LES DOSSIERS

# De l'espace pour le climat

# *Space for the climate*

AAE Dossier #47

2020

# *SPACE FOR THE CLIMATE*

**AAE Dossier #47** **2020**

*Cover credits top to bottom:*

Sentinel-2 © ESA - MetOp-B © ESA - Earth from Apollo 17 © NASA

JASON-3 © CNES David-Ducros

**AAE**

Ancien observatoire de Jolimont

1 avenue Camille Flammarion

31500 Toulouse - France

Tel : +33 (0)5 34 25 03 80

contact@academie-air-espace.com

**www.academieairespace.com**

ISBN 978-2-913331-83-9

ISSN 1147-3657

Dépôt légal : juin 2020

## *Recent Dossiers*

# TABLE OF CONTENTS

# TABLE OF FIGURES

# *FOREWORD*

*The Air and Space Academy decided to take part in the current debate on the impact of human activities on the climate by organising an international conference in October 2017 to examine the contribution of space-based resources to the monitoring of climate change variables, in particular greenhouse gases. The aim of this conference was, on the one hand, to raise participants' awareness as to the importance of space observatories in monitoring the climate and, on the other, to bring together scientists, space agencies and industrialists. Dossier no.47 endeavours to summarise the ensuing presentations and discussions and issue recommendations.*

*This issue is situated within the overall context of global climate change. The Paris agreement adopted in December 2015 seeks to limit global warming to 2°C by drastically reducing greenhouse gas emissions. To meet this challenge and assess the effectiveness of the decisions taken, it is vitally important to be capable of accurately measuring these emissions. The subject is a complex one, requiring the collaboration of specialists from many scientific fields, the development of technological tools and the cross-referencing of data with simulations from numerical models. Space technologies are at the heart of climate monitoring, indeed over half of the Essential Climate Variables defined by the Global Climate Observing System (GCOS) can only be measured from space. Space provides access to a global view of greenhouse gas concentrations and other atmospheric variables, with satellites in polar orbit rapidly covering the entire globe. Space-based measurements are supplemented by land, sea and airborne measurements.*

*This dossier reviews the questions raised by scientists about the processes behind climate change due to the increase in greenhouse gases (in particular carbon dioxide ($CO_2$) and methane ($CH_4$)), the state of the art technologies being developed by manufacturers for space-based observation of these constituents,* *and the programmes implemented by space agencies to provide scientists with the long-term data they need to forecast climate change.*

*The conference revealed that current space-based measurements have neither the accuracy nor the necessary geographic and temporal cover to estimate greenhouse gas sources (emitting areas, for example industrial zones) and sinks (absorbing areas, such as the oceans for $CO_2$). This would require several satellites to simultaneously carry out precise, well calibrated measurements of the same variable. These measurements must be part of a complete system that includes ground observation networks and inventories of greenhouse gases sources and sinks, in order to feed global models of the Earth system. Increased cooperation between the scientific community, industry and space agencies is therefore called for. Efforts should be made, with the help of the scientific community, to formulate a roadmap setting out priorities in terms of the acquisition of observation data, so as to enable space agencies to draw up a strategic plan consistent with these priorities.*

***Anne-Marie Mainguy***
President of the Air and Space Academy (AAE)

# *1 INTRODUCTION*

*COP21, which took place in November and December 2015 in Paris, was a crucial moment in terms of States' awareness as to the reality of climate change and its serious consequences for our planet. Alerted for years by the scientific community gathered in the IPCC (Intergovernmental Panel on Climate Change), political leaders appeared to have taken the measure of the problem and grasped the political and economic issues behind climate changes (escalation of natural disasters, regional planning challenges, climate refugees, etc.). In 2016, the World Economic Forum placed the failure to adapt to climate change and mitigate its effects at the head of its list of global risks (Figure 1).*

*At COP21, governments committed to reducing greenhouse gas emissions due to human activity (Figure 2) in an attempt to limit the rise in average global temperatures by 2050, as compared to 1900, to under 2°C. The challenge is huge and the task ahead onerous: if we are to reduce anthropogenic greenhouse gas emissions and assess the effectiveness of strategies implemented, what is needed, in addition to political will (which unfortunately seems since to be on the decline), is the ability to accurately measure these emissions. This challenge is at once scientific and technological.*

*The Air and Space Academy (AAE) decided to take part in this debate by organising a conference in Toulouse, on 10-11 October 2017, focused on the contribution of space systems to improving our understanding and observation of phenomena influencing the climate, in particular the main greenhouse gases: carbon dioxide ($CO_2$) and methane ($CH_4$). Climate change is a complex subject, which requires the collaboration of many different scientific fields and technological tools, the crossing of the many different models with land-based, ocean-based, airborne and satellite measurements (Figure 3). Space plays an important role in this analysis, since most of the Essential Climate Variables (ECV), as defined by the Global Climate Observing System (GCOS), can only be measured from space (Figure 6).*


*Figure 1: This graph indicates the main global economic risks and identifies "Failure of climate change mitigation and adaptation" and "Extreme weather events" as having the greatest impact and likelihood. Source: World Economic Forum, The Global Risks report 2019, 14th edition*

*Entitled "The Climate needs Space", the conference, held on the site of Météo France, brought together European and American scientists, representatives of space agencies (CNES, ESA, DLR, Eumetsat), engineers and industrialists (CNES, ESA, Airbus and Thales Alenia Space).*

*The scientists present stated their need for reliable measurements to predict climate change, and showed the complexity of the analytical models. The space instrument developers revealed the state of maturity of the technologies used. The space agencies presented the programmes currently under development, aimed at providing the scientific community with increasingly precise data over the long term (the European Copernicus programme with Sentinel satellites for instance).*

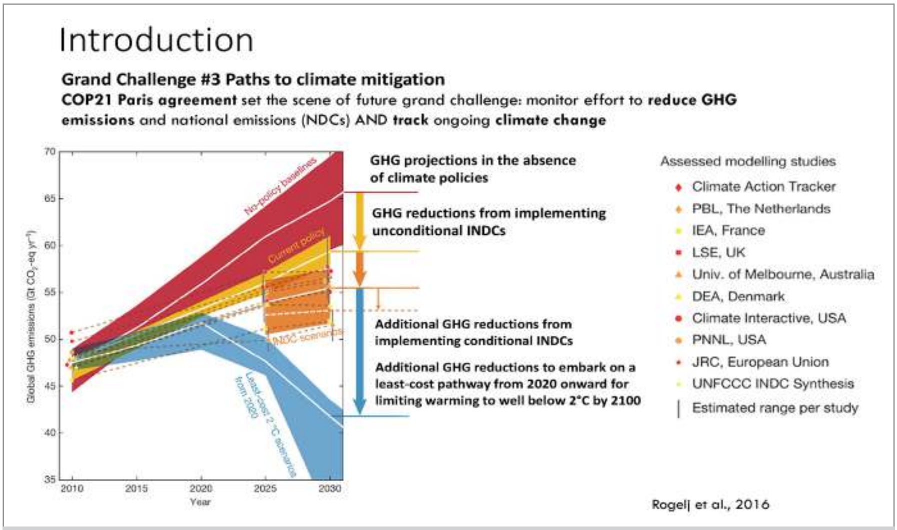


*Figure 2: Evolution of global greenhouse gas emissions resulting from implementation of the Intended Nationally Determined Contributions (INDCs), and needed if we are to limit global warming to below 2°C.*
*Source: Rogelj et al., 2016.*

## *Météo France, location of the AAE conference*

*The Météo-France International conference centre in Toulouse was an appropriate choice for the conference location. Meteorology is now operational and faces similar problems to climatology with the added issues of operating in real time and in the very short term. It also shares the same skills in terms of training, research, operational functions and observation networks. Weather forecasting is constantly having to adapt in order to integrate the latest advances in space engineering and remote sensing from space. Meteorological data is collected very quickly, the challenge is one of volume, of finding the computing power to integrate all these elements into digital models to forecast the weather, the atmosphere, oceans, continental surfaces and the cryosphere. At present, weather forecasting for the Earth system in the short term (five days and more) is highly satisfactory. Climate forecasting will match this in the future for the long term (month, year, decade).*

# 2 CONTEXT

*The Paris agreement on the climate, adopted in December 2015, aims to keep global warming below 2°C and to "pursue efforts" with a view to limiting this rise to 1.5°C. In order to achieve this, countries have submitted Intended Nationally Determined Contributions (INDCs) outlining their planned climate action after 2020. Rogelj et al. (2016) assessed the impact of current INDCs on reducing global greenhouse gas emissions and the implications for achieving the target limits for global warming written into the Paris Agreement. Compared to current policies, these INDCs were indeed found to reduce greenhouse gas emissions but they nonetheless involve a median warming of 2.6 to 3.1°C by 2100 (Figure 2). It is possible to achieve more. Actions to reduce greenhouse gas emissions must be substantially strengthened for us to have a reasonable chance of achieving the goal of maintaining global warming below 2°C.*

*The speed of current climate change, and the difficulty of adapting our societies to this rapid change to mitigate its consequences, are a major threat. Each year, the World Economic Forum assesses the risks to the world economy posed by various potential events. In 2019, the two main risks, with both a high impact and a high likelihood of occurrence (Figure 1) were two environmental threats linked to climate change: failure to adapt to climate change and increased likelihood of extreme weather events.*

## Climate models

### The Earth system

*Planet Earth is an integrated dynamic system. Energy exchanges and transformations generate change on all temporal and spatial scales. There is no stable state to our planet, rather it is in a state of perpetual flux involving all physical, chemical and biological phenomena in its atmosphere, ocean and continental surfaces.*

*Regarding the climate, many feedback mechanisms (i.e. when one quantity changes a second quantity, and the change in the second quantity in turn changes the first) are at work, notably through clouds and the albedo (the fraction of solar energy reflected back to space by a surface). These mechanisms can amplify the impact of energy variations or, on the contrary, mitigate them. Humanity, one component of the terrestrial ecosystem, affects the state of the planet by altering the energy transformations and disturbing the composition of the atmosphere so fast that the planet has no time to adjust by means of its natural feedback phenomena.*

*Analysing the Earth system and the evolution of its climate is a complex business. It requires continuous, accurate data and sophisticated, evolving models. It is based on the processing and reprocessing of long historical series, the combination of emission inventories, space- and ground-based observations and atmospheric transport models.*

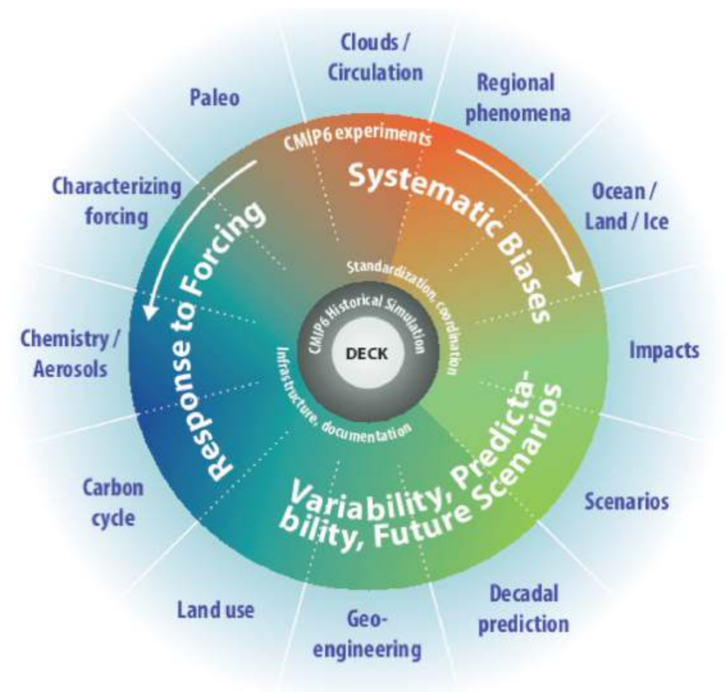


***Figure 3: Diagram showing CMIP6 simulations organisation. The CMIP DECK (Diagnostic, Evaluation and Characterisation of Klima) experiments and the CMIP6 historical simulations are at the heart of activities. The middle and outer rings indicate scientific subjects for which specific studies are carried out. Source: Eyring et al., 2016.***

## *Modelling the Earth system*

*The purpose of climate models is to simulate this system, integrating all its various interactions and chain reactions. The modelling of natural or anthropic physico-chemical phenomena, which are permanently interacting and causing the climate of our planet Earth to change, is of such complexity that over 40 models exist. Figure 3 is a diagram representing how simulations of the Earth system models are organised within CMIP6 (Coupled Model Intercomparison Project), an initiative aimed at coordinating climate simulations from different research groups. These simulations will be listed and compared with each other to assess the state of knowledge on the climate for the 6th IPCC report (Intergovernmental Panel on Climate Change) due to be issued in 2021.*

*These climate models predict changes over a horizon of 50 to 100 years or more. The accuracy of these forecasts is therefore difficult to verify. This uncertainty must be circumscribed and scientists aim to achieve this by characterising the various feedbacks more accurately. Moreover, the global warming expected by the end of the 21st century depends enormously on the assumed scenario for greenhouse gas emissions (Figure 4).*

