*

global mean of more than 1 800 parts per billion (ppb), two and a half times higher than 200 years ago. This spectacular increase is mostly due to development of intensive cropping (rice) and livestock breeding, but certain industrial activities (coal mining, natural gas drilling and landfills) are also to blame. Being able to map emissions precisely therefore represents a major challenge for climate research.

MERLIN aims by 2020 to begin measuring the integrated column of atmospheric concentrations of methane (CH_4) with an accuracy better than 27 ppb (approx. 2%) and a bias of less than 3.7 ppb. To achieve this goal, the mission will be carrying a differential absorption lidar (DIAL), which offers the advantage compared to passive instruments of greatly reducing bias thanks to a self-calibration system and of being able to sound night and day to observe high latitudes in any season. This lidar supplied by the German space agency DLR will be mounted on a new Myriade Evolutions spacecraft bus developed by CNES in partnership with French manufacturers Airbus Defence & Space and Thales Alenia Space. MERLIN is a French-German project that stems from the two nations' political commitment to contribute to climate research subsequent to the COP15 in Copenhagen in December 2009. MERLIN is scheduled to launch in 2020 on a mission planned to last at least three years.

Also for 2020, CNES is proposing to develop MICROCARB to characterize fluxes of carbon dioxide (CO_2). The mean global level of CO_2 in the atmosphere in the pre-industrial era is estimated to have been 278 ppm. Scientists have been measuring levels directly since 1958, notably at the reference site at the summit of Mauna Loa in Hawaii. It was 315 ppm in 1958, 350 ppm in 1988 and is now over 400 ppm.

In light of the expected social impacts, scientists are joining forces to obtain a denser grid of measurements around the globe and thus better quantify fluxes of carbon gas between the atmosphere, oceans, soils and vegetation, with a view to identifying sources and sinks. And as these fluxes are sensitive to climate variations through vegetation and water/air exchanges, it is important to learn more about them so that we can model the future evolution of the CO_2 cycle and in particular the absorption capacity of carbon sinks in a changed climate. Closer knowledge of the location and amplitude of CO_2 sources and the underlying processes is therefore vital to better understand how the climate system works and envision how certain practices might be changed. This goal cannot be achieved with ground-based measurements alone and satellites are the only way to acquire a global, uniform and independent picture.

Other dedicated missions around the world are either in service or in development: OCO in the United States and GOSAT in Japan are in service, while TANSAT is in development in China. The MICROCARB mission aims to learn more about the carbon cycle through reliable measurements of global and regional exchanges of CO_2 between the atmosphere, oceans and land surfaces. Comparing such measurements with models will enable us to refine our understanding of the processes driving these exchanges and then predict how ecosystems are likely to respond to expected global warming.

There is currently no way to measure carbon fluxes — sources or sinks — directly from space. The idea is therefore to measure atmospheric concentrations of CO_2 and interpret their spatial and temporal gradients in terms of flux. However, given the persistence of CO_2 in the atmosphere, the mean level (*i.e.*, the proportion of well-mixed gas) is high with respect to these gradients. As a result of this, gas concentration measurements must be very precise and above all unbiased.

MICROCARB will use a passive near-infrared spectrometer to sense solar radiation reflected from Earth's surface. This reflected radiation passes through the atmosphere twice and is thus partially absorbed by the species there. This modifies the solar spectrum and absorption lines appear at wavelengths specific to the molecules encountered. The line depth is directly related to the amount of absorbing molecules. Thanks to its clever and innovative optical systems, MICROCARB's instrument is compact (< 60 kg) and able to measure atmospheric concentration of CO_2 with a precision of a few ‰, that is, better than 1 ppm for a total gas column of approximately 400 ppm.

Pursuing the rich harvest of data and scientific results from the MEGHA-TROPIQUES and CALIPSO missions

MEGHA-TROPIQUES is a French-Indian mission led jointly by CNES and ISRO designed to study the water and energy budgets of convective systems in the tropics by acquiring frequent measurements of the parameters associated with radiative fluxes, water vapor and precipitations.

