













Space agencies, scientists, users and industry have formed a real community around the challenges of climate change.

This collaboration is also a deeply human adventure and a story of passion, which we all decided to tell together.

This is how the book "Climate change and satellites" was born.









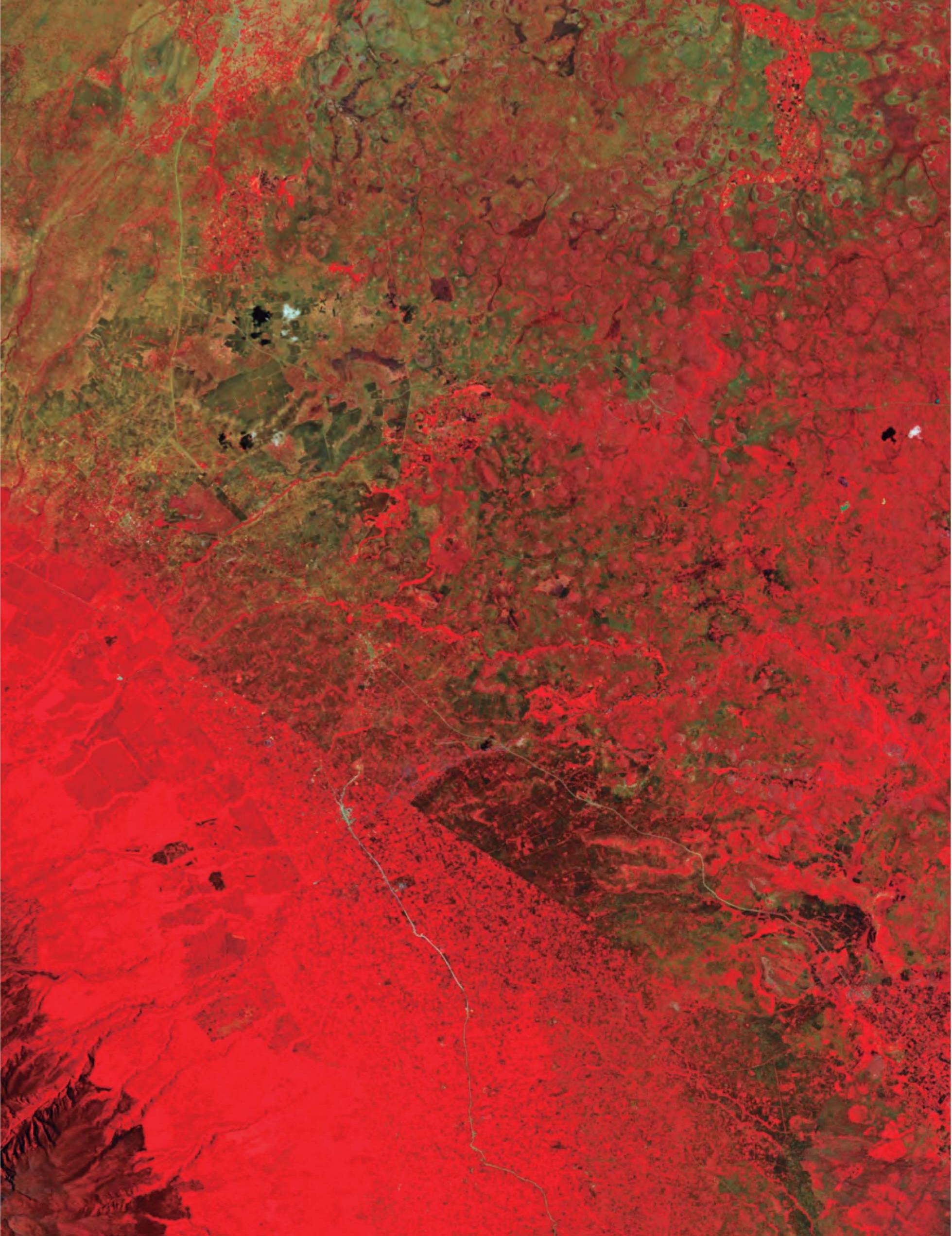




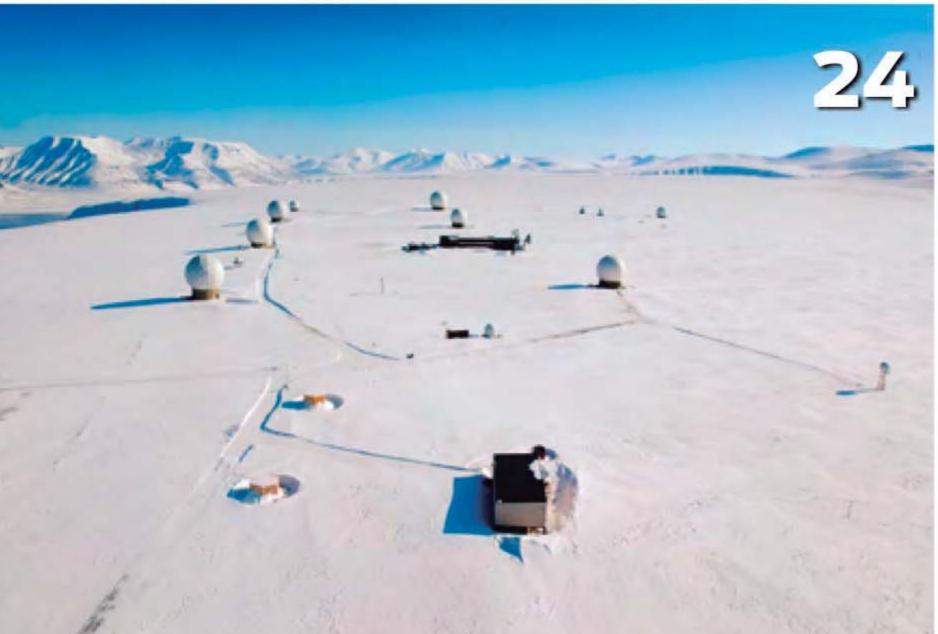
CLIMATE CHANGE & SATELLITES

Knowledge for action













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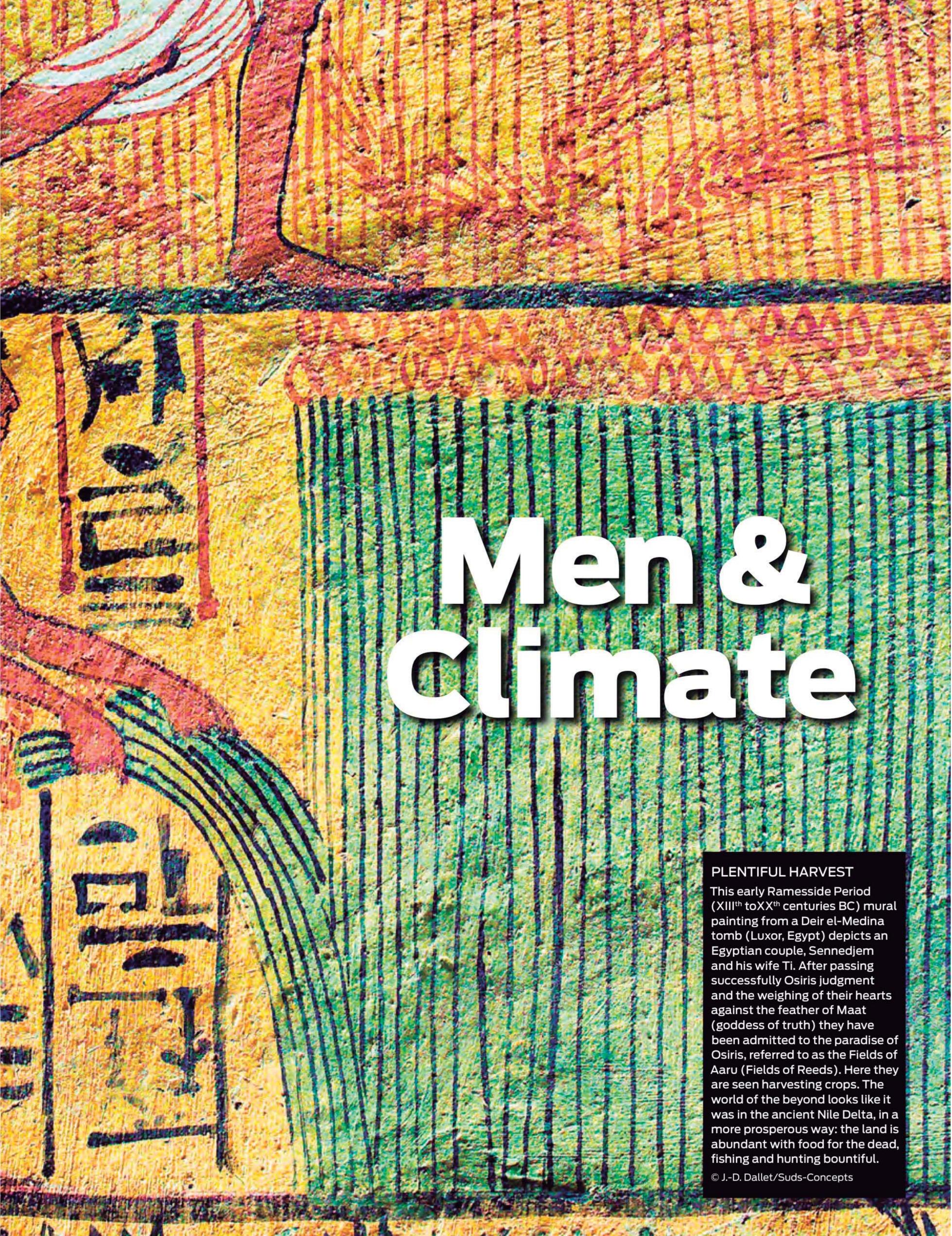












From myths to science

IEN THOUSAND years ago, when our distant Neolithic ancestors were first starting to cultivate their fields, and scoured the woods and savannah in search of game with which to feed themselves, they used to look up at the skies, observe the clouds, keep an eye on the wind, and look out for rain and snow. Armed only with their four senses for measuring instruments, and with their intuition and logic for theory, they had to try to forecast the changes in the weather that governed their lives. We have practically no record of how these early humans related to the weather. Certain paintings in the Mas d'Azil cave in the Ariège region of France may depict the rain or the sun, according to the prehistorian Kassner.

From myths to theories

Today, it's with the help of high precision instruments, probes, satellites and supercomputers that our contemporaries explore our planet's weather and climate. To get this far has required centuries of research, inventions and theories. It's an amazing adventure whose first tangible records go back as far as the XIIIth century BC in China, where inscriptions carved on bone have been found that relate weather phenomena (snow, frost, rain, wind, etc) recorded every ten days. However, there is no trace of measuring instruments. To find the first recorded instrument, the 'nilometer', we have to turn to ancient Egypt (see p. 11). As was frequently the case in ancient times, mythology and meteorology went hand in hand. The allpowerful gods completely controlled natural phenomena: winds and tides, heatwaves and downpours, thunder and lightning were exclusively caused by them. In India in 3 000 BC, for instance, philosophical texts such as the Upanishads connected the formation of clouds, the phenomenon of rain and the cycle of the seasons with the motion of the Earth.

It was only with the advent of the Greek philosophers, first Parmenides and Herodotus (Vth century BC), and then Hippocrates with his work *Air, Water and Places*, that the first global theories about climate concerning the whole planet emerged. We should remember that to-



La Grotte de Niaux (Niaux Cave), one of the most famous prehistoric caves in Europe, lies in the northern foothills of the Pyrenées, in Vicdessos valley (Ariège, France). There are more than two kilometres of galleries, with a hundred or more superb paintings from Magdalenian times (13000-15000 years BC. Here, the "Salon Noir".

© J.-F. Peiré, Ministère de la Culture (France)



The Kitāb Gharā'ib al-funūn wa-mulah al-'uyūn or' Book of Curiosities' is a treatise on Arabic cosmography. The manuscript is a copy of an anonymous work created during the first half of XIth century. This map (South on top) shows, from left to right, the Indian Ocean and Asia, Africa with Egypt and the Nile (top centre), then Spain separated from Africa by the Mediterranean Sea (top right). © The Bodleian Library, Oxford

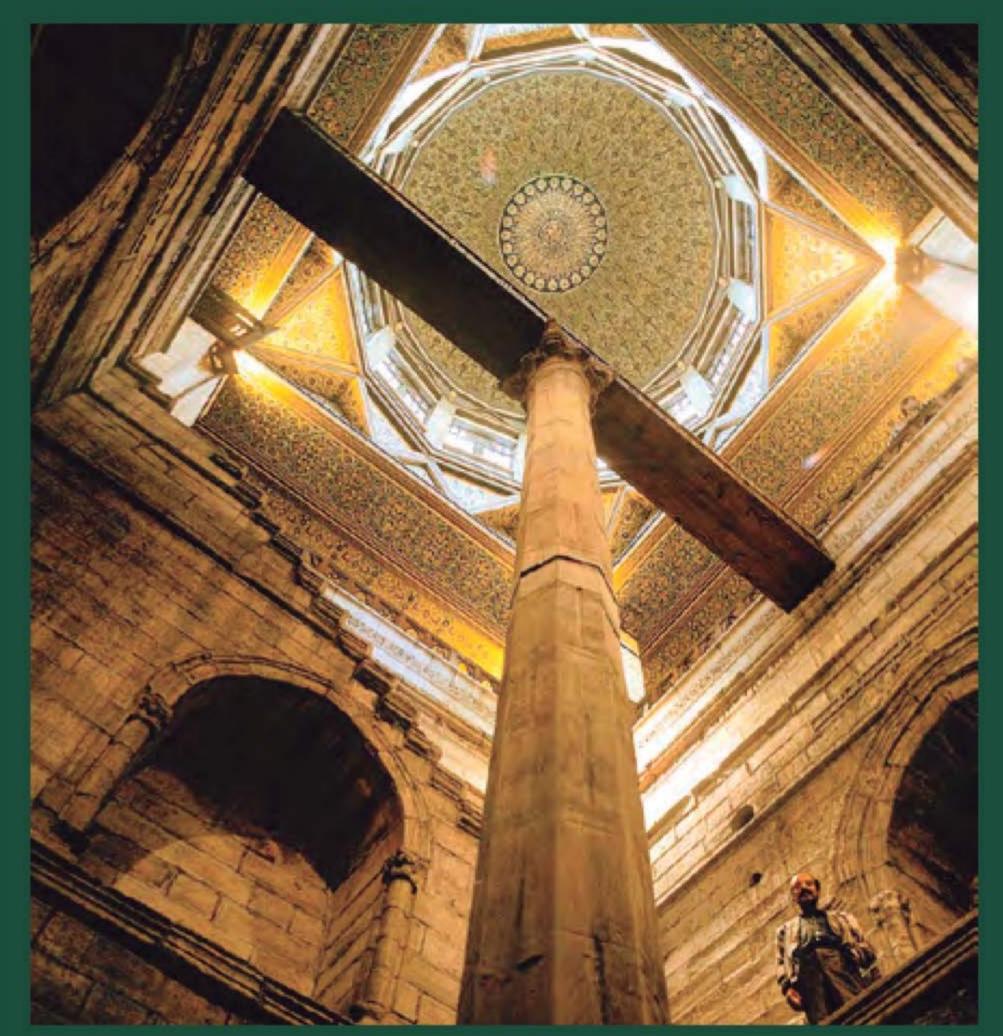
day we make a distinction between 'weather' and 'climate'. Weather has to do with the meteorological conditions in one place and over a short period of time. Climate, according to the World Meteorological Organization (WMO), is the synthesis of weather conditions in an entire geographical region over a long period of time. In short, the weather concentrates on the here and now, while the climate concerns entire regions over tens or even hundreds of years.

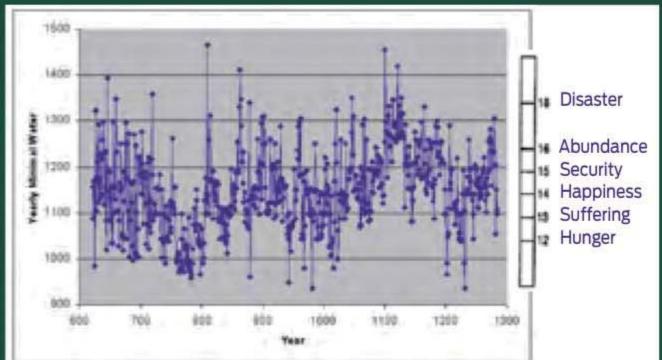
Aristotle's Meteorology

As early as the end of the IVth century BC, Hippocrates divided the world up into different climate regions, contrasting Europe where the climate varied in a sawtooth pattern to Asia where there reigned a perpetual spring. In the same century, Aristotle wanted to find order within the world. The result was a coherent and rational approach, put down in the four volumes of Meteorology, an impressive treatise that described not only astronomical phenomena in the vicinity of the Earth such as comets, but also phenomena that affected the atmosphere, such as snow, hail, wind, etc. Aristotle also talked about the key role of the Sun which extracts 'fluxes of heat from the Earth'. Depending on whether they were dry or humid, they caused wind and rain, heat-waves or storms. Over the years, Aristotle's theories about climate became widely accepted Admittedly, they were amended here and there by other philosophers such as Theophrastus, Posidonius and Aratus, but without them being fundamentally changed.

At the same time, the first measuring instruments were invented. For instance in around 40 BC, the astronomer Andronicus of Cyrrhos built in Athens the Horlogion, a wind tower 14 metres high that housed a hydraulic clock and a weather vane. Aristotle's work remained unknown in Western Europe for centuries, and right through the Middle Ages no scientific progress took place at all. At the time, the only instrument available to observe the weather was the rudimentary weather vane. But the intellectual ferment of the

But the intellectual ferment of the Renaissance was to change all that. In the space of a century, the first instru-





- The nilometer in
 Cairo (715 AD), on the
 southern tip
 of Roda Island.
 © Bill Hocker
- Time-series record
 of the Nile RiverRoda gauge minimum
 water levels from
 662-1208 AD
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Learning from the Nile

In Egypt, the priests had the crucial job of predicting the date and the size of the spring floods of the River Nile, vital for survival. The experts of the time invented an ingenious system of wells with marks carved on their walls that were used to measure the river level. Thanks to groundwater infiltration, and by comparing this with information gathered during previous floods, the Pharaoh's hydrologists were able to forecast the size of the floods as soon as the water began to rise.

The level of Nile River have been measured for more than five thousand years, with time series of minimum and maximum water levels stretching over 13 centuries, from 622 AD to 1922 AD. Gathered by Toussoun (1925), this data has turned out to have unanticipated uses: to have spurred the development of aspects of mathematics (Brownian motion and Gaussian noise) along with a field of statistics concerned with the behavior of long memory time series. This time series is too short to gain a complete understanding of how climate systems vary. To extend the history of climate further back in time, recent studies have employed various types of data as "proxies" for climate indices. These in turn can be related to other large-scale phenomena such as *El Niño* frequency. Recent studies (E. Eltahir and G. Wang, MIT 1999) show strong correlation between the Nile's water level and the existence of *El Niño* – so strong, in fact, that the Nile record can be used as a proxy for its occurrence.

Source: Waterhistory.org





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Set up during the Ist or IInd century BC at the foot of the Acropolis, the octagonal Tower of Winds is decorated on its sides with a sculpted frieze picturing the eight directions of the wind, each one linked to a deity. Above, Zephyr.

© J.D. Dallet / Suds-Concepts

ments able to measure the main characteristics of the atmosphere were developed. Leonardo da Vinci took up the plans that the German mathematician Nicholas of Cusa had drawn up in the mid XVth century, and designed a new hygrometer where water was absorbed by a sponge. Galileo came on the scene at the end of the XVIth century and designed the first air thermometer, whose graduations were developed years later by the Italian Santorre Santorio. At the same time, the German astronomer Johann Werner and the Danish astronomer Tycho Brahe carried out the first regular meteorological observations. At the beginning of the XVIIth century, the rain gauge was reinvented in Europe by Benedetto Castelli, while rudimentary anemometers gave way to instruments that were able to measure wind strengths and speeds. When Galileo died on 6 January 1642, Ferdinand II, Grand Duke of Tuscany, filled his position with a mathematician and philosopher called Evangelista Torricelli, whose name has come to us down through the centuries. For it was Torricelli who invented the

barometer. In a letter written on 11 June 1644, he described the famous experiment where he discovered that the weight of a column of mercury in a tube inverted over a basin balanced the weight of the column of air above it.

Barometric observations

In 1647, Descartes added a graduated scale to Torricelli's tube. And Pascal showed that the height of the mercury was lower at the summit of the Puy de Dôme volcano in France than at its foot, and therefore that atmospheric pressure varied with altitude. As early as 1653, the first meteorological observation network (7 stations in the north of Tuscany and 4 outside this area) was set up at the instigation of the same Grand Duke, to whom the science of weather owes a great deal. At the Hôtel de Thou, in Paris, the first systematic temperature records were taken three times a day from 1658 on, and the first regular barometric observations started up in 1670 thanks to Doctor Morin. However, at that time no weather map had ever been drawn. This was not to happen until the

voyages of the British astronomer and engineer Edmund Halley. During his expeditions in the tropics, he recorded numerous observations about the trade winds and monsoons. In 1686, he published the first map of sea winds between 30°N and 30°S.

While the engineers worked on new measuring instruments, others were thinking again about global climate theories. Aristotle and his Meteorology were rediscovered. From their voyages during the XVth and XVIth centuries great navigators like Christopher Columbus and Vasco da Gama brought back notes and ideas about the climatic conditions they had encountered in different parts of the globe. Francisco López de Gómara, a priest in the service of Hernán Cortés, mentions in his Historia general de las Indias the myth of the Five Suns of the Mexica (the Aztecs). Storms, floods and earthquakes were said to have destroyed the first four, and the Earth was plunged into night and its inhabitants decimated by natural disasters. Then ten years after the coming of the fifth Sun, humankind was regenerated. Three centuries later,



- In 1698-1700, Halley's explorations in the Atlantic Ocean aboard the Paramore, led to this printed map, the first of its kind and the first to use isogonic lines.
- © Princeton's Historic Maps Collection
- This Codex Vaticanus is supposed to picture the first four ages of the five Aztec Suns, with their procession of catastrophes.
- © All rights reserved



Alexander von Humboldt established a link between this myth and a document kept in the Vatican Library.

The idea that temperatures are distributed in bands between two latitudes on either side of the equator was gradually becoming popular again. This theory was taken up and refined all through the Age of Enlightenment.

In 1686, the English physicist George Hadley developed his theory about the rotation of the Earth and the trade winds. He drew up a picture of atmospheric circulation which was to be widely accepted for over two hundred years. This was how Diderot and d'Alembert defined the climate in their Encyclopedia, published between 1751 and 1772: 'Portion or zone of the Earth's surface bounded by two circles parallel to the equator up to the poles (...) Climates form as many zones parallel to the equator but [the text explains] it should not be thought that the temperatures are the same in all the countries located within the same climate,' since the action of the Sun, wind and volcanoes, the position of mountains, etc. must be taken into account.

Climatic determinism

It was also during this fruitful Age of Enlightenment that the first recorders were developed, systematic records were kept increasingly often throughout the world, the Swiss Leonard Euler established the first laws of hydrodynamics, while Lavoisier discovered the laws of calorimetry, etc.

While Europe was at the dawn of the Enlightenment, the Maharajah of Jaipur, Jai Singh II, built between 1727 and 1734 five astronomical observatories that can still be visited today. The Enlightenment saw the reappearance of the idea of climatic determinism, already defended by XVIIth century writers such as Boileau, Fénelon and La Bruyère. In L'Esprit des Lois (1748), Montesquieu put forward the idea that geographical factors affect the mentality of a nation, differences in latitude explaining the diversity of customs and consequently the differences between institutions or governments. He thus established a contrast between Asia and Europe, the former being the chosen place for slavery and the latter for liberty. At that time, the word 'climate' meant 'temperature'. From the XIXth century on, the science of weather observation made giant strides with the conquest of the third dimension, altitude. The first in situ measurements of the atmosphere took place in 1804, when Louis Joseph Gay-Lussac, a precursor of meteorology, and Jean Baptiste Biot boarded a hot-air balloon and rose up to over 4000 metres in order to record the vertical profile of the temperature and composition of air. The first international meteorological conference was held in Brussels in 1853, and it recommended regular observations from on board ships. From 1848, Russia set up its main physics observatory, which was to organise a network of weather stations and publish numerous documents, including the Climatological atlas of the Russian Empire (1900).

All over the world national weather services were set up: in 1870 in the USA, in 1873 in Sweden, in 1878 in France, in 1887 in Japan, etc. In India, the service set up in 1875 was run from 1904 by Sir Gilbert Walker. This British mathematician, who was fascinated by the mecha-





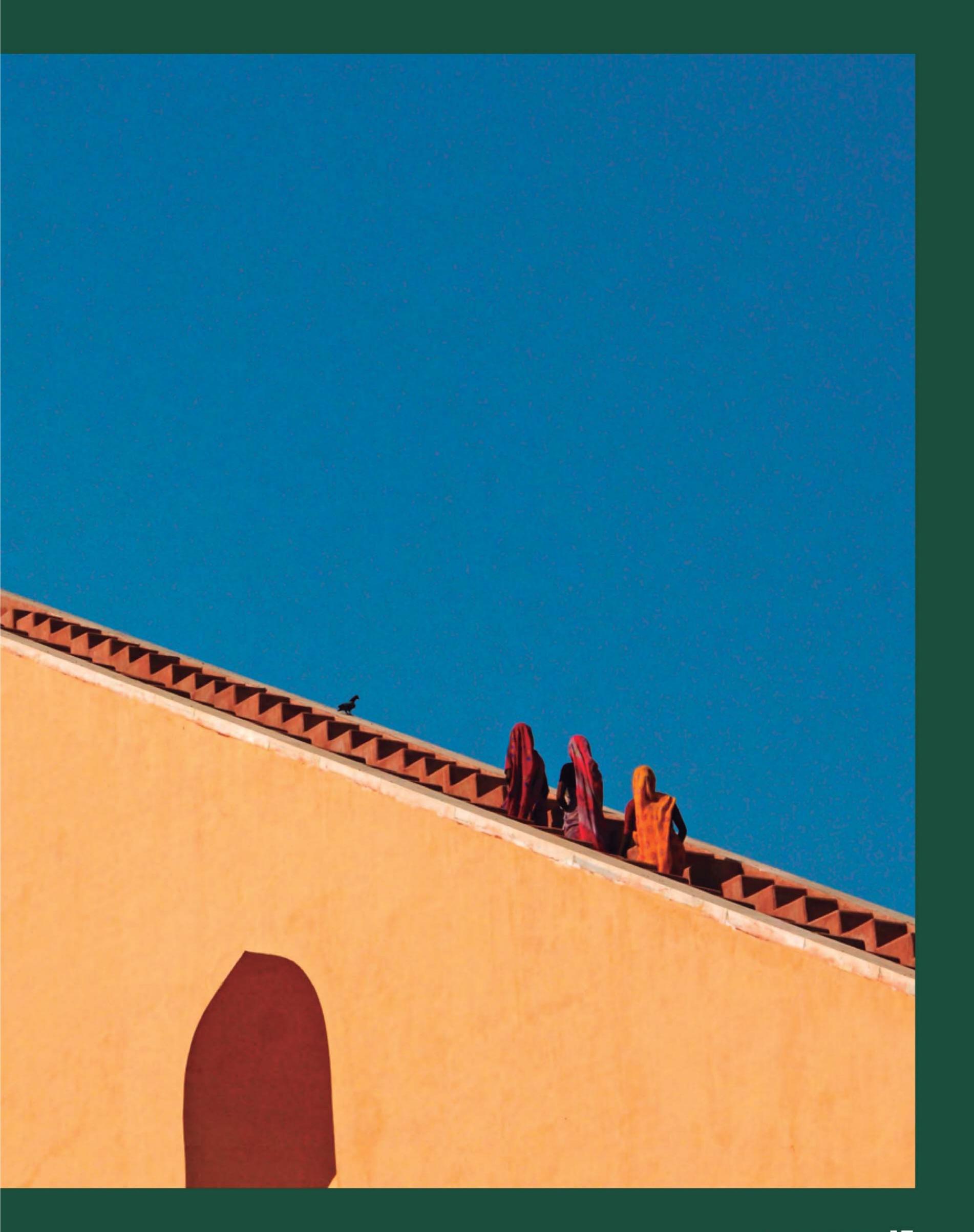


Observatory and work of art

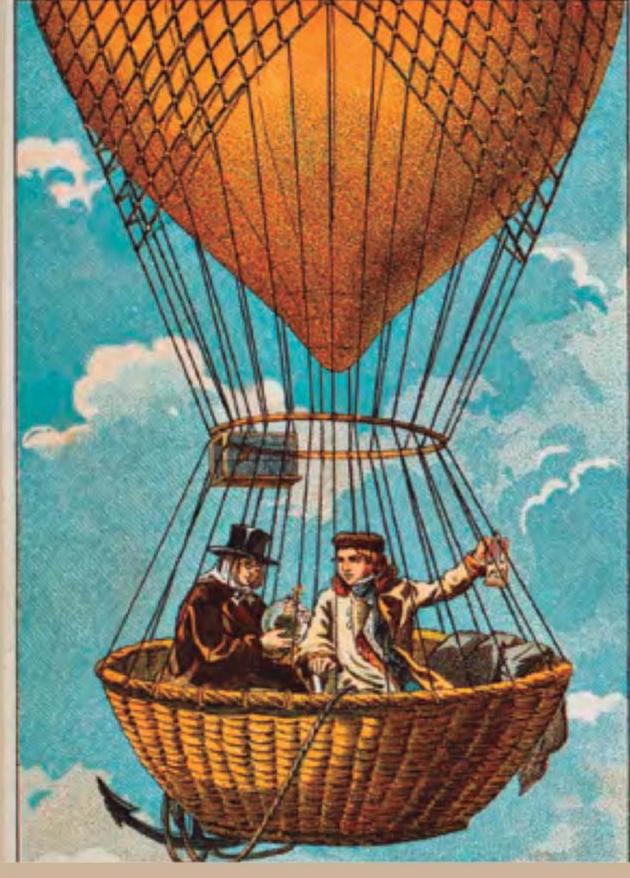
he Jantar Mantar, in Jaipur, was the second of five observatories built in the North of India. Their designer, Maharajah Jai Singh II, was fascinated by mathematics and astronomy, which he had learnt about through reading manuscripts of ancient Greek, Persian, Arab and Indian astronomers. This observatory, built between 1727 and 1734, was made up of buildings each of which specialized in one particular astronomical measurement or (on the right) in weather forecasting. Its twelve instruments, the Rasivalaya Yantras, linked to the signs of the Zodiac, were used to measure the latitude and longitude of the planets. An amazingly accurate sundial 27 metres high was able to give the time to the nearest second at the equinoxes. The Jantar Mantar is also a work of art, which draws Indian families and numerous tourists.

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 ✓ The theoretical bases of radar date back to April 1904, when the 22 year old German engineer Christian Hülsmeyer registered a patent for an instrument he called the

Alexander von Humboldt, left, with his friend Aimé Bonpland in the Amazon rainforest by Thomas Ender (1793–1875). © Berlin-Branderburgischer Akademie der Wissenschaften,

1 Louis-Joseph Gay-Lussac studied clouds and vapour pressure at very low temperatures, and built high precision thermometers and barometers. On September 9th, 1804 he and Biot travelled up in a balloon over Paris, in order to study variations in terrestrial magnetism. © All rights reserved

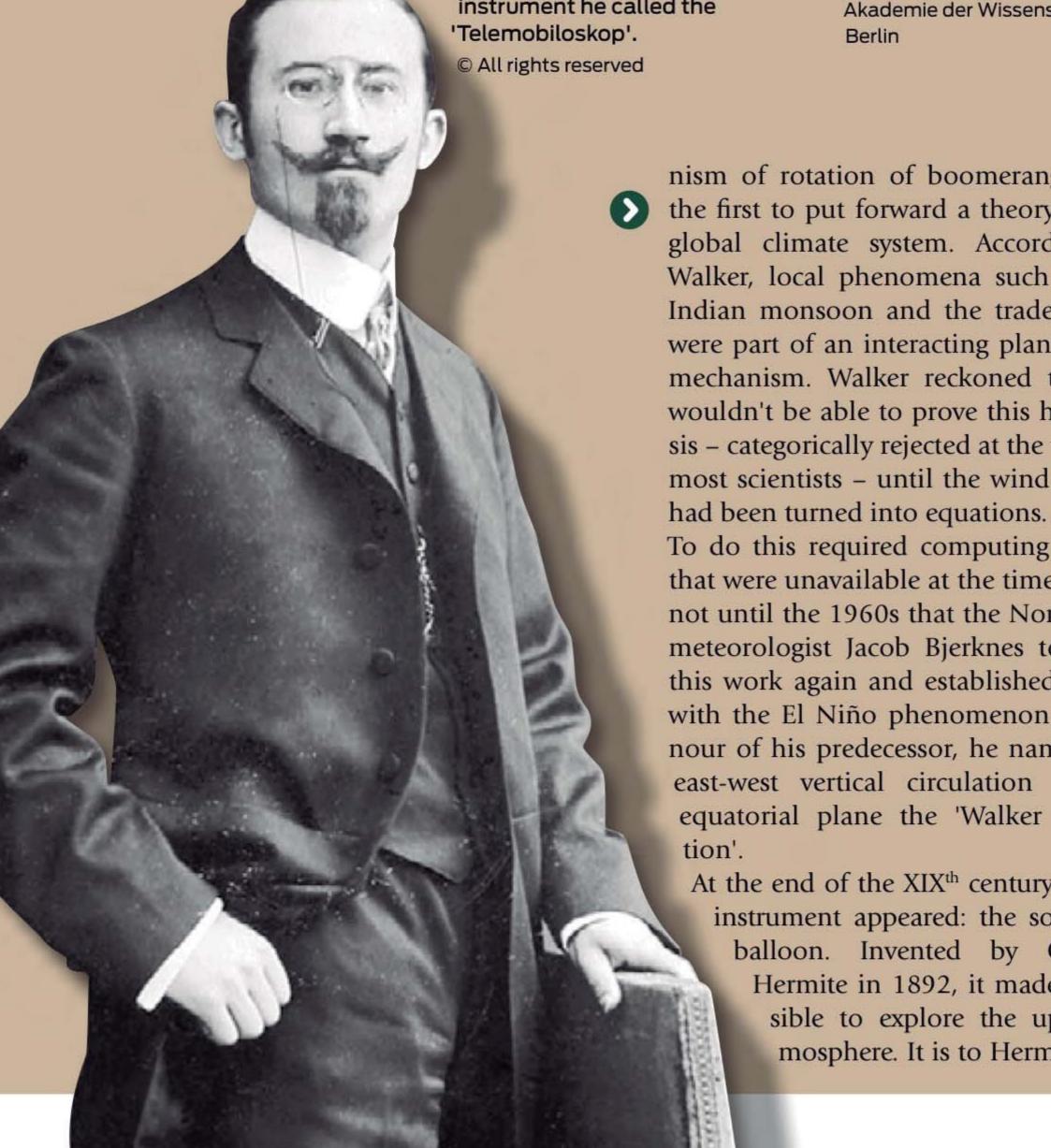
nism of rotation of boomerangs, was the first to put forward a theory of the global climate system. According to Walker, local phenomena such as the Indian monsoon and the trade winds were part of an interacting planet-wide mechanism. Walker reckoned that he wouldn't be able to prove this hypothesis - categorically rejected at the time by most scientists - until the wind system

Berlin

To do this required computing means that were unavailable at the time. It was not until the 1960s that the Norwegian meteorologist Jacob Bjerknes took up this work again and established a link with the El Niño phenomenon. In honour of his predecessor, he named the east-west vertical circulation in the equatorial plane the 'Walker circulation'.

At the end of the XIXth century, a new instrument appeared: the sounding balloon. Invented by Gustave Hermite in 1892, it made it possible to explore the upper atmosphere. It is to Hermite that

we owe the brilliant idea of launching balloons equipped with recorders, although these had to be recovered on their return. This was a drawback that was overcome in 1927 by Pierre Idrac, director the the observatory at Trappes, who developed the first radio transmissions from the stratosphere. Two years later, his colleague Robert Bureau put the finishing touches to the first radiosonde, which was to be used systematically all over the world from 1937. To complete the whole setup, all that remained to be invented was the weather radar. This was achieved in 1930 when the idea of the German Christian Hülsmeyer and his 'Telemobiloskop' took shape. This was the starting point for the development of increasingly sophisticated instruments, first the impulse radar, followed by highpower radars that work at decimetre wavelengths. Meanwhile, the physicists and mathematicians had realised that they needed precise, numerous, frequent measurements on a large scale in order to establish genuine climate theories on a



regional and planetary scale. It was the Prussian Alexander von Humboldt who, as early as 1817, paved the way by drawing up the first map of the world's isotherms. He was to take this up again twenty-eight years later in his monumental work *Kosmos*, published between 1845 and 1862, in which he showed the importance of the land-sea link for the climate. In 1800 he had discovered a cold current flowing off the coasts of Peru and Chile which is named after him. Humboldt developed topoclimatology, the science that links local climate and relief.

Meanwhile, the mathematician Joseph Fourier was writing his book *General Remarks on the Temperature of the Terrestrial Globe and Planetary Spaces* (1824). During this period of rapid development of experimental sciences, there were ever greater numbers of learned societies and international scientific exchanges. The International Meteorological Organization (IMO), the predecessor of the World Meteorological Organization, (WMO) was founded in 1873. Armed with the meteorologists'

measurements, the first official climatologists published the fruits of their labour, in particular the Russian Alexander Woeikof, the founder of Russian scientific climatology, who published in 1884 his book Climates of the Earth, and of Russia in particular.

Weather forecasting

However, it was only after the Second World War that climatology really took off. The first climate atlases were published, based on data from increasingly sophisticated instruments such as sounding balloons that ascended to altitudes of several tens of kilometres, radars exclusively designed for meteorology, and computers like the powerful ENIAC, the first large electronic calculator, which was used in the early days of weather forecasting.

The American John von Neumann began to use the first mathematical models, and the first soundings of the upper atmosphere took place in 1948 using rockets. And 1960 saw the launching of the first weather satellites, the American

The oldest terrestrial globe which has come down to us. It was built in 1492 by Martin Behaim. Presented in the Germanic National Museum in Nüremberg.

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TIROS satellites, which were to give a fresh boost both to meteorology and to climatology.

It will take over thirty years for climate change to become a key world issue, in the political field then as a societal challenge. Beyond some scientists acting as whistleblowers, it will mainly be channelled through United Nations initiatives, from the first Framework Convention on Climate Change (UNFCCC) signed in Rio de Janeiro in June 1992 during the Earth Summit to the Paris COP 21 conference in November 2015 and by the creation of the Intergovernmental Panel on Climate Change (IPCC), the world body providing policymakers with regular assessments of the scientific basis of climate change.

Françoise Harrois-Monin



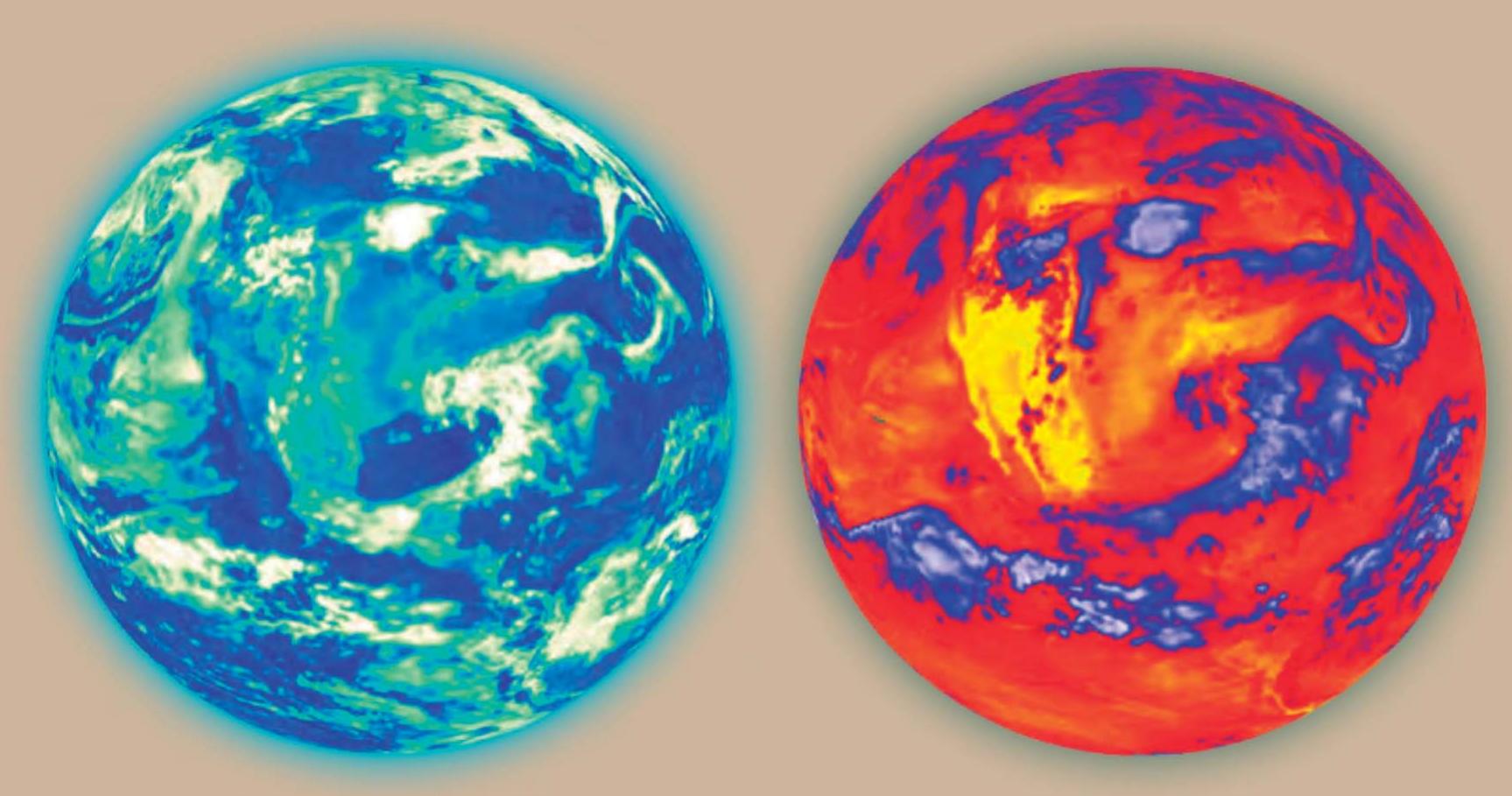
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Section of the Chimborazo volcano (6,268 metres, Ecuador) with terracing of vegetation and climate conditions: temperature, pressure, etc.. "Essai sur la Geographie des Plantes", Alexander von Humboldt & Aimé Bonpland, Paris, 1805.

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17

The radiation budget



These Aqua images show CERES measurements over the United States from June 22, 2002. Clear ocean regions, shown in dark blue on the left image, reflect the least amount of sunlight back to space. Clear land areas, shown in lighter blue, reflect more solar energy. Clouds and snow-covered surfaces, shown in white and green, reflect the greatest amounts of sunlight back to space. Clear warm regions, shown in yellow over much of the western United States on the right image, emit the most heat. High, cold clouds, shown in blue and white, significantly reduce the amount of heat lost to space.

© NASA/Goddard Space Flight Center Scientific Visualization Studio.

N THE NIGHT OF 4-5 October 1957, when the first artificial satellite in history sent its historic 'beep-beep' back from

space, Robert Kandel, who was then a young astrophysics student, was working in the observatory of Harvard University, where he was studying. At the time, he could hardly imagine that he was to become the ideal 'key witness' of the saga of Earth observation satellites and one of the world's top specialists in the planet's radiation budget. Right from the early 1960s, he followed the results of the observation of planet Earth from space by the American TIROS satellites. However, it was only with Nimbus 3, launched by NASA in 1969, with the ERB (Earth Radiation Budget) instrument on board, that the first data from space started to be collected. This data made it possible to

refine the value for the Earth's albedo and for the infrared radiation that the Earth emits out to space. "And it was then," Kandel points out, "that we discovered that our planet Earth was not quite as reflective as we'd thought."

The explanation for this was that previous, indirect, estimates were based on data for cloud cover in the northern hemisphere alone. However, in the southern hemisphere there are fewer continents and fewer clouds, which altered the initial estimates. After carrying out research in astrophysics in New York, Meudon and Paris, Kandel created a course about issues related to the planetary environment at the University of

Boston, where he was then teaching. "Already at that time I was talking about climate change and the potential of spacecraft for its study,"

says Kandel. "This is because it's only from space that we can measure parameters that were previously out of reach, such as the flux of reflected solar radiation, as well as that of the infrared radiation emitted by the Earth and its atmosphere, which are fundamental data for the climate system." Kandel was thus a pioneer. In 1978 his career took him on a new path and he joined CNRS's aeronomy department in Verrières-le-Buisson in order to study the diurnal variations in the Earth's radiation budget, using data from Europe's first weather satellite, Meteosat.

Thanks to the backing of the CNES and in cooperation with NASA, he took part as a

member of the scientific team in the ERBE (Earth Radiation Budget Experiment) project, whose first Low Earth Orbit satellite was launched in 1984. "With three ERBE instruments in operation (two of which were on NOAA satellites), plus the information sent back by Meteosat, we had very good sampling of the diurnal cycle at our disposal," Kandel explains.

It was at that time that Kandel joined the Laboratoire de Météorologie Dynamique. From 1986, as part of a Franco-Soviet collaboration, his team developed the ScaRaB (Scanner for Radiation Budget) instrument which was carried on board two Russian satellites (Meteor-3, Resurs) between 1994 and 1999.

To refine data even further, NASA developed CERES (Clouds and Earth's Radiant Energy System), whose instruments were carried on board the TRMM (Tropical Rainfall Measuring Mission, 1997) satellite and two satellites, Terra and Aqua, from the EOS (Earth Observing System). Over the years, the results built up. "First," Kandel explains, "the satellites enabled us to eliminate the role of the Sun as a factor in climate warming, and to show that the albedo has not changed in a systematic way. But, above all, we were able to draw up a more precise radiation budget for the Earth, and see how it varied over the course of a year, and from one year to the next, depending on the region and on El Niño.

We were able to estimate the role of cloud cover region by region and evaluate the impact of the greenhouse effect, which enabled us to verify the validity of some models and eliminate others." There remains one crucial question: how do the clouds react to warming?

So new space missions such as CloudSat and CALIPSO (launched together in 2006 following the Aqua satellite, a joint CNES-NASA operation) or Megha-Tropiques (Indo-French mission launched in 2011, see p. 54) have been sent to study what's going on in the very heart of the clouds. Other projects are on the drawing boards of the space agencies (see p. 46 and 55), using precisely calibrated radiometers and active instruments on board. All this with one goal in mind: understanding how human activity affects our climate.

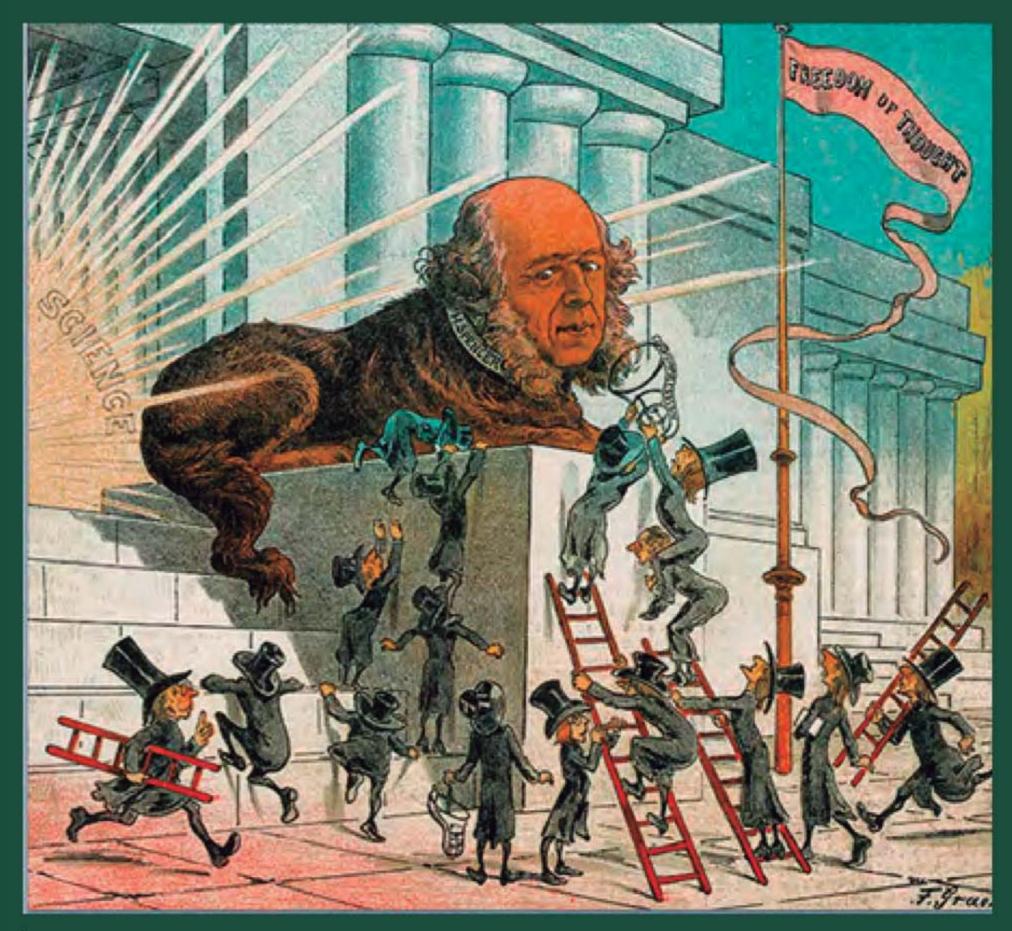
Françoise Harrois-Monin

Robert Kandel is a senior Researcher at CNRS (Laboratoire de Météorologie Dynamique)

The greenhouse effect

t was in 1824 that the physicist Joseph Fourier published his General Remarks on the Temperature of the Terrestrial Globe and Planetary Spaces. "The Earth," Fourier pointed out, "is plunged into the temperature of the planetary heavens, but it is warmed by the rays of the Sun, whose unequal distribution produces the diversity of climates. All the terrestrial effects of the warmth of the Sun are altered by the interposition of the atmosphere and the presence of the ocean." And basing himself on an experiment carried out years before by Théodore de Saussure, Fourier concluded that "the temperature [of the ground] is increased by the interposition of the atmosphere, because the warmth [solar radiation] encounters fewer obstacles when it penetrates the air, since it is in the state of light, than it encounters when it passes back through the air having been converted into dark warmth [the Earth's infrared radiation]." What a visionary he was! It remained for him to identify the gas that caused the phenomenon. It was John Tyndall, an Irish physicist who succeeded Faraday at the Royal Institute in Britain, who found the answer in 1861. He published a study on the theory of the greenhouse effect in which he stated that it was essentially due to water vapour. However, according to Tyndall, any variation in the quantity of water vapour, or of carbon dioxide, should lead to a change in the climate. In 1896, the Swedish chemist Svante Arrhenius, who won the Nobel Prize in 1903, published an article in which he calculated that if carbon dioxide completely disappeared from our atmosphere, the ground temperature would fall by 2°C. On the other hand, if the volume of carbon dioxide doubled, it would increase by 4 °C. And, in optimistic fashion, he concluded that the industrial activity of civilized humankind could provide a technical solution that would postpone the next glacial period! Arrhenius was thus the first person to link human activity - the industrial use of fossil fuels - to the greenhouse effect.

Source: 'Planète-Terre', website of the École Normale Supérieure de Lyon.



↑ John Tyndall (1820-93) who discovered the greenhouse effect is also known in medicine, along with Louis Pasteur, for having opposed the idea of spontaneous generation. He was the main protagonist in a number of scientific debates. The caption to this Puck cover of 1883 reads: 'The Society for the Suppression of Blasphemous Literature proposes to get up cases against Professors Huxley and Tyndall, Herbert Spencer, and others who, by their writings have sown widespread unbelief, and in some cases rank atheism'. © All rights reserved

Geodesy: triangulation

of the world that has come down to us is that of Homer in the Odyssey: a flat disc surrounded by an Ocean River. Later on, it was also from Greece that came the first theories stating that the Earth is round: theories that were philosophical for Aristotle, but scientific for Eratosthenes, who compared the length of shadows cast by the Sun at Alexandria and at Syene (Aswan). During the Middle Ages, the Earth was thought to be flat again. So called 'TO' maps (Terrarum Orbis) showed all the land in the shape of a T, surrounded by an ocean, O.