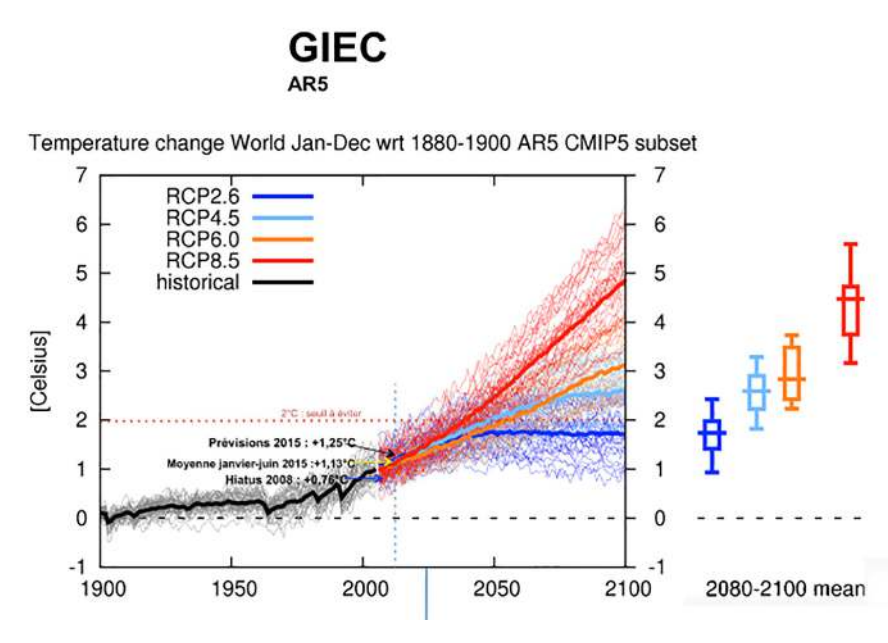


***Figure 4: Projections on temperature rise according to greenhouse gas emission scenarios from the 5th IPCC report. The error bars on the right represent the spread of the results according to model. Source: 5th IPCC report, 2014.***

*Each model has its particularities and weaknesses, depending on the emphasis it places on such and such a phenomenon. Certain atmospheric transport models work very well, for instance, in one part of the troposphere but not at all elsewhere. This introduces biases which feed into calculations of surface fluxes on the basis of measurements of constituents incorporated from the entire column (Figure 5).*

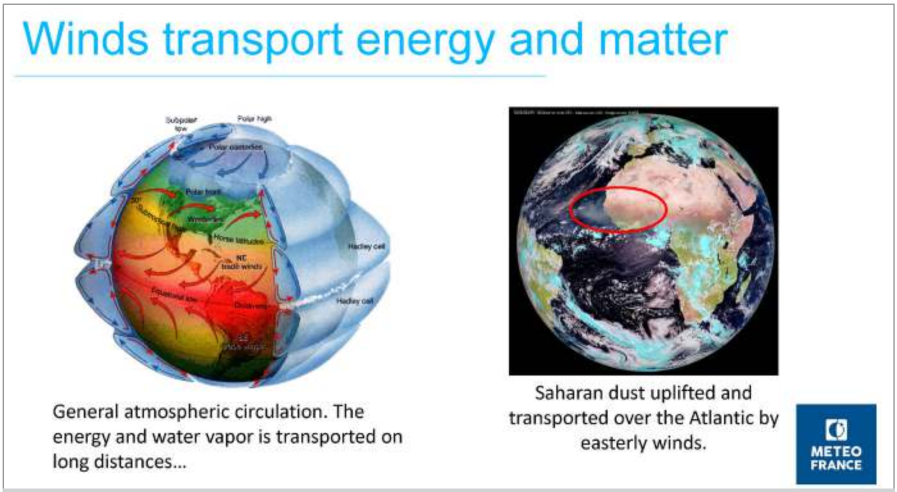


***Figure 5: Winds on the surface and at altitude transport energy, clouds and aerosols and disperse gases (including $CO_2$ and $CH_4$); measurements of concentrations in an air column give information on surface fluxes only if all atmospheric circulation is properly modelled. Source: Météo France.***

*The goal of the international GCOS programme, created in 1982, was to define a global climate observation system. One of its first actions was to identify climate variables needed to support the work of the IPCC. There are currently 54 of these "Essential Climate Variables" (ECV), relating to the atmosphere, the ocean and the continental surfaces (Figure 6). They were chosen not only because of their importance but also because they are accessible to systematic observation and to the production of consistent series of data over a very long period. 50% of these 54 variables can be charted directly by space instruments. The remaining half can be further divided into 2: 25% have a space component while the remainder require surface-based observation. So 75% of the data essential to measuring these essential climate variables is derived from satellite measurements.*

*One of the consequences of global warming is the rise in sea level. This is due to two factors: the expansion of the ocean due to warming, and the melting of the Greenland, Antarctic and mountain glaciers. Space altimeters (a French speciality) measure the rise in sea level (3.17 mm/year over the period 1992-2016, Figure 7). Since the ocean contains 90% of the anthropogenic heat accumulated over the past 50 years, this is a good warming tracer.*


*Figure 6: The 54 Essential Climate Variables.*
*Source: gcos.wmo.int/en/essential-climate-variables*

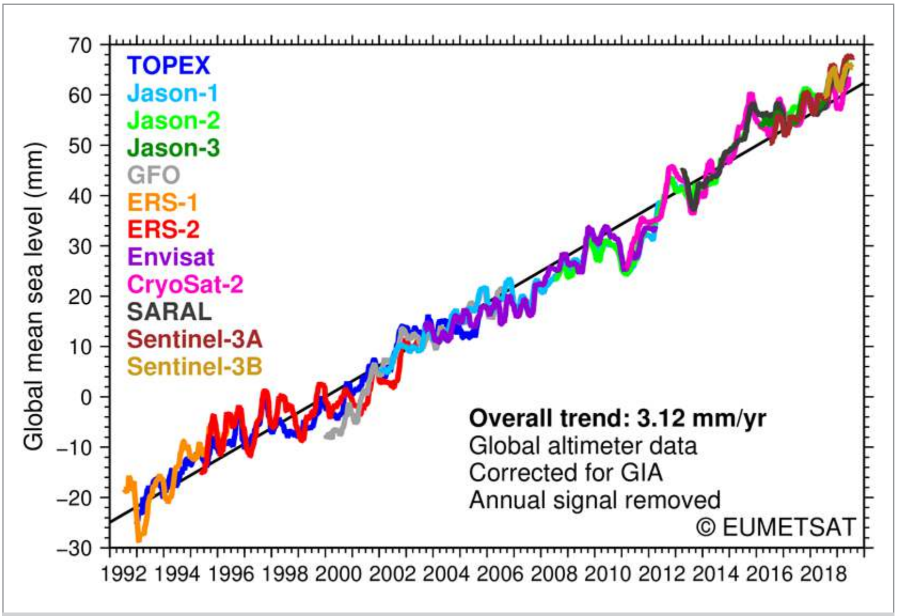


*Figure 7: Evolution in the sea level as measured by space altimeters.*
*Source : Eumetsat.*

# 3 THE MAIN GREENHOUSE GASES

*The Earth benefits from a natural greenhouse effect that is essential to our survival since it raises the surface temperature. This fragile balance is however threatened by human activities, which alter the chemical composition of the atmosphere, causing an additional greenhouse effect which is largely responsible for current climate change. The main anthropogenic greenhouse gases are carbon dioxide and methane, whose presence in the atmosphere has increased by 40% and 190% respectively in a century (Figure 8).*

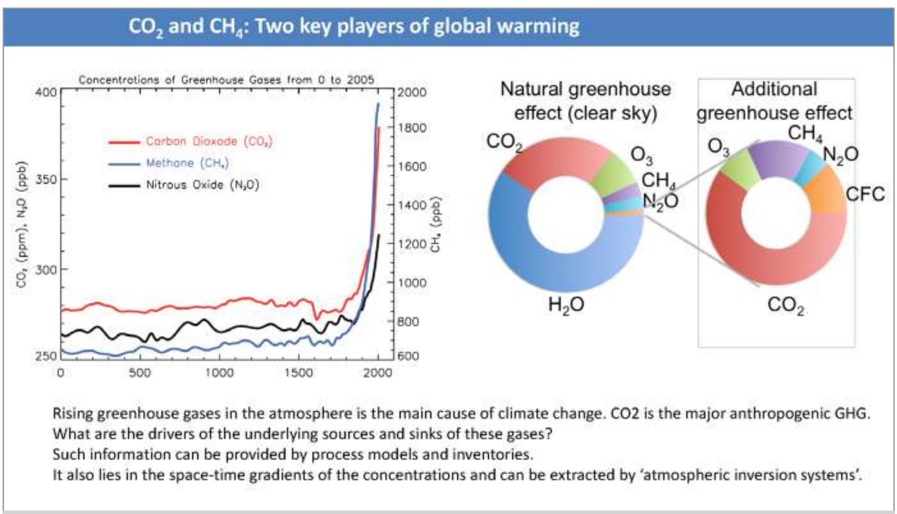


***Figure 8: Increases in the concentration of greenhouse gases in the atmosphere is correlated with strong growth in human activities emitting these gases in the same period. Source, C. Crevoisier.***

# Carbon dioxide

## Characteristics, sources and sinks

*$CO_2$ is a stable molecule, little affected by the chemistry of the Earth's atmosphere. Its concentration in the atmosphere is constantly rising, adding an additional greenhouse effect to the natural effect. It is considered to be the primary anthropogenic greenhouse gas. In the climate, there is always a natural aspect and an aspect that is forced by human activities. The natural greenhouse effect is mainly due to water vapour, with 26% due to $CO_2$. The additional contribution represents only a small part of this percentage. This is the crux of the problem, because when we talk about disruption caused by humans, we are concerned with very small signals when compared with the magnitude of natural cycles.*

*To study the concentration of $CO_2$ in the atmosphere, we use emission inventories, knowledge on carbon sources and sinks, transport models and observations. Two major grey areas prevent accurate prediction of the speed of climate change in the 21st century: the action of water vapour and clouds, and how carbon flows and stocks will react to climate change.*

*The two main sources of anthropogenic carbon emissions are the burning of fossil fuels (90% of emissions) and changes in land use, such as deforestation (10%). Almost half of the $CO_2$ thus emitted remains in the atmosphere, the rest is absorbed by so-called carbon sinks: up to 26% by the oceans and 28% by continental ecosystems (Figure 9). This latter estimate is, however, subject to great uncertainty,*

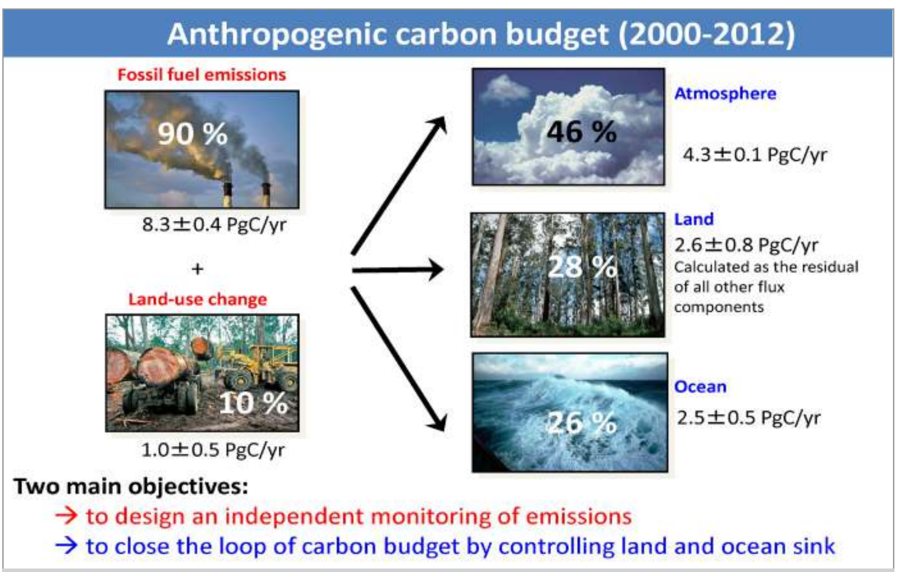


*Figure 9: Transfer between sources and sinks over twelve years.*
*Source: C. Crevoisier.*

*since it is obtained through deduction. Here, two phenomena partially offset each other: deforestation (via forest fires) is a source of carbon released into the atmosphere, while the vegetation itself, which feeds on carbon, absorbs $CO_2$. The sum of these two opposing effects is very uncertain. The best estimates consider that during the first half of the 20th century, deforestation prevailed, while the second half saw the carbon sink effect take over. A neutral balance would seem to have been achieved in 2000 (Figure 10).*

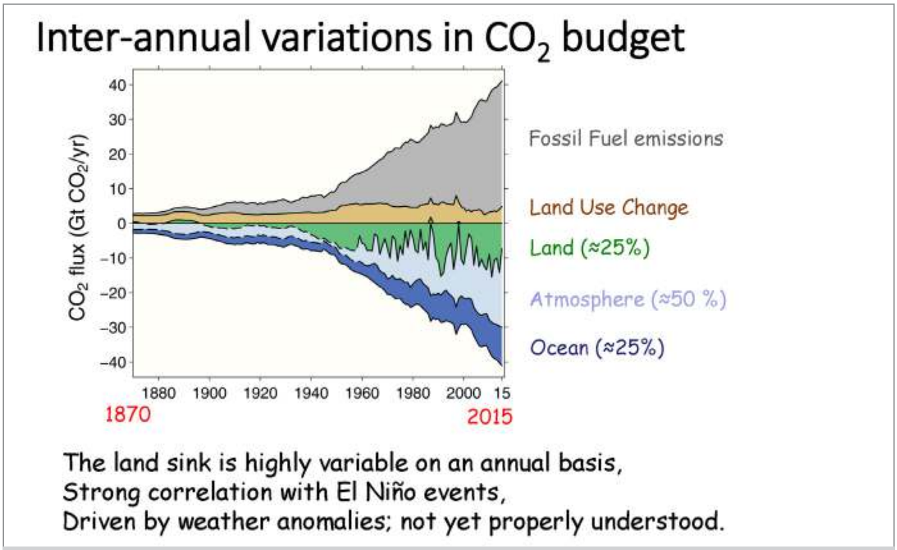


***Figure 10: Interannual variations in the $CO_2$ balance. One can note a sharp increase in emission sources after the Second World War and a great variability in the annual absorption capacity of vegetation.***
***Source: F.M. Bréon, adapted from Le Quéré et al., 2015.***