The original feature of the MEGHA-TROPIQUES mission is the combination of its instrument and 20-degree-inclined orbit, which enables a high revisit rate.

The payload comprises three instruments: a microwave imaging radiometer (MADRAS), designed chiefly to study precipitation and cloud properties; a microwave sounding radiometer (SAPHIR) capable of mapping water vapor; and a wide-band radiometer (SCARAB) for measuring radiation fluxes [1].

Water vapor and precipitations — as well as Earth's surface radiation budgets — are among the 50 essential climate variables (ECVs) defined in 2010 by GCOS(1) to track climate change and meet the requirements expressed by the IPCC(2) and UNFCCC(3). The MEGHA-TROPIQUES mission is therefore also helping to monitor climate by complementing measurements of the planet's radiation budget, water vapor and precipitations being acquired by NASA, offering increased resolution over the tropics. MEGHA-TROPIQUES is officially contributing to the international GPM effort coordinated by NASA and JAXA, for which it is supplying observations from SAPHIR. The GPM(4) constellation was also augmented in February 2014 with the addition of the GPM-Core satellite and its dual-frequency radar, obviously an important element for MEGHA-TROPIQUES. Moreover, the Tropical Rainfall Measurement Mission (TRMM) ceased operating on April 8, 2015, after 17 years in service, leaving MEGHA-TROPIQUES as the only tropical observing mission in operation today.

Since 2013, the mission is able to distribute SAPHIR data in real time via Eumetsat's EUMETCast system. The Meteo-France national weather service has been assimilating level 1 SAPHIR data into its operational Arpege and Aladin prediction models for Réunion since April 2015. SAPHIR data are currently only fed into models when skies are clear, but research is ongoing to assimilate them in cloudy and precipitation conditions, which means that hydrometeor scattering must be factored in, so they must be well represented in the model. Methodological developments for MEGHA-TROPIQUES will also be applicable to other microwave sounding and imaging instruments already in flight or in development, such as AMSU-A, AMSU-B, MHS, ATMS and future instruments on the METOP-SG satellites.

2016 provided the opportunity to conduct an in-depth review of the science results the mission has obtained since 2011 on tropical meteorology and assimilation, hydrometeorology and the life cycle of mesoscale convective systems.

Fig.5

Fig. 5: Pollution in the Mexico City © *Thinlstock*

As of April 2016, some 90 papers have been published, 70 of them written by French scientists. In terms of citation impact, as of April 5, 2016, there have been more than 1 400 citations (1 236 since 2011), an h-index of 16. The impact of MEGHA-TROPIQUES publications is on a near-exponential curve, having generated 407 citations in 2015, nearly one quarter of all citations.

Hydrometeorology has gained prominence over the years, taking advantage of the high revisit rate over SAPHIR's coverage zone, with up to six observations a day. A product called TAPEER [2] combining SAPHIR data with measurements from other satellites, notably in geostationary orbit, has been developed to estimate cumulative precipitation at a spatio-temporal resolution of one degree and one day, with an error bar. This product has been widely assessed and shown strong potential, especially in Africa, paving the way for its use at least offline and for research purposes in hydrological models. Research efforts in this area are thus actively laying the groundwork for downstream applications of the future French-U.S. SWOT mission (Surface Water Ocean Topography).