First with Copernicus, then with Kepler and Galileo, the Earth became round again and lost its place in the centre of the Universe. In 1670, the Abbé Picard used triangulation to carry out the first really precise measurement of a degree of meridian, from which he worked out the Earth's radius. He immediately passed on the result to Newton, who used it to give a definitive statement of the Law of Universal Gravitation. However, Newton's brilliant mind was none too happy with this overly perfect spherical Earth. What if

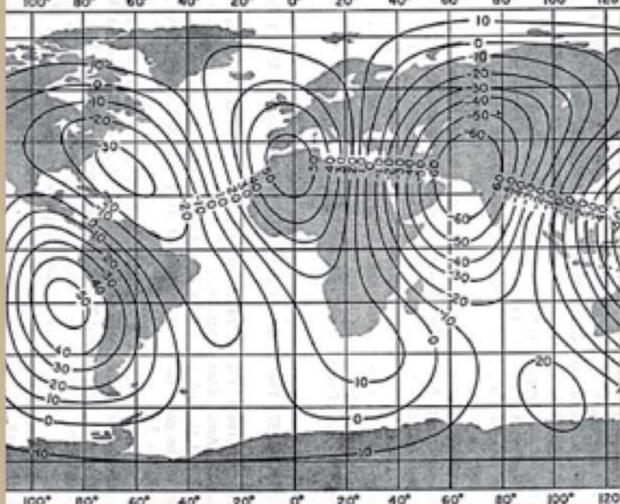
the Earth's interior was ductile, he wondered: in that case, its diurnal rotation would lead to a flattening of the sphere at the poles. No, it wouldn't, it would make it longer at the poles, retorted the French astronomer Cassini, putting forward the same reasons. So was the Earth shaped like a tangerine or a lemon? Two French expeditions, one as close as possible to the North Pole, the other to the Equator, settled the question: the English scientist was victorious.

From that time on, which saw Clairaut found modern geodesy, the Earth was considered to be an ellipsoid of revolution, flattened at the poles. In addition to such geodesic methods, d'Alembert and then Laplace employed field measurements to calculate the flattening of the Earth using astronomy. As part of his theory of perturbations, Lagrange invented the concept of potential, and was no longer content to define the terrestrial ellipsoid by its flattening. The notion 'shape of the Earth' was replaced by that of 'geoid', which represented the equipotential surface that coincided with the mean sea level.

The arrival of satellites was to radically change the field. With Sputnik 2, geodesy entered the space age. This is because while Lagrange's theory of perturbations explains how the shape of the Earth deviates the trajectory of an orbiting body, conversely, measuring such deviations makes it possible to find out the coefficients in which are part of the mathematical formula that defines this geoid. J2 can be obtained through terrestrial measurements. In 1958, D. King-Hele determined J2 with Sputnik 2 (and confirmed the value, which was already known).

Launched shortly afterwards, the American Vanguard 1 satellite was used to evaluate for the first time the differences between the ellipsoid and the geoid. The coefficients J3 and J4 were obtained in 1959 by Kozai. The Earth is pear-shaped: the geoid is 10 metres above the ellipsoid at the North Pole, and 30 metres below it at the South Pole. The US then launched satellites dedicated to geodesy (ANNA 1B and LAGEOS). W. Kaula developed models that opened the way for today's very complete models, such as EIGEN in





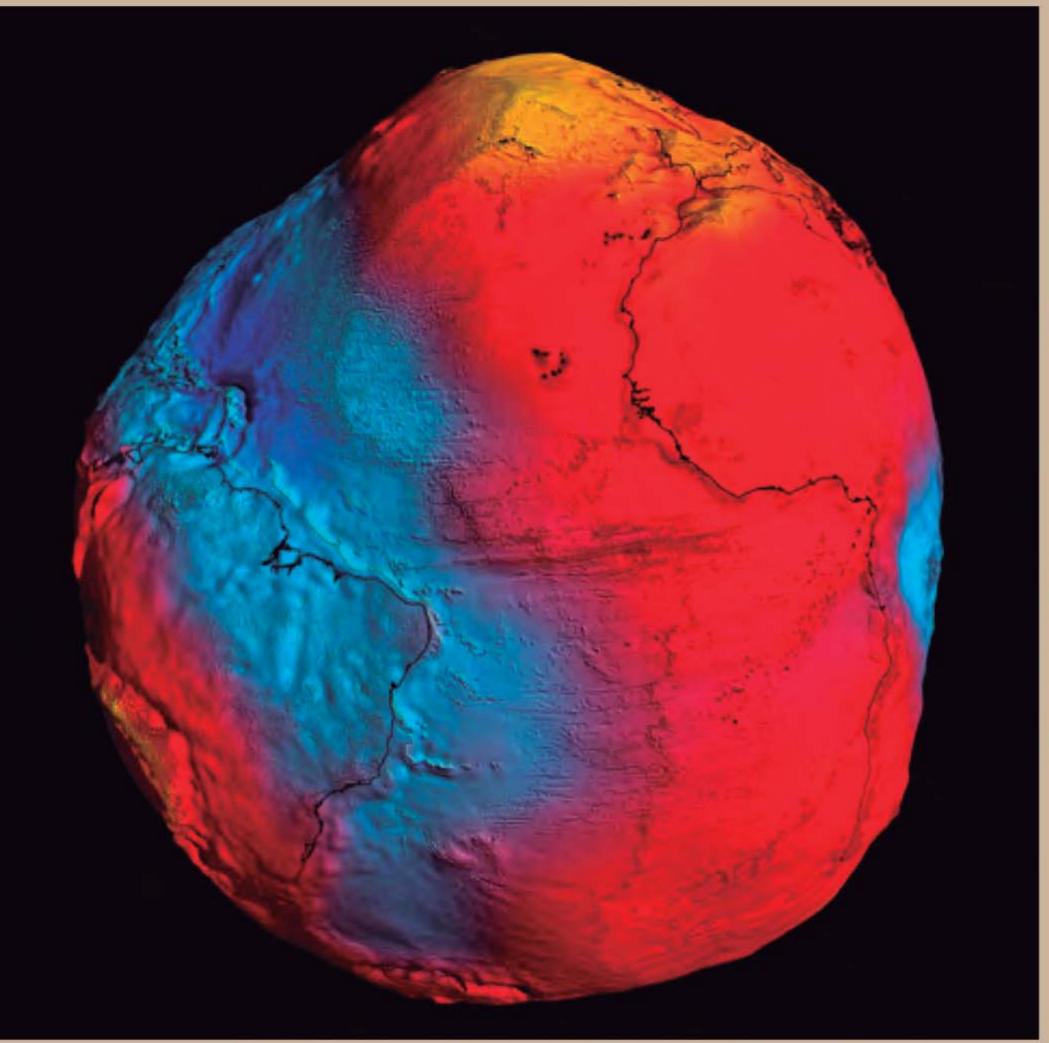
Measuring the width of a river by triangulation engraving by Levinus Hulsius(1546-1606). Born in Ghent (Flanders), maker and dealer of fine scientific instruments.

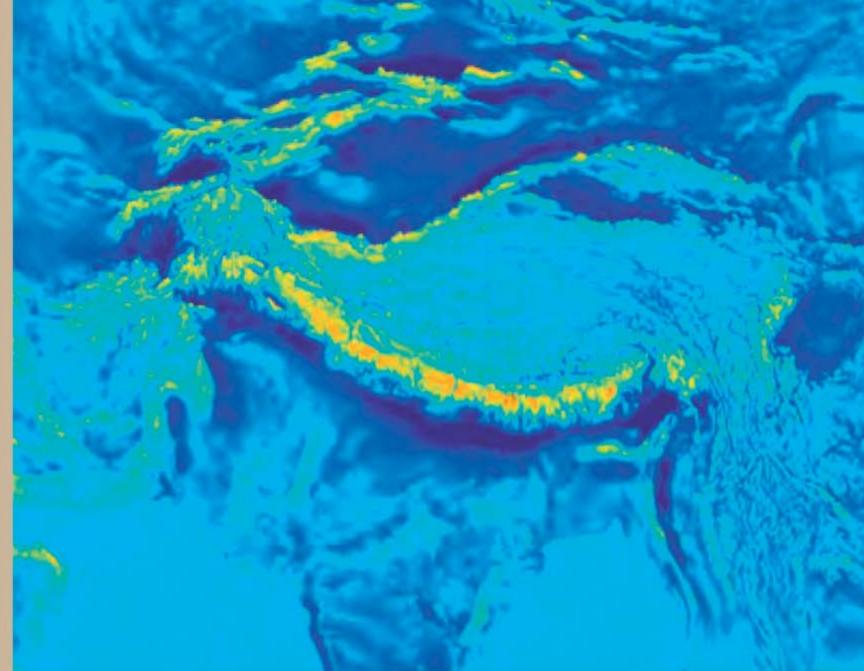
© All rights reserved

First map of a global model of the terrestrial geoid interpolated from measurements of terrestrial and marine gravity.

© Physical Geodesy, Weikko Heiskanen 1967, published by W.H. Freeman and Co

and satellites





ESA's GOCE mission has delivered the most accurate model of the 'geoid' ever produced. The colours in the image represent deviations in height (-100 m to +100 m) from an ideal geoid. The blue shades represent low values and the reds/yellows represent high values.

© ESA/HPF/DLR

Gravity disturbances over Himalayas, India and parts of South-East Asia. GGMplus is a composite gravity field model that is based on GRACE and GOCE information.

© GGMplus.

Europe, and EGM in the US. Compared to the reference ellipsoid, the geoid shows, in addition to the deviations along the axis mentioned above, anomalies of several tens of metres, extreme examples of which are a high in New Guinea (+83m) and a depression off the south of India (-103m). The first geodesic satellites orbited the Earth at high altitude (5 900 km for LAGEOS) in order to escape completely from atmospheric friction, with the risk of not being very reactive to small undulations in the geoid.

Things changed radically from the year 2000, with the development of ultra-sensitive accelerometers to measure very precisely the 'gravitational anomalies' allowing for the forces of atmospheric friction acting on the satellite. This means that CHAMP (400km) and the two GRACE (470 km) satellites can fly at very low altitudes. In order to improve the accuracy of these measurements, the European GOCE mission is placed into

an even lower orbit (250 km). Scientific reasoning and measurements made it possible for the 'shape of the Earth' to change from a sphere to the ellipsoid revolution. However, it was thanks to satellites that we discovered the slightly 'lumpy' shape of the ellipsoid. And knowing the shape of the geoid ever more accurately will make it possible to develop increasingly precise missions. Space geodesy is a

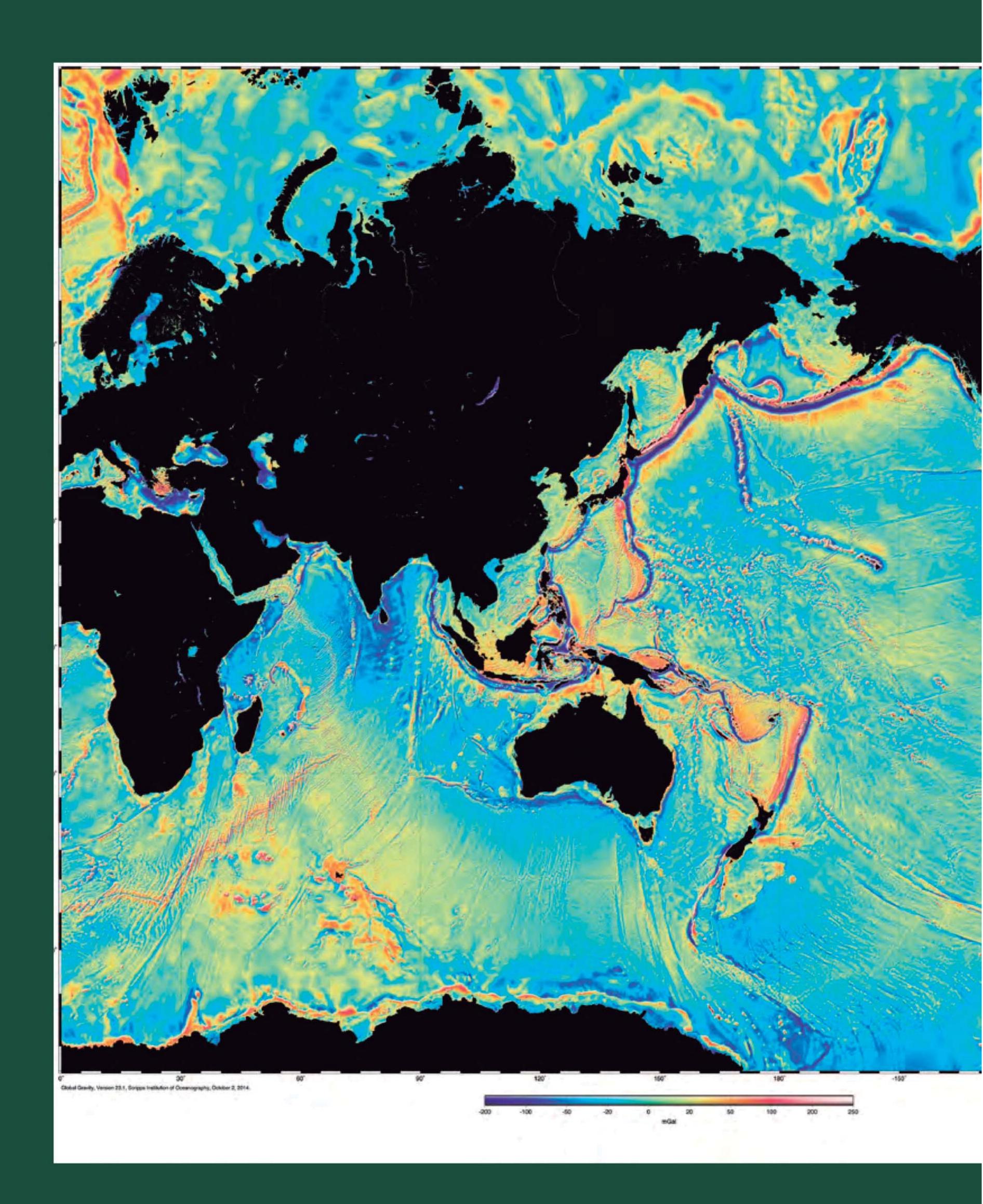
'dialectic' science: knowledge of potential models is improved by observing the trajectories of satellites, while the position of satellites is better determined by improved potential models.

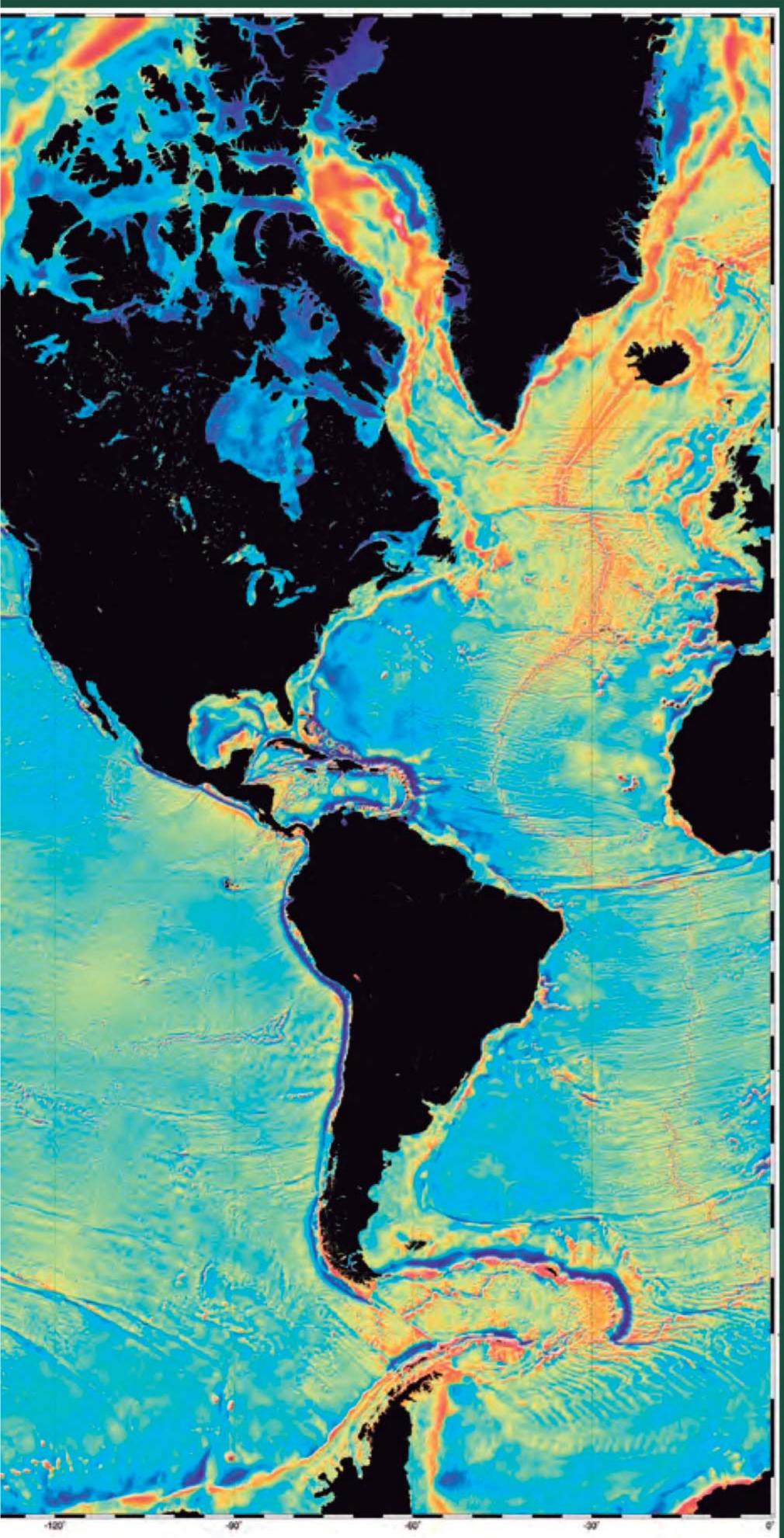
> Michel Capderou Université Paris 6/LMD



GOCE satellite with the Thales
Alenia Space team at the Plesetsk
Cosmodrome 2000 km north of
Moscow, Russia.

© ESA





Global Marine Gravity, from CryoSat-2 and Jason-1, 2014. Data on slight variations of the pull of gravity over the oceans are recorded with satellite altimetry, and are then combined to map the seafloor globally.

© Courtesy Scripps Institution of Oceanography, University of California, San Diego.



HMS Challenger. The science and ship crew in 1874. The original crew of 216 had dwindled to 144 by the end of the long expedition. © All rights reserved



Discovering the sea floor

or a long time, the ocean remained the realm of gods and sea monsters. It was only when the first telegraph cables were laid in the 1860s that the exploration of the sea floor got under way. The expedition of HMS Challenger, which from 1872 to 1876 sailed across all the oceans, marked the real beginning of deep sea exploration. Its goals were global and ambitious. Among other tasks, it was to "investigate the physical conditions of the Deep Sea, in the great Ocean basins ... in regard to Depth, Temperature, Circulation, Specific Gravity, and Penetration of Light.". At the time, less was known about the sea floor than about the Moon when the Apollo programme was launched. Since then, we have discovered mountain ranges, trenches and, everywhere, life, sometimes in abundance. The darkness that reigns in the depths of the oceans is the main obstacle to exploring the sea floor, and the first global map of its topography, drawn up from measurements made from on board ships, only dates from 1977. Altimeter satellites measure variations in the level of the ocean surface (considered to be equipotential) compared to the reference ellipsoid. These variations are the signature of variations in gravity, mostly attributable to submarine relief, which can thus be rapidly mapped. The dissipation of the energy of tides on submarine relief drives deep ocean circulation and the famous 'conveyor belt'. Therefore, the ocean transport of heat towards high latitudes.

Bruno Voituriez





Space missions unveiled

VERY ELEMENT of the Earth system is being studied by hundreds of researchers working in scientific laboratories the world over. Just slip into one of the many international scientific conferences and you'll become aware of the enthusiasm of these women and men as they share the results of their work in sessions, publications and meetings. You might be put off by some pages covered with complex equations, but you can be sure that they'd very patiently and modestly explain what they are about: namely, that models need to be supplied with accurate, regular data in order to validate their pertinence. Such data are of fundamental importance for forecasting, because you can't observe the future!

A long gestation

The goal of a space mission dedicated to climate change is to measure, from space, the key characteristics of a sphere in order to improve our understanding of it and our ability to forecast how it will change. Satellites are the favourite tool for this because they can be used for global, repeated and automatic observation of the whole planet.

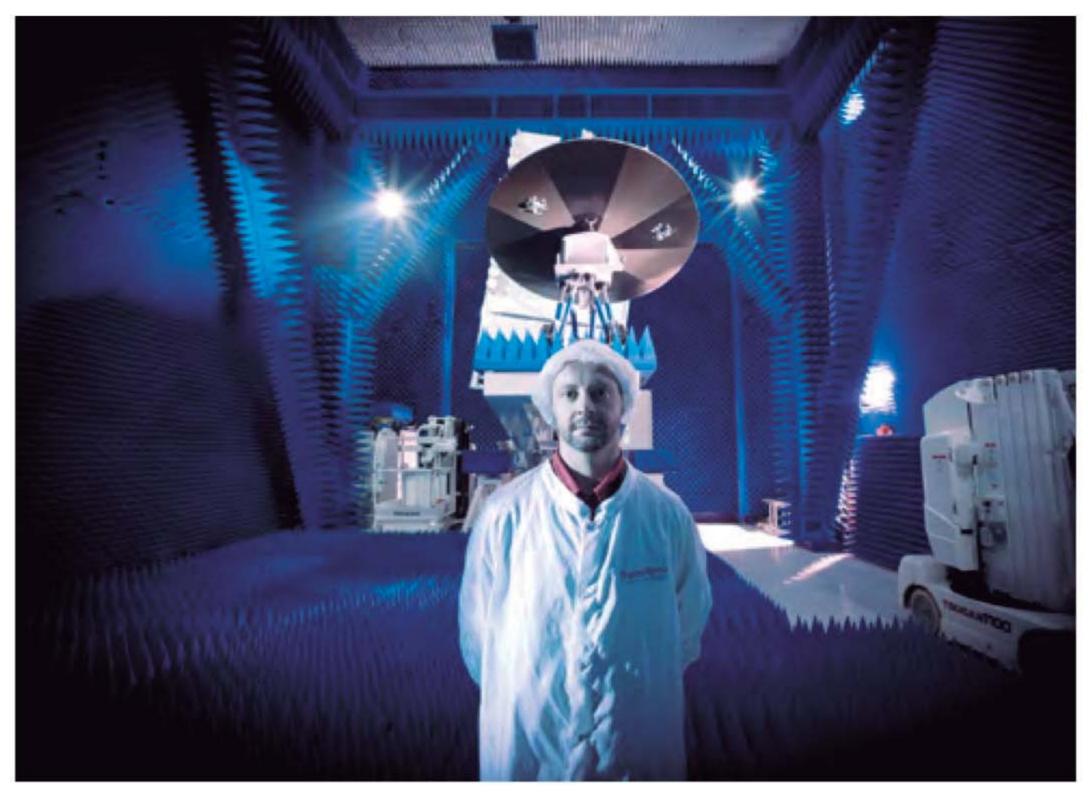
From the moment a satellite is first required until its launch, the time needed to complete a mission can be as long as ten or even fifteen years. The expected lifetime of an Earth observation satellite is often exceeded: the ESA satellites ERS-1 and ERS-2 collected critical data during 9 and 16 years, respectively. Lately, ENVISAT, one of the largest observation satellites ever built, was operational during 10 years.

Everything starts with the very large number of mission projects proposed by the scientific community. Space agencies are in charge of selecting the missions that will be given priority, within a given calendar and budget. A mission is made up of the space segment, which is the satellite and its instrument (if there are several instruments, this is called the payload), and the ground segment. The cost of a mission can range from 100-300 million euros, which can be compared with the cost of a kilometre of motorway, which is about 10 million euros. The agencies organise the preparation of

the mission and entrust its total or partial execution to an industrial prime contractor. The project gets under way with a concept-validation phase during which the agency and the P.I. (Principal Investigator, the chief scientist on the mission) ask one or more competing industry players to look into the technical feasibility of the whole project, establish a schedule for completion, and quote a price. There then follows a consolidation phase during which the industrial prime contractor makes the first models, and provides tangible proof that the requirements of the mission can be met. This is then followed by a construction phase carried out by the prime contractor with its own teams and external subcontractors. A major European programme involves thousands of people working for dozens of subcontractors and hundreds of manufacturers. During this phase, the P.I., in coordination with the agency, leads one or more validation campaigns on test areas, for example with a plane or sounding balloon equipped with an instrument similar to the one that will be on board the satellite when it is launched.

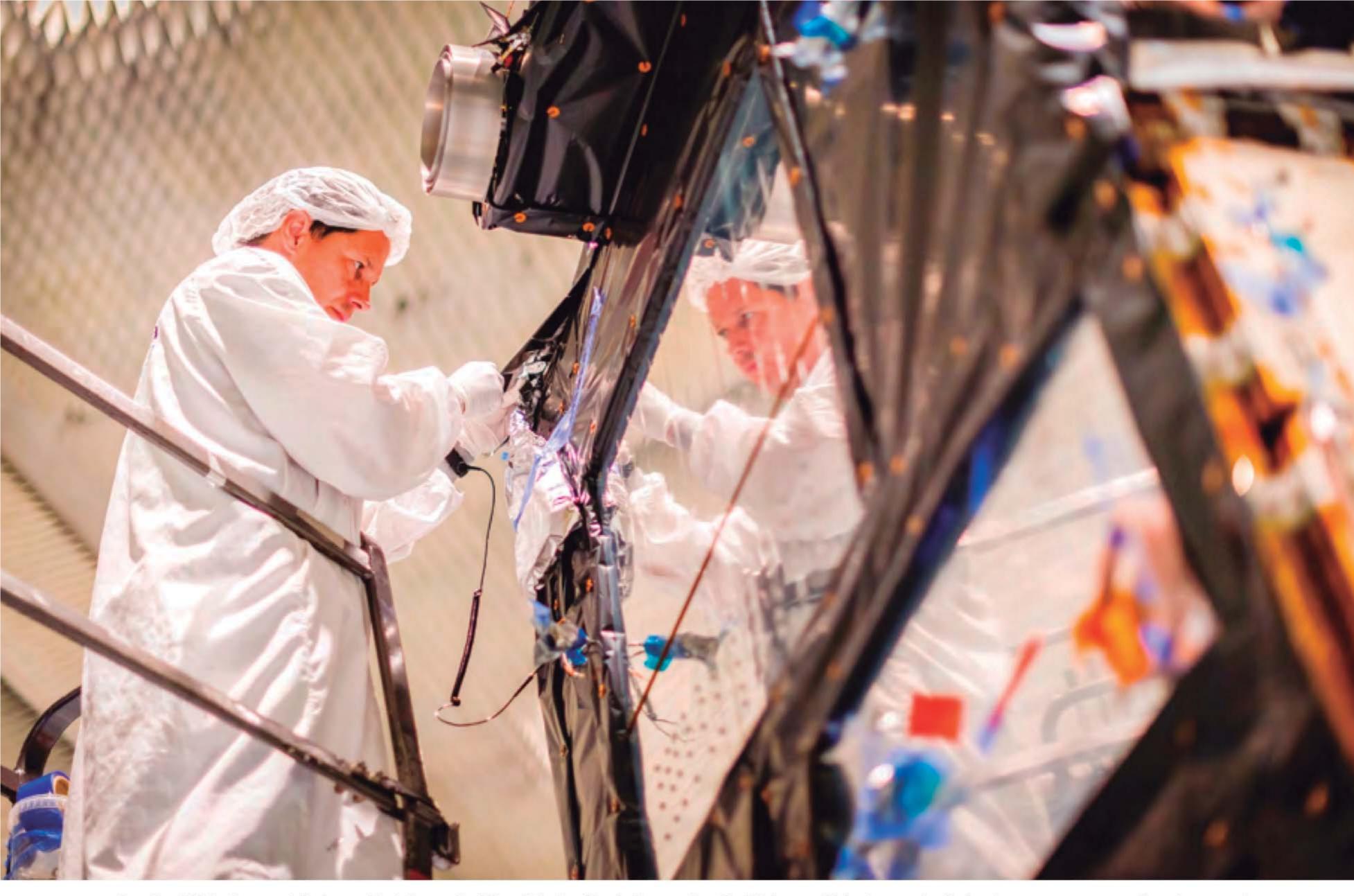
Complex technical systems

Then comes the validation phase of data provided by the satellite, which pass through the ground segment before arriving at the scientific laboratory. This is an essential stage, since it is necessary to make sure that the measurement given by the instrument is correct by corroborating it in particular on the test areas. Finally comes the phase when it is used by scientists to tackle climate problems. This requires regular, accurate data, with the guarantee that these observations will continue over a long period. A satellite is a complex technical system made up of several parts: the platform, the instrument, and antenna. The platform manages the scientific mission entrusted to the satellite, provides it with energy - thanks especially to its solar panels - and carries the measuring instrument. It also guarantees the necessary stability and alignment for the instrument to take measurements, and acts as a communications interface with the ground segment. A satellite has to survive on its own, since there is no after sales service in space. Autonomy and efficiency are absolutely essential. To



Satellite undergoes meticulous inspection and thorough testing before it is launched into space, in order to withstand the tough conditions outside of the Earth's atmosphere.

©Thales Alenia Space: /P. Masini



Sentinel 3A in Compact Antenna Test Range facility at Thales Alenia Space. Sentinel-3 is a multi-instrument mission to measure sea-surface topography, sea- and land-surface temperature, ocean colour and land colour with high-end accuracy and reliability. © Thales Alenia Space/C. Samson

increase the likelihood that it will carry out its mission in accordance with what it is expected to do, in all possible situations and during its entire lifetime (this is what is known as its reliability), the satellite must meet a very high level of equirements, that of being space-qualified. This is true during design, manufacturing and integration. The problem is that a satellite leads a pretty hectic life. When it is launched, and then when it is put into orbit, it is bumped and jolted around a great deal. It is then exposed to an extremely hostile environment, bombarded by solar radiation and heavy ions, and surrounded by several tens of thousands of pieces of space debris. It is constantly subjected to extreme changes of temperature (from + 100 °C in full sunlight to -100 °C in the shade). And on top of that, it is surrounded by the vacuum of space, in a state of near weightlessness. Before it is launched, therefore, it undergoes a long series of tests that reproduce such extreme conditions. Finding ways of combining scientific goals and technology is at the heart of the collaboration between

researchers, agencies and industry when defining space missions for climate observation. The state of one component of each sphere of the Earth system, for instance the humidity of a soil, the composition of an area of vegetation, or the state of the surface of a lake, can be characterised by a wavelength that is specific to a measuring instrument, which may be either active or passive. And in the electromagnetic spectrum, there is a particularly wide range of wavelengths to choose from.

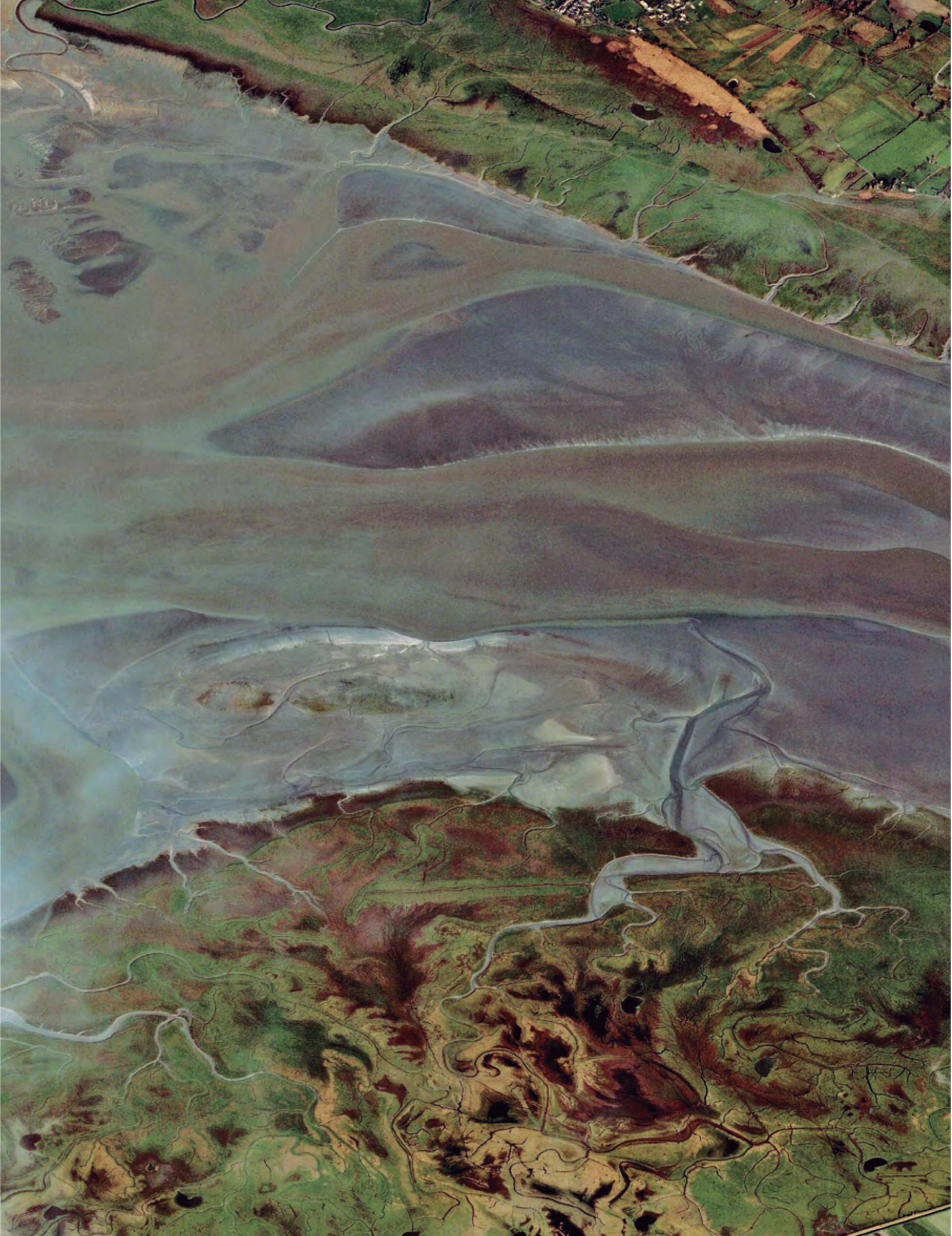
Field campaigns

Passive instruments react to 'natural' wavelengths (sunlight, infrared, etc.) in the same way as a camera. They make up the family of radiometers, which is divided into subfamilies according to the range of wavelengths processed, the wavelengths to be measured (called channels), and other characteristics requested by scientists. Some examples: optical cameras, spectrometers, multispectral or hyperspectral instruments, microwave radiometers, and sounders. Active instruments generate electromagnetic waves which are then

reflected off the surfaces that are targeted (these are known as lidars, SAR, altimeter radars, etc.) The signal that returns to the instrument contains information about the object observed. How does this end up as a visible 'image'? The instrument and/or the ground segment process this signal with powerful computers in order to extract the 'useful' part which contains information about the target, from the surrounding 'noise' of the measurement. Scientists frequently carry out field campaigns to update correspondence tables between measurements and physical and chemical properties of the target. It is essential to make sure that measurement remains stable for the whole length of the mission. This calibration is carried out, for instance, by aiming the instrument at a known terrestrial target and making sure that there is no measurement drift. Measurements from space are based on a precise reference, that of the geoid. Tomorrow's satellites and instruments are being prepared today with the space agencies.

Dominique Murat







Antennas are a key part of any satellite. The thermal and electromagnetic forces that could impact them are countered by the use of shielding that ensures electromagnetic compatibility (EMC) and other arrangements. Here under test in Thales Alenia Space's clean rooms. © J.-D. Dallet/Suds-Concepts

Radiations and microwaves

ly emit electromagnetic radiation, which carries energy, travels at the speed of light and is very often imperceptible to our senses. When an object is hot enough (over 700°C), we see part of this radiation. This is visible radiation: for example, the filament of an incandescent light bulb (around 1000°C) or the Sun (around 6000°C) emits radiation much of which is visible.

However, our eyes are not able to perceive radiation emitted by colder objects, for example objects at ambient temperature on the Earth's surface (15°C on average) or even our own body (about 37°C). The existence of this radiation is revealed by the fact that it transports energy, in other words that it warms objects that absorb it. So, what is the difference between the radiation emitted by an object at 20°C and by an object at 6000°C? Thus the Sun

emits a maximum of energy at wavelengths of between 0.4 and 0.7 micron which can be detected by our eyes. The Earth's surface or our own bodies emit a maximum of energy at wavelengths of between 4 and 20 microns, which is not visible. This is in the area of the infrared. Although for a given temperature the radiation emitted is at a maximum at one particular wavelength, it is also emitted across the whole electromagnetic spectrum at various intensities. For instance, the Earth emits a maximum of radiation at infrared wavelengths, but also emits at other wavelengths such as ultraviolet or microwave radiation. Space radiometers are instruments capable to detect those radiations in all spectral bands (i.e. wavelength) and therefore to provide vital data for climate monitoring, weather forecasting and ocean forecasting.

Spaceborne radar altimeters

These altimeters transmit microwave band signals towards the Earth, and then capture the echoes reflected from the Earth's surface. By measuring the "round-trip" time taken by these signals, the system can calculate heights on the Earth's surface, including oceans, ice formations, lakes and rivers. The radar altimeters in the Poseidon, Siral, AltiKa and SRAL families, mounted on the Jason, CryoSat and Saral satellites, plus the Sentinel spacecraft in the Copernicus program, offer particularly high performance, since they are capable of measuring heights to within less than a centimeter.

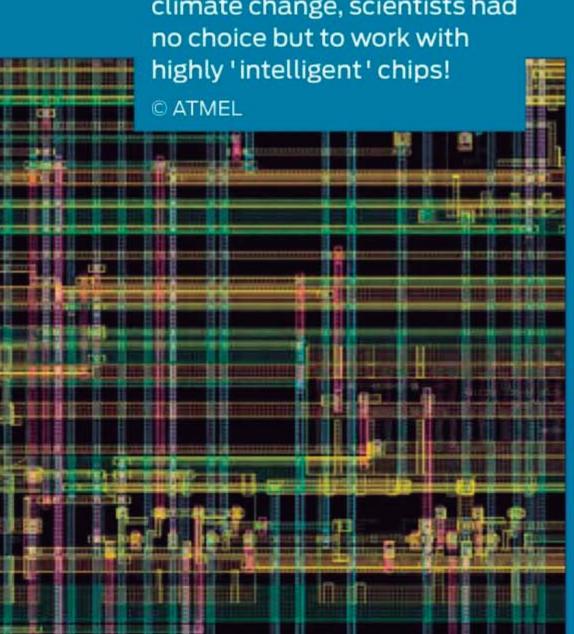
When used on oceans, they also provide wave height and wind speeds. Those data are vital for climate monitoring and ocean forecasting.

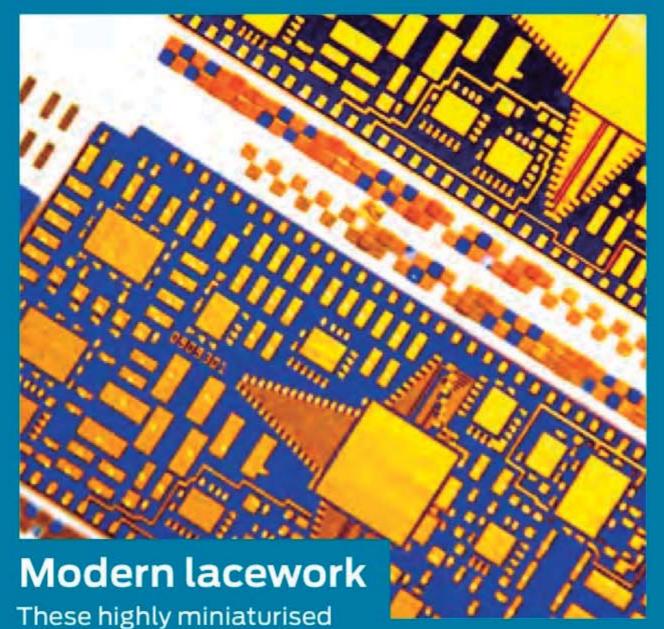
Laurent Phalippou, Thales Alenia Space

A microscopic world

Micro interconnections

An ASIC (Application Specific Integrated Circuit) is an electronic chip. This one was developed for signal processing on board an instrument. With an area of about one cm², it contains 3.5 million logic gates, i.e. 14 million transistors. This chip is the heart of the system, and beats at over 160 million pulses per second. You might think that it's suffering from tachycardia, but actually it's in excellent health. This ASIC uses CMOS (Complementary Metal Oxide Semiconductor) technology and has been 'radiation hardened', i.e. treated to resist the space environment for several years. The active structure of a transistor consists of a gate that allows the current (electrons) through or not. In a way, it's like a real entrance gate. Except that, in this circuit, it only measures 0.18 µm wide, in other words 180 billionths of a metre. Just as in your brain synapses are used for communication between your neurons, the shapes that can be seen below represent the interconnections between the transistors, which can just be made out. Given the complexity of the study of climate change, scientists had highly 'intelligent' chips!





ceramic substrates will be fitted with similar chips and other microcomponents.
They will then be powerhouses of cuttingedge space technology (above: two ceramic substrates before being fitted with chips).

© J.-D. Dallet/ Suds-Concepts



This electrochemical phenomenon takes place over time, in specific conditions that require the combination of several factors (humidity, temperature, electric voltage, etc). Here we can see a tin/lead dendrite connecting two conducting areas of a capacitor, which was acting as a short circuit. Don't worry, we spotted it!





is fairly well understood. Its effects on materials and components have to be taken into consideration in order to guarantee the satellite's lifetime. In this environment, the population of natural meteorites continues to give cause for concern, especially the larger ones, but these are relatively rare. On the other hand, ever since humans have been in space, a new population of 'debris' has made its appearance (with a size ranging from a micron to a metre), and causes a lot of local damage. This photo shows the impact of a microparticle on a solar cell. It has completely perforated the cell and a ballistic effect has blasted a large area of the glass that covered it into space. The cell can remain operational overall (except in the area of impact), but a large amount of additional debris is produced. The estimated size of the particle which struck it is less than a millimetre, and the size of the defect is around a millimetre. Protection from this type of damage is difficult for the most exposed materials and requires additional mass, which is a handicap for satellites. Monitoring the largest pieces of debris, with a constantly updated catalogue and studies of the likelihood of impacts makes it possible to evaluate risks and take operational decisions.

© CNES



The SMOS (Soil Moisture and Ocean Salinity) ESA satellite, launched in 2009, in integration. In the foreground, the radiometer. The objective of the mission - recently extended until 2017 - is to provide maps of soil humidity and ocean salinity. © Thales Alenia Space/Yoann Obrenovitch

From weather forecasts to climate

N 2013, we celebrated 50 years of space-based meteorology, marking the reception of the first satellite weather image at Lannion, in Brittany. The first satellite observations of sea surface temperature date to the early 1970s. With Topex-Poseidon (1992), then Jason (2001), we have a much better idea of the dynamic state of the oceans. Today, satellite observation gives us information on a very wide range of climate-related data variables: surface temperature, including for oceans, different layers of the atmosphere, sea levels, the breadth and even thickness of sea ice (ice floes), forest fire alerts, vegetation characteristics, rain, concentration of ozone and other greenhouse gases, etc.

We are just getting started on processing this type of data over long periods. Increasingly powerful algorithms to replay and process these variables have been developed to identify trends that are used in studying our climate, whether in the atmosphere, oceans, land masses or the "cryosphere" (snow, ice floes, glaciers and ice caps). In addition to addressing the question of identifying climate variables based on satellite measurements, we also have to resolve problems related to measurement disturbances, such as changes in satellites and the sensors they carry. This is referred to as data homogenization.

The ESA Climate Change Initiative, launched in 2009, is precisely designed

to produce a series of consistent climate variables. It will enable us to start the systematic production of these variables, which will be used as the basis for climate research and studies, and to monitor climate changes. The specific characteristic of our project, called the "Climate Modeling User Group", is to maximize the exploitation of this data for use in climate modeling. The second phase involves seven partners, including the British Met Office, project coordinator, plus the Max Planck Institute in Germany, the European Centre for Medium-Range Weather Forecasts in Reading, Météo-France and the Institut Pierre Simon Laplace.

Our main objective is therefore to create links between the communities that process satellite data to generate the essential climate variables, drawing on several decades of experience, and the community that does climate modeling so that these variables are used effectively in evaluations. There are several ways of using satellite data in climate studies. Climate models, unlike meteorological models, do not include observation data to define the initial states for forecasting. They simulate a climate solely on the basis of the equations used for these models. What we are aiming for is a model that realistically reproduces a climate, comparable to one that we can observe in terms of averages, variability and especially the number and type of extreme events.

Satellite data is therefore used, in part, to evaluate the climate reproduced by the models, by comparing it to observations. First, the radiation data from the upper atmosphere or on the surface, using satellite data, allows us to evaluate the radiation budget of the Earth, calculated using models.

Another way of using satellite data is for process studies. Climate models, like meteorological models, include for example a calculation of the interactions between clouds and radiation. But the satellites that until now mainly provide access to large-scale information on

cloud cover at different altitudes, now provided far more precise data. With the new Calipso and CloudSat satellites, and their LIDAR instruments, it is possible, for example, to determine the fine characteristics of ice clouds. But we also have to be able to use this information to support evaluations of the calculations made using climate models. To compare with the observation mode, we use the so-called satellite observation simulators. This entails reproducing a virtual image of what a Calipso or Cloudsat type satellite would see from their position above the atmosphere, where the temperature, humidity and other variables are in fact those calculated by the model. These simulators are developed in particular at the LMD (Laboratoire de Météorologie Dynamique), which works closely with CNES and the British Met Office. They were systematically used to evaluate IPCC (Intergovernmental Panel on Climate Change) models, and are made available to the entire scientific community.

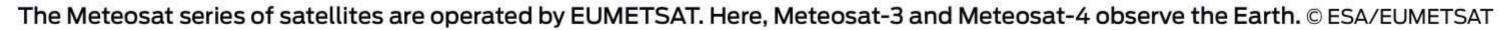
Another way of using this satellite data is for "reanalysis". These reconstructions use current data analysis systems, especially those used to determine initial states for weather forecasts, but applying them to a very large observation data set, whether gathered from terrestrial, satellite or other systems. The reanalyses themselves are used to evaluate the ability of models to simulate the climate in recent decades. Another use of reanalysis is climate forecasting, meaning forecasts beyond several weeks. Forecasting the climate does not mean announcing the weather on a given day, but rather knowing, for example, if the

average temperature for a season will be

hotter or cooler than normal.

For these climate forecasts, one must know not only the initial state of the atmosphere, but also that of the oceans. Ocean analyses play a specific role in identifying the most realistic possible picture of the oceans at the starting date for the forecast. The reanalyses, whether atmospheric or oceanic, play a key role in being able to "replay" the forecasts for past years, in relation to models of current forecasts, very similar to climate models, in order to evaluate the ability of these models to predict the climate several months ahead of time. There is of course another way of using satellite data, by analyzing series of essential climate variables. Monitoring the climate and detecting the impact of human activity is another important aspect, and one that is growing fast. Satellite data will therefore take a growing role in the analysis and forecasting of climate change, as well as in projecting our future climate by evaluating the climate models used for this purpose.

Serge Planton, Météo-France

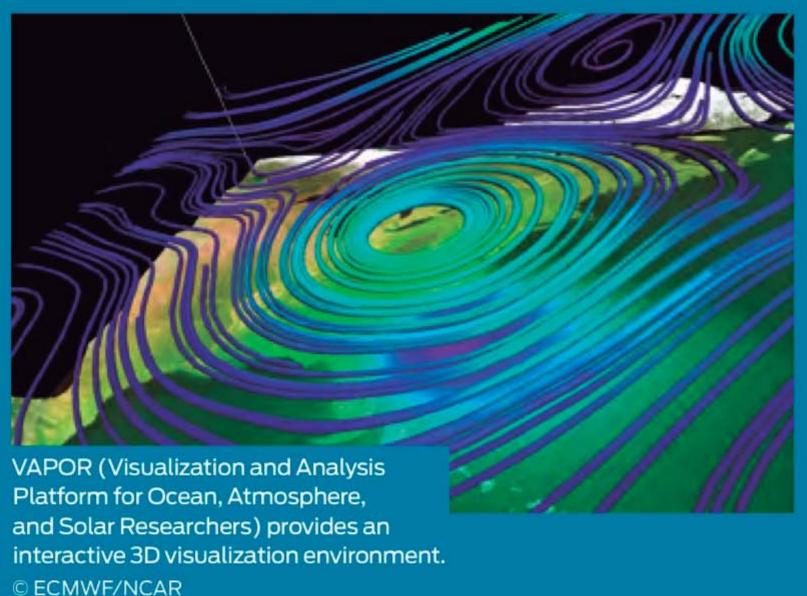




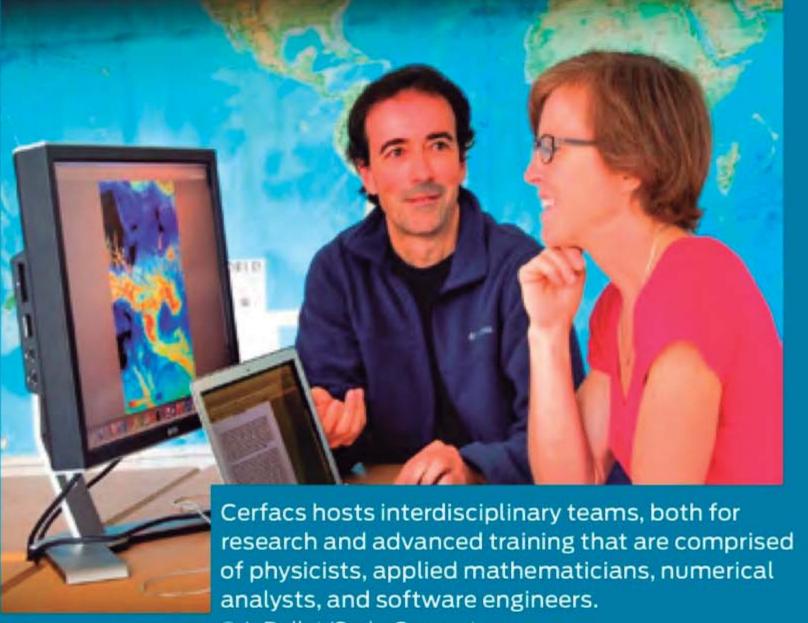
Observations and models

climate reanalysis gives a numerical description of the recent climate, produced by combining models with observations. It contains estimates of a number of essential climate variables (for example air temperature and wind, soil moisture content, etc.). The estimates are produced for all locations on earth, and they span a long time period that can extend back by decades or more. Reanalysis data are used for monitoring climate change, for validating climate models, for research and education at large, and for commercial applications in a wide variety of economic sectors **ECMWF** periodically uses its forecast models and data assimilation systems to 'reanalyse' archived observations, creating global data sets describing the recent history of the atmosphere, land surface, and oceans. Reanalysis data are used for monitoring climate change, for research and education, and for commercial applications. Current research in reanalysis at ECMWF focuses on the development of consistent reanalyses of the coupled climate system, including atmosphere, land surface, ocean, sea ice, and the carbon cycle, extending back as far as a century or more.