*To study the role of $CO_2$ in climate change and understand how its concentration in the atmosphere will evolve, it is important to correctly identify and monitor anthropogenic and natural emissions and understand the sinks linked to the carbon cycle which, in the end, determine the amount of $CO_2$ remaining in the atmosphere. The tools to do so consist of emission inventories, a priori knowledge of sources and sinks, transport models and observations. The reaction of continental sinks varies according to climate events such as El Niño and meteorological anomalies (Figure 11).*

*The top-down (or atmospheric inversion) approach is a means of improving knowledge on surface sinks and emissions. We compare simulated 3D fields of $CO_2$ concentration (generated from emission inventories and knowledge of flows) with available observations (ground, airborne or satellite) to refine the transport models.*

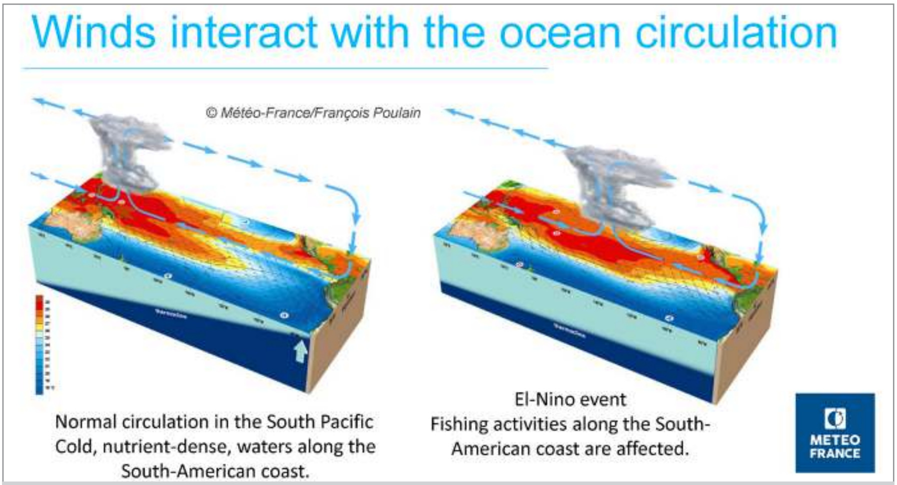


*Figure 11: Major meteorological phenomena like El Niño modify ocean circulation and have a significant impact on the concentration of CO2 in the atmosphere. Source: Météo France.*

*By monitoring the concentration of CO2 in the atmosphere, and thanks to the transport model, we can trace the CO2 emissions and sinks on the surface (Figure 12).*

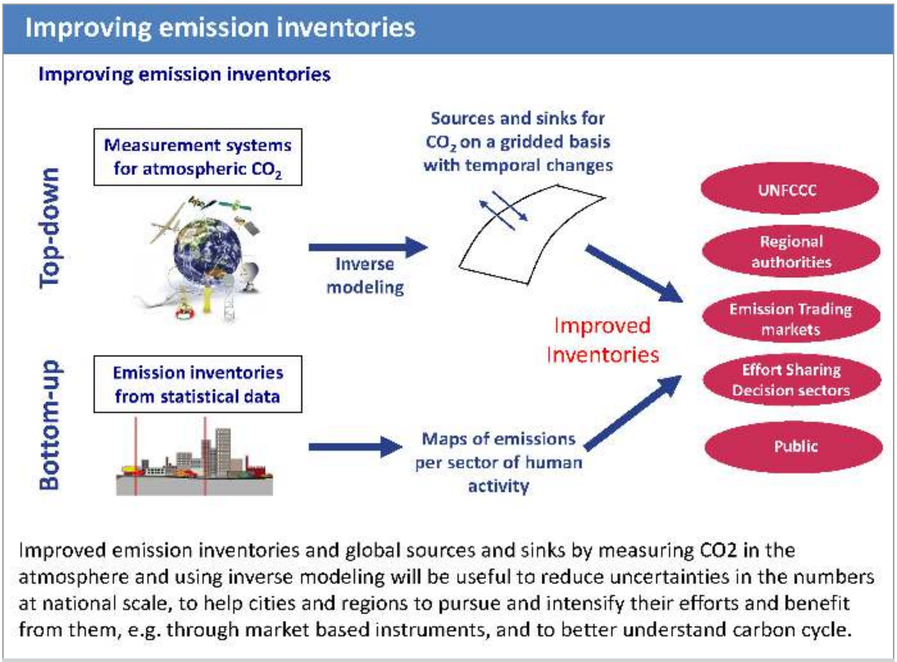


*Figure 12: Emission inventories are vital for monitoring efforts undertaken (or not) by players; they require very precise modelling of the transport of CO2 in the atmosphere. Source: C. Crevoisier.*

## *Satellites: a necessary but insufficient tool*

*There exist many stations for $CO_2$ measurement around the globe – whether ground and ship-based or airborne (aircraft and balloons) – but some areas, such as the tropics and the oceans, have little coverage. Space-based observation, for its part, provides a wealth of information across the entire globe on evolving $CO_2$ concentrations in the atmosphere. It also helps monitor the vegetation index and identify the start of fires linked to deforestation. Some missions operate in the short-wave infrared (SWIR), others in the thermal infrared (TIR). However, modelling the radiative transfer remains difficult, in particular in a diffusing sky, i.e. in the presence of aerosols and clouds. Satellites provide valuable data, although little at high latitudes, and suffer from bias.*

*Aside from the space system itself, what matters is the data processing chain that enables raw measurements to be translated into $CO_2$ concentrations in the air column. Currently, the same satellite observations processed using different methods do not arrive at the same results, which impacts flow estimation. It is therefore essential to calibrate and validate processing internationally.*

*Ultimately, satellites are a good tool for observing, measuring and thus monitoring $CO_2$. But they cannot meet all needs and should be therefore thought of as one element in a comprehensive observation system, complementing robust, ground-based infrastructures. There is a need for synergy between the different observation networks. Surface and lower atmosphere networks are necessary for absolute calibration and the long-term. Airborne measurements help validate specific satellite data in certain atmospheric zones and enhance transport models. This applies to both carbon dioxide and methane.*

## *The difficulty of measuring anthropogenic emissions*

*Satellites measure from space the total column of $CO_2$ in the atmosphere. It is very difficult, from this overall data, to extract a signal emitted at ground level. The level of precision required to measure anthropogenic emissions represents a major technical hurdle (Figure 13). For while the total concentration of $CO_2$ in the atmosphere varies from 380 ppm (parts per million) to 410 ppm, the variation linked to anthropogenic emissions is of the order of -4 to +4 ppm. We are thus talking about detecting an extremely weak signal from within overall measurements that level out $CO_2$ variation over the entire column. It is therefore not easy, on the basis of satellite data alone, to see the large difference in $CO_2$ concentration which nonetheless exists on the surface between an urban area and a wooded area. It is considered that the systematic biases associated with these measurements should be less than 1.25 per 1000. High resolution tools are therefore required (Figure 14).*

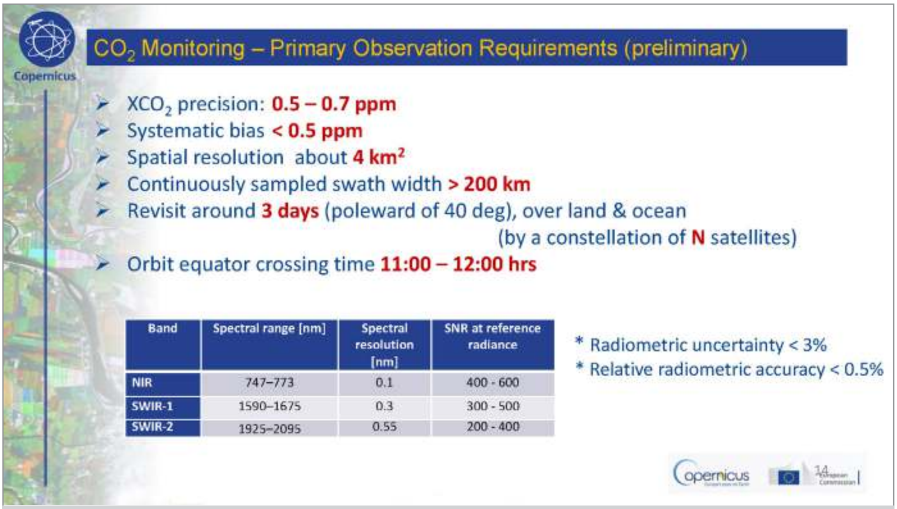


*Figure 13: Specifications required for a satellite system monitoring anthropogenic $CO_2$ emissions.*

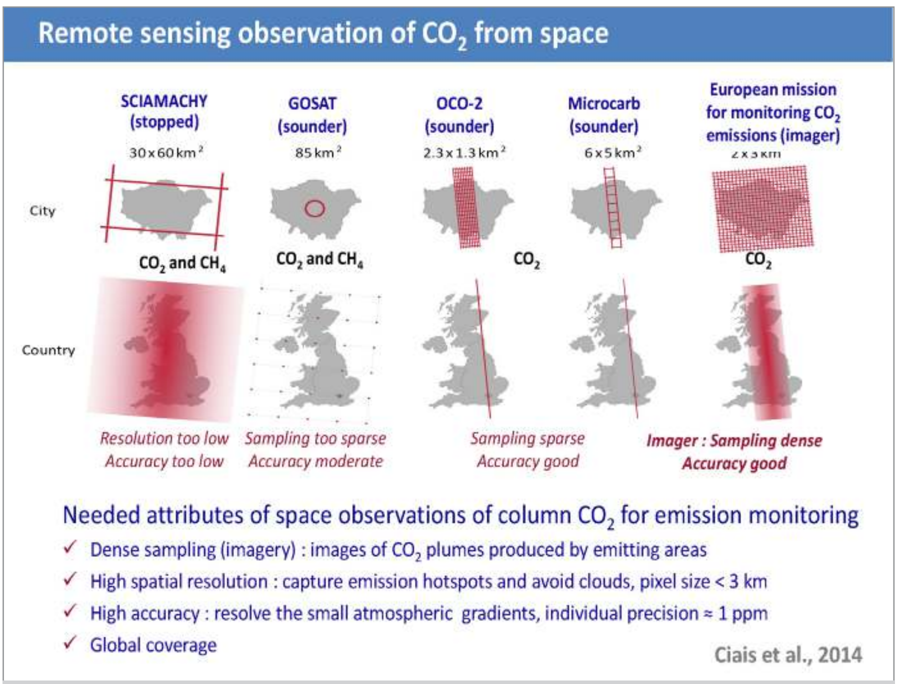


*Figure 14: Space programmes for the measurement of $CO_2$: past (Sciamachy), present (GOSAT and OCO-2) and future (Microcarb and EU-$CO_2$).*

*The European Copernicus programme is planning for a space tool composed of three satellites, measuring the column of $CO_2$ (as well as methane) with an accuracy of about 0.5 - 0.7 ppm, a systematic bias of <0.5 ppm, a resolution of around 4 km² and a swath of 180 km (Figure 15).*

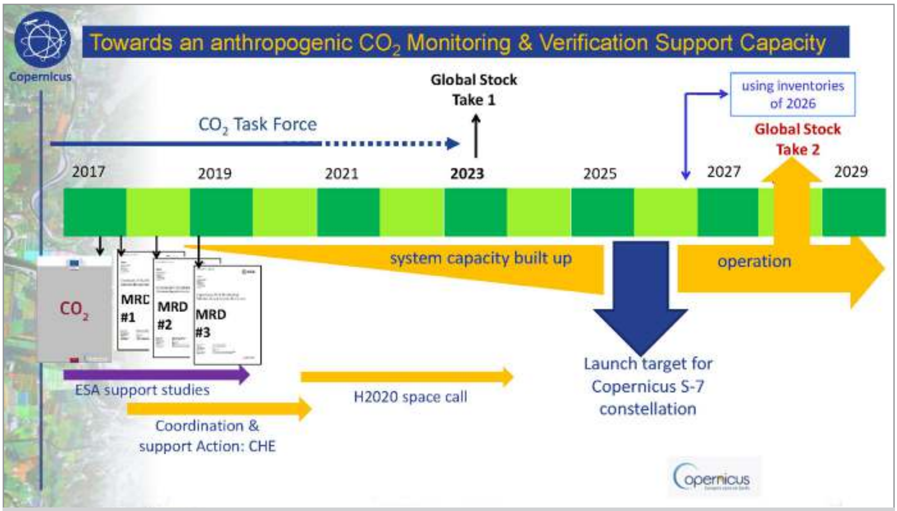


***Figure 15: Actions for monitoring $CO_2$ emissions carried out within the framework of the Copernicus programme by the European Commission assisted by ESA and its member countries.***

## *Political imperatives*

*The Paris Agreement provides for a global carbon quantity assessment every five years (in 2023 and 2028) to verify the impact and effectiveness of strategies implemented by States to reduce anthropogenic $CO_2$ emissions in the atmosphere. There is nothing binding to this initiative, however, no supranational body to totalise each country's emissions from space. States have merely committed to checking their own inventories. In recent years, though, uncertainty has increased regarding the annual inventories of $CO_2$ emissions reported by emerging countries, in particular China.*