Another water-cycle-related mission, CALIPSO (Clouds and Aerosols Lidar and Infrared Pathfinder Satellite Observatory), clocked up its 10th year in operation this year (launched on April 28, 2016). This French-U.S. (CNES-NASA) mission, in combination with measurements from instruments on the other satellites in the A-TRAIN (notably CLOUDSAT), has reduced a certain number of uncertainties regarding the impact of clouds and aerosols on climate. The IPCC's Fifth Assessment Report (2013) makes many references to the CALIPSO mission. As part of the Grand Challenge on Clouds, Circulation and Climate Sensitivity of the World Climate Research Programme (WCRP), continuous observations are much needed to gain insights into the interdecadal variation of global cloud and aerosol distribution. ESA's ADM-AEOLUS and EARTHCARE missions, set to launch in 2017 and 2018, are expected to meet this demand in the short term. The broad French scientific community that has won such acclaim for its work in this field over the years through CALIPSO is looking forward to actively using the data from these new missions.

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(1) *Global Climate Observing System*

(2) *Intergovernmental Panel on Climate Change*

(3) *United Nations Framework Convention on Climate Change*

(4) *Global Precipitation Mission*

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Atmosphere

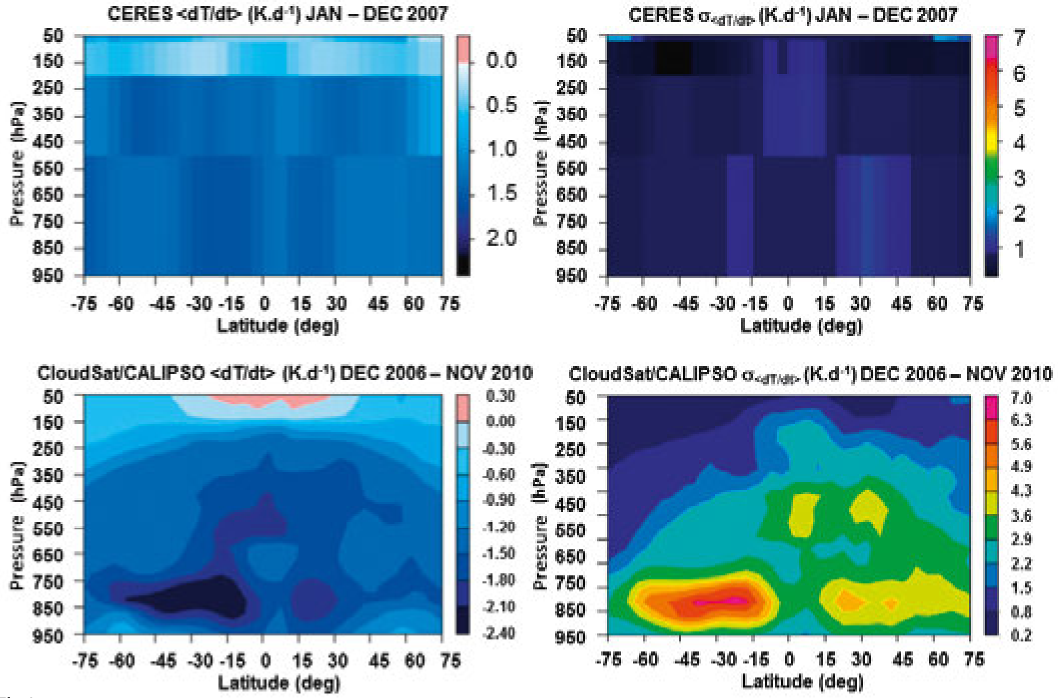
Contribution of the CALIPSO mission to better quantification of the role of clouds and aerosols in Earth's radiation budget

The main goal of the CALIPSO mission (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) is to gain a closer understanding of the radiative properties of clouds and aerosols in Earth's atmosphere. The vertical distribution of clouds and aerosols modulates the atmospheric heating rate due to the interaction and absorption processes influencing the large-scale dynamics. Clouds and aerosols modulate incident solar and infrared fluxes at the surface. The balance between these incoming fluxes and emitted fluxes (diffuse visible, thermal infrared and turbulent fluxes) is what drives variations in Earth's surface temperature.