The work involves collection, preparation and assessment of climate observations, ranging from early in-situ surface observations to modern high-resolution satellite data sets. Special developments in data assimilation are needed to ensure the best possible temporal consistency of the reanalyses, which can be adversely affected by biases in models and observations, and by the ever-changing observing system. Reanalyses will become an important component of the newly created Copernicus Climate Change Service, one of the six Services of Copernicus. This Service will combine observations of the climate system with the latest science to develop authoritative, qualityassured information about the past, current and future states of the climate in Europe and worldwide. They will however continue to rely on national investments and international research programmes and partnerships to further the science required to maximize the exploitation of the instrumental data records (especially from satellites) and to improve the assimilating models. J.-N. Thépaut, ECMWF



High resolution modelling



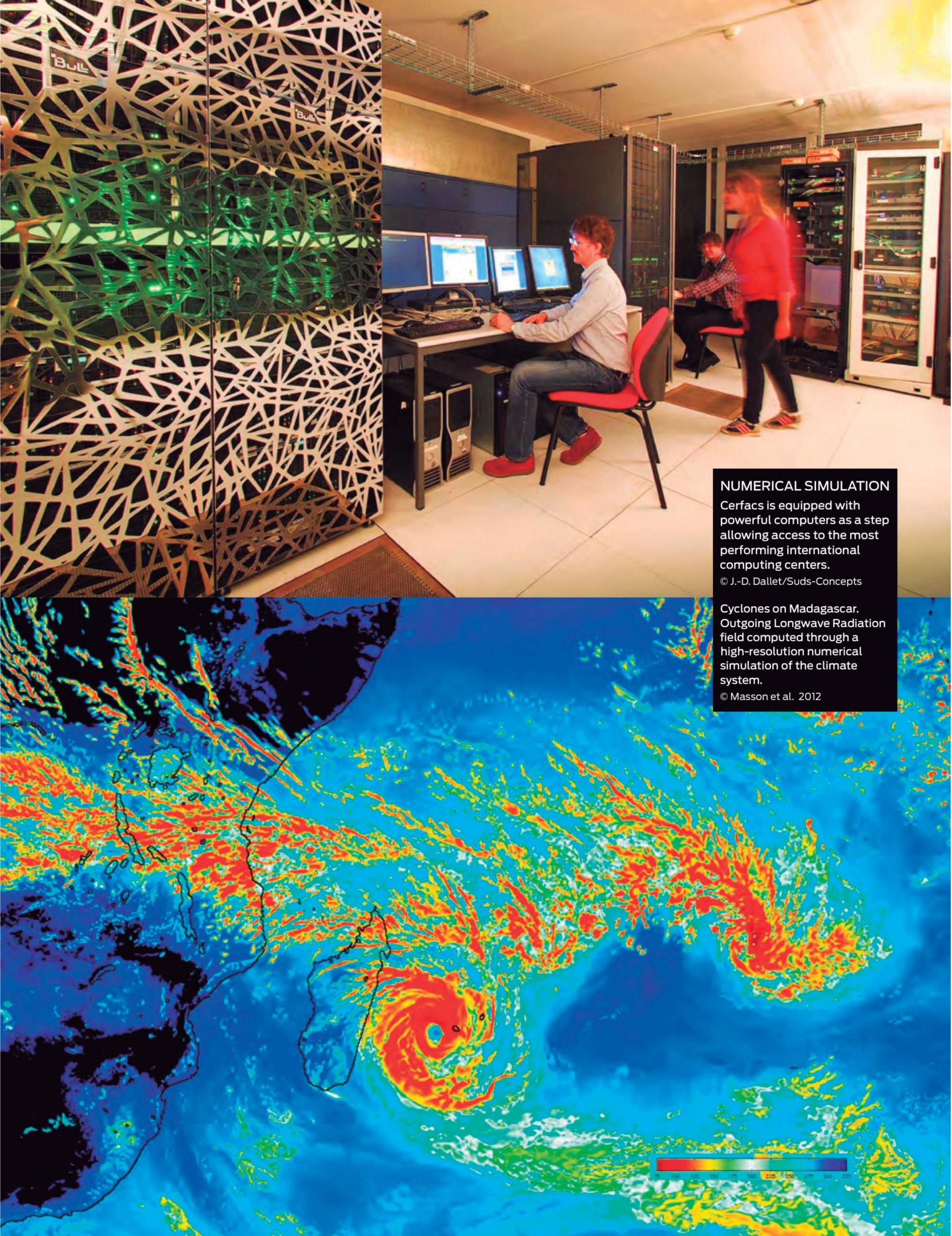
© J.-Dallet/Suds-Concepts

n synergy with the other Cerfacs activities, the "Climate Modelling and Global Change" team combines high performance computing skills and expertise in a specific application field. Back in the nineties, at the early stage of the coupling between atmosphere and ocean general circulation models, we specialized in developing coupling tools coping with the heterogeneity of the multiple climate components. The OASIS coupler is now used internationally by a large number of laboratories performing numerical climate simulations. This tool constantly evolves to leverage the progresses of computer technology. For instance, parallel coupling requires point-to-point data communications between the model processes, each of them being devoted to a restricted area of the ocean or the atmosphere. In collaboration with other groups, we have been pioneers in innovative experiments using stateof-the-art computers and modeling techniques. For instance, we have realized the first French climate change scenario, mandatorily based on ocean-atmosphere

coupled modeling, with

both technical and scientific perspectives. This breakthrough has opened the way to systematic climatic projections by Météo-France, our natural partner. Recently, we have assembled and run a high-resolution version of the coupled model (millions of grid points) on very powerful computers in the framework of European computing initiatives (FP7, PRACE). The scientific analysis of these numerical simulations has shown, among other interesting results, that the occurrence of extreme events, such as cyclones. was correctly represented only beyond a high enough spatial grid resolution. This refinement is now used in the high-resolution version of Météo-France climate model, CNRM-CM6, in the development of which we play an active role. Météo-France and Cerfacs have and will participate to the international IPCC program by sharing the task of performing millions of hours of climate simulations. In the framework of this collaboration, we specialize in the study of the climate decadal variability and the climate predictability at these scales.

The Globc team, Cerfacs





Climate missions to come

atellite observations of the Earth have led to major advances in understanding the climate system over the last thirty years and are today an indispensible means of motivating and informing climate policy. In the coming decades they will be a vital tool for guiding action on climate change mitigation and adaption worldwide. Long-term, global observations are essential for climate science and policy alike. Europe has made enormous progress in the last five years by securing operational continuity of crucial optical, microwave and infrared observations, with the Sentinel missions for Copernicus, and the next generation geostationary and polar orbiting platforms for meteorology. ESA's Earth Explorer research missions are pioneering further advances in scientific understanding of climate change by measuring, for the first time

from space, sea-ice thickness, ice sheet elevation changes, global soil moisture, and ocean surface salinity. Future satellites will measure cloud and aerosol optical properties, atmospheric wind profiles, above-ground biomass, and other key components of the global carbon and water cycles. These will complement research missions from other space agencies such as NASA, JAXA and CSA. Emerging space powers, notably China, India and Brazil, are also developing advanced technologies to monitor climate change.

ESA's 'Climate Change Initiative' is enabling hundreds of scientists around Europe to build up consistent global records of 'Essential Climate Variables', using data from all these satellites, to analyse natural climate variability and trends. In conjunction with this, the EU is implementing the Copernicus Climate Change Service, which

will ensure long-term operational availability of global climate-quality data-sets and provide information services into key sectors such as Agriculture and Forestry, Health, Energy, Transport and others.

This concerted effort by scientists and industry lays the basis for improving the climate models and prediction systems that governments and businesses will need to make informed policy, planning, and investment decisions in the future.

As the world's nations confront the consequences of already committed climate change, and strive to limit future emissions, strengthened international cooperation to secure an adequate and open global climate observing system will be an essential factor for the success of any global action finally taken on climate change.

Mark Doherty, ESA



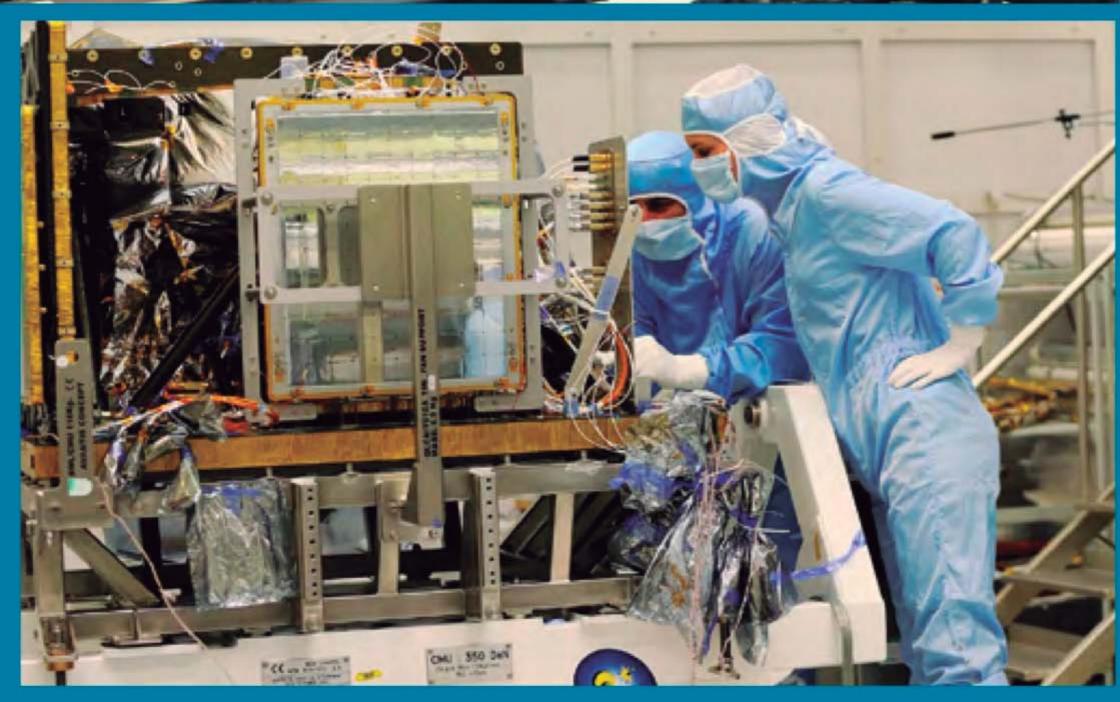
Located at Darmstadt (Germany), ESA-ESOC serves as the Operations Control Centre for ESA missions and hosts the Main Control Room (shown here), combined Dedicated Control Rooms for specific missions and the ESTRACK Control Centre - which manages ESA's worldwide ground tracking stations. © J. Mai/ESA

Space teams

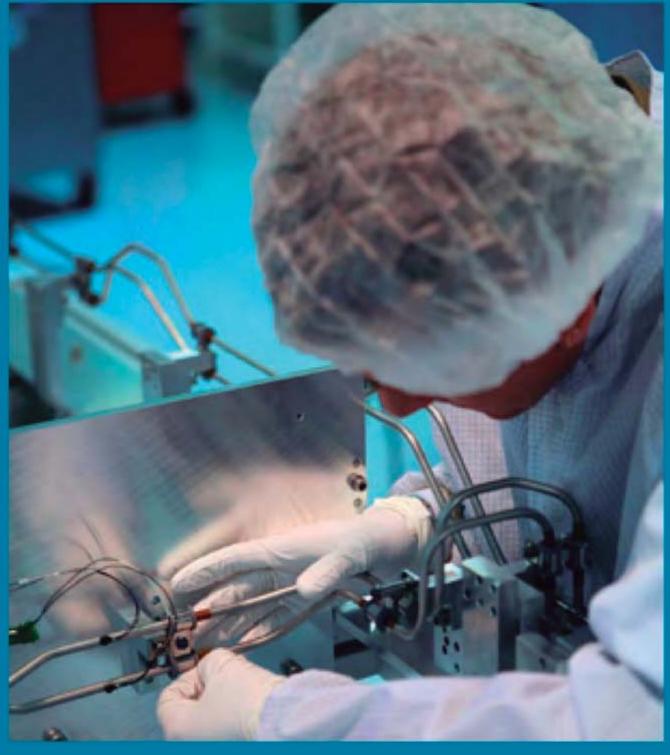
Just as the master builders of cathedrals relied on journeymen from a variety of trade guilds, the space prime contractor works with a team representing many different professions and its clients.

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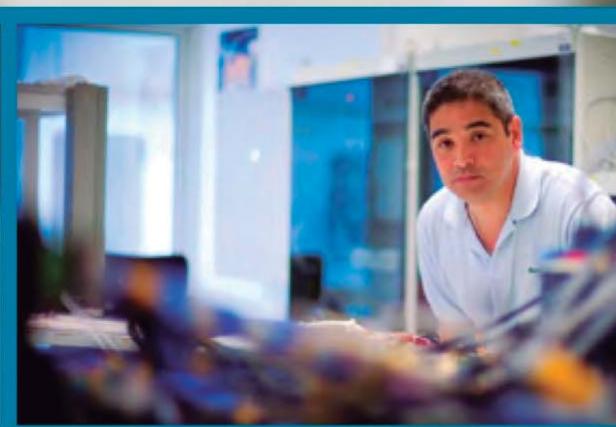


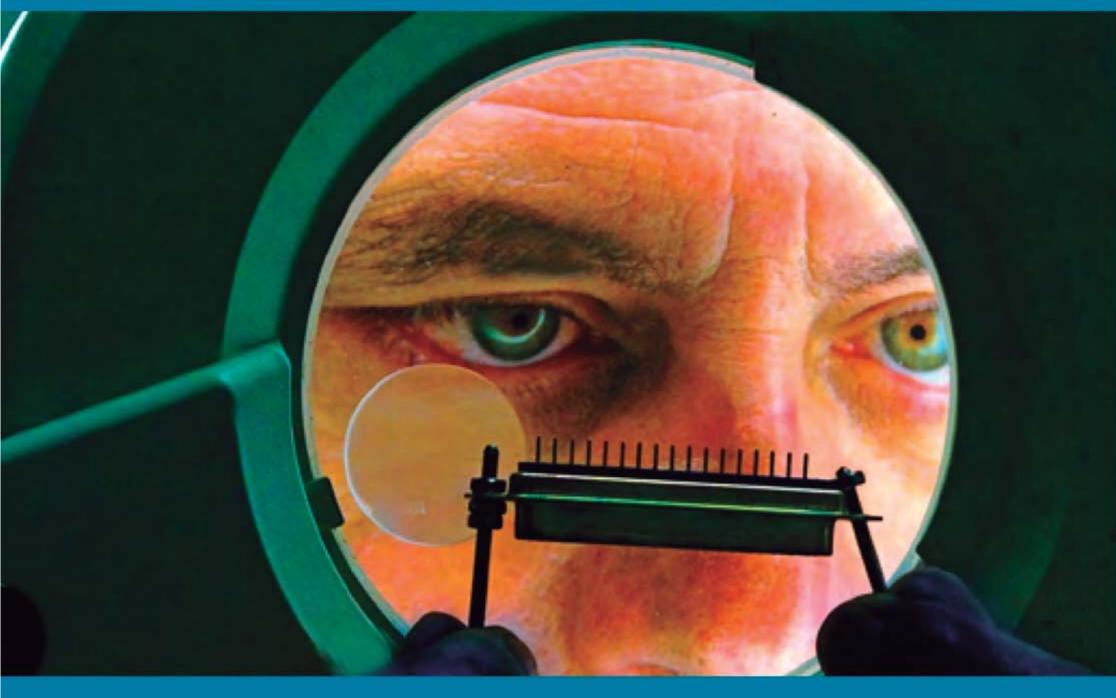




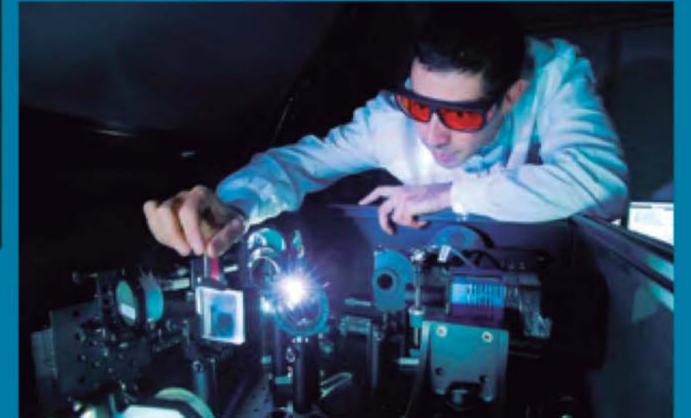


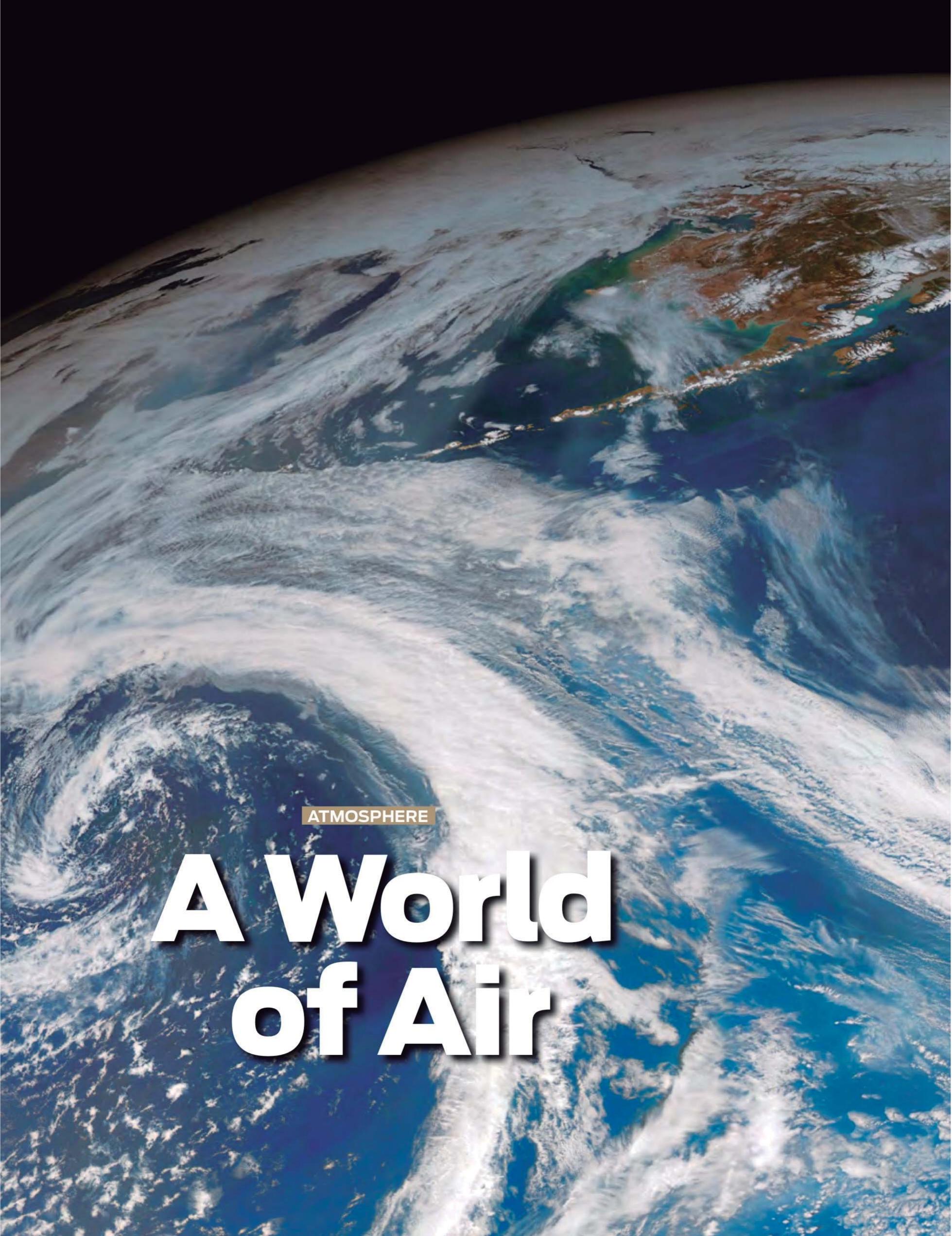


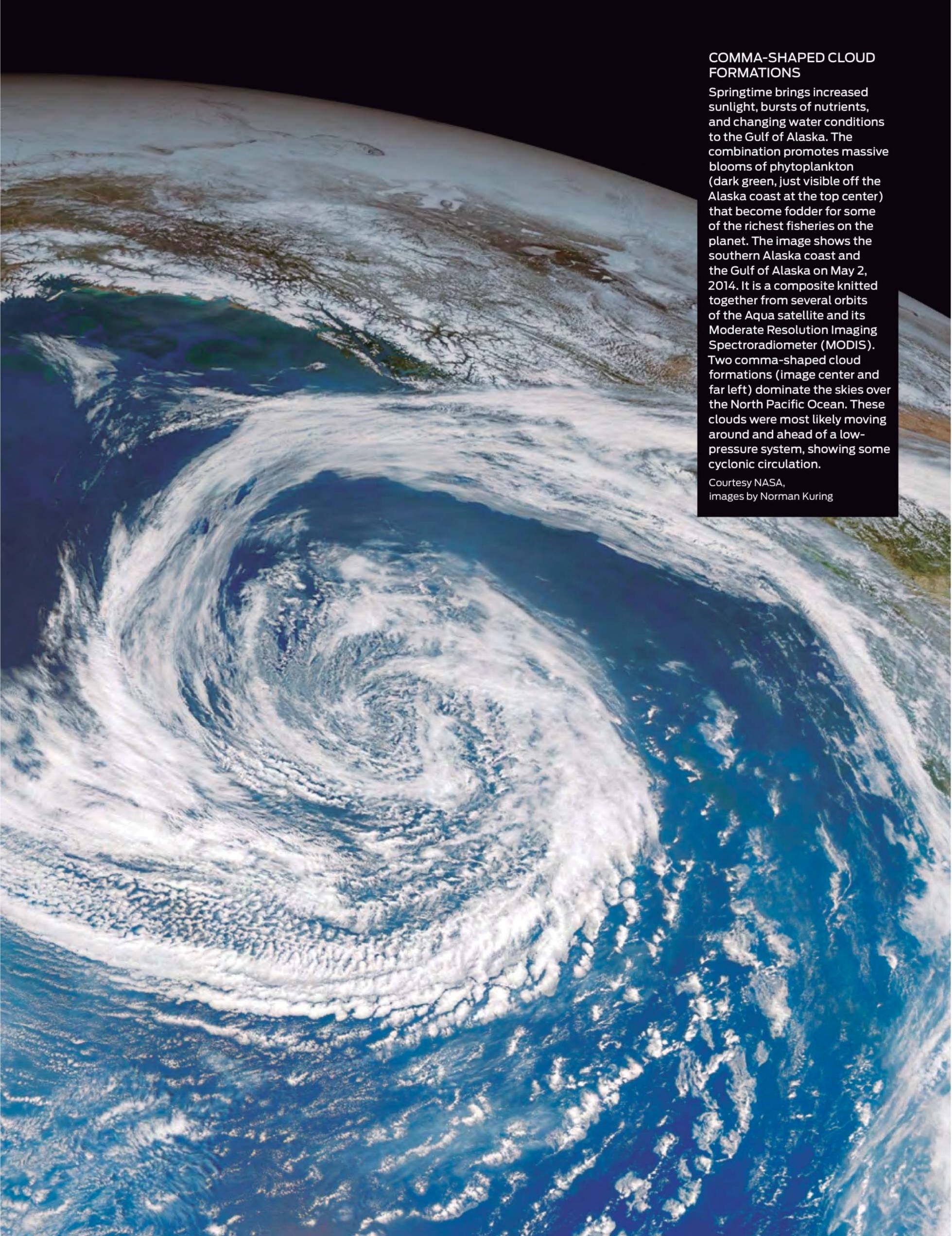












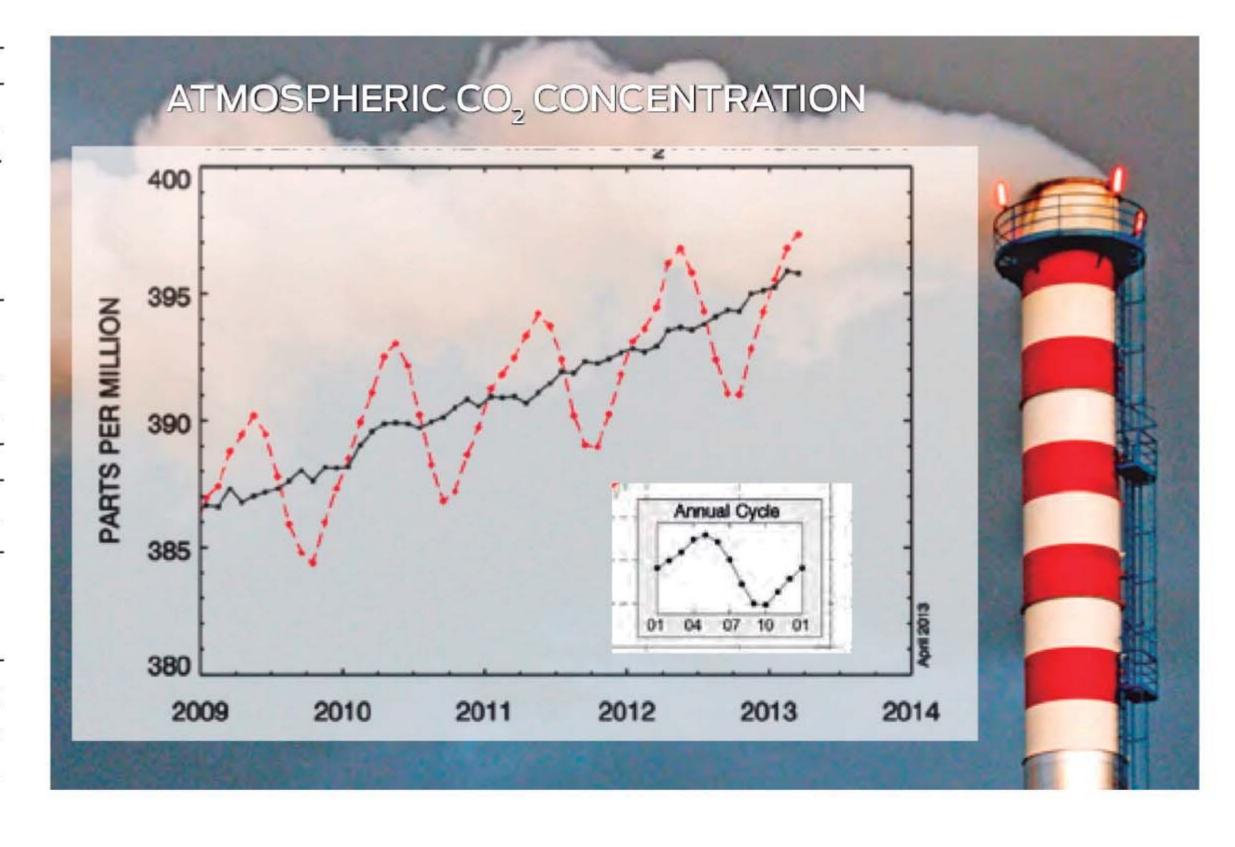
The core of climate change

HEN WE TALK about the atmosphere, the word meteorology immediately comes to mind. This is in fact a fundamental part of the Climate Engine. The atmosphere is a very thin envelope of gas around the Earth (equivalent to a few tenths of a millimetre if we downscale the planet to the size of an orange). This thin outer skin separates us from the vacuum of space. It acts as a screen between the Sun's rays, which are full of energy, and the Earth's surface. The way in which this screen works and its role in the radiative exchange with space affects the temperature of the Earth's surface. The composition of the atmosphere therefore defines the climate of our planet, and any alteration to this composition modifies the climate. Satellites are powerful tools that can be used to characterise what this thin layer contains, and that can help us to understand how the radiative energy is exchanged between the surface and space via the atmosphere.

Put simply, our atmosphere is made up of two layers: the troposphere, which goes from the surface up to an altitude of around 15 kilometres, and the stratosphere, which goes from 15 to 30 kilometres high. The main differences between these two layers concern temperature, chemical composition, wind patterns and clouds. In the troposphere, temperature decreases with altitude, whereas it increases in the stratosphere. Winds are very strong in the stratosphere and mainly horizontal (stratified atmosphere), whereas atmospheric circulation in the troposphere causes mixing (tropo means 'which changes' in Greek) between the top and bottom of the troposphere. Finally, there are no clouds in the stratosphere, whereas they are massively present in the lower part of the atmosphere.

A sphere difficult to observe

Each sphere of the Earth system has its own time scales. In the hydrosphere, change is measured in years or centuries, while in the cryosphere and the biosphere it is measured in seasons or years. For the atmosphere, change occurs from one hour, day or week to the next. It is the rapid component of the climate engine, and this is what makes it so difficult to observe.



A major advantage of satellites for the study of the atmosphere is the repeated nature of their measurements. More or less operational for nearly thirty years, the series of observations from space dedicated to meteorology thus provides a mine of information for the study of the operation of the climate engine and of ongoing climate change. This operational meteorological flotilla is made up of five geostationary and two Low Earth Orbit satellites operated by meteorological agencies (NOAA, EUMETSAT, JMA). The long term monitoring of the atmosphere is guaranteed thanks to strong programmatic commitments.

A clear, cloudless atmosphere is made up of air, which is itself made up of 78% nitrogen, 21% oxygen and 1% of argon and elements called 'trace gases'. Among the latter, there is, by order of importance, water vapour, carbon dioxide, methane, sulphur dioxide and ozone. These gases absorb the infrared radiation emitted by the Earth, preventing this energy from escaping directly from the Earth's surface to space, and warming up the atmosphere. Hence the name 'greenhouse gases'. Despite their extremely small concentrations, these gases determine a large part of the climate. Although some of

↑ Measured on Mauna Loa, the mean annual CO₂ concentration has been regularly increasing since 2009. The annual fluctuation (box) is linked to the vegetation growth cycle in the Northern hemisphere.

© Courtesy GFDL & CC-NC-SA, data NOAA.

Background: Chimneys of an oil factory at Villarta de San Juan, Castilla La Mancha, Spain.

© J.D. Dallet/Suds-Concepts



them take part in complex chemical reactions while others remain more passive, they are all transported by winds and clouds, thus establishing a very close coupling between atmospheric composition and wind patterns. Ozone is found especially in the stratosphere. The destruction by CFCs of this gas, which absorbs incident solar radiation in the ultraviolet, caused the well-known ozone hole. Political action at the end of the 1970s succeeded in halting this process, and the hole is slowly and naturally closing up again. In the troposphere, aerosols can also be found. These can be of natural or anthropogenic origin. These solid particles, about a micron across, are suspended in the air, and can be mineral (dust from deserts that forms plumes) or organic (such as soot caused by the burning of wood, petroleum or coal). These particles block solar radiation, and by a parasol effect, cool down the surface. Aerosols in suspension in the atmosphere are found mainly in the Northern hemisphere due to industrial actitvity. The accumulated effect is visible on a global scale, and it is even thought that it may mask part of the expected climate warming caused by the increase of greenhouse gases in the atmosphere.

Like dust, the other components of the atmosphere, such as water vapour, are also carried by the wind.

Climate trends

Being able to observe continuously and accurately water vapour in the atmosphere is of major importance since it is one of the main greenhouse gases and any alterations to its distribution have a powerful impact on the climate, especially in the free troposphere at around 5-10 km altitude. Teams of researchers and data processing centres, are now computing climatic trends, on the basis of the last 30 years of observations carried out by European and American meteorological satellites. At lower altitudes, near the surface in ocean regions, measuring atmospheric humidity is easier. In addition, passive microwave sensors such as the SSM/I on board of US Defence satellites enable us to go back about twenty years. This long, validated series of measurements confirms the foundations of the theory of climate change. In particular it allows confirming, in the details, the expectations from the Clausius-Clapeyron Law to the global warming.

Halny (foehn) in the Tatra mountain range forming a natural border between Slovakia and Poland. It occurs when the moving air mass encounters a mountain range. Warm moist air rises through the windward slopes, slowly losing its temperature and droping most of its moisture as rain. The air crosses the top of the mountain, falls down the leeward slopes reaching very high speeds and warming up very quickly. The strongest foehn (286 km/h) was noted in November 1965 on the Lomnicka Valley on the Slovak side of the Tatra Mountains.

Courtesy European Environment Agency



The atmosphere is not restricted to these layers of air, whether they are dirty or clean, humid or dry. It is also a highly active part of the water cycle, which links the hydrosphere, the source of water, with the biosphere and the cryosphere. It is the realm of clouds, storms, fronts and squalls, pounding the surface of the planet with water, snow and hail, irrigating crops and feeding rivers, but also sometimes causing damage. What happens to a water molecule as it travels round the water cycle? It is pulled out of the ocean and then transported by the wind in the form of vapour. It then rises through the atmosphere in a cloud. As it rises it cools, which changes the water vapour into liquid or solid water.

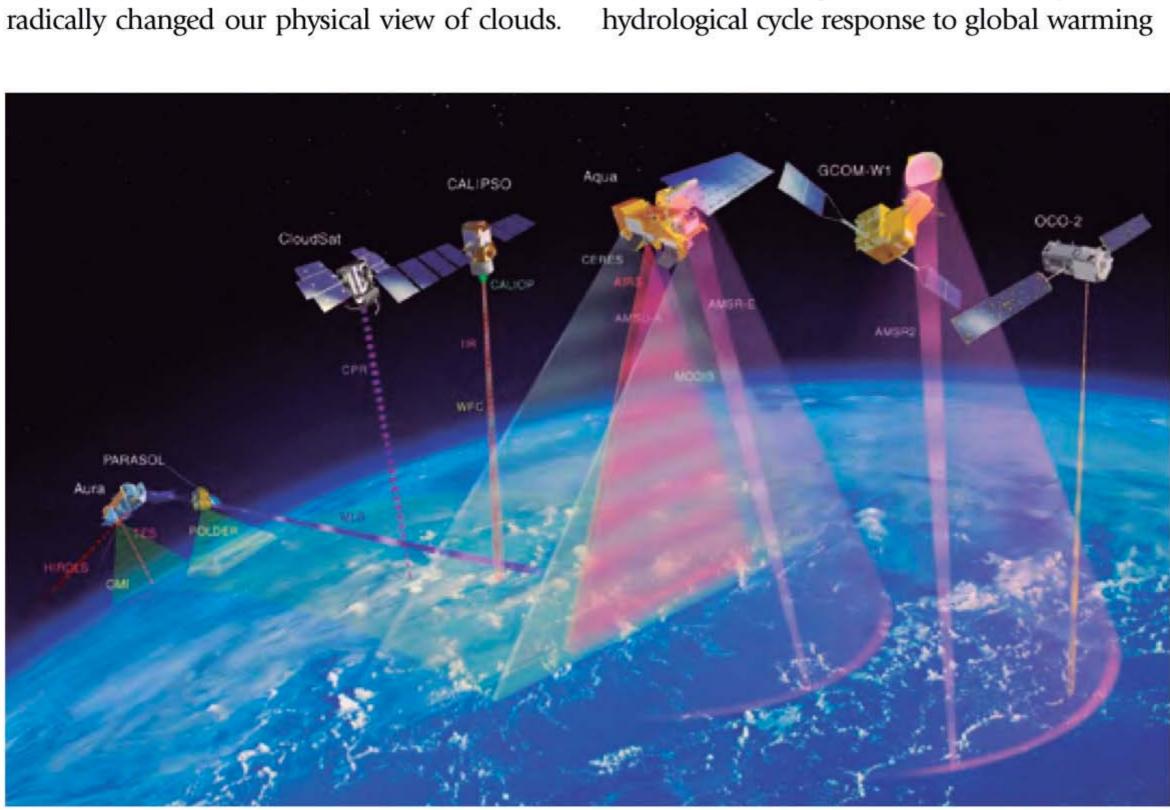
The tiny droplets and crystals which make up clouds give rise to precipitation - rain, hail and snow - thus bringing the wheel full circle. Here again, satellites have proved to be very useful for observing this part of the water cycle in the atmosphere, and especially for estimating the evaporation at the ocean surface. This is done indirectly from measurements of humidity, surface temperatures and winds, in particular by combining several passive microwave channels and measurements by infrared radiometers on meteorological satellites such as the AVHRR on board NOAA satellites, and SSM/I sensors on US defence satellites. The maps of evaporation obtained in this way reveals the role of the trade wind regions, located in the vicinity of the Tropics of Cancer and Capricorn, as a source of humidity for the atmosphere. This water vapour builds up in the equatorial regions where rain clouds are very common.

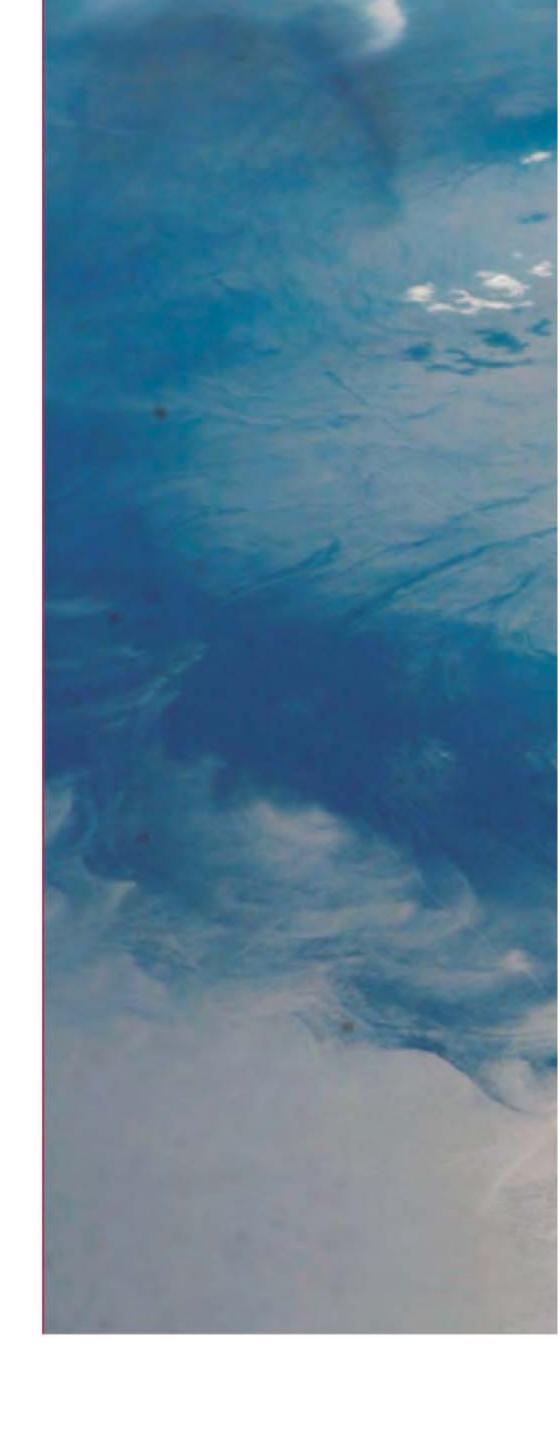
The arrival of Earth observation satellites has

Satellites have revealed structures and other masses of nebulosity that were hitherto unknown. The first efforts to build a climate record of clouds date back to the early 80's and are still up and continued. This consisted in archiving data from meteorological satellites, standardising them, and processing them in order to construct a homogeneous climatology of clouds. Terms such as cirrus floccus, cumulus humilis, congestus and cumulonimbus were no longer used: clouds were classified as being high, low or medium level, thin or thick. Instead of talking about octas (the standard units for measurements of cloud cover by human observers) the term 'percentage cloud cover' was used.

Rainfall patterns

This dataset obtained from the operational satellites fleet is complimented by a suite of research satellites, known as the A-Train, including Cloudsat and CALIPSO now operating for almost a decade! Every last detail of clouds is observed - altitude, temperature, phase (water or ice), droplets and crystals size distributions - mainly using active instrumentations (lidars and radars). Clouds also bring rainfall to the Earth surface. Precipitation in every form: snow, hail and rain, which is one of the characteristics of clouds that is hardest to quantify from space. Analysis of the rainfall climatology obtained by combining the operational fleet with the microwave imagers from the Global Precipitation Climatology Project of the GEWEX international research program, underlines the importance of tropical regions for the water budget. While the theory of the





The international A-train constellation consists of five NASA missions, OCO-2, GCOM-W1, CALIPSO, CloudSat, Aura and Aqua. PARASOL (CNES microsatellite) ceased operations in December 2013. Active instruments aboard CALIPSO/CALIOP and CloudSat/CPR are indicated with dashed lines. Color-codes instrument swaths are based on observed wavelength ranges. Microwaves (observed by both AMSRs, AMSU-A, CPR, MLS) are represented by redpurple to deep purple colors; solar wavelengths (POLDER, OMI, OCO-2), yellow; solar and infrared wavelengths (MODIS, CERES), gray; other infrared wavelengths (IIR, AIRS, TES, HIRDLS) red. © NASA



calls for an increase of rainfall as the Earth warms up, these data, available since 1979, have not for the moment shown any alteration to rainfall patterns. The starting of the new era of precipitation observations (See p. 46) will provide the needed tool to further survey global rainfall.

Exchanges with space

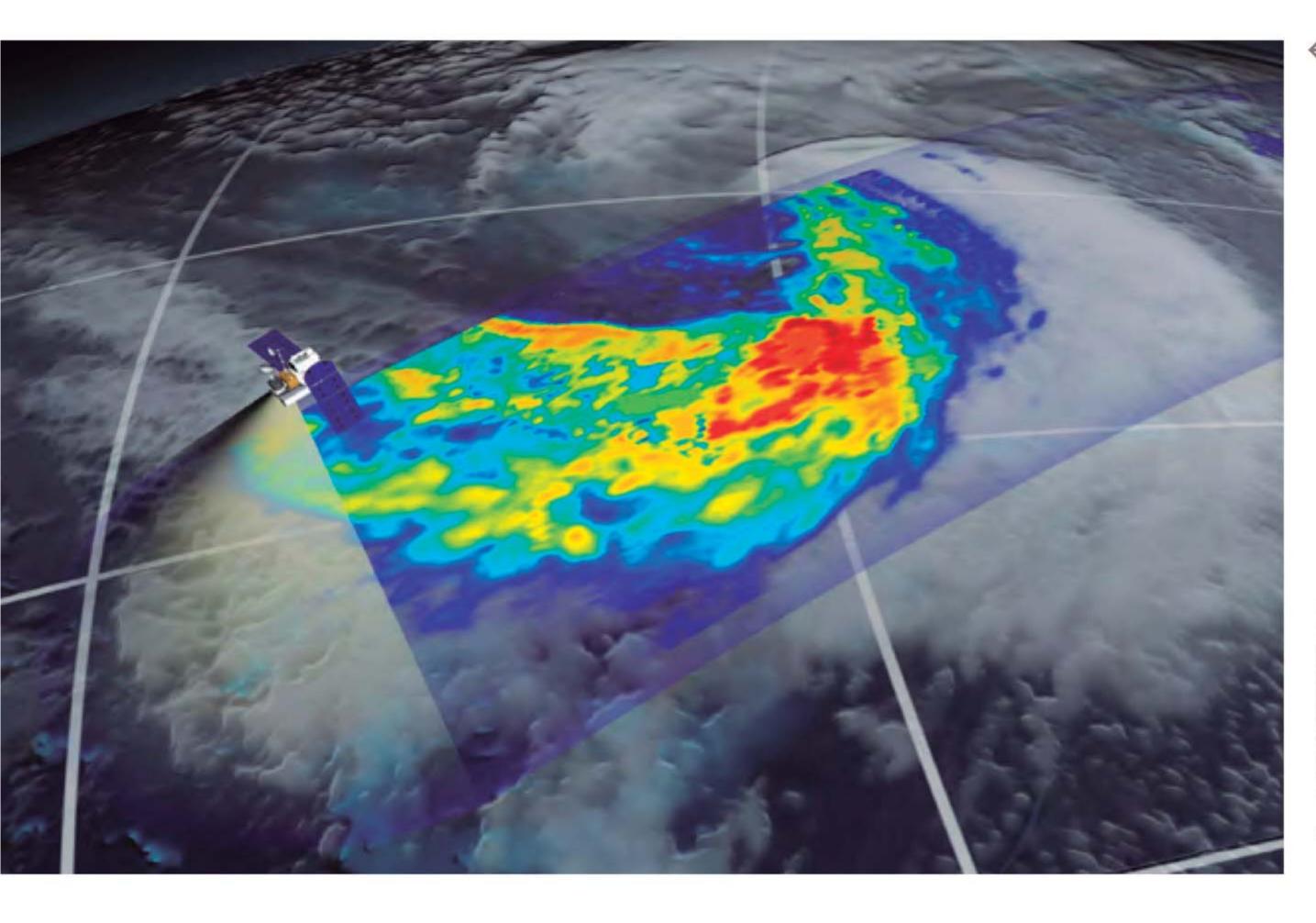
Now that we have looked at the whole atmosphere, both clear and cloudy, let's go right up to the top of it and consider energy exchanges with space. Notions like reflected or emitted energy, or the greenhouse effect, are a little abstract, and not as evocative as clouds, rain or dust. Nonetheless, there exists a direct link between the components of the atmosphere, their chemical composition, and the energy balance of our system. Yet again, this is revealed by satellites.

The atmosphere and its components control the way in which the energy exchanges that drive the climate engine occur. Satellites provide us with an original viewpoint, and are very useful for understanding how this energy is redistributed in the climate engine, thanks to the combination of all the various missions and instruments. And lastly, analysis of these long series of data enables us to estimate the change in the climate's operating mechanisms over time. And the climate is changing. The chemical composition of the atmosphere is evolving. A strong reminder is the well-known curve showing the carbon dioxide concentration in the atmosphere at the Mauna Loa observatory in Hawaii increasing every year. The first satellite estimations of greenhouse gas concentrations in the atmosphere are now becoming available. This is also the case for long series of precipitation, humidity, cloud properties, etc. This progress has been made thanks to enthusiastic researchers who share the same goal: to use meteorological data from the past to study the climate, pushing back the methodological and algorithmic limits. This requires long-term high-level research in the science of measurements. It also requires the development, in collaboration with cuttingedge industry, of new space systems henceforth dedicated to monitoring and understanding the climate. The constellations and longstanding families of meteorological satellites are already showing us the way forward.

Rémy Roca, LEGOS/CNRS

↑ ESA astronaut Luca
Parmitano captured summer
storms and sea currents in
Calabria, Italy, in August 2013,
from the International Space
Station.

© ESA/NASA



This visualization shows data from the GPM Microwave Imager. Rain rates across a 550-mile (885 kilometer) wide swath of an extratropical cyclone observed off the coast of Japan on March 10, 2014. Red areas indicate heavy rainfall, while yellow and blue indicate less intense rainfall. The upper right blue areas indicate falling snow.

© NASA's Scientific Visualization Studio. Data provided by the joint NASA/JAXA GPM mission.



This stamp celebrates 50 years of Indo-French space cooperation. Here, Megha-Tropiques.

GPM Constellation

✔ Illustration of the multiple precipitation measurement satellites which comprise the GPM constellation.

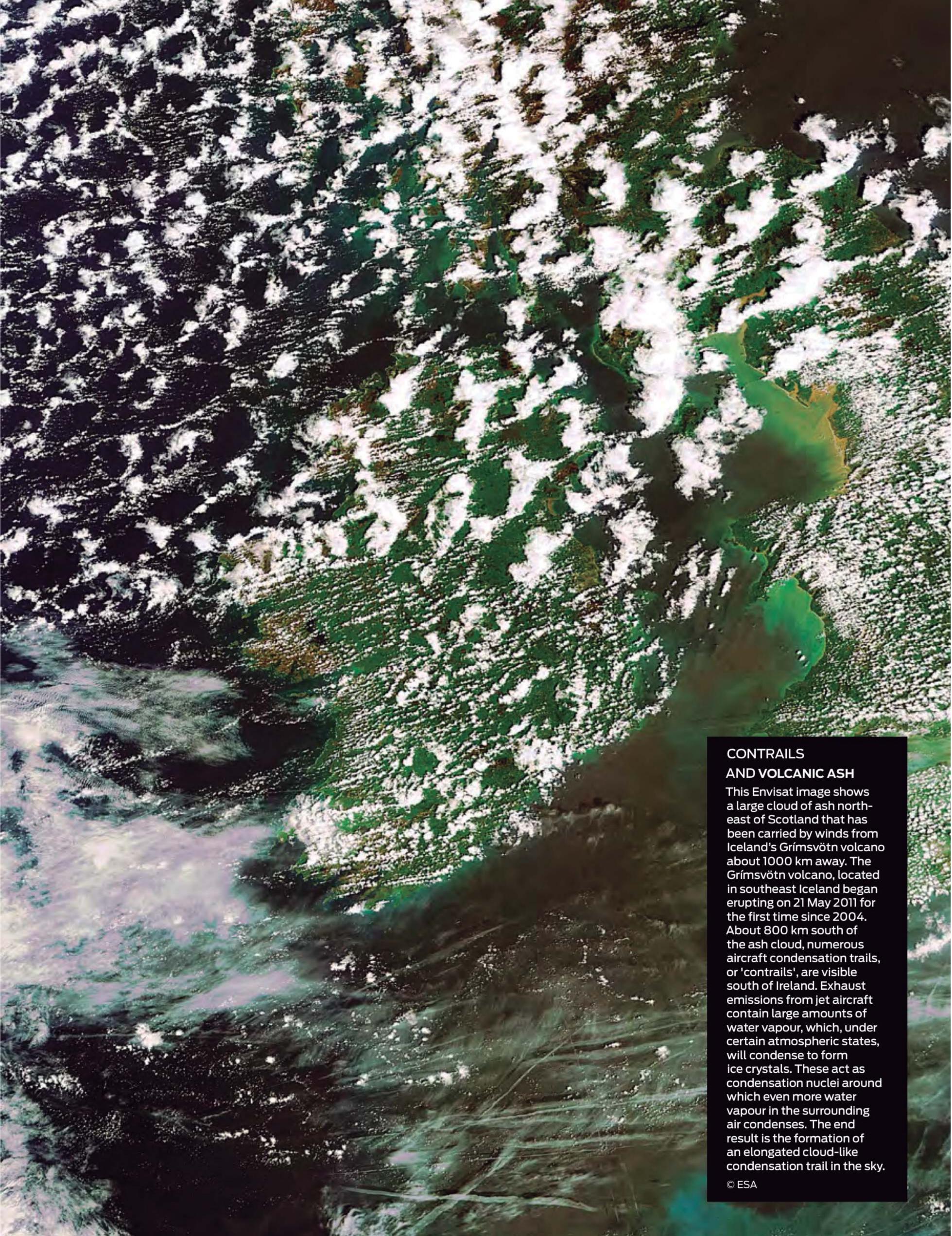
© NASA

Measurement mission (GPM) is an internal project to measure rainfall everywhere on the planet every three hours. It consists in a constellation of satellites carrying on board microwave imagers and sounders dedicated to the

Suomi NPP MetOp B/C (NASA/NOAA) **GPM Core Observatory** (EUMETSAT) (NASA/JAXA) TRMM (NASA/JAXA) Megha-Tropiques (CNES/ISRO) (NOAA NOAA 18/19 (NOAA) GCOM-W1 DMSP F17/F18 (JAXA) F19/F20 (DOD)

measurement of the hydrometeors in the atmosphere (see illustration). NASA and JAXA recently completed the constellation with the GPM Core satellite which provides an enhanced set of instruments to help calibrate and interprete the data from the constellation. The Core mission flyes a multi-frequency passive microwave radiometer and a dual frequency precipitation radar dedicated to snow and rainfall accurate estimations. Building on the success of the Tropical Rainfall Measuring Mission (TRMM), the GPM era opens up on a new philosophy of climate monitoring where new satellite missions are now coordinated towards a common ambitious objective that could not be achieved by a single mission. After more than 18 years of service, TRMM stopped data acquisition in April 2015 and the Megha-Tropiques sounder is the only remaining tropical orbiter in the constellation. The scientific community is now actively trying to showcase the importance of sustaining such an effort in the long term to benefit the climate monitoring from the enhanced ability to quantify rainfall at the surface of the Earth.

Rémy Roca, LEGOS/CNRS









Climate reanalysis

↑ Mont Blanc captured by Pléiades 1A satellite. The front of the Mer de Glace has retreated upwards by more than 2.5 km since 1830. It is expected to recede further by 550 m to 1.000 m by 2030. However, it is difficult to anticipate precisely these developments as they depend not only on future temperatures but also on future precipitation, the latter being very complex to predict.

© CNES/Distribution Airbus DS, 2012

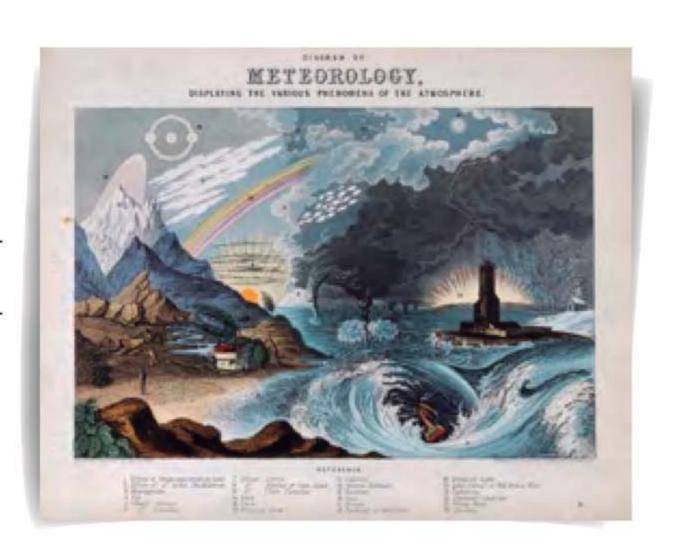
Diagram of Meteorology displaying the various phenomena of the atmosphere. Published by J. Reynolds, 1848.