*In view of these global assessments, the climate component of the European Union's Horizon 2020 programme brings together European partners to pool and use all available data, both in situ and satellite. The monitoring system is based on detecting hot-spots (high emissions from mega-cities and factories), observing emissions (increase or reduction), evaluating systems initiated by countries, and measuring the impact on overall carbon footprints.*

# *Methane*

## *Characteristics*

*To restrict the rise in temperature to 2°C, it is necessary to target all greenhouse gases of anthropogenic origin, and not merely $CO_2$. Methane ($CH_4$) is a less complicated target. The second anthropogenic greenhouse gas, its concentrations are responsible for about 20% of global warming. Its anthropogenic share is over 60% today and it has a lifespan of ~9 years (Figure 16).*

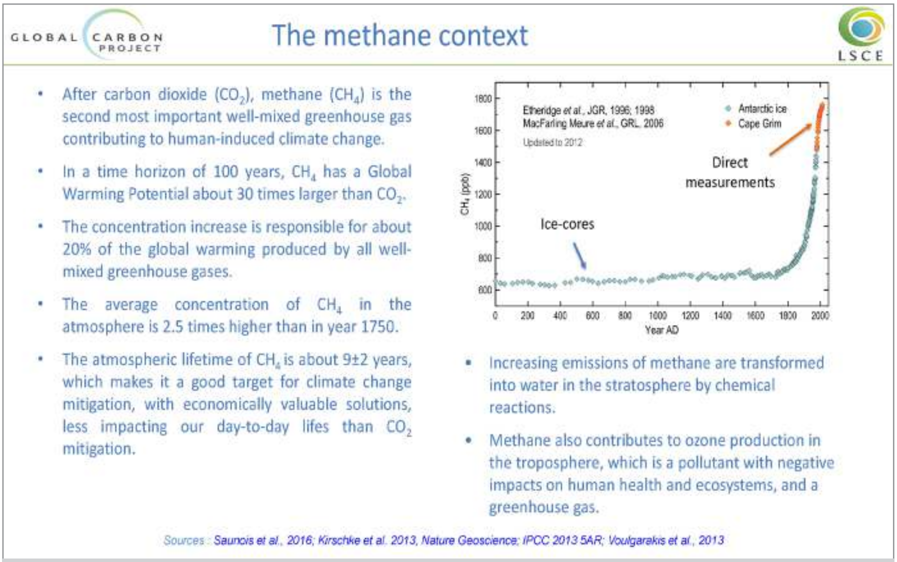


***Figure 16: Methane, another greenhouse gas. Source: P. Bousquet.***

*Atmospheric sinks remove about 90% of the methane present in the atmosphere. Wetlands are its main natural source of emissions, while the main anthropogenic sources of emissions are fossil fuel extraction (and the natural gas leaks it can cause), agriculture and waste processing.*

## *Methane budgets*

*Efforts to harmonise methane budgets (bottom-up or top-down) are being made at the international level (Figure 17). According to the top-down vision, total emissions are around 560 million tonnes (teragrams - Tg) per year. There remains a large element of uncertainty concerning these flows, including the anthropic portion. The bottom-up vision advances the figure of 730 Tg (not constrained by the atmosphere) but unlike $CO_2$, for which inventories have roughly a 5% margin for error, there are once again great uncertainties even for the anthropic portion. Our knowledge of sources must therefore be improved.*

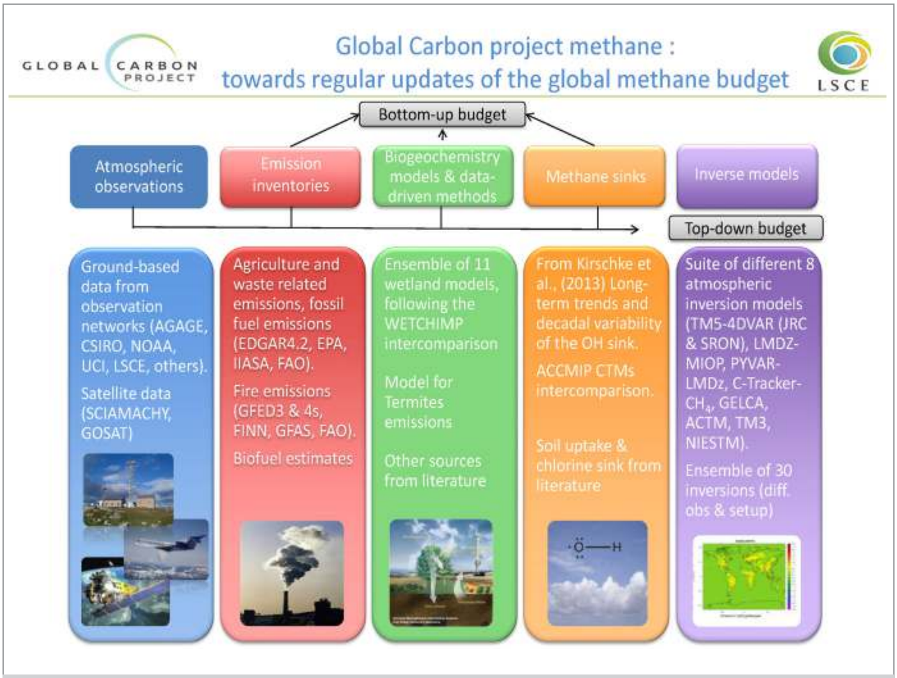


***Figure 17: The overall methane budget is established by means of observation data, emission inventories, sink estimates and physico-chemical and transport models.***

*A major problem stems from the coexistence of several classifications, with each scientific community (whether studying lakes, wetlands, rivers or dams) having formed its own. To eliminate the risk of double-counting in global inventories, work should go into harmonising classifications. A problem with wet areas is that not all are wetlands – i.e. an ecosystem with specially adapted plants – and likewise not all wetlands are flooded. This raises difficulties in their detection from space. Finally, there are great uncertainties regarding the figures for methane emissions from geological sources.*

*Methane budgets on a regional level also present significant uncertainties. To reduce these it is necessary to go constantly back and forth between inventories, inverting data and using both ground and space-based data.*

*It is also important to understand recent changes in atmospheric methane concentration: a stagnation in the 2000s, then an increase, accelerating from 2014-2015. The estimates given by the top-down and bottom-up visions are consistent at the global level, but diverge at the regional level, as is the case for each process (wetlands, other natural sources, agriculture and waste, biomass, combustion of biomass, fossil fuel) (Figure 18). There are large regional uncertainties about methane sources and sinks; take the Arctic, for example, where the melting of permafrost could release a significant, but unknown, amount of methane into the atmosphere.*

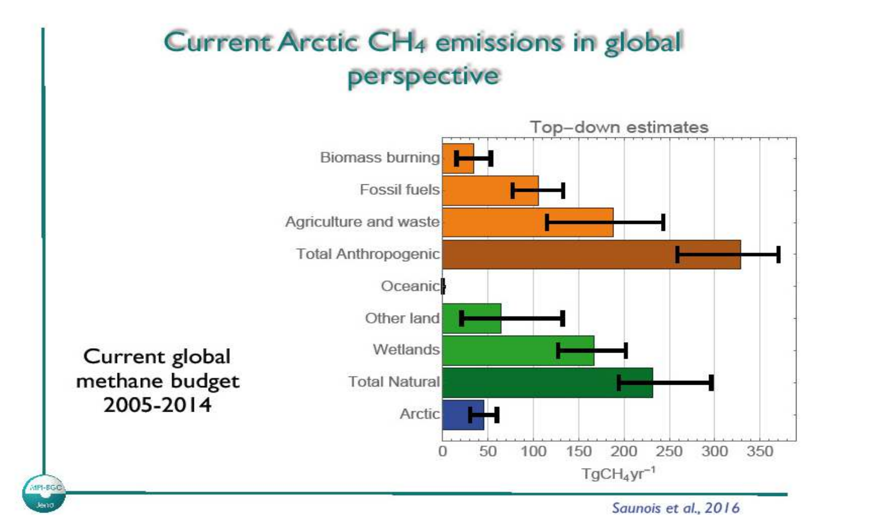


*Figure 18: The anthropogenic and natural methane emission budget has large bars of uncertainty.*

*Analysing methane sinks and variations of the OH hydroxyl radical (an element in the atmosphere that helps absorb methane) is also complicated. Transport models help bridge the gap between emissions and concentrations, but they are complex: unsatisfactory in the stratosphere, they are not always in harmony with each other. As scientists like to point out: biases kill.*

## Observations of other atmospheric variables

*To fully understand the role of greenhouse gases in the climate, we must also observe and model the evolution of other atmospheric variables which interact with the climate, such as water vapour, clouds, aerosols and wind. Space systems also make an essential contribution to the measurement of these variables.*

### Water vapour, clouds

*To understand how changes in the carbon cycle are likely to affect the climate it is also necessary to observe, forecast and comprehend the water and cloud cycles. These two cycles are closely linked. Water vapour is the primary natural greenhouse gas in the atmosphere. Atmospheric warming due to a rise in greenhouse gases intensifies surface evaporation and causes an additional greenhouse effect due to water vapour. It also modifies the cycle of cloud formation and dispersal with, depending on the case, positive or negative feedback for which a high level of uncertainty remains. High clouds will have a positive feedback by blocking the infrared radiation emitted by the surface and the atmosphere, while low clouds will have a negative feedback by reflecting back some of the solar radiation; we do not* *however know how the frequency of these two categories of clouds will evolve with climate change.*

*Atmospheric circulation can be disrupted by such modifications. A latitude change in circulation of only a few degrees can have a strong impact in terms of rain: the great droughts in the Sahel for example were caused by a slight change in circulation latitude. If we want to assess this, we must understand what controls the position, robustness and variability of these tropical rainy areas.*

*In recent years scientists have realised that there is a high sensitivity to interactions and coupling between clouds and circulation. We are now discovering that it is not only the clouds high up in the atmosphere that have an impact, but that clouds in fact cool the atmosphere down over the entire column, a discovery made possible thanks to information on the vertical distribution of clouds provided by the CALIPSO satellite lidar.*

*We should not only be interested in global warming but also in the resulting intensification of extreme weather events. For example, it is important to forecast tropical storm episodes and gauge how such episodes may change in the future. The fundamental ingredient in the genesis of tropical storms is ocean surface evaporation. This evaporation, and therefore the wind speed, must be quantified. It is also clear that water vapour in both humid and dry areas can be a significant factor in the genesis of storms.*

*Another important question is to discover the rate and extent of this global warming in coming decades. This rate depends not only on the evolution of greenhouse gas emissions in the future but also on climate sensitivity to them, which is often expressed as the increase in average surface temperature for a doubling of atmospheric $CO_2$. There is a great deal of uncertainty surrounding climate sensitivity due to uncertainty as to the positive or negative feedback from clouds and aerosols. Adaptation studies are impacted by these uncertainties.*

*We can make two recommendations:*

- *The first is to obtain long-term, homogeneous cloud profiles based on satellite data. Such vertical information on cloud distribution is vital in order to manage the change in distribution over time.*
- *The second is to improve the measurement of water vapour profiles in the lower layers of tropical atmospheres. This is very important if we are to monitor the evolving vertical mix of water vapour in the low troposphere, a very important factor in feedback from low clouds.*

## *Aerosols*

*Aerosols have a significant effect on meteorology and climate because they impact both radiation and clouds. Aerosols absorb or diffuse incidental solar radiation (the direct effect) and also, by absorbing this radiation, modify properties of the atmosphere, thereby altering the cloud cover (semi-direct effects).*

*The 5th IPCC report assessed the contribution of each of these factors to global radiative forcing (Figure 19). Two lines relate to aerosols. The first concerns the direct effects of the aerosol/radiation interaction, which tend to be negative. The second concerns the indirect effects due to the interaction of aerosols with clouds, which are also negative. So aerosols partially offset the effects of greenhouse gases, but the uncertainties here are much greater than for greenhouse gases, which is why it is important to better characterise the effect of aerosols on the climate.*

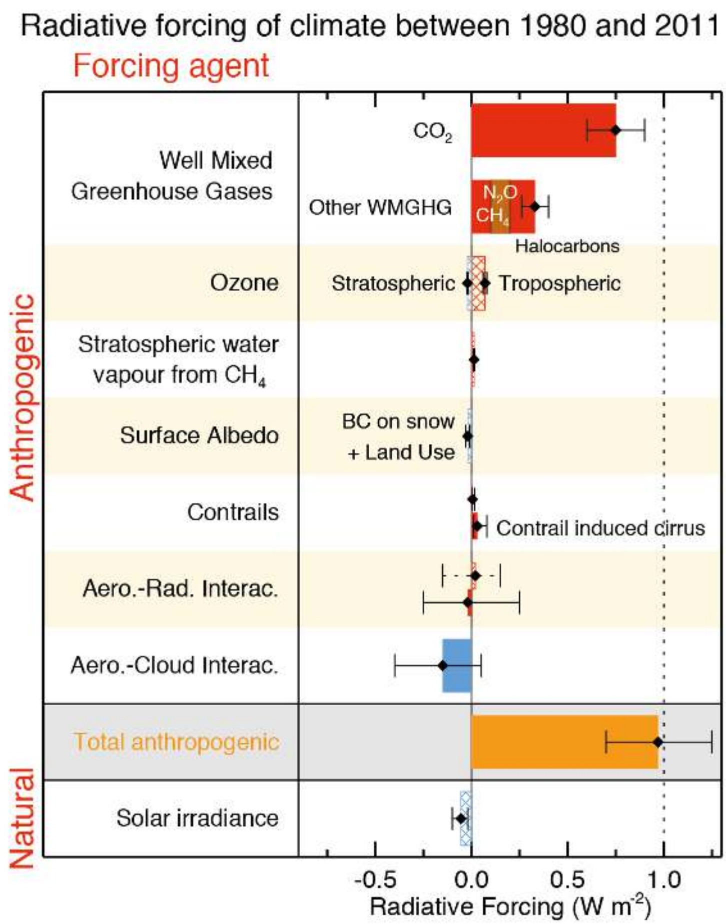


**Figure 19: Radiative forcing over the period 1980-2011 due to human activities. Error bars represent the confidence interval of between 5 and 95%. Source: IPCC 5th climate change report, 2014.**