CALIPSO is a French-U.S. mission led jointly by NASA and CNES launched in April 2006. It is one of the key elements in the A-TRAIN(1) Earth-observing constellation organized around the AQUA satellite built for NASA's Earth Observation Science program. The A-TRAIN is the only space observatory with as many satellites in orbit (initially five, now six, with AQUA, CLOUDSAT, CALIPSO, CGCOM-W1, AURA, and OCO-2). The CALIPSO mission has thus played a pioneering role in characterizing clouds and aerosols and in measuring vertical optical properties for studying Earth's radiation budget from space. The satellites in the A-TRAIN constellation are flying in close formation in very similar orbits that enable them to acquire local measurements in almost identical conditions, trailing each other by only seconds to a few minutes. Complementing observations from the CALIOP (Cloud and Aerosol Lidar with Orthogonal POlarization) backscattering lidar, the Imaging Infrared Radiometer (IIR) with its French-designed uncooled microbolometer array has helped scientists to measure the optical and microphysical properties of ice clouds with low optical thickness, and to achieve convergence of physical models used to invert data from CALIOP and the MODerate resolution Imaging Spectroradiometer (MODIS). A camera calibrated to MODIS's visible channel gives a spatial resolution of up to 125 m × 125 m, matching that obtainable with the lidar, to analyze fine-scale variability. Several products have been developed to take advantage of the synergy between observations. The ICARE data center in France is archiving these new products derived from the mission alongside operational products.

CALIPSO observations are thus used intensively by modelers and the international scientific community has undertaken numerous studies to better understand meteorological processes (and how to parameterize them in numerical weather prediction models), physical and chemical processes (air quality) and climatic processes (model representativity). More than 1 500 research publications (Fig. 2) have cited CALIPSO observations, mostly for comparing analyses (both directly and with a lidar simulator), but also for assimilation purposes [1]. A large number of these publications cover analyses conducted for the IPCC's Fifth Assessment Report and analysis of radiative forcings. CALIOP's unequalled observing capability has also spawned new applications for ocean research, in particular for analysis of surface state and ocean color.

In France, the combination of lidar, radar and radiometer measurements has enabled advances in numerical prediction models through the Dardar product developed at the ICARE data and services center within the AERIS(2) hub. New approaches linking the microphysical properties of ice clouds to infrared radiation [2] have facilitated assimilation of cloud observations in the infrared into such weather models. By coupling observations from the A-TRAIN, particularly from CALIOP and CLOUDSAT's cloud radar, the radiative atmospheric heating rate has been measured with unprecedented vertical resolution (Fig. 1). Vertical measurements are unambiguous and analysis of induced radiative forcings is more precise thanks to the measurement of optical thicknesses and the ability to identify multiple layers. The CALIPSO mission is playing a key role in this approach, as it is able to target not only aerosols and ice clouds of low optical thickness, but also warm low clouds, whose importance at southern hemisphere latitudes is clear (Fig. 1C, 1D), whereas CLOUDSAT



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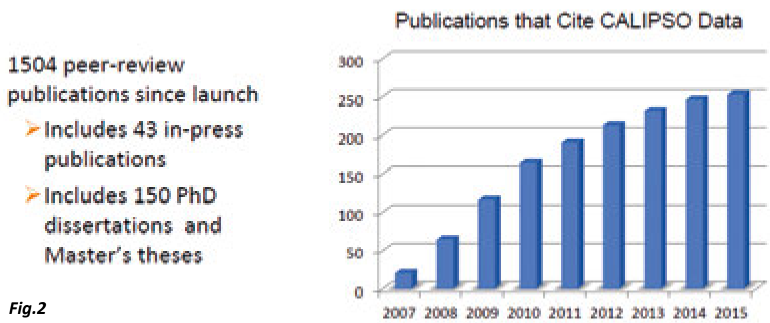

Fig.2

Fig. 1: Illustration of capabilities offered by active-sensor missions, pre-Calipso (CERES, top two figures) and post-Calipso (A-Train, bottom two figures). Annual means and standard deviations (left and right figures) for CERES (one year, top left and right) and for Calipso/Cloudsat (four years, bottom left and right) of the radiative heating rate induced by clouds and aerosols as a function of atmospheric pressure. According to [3].