© Wellcome Images

we, the people working for it, have made substantial progress over the last decade addressing the needs of climate monitoring using satellite data. Following our approach of combining scientific understanding of the existing long satellite data records with the capability to operationally process the data, the group at the EUMETSAT Secretariat and the network of Satellite Application Facilities was able to deliver high quality climate data records to the scientific community and to emerging climate services.

Forgotten archives

We have fully realised that the basic technology for monitoring weather from space was established 50 years ago, and was very successful in measuring what it set out to measure. But the fact that almost nobody was thinking about using the data for climate monitoring had consequences on the availability of original data, information about the data and how pre-launch calibrations were



done. Many satellite data were not archived and got more or less forgotten over time. Also the level of documentation of the pre-launch calibration and performance during the life time of the instruments in the early days was not where it is today. Luckily many existing documents were preserved on paper, which has a much longer lifetime than not maintained electronic copies, allowing rebuilding meta data into the existing data records.



Since a couple of years we have started to systematically support weather prediction model-based reanalysis and the generation of geophysical climate data records, e.g. state variables related to the energy and water cycle, with targeted re-calibration and reprocessing of EUMETSAT instrument data records. For instance, the European Union ERA-CLIM projects facilitate data rescue and improved reanalysis under one roof. EUMETSAT provides a large range of different reprocessed data records from classical Meteosat radiances to radio occultation bending angles as well as ocean backscatter from the ASCAT instrument on the Metop satellites.

Increasing understanding

The successful use of the data records in global reanalysis highly amplifies the value of the instrument data. There is only a handful of Centres in the world that are capable of doing a global reanalysis, but a reanalysis as produced by ECMWF has more than 10.000 users.

The usage of the improved fundamental data records for deriving geophysical products helps to increase scientific understanding of the global and regional energy and water cycle, feedback mechanisms in the climate system. In addition to our own scientific and technical work the international coordination of assessing needs for climate data records from satellite for decision and policy making and the ability to collaborate on the generation of climate data records is substantially higher compared to ten years ago. The recently published architecture for climate monitoring from space has provided a framework that is compliant with the GCOS requirements for Essential Climate Variables in which space agencies can address the needs of the society for climate information. Also international collaboration between EUMETSAT, NOAA, and the Chinese and Japanese meteorological administrations and other partners in a network for sharing tasks of producing climate data records from many satellite instruments has further positively evolved over the last few years. However, the challenge remains to further sustain these collaborative activities into the future by ensuring that we deliver what is needed for climate science and climate services and by keeping scientific innovation for climate data record generation and uncertainty characterisation at a high level.

Jörg Schulz, EUMETSAT

According to the Department of Geography of the University of Zurich there exists for the Mer de Glace a glacier length curve for the period from 1590 to 1911 made by Mougin (1912). Further investigations of glacier fluctuations during the late Holocene were made by Wetter (1987). The comparison of an old picture with today's situation in the field and the mapping of moraines is helpful for the determination of former glacier extents. Here Crossing the Sea of Ice (around 1902). © Zentralbibliothek Zurich

SPACE TOOLS

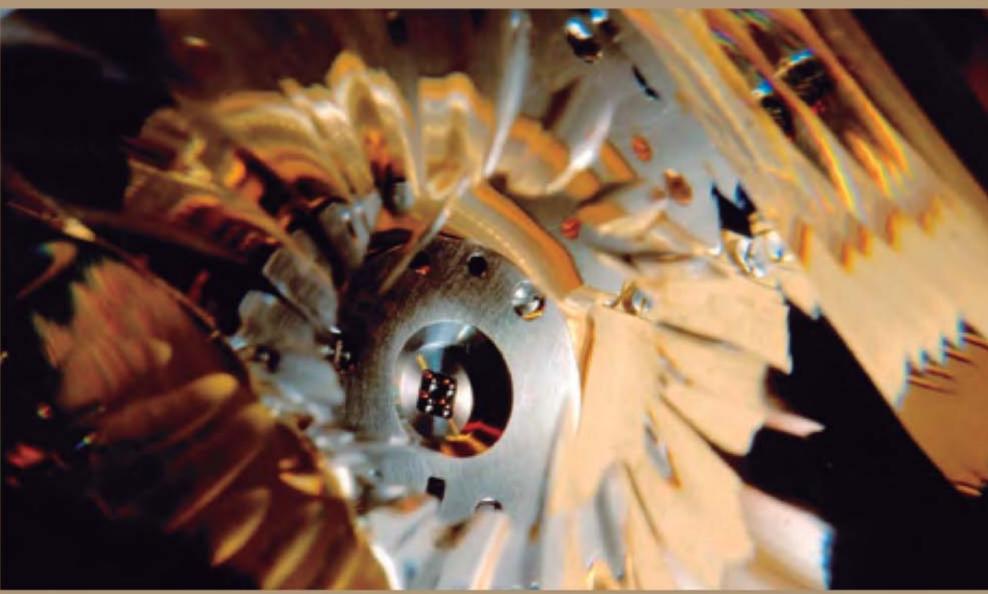
IASI contribution

The Infrared Atmospheric Sounding Interferometer (IASI) on board the Metop satellite has become a real asset for climate science. The availability of the IASI instruments since 2006 has enabled the analysis of infrared instrument data records from all geostationary satellites around the Earth and also other instruments in polar orbit such as the High resolution Infrared Radiation Sounder (HIRS). This all becomes possible due to the excellent work done prior to the launch of the instrument resulting for instance in a high temporal stability of measurement quality that is exactly what is needed to improve other sensors data records.

EUMETSAT is using IASI to recalibrate historic Meteosat data by a successive chain of calibrations that reference each radiometer to the IASI instrument in the end. A big remaining challenge in this exercise is to address the uncertainty of the Meteosat instruments calibration which is of course enhanced the further back in time we go with the inter-satellite calibration. IASI instrument data play an essential role in the new European Union FIDUCEO project where IASI will function as a reference for the systematic assessment of assumptions in calibration algorithms for historic instruments such as HIRS.

IASI data are not only used to calibrate other instruments. Scientists have successfully derived a multitude of products including atmospheric temperature and moisture, cloud properties and atmospheric composition that are used to better understand atmospheric processes and also contribute to long term climate monitoring.

Jörg Schulz, EUMETSAT



Maintained in space at -173 ° C, 4 small lenses visible at the centre are designed to focus the light collected by the IASI instrument to its detectors.

instrument at Thales Alenia Space.

Testing the IASI

© J.-D. Dallet/Suds-Concepts

© D. Sarraute/CNES





SCIENCE

↓ System Validation Bench engineer Nguyen Phyong Neim at the Vietnam National Satellite Center (VNSC).

© J.-Dallet/Suds-Concept

Villagers of Ha Long Bay (World
 Heritage Site, Vietnam) fear
 cyclones. They live in small wooden
 boats that act as transportation, a
 means to earn a living, and as living
 quarters. Floating villages are often
 submerged by whirlwinds, tidal
 surges and cyclones destroying
 infrastructures used for farming fish,
 oysters and clams. A climate change
 adaptation project funded by the
 Vietnamese government and the
 International Fund for Agricultural
 Development (IFAD) was launched
 in July 2014.

© J.-Dallet/Suds-Concepts

Tropical precipitation

echanisms of climate change occur in tropical regions, which are also the place where its effects are potentially the most serious. There, the water cycle, rather than temperature, is the most sensible element. Surface observations are too sparse to monitor accurately the relevant parameters.

Tropical deep convection presents high space-time variability at a large range of scales. This can be observed from geostationary satellites, but most of the key parameters can only be retrieved from low orbiting satellites carrying passive or active instruments among which microwave imagers and radars. Unfortunately, low orbit satellites are generally near polar orbiters, resulting in deficient time coverage of the tropical regions. This is particularly detrimental for precipitation retrieval.

Satellite constellations for operational monitoring

Radars as in TRMM (Tropical Rainfall Measuring Mission) have outstandingly contributed to the tropical precipitation knowledge, but their narrow coverage results in a poor sampling. Improving this requires constellations of satellites (as GPM, the Global Precipitation Mission), including platforms with near equatorial orbits (as Megha-Tropiques). Combination of these systems with operational meteorological satellites is now used successfully. These multiple satellite systems are used for operational monitoring, and, in conjunction with models at different scales (clouds, meteorology, climate) for understanding the mechanisms determining the climate variations in tropical regions. Key problems addressed include for example: "what control the position, strength and variability of the tropical rain belts" or "what role does convective aggregation play in climate". These constitute fundamental research objectives, which require both continuous observation from satellite systems, and development of improved satellite instrumentation, with emphasis on investigation of deep convection in the Tropics, over land as over oceans.





Carbon measurements

in CO₂ emissions from fossil fuels with future scenarios drawn up by the IPCC, we can clearly see that we are following the most intensive scenarios, which are not compatible with a target of keeping warming to under 2°C, or even 3°C. A rise of 2°C can be linearly correlated with cumulated CO₂ emissions since the pre-industrial period, and this total is about 3.2 trillion metric tons of CO₂, with more than two-thirds to be emitted in 2020 if emissions continue to grow at the current rate.

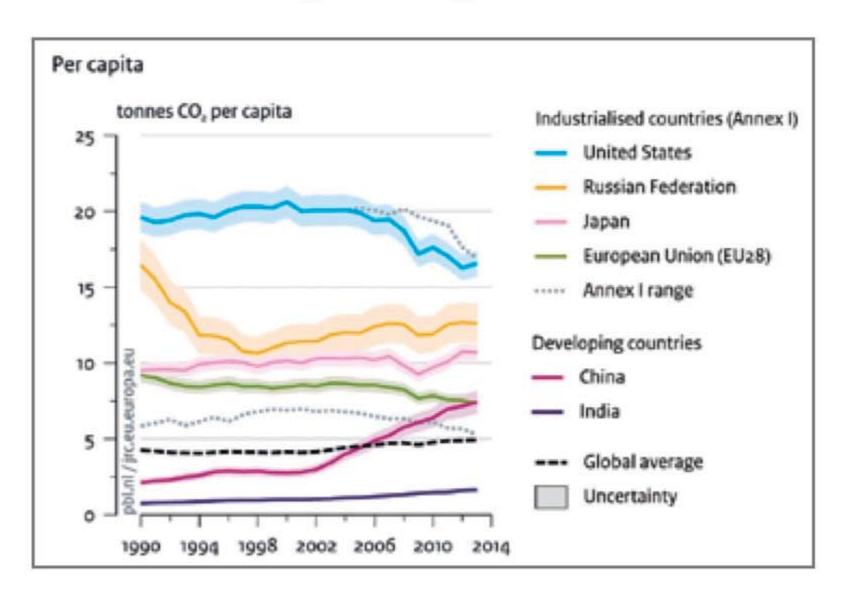
The CO₂ concentrations seen in the atmosphere reflect emissions and re-absorption by the oceans and vegetation, which are carbon sinks. The Mace Head measurement station, representing average concentrations in the mid-latitudes of the northern hemisphere, registered for the first time a value of over 400 ppm for over a month in 2013, for an increase of 227 ppm in relation to 1750, reaching an average of 395 ppm in 2013.

Natural CO₂ fluxes exchanged with vegetation and oceans vary according to climate conditions and atmospheric CO₂ among other drivers. The fluxes exchanged by vegetation and soils are the most uncertain, and known to be

sensitive to changes in ecosystem management, disturbances such as forest fires, and to the deposition of reactive nitrogen, a nutrient that can enhance growth. At a planetary level, the ocean absorbs about one-fourth of CO_2 emissions and the vegetation one-fourth as well, but there are major differences between regions. To effectively understand where and how carbon is stored via natural flows and discover the regional details of the carbon cycle, we need accurate observations, with global coverage. Most of our knowledge on the regional dis-

- Due to its pig iron making and steel rolling plants, iron ore mining operations, coking, chemical and power generation plants, Benxi (People's Republic of China), faces various pollution problems.

 © A. Habich
- ◆ CO₂ emissions from fossil-fuel and cement production in the top 5 emitting countries and the EU. Source: EDGAR 4.2 FT 2010 (JRC/PBL 2012); UNDP 2013 (WPP, Rev. 2013); World Bank 2014; IMF 2014





Large smoke plumes originating from burning peat fields and forest fires are visible in this Envisat image, acquired in 2010, covering the east of Moscow. Combined with the air pollution in the city, they can cause pollution levels ten times the normal levels for the capital.

© ESA

tribution of CO, exchanges comes today from ground-based networks, but there is unfortunately very few stations in vulnerable regions of the carbon cycle, such as tropical or arctic regions, that may lose CO2 in the future. The idea of spaceborne measurements of CO₂ (and CH₄, another powerful greenhouse gas emitted by anthropic activities) emerged in the early 2000s. The principle is to use very precise spectrometers to measure their concentrations from the surface to the top of the atmosphere. This type of measurement is difficult, and requires very high precision, because there are very small differences in concentrations between regions and these small differences are what scientists use to understand fluxes. They use 3-D atmospheric transport models to unravel the distribution of surface fluxes, based on differences in satellite concentration measurements between regions.

Satellite constellations

The first instrument dedicated to measuring greenhouse gases, SCIAMACHY, established a map of atmospheric CH₄, but for CO₂, the accuracy of the instrument was insufficient to deduce the fluxes exchanged in each region in the world. Since 2009, the Japanese satellite GOSAT has delivered new CO₂ and CH₄ measurements, enabling scientists to improve

their models to deduce CO_2 and CH_4 fluxes; however, the small sample size provided by GOSAT did not enable to reduce the uncertainty on the CO_2 budget of regions often subject to cloud cover, such as the Amazon. New satellites, such as CNES's OSCAR project, should provide additional data and information that will reduce the uncertainties about natural CO_2 and CH_4 fluxes.

Thanks to its high precision and spatial resolution, NASA's OCO-2 satellite, launched in 2014, should deliver the first global picture of natural CO, fluxes seen from space. By contrast with natural fluxes, human caused CO, emissions are more difficult to observe because they are only very intense in localized areas of the World (cities, industrial zones). Major progress are expected in the near future from satellite constellations, providing dense sampling in emitting regions, in order to clearly separate using space-borne data, the human caused emissions and the natural fluxes of the oceans and land ecosystems. One example is the CarbonSat imager, studied by ESA. The challenge of measuring emissions is to help countries that are fighting climate change better understand how to effectively reduce and manage them.

Philippe Ciais, Laboratoire des Sciences du Climat et l'Environnement

CONCERN



Opening the Heavens

A lthough the King of Oussouye, who is always dressed in red, has no political power, this traditional sovereign of the Diola ethnic group in Lower Casamance, a southern province of Senegal, is universally respected: Sibiloumbaye Diedhiou feeds his poorest subjects and he knows how to make the heavens open.

Of course, these twin roles are connected, since the king is able to provide the most needy of his subjects with their daily rice, thanks to the harvest from the royal rice fields which have been generously drenched by the summer monsoon. However, this ideal scenario is borne out increasingly rarely. Over the last thirty years, there have been very few years when the left bank of the Casamance River has seen 1.5 m of rainfall. At Sindone, a few kilometers from Ossouye, inland, rainfall is erratic too. Every time June comes round, it's there that a worried Taïrou Sané scans the sky for signs of rain. Each new season, he lengthens his well's rope: his bucket must go down deeper and deeper.

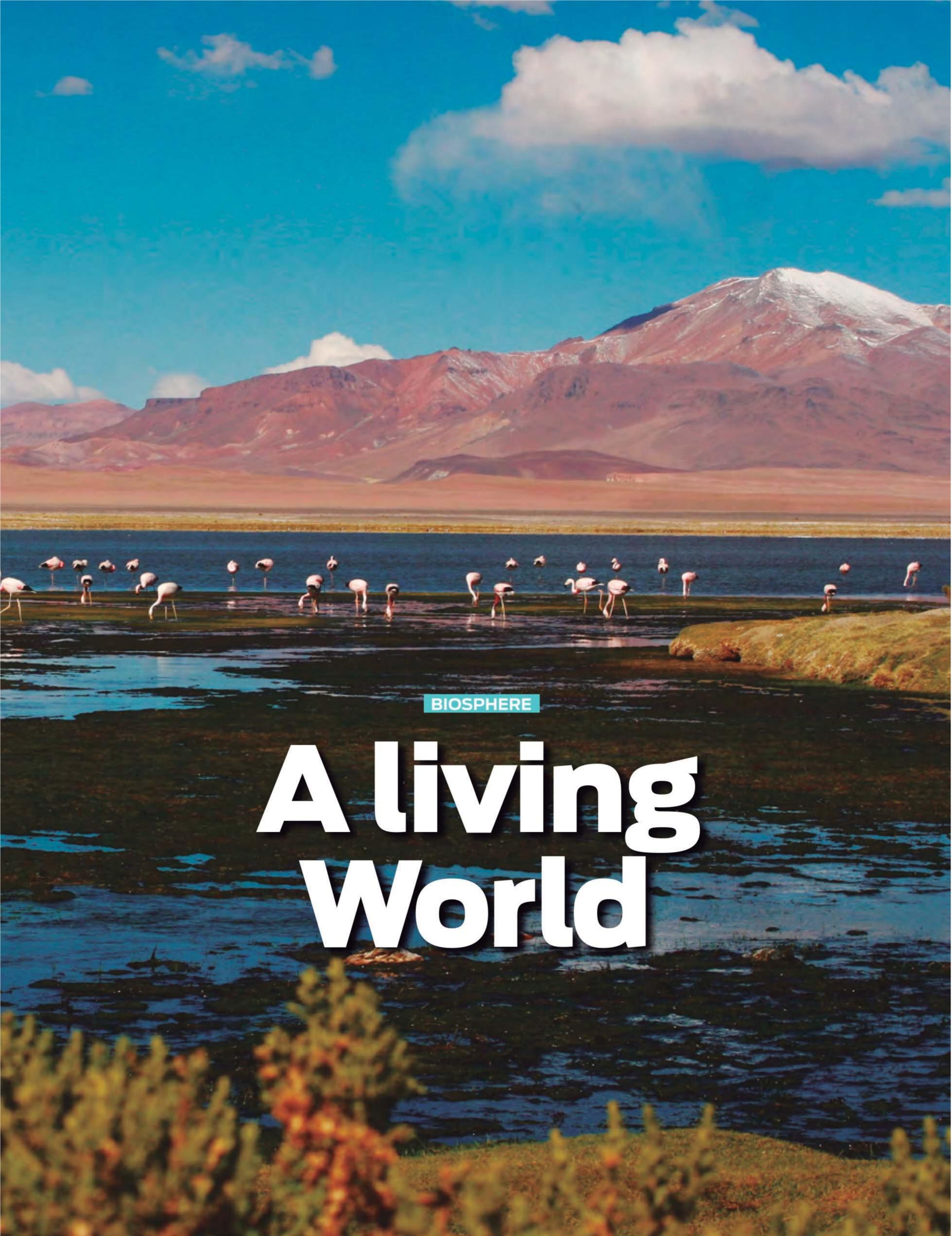
The Sané clan farm two types of land: ground liable to flooding where they plant rice, and land which is scarcely higher but which remains dry, where they grow millet, maize, beans and groundnuts. In the rice fields, there is a permanent battle between fresh water and salt water. The shallow incline of the river means that the tide can reach up to a hundred kilometres inland. When there is enough rainfall, the sea water is flushed out. But when rain is scarce, the Atlantic tidal bore prevails, salt is deposited, rendering the soil infertile. A dam has been built, but it is too low to be of much use. Less land under cultivation means less rice: the region, which once used to export rice, now has to buy rice from Thailand to make up the difference.

Dry food crops need rain too. "We plant when the first rainstorm comes, hoping that the next one won't take a month to come along," Sané explains. The harvest depends on the amount and above all on the pattern of the rainfall. "The Government does help us by giving us seeds of early beans that are ready in 45 days." Still, there is something for the Sané clan to be happy about: the village is going to be connected to the electrical grid. So at least they'll be able to watch television while waiting for... the rain.

Hervé Quéméner

↑ Taïrou Sané, who is a Diola farmer living together with his clan in Sindone, south-east of the regional capital Ziguinchor, has lived through more than fifty rainy seasons. His first problems date from the drought years of 1973-1974. "Before that, we got a big harvest from a small amount of land. Now, we have to cultivate larger plots and the yield has fallen. When it is very windy, it usually brings rain, but some years the weather remained dry." © H. Quémener





A remarkable ecosystem

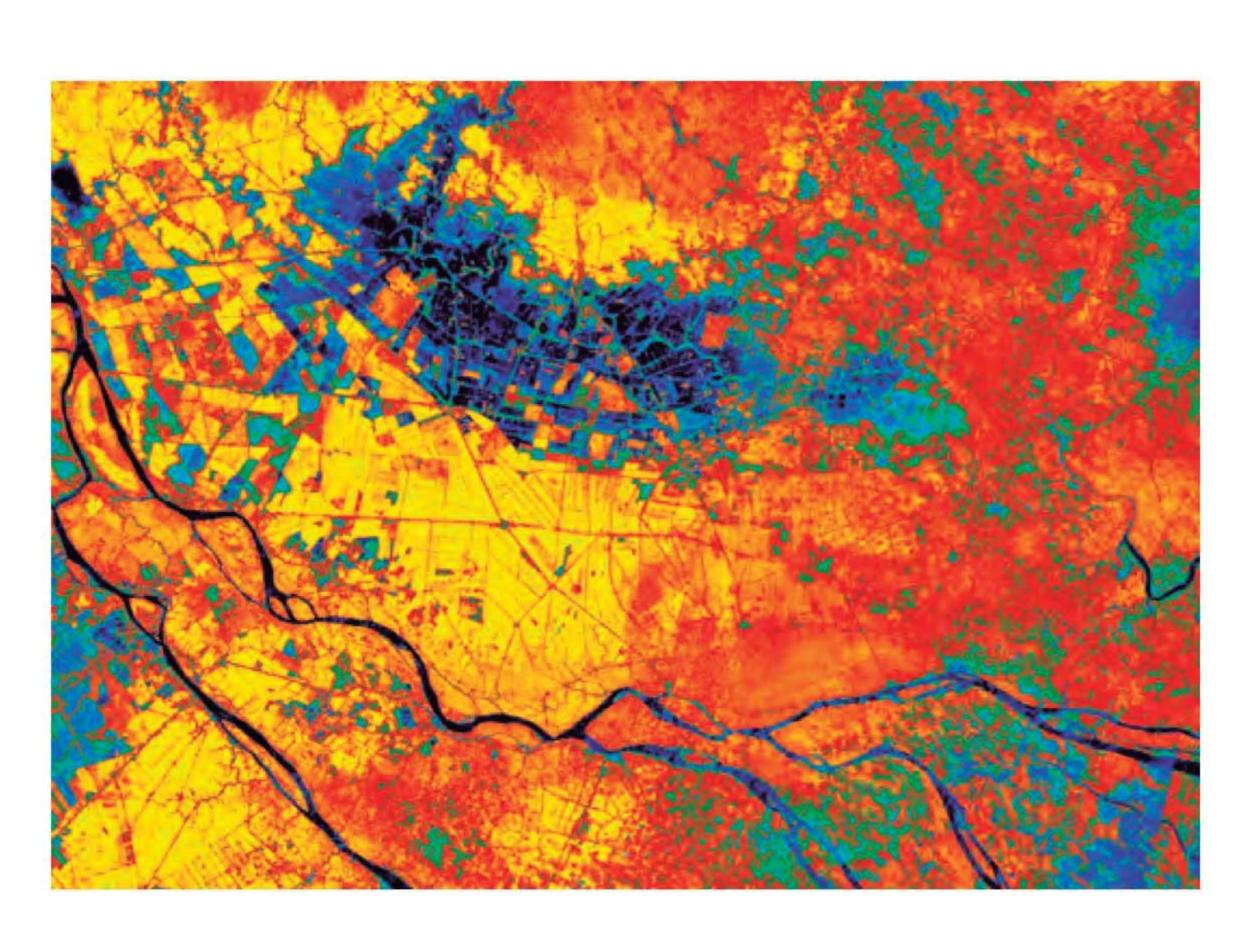
NY SPACE TRAVELER looking for interesting places to visit in our corner of the galaxy would know instantly from the chemical properties of the atmosphere that there was something extraordinary about the Earth: its atmosphere is not in chemical equilibrium, but contains far too much of the highly reactive gas oxygen. That is an unmistakable signature that something remarkable is going on here: the remarkable thing called life. Since it discovered photosynthesis over 2.7 billion years ago, life has radically transformed the atmosphere, but a drastic new transformation began when the upstart life-form known as humanity developed a thirst for energy to drive industrialization.

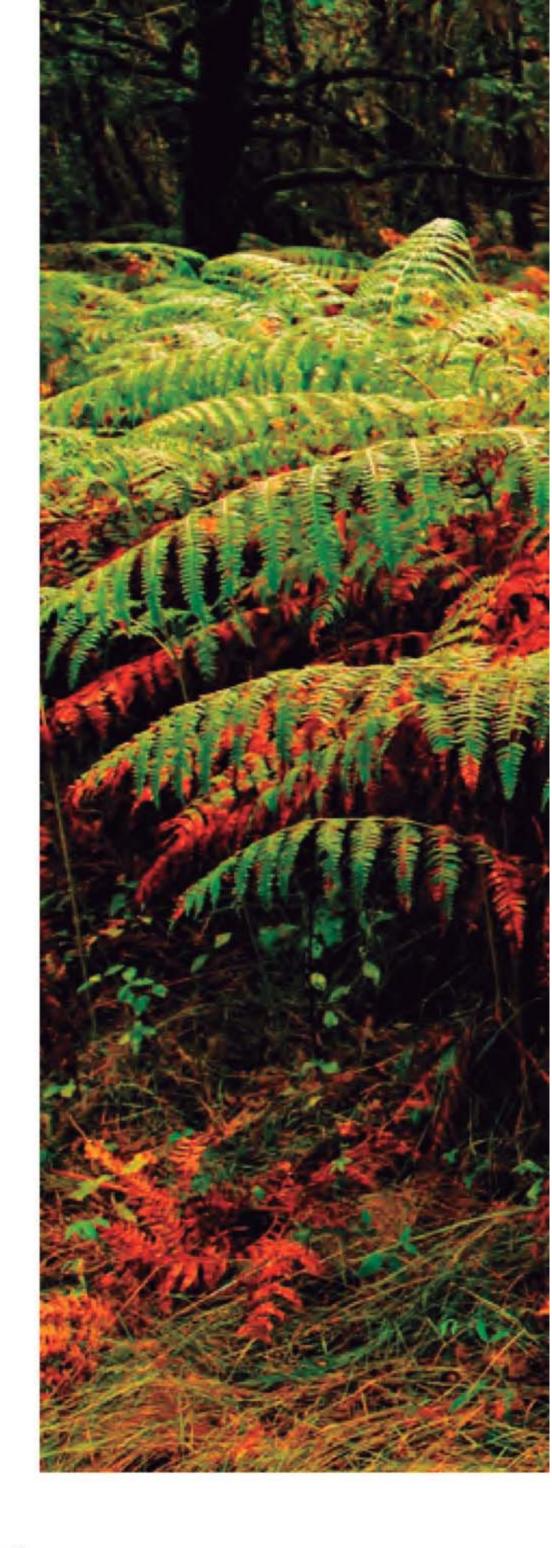
This has led to an ever-increasing injection of greenhouse gases (carbon dioxide, methane and nitrous oxide) into the atmosphere, which is the fundamental driver of climate change. Our modification of the atmosphere is clearly seen in the continuous series of measurements of CO₂ begun by David Keeling in 1958. The increasing upward trend is from fossil fuel burning and tropical defo-

restation, but it carries an annual ripple, maximizing in winter - a seasonal variation that can be clearly seen from space, for example by the SCIAMACHY instrument onboard ENVISAT satellite (operational from March 2002 to April 2012). This is the biosphere at work, sucking down CO₂ by photosynthesis in the Northern hemisphere summer, then changing over to release of CO₂ from soil respiration as vegetation becomes dormant in winter.

Plants and phytoplankton

What can't be seen in measurements of CO₂ is that the biosphere - the global ecological system integrating all living beings and their relationships - also plays a major part in reducing the upward trend in CO₂. In fact, only 44% of the CO₂ emitted into the atmosphere from human activities stays there. The remainder has to flow back into the surface, since CO₂ does not decay and is too heavy to evaporate from the atmosphere. Around 30% is taken up by the land through photosynthesis, and 26% into the ocean by a mixture of photosynthesis by phytoplank-





Coloured vegetation index of the Mekong Delta in Vietnam derived from Proba-V data in 2013. Located on the Indo-China Peninsula, the delta's water source is the longest river in Southeast Asia, the seventh longest in Asia and the twelfth longest in the world.

© ESA/VITO.



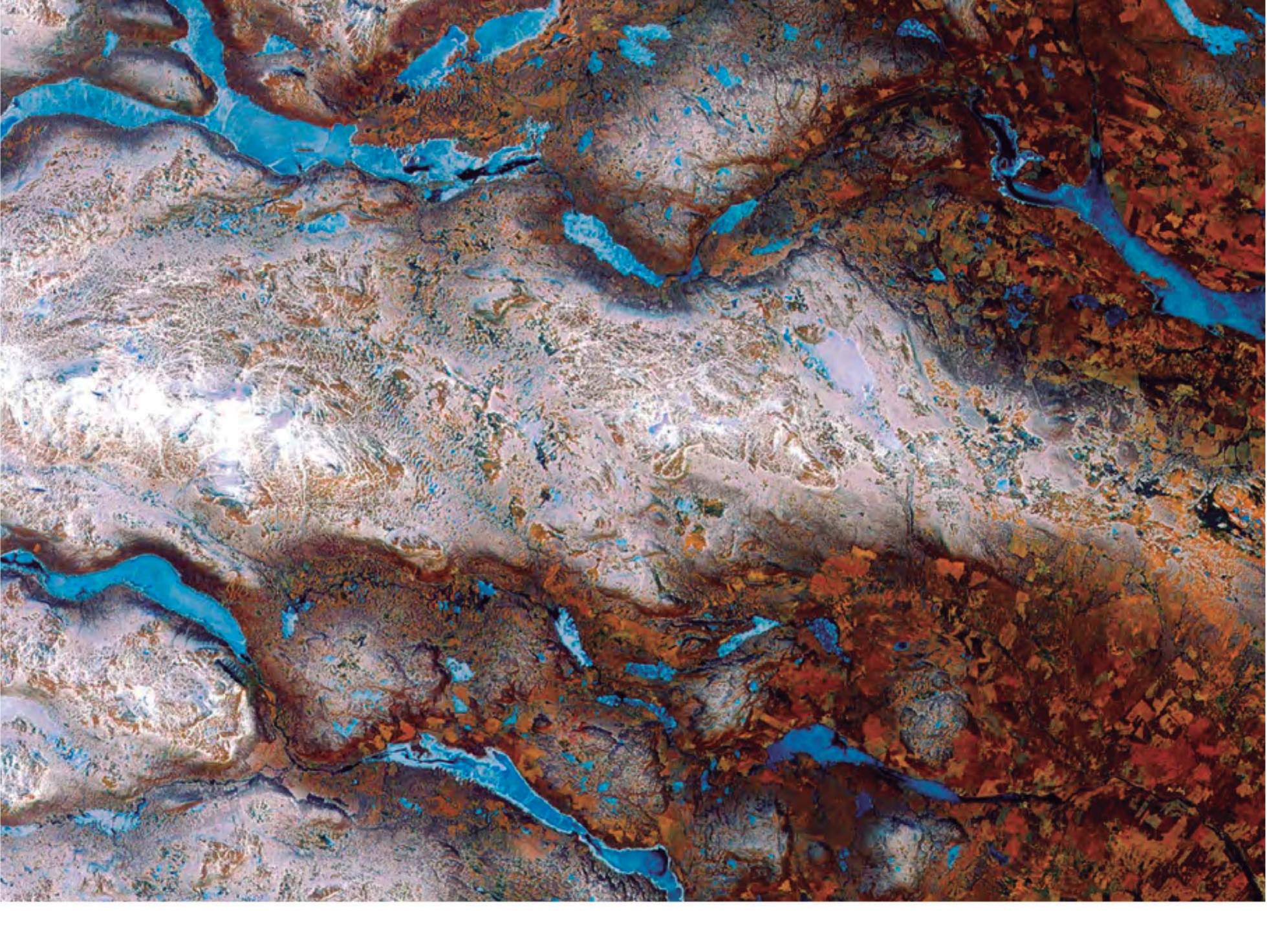
ton and absorption in seawater (leading to increased acidity of the oceans).

Hence the biosphere is playing a crucial role in slowing down climate warming, but can't keep pace with our insatiable demand for energy from fossil fuels. Although the biosphere includes all living things, the most important elements in terms of climate, (other than mankind) are plants and phytoplankton (which take up carbon) and micro-organisms in the soil (which act as decomposers, releasing carbon back to the atmosphere). Satellite data are fundamental in monitoring photosynthetic activity, for example by measuring the fraction of photosynthetically active radiation absorbed by plants (fAPAR), or blooms of phytoplankton that manifest themselves in ocean colour. Images of fAPAR show clearly how climate affects vegetation; for example, plant productivity was severely reduced during the 2003 European heatwave but bounced back in 2004.

Space-based measurements of soil moisture using radiometers and scatterometers also help us to understand the mechanisms underlying the heatwave; they show unusually low soil moisture in the early part of the year, aggravated by early onset of plant growth which took further moisture from the soil. This reduced atmospheric cooling by evaporation, giving a positive feedback that made the heatwave more extreme. Photosynthesis leads to the production of biomass, and the fate of that biomass has major effects on climate. When it is stored in growing forests, it locks up carbon in both the vegetation and soil, but when those forests are cleared or burned, a large fraction of this carbon returns to the atmosphere.

Carbon captured by croplands mainly returns to the atmosphere after harvesting, while undisturbed grasslands can retain carbon over long periods by storing dead material in the soil. Hence land cover and land use are fundamental factors in the interacAn ecosystem is an extraordinarily complex environment that brings together biological, geologic, hydrologic and atmospheric components. Among these components are trees and other plants. Here, fern in the undergrowth in the Dronne valley (Charente, southwestern France).

© J.-D. Dallet/Suds-Concepts



The vast and widely varied landscape of northern Sweden, just below the Arctic Circle, is shown in this SPOT-4 image. Mountains, lakes, rivers, streams, valleys, rocks, boulders and barren cliffs make up this area. Often called 'Europe's last wilderness' it is part of the 'Land of the Midnight Sun'.

© CNES, Spot Image

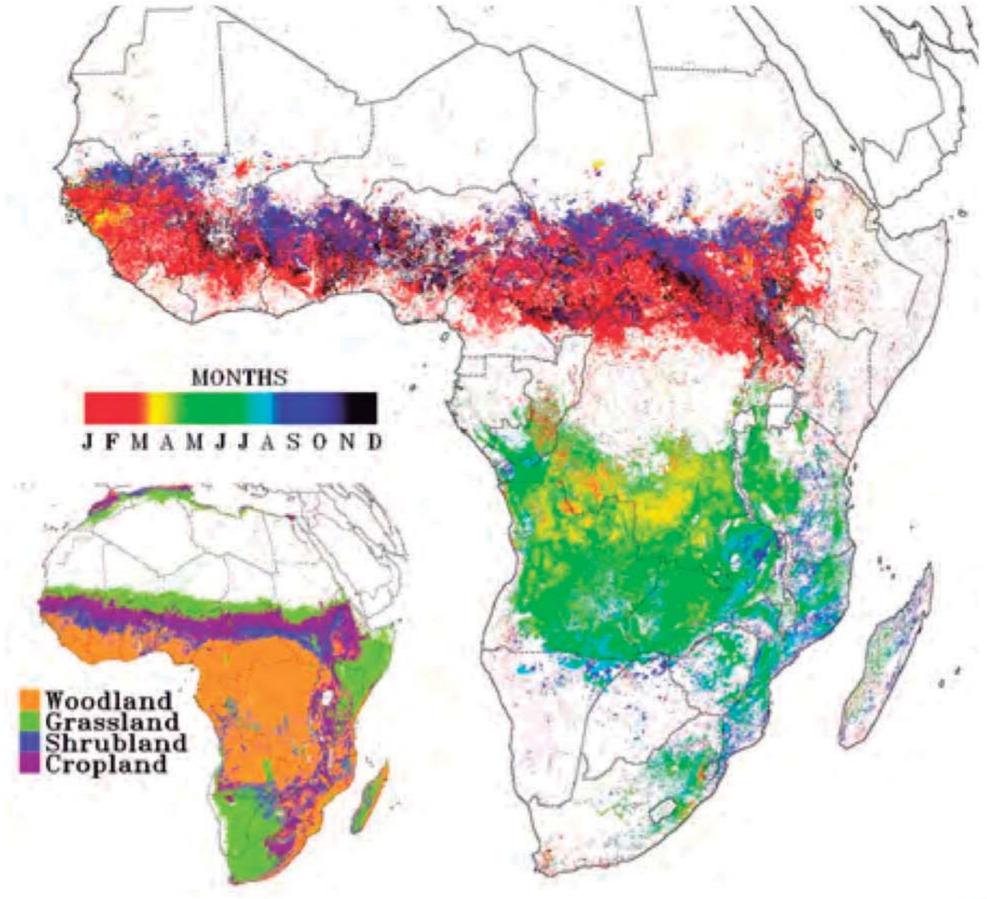
tion between the biosphere and climate, affecting not just the interchange of greenhouse gases, but also flows of energy and water. Satellite data are our primary means of keeping track of how land cover is changing; they show huge changes across the planet, with major impacts for mankind, both positive by providing agricultural and farming land and negative from effects such as loss of biodiversity, soil erosion, changes in the water cycle, and modification of local and global climate.

The simplest approach to estimating the CO_2 emissions from deforestation just measures the area of forest cleared and multiplies by an average biomass (of which half is carbon). However, more accurate assessments, such as are needed for carbon trading, require the biomass of the forest that was actually cleared. Maps of tropical forest biomass are unavailable, and there are few measurements within this vast inaccessible area on which to base them, so measuring biomass from space has been a long-lasting dream; this is now becoming a reality,

through the advent of space-based vegetation lidars and long-wavelength radars. Emissions from biomass burning can also be estimated by measuring the radiated energy using meteorological satellites in geostationary orbit that give nearly continuous observation of the fires. These estimates can be improved by interpolating periodic energy measurements from polar-orbiting instruments, such as MODIS, which are able to see smaller, less intense fires.

Observing from space

We are at an exciting time for observing the biosphere from space, with multiple sensors contributing complementary information, and radically new sensors in preparation by ESA and NASA. Multi-spectral imaging of the Earth at 20-30 m spatial resolution, which has been the backbone of monitoring land cover and land use change throughout the Landsat era, will be significantly enhanced with the EU/ESA Copernicus operational satellites Sentinel -2A launched in June 2015, a few months before COP 21,



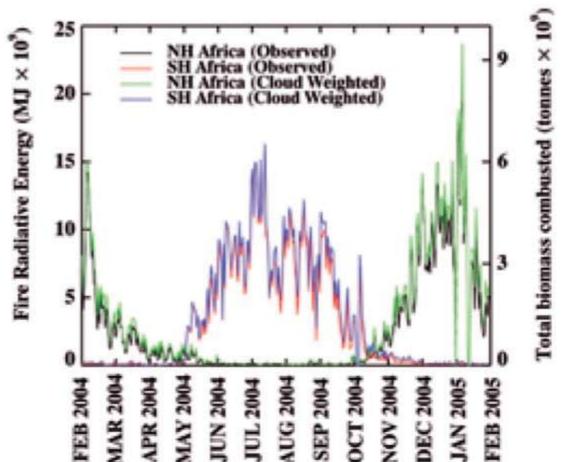
Fires detected over Africa from Feb. 2004 to Feb. 2005 using the SEVIRI sensor onboard the Meteosat 2nd Generation geostationary satellite. Left, date and location of the fires detected by their intense thermal emissions.

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Time series estimate of the thermal energy radiated by the detected fires, along with the equivalent biomass consumption: 362-414 Tg and 402-440 Tg in the Northern and Southern hemispheres respectively.

SEVIRI can detect changes in fire activity every 15 minutes, though adjustments are needed to account for smaller fires that can't be detected because of the coarse resolution from geostationary orbit. Note that carbon emissions due to fire in grasslands are taken up again in the next growing season, but recovery is much slower in forest, so the climate consequences of fire also depend on the cover type.

Image courtesy: Gareth Roberts & Martin Wooster, King's College London; SEVIRI data: EUMETSAT



and 2B, to go into orbit in 2016. Combined with Landsat 8 (and the newly approved Landsat 9, to be launched in 2023), this will ensure global coverage of the Earth every 5 days or better, yielding unprecedented capability to monitor processes on the land surface. Advances in computing concepts will enable us to realize the full potential of these data. Such Big Data methods are already revealing their power: for example, by spreading the computing across 10,000 processors, the full 21st century archive of Landsat data has been processed to measure forest changes between 2000 and 2012 globally at 30-m resolution. Long-term global measurements of plant activity and fAPAR that build on the legacy from MODIS, MERIS and SPOT-VGT at resolutions between 300 m and 1 km are also secure through the Copernicus Sentinel-3 and NASA NPP satellites, together with the upcoming Japanese G-COM series. New, more direct estimates of photosynthesis using solar induced chlorophyll fluorescence have

already been demonstrated with GOSAT and OCO-2, and are the specific target of the FLuorescence EXplorer (FLEX) mission proposed as ESA's 8th Earth Explorer (its competitor for selection, Carbonsat, will also be able to measure fluorescence, but not at such fine resolution).

Measurements from geostationary orbit of the energy radiated by biomass burning are assured well into the future with the Meteosat Third Generation and GOES ABI systems, covering Europe and the Americas, while the Japanese Himawari-8 geostationary will cover SE Asia and China, though the area around India is not yet well covered by suitable sensors.

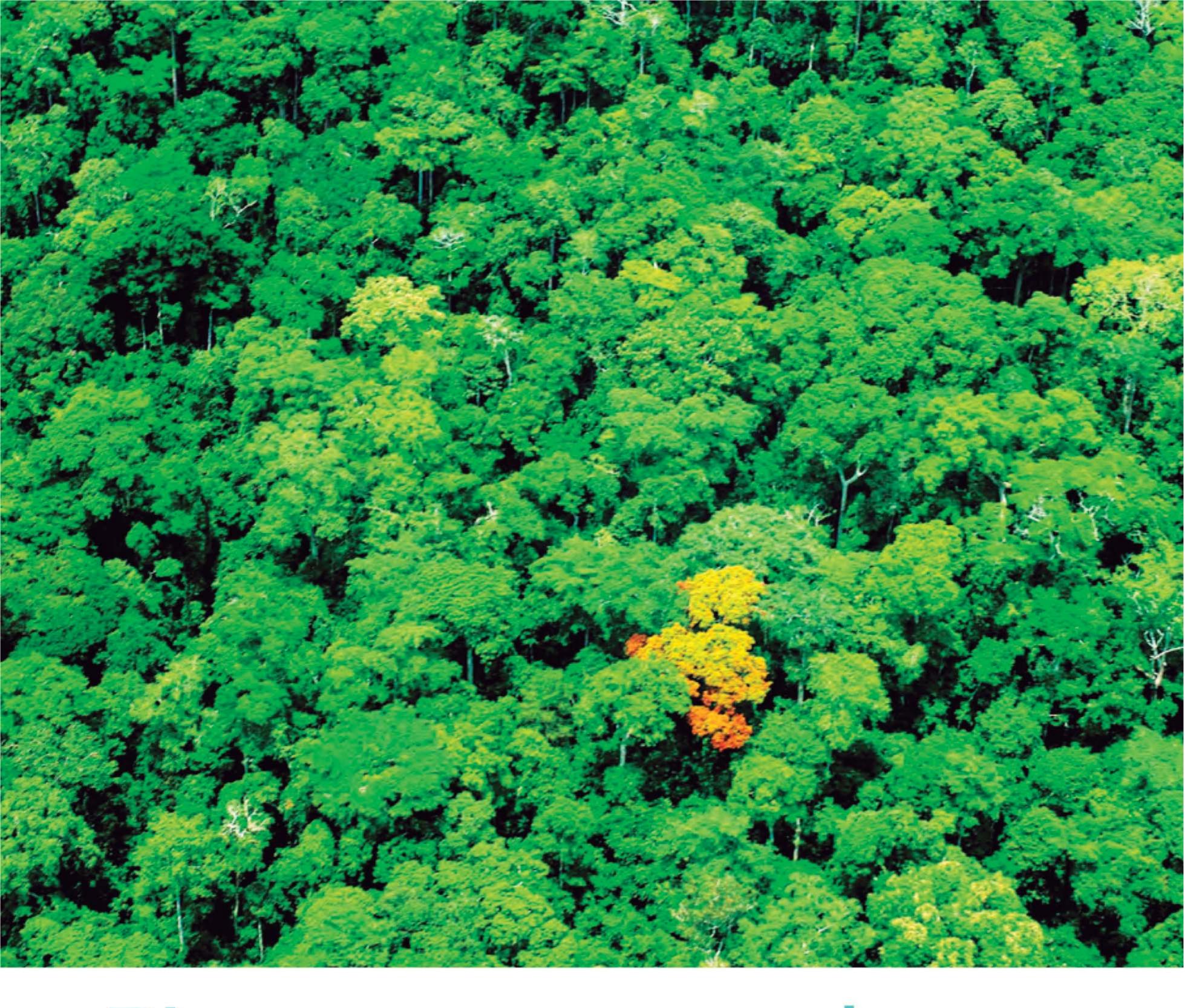
Polar orbiters, such as Suomi-NPP VIIRS and Sentinel-3, will be able to provide finer resolution measurements to deal with smaller fires, though it would be advantageous to have systems with a mid-afternoon equator crossing time, as this is when fire activity peaks in many places. Optical instruments are currently the primary means of monitoring land use change, but the Sentinel-1 satellites should lead to radar becoming much more influential.

These data will be frequent, global, operational and unaffected by cloud, making it worthwhile to invest in the necessary processing chains, particularly for cloudy regions such as tropical forests. Sentinel-1 operates at C-band (6 cm wavelength) but L-band (24 cm wavelength) is even better for forest observations (including measuring the biomass of lower biomass forests). L-band data should become plentiful (the Japanese ALOS-2 satellite is already in orbit and Argentina aims to launch the SAOCOM pair of L-band satellites in 2015 and 2018). But, at present, the pricing policy for ALOS-2 makes it unattractive for climate applications.

High resolution Lidar

Two key missions giving information on forest structure and dynamics will be in space around the end of this decade: the NASA Global Ecosystem Dynamics Investigation (GEDI) on the International Space Station and BIOMASS (ESA). GEDI will provide global high-resolution lidar observations of the vertical structure of forests, from which biomass may be estimated, while BIOMASS carries a 70 cm wavelength radar and is dedicated to measuring global forest biomass and height at 200 m resolution. The combination of measurements from these two missions will sharply increase our knowledge about forest structure and change, especially in the high biomass tropical forests that are critical for climate and climate change treaties.

Shaun Quegan, University of Sheffield



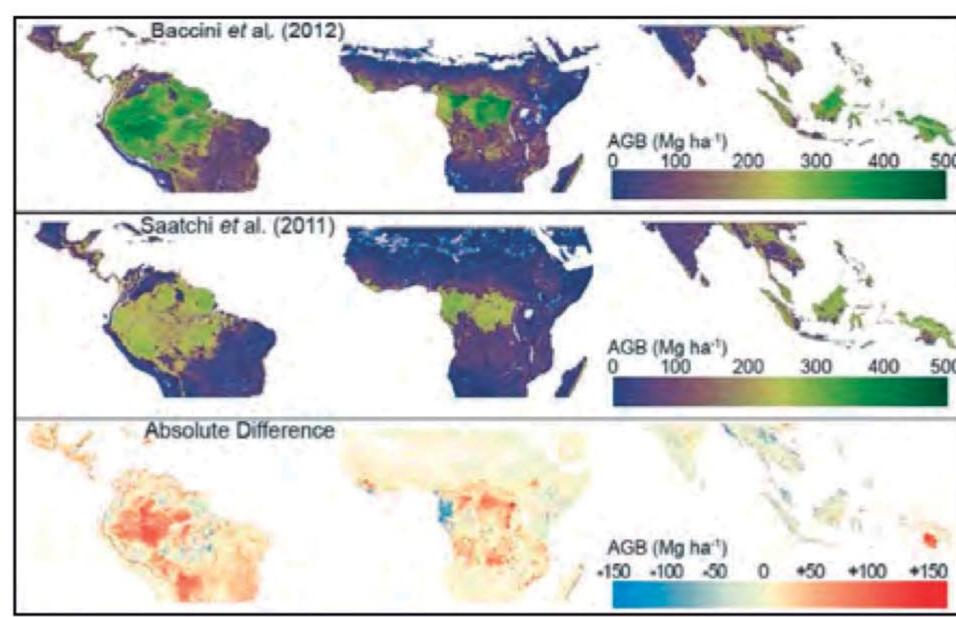
Biomass measured

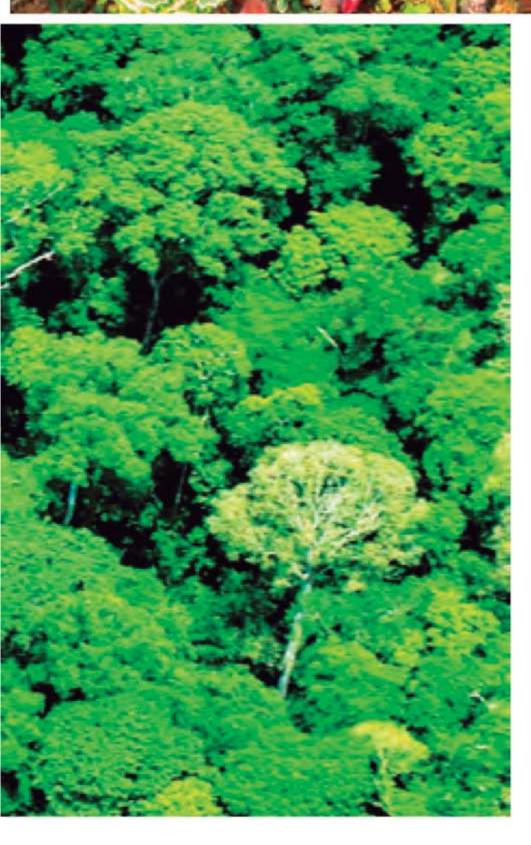
forest, all around you is biomass – the mass of living organisms in the forest. Only a tiny part of that is in birds and animals, and by far the largest part is in the woody biomass contained in the trunks and large branches of the trees, but also in the living roots beneath you. Such woody biomass has always been important for mankind as a source of energy and building materials, but in recent decades it has gained even greater significance because of its role in climate change. This is because about half of biomass is carbon. Hence clearing forests leads to emissions of carbon dioxide

and enhances climate warming, while growing forests take up carbon dioxide from the atmosphere: forest biomass is the only internationally recognised carbon sink for offsetting greenhouse gas emissions. Most of what we know about the amount and spatial distribution of biomass is from ground measurements; there are extensive forest inventories throughout the temperate and boreal zones motivated by the needs of commercial forestry. However, because they have never been exploited in this way, there are few in situ biomass measurements in natural tropical forests. This gap in our knowledge assumed major importance once









The Réserve Spéciale de Forêt Dense de Dzanga Sangha is part of the Sangha Tri-national institution, an initiative of the Central African Forest Commission (COMIFAC) to protect the second largest rainforest area on earth. The protected areas together are approximately 2.8 million hectares. Away from densely populated areas and traffic routes, they have been spared from intensive economic use for a long time. Thus, a unique natural landscape comprising a high density of large mammals has been preserved. © P. Prokosch/GRID-Arendal

A Bambuti also called Mbuti, a group of Pygmies of the Ituri Forest of eastern Congo (Kinshasa), are highly vulnerable to being dispossessed of their ancestral lands and experiencing displacement, marginalisation and poverty.

© UNEP

it was realised that forest clearance in the tropics was contributing significantly to overall carbon emissions. Currently this is estimated to be around 10% of the total anthropogenic emissions, but the uncertainty in this estimate exceeds 50%.

The vastness, remoteness and difficulty of access of the tropical forests make it very difficult to address this knowledge gap by in situ measurements, although airborne lidars can play a useful role in mapping biomass at regional scale. This has fuelled major efforts to measure biomass from space, using both lidar and radar instruments. Both types of sensor are active, *i.e.* they transmit energy and measure the return, but both have limitations.

BIOMASS mission

Over the period from 2003 to 2009, the lidar onboard the NASA ICESat satellite measured forest height globally. Exploiting relations between height and biomass, these data form the basis for two pan-tropical biomass maps, but these exhibit significant differences (see above).