*Satellite data is used to assess climate models over past periods. Global climate models are used to perform multi-decade simulations, but due to resolution limitations, it is not possible to represent all processes. To do so, regional climate models are used, achieving resolutions of a few kilometres and thus representing small scale processes more precisely.*

## *Wind*

*The first reason to pay attention to wind, including for the climate, is because it is a primary atmosphere variable. When looking at the atmosphere, the first fields we attempt to characterise are those of pressure (depressions and anticyclones), temperature and humidity, and also of wind. These different variables are linked together by the laws of fluid dynamics and thermodynamics.*

*The second reason is that wind has an impact on human activities (not necessarily always harmful). Cyclones generate strong winds that create significant damage. Wind also disrupts certain activities, notably aviation, for example when aircraft come to land. Meteorology has developed considerably alongside aeronautics, indeed for a very long time Météo France was a branch of the air navigation services in France. Wind is also used as a source of energy in the form of wind turbines. Due to the impact of wind on human activities, it is worth forecasting it as far in advance as possible, to enable individuals to protect themselves and authorities to set up means to ensure public safety.*

*It is wind that carries energy and matter. One might give two examples:*

- *Desert dust that has been generated in the Sahara can be transported over long distances to Europe and the Atlantic by winds in the upper troposphere. But for there to be aerosol production, dust has to be lifted off the surface by strong enough winds. So surface winds have to be known precisely in these regions, where there are very few observations.*
- *Another example is the El Niño phenomenon that occurs in the Pacific off the west coast of South America. Normally winds blow from America to the Pacific and propel warm surface water towards Indonesia; then by compensation there is an upwelling of cold waters along the coasts of South America. From time to time the wind is less strong and the cold water no longer rises to the surface. This is disastrous for fishing activity off the coast of South America, and causes climate variations in other parts of the world. To understand such phenomena we need precise measurements of the surface wind.*

*Measuring the wind directly from space is not easy. Currently the two space-based sources of information on wind are indirect measurements: radar measurements of the ocean surface roughness proportional to the surface wind (ASCAT scatterometers on MetOp satellites), and Atmospheric Motion Vectors (AMV) which deduce windspeed from the displacement of clouds on Meteosat images.*

*The present and the future involve direct measurement of wind by lidar. The Aeolus mission, launched by the European space agency in August 2018 for a nominal lifespan of three years, is the first Doppler lidar in space. Its goal is to demonstrate how wind measurements by lidar contribute to improving numerical weather forecasts. Preliminary findings, after assimilation of Aeolus wind measurements into the ECMWF weather forecast model, are encouraging and indicate a real contribution of these measurements, mainly in tropical regions (Figure 20).*

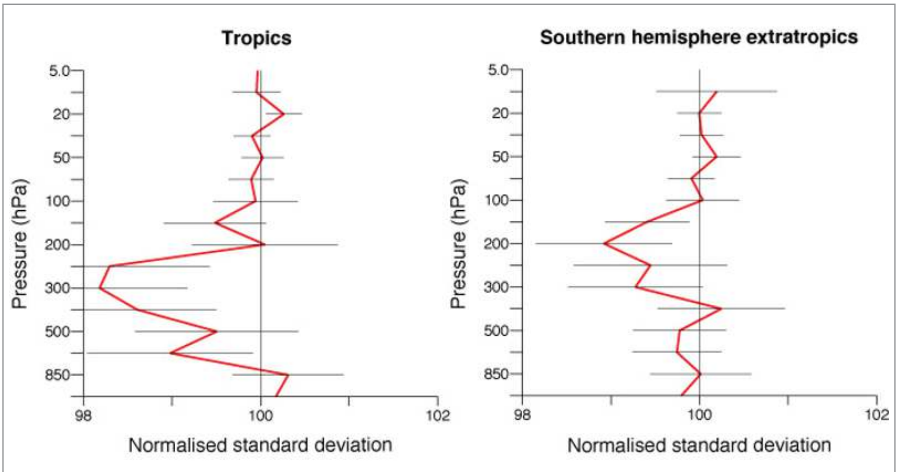


***Figure 20: Changes in wind speed forecasting errors over 12 hours relative to wind sounding and profiling data when Aeolus data is used to help determine initial conditions. Values under 100% mean a better match with observations. The horizontal bars indicate 95% confidence intervals. The experiments cover the commissioning phase of Aeolus from 12 September 2018 to 12 January 2019. Source Michael P. Rennie et al., ECMWF, 2019.***

*To summarise, satellite data are essential for evaluating models. To enhance the use of this space-based data, attempts should be made to improve its consistency over long periods of time, and perhaps to create products more suited to climate models, thanks in particular to their spatial and temporal coverage.*

## The role of space systems

*To understand our planet, it is necessary to observe it as a whole, and at all scales. Data provided by satellites is used to refine, assess and enhance the models used to study the impact of climate change, particularly as regards the seasonal carbon cycle.*

*Scientists need high-performance computing to process increasingly high-resolution, complex satellite data and ever more comprehensive results of models that include* *the effects of wind, clouds and aerosols throughout the air column. The space community must be able to provide and make accessible data, and ensure continuous, consistent missions.*

*Satellite coverage must be enhanced, improving the accuracy of measurements (and therefore instruments), as well as the algorithms which render these observations exploitable, and limiting large systematic biases as much as possible. Inversion models also need to be improved, as well as high-resolution atmospheric transport models.*

*The measuring instruments on board satellites in low orbit (from 600 to 2000 km) or geostationary orbit (36,000 km) are either active or passive.*

*Passive instruments measure and analyse the spectrum of sunlight reflected or backscattered by the Earth (Figure 21). They thus give access to a multitude of climate variables such as solar irradiance, the radiation balance of the Earth, the temperature of the atmosphere, water vapour, ozone, cloud cover, aerosols, precipitation, carbon dioxide, methane, the chemical composition of the atmosphere, vegetation and forest cover, snow and ice cover, ocean salinity and surface temperature. These are spectrometers, often associated with imagers, with very many spectral channels, or spectro-interferometers (like IASI), capable of covering a wide spectral band.*

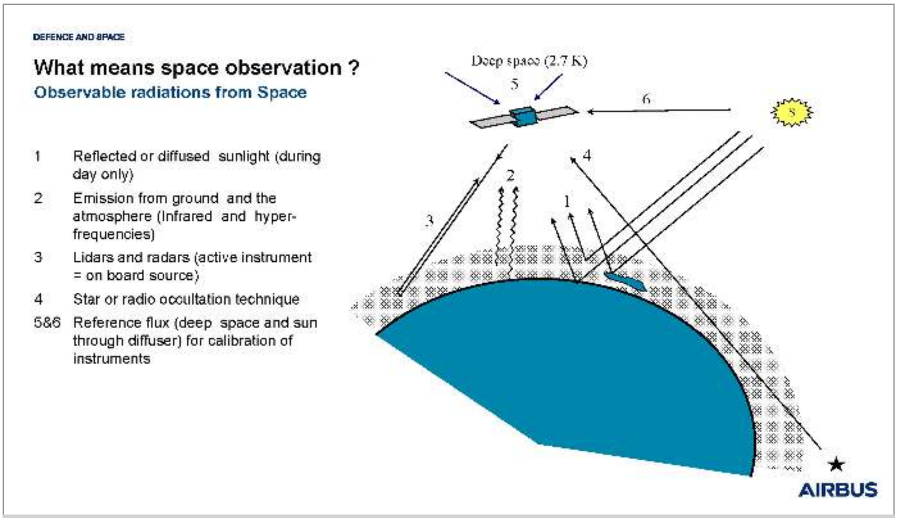


***Figure 21: The different types of space instruments.***

*Active instruments measure and analyse the echo of the electromagnetic wave they have emitted after it has passed through all or part of the atmosphere twice. Depending on the wavelengths used, they provide information on climate variables such as atmospheric chemistry, sea currents, sea level, intensity and direction of*

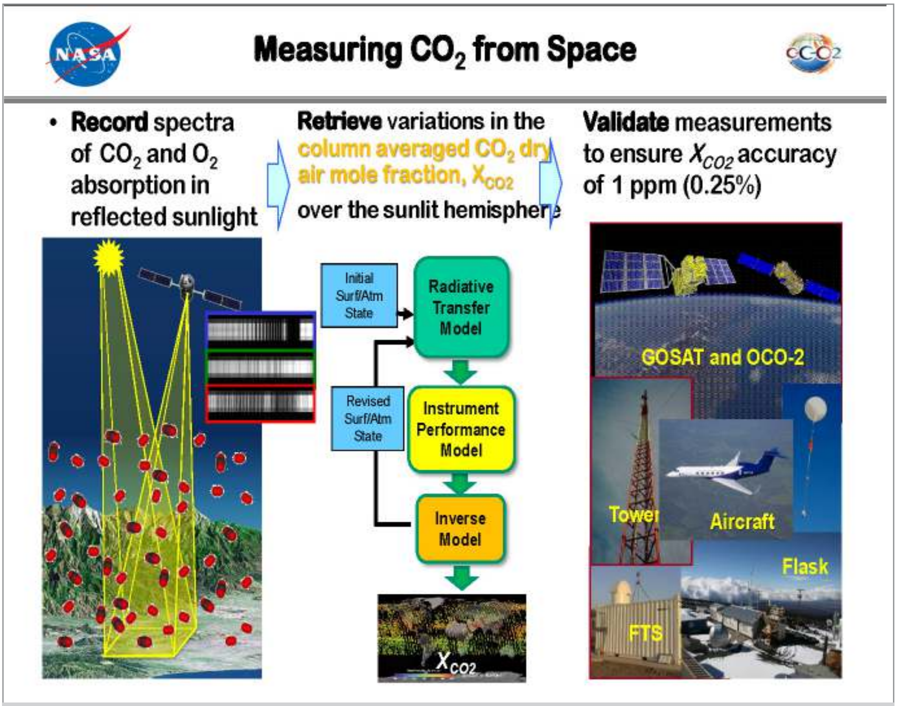


*Figure 22: Example of the processing of the backscattered sunlight spectrum for carbon dioxide and oxygen wavelengths.*

*sea winds, soil humidity, cloud elevation, humidity levels, topography of soils and ice, etc. Active lidar-type instruments are emerging in the space sector. By their nature, the spectrum backscattered in response to laser remote sensing is narrow, and therefore associated with the particular aerosol or gas element that is to be observed.*

*Meteorology has used space instruments for longer than climatology. Although it is less concerned with carbon dioxide and methane, since they interfere very little in the short term, it nonetheless has long temporal sequences of measurements that can be used for studying the climate. These instruments can also serve as examples: IASI sounders (Infrared Atmospheric Sounding Interferometer) mounted on Eumetsat MetOp satellites, for instance, are essential for weather forecasts and also constitute a reference for many space sounders (Figure 23).*

*However, measurements are not enough: they must be validated, calibrated and inter-calibrated. Effort should also focus on inversion models to provide the scientific community with the right inputs.*

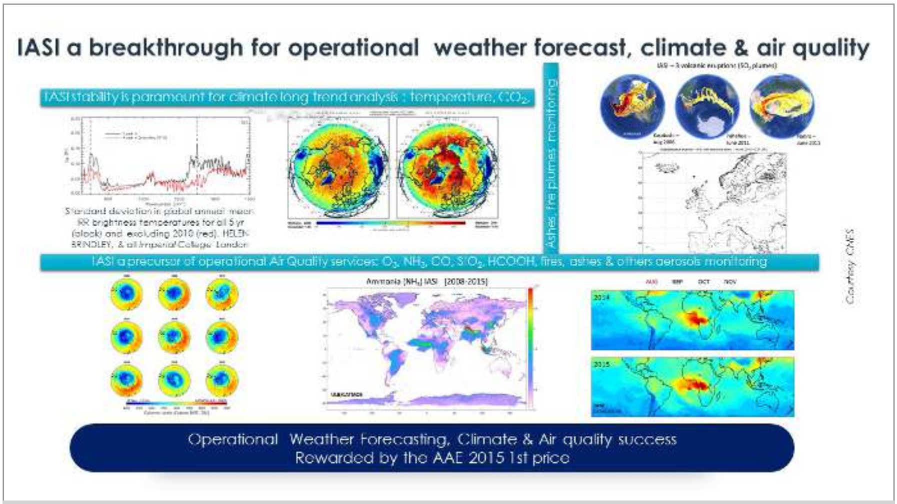


*Figure 23: Example of the IASI sounder, a major breakthrough for weather and climate forecasts, thanks to its spectral resolution.*

# 4 PROGRAMMING OF SPACE MISSIONS FOR THE CLIMATE

## Technical and financial limits

*Measurements made from space do have their limits: electromagnetic waves barely penetrate solid or liquid surfaces, the parameters of the lower atmosphere are difficult to access and many passive measurements require a clear sky. In addition, in the hostile environment of space, instruments degrade. Their calibration is difficult and unstable and must therefore be carried out regularly.*