Fig. 2: Publications in peer-reviewed journals citing Calipso data from 2007 to 2015 (source: NASA-CNES)

is not sensitive enough to detect them. In this regard, it is noteworthy that representing these clouds was previously a major headache in weather prediction models, generating a radiative imbalance at southern hemisphere mid-latitudes that has been resolved by modifying the cloud processes in the European Center's model, which now allow for mixed-phase clouds as had been observed by CALIPSO and MODIS. We also note the increase in radiative forcing in the middle troposphere in the northern hemisphere due to medium-altitude clouds, which until now were poorly identified by passive measurements and poorly represented in models.

The data record built up by CALIPSO is now approaching 10 years and the continuing good health of the instruments and satellite hold out the prospect of extending it several years further. Reprocessing exercises are also planned to enhance the results already obtained and push the boundaries of what we know about the optical, radiative and microphysical properties of clouds and aerosols.

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Atmosphere

IASI mission helping to study climate and atmospheric pollution

IASI is an infrared atmospheric sounding interferometer dedicated to improving knowledge and services in at least three areas. While it is primarily working for weather services that assimilate IASI radiance data to improve their forecasts, it is also playing a key role fulfilling the needs of scientists researching atmospheric chemistry and climate. In particular, IASI measurements are used to monitor changes in atmospheric composition (gases and particles), notably greenhouse gases like carbon dioxide (CO_2) and methane (CH_4) in the troposphere, as well as components responsible for pollution like carbon monoxide (CO).

Through a joint program led by Eumetsat and CNES, a first IASI instrument was launched in October 2006 on the METOP-A satellite, a second on METOP-B in September 2012 and a third is set to launch in late 2018 on METOP-C. The IASI instrument consists of a Fourier transform spectrometer that sounds the atmosphere at nadir — scanning across track to provide global coverage — in the thermal infrared portion of the spectrum. Data are available for delivery through the ground segment about two hours after each satellite pass. This mission is therefore a key element of operational weather forecasting and for the study of atmospheric composition and real-time applications (e.g. for the European Union's Copernicus program). With the IASI-NG (New Generation) instruments scheduled to come on stream in 2021 and extend service for another 21 years, long-term data continuity is assured and scientists will be able to draw on a long record of consistent measurements vital for assessing climate trends.

Thanks to CNES's support in designing and building the IASI instrument, French research laboratories have developed a broad spectrum of expertise in studying gas and particles, spanning development of dedicated radiative transfer codes, inversion algorithms used to calculate concentrations from measured spectra, assimilation of observations in atmospheric models, and validation of measurements. Their efforts are focusing on variations in atmospheric composition at different spatial (local and global) and temporal scales (daily, seasonal and annual) and are also improving characterization of ground emission sources and helping to monitor short-term (pollution) and long-term (climate) variations.

Moreover, in combining data with those from the METOP-A and METOP-B satellites, which are in the same orbit trailing 45 minutes behind one another, and by delivering data in near-real time, the IASI mission has also shown great potential for tracking exceptional events like large wildfires, peak pollution episodes and volcano plumes.

Atmospheric carbon monoxide pollution

2015 was an exceptional year due to a particularly strong El Niño episode. The map (Fig. 1) compares distributions of carbon monoxide (CO) measured by IASI in early November 2015 (an El Niño year) and over the same period in 2014 (a normal year). This phenomenon created exceptional drought conditions that fueled the wildfires raging in Indonesia, Borneo and Sumatra at this time of the year. As a tracer of incomplete combustion of wildfires, CO can be used to track the drift of plumes blown by the wind and their regional distribution.