This is partly because they used different methods and different calibration data, but also because of spatial variation in the height-biomass relationship. Above-ground biomass in Mg hectare-1 from top Baccini et al. (2012), middle Saatchi et al. (2011), and bottom the absolute difference (Baccini minus Saatchi)

Courtesy of Alessandro Baccini of Woods Hole Research Centre, Sassan Saatchi, Jet Propulsion laboratory and Ed Mitchard, University of Edinburgh

Radar is limited by the wavelengths of current sensors. Penetrating through to the lower canopy where most of the biomass resides needs use of as long a wavelength as possible. Until 2004 this restricted radars to wavelengths no greater than 24 cm, which are valuable for low biomass forests, such as tropical woodland or regrowing forests, but are ineffective in the high biomass rainforests where information is most urgently needed. However, new regulations in 2004 opened the door to ESA's BIOMASS mission to launch around 2020.

This mission is based on a 70-cm wavelength radar, which should be sensitive to the full range of biomass across the planet, and will map forest biomass and height twice a year for four years at a resolution of 200 m. A really valuable complement to BIOMASS will be the NASA Global Ecosystem Dynamics Investigation lidar to be deployed on the International Space Station in 2018.

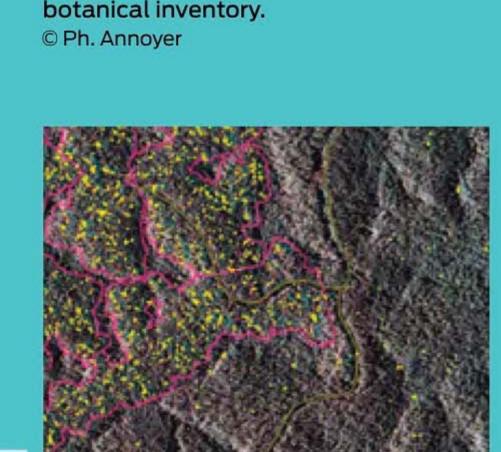
This aims to provide the first global, highresolution observations of the vertical structure of tropical and temperate forests, which will be of great value in estimating the distribution of above-ground biomass.

> Shaun Quegan University of Sheffield



- Illegal deforestation occurs frequently in the tropical forest and exacerbates the impact of climate change. This radar satellite image of the Guyanese forest shows trees cut down (in yellow) between December 2013 and August 2014 outside the authorized logging areas (red).

 © COSMO-SkyMed Product ©ASI, ©ONF, (2013-2014), ©Telespazio France
- The rainforest canopy (here, northwest of Bayanga, Central African Republic) is a rich ecosystem. The Insectes du Monde association installed a platform 40 m above ground to carry out an entomological, arachnological, ornithological and botanical inventory.



Leveraging forest ecosystems

Primary, semi-natural and planted forest ecosystems cover a total area of 4 billion hectares, 30% of the world's land surfaces. Such huge forest expanses are an invaluable reservoir of biodiversity and a significant source of economic wealth. What's more, they have the unique ability to mitigate the effects of climate change by storing carbon and offering an alternative to fossil fuels.

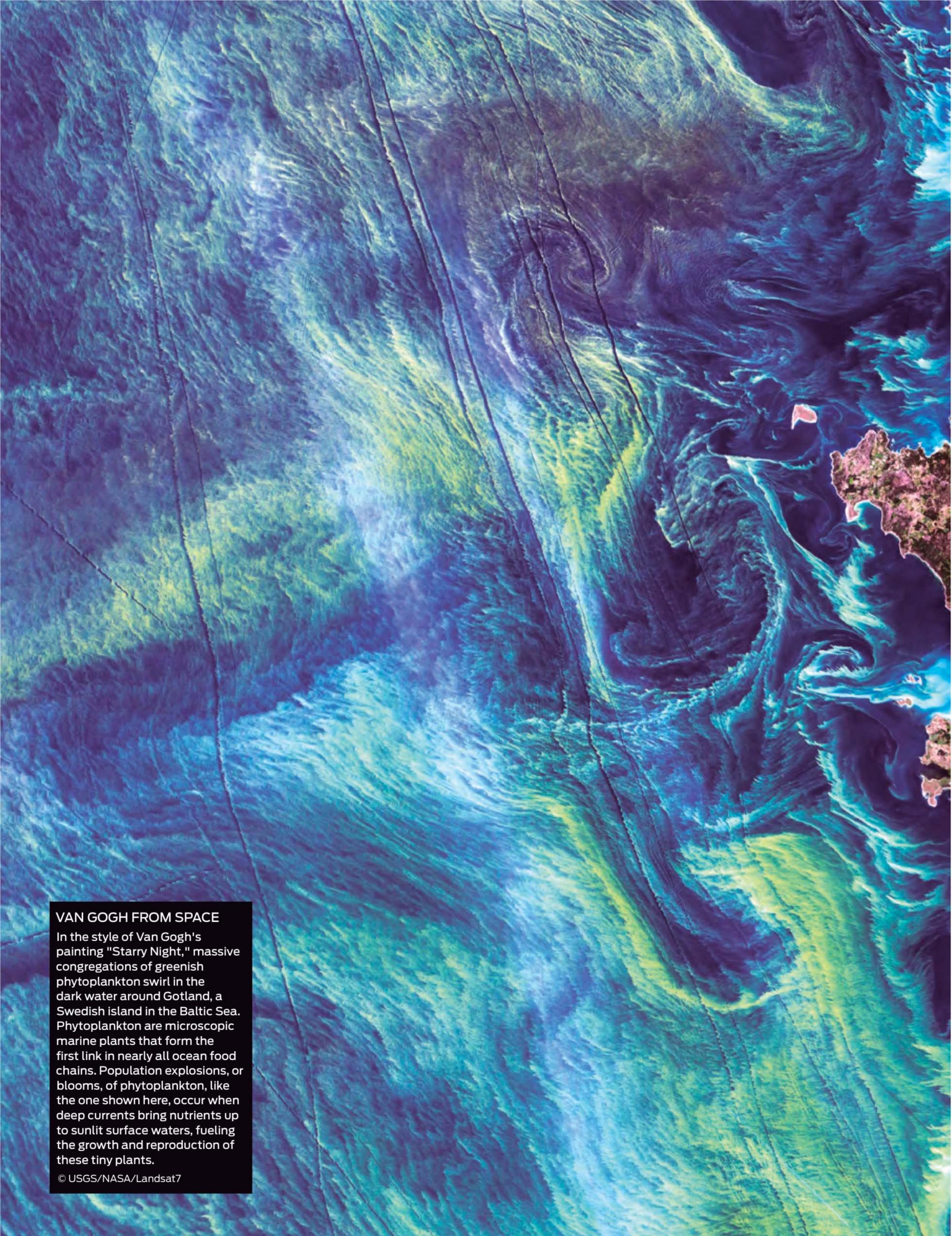
The impacts of environmental changes like faster tree growth, shifting ranges of species in temperate regions or increased exposure to phytosanitary and physical risks—fungi, pests, fires, storms, etc.—are just some of the new challenges facing the forestry profession today.

Likewise, regular monitoring of these ecosystems from space is a strategic challenge for new forestry policies and will be key to ensuring they are managed sustainably. The geo-information branch of the Telespazio group has developed the EarthLab network of operational environmental monitoring centres to establish close operational ties between space and forestry.

Whether qualifying tree species, biomass and timber volumes, monitoring yields from its centre in the Aquitaine region of Southwest France in the largest expanse of forest in Europe or detecting illegal clearing and keeping a check on forest health in Gabon, this network offers a palette of solutions underpinning a cross-disciplinary end-to-end service to effectively inform decision-making. It draws on unique expertise in analysis of multi-source imagery (radar, optical, lidar and UAV) and close collaboration with scientific and technical experts in the forestry sector. And the international interconnectedness of these centres is enabling a global and resourceful response to the challenges facing our planet

Jean-Charles Samalens, Telespazio France







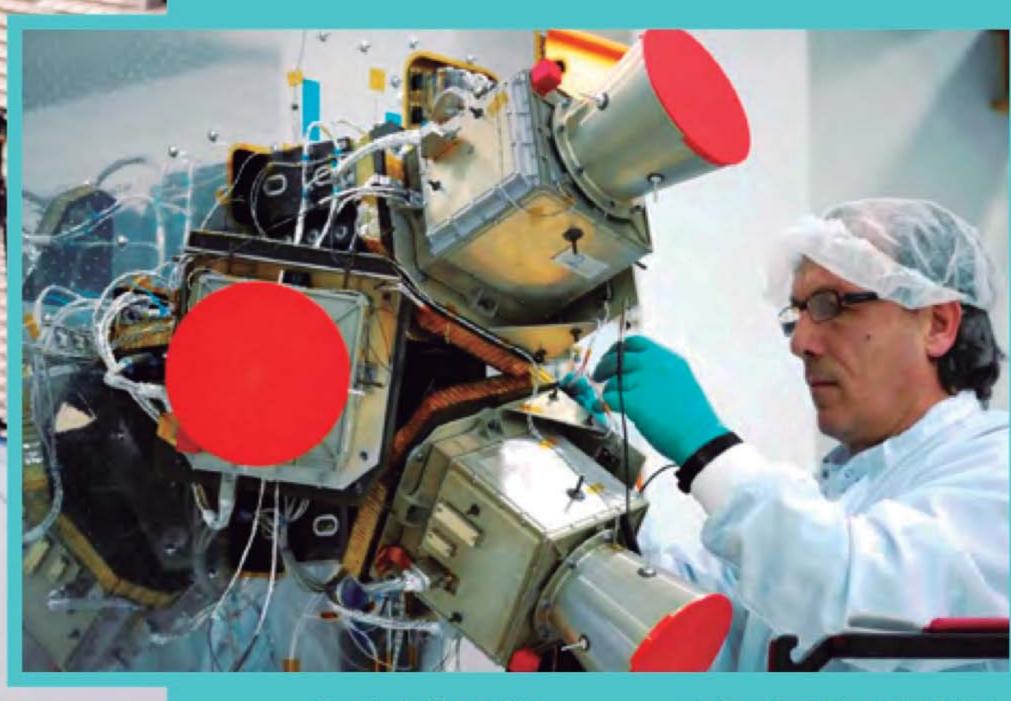


SPACE TOOLS

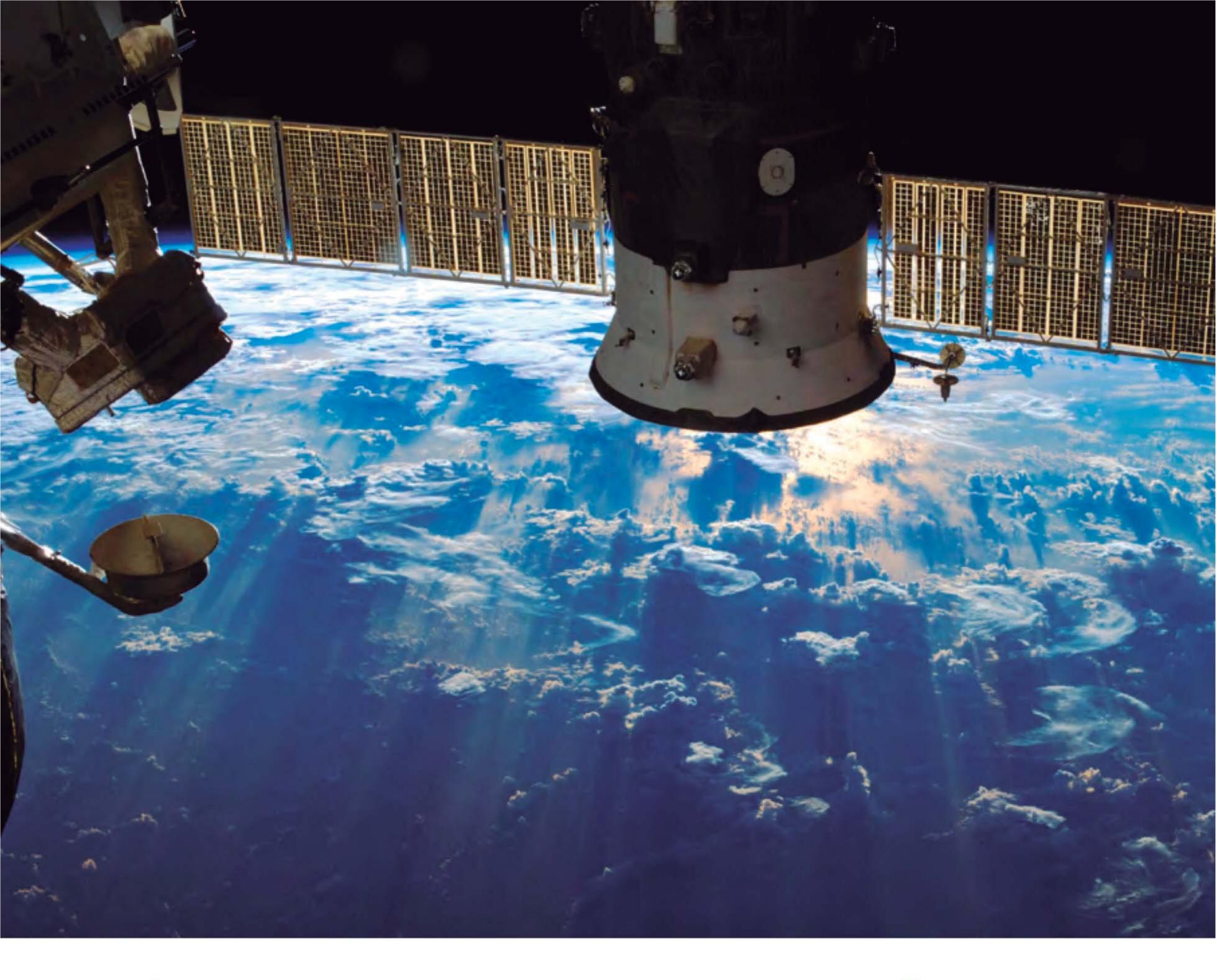
Space Sentinels

ach Sentinel mission is based on a constellation of two satellites to fulfil revisit and coverage requirements, providing robust datasets for Copernicus Services. This "Sentinels" family comprises six series of satellites or instruments: Sentinel-1 will ensure continuity with the radar data from ERS and Envisat; Sentinel-2 and -3 are dedicated to surveillance of land and oceans; the Sentinel-4 and -5 instruments are designed for meteorology and climatology missions; Sentinel-6 will provide operational continuity with the Jason altimetry missions. Thales Alenia Space is prime contractor for the Sentinel-1 and -3 missions (each including 2 satellites), and will also provide the ground segment on the second mission, and two instruments for Sentinel-6. These operational missions involve several hundred partners from industry. The Sentinels are state-of-theart satellites, combining reliability and effectiveness, and will meet the expectations of many different users. For example, Sentinel-3 will carry four payloads in a highly optimized space: an altimeter connected to a microwave radiometer for surface topography, and two instruments, each independently measuring the surface temperature and color of oceans. The Sentinel satellites are also designed to self-destruct in an atmospheric reentry at the end of their mission.

Yvan Baillion, Thales Alenia Space



- Sentinel-3's mission covers oceanography, continental hydrology and monitoring of vegetation on land. It comprises two satellites, to date, Sentinel-3A and -3B, and ensures operational continuity with the data provided by instruments on the Envisat satellite.
- © Cedric/imag[IN]
- ↑ Sentinel-1A was built by Thales Alenia Space as prime contractor (here, Rome). Data will be collected by European centers, and in Italy by the ground station at the e-GEOS space center in Matera (Basilicata region, southern Italy).
 - © Thales Alenia Space



The runaway train of climate change

Andre Kuipers took some amazing pictures of the Amazon rainforest from the International Space Station's Cuppola, which are both strikingly beautiful and scary. The rainforests are essential to sustaining the global climate and the security of future generations. Forests condition the climate, generate stability and create a comfort zone, a shelter that enables human societies to flourish. The Amazon rainforest is a concrete example of nature's power. From space, this vast area, with its maritime

clouds and clean air, looks like a Green ocean. According to the biotic pump theory (Makarieva & Gorshkov, 2007), profuse tree transpiration, combined with very strong condensation in the formation of clouds and rainfall –far greater than over adjacent oceans – leads to a reduction in atmospheric pressure over the forest which, in turn, draws moist air over the oceans inland, maintaining rainfall levels. Evenly distributed condensation precludes the concentration of wind power in damaging vortices like hurricanes or tornadoes on

land, while the depletion of atmospheric moisture by lateral transport over the ocean deprives the storms of their food (water vapor) in the oceanic regions adjacent to big forests. This theory explains why the Amazon Forest survived cataclysmic events for over 50 million years.

Yet, over only 50 years the damage inflicted on the Amazon climate by deforestation is already apparent in both scientific field measurements and in leading climate-modeling scenarios: drastic, widespread decreases in forest transpiration, changes in



One of the expedition crew members aboard the International Space Station recorded this image of a large mass of storm clouds over the Atlantic Ocean near Brazil. Europe is sharing the ISS international project in partnership with the United States, Russia, Japan and Canada.

© NASA

 ↓ Centrolene ilex is the largest species of glass frog in Central America.

© Brian Gratwicke

Limpkin (*Aramus guarauna*), also called carrao is found mostly in wetlands in warm parts of the Americas.

© Pamala

The rainforests of South America are among the most dense, diverse and complex terrestrial biomes on the planet.

© Alexander Lees



the dynamics of clouds and rain, and the extended duration of the dry season. Analysis based on updated climate models and on new physical theory predicts a worse future. The extent of deforestation in the Brazilian Amazon amounts to nearly 763,000 km2 (the combined area of two Germanys or two Japans). This surface measurement needs to be added to the areas that have been gravely-wounded (estimated to exceed 1.2 million km²). Because most of the rainfall that irrigates central and southern South America originates from the Amazon, continuing the present deforestation trend might push the climate of the continent to resemble present-day Australia. Deforestation in the Amazon has been a disaster. We are annihilating those incredible natural irrigation machines: the trees! But deforestation has met in climate an implacable judge that counts trees and never forgets nor forgives.

Awaking consciousness

Understanding these phenomena requires data and images. Satellites deliver temporal, detailed data, which are essential to scientists. For instance MEGHA-TROPIQUES provides very useful data about where and how much it's raining. What we are still lacking are frequent and accurate images of the earth surface in 3D, complementing other satellite data coming from multispectral instruments. An orbiting lidar, for example, would be useful to quantitatively assess what is happening to the biosphere and how it's interacting with a changing climate. Digital Topography Maps generated from penetrating 3D images from space, such as the ones used to depict urban areas, would be precious





tools for improving the climate models we use, but also in predicting water paths during floods, in better monitoring land vegetation and in understanding factors such as soil moisture dynamics. The wealth of privileged views from space provided by the satellite age has also awakened our consciousness of the rapid impact of climate change, highlighting the fact that earth is our only home, lost in the hostile darkness of empty space, which lies just a few kilometres above our heads. Given the awareness about the state of climate change, and in particular the situation of the Earth forests, the only responsible option is to act immediately and forcefully to combat the causes. If qualified scientific knowledge, the precautionary principle and even plain common sense have failed to spark an adequate reaction from those

The primary result

document,

© L. R. Lima

was the nonbinding

"The Future We Want".

other natural disasters must surely provoke some reaction. We need a mitigation plan that is based on a radical reversal of both past and expected future damage: a war effort, such as the one the United States set up after Pearl Harbor, when they decided to join World War II. In a few months, car manufacturers started to produce tanks, while other factories began producing materials and equipments that was required. Without such a concentrated and extraordinary effort, the allies would not have won. And there is little chance we will win the

the pinheiral

© T. Fioreze

(pine forest) zone of

and the southern

the Brazilian Highlands

coastal Atlantic Forest.

long-term war against climate change. People should be aware that once the Earth's climate system derails, it might take millions of years to get back to its friendly state, which humanity has enjoyed. Scientific evidence shows that we may already have gone over the tipping point. Procrastination is no longer an option. Informing citizens, appealing to people's sensibilities and fostering local,

individual action should be part of a large-scale effort at all levels of society. I have the firm hope that COP 21 in Paris becomes a major turning point for a climate recovery and awareness of world consciousness. There is a need for universal, facilitated access to scientific discoveries, in order to reduce pressure from the primary cause of environmental destruction: ignorance. XIXth century Alexander Humboldt best illustrates the holistic, integrative type of approach we need to study Earth and its complex systems. For the Amazon, we obviously need to stop

the bleeding and destruction of its forests, with mid and long-time perspectives, and urgently replant and restore what has been destroyed, so the rainforest can continue to provide fundamental ecological support for human activities both within and beyond the Amazon. Otherwise, human occupation of the Amazon will have triggered an unthinkable contest, a race in which two nefarious influences - deforestation and global climate change - compete for first place on the podium for orchestrating the final destruction of the largest and most diverse rainforest on Earth. Antonio Donato Nobre, National Institute for Space Research, Brazil

who have the financial means and strategic

resources to change things, then the shock

of dry taps here, flooded cities there and

CONCERN



Protecting the Maasai Mara ecosystem

The Maasai Mara ecosystem is experiencing unprecedented changes associated with climate change. The Maasai people who call the Maasai Mara their home have in the past been able to predict and respond to changes in weather conditions as the seasons and rainfall patterns in the Mara were well understood. It shaped the grazing patterns of livestock and interaction with wildlife in the Mara. However, changes in climatic patterns have thrown everything out of kilter and Maasai in the Mara have had to adjust their lifestyles accordingly.

The Maasai Mara is famous for its annual wildebeest migration when millions of wildebeest follow the rains and green grass from the Serengeti in Tanzania to the Maasai Mara in Kenya and back. In the past the wildebeest migration pattern was consistent but in the last few years this pattern has shifted due to irregular rainfall. This means that the wildebeest now give birth in the Maasai Mara and by doing so are spreading Malignant Catarrhal Fever which is fatal to the Maasai livestock.

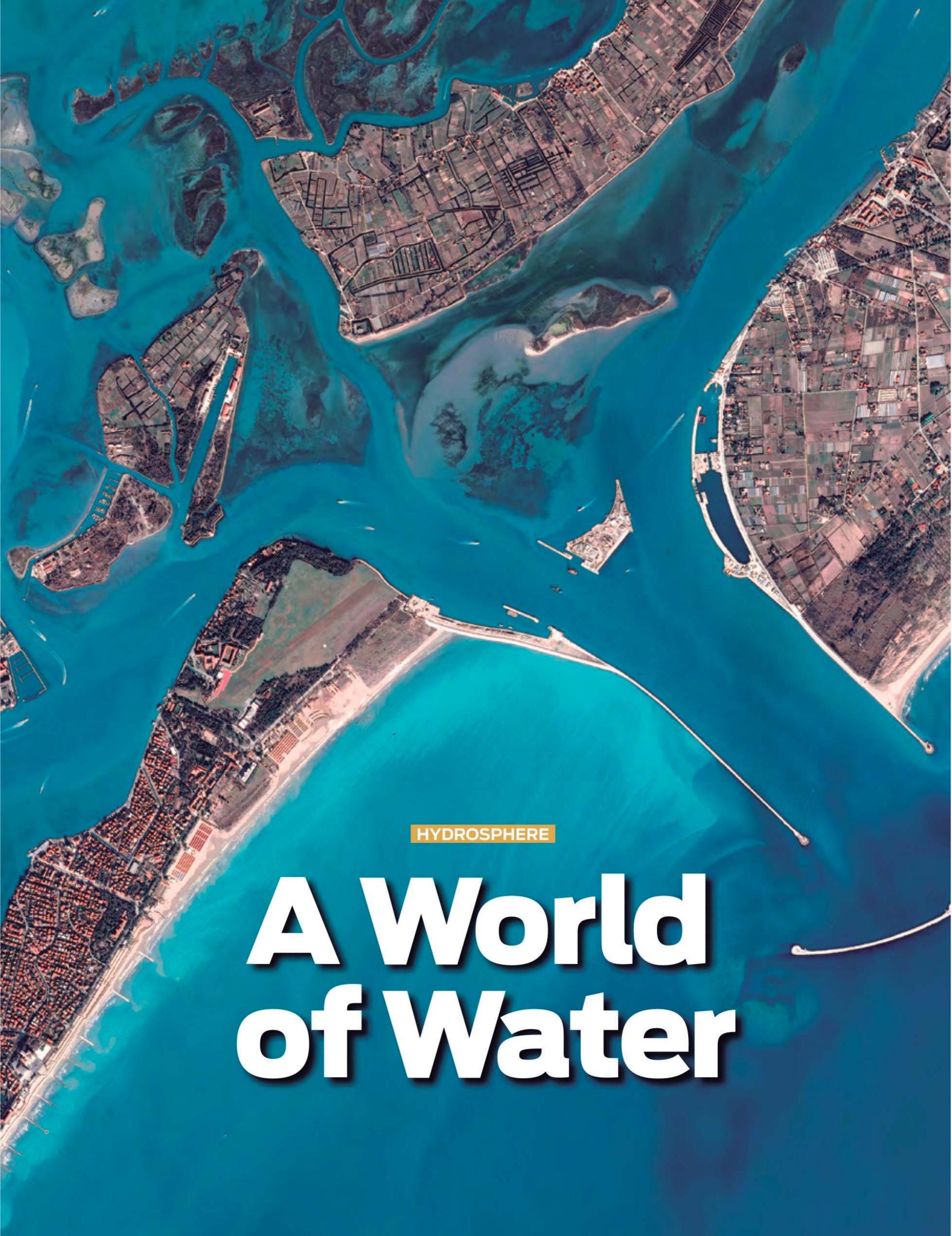
Mapping with satellite imagery

In an effort to avoid disease and secure grass for their livestock many Maasai have started building permanent homes and have resorted to fencing their piece of land. Fences interfere with migration routes for wildlife as corridors are blocked and more people are encroaching into wildlife areas. With these changes comes an increase in conflict between humans and predators, such as cheetahs (*Acinonyx jubatus*) as natural prey is reduced, livestock and predators are forced to share the same area and there is more competition for water as the rains are becoming more unpredictable. To determine the impact that these changes have on cheetah movement and ecology, the Mara Cheetah Project set up by the Kenya Wildlife Trust uses high resolution satellite imagery provided by CNES (SPOT and Pléiades data/ISIS Programme), to map *manyattas* (Maasai settlements), fences and habitat changes. The findings from this research will help drive cheetah conservation efforts in the Mara, an area of global importance for cheetahs. *Michael Kaelo and Femke Broekhuis, Mara Cheetah Project, Kenya Wildlife Trust*

Guides play a key role in fauna monitoring. The most important element for wildebeest migration (top) is the cycle of seasons, now disturbed by climate change. January, which Maasai people refer to as Olodalu (hot month), was characterised by intense heat. February was expected to come with short rains that gradually increased towards March and April. In June Mara was covered by red oat grass which is both nutritious and provides good camouflage for wildebeest calves. July, August and September were dry months when the Maasai people would migrate to look for green pasture elsewhere.

© T. R. Shankar Raman (top) © F. Broekhuis (above)





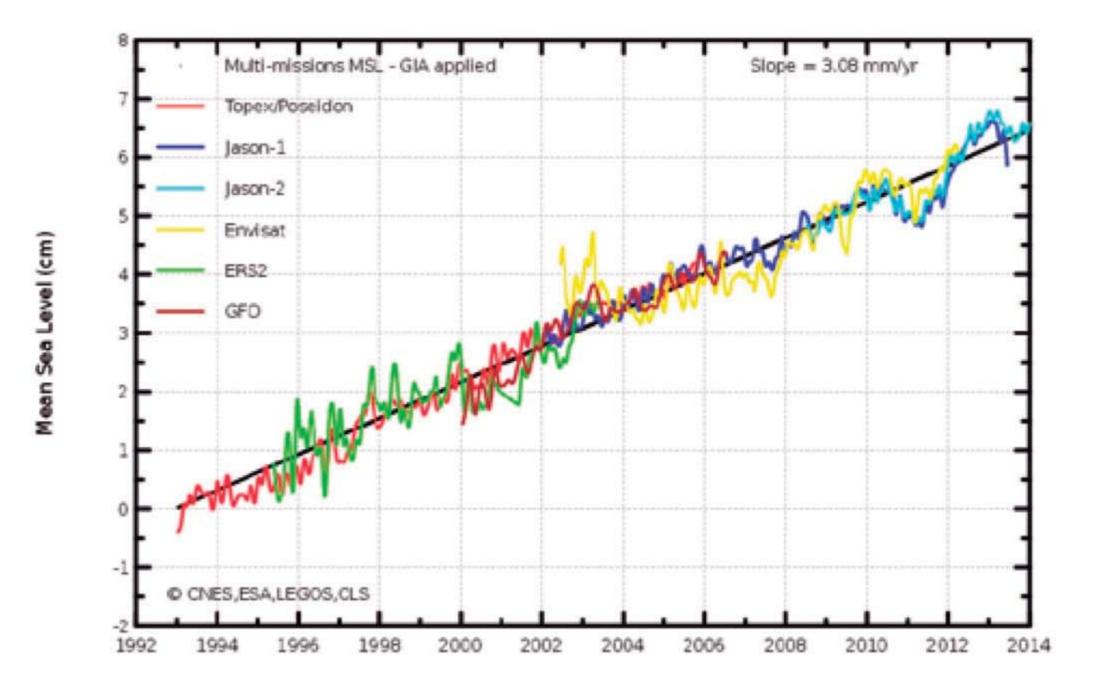
Ocean and inland waters

NE OF THE MOST significant effects of the warming of the planet is the rise in mean sea level and its acceleration over the last decade. This phenomenon has been measured since the end of the 19th century with the help of several dozen tide gauges distributed around the world, in coastal regions or on islands. Over the past 15 years, these field observations have been supplemented by measurements of sea level from space, using satellite altimetry. Whereas the mean rate of increase during the last century was estimated to be about 1.7 mm per year, this rose to 3.1 mm over the last decade. This means that it has nearly doubled. Should this acceleration be ascribed to climate warming, or is it simply part of long-term cycles of variation in sea level? We don't yet know, since the data is too recent. Besides measuring sea level rise, scientists are also attempting to draw up a list of the phenomena that contribute to it. They can be classified into two categories: effects directly linked to the rise in the temperature of the ocean, characterised by its global expansion, and the contribution of additional masses of water, mainly due not only to the melting of glaciers (the polar ice sheets and mountain glaciers) but also to changes in outflow from rivers. The latter is not so well understood, and is currently the subject of much research. The study of natural hydrological cycles and their interaction with human activity (irrigation, deforestation, dams, urban development) will also lead to a better understanding of interannual variability in sea level and its correlation with the mean rise in temperature at the Earth's surface.

Impact on water resources

Inland waters (rivers, lakes, reservoirs, marshes, aquifers, soil moisture and wetlands) account for less than 1 % of the Earth's water, but are of key importance, playing a major role in climate variability. These inland waters constantly exchange energy with the atmosphere and the oceans via vertical and horizontal fluxes, through evapotranspiration and direct and underground runoff. These stores of water are increasing in some regions and decreasing in others, for various reasons. Such phenomena can

be linked to changes in temperature (acceleration of glacial retreat, thawing of permafrost) and to changing precipitation caused by global climate change. Their impact on water resources depends on variations in volume or surface flows, on changes in river basin management systems and on measures taken to adapt to climate change. Regional differences and dissimilar adaptive



abilities affect their vulnerability. It is therefore necessary to quantify their respective effects very precisely. Conversely, changes in hydrological cycles affect the economy, society and the environment. The 'good health' of many ecosystems is very sensitive to the quantity and quality of the water in rivers, lakes and aquifers. Their global distribution and their variability over space and time are still poorly understood due to a lack of in situ data on the scale of the planet. This is why space missions have been used more systematically over the last twenty years. How are hydrological cycles affected by climate change? Water budgets are very sensitive to the slightest changes, on daily to decadal scales. Such variability is chiefly driven by precipitation. Not only change from one year to the next but also very sudden change over a

few days play a very important role in flooding,

for instance. Such change also has an impact

on the frequency and duration of periods of

- ↑ 21 years of Multi-mission global sea level trend from altimetry (1993-2013) with the Glacial Isostatic Adjustment correction applied and the annual and semi-annual signals removed. The altimeter standards and algorithms used to compute the Sea Level Anomalies of each mission have been selected following a formal inter comparison approach so that the products associated with the Sea Level CCI Essential Climate Variable are homogeneous in time and as accurate and stable as possible.
 - © ESA/CLS/CNES/LEGOS



drought that can affect a region. Changes in precipitation are themselves very dependent on variations in the transfer of water into the atmosphere, which is partly linked to variations in ocean temperatures. Thanks to their climate models, scientists can explore every last aspect of this mechanism with the aim of better forecasting future change.

Contrasting effects

In addition, lower precipitation will lead to a greater risk of drought, which can bring about a fall in soil moisture, stored groundwater and river flow, and even cause lakes to dry up. Not forgetting the effects it has on human populations. Variations in temperature are also a factor of hydrological variability, since they alter potential precipitation: higher temperatures increase evapotranspiration by increasing the atmosphere's ability to hold water vapour, with contrasting effects from one region to another. Temperature is

also a key variable for the study of soil moisture, which depends at a given moment on the evaporation rate, on recharge and discharge in deeper aquifers, and on surface runoff.

In the absence of any dedicated space missions, soil moisture on the scale of the Earth is only known via climate models. However, it is also important to emphasize the lack of current and historical global data, and the fact that the models are based on a certain number of hypotheses and climate variables (wind, sunshine and precipitation). This leads to greater uncertainty and to a limitation in the estimation of long-term trends. It should prove possible to refine models for water transfer between the continents and atmosphere thanks to the European space mission, SMOS, whose goal is to map water held in soils and its variability over time. The increase in the temperature of the atmosphere will modify runoff linked to the

melting of continental glaciers, alter snow-

Bangladesh coastline seen by Envisat's Medium Resolution **Imaging Spectrometer** (MERIS). Most of Bangladesh lies within the broad delta formed by the Ganges River and the Brahmaputra River. The Ganges is the most important river of the Indian subcontinent. It flows through Bangladesh into the Bay of Bengal in the Indian Ocean, Several distributaries form a vast network of waterways and one of the world's largest, most fertile deltas.

© ESA



fall episodes, increase thawing of permafrost and increase surface evaporation from lakes. For example, in Siberia the period of snowfall has shortened by several weeks, lakes are thawing earlier, and permafrost is melting on a large scale. Surface snow is also melting earlier, triggering floods earlier in the season. In addition, satellite images have revealed a decrease in the area of over ten thousand 'small' lakes in Siberia.

Another region that is sensitive to rising temperature is the Andes, where the last tropical glaciers are melting. Relatively unimportant on the scale of the South American continent, these glaciers nonetheless form a natural reservoir that is essential for the regional economy. The rivers they feed irrigate the farmland in areas where the population depends on agriculture, provide drinking water to large cities, and produce hydroelectric energy.

Currently, the melting of the glaciers is increasing river flow, but their eventual disappearance would mean the end of naturally regulated water supply, bringing with it serious economic and human consequences. For surface water, the presence of water and its variability depends almost exclusively on precipitation and temperature (disregarding human activity), and this is also true for groundwater. This is the case for aquifers recharged directly by local precipitation, rivers or lakes. They are very sensitive to variations in precipitation that can lead to significant increases or decreases in stored water. Some aquifers that outcrop along flood plains can also be subject to major evaporation, and are therefore, like surface waters, affected by climate change, with stores dwindling or building up again according to the region. They play a vital role as the main water resource in arid or semi-arid rural regions.

The warming of the planet has an indirect effect on groundwater reservoirs in coastal regions or on islands, potentially leading to the increasingly rapid intrusion of sea water, making the fresh water salty and rendering the aquifers unsuitable for consumption. A rise of global sea level would have a similar impact on the deltas of major rivers.

How can long-term trends in hydrological variables be assessed? It's a difficult job, for several reasons. In situ data are fairly recent. Most data come from areas with a long history of land-use and resource-use planning, which leads to non-'natural' variability. In addition, many observation networks (for instance of river flow) have been abandoned or banned. And to make things even more complicated, climatic cycles with long periods overlap with current climate change. In order to make progress, it is necessary to have long time series, and have an overall view. In the absence of terrestrial systems that fulfil these two conditions, space remote sensing, although still in its infancy if one considers the time scales sought after, is promising. For example, satellite altimetry can be used to monitor variations in the levels of major rivers, lakes and wetlands. The same is true of gravimetry missions. Optical and infrared sensors can detect the presence of water at different spatial resolutions (from a metre to a kilometre), providing essential information.

Global and integrated vision

By supplementing in situ measurement networks with observations from space and incorporating this information into hydrological models, we can begin to get a better understanding of the processes that take place on the scale of large river basins, although it will still be very difficult to separate natural effects from effects due to humans, a challenge that must be met in the future. To do this, we need a global and integrated

vision of continental hydrological systems.

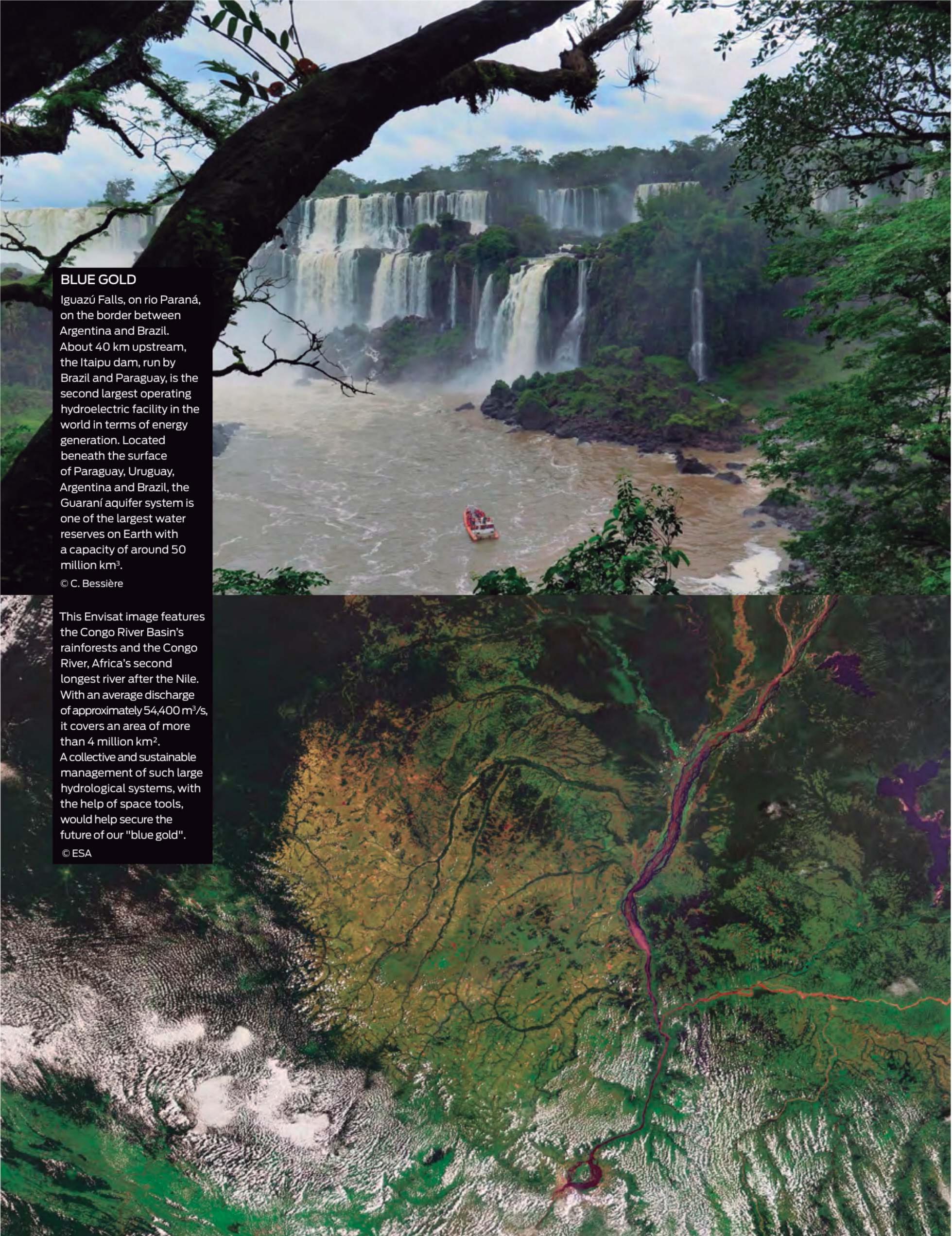
ESA's Soil Moisture and Ocean Salinity (SMOS) at Thales Alenia Space premises. This mission is dedicated to making global observations of soil moisture over land and salinity over oceans. By consistently mapping these two important components in the water cycle, SMOS is advancing our understanding of the exchange processes between Earth's surface and atmosphere and is helping to improve weather and climate models.

© J.-D. Dallet/Suds-Concepts



This can only be achieved through close international cooperation, via major structuring programmes, as it has been the case for operational oceanography or meteorology. From this perspective, cooperation between hydrologists, climatologists, river basin agencies, designers of space systems from both the private and public sector, and political decision makers is essential.

Jean-François Crétaux, LEGOS



SPACE TOOLS

Monitoring the Aral Sea

tuated in central Asia, the Aral Sea was 60 years ago the fourth biggest lake in the world area-wise. Since the 1960s, it has shrunk by a factor of ten, as a result of increased irrigation for the development of cotton and rice crops. At the end of the 1980s, it split into two basins, the small Aral Sea in the North, and the large Aral Sea to the South. Since then, these two basins have developed in very different ways.

The small sea has more or less stabilised, its level even rising at times due to the building of a dam that retains the spring floods of the river that continues to flow into it, the Syr Darya. On the other hand, the large Aral has continued to shrink inexorably, more or less rapidly depending on the year, separating again into sub-basins in the 2010s. Its salinity has increased to values that exceed 100 g/l, thus making it totally hostile to life. In contrast, the salinity of the small Aral has remained fairly low (around 10-15 g/l), and since the mid -2000s fishing has started up again, bringing with it limited but genuine economic recovery.

With regard to the climate, the situation is complex, because the fall in the level of the sea caused by human activity has led to higher temperatures in and around the sea, magnified by global climate change. It is therefore not easy to study and separate the combined effects of these two phenomena, but altimetry satellites and various other instruments, associated with current climate models, will enable us to better understand change in the Aral Sea.

Jean.-François Crétaux, LEGOS



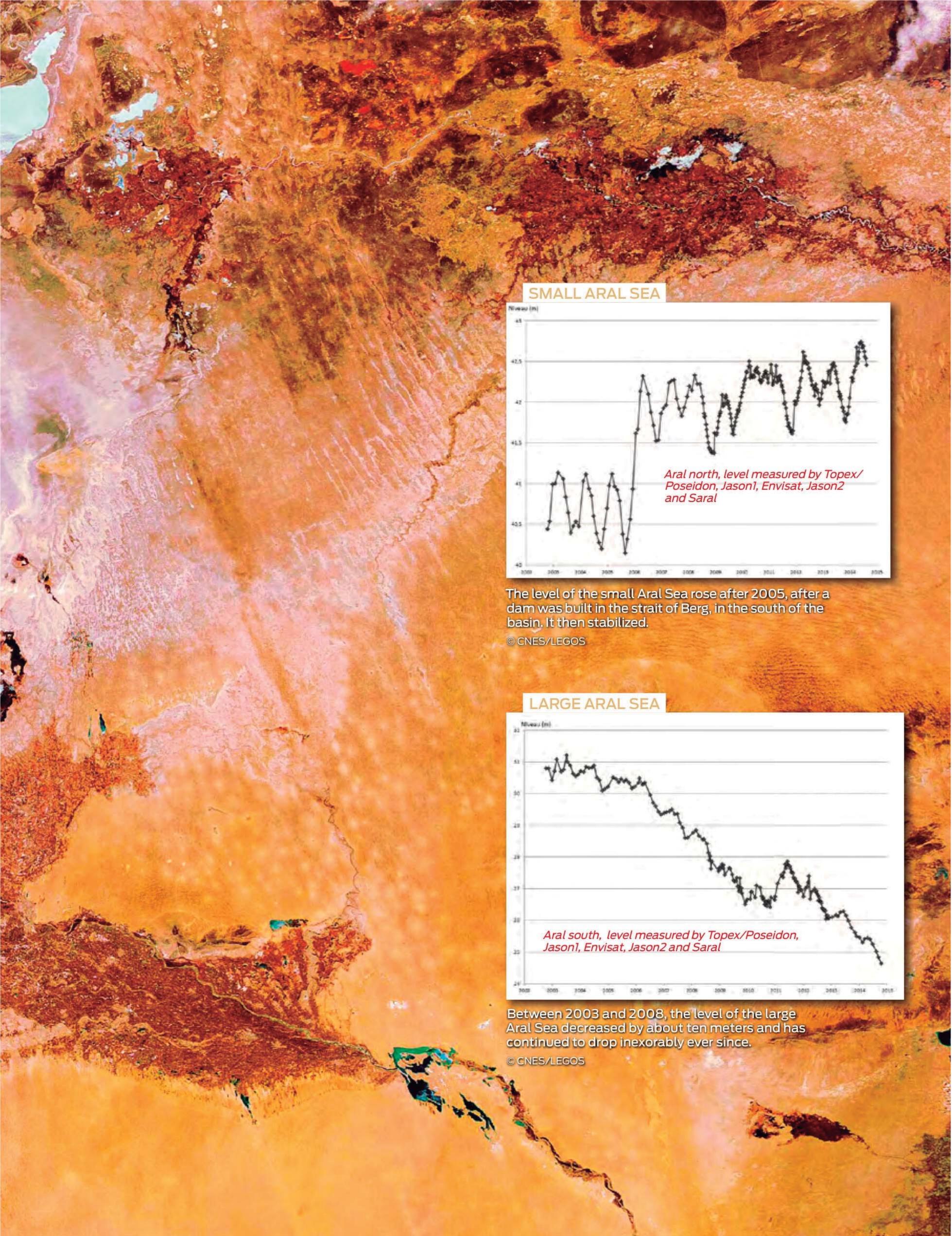
For the past twenty years, scientists have been monitoring changes in the Aral Sea. Shown here, a validation campaign of altimetric measurements.

Image of the Aral Sea, taken in July 2003 by the MERIS instrument on board the ENVISAT

split into two basins, satellite. © ESA **CLIMATE CHANGE & SATELLITES**



© J.-F. Crétaux

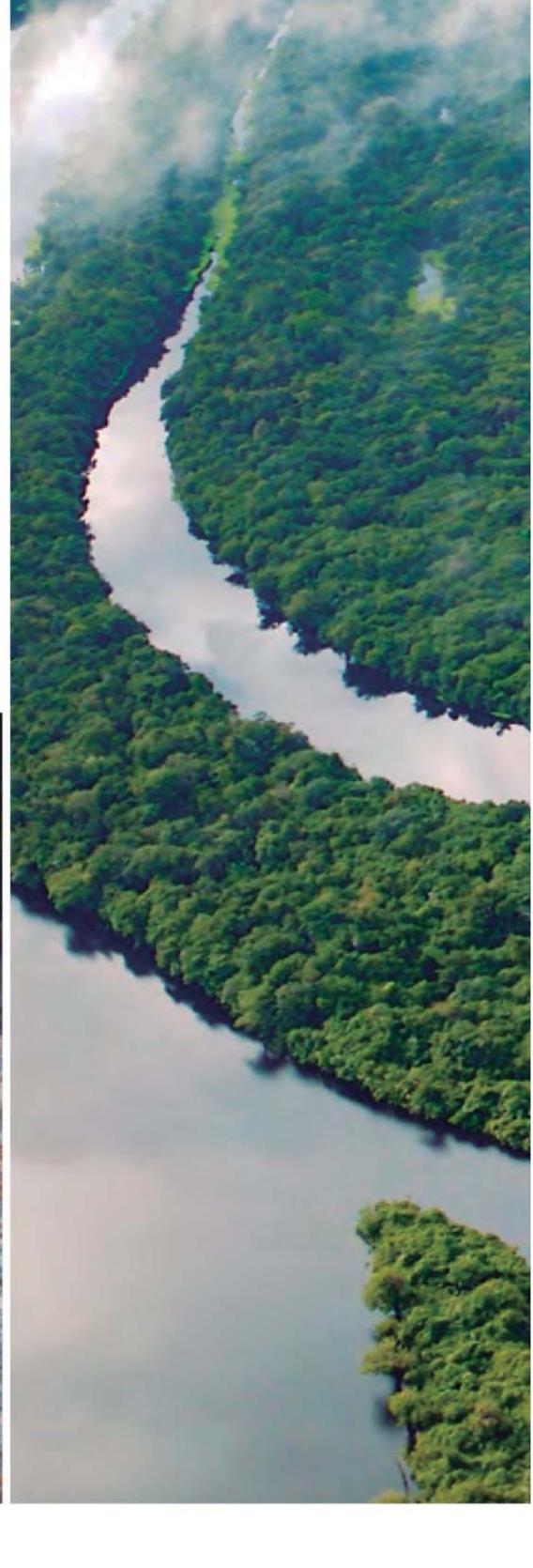


Brazil: droughts and floods

HE AMAZON acts as a natural laboratory, allowing us to see how climate change impacts our planet from both the scientific and socio-economic viewpoints. It is in a sense a marker showing what is happening planet-wide today, and indicating our planet's future.

impacted transport systems: boats can no longer travel along their usual routes, which eventually results in higher food prices. At the same time, flooding weakens fishing and, when it occurs before harvests, destroys crops. These changes also have an effect on people's health, for example through water





We have a network of ground stations, plus 120 years of data on the Amazon, along with a long series of water heights on the Rio Negro, available in Manaus. As early as the late 1970s, we noted an increase in the flowrate of the Amazon river, followed by a rise in its level. Since the 2000s, we have also noticed a major increase in flooding, particularly marked in 2012 and 2014. In certain states, 60% of the population is concerned. Amazonian populations have traditionally adapted to these floods, for example by building houses on pilings. But the changes today are so sudden and so extensive that the people have been caught short. Furthermore, the displacement of sediment deposits, and diversions of river thalwegs have strongly

The Madeira River, (here the Teotonio Rapids) will be covered by the waters of two hydroelectric dams, the Santo Antonio Dam near Porto Velho and the Jirau Dam about 100 km upstream. This river is one of the biggest tributaries of the Amazon and also one of the basin's most active waterways. Brazil hopes a bevy of hydroelectric projects will feed its growing energy demands, but environmentalists are voicing concerns. Thousands of people who depend upon the river and forest for their survival, as the small Pirahã tribe, will be affected. © M. Jégu/IRD

pollution, and increasing cases of malaria. These problems concern not only Brazil, but also Bolivia and Peru, which recently experienced historic flooding.

Drastic situations

The Amazon is also a victim of droughts, for example those of 2005 and 2010, sometimes with Amazon river waters several meters below average. These droughts are linked to deforestation, higher temperatures in the tropical North Atlantic in the winter and in the southern spring, and reduced transmission of water vapor towards the basin. *El Niño* events also play a major role.

Some 40 years ago in the Amazon, we didn't talk about extreme poverty: people had the



The Anavilhanas archipelago includes hundreds of islands in the Rio Negro. An area of 350,000 hectares with a perimeter of 380 km has been put forward by the Brazilian government as a tentative World Heritage Site since 1998. This comprises 100,000 hectares of islands and canals within the Rio Negro and a further 260,000 hectares of riverside forest.

© J. Auch

resources needed to feed themselves, thanks to farming, gathering and fishing. But today, some states face drastic situations because of the droughts, for which their populations are totally unprepared. Another major fact is that mono-culture farming, especially soy beans, is developing under the control of huge agrifoods groups, to the detriment of subsistence agriculture. Elsewhere, hydropower dams are being built, as in Jirau on the Madeira river, near the Bolivian border, and these will also have an impact on a biosphere with limited adaptability, and on local populations.

Our collaborative efforts are top down initiatives (see p. 87). But from the standpoint of fighting and adapting to climate change,

the most urgent objective is still training scientific teams for fieldwork, across the continent, and deploying them for projects targeting local communities, as well as listening to local populations.