*Space instrumentation calls on many skills: optical, mechanical and thermal for telescopes; electronic, optoelectronic for focal planes, and numerical for processing. The instruments developed for climate research, in particular for measuring carbon and methane, are relatively recent; they were only promoted by space agencies at the start of the 21$^{st}$ century. In addition, scientists' constant need for an increasing level of resolution, precision and coverage makes instruments more and more complex and tricky to build. Very often the useful signal is very weak in the midst of a very strong "ambient noise". Only a few manufacturers have mastered these technologies. A new generation of tools typically only appears every ten years and it takes an additional five years to produce them, which represents a considerable cost. Such advanced technologies have not yet benefited from an industrial cycle, with a series effect to reduce costs, as is the case for telecommunications satellites. These instruments are therefore hand-crafted.*

## Ambitious programmes

*The ambition today is to be able to measure greenhouse gases, such as $CO_2$ and $CH_4$, from space, in order to carry out an inventory of emissions and absorptions, observe their evolution, monitor and perhaps predict the patterns of the global cycle, and ideally distinguish the emissions produced by human activity from the natural cycle. The latter constitutes a kind of background noise in which we must recognise the anthropic part due to human activities.*

*Many programmes are currently being launched by the European, American, Japanese, Indian and Chinese space agencies (ESA, NASA, JAXA, ISRO and CAST), the German Aerospace Centre (DLR), the French space agency (CNES), as well as by organisations representing users such as EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites), or the international project GPM (Global Precipitation Monitoring) (Figures 24 to 29).*

### European Space Agency

*The European Space Agency, an intergovernmental organisation of 22 member States, manages three categories of Earth observation programme:*

1) *The **Earth Explorer** programme of satellites for scientific research and the testing of new observation techniques. This programme, which fully meets the vocation of a space agency, is a great success because, as well as improving our understanding of the functioning of the Earth system and the impact of human activities, it also enables new measurement techniques to be tried out and the corresponding instruments to be perfected, some of which may become operational. Among the satellites already in orbit, which are already contributing to our understanding of climate change, it is worth mentioning:*
   - *the Cryosat satellite, which measures the thickness of polar ice by interferometric radar altimetry;*
   - *the SMOS satellite (Soil Moisture and Ocean Salinity), launched in 2009, which measures the surface water content of soils as well as the salinity of the surface layer of the oceans, using a passive interferometric radiometry technique;*
   - *also Aeolus, a satellite launched in August 2018 which is dedicated to measuring winds in the upper troposphere and the stratosphere using onboard lidar sounding technology.*

   *In coming years, several missions are in preparation:*
   - *the EarthCARE mission, carried out in cooperation with Japan, which will focus on the role of clouds and aerosols in the Earth's radiation balance. Scheduled to launch in 2022, it is based on very advanced lidar and radar technologies never before used in space;*


*Figure 24: European Space Agency programming.*

- *the Biomass satellite which, due to launch in 2022, will carry a synthetic aperture radar operating in P-band, thus providing information on the thickness of the vegetation in tropical forests, which we know is an important carbon sink;*
- *the FLEX (Fluorescence Explorer) mission, planned for 2023, which will be devoted to measuring the fluorescence of vegetation in order to provide a better understanding of the mechanisms of carbon transfer between plants and the atmosphere and how photosynthesis affects the water and carbon cycles;*
- *the FORUM (Far-infrared Outgoing Radiation Understanding and Monitoring) satellite, dedicated to measuring the radiation balance of the Earth in far infrared; its launch is scheduled for 2026.*

2) *The **Copernicus programme**, in conjunction with the European Union, which essentially comprises operational observation satellites where continuity of observation is a major imperative, which is the case for meteorological satellites. At the end of 2019, the Copernicus programme included the "Sentinel" satellite families 1 to 6 (Figure 25), for which continuity over several decades was ensured through the launch of four units A, B, C, and D, each designed with a lifespan of seven years:*
   - *Sentinel-1 satellites are C-band synthetic aperture radar satellites that provide images of land and sea surfaces. Sentinel-1A was launched on 3 April 2014 and Sentinel-1B on 25 April 2016. They allow the monitoring of polar zones, coastal erosion, vegetation cover (and its change), deforestation, etc.*

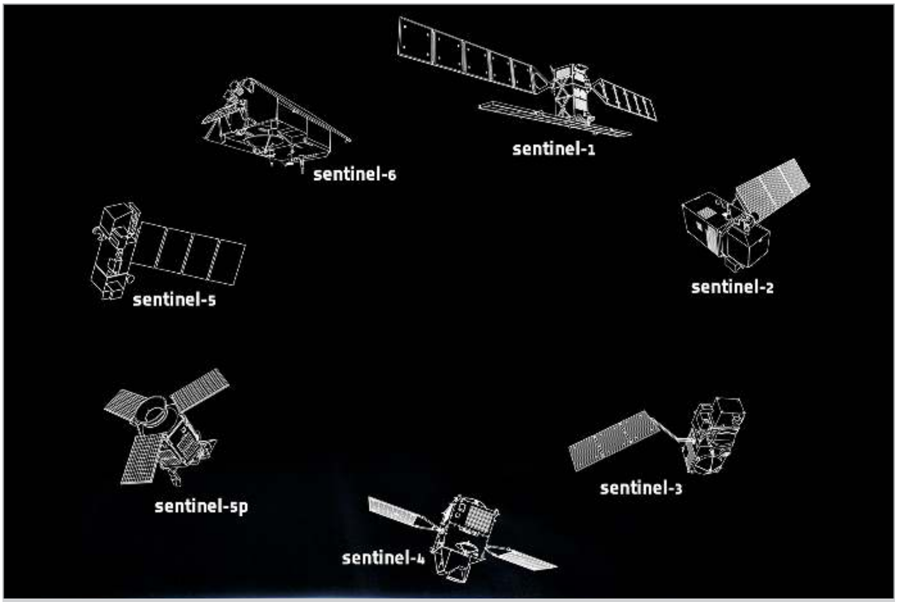


*Figure 25: Graphic illustration of the Sentinel satellite family.*

- *Sentinel-2 satellites are satellites carrying optical imagers producing multispectral images of land surfaces, continuing on from the American Landsat satellites. Sentinel-2A was launched on 23 June 2015 and Sentinel-2B on 7 March 2017. They provide continuous observation of vegetation, water resources, coastal areas, forest fires, "alga blooms", sedimentation of estuaries, etc.*
- *Sentinel-3 satellites are focused on ocean observation. They carry an oceanic altimeter, SRAL (Synthetic Aperture Radar Altimeter); a microwave radiometer (MWR) for the vertical sounding of water vapour; a wide-field multispectral optical imager, OLCI (Ocean and Land Colour Instrument); and an imaging radiometer SLSTR (Sea and Land Surface Temperature Radiometer). Sentinel-3A was launched on 18 February 2016 and Sentinel-3B on 25 April 2018. The launch of Sentinel-3C is scheduled for 2021 and that of Sentinel-3D later in the decade. These satellites are operated by the European organisation EUMETSAT.*
- *Sentinel-4 is not an autonomous satellite but a payload dedicated to sounding the atmosphere which will be carried on the Meteosat Third Generation satellites (MTG) dedicated to atmospheric sounding (MTG-S) placed in the EUMETSAT geostationary orbit. The Sentinel-4 payload includes the UVN (Ultraviolet Visible Near-infrared) spectrometer and the thermal IRS (InfraRed Sounder), which will be carried on the MTG-Sounder satellite.*

- *Sentinel-5 Precursor was launched on 13 October 2017 (Sentinel-5 is not planned until 2021). Sentinel-5P carries the TROPOMI instrument, a spectrometer developed by the Netherlands measuring gases and aerosols in the atmosphere (concentration of certain gases such as bromine oxide, carbon monoxide, chlorine dioxide, methane, formaldehyde, oxygen). TROPOMI is a gap filler between SCIAMACHY on Envisat, OMI on Eos/Aura and Sentinel-5 on MetOp Second generation.*
- *Sentinel-5 is an instrument dedicated to measuring atmospheric ozone and other minor components of the atmosphere from a low orbit. Its instruments are the UVNS (Ultraviolet Visible Near-infrared Shortwave) spectrometer and the continuation of the IASI programme (IASI-New Generation) which will be carried on MetOp Second Generation satellites (MSG) operated by EUMETSAT.*
- *Sentinel-6 satellites are very high precision ocean altimetry satellites which follow on from the series of Franco-American satellites Jason 1, 2 and 3 and (for the ocean altimetry part) the ESA ERS-1 and -2 satellites and Envisat. They carry a radar altimeter and ultra-precise positioning system to measure ocean topography on a global scale, thus contributing directly to monitoring the rise in sea level due to global warming, and to operational oceanographic applications. This programme is carried out in cooperation between ESA and EUMETSAT on the European side and NASA and NOAA on the American side. The first Sentinel-6 satellite is to be launched by NASA in November 2020.*

*For the future of the Copernicus satellites, several missions are being studied which could be funded by ESA following the Ministerial Council in Seville in late November 2019 and by the European Union through its "Space" budget during the period 2021-2027. Among these missions, one should note in particular the Copernicus Anthropogenic Carbon Dioxide Monitoring mission CO2M for measuring atmospheric $CO_2$. Each of three identical satellites would carry a near infrared and far spectrometer with a swath of 300 km to observe and measure concentrations of carbon dioxide in the atmosphere and in particular to map over sufficiently large areas (thanks to the swath) $CO_2$ concentrations in the vicinity of emission sources from human activity. The payload would also measure $NO_2$ concentrations and observe clouds and aerosols to improve the ability to distinguish between anthropogenic $CO_2$ and "natural $CO_2$"*[1].

1 *At the ESA Ministerial Council, held in Seville on 27 and 28 November 2019, it was decided to finance six Earth observation missions: in addition to the CO2M mission described above, the following missions were decided: CHIME (Copernicus Hyperspectral Imaging Mission for the Environment), CIMR (Copernicus Imaging Microwave Radiometer) for monitoring the Arctic, sea ice, salinity and ocean surface temperature in all weathers, CRISTAL (Copernicus Polar Ice and Snow Topography Altimeter), Cryosat follow-on, LSTM (Copernicus Land Surface Temperature Monitoring), ROSE-L (L-band Synthetic Aperture Radar), complementary to the Sentinel-1 satellite radar in C band.*

3) *The **third category of programmes** managed by ESA concerns the development of the first series of operational weather satellites for EUMETSAT, the Meteosat satellites in geostationary orbit and the MetOp satellites in low orbit (c.f. the chapter dealing with EUMETSAT satellites below).*

## *CNES*

*The French space agency CNES has been actively contributing for many years to space systems for studying the climate (Figures 26 and 27), either through dedicated missions such as the Jason 1, 2 and 3 oceanic altimetry satellites (in Franco-American cooperation) or through missions like Calipso (Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations, a Franco-American cooperation) launched in 2006 and Megha-Tropiques, launched in 2011 (Franco-Indian cooperation), or else by developing and delivering very advanced observation instruments such as the IASI instrument which equips the EUMETSAT MetOp satellites.*

*This latest contribution will continue with IASI NG (IASI New Generation) for MetOp Second Generation (MSG) satellites. CNES is also preparing new missions which are of direct interest to the study of the greenhouse gas cycle, such as MicroCarb for monitoring carbon dioxide, scheduled for 2021. It will carry a networked dispersive spectrometer capable of measuring carbon dioxide concentration in the atmosphere very accurately (of the order of 1 ppm) over the whole globe with a rectangular base pixel of 4.5 km by 9 km. In 2024, the Merlin mission (Methane Remote Sensing Lidar Mission), carried out in cooperation with the German DLR,*


*Figure 26: CNES programmes (or including a CNES contribution) in operation.*

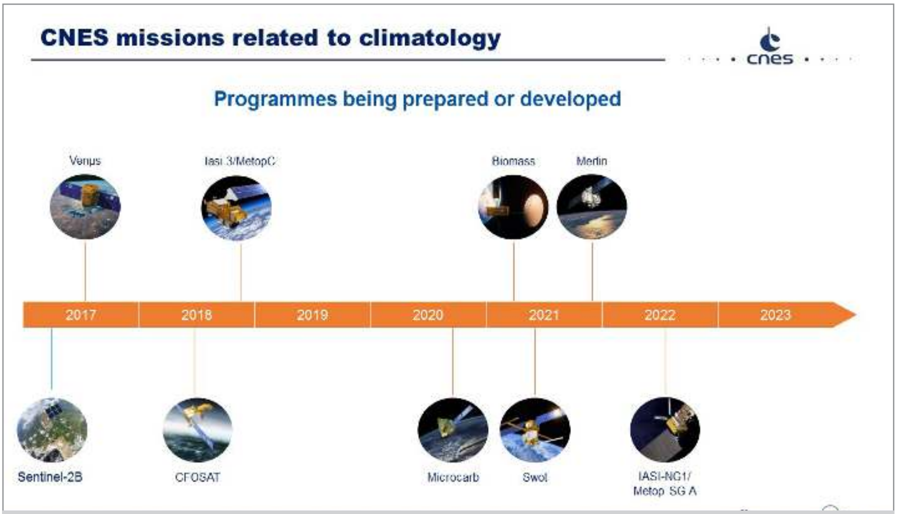


*Figure 27: Programmes planned at CNES (or with a contribution from CNES).*

*will carry the Integrated Path Differential Absorption (IPDA) lidar for methane column density measurements, developed by DLR.*

*In the field of oceanography and continental hydrology, CNES is a partner in the CFOSAT satellite (China-France Oceanography SATellite) developed in cooperation with China and launched in 2018. Its payload includes two instruments, a Ku-band radar SWIM (Surface Waves Investigation and Monitoring), supplied by France, and a Ku-band wind scatterometer (SCAT), under Chinese responsibility. The SWIM instrument measures the properties of waves (direction, wavelength, etc.) while SCAT measures the wind intensity and direction.*