Carbon monoxide (CO) and ozone (O_3) data from IASI are available on the website of the AERIS/ETHER(1) data center, where daily and monthly maps of daytime and nighttime IASI CO data can also be viewed. These data are also continuously assimilated by the European Centre for Medium-

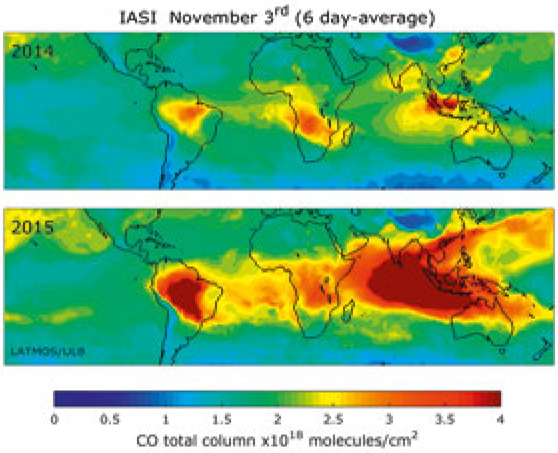

Fig.1

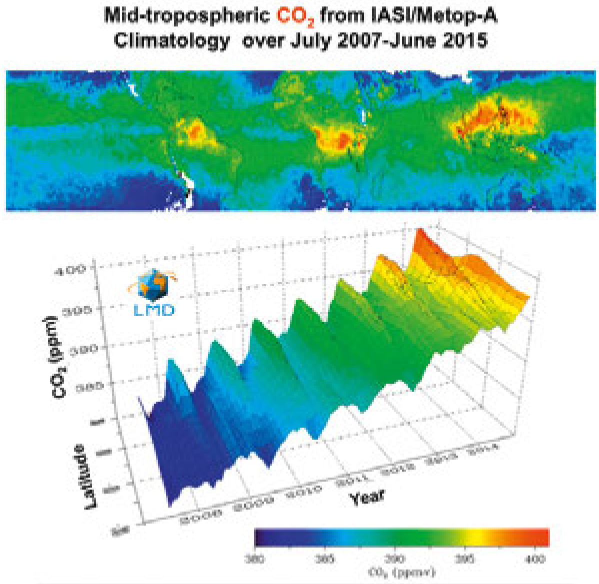

Fig.2

range Weather Forecasts (ECMWF[2]) to predict CO concentrations several days ahead.

Retrieval of greenhouse gases related to the carbon cycle

Estimates of carbon dioxide (CO_2) and methane (CH_4) concentrations in the mid-upper troposphere have been derived from IASI data and are now delivered for assimilation to ECMWF through the Copernicus Atmosphere Monitoring Service[3] with a view to providing vertical profile forecasts for these two greenhouse gases.

Nearly nine years of CO_2 and CH_4 data are now available from IASI observations on METOP-A. The time series of CO_2 and its mean geographic distribution over this period are shown in Fig. 2. High values due to emissions from burning of tropical biomass can be clearly seen, as can the overall growth rate of CO_2 of approximately 2 ppmv.year^{-1}. As for any climate variable, measurement of greenhouse gas trends requires space-based instruments to be constantly monitored and in this respect the spectral and radiometric stability of IASI on METOP-A is exceptional. The recent extension of CO_2 and CH_4 estimates to IASI observations on METOP-B (already three years) show that the second IASI instrument is delivering similar performance to the first, making it possible to monitor these greenhouse gases and other climate variables like dust aerosols, clouds and surface characteristics over the long term.

CH_4, CO_2 and aerosol data from IASI are available on the website of the AERIS/ETHER[1] data center.

Fig. 1: Carbon monoxide concentrations measured by IASI from 1-6 November 2014 (top) and 2015 (bottom). The zones in red indicate high concentrations observed in wildfire plumes. *© M. George/C. Clerbaux (LATMOS).*

Fig. 2: CO_2 mixing ratio (tropospheric column) estimated from IASI. Global means from July 2007-June 2015 (top) and monthly variations with latitude.

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