Local initiatives

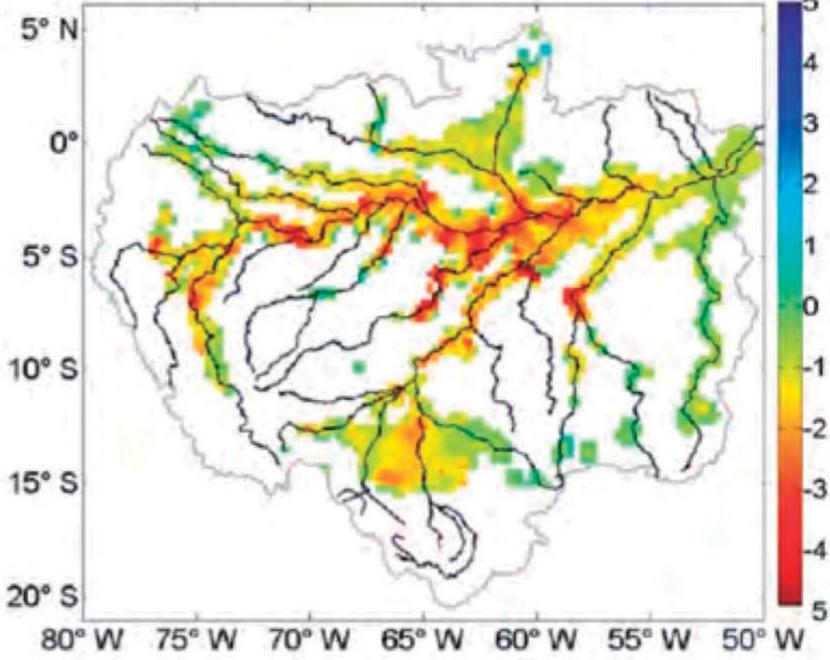
This also applies to major international bodies, such as IPCC, and for our expectations of the conference Climate COP21: we have to take greater account of information from the field, train scientific teams for fieldwork, and deploy them on local projects, via associations. Some have already published results, and manage to be heard in diplomatic circles. For example, "Iniciativa MAP" (border between Brazil, Bolivia and Peru) a poly-





In June 2010, heavy floods battered the states of Alagoas and Pernambuco, leaving a huge trail of destruction and major human, social and economic losses, strongly impacting the economy of the municipalities affected by flooding. According to Brazil's civil defense agency, more than 40,000 were left homeless.

© A. Cruz



The difference, in meters, between the minimum water height on the surface of rivers in the Amazon basin in 2005 and the average minimum height from 2003-2007. Map drawn up by researchers at GET, LEGOS, Observatoire de Paris and ESPACE-DEV, in France, and the State University of the Amazon, in Brazil.

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centric structure, is a local initiative that now comprises other governmental organizations, NGOs, groups of universities and communities. All partners are committed to a planning process that links scientific data with public debate, in order to attenuate the effects of new infrastructures and climate change.

These initiatives may prove to be very effective in terms of services delivered to populations that are regularly impacted by climate change, and which often remain isolated in the middle of the forest. That is also due to unfamiliarity with administrative procedures to gain support, or a lack of knowledge of local conditions by their contacts. Knowledge at local level must be recognized and integrated in international negotiations, especially to deploy policies that help local populations adapt to changing conditions. The biosphere is undergoing continuous changes, and local populations have adapted to changing environments for centuries. In the Amazon, as elsewhere, each family has its own history, techniques, warning systems and methods of construction. By combining today's technologies with local knowledge, we can build very effective systems to adapt to new conditions.

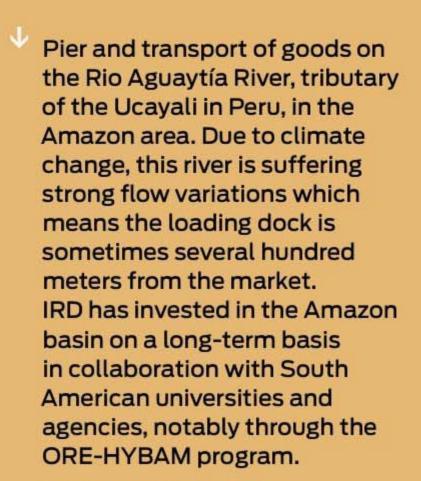
Naziano Filizola, Universidade Federal do Amazonas SCIENCE

Scientific collaborations

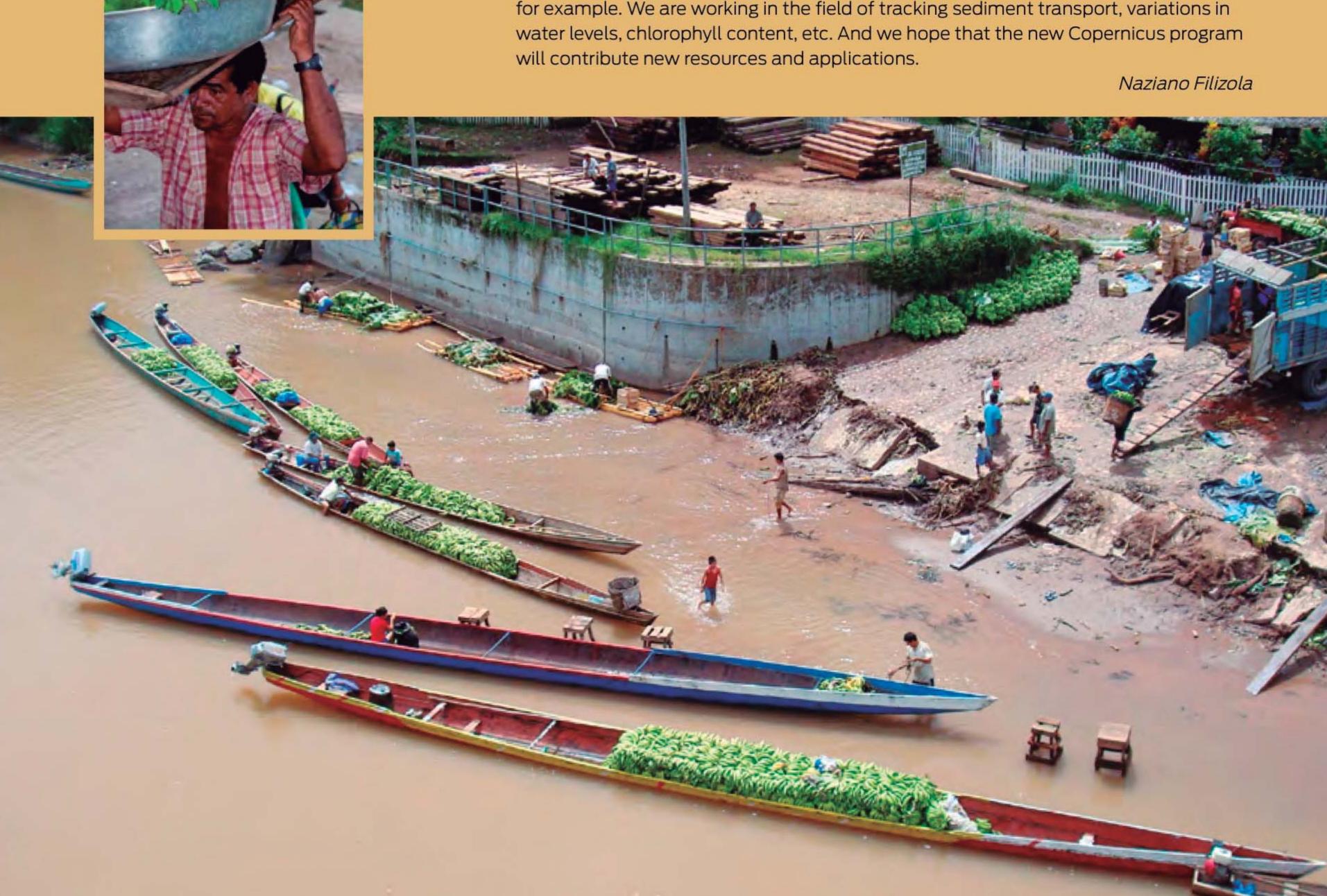
One of our tasks is to further the understanding of climate-related events and the impact of these human actions. We have to be constantly on the alert, intensify our research, improve our analytical capabilities and deploy new tools, in particular using spaceborne resources. We are working with scientist colleagues in San Paulo and Rio de Janeiro, specialists in regional development, and regional occupation scenarios. We are training teams in Brazil, the United States and France to built hydrology, biology and climatology research centers. And we have a number of collaborative efforts under way with our neighbors. For example, the network RAISG (Red Amazónica De Información Socioambiental Georreferenciada), grouping Bolivia, Brazil, Colombia, Ecuador, Peru and Venezuela, the Amazon Cooperation Treaty Organisation (ACTO), founded by several South American countries (Bolivia, Brazil, Colombia, Ecuador, Guiana, Peru, Suriname) and associated with the European Commission's Joint Research Center (JRC) to support the creation of pan-Amazonian environmental information systems.

Cooperation with France

We also manage projects in conjunction with European countries, especially France. For instance, the HYBAM environmental research center "Geodynamical, hydrological and biogeochemical control of erosion/alteration and material transport in the Amazon, Orinoco and Congo basins", which enjoys the support of IRD, INSU and OMP Toulouse. Its aim to provide the research community with the high quality scientific data needed to understand and model the systems behavior and their long-term dynamics. Our Universidade Federal do Amazonas (UFAM), has been working with IRD since 2003 on real-time satellite observations, via Jason and Saral/AltiKa, for example. We are working in the field of tracking sediment transport, variations in water levels, chlorophyll content, etc. And we hope that the new Copernicus program will contribute new resources and applications.



© M. Jégu/IRD



Jason, the ocean mapper

CEANS have a fundamental influence on the Earth climate. Over the last 50 years they have absorbed more than 90% of the excess heat received by the planet because of the anthropogenic increase in the concentration of greenhouse gases (especially CO₂). At the same time, they have absorbed nearly 30% of anthropogenic CO₂ emissions. These major buffering effects are not without consequences on the ocean physics and chemistry: sea level rise, increase in temperatures at the surface and at depths, sea ice melting, deoxygenation and expansion of oxygen minimum zones, acidification. These changes in the physical-chemical parameters of oceans have a large impact on ecosystems and marine resources, which are already subject to strong pressures from other human activities, including pollution and overfishing. Furthermore, the oceans' ability to absorb CO₂ is not unlimited, and the increase in temperature and stratification could reduce its' buffering effect in the coming decades.

Long-term observations of all oceans are imperative to better characterize climate change, understand and predict their role on climate, and also to make informed political decisions on how to attenuate and adapt to climate change. You cannot manage what you do not observe and do not understand.

Global and integrated vision

Satellite altimetry is a key component of the global ocean observation system set up by the oceanographic community to address these challenges. The Jason series provides the altimetry reference system with very high precision missions optimized for climate monitoring of the oceans. After TOPEX/Poseidon, the Jason-1 and Jason-2 satellites took over this task, and will soon be followed by Jason-3. More than 20 years of continuous and remarkably accurate measurements of sea level (thanks, in particular, to the series of Poseidon-1, 2 and 3 radar altimeters) have driven major advances in our understanding of the oceans and the climate. Mean sea level variations

and their geographical changes have been precisely characterized. The mean sea level rise is slightly over 3 mm/year for the last 20 years, which seems to confirm a sea level rise acceleration (measurements gathered by tide gauges from the start of the XXth century gave an average rise of less than 2 mm/year). Regional variations reflect the influence of ocean dynamics, and will be important factors in deciding on local protection measures. Jason satellites have also enabled us to characterize and track in real time the development of El Niño and La Niña events in the equatorial Pacific, whose effects can be felt planet-wide. A number of other major scientific advances have been made possible thanks to altimeter data (e.g. large-scale variations of ocean circulation, monitoring and characterization of ocean eddies, tides and internal tides).

Outstanding synergy

The oceans should be permanently observed by several altimeters flying simultaneously. The TOPEX/Poseidon and Jason series has benefited for more than 20 years from the complementary ERS-1/2, ENVISAT and SARAL/Alti-Ka missions.

This will be pursued in the future with the Sentinel-3 mission from the Copernicus European program. Argo, the international array of profiling floats, has been providing temperature and salinity measurements from the surface down to a depth of 2000 meters for the last couple of years. Argo data are very complementary with that from altimeters. This outstanding synergy (Jason and the Argonauts!) drives even more important advances, which in turn strengthens the contribution of Jason satellites. For example, we can now characterize far more accurately the respective roles of ocean warming (thermal expansion) and the melting of continental glaciers and ice caps (Greenland, Antarctica) in changing sea levels. This plays a vital role in improving our long-term forecasts. In recent years, it is estimated that about one third of the mean sea level rise is due to thermal expansion and the rest due to mass variations.



↑ Jason 2 is a satellite designed to make observations of ocean topography for investigations into sea-level rise and the relationship between ocean circulation and climate change. The satellite also provides data on the forces behind such largescale climate phenomena as El Niño and La Niña. The mission is a follow-on to the French-American Jason 1 mission, which began collecting data on sea-surface levels in 1992. Here, Jason 3. © Cedric/imag[IN]

Geographical variations of mean sea level rise derived from more than 20 years of altimeter measurements. The figure highlights large regional variations due to ocean dynamics (e.g. El Niño/La Niña).

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Also worth mentioning is the very important contribution of the GRACE gravimetry mission, which provides a direct measurement of these changes in mass, and especially exchanges between oceans and continents.

Regional MSL trends from Jan-1993 to Oct-2014 (mm/year)

© CNES/LEGOS/CLS, 2015

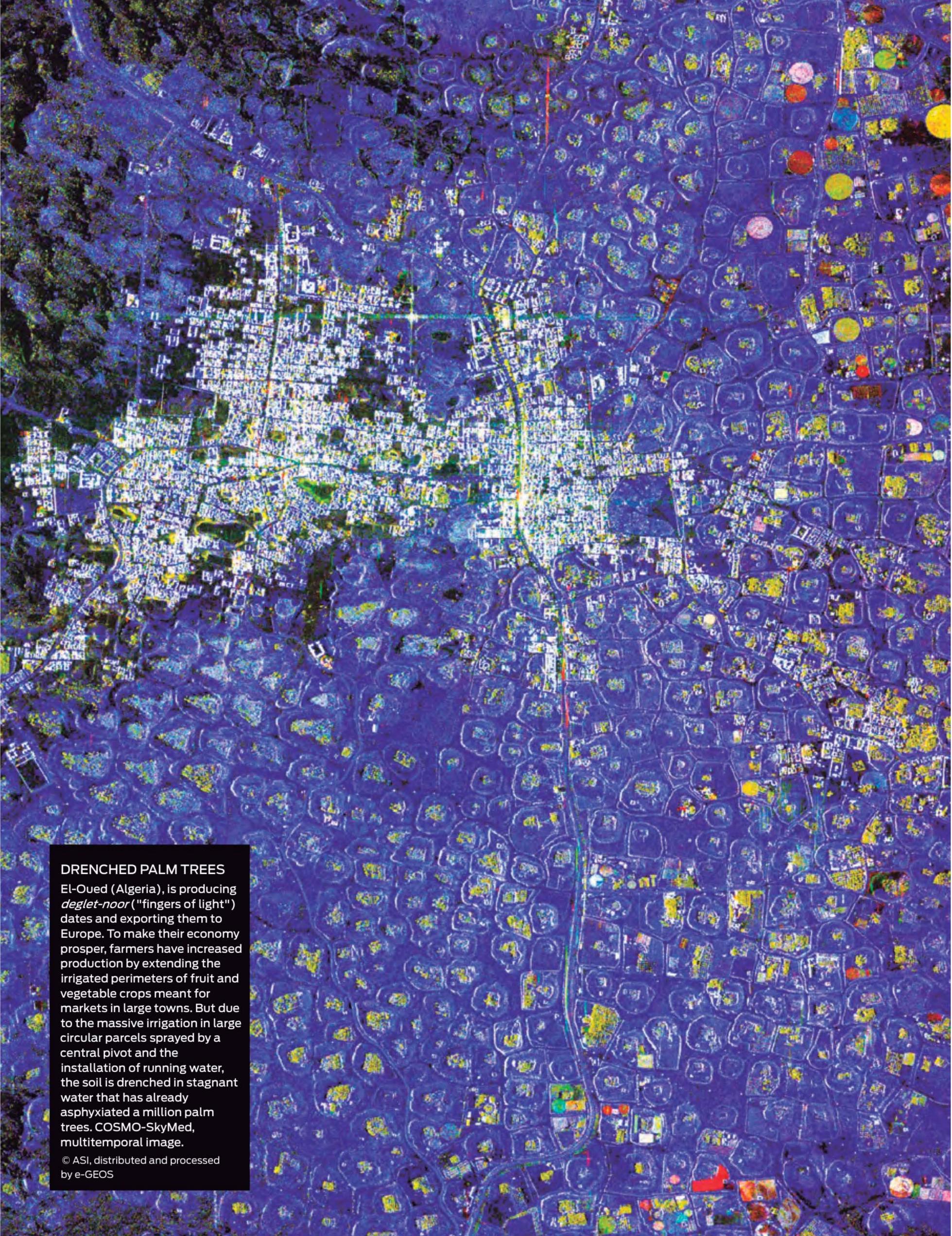
More generally, by integrating data from Jason with other satellite measurements and all *in-situ* measurements together with ocean models, using powerful assimilation methods, we can provide detailed des-

criptions of the ocean state at all depths, and predict changes in the next few weeks. These detailed ocean descriptions are also essential in initializing coupled ocean/atmosphere models to predict changes in the atmosphere and in our climate over longer time periods. Mercator Ocean, the French operational oceanographic center, has applied these techniques for more than 10 years and is coordinating the marine service of the European Copernicus

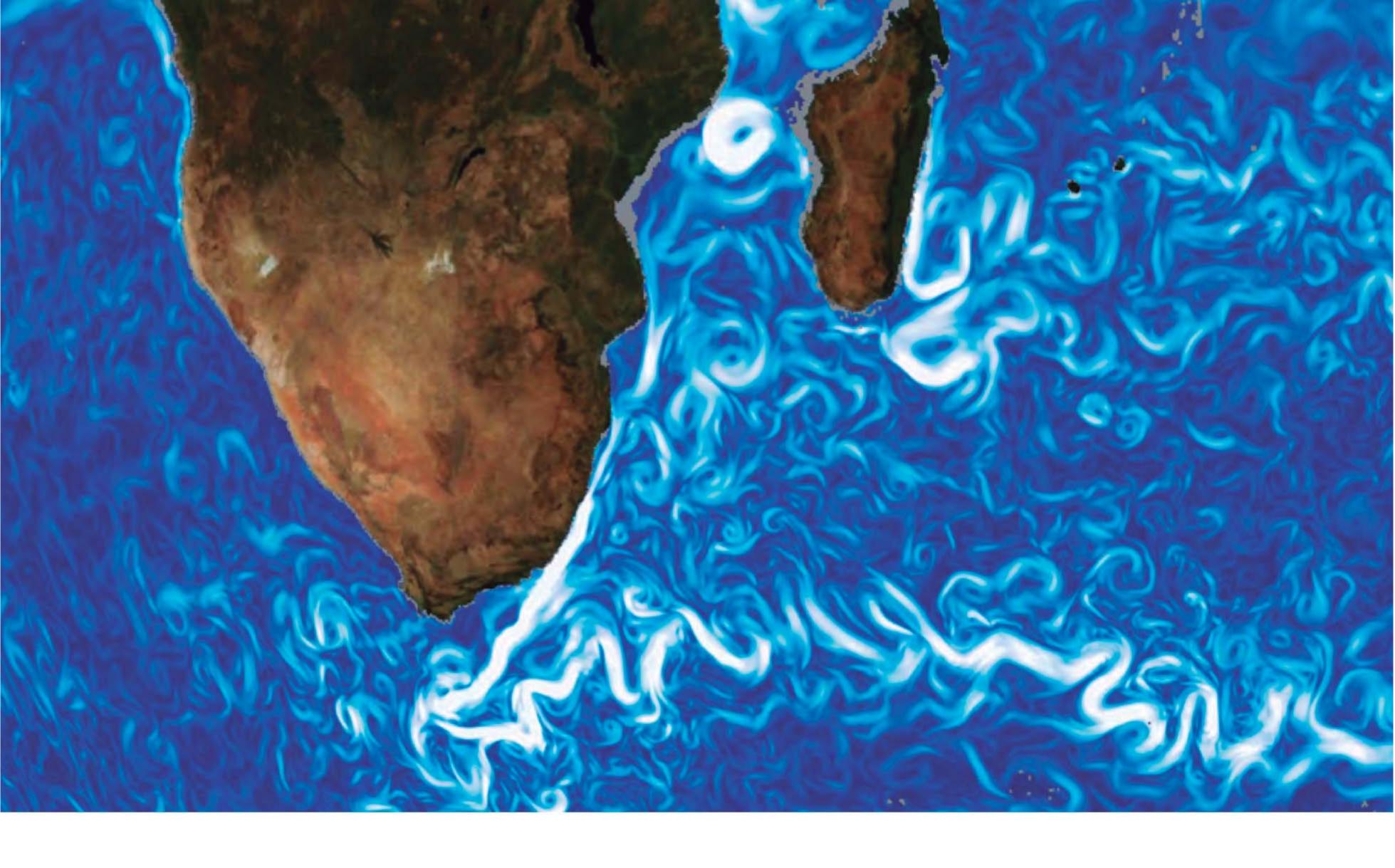
program. Jason satellites therefore have made considerable contributions in these areas, strengthened by complementary altimeter missions, the implementation of the Argo array and the development of advanced global ocean analysis and forecasting capabilities.

It is vital that the Jason series be maintained in the coming decades to track and predict changes in the oceans and the climate, as well as to address a wide variety of application needs. The message has been well received, and Europe, via its Copernicus program, has already planned a follow-on to Jason-3 for the period 2020-2030, with the two Jason-CS satellites (Sentinel-6). Furthermore, Jason-CS will provide the large-scale context for the upcoming SWOT altimetry/interferometry satellite, a revolutionary new concept for very-high-resolution ocean and continental surface water observation, to be launched in 2020.

Pierre-Yves Le Traon Mercator Océan and Ifremer







Marine monitoring

AUNCHED IN MAY 2015, the Copernicus Marine Environment Monitoring Service (CMEMS) is part of the EU Earth Observation Programme implemented by the European Commission, jointly with the European Space Agency (ESA) and the European Environment Agency (EEA). Its implementation has been delegated to Mercator Océan, the French centre for analysis and forecasting of the global ocean, located near Toulouse. This EU information marine service provides regular and systematic reference information on the physical state and on marine ecosystems for the global ocean and the European regional seas (temperature, currents, salinity, sea level, sea ice, nutrients, chlorophyll and primary production). This capacity encompasses satellite and insitu observation-derived products, the description of the current situation (analysis), the prediction of the situation a few days ahead (forecast), and the provision of consistent retrospective data records for recent years (re-analysis). This is a unique service worldwide, based on the conti-

nuation of a service concept successfully demonstrated through the MyOcean projects (2009-2014) co-funded by the European Union and Member States and having involved 60 partners from 28 countries, all pivotal actors in the European marine research and operational oceanography communities.

CMEMS offers the guarantee of providing the latest scientific knowledge through a permanent dialogue established for years with a community of specialists in operational oceanography, whether they be producers of data or experts. The service is on full, open and free access for users via a single point of entry, a dedicated portal that gives access to a catalogue of a more than a hundred oceanography products (Observations and Models) that are regularly updated.

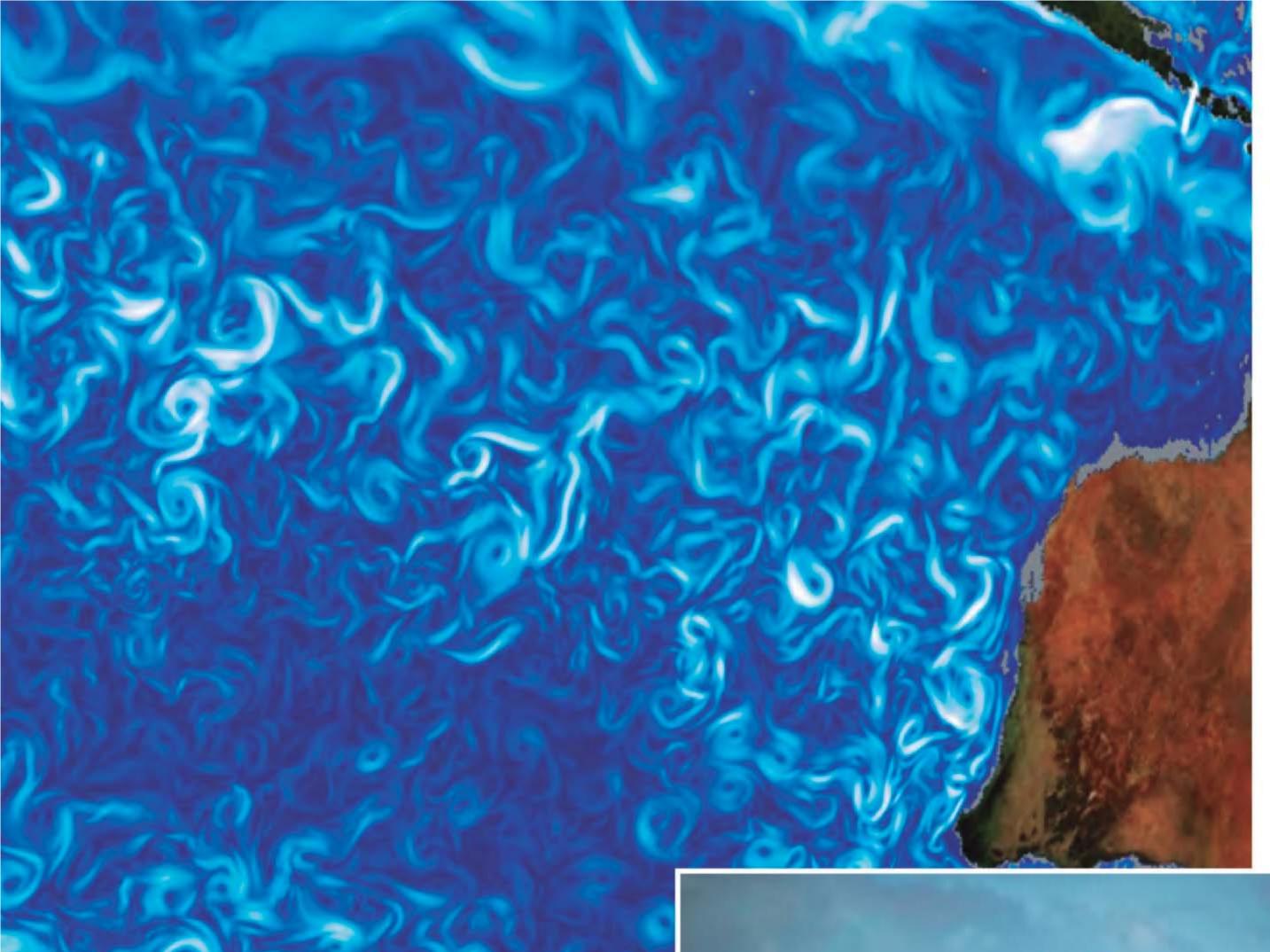
Improving forecasts

CMEMS is a "core "service providing a sustainable response to European user needs in four areas of benefits for which improving knowledge of the seas and oceans is of utmost importance: maritime safety,



Agreement of Copernicus
Marine Environment Monitoring
Service to Mercator Océan,
November 2014. From right
to left: Daniel Calleja-Crespo,
Director General of the EC's DG
Enterprise and Industry and
Pierre Bahurel, Director General
of Mercator Océan.

© European Union



Eddies caused by the Agulhas Current, along the southeast of Africa. Ocean general circulation model. Located at the interface between the Indian and Atlantic Oceans, this current multiplies injections of warm and highly concentrated salt water into the Atlantic from the Indian Ocean. This process of interocean exchange is a key link in the global thermohaline circulation and is largely

© Mercator Océan

controlled by impulses

coming from far upstream.

marine resources, coastal and marine environment, weather, seasonal forecast and climate. Information provided helps improving weather and seasonal forecasts and contributes to climate monitoring and assessment for the marine component of the Earth system. Reliable and robust data is for instance delivered to the national meteorological weather services: physical parameters of the ocean's surface are used as boundary conditions for atmospheric models and/or to constrain coupled ocean/atmosphere models.

On longer time scales, predicting the evolution of our atmosphere and climate requires a precise knowledge of the ocean at depth. Seasonal forecasting centers are therefore heavily dependent on a precise description of the state of the upper ocean; they use *in-situ*/satellite observations and models from the CMEMS to initialize their coupled ocean/atmosphere models.

Future sea-level rise

CMEMS Sea Level and Sea Surface Temperature anomalies are also closely monitored by meteorologists to study occurrence probability of Ocean/Climate phenomenons like *El Niño* (ENSO) events causing drought, flooding and hurricanes around the world. Global and regional ocean reanalyses provide an integrated description of the 3D ocean state over the past decades and contribute to the monitoring of key ocean climate indicators (*e.g.* sea level rise,

ocean heat content, overturning circulation) and long term evolution of the global ocean and European regional seas. They are complemented by information derived directly from *in-situ* observations (*e.g.* the Argo global array of profiling floats) and satellite observations (*e.g.* Jason-2, the future Jason-3 and Sentinel-3A altimeter missions). These results contribute to the definition of future Sea Level Rise and Global Warming Projections IPCC scenarios.

Sea ice extent, concentration and volume data are also closely monitored through observations and data assimilative models; they provide essential information to assess and understand climate change and its impacts in the Arctic Ocean, a region extremely vulnerable to climate change.

Pierre-Yves Le Traon, Mercator Océan

Coast Guard during storm.

Many scientists now
project that the Eurasian
side of the Arctic could be
ice free in summer within
five to 30 years, which
would allow passage
between Asia and Europe
for up to three months
a year. The Coast Guard
would have to ensure
safe passage for vessels
traversing the Arctic.

© iStock/Mercator Océan



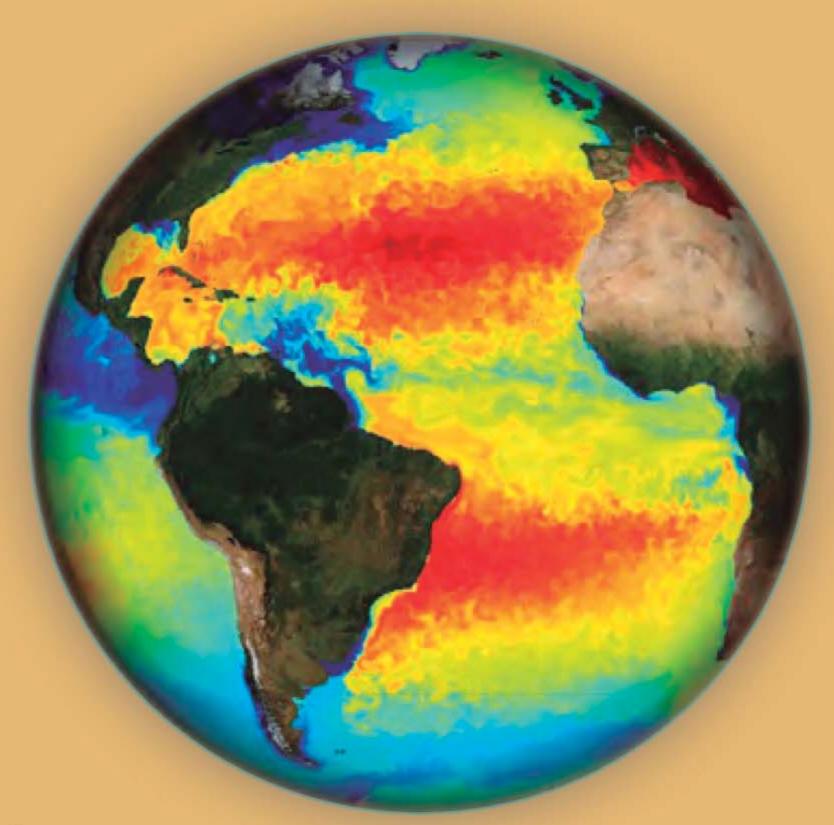


SPACE TOOLS

Successful teamwork

he Jason-3 operational oceanographic satellite was built by Thales Alenia Space within the scope of a quadripartite agreement between EUMETSAT, NOAA, and the French (CNES) and American (NASA) space agencies. Jason 3 will ensure operational continuity for the high-precision oceanographic topography measurements delivered by Topex-Poseidon, Jason 1 and Jason-2, still operational in orbit. It will provide the same accuracy as Jason-2 for oceanic measurements, including coastal zones, as well as lakes and other bodies of water. Thales Alenia Space is the industrial architect. The Topex-Poseidon and Jason missions are "state-ofthe-art" for altimetry-based operational oceanography, and also provide a perfect illustration of a successful team effort between France and the United States. In fact, these were baseline missions that enabled measuring ocean heights, along with changes since the early 1990s. The Poseidon altimeter played a major role in these missions, giving climatologists vital data on oceans. The next generation of Poseidon altimeters will be used on Sentinel-6, scheduled for launch towards 2020.

Yvan Baillion, Thales Alenia Space

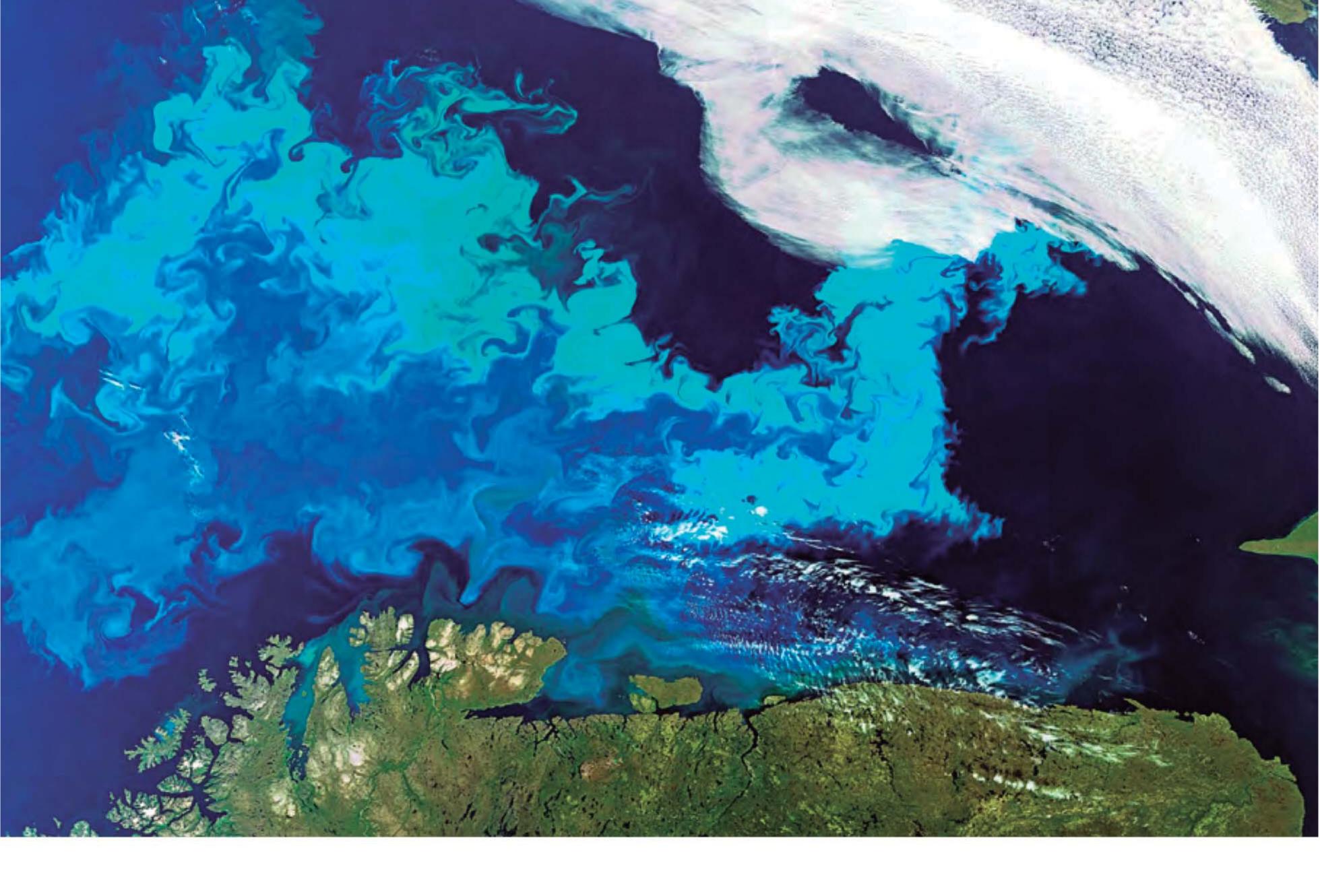


The Jason-3 satellite is being prepared for its weight, balance and inertia tests, all necessary to confirm its compatibility with the launcher, and also to make final precise predictions for its in-orbit performance.

© Cedric/imag[IN]

Ocean state description and forecast from the global modeling and data assimilation system at 1/12° resolution operated by Mercator Océan. The figure represents an analysis of surface salinity.

© Mercator Océan



SWOT: a generation ahead

Water & Ocean Topography) brings together French and North American oceanographers and hydrologists to focus on a better understanding of the world's oceans and its terrestrial surface waters. Launch date: 2020. The aim is to make the first global survey of the Earth's surface water, observe the fine details of the ocean's surface topography, and measure how water bodies change over time.

The SWOT satellite with its wide-swath altimetry technology, will completely cover the world's oceans and freshwater bodies with repeated high-resolution elevation measurements.

Hydrological observations of the temporal and spatial variations in water volumes stored in rivers, lakes, and wetlands are extremely important for monitoring the world's freshwater resources. By measuring water storage and making it possible to estimate discharge

in rivers more accurately, SWOT will contribute to a fundamental understanding of the terrestrial branch of the global water cycle.

For the oceans, a global study of the ocean circulation at scales of 15 -200 km is essential for quantifying the kinetic energy of ocean circulation and the oceanic uptake of heat and carbon that are key factors in climate change. The oceanic uptake of heat and carbon is regulated by the 3-D ocean circulation, and we estimate that 50% of the vertical velocities in the ocean occur at the submesoscales. So our understanding of how the ocean uptakes heat, carbon and nutrients in a changing climate, will depend on our ability to observe and understand these submesoscale processes. The improved ocean dynamics observed by SWOT will open a new window for studying these processes.

Coastal observations

Coastal ocean dynamics are important for many societal applications. They have smaller spatial and temporal scales than the dynamics of the open ocean and require finer-scale monitoring. The SWOT interferometric processing will provide global, high-resolution observations in coastal regions for observing coastal currents and storm surges. While SWOT is not designed to monitor the fast temporal changes of the coastal processes, the swath coverage will allow us to characterize the spatial structure of their dynamics when they occur within the swath, and help improve coastal models and forecasting for many applications, including navigation, search and rescue and coastal engineering.

Coastal tides

The SWOT orbit has also been chosen to detect ocean tides, and the new capability of mapping sea surface height down to

15 km scales will improve the knowledge of coastal and polar ocean tides as well as internal tides that have not been well sampled by conventional altimetry.

This new information is crucial to achieve our ocean circulation objectives, by separating the tidal signals from the ocean circulation signals. Improved tides are also important for both coastal and open oceans applications and for an improved understanding of ocean mixing.

Biological cycle

Vertical velocities in the ocean associated with the divergence and convergence of ocean currents can penetrate to a few hundred meters below the ocean surface. These vertical velocities are important for the exchange of nutrients between the surface and deeper layers, with consequences for the biological cycle and the oceanic carbon pump.

The new SWOT observations of the finescale dynamics is thus of great value to biogeochemical studies of the ocean.

Rosemary Morrow (LEGOS) Lee-Lueng Fu and Ernesto Rodriguez (JPL) The phytoplankton bloom pictured in this Envisat image stretches across the Barents Sea off the coast of mainland Europe's most northern point, Cape Nordkinn. Although most types of phytoplankton are individually microscopic, the chlorophyll they use for photosynthesis collectively tints the colour of the surrounding ocean waters.

© ESA

French space agency
CNES signed a contract
with Thales Alenia Space,
covering the design and
development phase for the
Poseidon-3C radar
altimeter on the SWOT
satellite, built by Thales
Alenia Space as prime
contractor. The choice of
this altimeter can be traced
to the instrument's perfect
precision and unrivaled
performance.

© CNES/Pierre Jalby, 2015

The Florida Straits as seen from Envisat. The Bahamas consist of a chain of islands and shallow water banks extending from Florida (top left) to Cuba. Hurricanes resulting from increases in ocean temperature are expected to occur with greater frequency and intensity. This could threaten the survival of unique coral reefs and affect the economies of the region.

© ESA







CONCERN



Devoted to water

When I was a child, in 1994, a public fountain was installed close to our settlement ('douar') and I was very happy to see a real fountain for the first time. It was aimed to serve 450 families in Oued Sbaihya (Zaghouan). In total, 34 public fountains were installed. Nevertheless, our potable water network run into difficulties since it was installed in 1994:

- Due to technical problems, water has never reached the 4 installations and 60 families had to fetch water from distant fountains, wells, etc. under hard conditions;
- -Water from the public fountain is 10 times more expensive than urban water:
 1.5 tunisian dinar/m³ (about €0.68) instead of 0,155 charged by the Tunisian National Water Distribution Utility;
- -Technical and especially management problems caused repeated and often long supply cuts throughout the network; the worst one lasted from 2004 to 2009;
- In August 2010, the Agriculture Development Group (GDA) of Oued Sbaihya was designated by the local administration to manage the distribution of water in the territory of Oued Sbaihya with the supervision of the technical department of the Ministry of Agriculture in the Zaghouan Governorate.
- The GDA set up a system for the participatory management of the fountains: 30 volunteers (22 men and 8 women) were designated by the community to help the GDA.

Claiming the right to water

Up to 2011, I took care of our fountain for selling water to the neighbors at the price set by the GDA per can, or more rarely per tank. The GDA manager visited our 'douar' to collect the money based on the measurement of the meters. However, due to a number of issues (transportation, weather, other engagements, etc.) he did not come very often and the electricity bill (for pumping) was not paid in time. The Tunisian National Water Distribution Utility then cut the electricity supply and this also resulted in cuts in the water supply. After the revolution of January 2011, the community of Tbainia, just like all rural communities in Tunisia claimed their right to water. Most families decided to connect to the water supply network, providing them with piped drinking water at home. They installed their individual meters and GDA members now collect payments periodically based on the measured water consumption.

Chafia Tbini, ex-volunteer in charge of a public drinking water fountain in Tbainia with Noureddine Nasr & Szilvia Lehel (FAO)

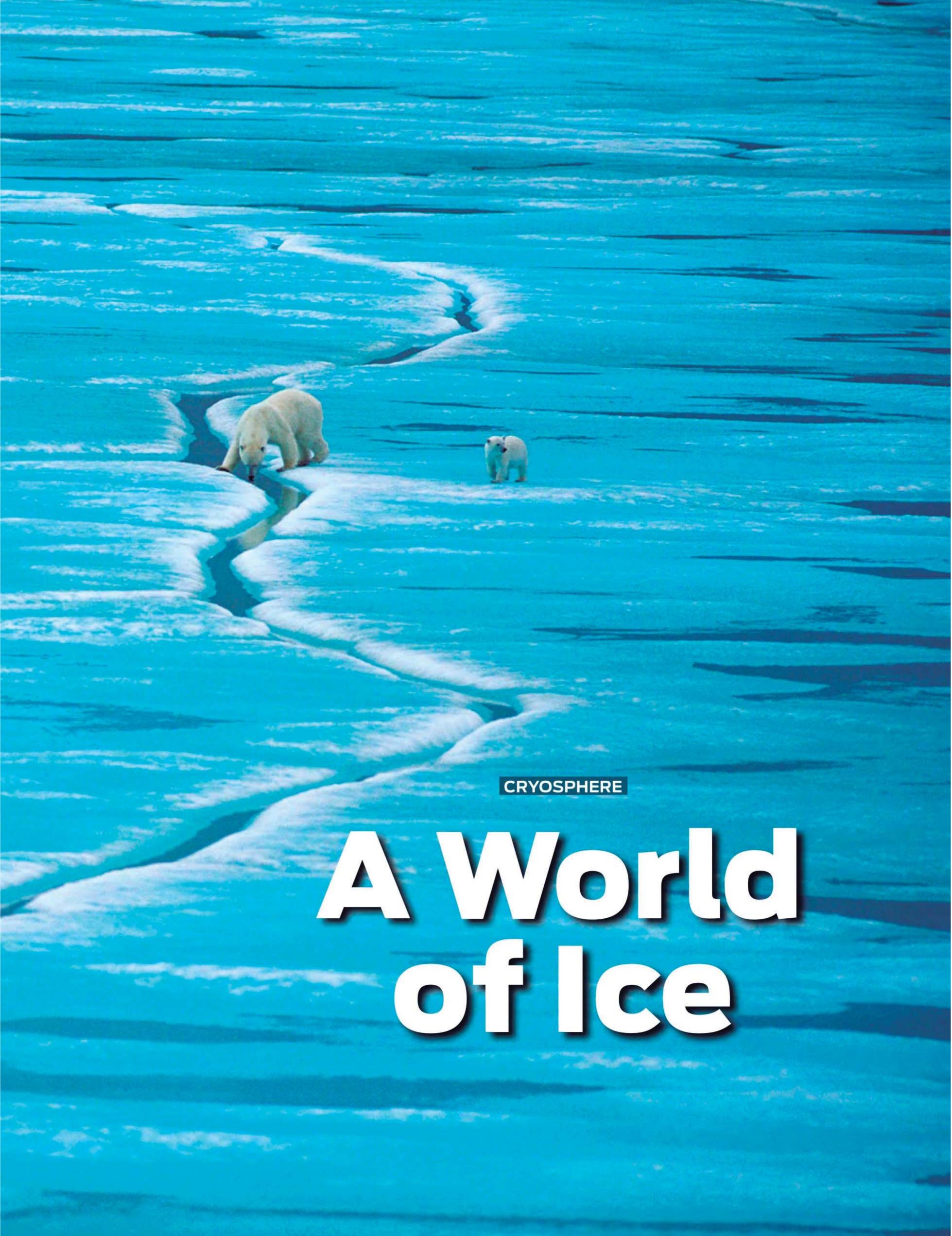
Since I was a child, I have devoted a significant part of my life to drinking water. As a little girl, I went with my mother to fetch water from springs and from wells in the valleys, so called 'wadis'. This was a difficult task, especially in summer and winter. I got married 2 years ago and left Tbainia to live in a village where we have access to piped water at home. Nevertheless, in Tbainia, as in other rural areas, many girls and boys leave school behind to be engaged in livestock activities and fetching drinking water.

C.T

Women fetching water from fountains, Merguellil basin (top) and Tbainia (bottom)

© IRD/R. Calvez







lce and climate

EA ICE, mountain glaciers, the polar ice sheets and the snow that covers the continents all go to make up the cryosphere. They not only affect the climate, but in return are affected by climate change. They affect the climate by reflecting a large part of the energy they receive from the Sun, thus cooling down their environment. And they are affected by it, because the slightest fluctuation in the climate sooner or later alters their volume or their area. Ice and snow play a key role in the climate. This is because they both have high reflectance - known as albedo which can lead to a kind of 'snowball effect'. For snow, this ability to reflect the energy received from the Sun has a value ranging from 0.85 to 0.9. In other

words, 85-90% of the solar energy is reflected and only 10-15% is absorbed. In comparison, the albedo of ice-free sea and land is around 0.2-0.3, which means that about 75% of the heat is absorbed and 25% reflected back into the atmosphere. When an area becomes free of ice or snow, it absorbs 4-5 times more heat than previously. So the larger the area covered by ice and snow, the greater effect they have. And this area is huge: depending on the season, it ranges from 40 to 85 million km², in other words 7-17% of the Earth's surface.

Continental ice melting

In addition, snow and ice have very high latent heat: when they melt, they absorb a great quantity of heat, which cools

down the climate, thus lengthening the spring season. In turn, the climate has an effect on snow and ice. Warming obviously leads to greater melting of snow. However, paradoxically, it can also increase the volume of snow, because warm air contains more humidity than cold air, which steps up the water cycle, leading to increased snowfall. So, depending on the mean ambient temperature, the cryosphere reacts to the climate in different ways. If temperatures rise from -1°C to 0°C it shrinks, whereas if they rise from -10°C to -9°C it grows.

Satellites monitor ice cover

However, these are the only things that continental glaciers, polar ice sheets and



Greenland melt stream. Over the course of several years, turbulent water overflow from a large melt lake carved this 60-foot deep canyon (note people near left edge for scale).

© I. Joughin, University of Washington

Research director emeritus at French national scientific research agency CNRS, Claude Lorius explained that antarctic ice contained memories of our past climate and showed the role played by greenhouse gases in climate warming. This glaciology pioneer is the hero of Luc Jacquet's 2015 film, La glace et le ciel ("Ice and Sky").

© M. Perrey/Wild Touch

sea ice have in common. Sea ice is very thin, a few metres at the most, and it is very sensitive to the climate since it is in contact with both the ocean and the atmosphere, which are both currently warming up. On a seasonal scale, its area varies enormously. So it is sea ice which has the greatest influence on climate due to the effect of albedo. On the other hand, when it melts it has no effect on sea level. Since it is floating in the sea, it occupies the same volume, whether it is frozen or not. Continental glaciers, however, are thicker and more inert. They therefore don't react as much or as quickly to climate fluctuations: several years for a small glacier, and thousands or even tens of thousands of years for the large polar ice sheets. The melting of this continental ice contributes to rising sea levels. It can also alter the circulation of oceanic water masses and hence the transport of heat.

Ice, glaciers, ice sheets and snow are highly sensitive indicators of climate change, sometimes because they are impacted by new climate conditions which can affect their very survival, which is the case for certain mountain glaciers, and sometimes because they are located in the Arctic where the climate is warming much faster than elsewhere.

This is why it is important to monitor such change very carefully. The problem is not only that the areas covered with snow and ice are huge, but also that they are generally located in remote areas in high mountains or near the poles, where the climate is exceptionally cold and windy. Because of their ability to carry out global observations, repeated over time, spaceborne instruments therefore have a vital role to play. In addition, they can observe over a wide range of wavelengths, including the infrared, visible wavelengths (radiometers) and microwaves (radar altimeters and SAR-Synthetic Aperture Radar- imaging radars).

The extent of winter snow cover or of sea ice is extremely variable. In the Northern hemisphere, and depending on the season, the area covered by sea ice can range from 7 to 14 million km², and that of boreal snow cover from 1 to 50 million km². From one year to the next, these values can vary by up to a million km². Radiometry measurements carried out since 1978 by American Nimbus and then DMSP (Defence Meteorological Satellite Program) satellites show that the mean decrease in Arctic ice surface is currently of a few per cent per decade.



Warming of the Arctic

This reduction is particularly marked in September. From the 1980s until now, during this month alone, more than three million km2 of ice has disappeared, in other words six times the area of France. Due to feedback mechanisms, this phenomenon is contributing to the warming of the Arctic. And because of this mechanism, the reduction in sea ice may speed up in the future, in turn accelerating the warming which has already begun. Today, it is estimated that one third of global warming is due to the warming of the Arctic. However, it is still extremely difficult to measure the thickness of sea ice. The reason is that this

thin layer of ice is too wet for electromagnetic radiation to be able to penetrate it. The only solution is to measure, in the numerous water holes that form in the ice, the difference in height between the surface of the sea and that of the ice, since it is well-known that only one tenth of the ice emerges above the water. This is the mission of ESA's CryoSat2 satellite, launched in 2009.

Unfortunately, it is still extremely difficult to measure the volume of continental ice. The only solution therefore is to survey variations in its volume by monitoring its surface topography using altimetry, or its mass using gravimetry.

Since the launch of ERS-1 (European

Remote Sensing Satellite) in 1991, followed by ERS2, EnviSat and now AltiKa (French-ISRO) on the same historical 35-days orbit, it has been possible to measure with great precision the topography of the Greenland and Antarctic ice sheets.

Repeated monitoring has shown that the Greenland ice sheet is changing shape: at the centre its altitude remains roughly constant and at the sides it decreases so the Greenland looses 140 GT/ year between 1991 and 2011 (or 0.45 mm/yr s.l.e) and reaches now 370 Gt/yr (around 1 mm/yr s.l.e). Here, surface melting appears to be increasing, as well as ice flow rates on the coast. East



A Concordia crew member inspecting ▼ scientific equipment near the Italian— French Concordia research station in Antarctica. Situated 3200 m above sea level with temperatures that can reach -80°C, oxygen is scarce. The crew live with permanent hypoxia. Despite the hardship, scientists flock each year to this unique station to research the Antarctic continent, the climate, our planet and the stars. During the winter a core crew of up to 15 stays behind to tend the equipment and fend for themselves. ESA-sponsored medical research doctor Alex Salam recalls his experience: "A privilege to live in the coldest most remote place on the face of the Earth". © ESA/IPEV/PNRA -



A. Salam and A. Kumar

Antarctica appears to be relatively stable. On the other hand, large areas of West Antarctica appear to be undergoing a loss of mass of 100 Gt/yr corresponding to a rise in sea level of 0.3 mm per year. Since 2003, observations by GRACE, a satellite than can detect changes in mass of the areas it flies over confirm the loss of mass of Greenland and the relative stability of Antarctica, with an approximate balance between losses in West Antarctica and gains in East Antarctic. Meanwhile, most glaciers, not only in the Arctic and the Antarctic peninsula but also in Iceland, the Alps, the Himalayas and the Andes, are retreating. Variations in their volume remain trickier to measure because of their small size. Only very high resolution sensors, such as those on the SPOT satellites, enable them to be observed accurately.