*CNES is also preparing the Surface Water and Ocean Topography (SWOT) mission in cooperation with NASA, a follow-on from its long, very fruitful cooperation on the Topex-Poseidon mission (1992) and the Jason-1 to 3 satellites. SWOT, to be launched in April 2021, will carry a radiometer-altimeter (NADIR) with the same performances as those of the Jason satellites. It will also include a wide-swath Ka-band interferometric radar called KaRIn which will enable measurements close to the nadir with a 120 km wide swath, where current altimeter radars are limited to a band of a few kilometres vertical to the satellite. This broad ground trace will provide access to the spatial field of water levels for rivers greater than 100 m in width, as well as for lakes and surface flood zones greater than 250 m x 250 m, with decimetre precision, and will enable slopes to be quantified with an accuracy of around 1.7 cm/km (after averaging over an area of water > 1 km$^2$). Coupled with precision geoid models and precise numerical terrain models, the SWOT mission data will radically improve hydrodynamic river models leading to flow estimates. They will also help determine the temporal variations of water stock in surface* *hydrosystems (lakes, reservoirs and wetlands), and their flow dynamics. To give a rough idea, it is estimated that more than 30 million lakes worldwide have an area of more than 1 ha. SWOT is eagerly awaited not only by hydrologists but also by oceanographers. KaRIn will be able to observe sub-meso and mesoscale type flows (from a few hundred to a few tens of kilometres) such as vortices or filaments, to characterise their very dynamic vertical transport, study coastal circulation, and refine current oceanographic as well as climate predictive models. And all this with centimetre accuracy.*

## *EUMETSAT*

*EUMETSAT satellites (Figure 28) are mainly devoted to short- and medium-term weather forecasting, but several of their instruments provide data which are of great value for the study of the climate and more particularly for understanding the role of the atmosphere in the regulation of greenhouse gases.*

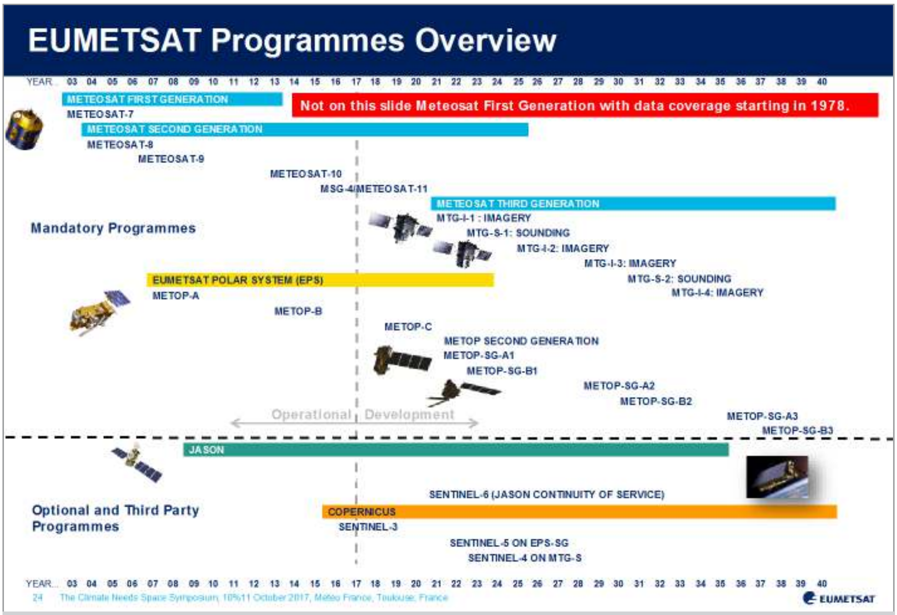


*Figure 28: EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites) programme planning*

*They include the family of Meteosat satellites in geostationary orbit, the second generation of which is currently in operation, to be replaced over the next decade by Meteosat Third Generation (MTG) satellites, deployed from 2021. The MTGs will provide a more advanced imaging service and a state-of-the-art atmospheric sounding service providing measurements in the infrared and ultraviolet spectrum. Six MTG satellites are planned, four imaging satellites (MTG-I) and two sounding* *satellites (MTG-S). The full MTG operational configuration will consist of two MTG-I satellites operating in tandem, one scanning Europe and Africa every 10 minutes and the other scanning Europe only every 2.5 minutes, and one MTG-S satellite.*

*The second family of satellites operated by EUMESAT is that of the MetOp satellites placed in low orbit, the first generation of which has been in operation since 2006. Again, EUMETSAT is preparing the next generation called MSG (MetOp Second Generation) which will include two types of satellites, MetOp -SG A and MetOp-SG B:*

- *MetOp-SG A satellites will be dedicated to imaging and sounding, profiling temperature, humidity and minor constituents in the atmosphere by means of a set of infrared, microwave and imaging instruments: IASI-NG (Infrared Atmospheric Sounding Interferometer - Next Generation); MWS (Microwave Sounder), METimage (multi-spectral imaging radiometer) in the visible and infrared, which will take over from the American AVHRR instruments); 3MI (Multi-viewing, Multi-channel, Multi-polarisation Imager), and finally the UVNS Sentinel-5 spectrometer described above.*
- *MetOp-SG B satellites will be dedicated to microwave radar imaging of the wind at sea surface, soil moisture, precipitation and ice clouds thanks to its three onboard instruments: SCA (Scatterometer), MWI (Microwave Imager) and ICI (Ice Cloud Imager).*

*Both types of satellites will be equipped with instruments for radio-occultation (RO) of the signal received from navigation satellites (Global Navigation Satellite System - GNSS) in order to sound temperature and humidity within the Earth's limb with high vertical resolution.*

*The six MetOp-SG satellites (three type A and three type B) are expected to be put into orbit from the end of 2022 and to operate until 2043.*

## *NASA/NOAA*

*Figure 29 shows the set of satellites contributing to the measurement of precipitation in the Earth's atmosphere and highlights the role of NASA and NOAA in this constellation. NASA also actively contributes to the study of greenhouse gases, although its ambitions in this area have been cut back due to the political orientations of the current federal administration, which is very reticent about research programmes devoted to studying global warming. However, it has had some major success, in particular the famous "A-Train" formed by the satellites Aqua, launched in 2002, Aura, launched in 2004, Calipso (in cooperation with France), launched in 2006, GCOM-W and GPM Core (in cooperation with JAXA), launched in 2012 and 2014 respectively, Cloudsat (in cooperation with Canada), launched in 2016, OCO-2 (Orbital Carbon Observatory), launched in 2014 after the loss of the first OCO during launch in 2009. We should add those satellites that are not part of the A-Train: SMAP (Soil Moisture Active Passive), launched in 2015, and Icesat-2 launched in 2018. An OCO-3 instrument is flying aboard the International Space Station.*

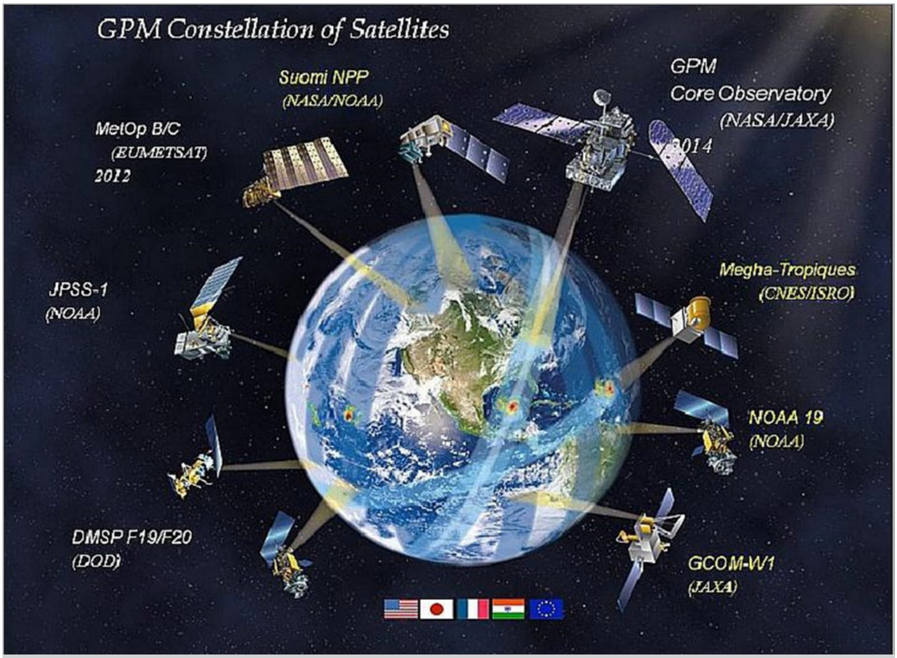


***Figure 29: The constellation of GPM (Global Precipitation Measurement) satellites coordinated by five space agencies: NASA (United States), JAXA (Japan), CNES (France), ISRO (India) and EUMETSAT.***

*For the future, several missions are in preparation including GeoCarb, an instrument which will be placed on board a geostationary platform, planned for 2022, and SWOT which we have already mentioned.*

## *JAXA*

*Japan is also very active via JAXA and conducts space missions dedicated to the study of the climate. There have been a number of missions to measure atmospheric carbon dioxide: GOSAT (measurement of carbon dioxide distribution) launched in 2009 and renamed "Ibuki", followed by GOSAT-2 launched in 2018 (Ibuki-2) and soon GOSAT-3, planned for 2022. To this must be added the two missions GCOM-W (Shizuku) and GPM-Core in cooperation with NASA, mentioned above, and the mission GCOM-C (Shikisai) for measuring the carbon and energy cycle, which was launched in 2017. Japan is also contributing to ESA's EarthCARE mission, which is scheduled to launch in 2021.*

## *Chinese Earth observation programmes*

*China has set up a satellite Earth observation system for global and local observation of the atmosphere, oceans and land masses. These satellites collect information on the causes and consequences of climate change in terms of land* *use, vegetation parameters, water resources and water-related parameters, content and parameters of the atmosphere, etc., as primary or secondary missions.*

- *The Feng Yun meteorological satellites, in heliosynchronous polar orbits at 836 km altitude, are equipped, for the most recent generation, with a medium-resolution spectro-imager, an infrared hyperspectral atmospheric sounder, microwave sounders (temperature and humidity), a microwave imager, a hyperspectral absorption spectrometer for the observation of greenhouse gases, etc.*
- *The Fen Yun meteorological satellites in geostationary orbit are equipped with a visible and infrared multispectral imager with a resolution of 0.5 to 4 km, plus temperature and humidity sounders.*
- *The latest generation Hai Yang ocean surveillance satellites are equipped with an imager for coastal areas, an optical radiometer for measuring ocean colour and temperature, a microwave imaging radiometer, a radar altimeter and scatterometer.*
- *Other satellites provide data that can be used for climate-related research and monitoring. These include: the Zi Yuan (Resource) and Tian Hui (Topographic Mapping) satellites for observing resources (multispectral camera), as well as the Gao Fen optical or radar satellites at high or very high resolution.*
- *In the area of satellites specifically dedicated to climate studies, cooperation with CNES for the CFOSAT satellite (China-France Oceanography SATellite) was mentioned above. Cooperation with CNES should continue with the agreements signed at the end of 2019 for the development of a water cycle research satellite. This satellite could include a next-generation L-band interferometric radiometer for observing soil moisture and ocean salinity, as well as a high-resolution interferometric radiometer in X and Ka bands to measure the water equivalent of the snow cover and to observe the freeze/thaw condition of the ground surface.*
- *The TanSat mini-satellite, funded in China by the Ministry of Science and Technology and launched in December 2016, is dedicated to the detection and monitoring of carbon dioxide on a global scale. The scientific objective is to improve our understanding of the distribution of $CO_2$ and its seasonal variations. Calibration tests were completed in the summer of 2017. The data extraction algorithms were validated on the basis of simulations and ground measurements. The maps of $CO_2$ concentration produced since mid-2017 highlight the seasonal variations between the two hemispheres. They also highlight areas of high $CO_2$ emissions linked to human activity.*

  *The precision of the estimates on $CO_2$ concentration is however limited by the low coverage rate of measurements made by the satellite at each orbit (linked to the swath of the instrument). It is possible to combine measurements made by OCO-2 (US) and TanSat but this introduces uncertainties linked to the calibration uncertainties of each satellite.*

# 5 FINDINGS AND RECOMMENDATIONS

*Many space missions are currently dedicated to the environment and climate, either specifically or in conjunction with meteorology and the study of the atmosphere as a whole. They enable the community of experts to identify the gaseous content of the atmosphere and to periodically assess, at certain available scales, the global molecular concentrations impacting the climate as well as their large-scale seasonal and regional variations.*

*Progress made by on-board instruments, especially spectrometers and high spectral resolution interferometers, is very significant in this regard. Interpretation difficulties have been underlined and efforts must still be made regarding data from the various processing models as well as measurement biases which must be minimised.*

*In article 13, paragraph 7, of the treaty established by the Paris Agreement in 2015, it was stipulated that each of the Parties should draw up "a national inventory report of anthropogenic emissions by sources and removals by sinks of greenhouse gases", in order to inform the committee of experts responsible for plotting climate change and for verifying the effects of measures taken to attenuate it.*

*The technical difficulty of separating out the anthropogenic part of the concentrations of such gases from the natural part, both at emission and at removal, has been stressed above. The reliability of the inventory estimates made by the various authorities engaged by the treaty is a problem of another order, but one which adds to the difficulty of distinguishing the anthropogenic part of the global signal.*

*Space-based observations are capable of measuring the concentration of carbon dioxide and methane over the entire atmospheric column, with the respective indicated accuracies of the order of 1 to 2 ppm and 5 to 10 ppb, but the portion of* *this concentration relative to the very low atmosphere, where anthropogenic sources and sinks actually occur, remains less precise with a view to comparing with objective measurements made in situ or at nearby low altitudes. At present, no space-based $CO_2$ measurement is sufficiently accurate, with high enough resolution, to meet the demands made in the Paris Agreement for monitoring and controlling emissions produced by human activity.*