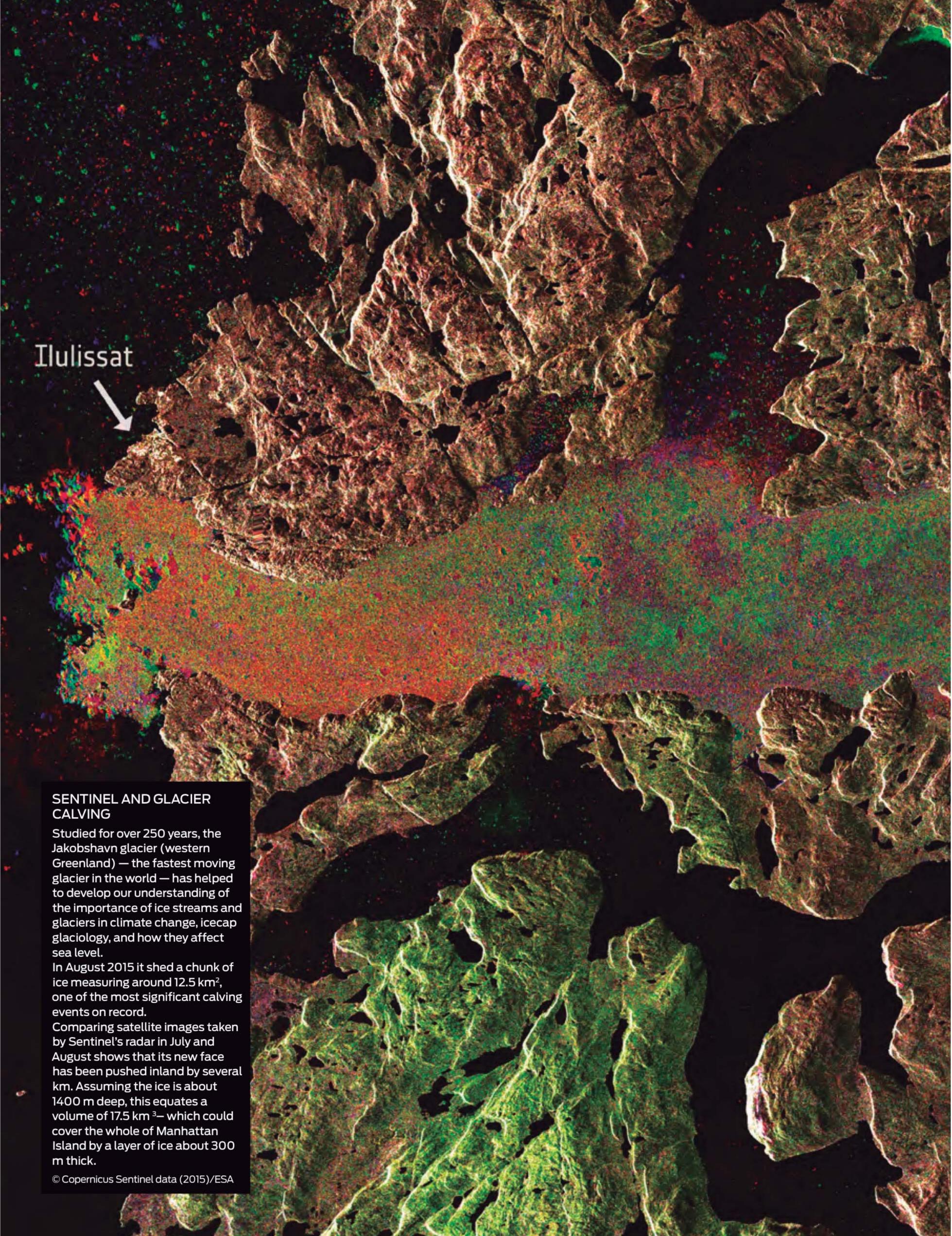
Glacial retreat

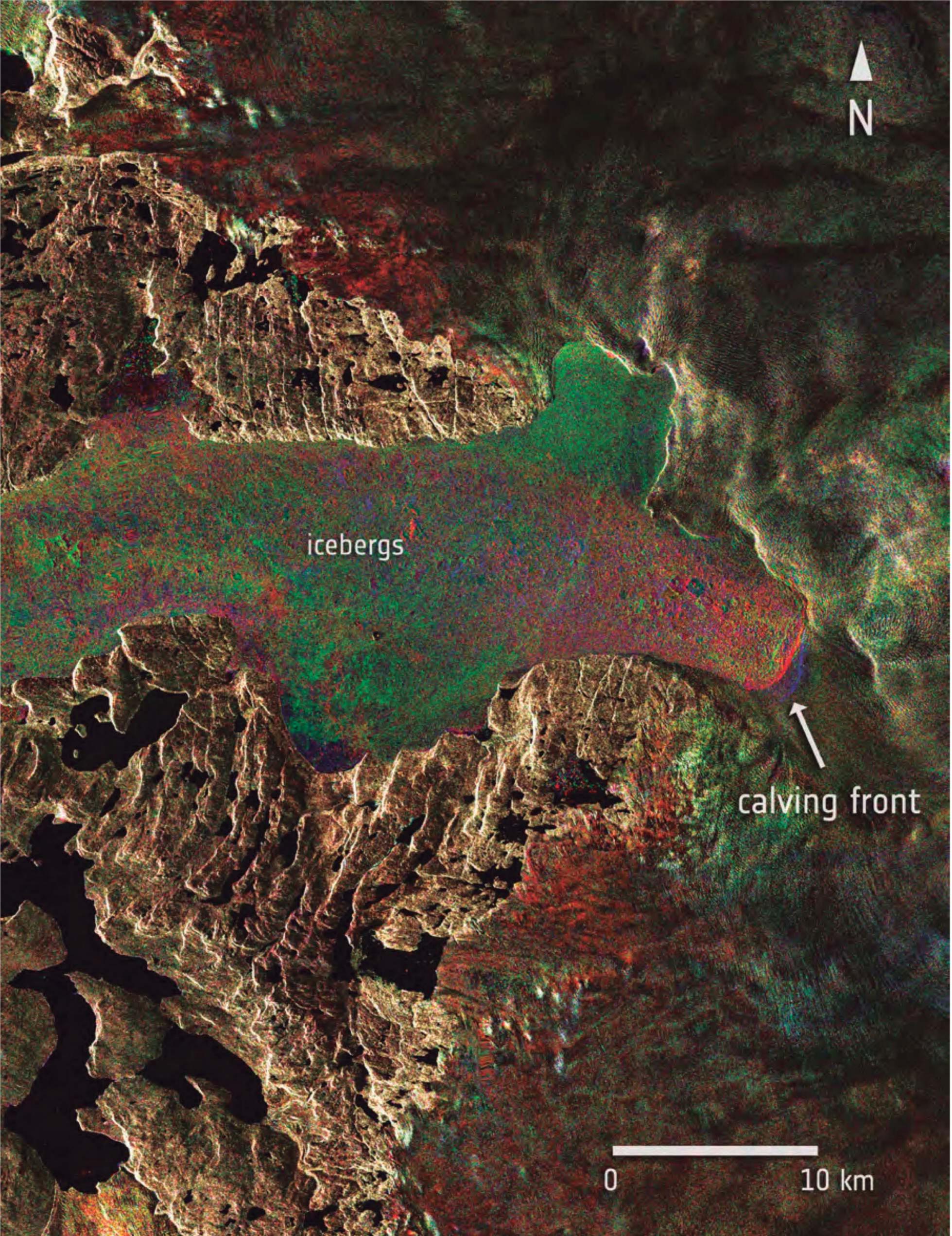
With two images it is possible, thanks to the binocular vision, to reconstruct the surface and thus estimate its variations. In many cases, especially in the Alps, the reduction in thickness is greater at low altitude due to summer melting. This observation appears to directly incriminate climate warming as being the cause of the glacial retreat already detected. Currently, the loss of mass from all mountain glaciers is causing a rise in sea

level estimated at around 1 mm per year. Even though spaceborne instruments have vastly increased our knowledge of the polar regions, there is still progress to be made.

The thickness of sea ice is still not very well known with any precision, even since the launch of CryoSat2. Also, the thickness of continental ice, or for the quantity of snow, which settles every year, are still major unknown. In addition, the polar regions must continue to be constantly monitored, so that the longest possible time series may be analysed and interpreted.

> Frédérique Rémy LEGOS/Observatoire Midi-Pyrénées





CryoSat pole position

FTER A CENTURY of polar exploration, the last two decades of satellite measurements have painted an altogether new picture of how Earth's ice sheets are changing: they are no longer considered to be the slumbering giants they once were, expected to respond slowly to climate change. Now, modern satellite observations tell a different story; coastal glaciers are accelerating and thinning around Antarctica and Greenland, and it seems that the vast quantities of heat delivered by Earth's warming climate are to blame.

The need for CryoSat

Even though satellites have been monitoring Earth's climate for several decades, there are still large gaps in our understanding of ice sheet imbalance. For example, although the Antarctic ice sheet is over 5,000 km wide in places, about half of all ice losses occur within a narrow 100 km wide strip around its coast. The pattern of losses in Greenland is the same. And yet the current generation of satellite altimeters is not well suited to monitoring these regions due to their steep terrain, which is difficult to track using the early sensors that were designed to look at flat oceans.

As a consequence, less than 10 % of the Antarctic and Greenland ice sheet margins have been surveyed by satellite altimetry to date. To provide complete picture requires an altimeter system than is capable of tackling the complex geography of the outlet glaciers and ice streams that drain the polar ice sheets. The interferometric mode of the CryoSat altimeter was specifically designed for this task and this, coupled with the satellites' dense ground track and high latitude orbit, provides a unique opportunity to capture the pattern of change in the coastal regions of Antarctica and Greenland for the very first time.

Since its launch in April 2010, the mission has provided near-continuous measurements, leading to a step increase in our understanding of where ice losses have occurred. In its first four years of operation, CryoSat has been

able to detect changes in the mass of the Antarctic and Greenland ice sheets with accuracy comparable to that of the past 20 years of conventional satellite altimetry. The mission has revealed that important changes have occurred. For example, ice losses from West Antarctica have continued to rise - increasing concerns over future sea level rise – and Greenland is losing five times as much ice today as it was in the early 1990s. Elsewhere

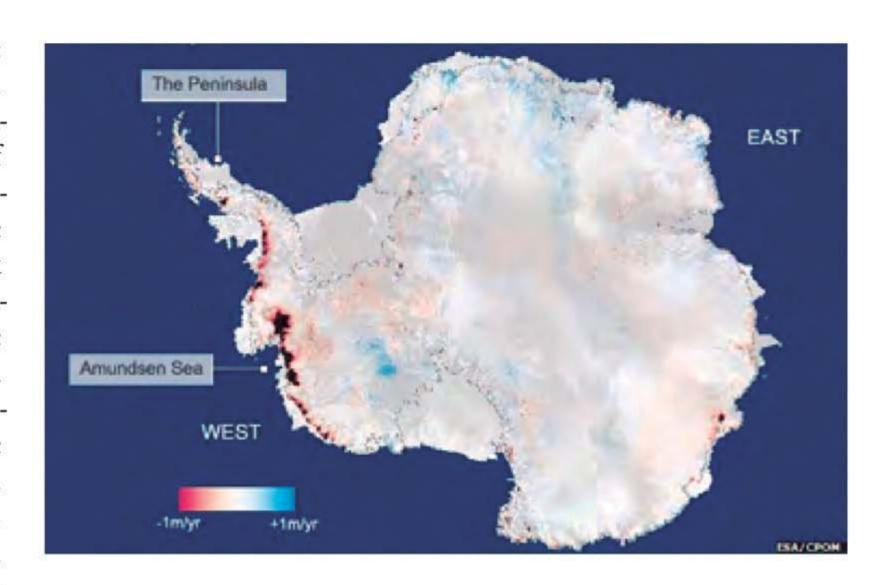
in Antarctica, changes in ice sheet thickness have been small in comparison to natural fluctuations in snowfall, and so a longer record of CryoSat measurements is required before we can detect whether other parts of the continent are out of balance.

Future challenges

CryoSat has new technology that allows it see the shape of the ice sheets with exceptional clarity. And there is far more to come. Whereas past altimeters were designed to measure Earth's height at just a single point as the satellite flies overhead, early studies have revealed that CryoSat's dual-antenna system is capable of mapping huge swathes of data stretching many kilometres wide. Once this capability is perfected, the archive of data will be able to image the Antarctic and Greenland ice sheet terrain as never before.

The greatest challenge is maintaining the missions' unique capability into the future, as CryoSat is already two years past its original lifetime. In addition to monitoring ice losses from Antarctica and Greenland, CryoSat plays a vital role in charting the volume of Arctic sea ice, and together, these parts of the cryosphere are among the most sensitive indicators of global climate change. Thanks to CryoSat's pioneering technology, it is clear now that a capability to monitor changes in the Polar Regions is of major importance for science and for society.

> Andrew Shepherd University of Leeds



Antarctica and Greenland are among the world's last great wildernesses, and changes in the amount of water frozen in their vast ice caps affect global sea levels. As the ice sheets grow, sea levels fall, and as they shrink, sea levels rise. Map of Antarctic ice sheet elevation change, scaled between -2 (red) and +2 (blue) metres per year Antarctica is losing ice, mainly due to rapid thinning of glaciers in the west which, according to CryoSat, now account for 10% of global sea level rise.

© CPOM/ESA





SCIENCE



Sea ice: a major concern

Cean forecasting and analysis systems are based on ocean or sea ice models. These models are very useful for reinforcing maritime safety but also for researchers and climatologists studying the evolution of the climate and its consequences. Sea ice or pack ice is saline sea water, unlike icebergs which are made up of fresh water from continental glaciers. It is located between the atmosphere and the sea and may be considered to act as a blanket isolating the heat in the ocean from the cold air of the poles. Operational oceanography enables us to monitor the evolution of sea ice in the Arctic and Antarctic, thus providing a major indicator for studying global warming.

Operational oceanography systems

The main numerical ocean models used for operational oceanography include a sea ice component: by combining these models with data from altimetry satellites such as Jason or CryoSat, operational oceanography systems are able to realistically reproduce the geographic spread of frozen areas, the thickness and concentration of ice and the drift "currents" which deform it.

The Arctic marine environment currently experiences change at an unprecedented pace. Mercator Ocean and the Copernicus Marine Service are contributors to projects related to this major concern, like the EU FP7 funded ICE-ARC project. The project aims at understanding and quantifying the multiple stresses involved in the change with a particular focus on the rapid retreat and collapse of the Arctic sea ice cover and on the assessment of the climatic (ice, ocean, atmosphere and ecosystem), economic, and social impacts of these stresses on regional and global scales..

Pierre Bahurel, Mercator Océan

Fishing boat in Disco Bay, West-Greenland with icebergs in the background.

© P. Prokosch/GRID Arendal

Mean monthly concentration of ice in the Arctic and Antarctic, September 2014.

Source: Copernicus marine Service 1/4º global ocean model



SPACE TOOLS

SIRAL waves

The spaceborne instrument Siral is like a messenger. It lifted off on April 8, 2010, aboard the CryoSat satellite, being positioned in orbit to keep a close eye on our planet and start its carefully planned mission. To rise to the challenge of producing this instrument, we had to call on our full range of skills and leverage a shared passion for performance.

As the instrument is activated and we eagerly await the first "heartbeat", all of these questions rush into our minds, and it's with a sense of wonder that we receive the first sign of good health for an instrument we know like the back of our hands.

For us, Siral paves the way for a whole new generation of instruments. In fact, we still have a lot to learn about all the new functions we built into the instrument. On the ground, we used a wide range of scenarios during ground tests to check out its ability to escape all the pitfalls we could imagine.

out its ability to escape all the pitfalls we could imagine. We take advantage of the first months in orbit, as it confronts the reality of our blue planet, to complete its apprenticeship. It almost feels like we're teaching our "baby" to walk, to be independent, and then to use its sensors to describe for us the changes it sees. Sending out invisible waves towards our planet and picking up the return signals, it meticulously examines ice formations and oceans, how they breathe and live.

We gave our instrument the ability to increase its measurement accuracy when the terrain becomes more disordered – and that is indeed the data we subsequently analyze using our powerful ground-based computer systems. Siral has proven to offer a significant improvement

in the observation of the chaotic conditions produced by melting ice, all with unprecedented coverage and accuracy.

The contribution of its high-resolution technology also showed substantial improvements in measuring ocean heights. The future generations of instruments are already following along this technology path.

We are tracking Siral's health on a monthly basis.

It is perfectly stable, an essential prerequisite to guarantee the accurate observation of the slightest changes in our planet. Little by little, Siral is opening new possibilities in understanding the changes affecting the Earth, but we still have a long way to go before we can definitively establish the trends affecting its areas of observation.

Our unique messenger reflects both this impressive human achievement and the satisfaction of all those who contributed to it.

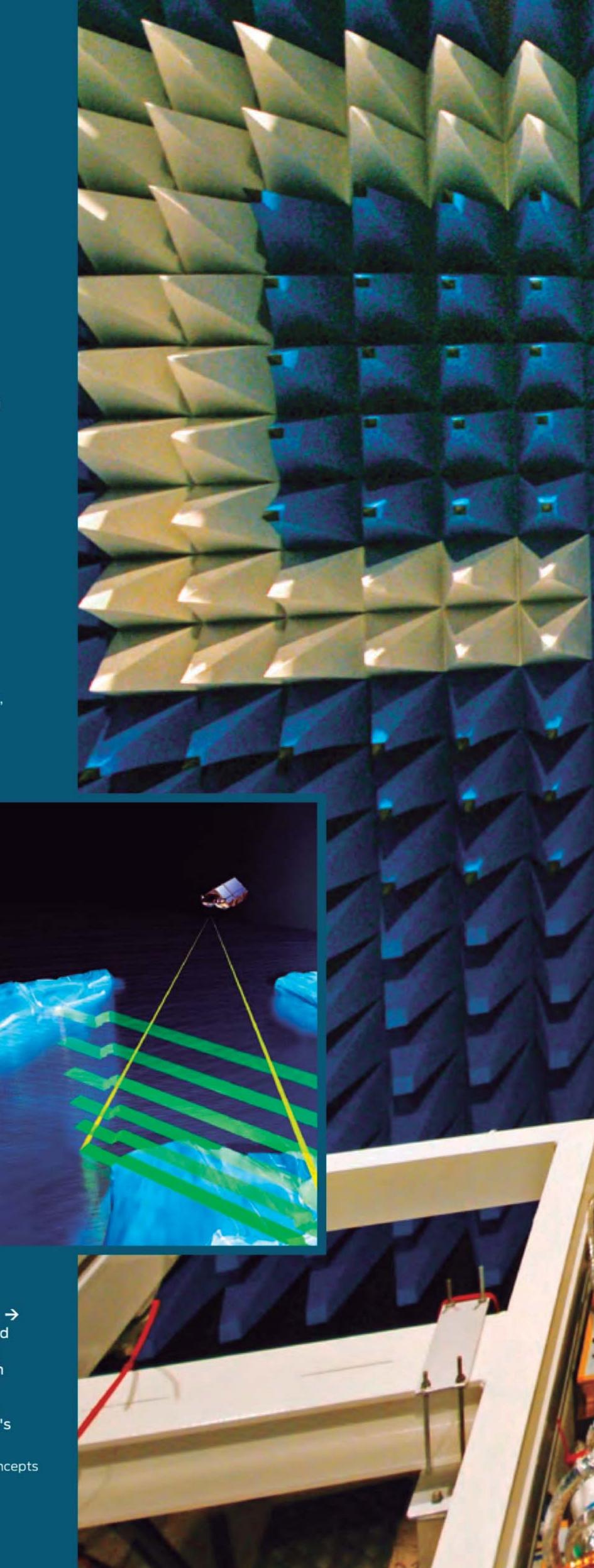
Laurent Rey, Thales Alenia Space

Using the sophisticated SIRAL radar altimeter, CryoSat makes accurate measurements of the floating sea-ice thickness.

© ESA - AOES Medialab

To make sure it would survive the shock of launch and the harsh conditions of space, SIRAL was tested in Thales Alenia Space's anechoic chamber.

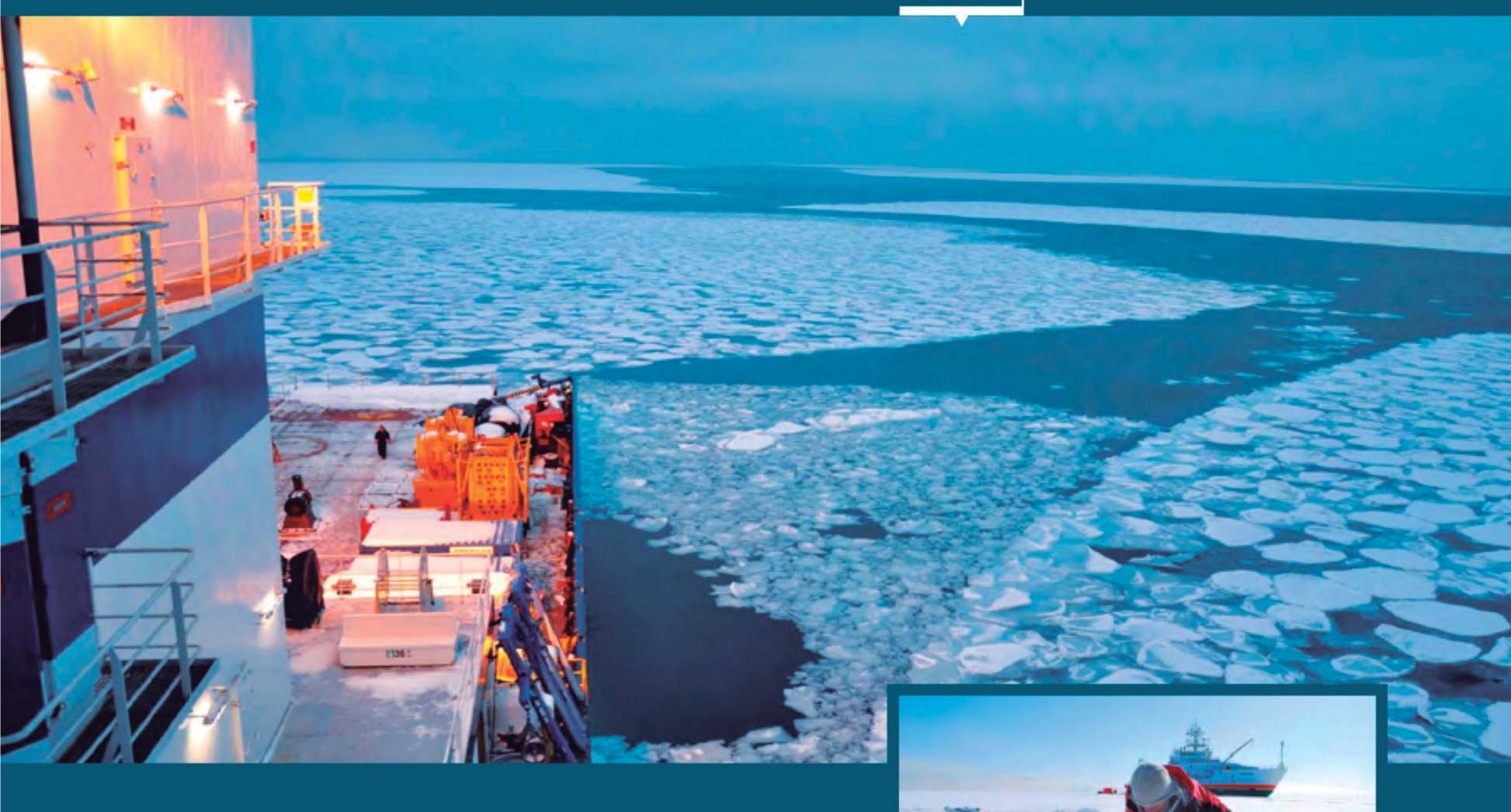
© J.-D. Dallet/Suds-Concepts







CONCERN



Navigation in Finland

he Finnish Ice Service has provided ice information and charts for the Baltic Sea for more than 100 years. As all Finnish harbors freeze every winter, daily ice information is required for safe navigation as relatively thin ice can change into a safety threat in just a few hours. Satellite technology is a good way to get an overview of ice conditions over large remote sea areas. Synthetic Aperture Radar (SAR) satellites allow ice services around the world providing customers with an overview of ice conditions over large remote sea areas, even in cloudy regions and the darkness of the polar night. In June 2012, e-GEOS signed a contract for the setting up of a COSMO-SkyMed (SAR X-band) receiving Ground Station in Sodankylä, operated by FMI, which became operational early 2013.

The FMI ground station in Sodankylä, Finnish Lapland, is ideally located to receive data as satellite is flying over the Kara-, Barents- or Baltic Sea. Every day, more than 40 overpasses from the four COSMO-SkyMed satellites are visible to Sodankylä and images are processed by our ice analysts to deliver useful information to the end user less than thirty minutes after.

A reliable tool for ice monitoring

This direct COSMO-SkyMed reception asset in our region and new capability to monitor ice formation and motion and temporal Arctic changes is now part of our ice charting operational chain. Sea ice information is required by a wide spectrum of users operating at high latitudes, including navigation (rivers, lakes and sea) and off-shore operations. Satellite Earth Observation and in particular SAR instruments represent a reliable tool for ice monitoring, providing a synoptic view complementing the accurate but low coverage reports from ships and airborne sources.

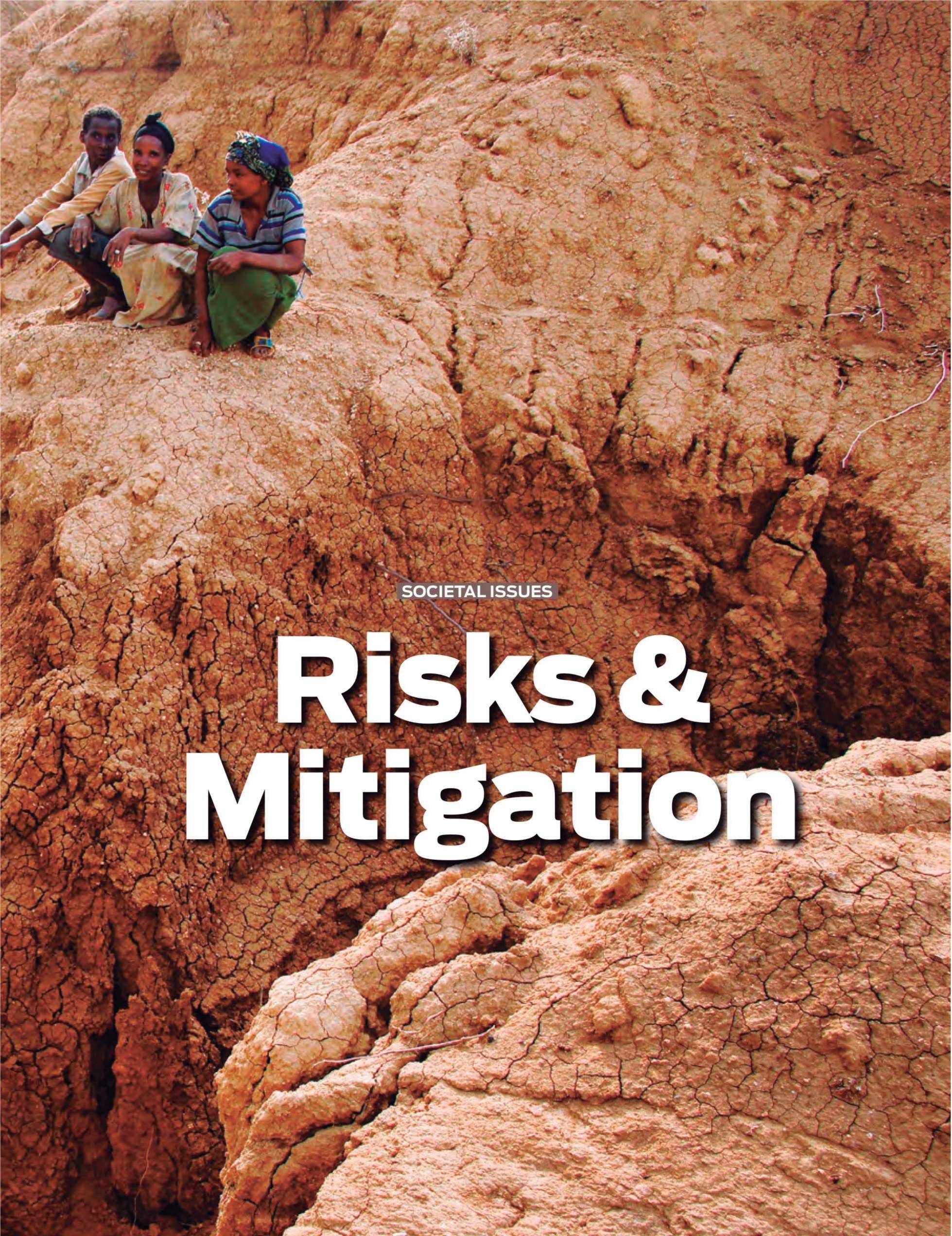
Combined with satellite archive data, our services show the striking loss of Arctic sea ice. As the Arctic sea ice recedes, ship traffic in the Arctic will increase on these emerging routes requiring safe and high performing services that are now available.

Eero Rinne, Finnish Meteorological Institute

The vessel Aranda during a mission in the Gulf of Finland, located in the seasonal sea ice zone, where sea ice forms in the wintertime and melts in late spring. This seasonality entitles this sea as a key area regarding climate change. Owned by the Finnish Environment Institute, Aranda has state-of-theart equipment for receiving satellite and meteorological images that are vital for research purposes and for safety.

© Jari Haapala/FMI





Prevention, mitigation and response

INCE THE 1980s, the impacts of disasters have risen rapidly, affecting developed and developing countries and almost all sectors of economy at local, national, and regional levels. Several hundred million people are affected annually, and, according to Munich RE reinsurance company, losses reached over USD 400 billion in 2011.

Hydro-meteorological and climatological hazards are the most frequent causes of the disaster events among all natural hazards. Due to heavy rains, flash floods are increasing in many parts of the world especially in urban areas. Due to the sub-surface water temperature increase in the sea, cyclones tend to grow beyond ordinary limits as energy supply from the warm oceans. Typhoon Haiyan in 2013 grew to a super typhoon and hit Micronesia, Philippines, South China, and Vietnam.In the Philippines, where very high and extra-large scale storm surge, similar to tsunami waves, hit the Leyte Island, it killed over 6,000 people (and more than 1000 people were missing).

Storm surges caused by the super cyclonic storm Bhola in 1970 killed at least 300,000 people in Bangladesh, and the New Orleans city was almost submerged owing to storm surges caused by Hurricane Katrina in 2005. Coastal floods become increasingly serious threats as sea level rises. Many small islands experience more frequent storm surges and high tides, such as Kiribati (in the central tropical Pacific Ocean) and Mauritius (in the Indian Ocean). Rainstorm floods are the flood disasters which appear in specific areas due to short-time torrential rains or several continuous torrential rain processes.

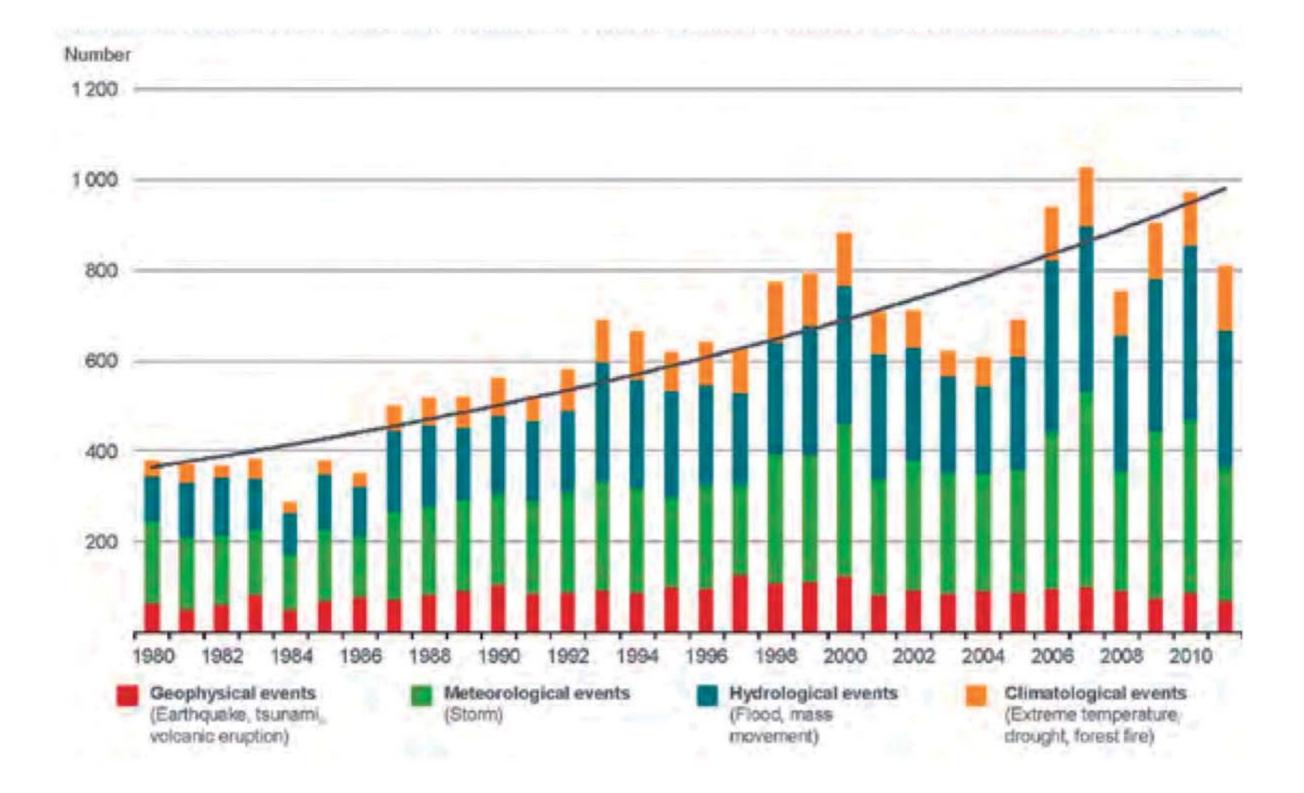
Droughts can occur across a range of time scales; for example, from seasonal and multi-year droughts, decadal droughts, and severe or extended droughts like those occurring in Australia between 2001 and 2009. In some cases such drought hazards can be influenced by El Niño – Southern Oscillation conditions in the tropical Pacific.

Reducing vulnerability

Heat waves may cause disasters. The 2003 summer heat wave, for example, killed at least 35,000 people in Europe. India is one of the regions most seriously influenced by heat waves. Low temperature hazards include snowstorms, chilling, freezing damage, and ice storm and refer to the weathers caused by abnormal activities of cold air. Such hazards can also escalate into disasters.

Super Typhoon Haiyan made landfall over the central Philippines in 2013 (here the city of Tacoban). The official death toll from the storm was 6,300, but a full tally of the lives lost may never be achieved. Millions of people in 20 provinces were affected. The category five storm brought winds as strong as 314 km/h, and analysts believe it may be one of the strongest storms to make landfall in recorded history. Buildings were flattened under the strong winds, with wooden houses particularly susceptible to the storm.

© Jason Gutierrez/IRIN



Natural catastrophes
worldwide 1980-2011,
number of events with trends.
Source: Geo Risks Research,
NatCatSERVICE

© Munich RE



We still need to promote a strategic and systematic approach to reducing vulnerabilities and risks to hazards. In 2005, the United Nations World Conference on Disaster Reduction Building the Resilience of Nations and Communities to Disasters held in Kobe-Hyogo (Japan) adopted the Hyogo Framework for Action (HFA) 2005-2015: Building the Resilience of Nations and Communities to Disasters. How can we support HFA from 2015 and beyond? Although science is wellrecognized in its priorities the UN can better promote and coordinate science and technology for Disaster Risk Reduction (DRR). There is a need to develop the scientific basis for the policy agenda and to assess empirically progress towards achieving it.

Significant progress have been made in scientific understanding of physical phenomena leading to natural hazards as well as of vulnerability and exposure, particularly in early warning and evacuation systems, building safety, community education, etc. For example, local and regional warning systems generate accurate scientific-based information to be communicated to the exposed communities. Yet we are not seeing a concomitant decline in disaster impacts and losses. While disaster costs are increasing, death

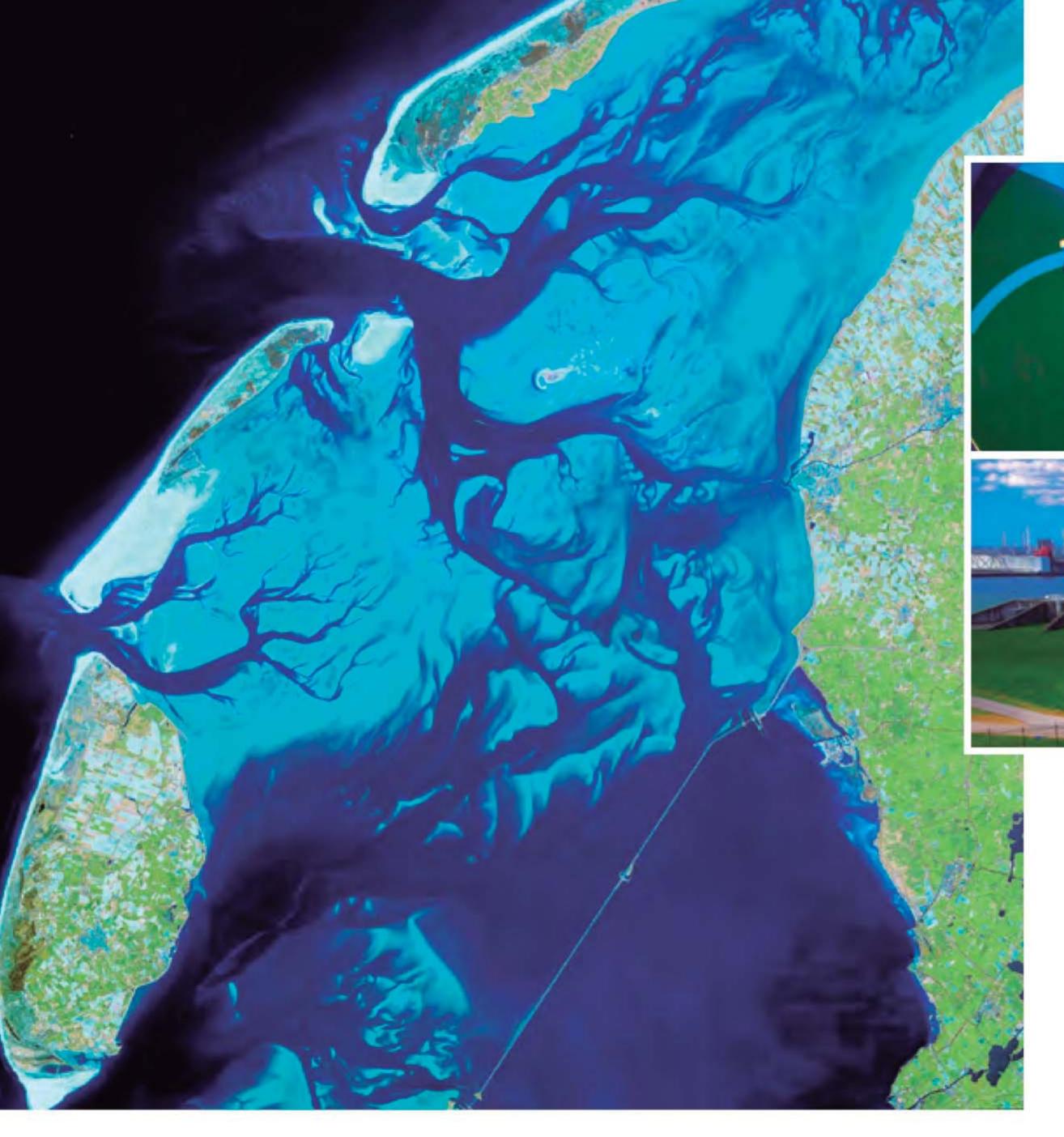


rates (per unit of population) are generally decreasing. The major factors in growing losses are increasing population and the exposure of increased wealth to natural hazards. A comprehensive integrated system analysis and periodic assessment of disaster risks at any scale, from local to global, based on knowledge and data/information accumulated so far, are essential scientific tools that can assist in recognition and reduction of disaster risks.

During August 2013, monsoon rains have led to widespread flooding in the Punjab and Sindh Province's of Pakistan. Flash floods affected almost 2000 villages. 15,000 people have been evacuated to relief camps. Here a family trying to escape.

© Abdul Majeed Goraya/IRIN





The Maeslantkering is part of the Europoortkering project, final stage of the Delta Works. This storm surge barrier automatically closes when needed. The main objective of the Delta Works was improving the safety against flooding of the Rotterdam Harbour. This enormous project was sometimes referred to as the 'eighth wonder of the world'.

© J.-D. Dallet/Suds-Concepts

This Envisat image features the Netherlands, with the capital city of Amsterdam visible in white on the south bank of the waterway (North Sea Canal) and the port of Rotterdam visible at the bottom left of the image.

Like other European ports (including Antwerp, Hamburg, Valencia and Le Havre), it is vulnerable to extreme weather events.

© ESA

Disaster events will continue to grow, if vulnerability is not reduced, and the economic impact will far exceed the cost of mitigation and preparedness by orders of magnitude. Large sums are expended on international emergency assistance after disasters that effectively transfer the risk (and responsibility) from the affected local area to the global community. Such international aid becomes a *de facto* risk transfer mechanism.

More timely interventions and sustained multi-year efforts to support Disaster Risk Management (DRM) including research, management and resilience building can enhance sustainable development efforts. Greater efforts are needed to communicate science-based disaster risk assessments, socio-economic impacts, evaluations of mechanisms for risk reduction, and prescriptive options for translating scientific findings to practice. Periodic scientific findings to practice. Periodic scientific assessments of disaster risks can contribute to the significant enhancement of knowledge on specific risks at global, regional, national, and local levels.

Our proposal is that a baseline assessment should be undertaken by a high-level, trans-disciplinary body of experts appointed by national governments together with international and intergovernmental scientific organizations dealing with disaster risks and also include, where relevant and appropriate, inputs and engagement with various sectors and civil society. Linking DRM to broader sustainable development goals can be achieved through proactive and community-based resilience efforts. However, this is only possible with the knowledge transfer generated through integrated research on and periodic assessments of disaster risks that are effectively communicated to society and governments.

Susan Cutter,
University of South Carolina, Columbia,
Alik Ismail-Zadeh,
Karlsruhe Institute of Technology/
Russian Academy of Sciences, Moscow
Gordon McBean,
Western University, London, Ontario,
and the ICSU/ISSC ad-hoc group

SCIENCE

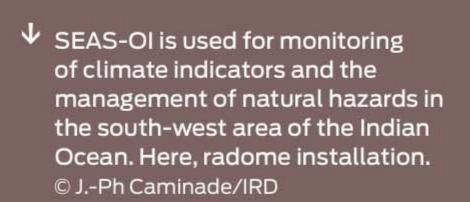
Climate-Energy Plan

Reunion island is subject to major risks related to climate change: higher temperatures, shifts in terrain, wind damage, erosion, tropical diseases, etc. A diagnostic carried out with Météo France, within the scope of the Climate Plan, underscores a rise in temperatures over the last 40 years, in addition to strong drops in rainfall in the southwest part of the island. The lack of water penalizes farming, in particular sugar cane. More violent hurricanes and the rise in sea levels may well exacerbate most of these factors.

Along the coastline in our West Coast Territory (TCO) are a number of infrastructures – housing, hotels, restaurants, etc. Those with the greatest exposure may one day have to be moved. The aim of public authorities is to set up adaptation measures. The region is also working on formalizing various key actions within the scope of its PCET – Climate-Energy Territorial Plan.

We're getting in closer touch with scientists, and we're interested in potential contributions from the space sector. One example is the Sea-OIS program. Financed by the Reunion Region, the State, IRD and the University of La Reunion, and supported by Europe, this is both a satellite imagery reception station and a center of excellence in remote sensing, covering biodiversity, agro-forestry areas, the marine and coastal environment, urban planning, healthcare and natural risks. The question is how to establish an interface with scientists and build new skills. That will help us move forward and improve our communications with the public, without making announcements that could cause anxiety. We want to get people to join the movement and stimulate them to act – and not to paralyze our citizens.

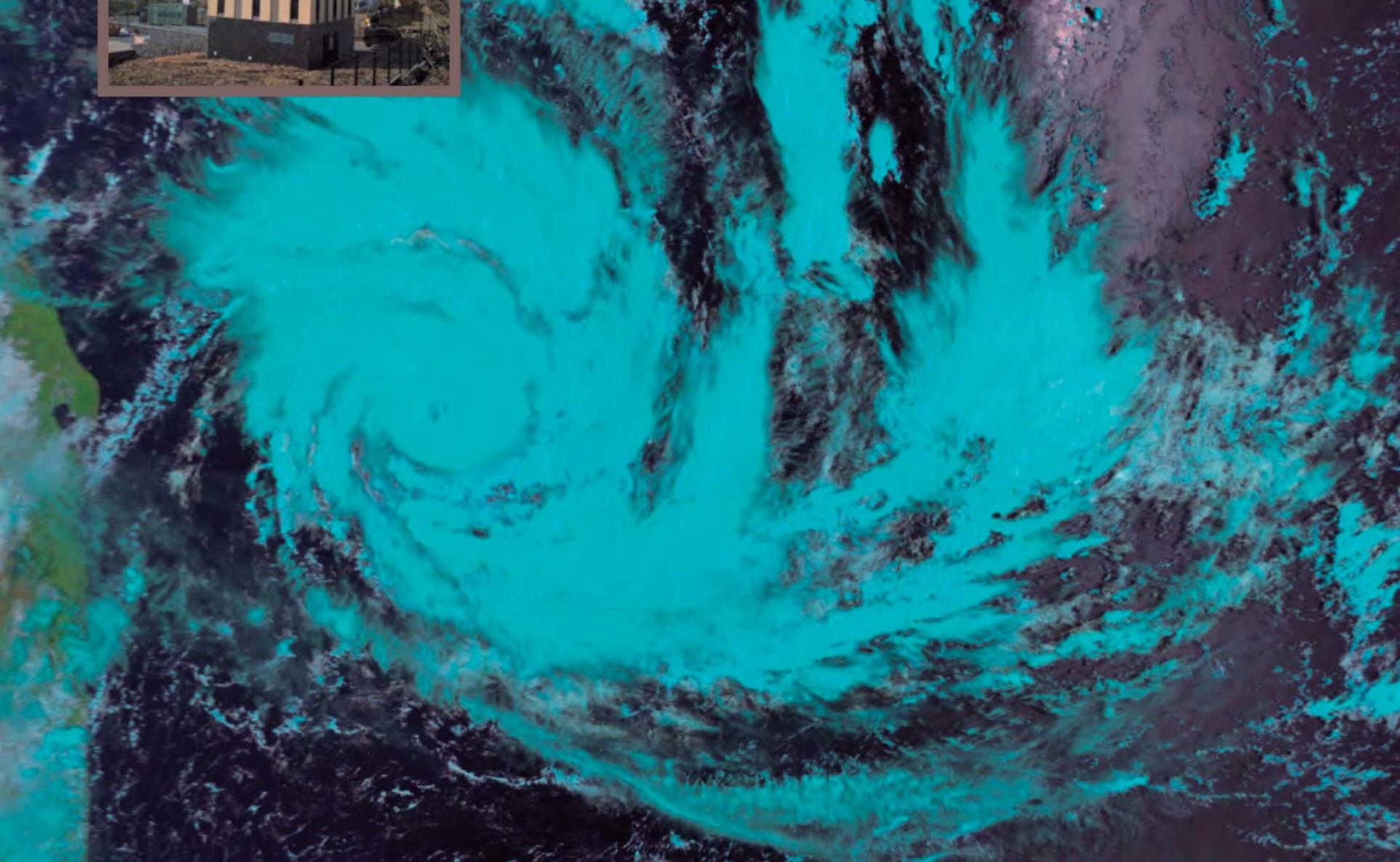
Joseph Sinimalé*, President of the West Coast Territory and Mayor of Saint-Paul, La Reunion

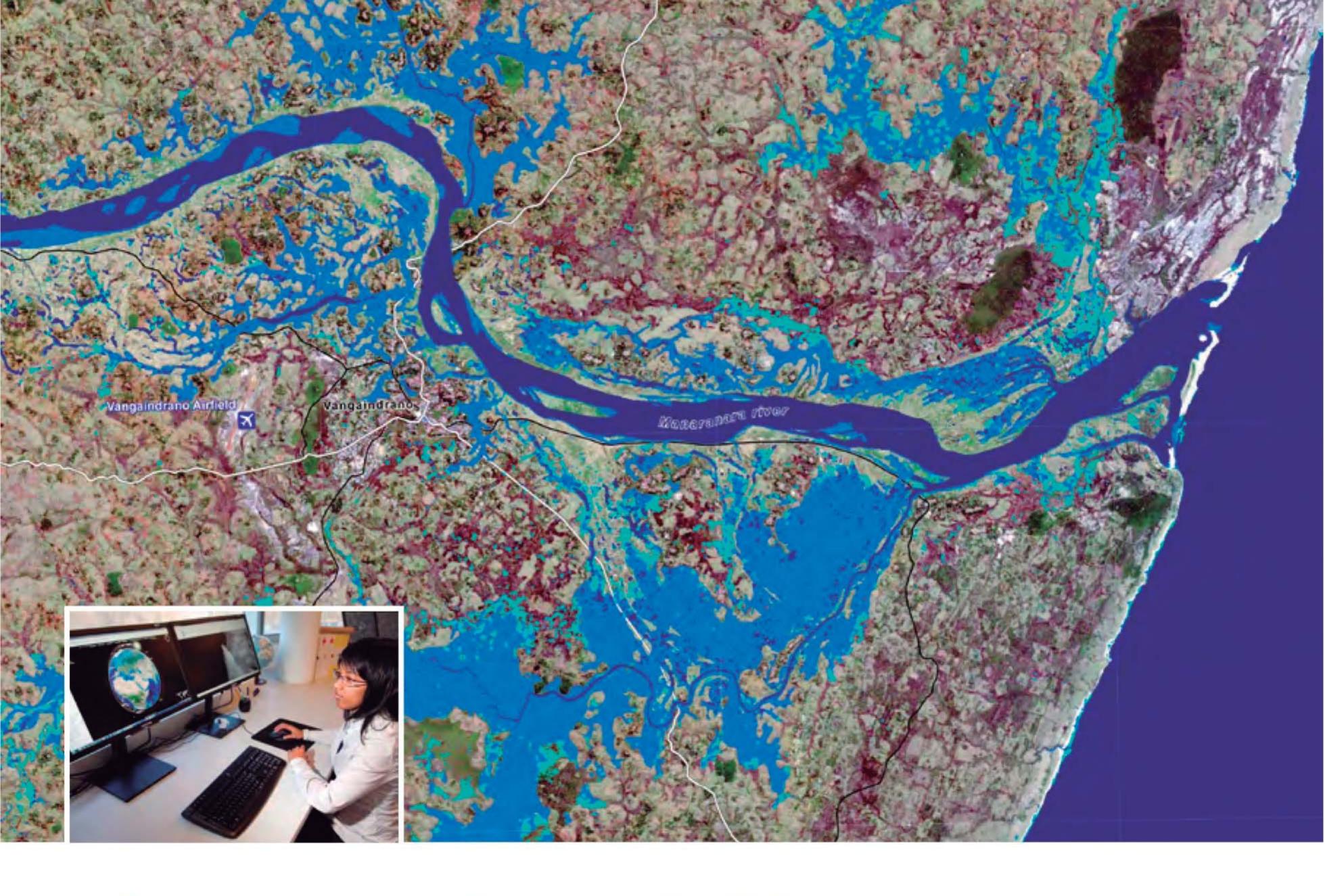


On January 11, 2015, tropical cyclone Bansi formed north of Reunion Island in the Southern Indian Ocean and in less than 24 hours had intensified into a category 3 storm.

© EUMETSAT







International Charter

Tropical storm Chezda, combined with heavy rain, hit the coast East of Madagascar and the capital Antananarivo on 16 and 17 January 2015. Authorities counted 68 deaths and approximately 130,000 people affected. The General Directorate for Civil Protection and Crisis Management (COGIC), on behalf of the National Bureau of Risk and Disaster Management (BNGRC), triggered the International Charter "Space and Major Disasters".

This product map, generated by SERTIT, shows the flood extension (light blue) imaged by SPOT-5.