*The space sector contribution is part of a complete observation network, even if it has already succeeded in highlighting, at the scale of large regions or urban areas, variations in intensity compared with average concentration values charted by reference observatories. To which should be added the transport link via meteorological dynamics, together with the ability to measure the traces of many other anthropogenic gaseous components linked to the production of carbon dioxide. The latter correlation is by no means negligible for inventorying sources and drawing attention to the validity of so-called national inventories.*

*The fact remains that the requirements of the Paris Agreement are extremely challenging, and that the scientific community and industry must both be mobilised in order to develop a system of measurements based on all different types of sensors and vectors: space-based, airborne, ground and ocean-based. The measurements from all of these sensors will be compared by enhanced modelling and effective inter-calibration, and improvements to the physical assimilation models will enable all data to be exploited.*

*Obviously "the climate needs space" in order to better understand, monitor and predict the state of our planet and its current changes with ever increasing urgency.*

*Several recommendations can be made to complete this review.*

► ***Recommendation no. 1:***
*Prioritise in the programming of space agencies and associated organisations the development of instruments capable of improving data acuity, spatial coverage and periodicity, all factors allowing climate change models and forecasts to be fine-tuned. The search for innovative techniques and processes must be supported when it enables better resolution of the targeted physical parameters or when it makes it possible to intensify observations and guarantee their continuity. Continuity of observations is essential for today's forecasting of the future and for tomorrow's analysing and reanalysing of the past to assess the impact of actions aimed at reducing anthropogenic greenhouse gases.*

► ***Recommendation no. 2:***
*Organise the provision of experts to map $CO_2$ sources and sinks at the best possible scale from calibrated space-based data. The building of this shared database will bring about reduced biases and the comparison of models in order to improve our assessment of trends.*

► ***Recommendation no. 3:***
*Improve interdisciplinary scientific coordination for the use of space-based data so that impacts, correlated with various markers (biophysical and biological in terrestrial and marine environments), can be associated with greenhouse gas concentrations and thus better taken into account in the long-term forecasting model.*

► ***Recommendation no. 4:***
*With the help of the scientific community, which is fairly well coordinated, strive to formulate the priority stages in terms of obtaining observation data, as is practiced by the community of astronomers, so that contributors to space agencies and these agencies themselves come up with a strategic plan consistent with these priorities.*

# *GLOSSARY*

| | |
|---|---|
| *AAE :* | *Air and Space Academy* |
| *AMSU :* | *Advanced Microwave Sounding Unit* |
| *CCI :* | *Climate Change Initiative (ESA)* |
| *CEA :* | Commissariat à l'énergie atomique et aux énergies alternatives *(French Alternative Energies and Atomic Energy Commission)* |
| *CEOS :* | *Committee on Earth Observation Satellites* |
| *CMA :* | *Conference of the Parties serving as the meeting of the Parties to the Paris Agreement* |
| *CNES :* | Centre national d'études spatiales *(French space agency)* |
| *CNRM :* | Centre national de recherches météorologiques, Météo-France *(Météo France research unit)* |
| *CNRS :* | Centre national de la recherche scientifique *(French scientific research centre)* |
| *DLR :* | Deutsches Zentrum für Luft und Raumfahrt *(German aerospace centre)* |
| *ECMWF :* | *European Centre for Medium-Range Weather Forecasts* |
| *ESA :* | *European Space Agency* |
| *EU :* | *European Union* |
| *EUMETSAT :* | *European Organisation for the Exploitation of Meteorological Satellites* |
| *GCOS :* | *Global Climate Observing System* |
| *GIEC :* | *Groupe d'experts intergouvernemental sur l'évolution du climat (in English IPCC)* |
| *IASI :* | *Infrared Atmospheric Sounding Interferometer* |
| *ICOS :* | *Integrated Carbon Observation System* |
| *IPCC :* | *Intergovernmental Panel on Climate Change (in French GIEC)* |
| *JAXA :* | *Japan Aerospace Exploration Agency* |
| *JPL :* | *Jet Propulsion Laboratory (NASA)* |
| *JRC :* | *EU Joint Research Centre* |
| *LATMOS :* | Laboratoire Atmosphères, milieux, observations spatiales *(mixed research laboratory unit under the aegis of CNRS, Versailles St Quentin University (UVSQ) and Pierre et Marie Curie University (UPMC) in Paris)* |
| *LEO :* | *Low Earth Orbit* |

*LIDAR :* *Laser detection and ranging*

*LSCE :* Laboratoire des sciences du climat et de l'environnement *(mixed research laboratory under the agis of CEA, CNRS and Versailles St Quentin University (UVSQ))*

*MFF :* *Multiannual Financial Framework (European Union)*

*MWS :* *Microwave Sounder*

*NASA :* *National Aeronautics and Space Administration (USA)*

*NOAA :* *National Oceanic and Atmospheric Administration*

*SMOC :* Système mondial d'observation du climat *(in English GCOS)*

*UE :* Union européenne

*UNFCCC :* *United Nations Framework Convention on Climate Change*

*WCC :* *World Climate Conferences (WMO)*

*WMO :* *World Meteorological Organization*

## *PARTICIPATION*

*The following members were involved in drafting this report:*

- *Marc Pircher (conference chairman)*
- *Gérard Brachet*
- *Jean Broquet*
- *Cathy Clerbaux*
- *Alain Hauchecorne*

## Programme du colloque « Le Climat a besoin d'Espace », 10-11 oct 2017
## *Programme of conference "The Climate needs Space", 10-11 Oct 2017*

### Mardi 10 octobre / *Tuesday 10 October*

**08:30** **Enregistrement, café d'accueil** / ***Registration, coffee***
**09:30** **Discours de bienvenue** / ***Welcome speeches***

- Anne-Marie Mainguy, *présidente de l'Académie de l'air et de l'espace / president of Air and Space Academy*
- Marc Pontaud, *directeur de la recherche / director of research, Météo-France*
- Jean-Claude Dardelet, *vice-président / vice president, Toulouse Métropole*

**10:00 Session 1- Défis scientifiques / *Scientific challenges***

President: C. Clerbaux (LATMOS-IPSL, AAE)

**Introductions et vue d'ensemble** / ***Introductions and overview***
**Vers une capacité opérationnelle à contrôler les émissions de CO2 provenant des combustibles fossiles**
***Towards an operational capacity to monitor fossil fuel CO2 emissions***
B. Pinty (Copernicus, European Commission)

**Mesures spatiales dans un cadre de changement climatique mondial** / ***Space measurements in the context of global climate change***
R. Séférian (Météo-France, CNRM)

**Questions-réponses** / ***Questions & answers***

**11:00** **Pause café** / ***Coffee break***

**Intervenants** / ***Speakers***

**Surveillance du CO2 et du CH4 depuis l'espace : défis, réalisations, promesses**
***CO2 and CH4 monitoring from space : challenges, realisations, promises***
P. Bousquet (LSCE)

**Les évaluations empiriques spatiotemporelles de flux de CO2 à partir d'observations de la surface et de l'atmosphère** / ***Empirical spatio-temporal estimates of CO2 fluxes from surface and atmospheric observations,***
C. Crevoisier (LMD/CNRS)

**L'Arctique : une concentration d'émissions de gaz à effet de serre**
***The Arctic: a greenhouse gas emission hotspot***
M. Heimann (MPI-BGC)

**Questions-réponses** / ***Questions & answers***

**13:00** **Pause déjeuner** / ***Lunch break***

**14:30 Session 2 - Mesures atmosphériques nécessaires depuis l'espace / *Needed atmospheric measurements from Space***

President: G. Ehret (DLR)

**Introduction**
S. Briggs (Chairman of GCOS)

**Intervenants** / ***Speakers***

**Prise en compte des observations des nuages et de la vapeur d'eau dans la sensibilité du climat et de la circulation atmosphérique** / ***Water vapor and cloud observations needed to solve climate sensitivity and circulation puzzles***
S. Bony (LMD)

**Exigences relatives à la surveillance du CO2 depuis l'espace : Est-il réaliste de viser le contrôle d'émissions anthropogéniques ?** / ***Requirements for the monitoring of CO2 from space: Is it realistic to aim at the monitoring of anthropogenic emissions?***
F-M. Bréon (LSCE-CEA)

**L'observation du vent à une échelle globale : comment, et quel bénéfice pour la prévision du temps et du climat ?** / ***Observation of the wind at global scale: how, and what benefit for weather and climate forecasting***
A. Dabas (Météo-France, CNRM)

**Exigences relatives à la surveillance du CH4 depuis l'espace : de quoi aurions-nous besoin pour séparer les processus ?** / ***Requirements for monitoring CH4 from space: what would we need to separate processes?***
J. Marshall (MPI-BGC)

**De la contribution de la mesure des aérosols depuis l'espace à l'étude des interactions aérosols-climat**
***Contribution of aerosol measurements from space to the study of climate-aerosol interactions***
P. Nabat (Météo-France, CNRM)

**Questions-réponses** / ***Questions & answers***

**17:30** **Cocktail**

## Mercredi 11 octobre / *Wednesday 11 October*

**09:00 Session 3 : Les instruments spatiaux pour le climat : une vision technique** / ***Space instruments for climate: a technical overview***

President: E. Boussarie (CNES)

**Point hors Europe** / ***Overview outside of Europe***
D. Crisp (NASA-JPL)

**Intervenants des industries et agences** / ***Speakers from industries and agencies***

**La mesure du méthane avec le Lidar de Merlin** / ***Methane measurement with Merlin Lidar instrument***
M. Alpers (DLR)

**Airbus DS : Les instruments spatiaux pour le climat ; une vue d'ensemble** / ***Airbus DS Space instruments for climate: an overview***
D. Gillieron (Airbus)

**Thales Alenia Space : Les instruments spatiaux pour le climat** / ***Thales Alenia Space: Space instruments for climate,***
Y. Baillion (TAS)

**10:30 Pause café** / ***Coffee break***

**Les différentes façons de mesurer les paramètres atmosphériques** / ***Different ways to measure atmospherics parameters***
B. Cugny (CNES)

**Les instruments de l'ESA** / ***ESA instruments***
R. Meynart (ESTEC)

**Les instruments Eumetsat pour les relevés de données climatiques** / ***Eumetsat instruments for climate data records***
J. Schulz (Eumestat)

**Questions-réponses** / ***Questions & answers***

**12:30 Pause déjeuner** / ***Lunch break***

**14:00 Table ronde** / ***Round table***

President: P. Lecomte (ESA)

**Participants :**

**Présidents des sessions** / ***presidents of sessions:***

**Cathy Clerbaux**, *directrice de recherche CNRS au Laboratoire Atmosphères, milieux, observations spatiales (LATMOS-IPSL), AAE*
**Éric Boussarie**, *sous-directeur Systèmes instrumentaux au CNES*
**Gerhard Ehret**, *head of Lidar department, Institute of Atmospheric Physics, DLR*

**Des décideurs d'agences et d'industries** / ***Agency and industry leaders:***

**Nicolas Chamussy**, *executive vice president space systems, Airbus Defence and Space*
**Mark Doherty**, *senior advisor, ESA*
**Pr. Pascale Ehrenfreund**, *chair of the DLR Executive Board*
**Jean-Loïc Galle**, *président-directeur général de Thales Alenia Space*
**Jean-Yves Le Gall**, *président du Centre national d'études spatiales (CNES)*
**Dr Jörg Schulz**, *climate service product manager, Eumetsat*

**16:00 Conclusions**

**Nadia Pellefigue**, *vice-présidente du conseil régional Occitanie / vice-president of the Occitania regional council*

**Marc Pircher**, *président du comité de programme, correspondant AAE, ancien directeur du Centre spatial de Toulouse, CNES / programme committee chairman, AAE correspondent, former director of Toulouse space centre, CNES*

**16:45 Fin du colloque** / ***End of conference***

La COP 21 a été le point d'orgue d'une prise de conscience des États face au changement climatique et ses graves conséquences pour notre planète. Alertés depuis des années par la communauté scientifique, les gouvernants se sont enfin engagés à réduire les émissions anthropiques de gaz à effet de serre, pour tenter de limiter la hausse des températures moyennes du globe. Or, pour évaluer l'efficacité des stratégies mises en œuvre, il faut des mesures précises, ce qui représente un défi à la fois scientifique et technologique.

L'Académie de l'air et de l'espace a souhaité prendre part à ce débat en organisant un colloque international en octobre 2017 pour mieux examiner l'apport du spatial dans la surveillance des variables climatiques, en particulier les gaz à effet de serre, et faire dialoguer entre eux les scientifiques, les agences spatiales et les industriels. Ce dossier 47 présente une synthèse des discussions et élabore des recommandations à l'attention des décideurs.

*COP21 was a crucial moment in terms of the growing awareness of states of the reality of climate change and its grave consequences for our planet. Alerted for years by the scientific community, governments at last committed to reducing anthropogenic greenhouse gas emissions in order to slow down and halt the rise in average global temperatures. However, precise measures are needed to assess the effectiveness of these strategies, and this represents a scientific and technological challenge.*

*The Air and Space Academy decided to take part in this debate by organising an international conference in October 2017. The aim was to examine the contribution of space systems in improving our understanding of phenomena influencing the climate and to bring together scientists, space agencies and industry to discuss the different issues. Dossier 47 presents a summary of findings along with key recommendations for stakeholders.*

**www.academieairespace.com**

9 782913 331839

ISBN 978-2-913331-83-9
ISSN 1147-3657

15€