© CNES 2015, distribution AIRBUS DS / Spot Image

↑ Box: SERTIT operator in Strasbourg (France)

© F. Maigrot/L'A.M.I

lions of people live in areas which are particularly subject to major disasters. Sometimes the scale of these disasters is such that on-site rescue teams may be stretched by events, here, information from space can be a great help in organizing the rescue and relief efforts.

In the mid-1990s, satellite images (which, at that time, were of around 10-20m resolution) were mostly used for environmental applications. Earth Observation engineers then wondered if these images could not be useful for disasters - with satellites being able to quickly image any point on the globe. This idea has been brought by CNES (French space agency) and ESA (European space agency) to the UNISPACE III conference (UN) in 1999, and resulted in a declaration: "The international space community is asked to initiate a programme to promote the use of [...] Earth observation data for disaster management by civil protection authorities, particularly those in developing countries".

Following this conference, in 2000, under the initiative of CNES and ESA, very soon joined by CSA (Canadian Space Agency), the International Charter "Space and Major Disasters" was created. Today the Charter consists of 15 space agencies.

This international cooperation aims at providing a unified system of acquisition of space-based data and information in support of relief efforts during emergencies caused by major disasters. Civil protection agencies, governmental relief organizations, or other authorities with a mandate related to disaster management, known as 'Authorized Users' (AUs), can activate the Charter. Certain UN bodies can also trigger the Charter for UN users.

Rapid mapping services

The Charter can be activated 24 hours a day, 7 days a week through a single access point. In less than three hours, an on-duty operator relays requests for tasking satellites over the disaster hit area to the member space



agencies. According to weather conditions and satellite orbits, the first images can be acquired within 12 to 24 hours. A project manager is appointed for each activation (generally from the country that has triggered the Charter) in order to manage all satellites tasking, the reception of the acquired data, their transfer to rapid mapping services and the provision of images and cartographic products to users. Requests for archives images can also be carried out in order to establish reference maps or make comparisons before and after the disaster.

Human and material losses

The Charter is involved in the phase of crisis response, just after a major disaster. Activations can last from one to four weeks depending on the impact of the disaster and the needs of users. The Charter can even be activated before the event, especially in the case of cyclones and other weather related events where reliable forecasts are available. A major disaster is one which involves substantial material and/or human losses, and when the assistance provided by satellite data is of use. These disasters can be of natural (floods, tsunamis, cyclones, fires, earthquakes, volcanic eruptions, landslides...) or man-made origin (oil spill, explosion of factories...).

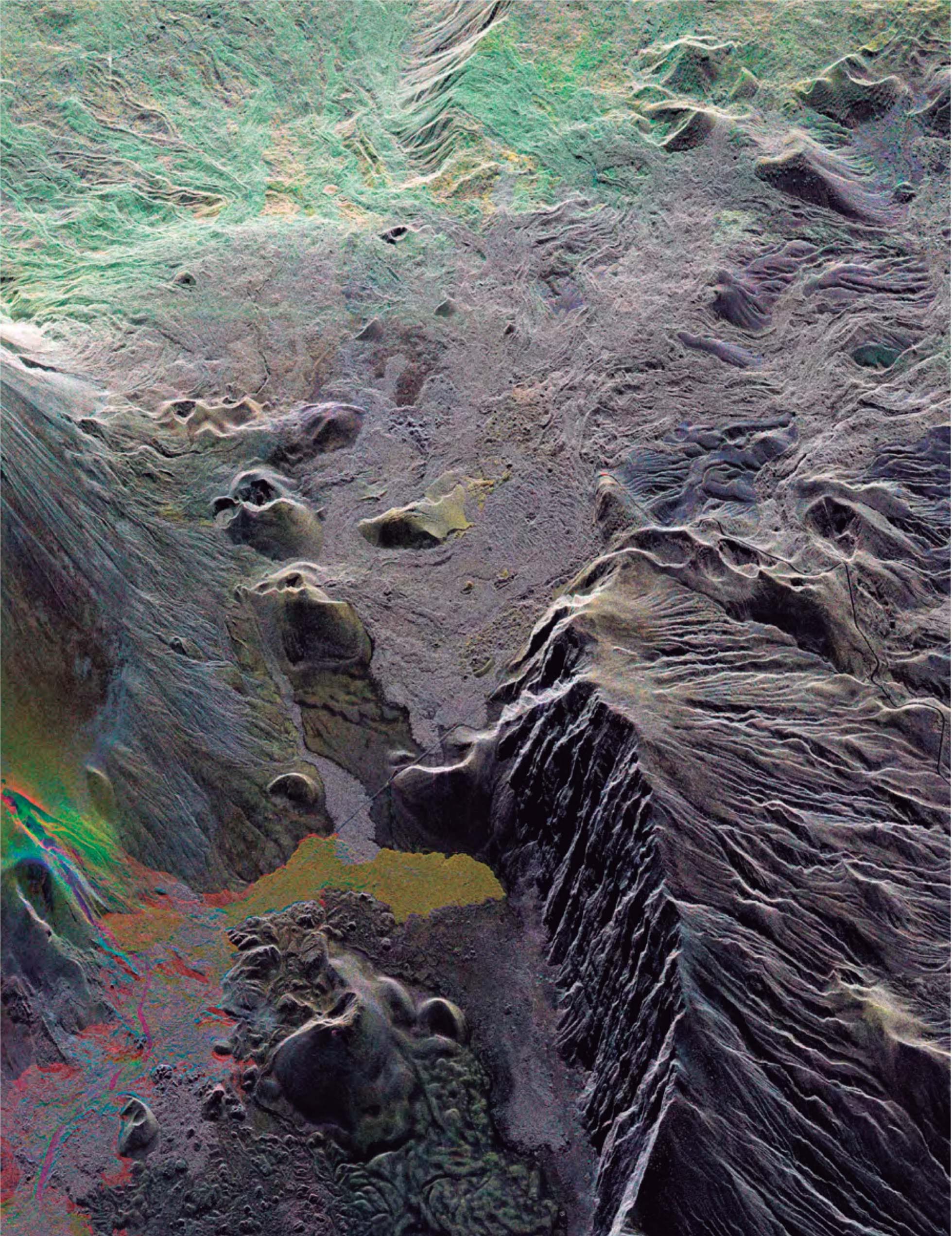
Since its creation, the Charter has been activated more than 460 times, with an annual average of 45 activations for recent years. The majority of activations are due to hydrometeorological hazards (floods, hurricanes, storms...), however geological hazards such as earthquakes, volcanic eruptions and landslides have a significant impact in terms of human and material losses. The number of activations of the Charter continues to increase, not only because the Charter is called on more frequently but also because of increasing impact due to higher vulnerability with larger populations and more hydro-meteorological hazards due to global warming. Today, the Charter's "Virtual Constellation" of satellites consists of 41 (optical and radar) imaging satellites. The Charter has been activated for many of the biggest recent disasters including the SE Asia Tsunami of December 2004, the Haiti earthquake in 2010, the tsunami in Japan February 2012, Haiyan supertyphoon in the Philippines in 2013, and the Nepal earthquake in March 2015.

Claire Tinel, CNES

Vehicles stuck on a flooded road close to Lake Albert. The poor quality of roads in North Eastern DRC makes it difficult to transport humanitarian aid to remote areas.

© Z. Moloo/IRIN







Salares in the Axarquia mountains (Malaga, Spain). This region is sprinkled with pretty pueblos blancos, or white towns and villages with an architecture adapted to climate change impact. © J.-D. Dallet/Suds-Concepts

Resilient cities

ITIES are a very special environment, different from the natural environment, that concentrates populations, goods and capital. How they are impacted by climate change depends on their characteristics, their location - most large cities are on or near coastlines, heavily affected by the rise in sea levels - local governance and degree of economic development. The result is specific adaptation strategies, based on an interdisciplinary approach that brings together urban planners, architects, construction engineers, meteorologists, social scientists and, at various levels, the space sector.

Islands of urban heat, identified in the 1970s, and spotlighted in France after the heat wave in 2003, is one of the main climatic characteristics of cities. They are the reason that cities are often warmer than the countryside: during the day, the sun heats walls, roofs and the ground, which absorb this heat and then return it to the atmosphere at night. This does not apply to vegetation, which can absorb ground water via its roots to "sweat" and thus cool off. This situation causes a major contrast between city and country at night, with up to ten degrees difference if the

weather conditions are favorable (clear sky, little wind). However, cities are growing, and the impact of these urban heat islands will also increase, which will exacerbate the consequences of climate change. We must therefore deploy adaptation strategies. There are a number of examples of older adaptation strategies: for example, the "white towns" in Andalusia, or the shutters used to keep houses cool in southern France.

Local climate level

A number of studies were performed on urban development, with the main objective of reducing energy bills and conserving public health. But these were not climate studies, unlike those carried out over the last 20 years concerning process modelling. For example, our own model, TEB (Town Energy Balance), was developed to calculate the energy and water exchanges between cities and the atmosphere. To take this further, we should work at the local climate level. There is still a major difference of scale between the global climate and the impact on an urban zone measuring 100 X 100 km. But we are starting to perform coupling between city and regional climate models.

Météo France participated in the study "The challenge of the greater Paris area", ordered by the Ministry of Culture. Ten consortiums (each comprising town planners, architects, researchers, engineers, etc.) carried out an interdisciplinary study, offering general visions on how the Paris conurbation could evolve between now and 2030.

Spaceborne resources already help us in everything concerning descriptions of cities, to see how they're built, the materials that reflect light (albedo), and for modelling. With very-high-resolution satellites like Pleiades, we will acquire much better data.

Changing behaviors

Scientists are no longer the only ones working on these questions. Some local communities have been mobilized for many years, like Stuttgart in Germany. A pioneer in this area, Stuttgart has been working with meteorologists since the 1970s, for example creating ventilation and cooling corridors that have changed a climatic situation that had been causing concern. In France, the MApUCE project, launched in 2014 with the Fédération Nationale des Agences d'Urbanisme (FNAU, national federation of urban agencies), is aiming to make quantitative data on the urban microclimate, climate and energy part of its urban policies and legal documents, in an initiative that could be applied to all French cities.

To adapt to climate change, we also have to

(studies in Tokyo and Paris showed that airconditioning could increase the temperature in a city of a degree or two!) are often as effective as better building insulation. Placing truck farms around cities would not only provide shorter food chains (and thus decrease CO₂ emissions), but also attenuate the heat island.

It is clear that cities are the heart of a much larger system that acts on its microclimate. The increasing concentration of populations in urban zones makes it indispensable to integrate this ecosystem in global and local policies that aim to reduce the impact of climate change. In turn, this requires the deployment of dedicated multidisciplinary structures that enable bolstering collaboration and transferring knowledge between scientists and regional development experts, for example, and also setting up shared databases and measurement networks. Lastly, the city should be at the core of long-term analyses involving all the political, economic and scientific actors concerned.

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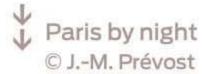
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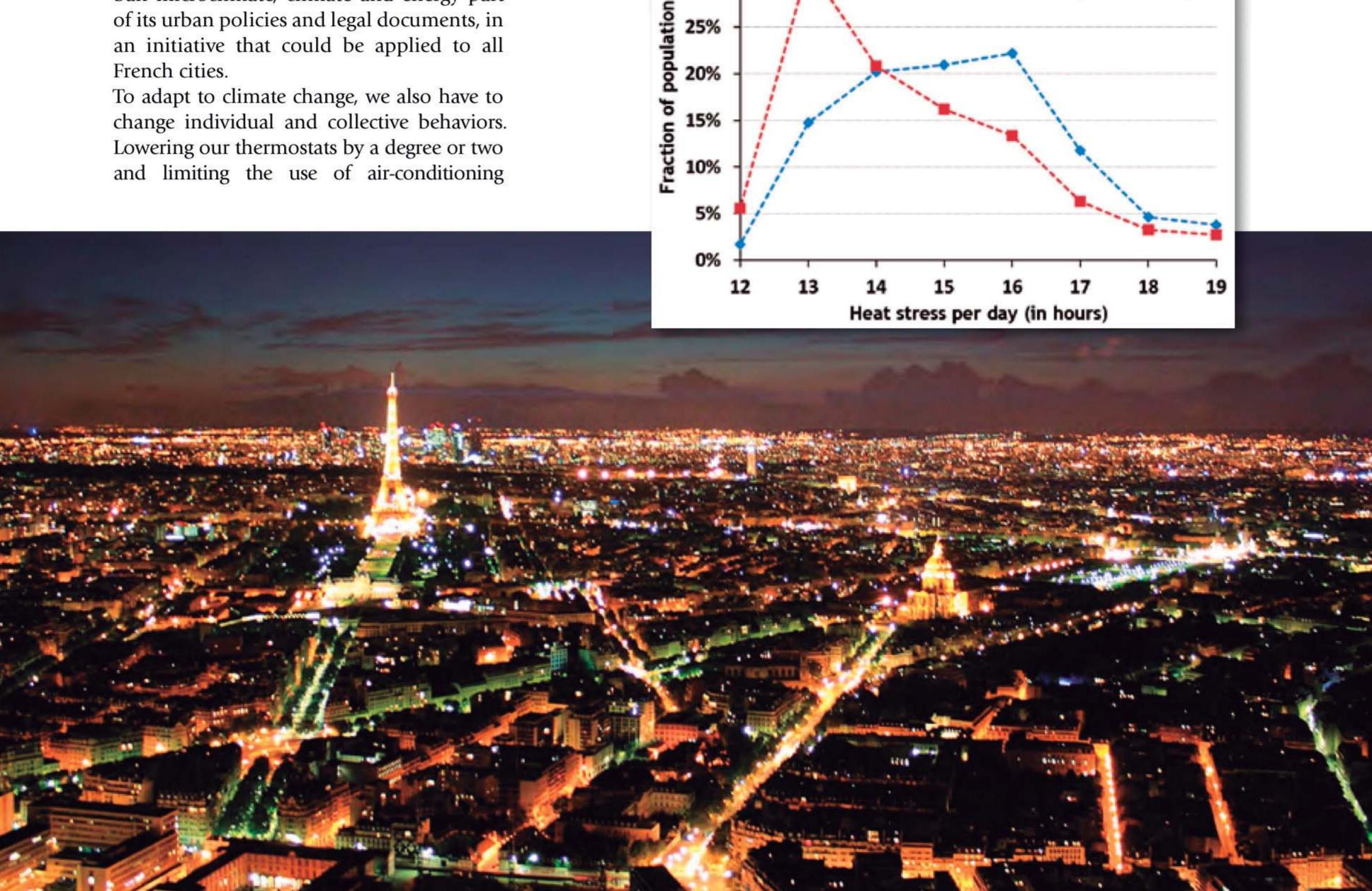
Valéry Masson, Météo France

Influence of the shape of future possible Paris agglomeration expansions (spread-out or compact) in 2100 on the comfort of its inhabitants.

Source: MUSCADE project

Compact city







SPACE TOOLS

Meteosat heritage

uccessive generations of European geostationary meteorological satellites have delivered increasingly accurate weather information for the benefit of all citizens. All three generations of Meteosat satellites were built or are being built by Thales Alenia Space as prime contractor, working for the European Space Agency (ESA) and EUMETSAT. After building seven first-generation Meteosat satellites, and four Meteosat Second Generation (MSG) models, the company will build six Meteosat Third Generation (MTG) satellites in conjunction with OHB of Germany. The MTG family comprises four imaging satellites and two atmospheric sounders.

Meteosat Second Generation satellites made a significant contribution to weather data. Like the previous generation, these are spin-stabilized satellites, rotating at 100 rpm. The MSG satellites incorporated a number of technological innovations. Meteorologists get higher quality images because of a significant increase

> in the number of observation channels, and better radiometric performance coupled with shorter revisit cycles.

> > technologies, Europe's meteorologists have improved the accuracy of their weather forecasts over the decades. On the first generation of

Thanks to Meteosat's advanced

Meteosat, images were updated every 30 minutes, a time that was cut in half on the second generation. For the third generation, this figure will be further reduced to 10 minutes, making weather forecasts increasingly reliable.

Yvan Baillion, Thales Alenia Space

Managing our planet today requires timely and reliable access to information that only satellites can provide. They continuously monitor natural phenomena in their entirety, whatever their scale or duration, to millimetric precision.

MSG-4 satellite during integration at Thales Alenia Space, in Cannes. The MSG satellites continually return detailed imagery of Europe, the North Atlantic and Africa every 15 minutes, for operational use by meteorologists.

© Alizée / imag[IN]

© ESA



CONCERN



Satellites watch over the coastline

Ur coastal towns are sentinels. They are on the 'front line' and as such the first to feel the direct impacts of climate change, through rising sea level and increasingly frequent and severe winter storms. The result is that the sea is significantly eroding our shores, as it did during the 2013-2014 winter, in geological conditions highly conducive

to landslides. In response, public policymakers need to anticipate and adapt their strategies to better protect people and property here in the Pyrenees-Atlantiques department. Considerable resources are being marshalled to combat marine erosion by monitoring shorelines, maintaining and consolidating sea defence structures, replenishing beaches, and tracking landslides and/or collapsing cliffs and infrastructures. In this southwest corner of France, climate change-related hazards are a major risk due to dense urban development most often near the coastline, but they also pose a threat to the local economy and in particular tourism.

Keeping track of the shoreline

Today, traditional coastal monitoring tools are being supplemented by satellite imagery, underpinning complementary approaches to achieve a closer understanding of climate change-related hazards and above all of concrete applications in places that are especially hard to reach. Satellite remote sensing of our coastline gives us a department-wide view and repeat data to support frequent analytics that would be well-nigh impossible using traditional resources alone. Innovative tools are being implemented to keep track of the shoreline, to qualify marine erosion by evaluating submarine sediment and to quantify vertical ground displacements. Applied to coasts, such satellite-based tools are invaluable to inform decisions and adapt our land planning policies.

Bernard Gourgand, Department of Pyrenées-Atlantiques

- ↑ Block supply maintenance
 ↑ operations of Saint-Jean
 de Luz harbour dikes and
 breakwater. The temporal
 survey by remote sensing
 supports the sea defense
 maintenance strategy to
 improve both the costs and
 the efficiency face to ocean
 swell.
 - © Telespazio France
- ↑ Storm-induced river plumes assess both apparent optical properties and total suspended matter concentrations of the water column. These remote sensing derived parameters feed and validate the near real-time numerical models that survey health risks of the nearshore recreational environment.

© A. Roudil





Round table

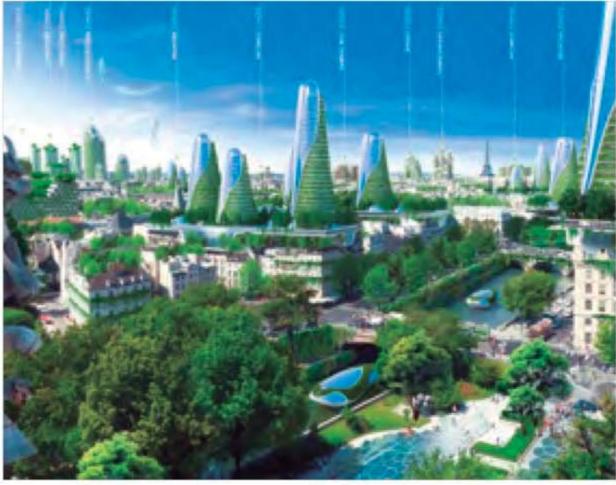
Sharing knowledge

Scientists are no longer the only ones interested in how the climate machine works and the consequences of global warming on oceans. Architects, insurance companies, local elected officials and many others are looking for solutions to adapt to the changing situation and protect people. As reflected in this Climate Change & Satellites round table, the time is ripe for dialog and an interdisciplinary approach.

Vincent Callebaut, Vincent Callebaut Architectures Jérôme Benveniste, ESA Emilie Scherer, Risk Management Solutions Benoît Meyssignac, CNES/LEGOS

While scientists play a pivotal role in research on climate change and its current and future impact, architects and insurance firms are also concerned. Will this force them to change their practices?

Vincent Callebaut: At school, I was taught to work alone, but today this is no longer possible if we are to integrate the impact of climate change, and invent new, more ecoresponsible ways of life. We are working on an interdisciplinary basis, not only with scientists, biologists, physicists and realtime urban modelling experts, but also with economists and politicians. Over the last few years, we have been working together to develop architectural designs with minimum energy consumption, or even self-sufficient, or energy producing models. One example is our participation in Paris-Smart Cities, a 2014 Paris city hall project. We are managing to do this without being called science fiction writers or comics artists.



Vincent Callebaut projects.
The floating structure in
"branches" of Lilypad, a
floating ecopolis for climate
refugees, is inspired by the
highly ribbed leave of the
great lilypad of Amazonia
Victoria Regia increased
250 times.

Prototype of positive energy towers eco-conceived for Paris smart city 2050. Political and social challenge, urban sustainable development should be guided by human sustainable development. © V. Callebaut

With this onslaught of new projects, adding dozens of notable buildings to the city's skyline, many Torontonians are left wondering what the city will look like in the not too distant future.

© Maldive



Another area is sea-based structures. For the moment, there are only two solutions to urbanize the sea: construction on pilings, as in Amsterdam or Venice, or so-called artificial constructions, as in the Netherlands and the United Arab Emirates, on sand banks. But by working with a scientific research lab in Singapore, we were able to propose the construction of cities on floating platforms, which would offer the advantage of preserving natural marine ecosystems.

Emilie Scherer: For the insurance industry, climate change is a challenge for long term risk management, one that forces them to collaborate with other actors in the field. For example, they call on specialists in disaster modelling, like us. We produce risk models based on all historic data, which are constantly revamped. With Hurricane Sandy in 2012 in the U.S., we saw in New York how the impact of rising sea levels combined with that of hurricane. We are able to add a scenario for rising sea levels, provided by the IPCC, to our tropical cyclones storm surge model to see how risks change for coastal communities in the United States.

Policy makers are also interested in our work, as is the United Nations and the World Bank which could use our disaster models as a tool to evaluate the risks entailed in developing countries. For example, the business led 'Risky Business' project in the U.S., in which we are participating, aims to quantify and communicate the economic risks related to climate change.

Benoît Meyssignac: Scientists have also noted a fast-growing need to exchange information and collaborate. People contact us very easily, in general to get our well-documented studies, and give them the state-of-the-art research on their problems, and also to see how we could team up on their own studies.

Jérôme Benveniste: The stakes for climate change concern a large number of people, and the practices of space agencies have therefore also changed. We changed the paradigm: one no longer develops expertise for oneself, to be more competitive in the market, but rather to share it as quickly as possible, on an open-source basis, to contribute to the general undertaking by being as transparent as possible. This also helps calm down climate change skeptics, who tend to use arguments such as: "you're puttering around in the dark, and then sounding the alarm: the planet's getting warmer, sea levels are rising, etc."

How can we set up development and regulatory policies whose benefits

- Women wash clothes in floodwater at an Internally displaced person (IDP) camp in southern-Somalia.

 The humanitarian situation in Somalia is often among the gravest on the planet.

 © Manoocher Deghati/IRIN
- ✓ Environmental officials and scientists warned that Puerto Rico is dangerously vulnerable to the effects of global climate change.
 © B. Baldwin
- ✓ Aerial views of the damage
 ✓ caused in 2012 by Hurricane
 Sandy to the New Jersey
 coast taken during a search
 and rescue mission.
 © M. C. Olsen/ U.S. Air Force







will not automatically be felt within the current generation?

Vincent Callebaut: Regarding eco-responsible projects for climate change, the business model has to be conceived over two or three terms of office, so that the initial added value can see a return over ten years of operation; during those ten years we can lower the project's energy bill by 50 to 75%. Which means that the overall budget becomes identical to that of a project without the same energy intelligence. It's difficult to get public approval for this type of project, because it's ordered by politicians with relatively short terms of office. So we're mainly working with private investors, who may have a more medium-term vision.

Emilie Scherer: In terms of financing resilient infrastructures, this can be difficult to justify as public investment, since the effects are on a long-term basis, and hard to quantify. But there are also very innovative solutions, in which we are participating, such as "resilience bonds", in which we

can scientifically model the financial benefits of resilient infrastructure projects. This helps find, via insurance and innovative financial products, the funds needed to build resilient infrastructures and provide insurance coverage. And that helps communities protect themselves starting right now.

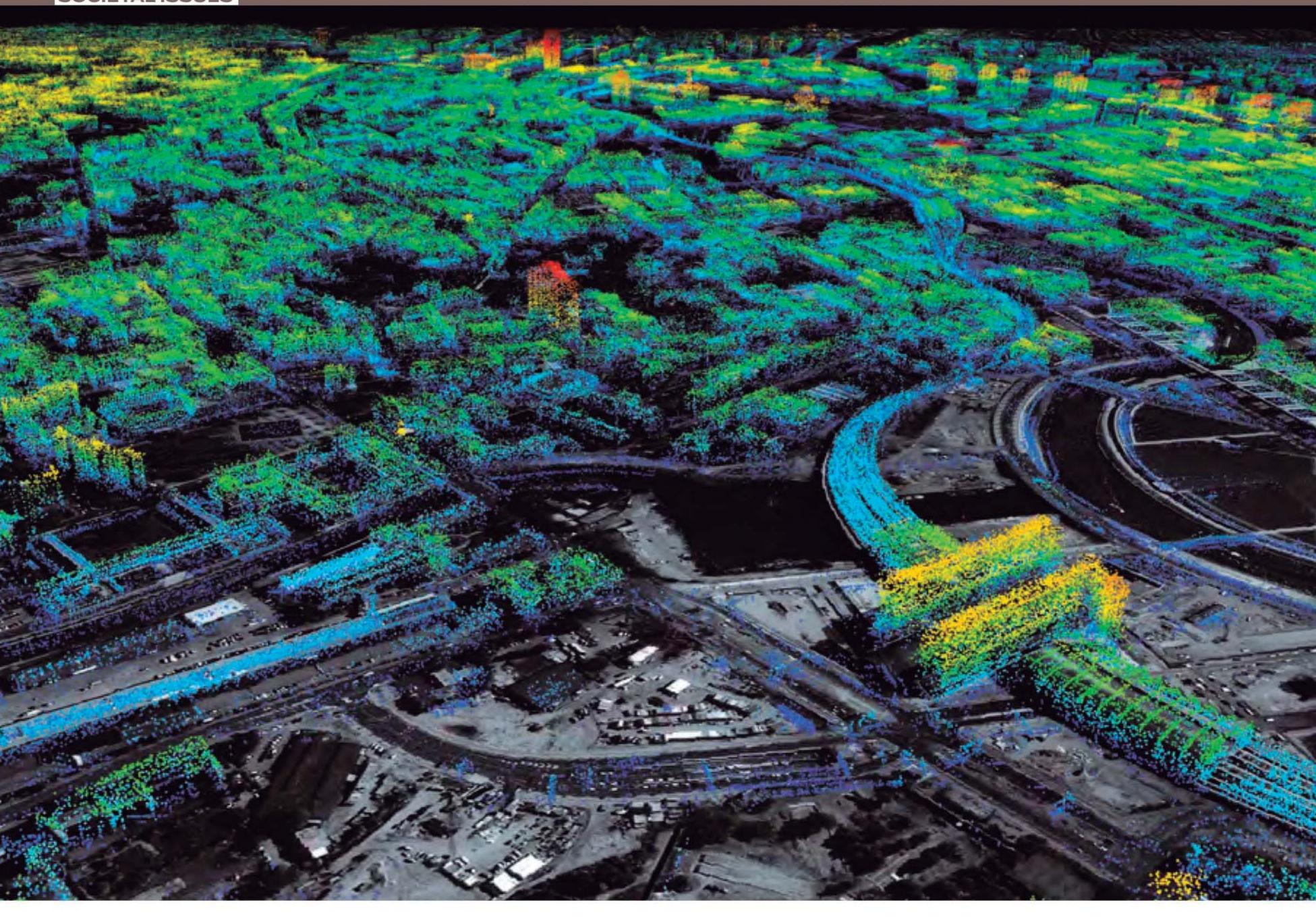
Political authorities need to be sure to launch major projects and gain the support of their citizens. But you scientists have so many uncertainties. How do you manage this paradox?

Benoit Meyssignac: That's absolutely true, especially in terms of how to integrate rises in sea levels. Looking ahead to 2100, the forecast rise ranges from 30 cm for the most optimistic – but also improbable – scenarios, to the most pessimistic, which give a rise of 1 to 1.1 meters. We also have to take into account internal climate variability. For example, we could see a much lower rise in 2050, and then suddenly much bigger one in 2060. And don't forget another uncertainty: we don't really know how public authorities

will integrate our results in their adaptation policies, which can change the final scenario for their populations.

What we are trying to do today is to provide probability curve instead of "best estimates". From the local standpoint, in certain areas and for specific projects, we can have a high degree of uncertainty, and large error bars because there are plenty of factors we still don't understand well (in the ground motion or in the Coastline movements for example).

Jérôme Benveniste: We're working very hard on characterizing errors in the Essential Climate Variables (ECVs), vital data to analyze climate change. Without this work on error bars, we know that the modelling experts who will make the forecasts, or the specialists who will later analyze or quantify the risks, or the architects, cannot do very much. Today, these error bars are recognized as such, meaning that the value can no longer be discussed, because we are all converging towards a certain understanding.



Emilie Scherer: We, catastrophe modellers, are scientists, and therefore uncertainty is at the heart of our profession. What's important is to recognize this fact, and that's one of the factors underlying our usual dialog with our partners.

Do you think that people are sufficiently well informed on the consequences of climate change, and are ready to change behaviors to attenuate its effects?

Benoit Meyssignac: The strongest resistance I see in discussions does not come from the climate-change skeptics, but rather from the fact that we're providing information that disturbs people. For example, the figures for the rise in sea level that we submit to public authorities, to be used for prevention plans in coastal regions, are sometimes softened by local officials, because they lead to difficult constraints on buildable zones and may dissatisfy too many people.

Vincent Callebaut: We've been doing this for over 50 years. But now we know that if we don't convert all the restrictions of climate disturbances into opportunities to invent new models, we're not going to succeed. We can still fool ourselves a bit, but we're not going to get very far ... People are in fact ready to acknowledge real figures and change their way of life, and how they perceive local regions. That's the challenge facing our generation, to show that deeply transforming the society will launch a "green" economy on land, and a "blue" economy on the oceans. We have to take a positive attitude, and not a negative one.

Emilie, are you able to explain to investors that funding your resilient projects will ensure economic development?

Emilie Scherer: Yes, we are now attracting the interest of the capital markets because we can quantify the risk of projects that can generate a positive return.

Unfortunately, we need to experience major events for the level of investment to really change, especially on the political and regulatory levels. That was the case after 2005 Katrina in the U.S., or 2010 storm Xynthia in France, thousands of houses were built in high-risk flood zones. These storms play a very important role in unlocking certain regulatory and administrative processes.

What is the top priority in terms of climate change?

Vincent Callebaut: Converting constraints into opportunities to invent new models and new architectures. Given the projects in the pipeline, we know that, no matter which country is involved, there's strong demand to live in better designed buildings, planned in advance to receive government environmental accreditation, that can be recycled and where we can live without damaging the planet. To meet this goal, we have to address the root of



This image illustrates uplift and subsidence in Berlin, Germany, as detected by satellite radars. Different colours represent different rates of deformation. This type of information can be used by urban planning officials to ensure what areas are safe to develop, or if any structures may pose a safety risk. Data visualisation is key to understanding and communicating the complex content of this scientific data. © DLR

Flooded landscape in
Cambodia between the
Mekong River (right) and
Tonlé Sap river (left). Tens
of millions of people rely on
the rivers for fishing, while
agriculture is intensive along
parts its course.
© JAXA/ESA

problems. Our aim is to design the most sustainable and intelligent structures possible, and see that our current urban development policy, now following a post-war energy-intensive model, is abandoned. Construction in cities must no longer contribute to deregulating the climate, a phenomenon that will only be exacerbated in the coming years.

Emilie Scherer: The top priority is to be prepared and proactive, and to not just wait around for the next big disaster. We should use the available tools, the information that is available from satellite observations allied with modelling, to develop deeper awareness of the risks to which we are exposed. And we have to begin to plan urban zones for the changes to come, using innovation and imagination to find new ways of financing these measures over the long term.

Jérôme Benveniste: We have to continue to improve our understanding of the Earth as a system, and especially the processes that control our climate. As an oceanographer, I would say that we also have to focus on what happens along our coasts, because people like to live there. We shall make sure that our forecasting models really integrate all factors or if, despite all our efforts to show their performance with error bars, they still lack a lot of physical data. This is all to plan ahead better, to send data to decisionmakers, and above all to cooperate with them, by ensuring them that we – scientists and space agencies, with satellite and in situ data - give them what they need to draw up a treaty that is quantifiable, measurable and monitored in the future.

Benoit Meyssignac: One key aspect is in effect to continue to improve our understanding of the climate, which depends on long -term observations and long model runs. The climate is in fact something relatively new, we're discovering it at all timescales, not just the climate in 100 years, but also what it will be next year. We are gaining a better and better understanding of what's happening; for example, we have a better perception of disasters, and we should be able to predict them better and more effectively protect ourselves. The second main aspect is to improve our communications, because there's still far too much confusion. We have to state what we know and don't know, speak about inter-annual scales and also century-long timescales, because the challenges are different, depending on the scale. We should also evoke what could happen after 100 years. This horizon is not so far and our present-day greenhouse gases emissions are already shaping it. It may be hard for our grandchildren to live with the amounts of CO₂ that will be in the air at this time. We're taking significant risks for them without even talking about it.

Jérôme Benveniste: We will also have to "mitigate". Even if politicians today make draconian decisions in terms of suddenly stopping all carbon emissions, there is still a certain momentum and climate change will continue. The reality is that we have already taken out a "loan" for the next two or three generations. A bit like "living on the credit plan", it's our children and grandchildren who have to pay it back. We are already overdrawn in terms of the continuity of climate change and global warming. So it's important to be able to model these phenomena accurately, to include that in the quality of models. We must have continuity of the observations to improve the models that take into account our repayment of the carbon "debt" over 50 or 100 years.

It's up to the politicians to tell us if they're satisfied with this information we're giving them to draw up a treaty, and then measure its application in the same way we use radars to measure speed on the highway or the level of the sea. That allows us to apply the law: without a global observation system, it's not worth signing treaties. Ten years ago, at COP-10, a coordinated response to climate observing requirements was requested; ESA offered its member states a major climate program and it was funded. We are eager to continue to develop the tools needed to measure these climate variables and sign treaties, like Kyoto, Rio and COP 21 in Paris.







Climate Research Gaps and Uncertainties

THE 5TH ASSESSMENT REPORT (AR5) of the IPCC (Intergovernmental Panel on Climate Change) Working Group I, published in September 2013, confirmed the human influence on the climate system (IPCC, 2014). This updated assessment reaffirmed findings from the previous reports, with increased robustness on observed changes and associated causes. Let's briefly summarize the AR5 main conclusions:

 Warming of the climate system in unequivocal. Since the middle of the 20th century, the atmosphere and ocean have warmed. The Earth's mean surface temperature has increased by 0.85°C since 1900. The ocean heat content has also increased, as shown by temperature measurements of the upper ~1000 m of the ocean available since the 1950s. Estimates of the Earth's energy budget by

various methods indicate that the planet currently receives more energy from the sun than it reemits into space. About 93% of this energy excess is accumulated as heat into the oceans. The remaining is used to warm the atmosphere and land surfaces, and melt land ice.

Mean sea level rise

- Arctic sea ice is decreasing in extent and thickness. Boral snow cover has diminished. Glaciers have melted worldwide and the Greenland and Antarctica ice sheets have been losing mass. Permafrost temperatures have increased in most regions since the early 1980s.
- As a result of ocean warming and land ice melt, sea level has been rising, by about 17 cm on average over the 20th century. But since the early 1990s, global mean sea level rise has accelerated, as shown by altimeter satellites.



The small island of Uummannaq lies on the West coast of Greenland, a land mass where 80% of the land is covered by an ice sheet that in some places reaches up to 4 km thick. © UN Photo/M. Garten

 There is some evidence that averaged over mid-latitudes land areas of the Northern Hemisphere, precipitation has increased since the beginning of the 20th century. Observations of ocean surface salinity indicate that the global water cycle has changed. Ocean areas of high salinity where evaporation dominates have become more saline while regions with low salinity where precipitation dominates, have become fresher since the 1950s.

Changes in many extreme weather events have been observed during the past decades. Some of them such as decrease in cold or warm temperature extremes, heavy precipitation events and extreme high sea levels have been linked to human influence.

 The anthropogenic emissions of greenhouse gases (GHG) have never been as high in human history. Emissions have increased since the pre-industrial era. These are driven by economic and population growth. In 2014, CO₂ concentration in the atmosphere has reached 400 ppm, an unprecedented value in at least the last 800 000 years. This represents about 40% of the total anthropogenic emissions, the rest being removed from the atmosphere by the land vegetation and oceans.



Aerial view of the dwindling ice on the summit of Mount Kilimanjaro, as seen by the UN Secretary -General Ban Ki-moon's mission to Africa in 2009. © UN Photo/M. Garten

Oceans have absorbed about 30% of the emitted anthropogenic CO₂, causing ocean acidification.

• The evidence of human influence on the climate system has grown since the 4th Assessment Report published in 2007. Anthropogenic forcings have likely made substantial contribution to the observed warming (both atmosphere and ocean), glacier retreat and surface ice melting in Greenland, global mean sea level rise, changing water cycle and Arctic sea ice loss. Observed changes affecting the climate system since





Haiti's North including Cap-Haïtien (here) suffers on many occasions serious flooding leaving thousands homeless. The Haitian government with the support of the United Nations mission in Haiti (MINUSTAH) and UN agencies including the World Food Program, respond with evacuations, temporary shelters and food and supplies distributions. © Logan Abassi UN/MINUSTAH

several decades have caused impacts on natural and human systems in almost all regions of the world. There is little doubt that continued GHG emissions will further cause changes in almost all components of the climate system. However, projections of GHG emissions over the XXIst century remain uncertain since they are mainly driven by population growth, economy, energy use, land use, new technological developments and climate policy. For its 5th Assessment Report, IPCC has adopted four new scenarios for the XXIst century GHG emissions and atmospheric concentrations (called Representative Concentration Pathways, expressed in terms of net radiative forcing on the climate system by 2100 -RCP2.6, 4.5, 6.0 and 8.5-). In AR5, climate projections are based on these scenarios. Trends observed over the recent years/decades will continue in the same direction for almost all climate parameters, the higher the net forcing (or RCP scenario), the more amplified the associated change. For example, AR5 projected global mean surface temperature over 2081-2100, based on an ensemble of 40 climate models, is estimate to exceed the 1986-2005 value by ~ 4 °C. However the uncertainty is quite large and ranges from 2.6°C to 5.5 °C. Similarly large uncertainties are reported for other projected parameters. For the same RCP 8.5 scenario, global mean sea level is projected to be higher over 2081-2100 by 75 cm on average compared to 1986-2005, with an uncertainty

ranging from ~50 cm to ~1m. Projected changes in precipitation are even more uncertain. Yet to assess future risks and impacts of climate change and to decide for the best strategies for adaptation and mitigation, it is highly important to reduce projection uncertainties. For a given scenario, uncertainties result from differences modeling the response of the climate system to forcing factors, especially anthropogenic forcing. Many processes and mechanisms are now rather well understood. But some are not. In particular complex, non-linear interactions between component responses are still imperfectly understood and modeled. Additional uncertainties in projected changes arise from the inability of climate models to simulate natural climate variability that superimposes the forced response.

Grand Challenges

As summarized by the AR5 of the IPCC WGI, some key uncertainties are still remaining, preventing more precise projections. These concern: radiative forcing and physical feedbacks, changes in the water cycle, in particular precipitation, the dynamical behavior of the ice sheets and inferred future sea level rise, the anthropogenic carbon cycle including the role of vegetation as source and sink of carbon, near-term predictions, deep ocean heat uptake and its role in the current hiatus in global warming. The World Climate Research Programme (WCRP) of the World

Meteorological Organization (WMO) has defined a few years ago a number of Grand Challenges (GC) with the objective of federating the world climate community around a few themes addressing major issues in climate research supposed to improve process understanding and reduce the longstanding uncertainties in IPCC assessments. The six WCRP grand challenges are: (1) clouds, atmospheric circulation and climate sensitivity, (2) changes in the cryosphere, (3) understanding and predicting weather and climate extremes, (4) regional climate, (5) regional sea level rise and coastal impacts and (6) water availability. In September 2014, representatives of the world climate community participating in either IPCC assessments or WCRP activities (or both) met during a workshop held in Bern with the objective to identify emerging themes, key uncertainties and research and data gaps and discuss how WCRP can handle these issues. For each of the 6 GC themes, a number of key gaps in process understanding and uncertainties have been reported and recommendations have been provided for observations and modelling improvements. Concerning observations, requirements stress the need for data continuity and global coverage, better use of available observations and usefulness of reanalyses. An important outcome of this workshop is the proposal for a twentieth century Earth System reanalysis. However, the decline of in situ networks (e.g., in hydrology, glaciers) or observational gaps at the regional level or for some climate variables has been identified as a severe drawback.

Climate Change Initiative project

Since 3-4 decades, space observations provide invaluable information on the different components of the climate system and their evolution. Long satellite data records of several essential climate variables

(ECVs, as defined by the Global Climate Observing System - CGOS-; GCOS, 2010) are now available to investigate how the Earth's climate is currently changing in response to natural variability and anthropogenic forcing. The Climate Change Initiative project of the European Space Agency, initiated in 2010, is currently providing long, accurate and homogeneous time series for several space-based ECVs. Such observations not only contribute to increased understanding of the complex physical, chemical and biological processes at work in the climate system under different forcing factors, but also help validating the climate models developed to simulate future changes. Owing to their use in synergy with in situ observing systems and modelling approaches, satellite-based climate records are now considered by the international science community as a fundamental pillar of climate research. In October 2014, a symposium entitled "Climate Research and Earth Observation from Space - Climate Information for Decision Making" was organized by EUMETSAT and WCRP around themes related to the six GCs in order to address the specific need for, and role of, climate observations from space. Main recommendations can be found in Asrar et al. (2015).

Climate scientists, space agencies representatives and international organizations such as GCOS and WCRP are increasingly working together to identify gaps in the current space-based component of the climate observing system and discuss how future developments expected from planned or proposed space missions can fill these gaps. An important issue is to identify areas where international coordination in mission planning can be envisaged in order to augment the value of space-based Earth observations to addressing interdisciplinary aspects of climate research.

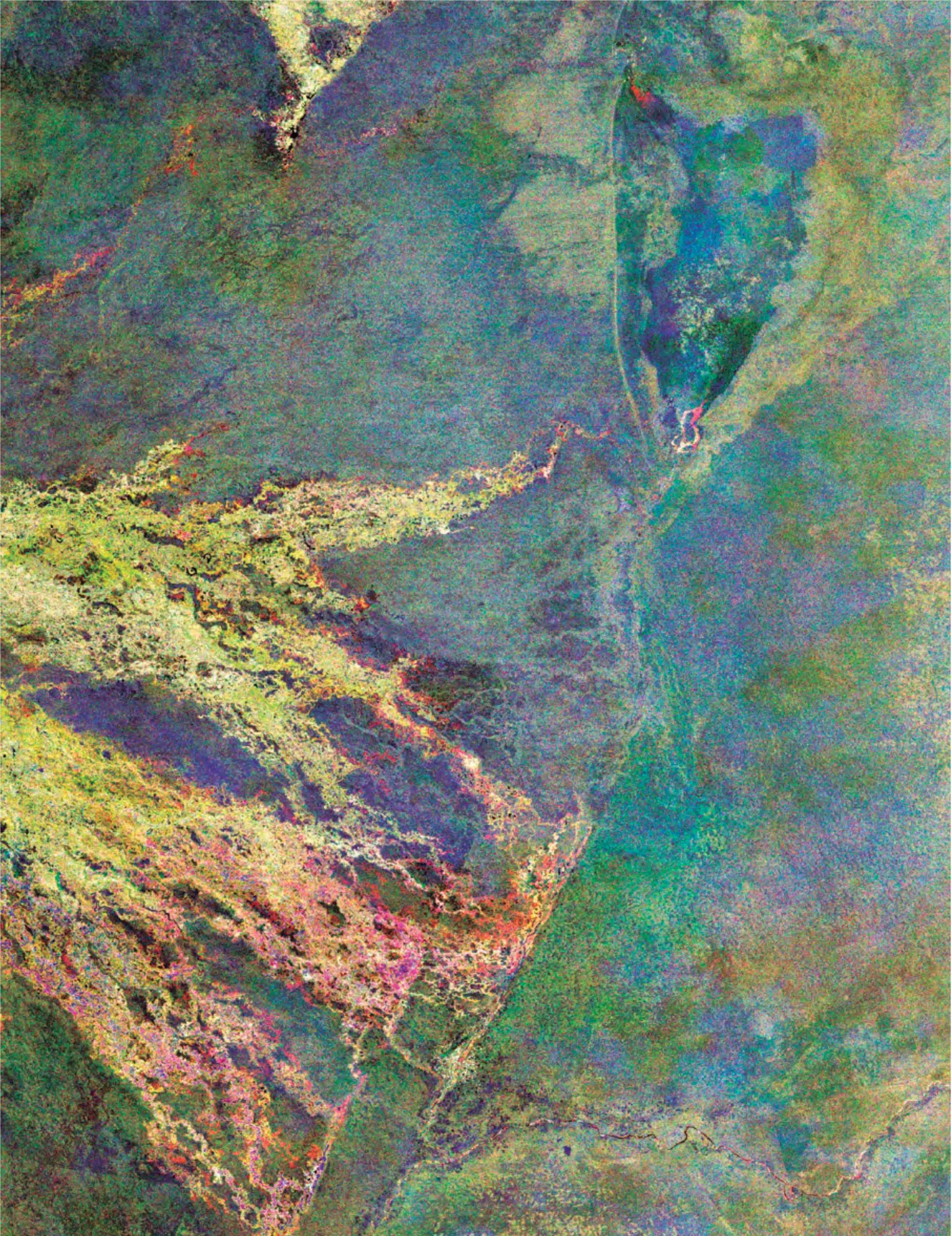
Anny Cazenave, LEGOS/CNES



Mothers walking home with supplementary rations for their under-two children in Niger's Central region of Tahoua. © Catherine-Lune Grayson/IRIN

Butare region, Rwanda. Despite the World Food Program's "Food For Work", this country lives in food insecurity, in particular in 2015, because of a massive influx of refugees from Burundi. © Wendy Stone/IRIN





Europe's space flagship programme My vision about Copernicus

N THE 1990s Europe was in an Earth observation crisis. Although ESA had just successfully launched ERS-1 and ERS-2, which were defined by the science community, and was developing the largest ever Earth observation satellite, the 8-ton, 10-instrument Envisat, Europe lacked a coherent concept for a long-term, operational Earth observation programme. It was clear that the relatively small but highly sophisticated user community, driven mostly by science, would reach its limits. What was needed, in addition to a strong science programme, was a wider, more far-reaching vision that would place Earth observation at the core of people's needs and which would better respond to the political challenges in Europe.

This required a fundamentally different user engagement at institutional, commercial and political level. However, to reach this, users would need to rely on decades of observations, not just a single satellite mission that would eventually be replaced by another one in a rather piecemeal approach. In a way, what was needed was something similar to what meteorology had built up since the launch of Meteosat-1 in 1978. However, the domains needed to be much wider to encompass a large variety of issues of concern to society such as environmental monitoring, climate change, resources management, regional and urban planning, energy, food security, disaster responsiveness, humanitarian aid, to name a few.

At global political level, the climate change debate recognized that mankind was severely influencing, if not threatening, its own living space in the foreseeable future. This led to the adoption of the Kyoto Protocol in 1997, which entered into force in 2005 due to a complex ratification process.

The Earth observation crisis in Europe, coupled with the climate and environmental debate worldwide, triggered the creation, in 1998, of a European initiative called Global Monitoring for Environment and Security, GMES. The scope of GMES, which is

still valid today and has remained unchanged after its renaming to Copernicus, is to establish a sustainable Earth monitoring system that supports the European political agenda and, ultimately, the needs of its citizens for crucial information to better manage their living environment. This programme was designed to complement the ESA Earth Explorer science missions as well as European national missions to become a fully operational programme. It is worth recalling that the science community was closely involved in the definition of the GMES initiative and will become a major user of it.

Pro-actively engaging the user

The first years of GMES focused on the creation of a solid user base. The need for stronger integration of Earth observation into EU and national policies, for example, was well recognized, but the engagement of its institutional users remained the biggest hurdle to overcome. Regularly organized 'user fora' in the early years saw only a handful of real users, while the service industry and institutional actors representing either the supply or intermediary layer were the dominant sector in such meetings. This had to change. ESA initiated a systematic user programme, called GMES Service Element, which engaged users through Service Level Agreements to become active partners in industrial consortia that demonstrated the use of Earth observation for a variety of different application domains.

The European Commission joined efforts through successive Framework Programmes where largescale projects in support of European policies were implemented. The goal was to create a critical mass of engaged users who would articulate observation needs for major, European services. This led to the definition of the ESA-led Sentinel programme, which responds to user needs federated by the Commission.



ESA and the EU partnership

GMES/Copernicus would not exist without the EU, nor without ESA. Both organizations have very different political and institutional goals. Legal, financial and procurement rules are adapted to each organization's objectives. Nevertheless, the complementary skill base of both partners is essential to successfully implement a multi-billion space programme like Copernicus. It requires maximum flexibility within the respective boundary conditions, which proves difficult at times to achieve. In addition, the institutional roles have evolved, driven by wider political debate on the governance of both organizations in the space domain.

During the first years, until 2005, ESA and the EC were co-leading GMES with equally shared responsibilities. Member States were also an essential partner, not only in the decision making on both sides, but also by developing national projects to support the European process. After 2005, a division of roles was agreed at political level, whereby ESA was made responsible for the overall space component including all space R&D aspects as well as some operational tasks, while the EU was given overall responsibility for GMES from a political point of view including the services component. Funding streams were organized accordingly.

In 2005, GMES became an EU space flagship programme, along with Galileo. This was a key political commitment which paved the way for the establishment of a decade long observation system that feeds geospatial information services in support of European and national political priorities with the necessary data. This evolving relationship led to the transfer of the Sentinel ownership at lift-off from ESA to the EU. Two major EU-ESA agreements were concluded, in 2008 and 2014, that provide a stable financial and institutional framework for Copernicus for decades to come. In addition, an EU-EUMETSAT agreement was concluded, also in 2014, to operate those Sentinels that focus on atmosphere and marine services. The launch of the first dedicated Copernicus satellite, Sentinel-1A, in April 2014 signified a step-change for Earth observation not only in Europe, but world-wide, as it has put a vision written down in 1998 in the 'Baveno Manifesto' into reality.

Many challenges still remain

Although today Copernicus is on firm ground, financially and programmatically, there are several important challenges remaining. The first and foremost is to ensure its long-term sustainability. Today, financing is guaranteed for the system's operation until 2021 and first generation Sentinels, including recurrent units, are fully funded until 2028 and beyond, depending on the Sentinel. However, the operation of these recurrent missions, as well as a solid and evolving services and ground segment, need to be funded beyond 2021. In addition, the next generation Sentinels, to be launched from 2028 onwards, needs to be defined, funded and developed in response to user requirements. This involves close EU-ESA interactions, whereby the European Commission provides user requirements to which ESA responds with

the corresponding space infrastructure. The principle of ESA focusing on R&D, i.e. funding the first satellite and ground segment elements, and the EU funding recurrent elements and the system's operation, shall remain in place, similar as for the first generation but with adaptations as needed.

Secondly, the system needs to constantly adapt to technological advances, in the space, services and ICT domain. Although the Sentinels are of excellent quality and represent the needs of large-scale operational European or global services, new technologies and/or user requirements may impose new solutions in addition to the current six Sentinel lines. For example, the advent of micro and nano satellites, which are launched in constellations of 100 or more individual satellites, including video-capability, allows for more continuous observation streams that are needed by several users. Furthermore, the ICT revolution of the 21st century poses new opportunities and challenges. Cloud-based processing allows bringing users to the data and therefore sharing infrastructure and knowledge among an increasingly global community. These technological advances will always lead to an evolution of the overall system while, at the same time, users will likely request a certain operational stability by maintaining core Sentinel observation technologies as they are in place today.



Sentinel-1A satellite in the anechoic test chamber during radio frequency tests, at Thales Alenia Space. © S. Corvaja/ESA

Other challenges are of industrial nature, where system design and manufacturing need to be streamlined in order to shorten times between definition and launch of Earth observation systems. Satellite telecommunication, which has a much higher commercial revenue stream, has already successfully undergone such shortening of project cycles. Earth observation will be next in line, going from tailormade towards mass production of satellites. Science missions may be exempted from this trend, though not completely, as they serve a different purpose and, apart from answering the most pressing questions of knowledge, they are often also specifically designed to push the envelope of technology itself.





Studies show that Copernicus could generate a financial benefit of some €30 billion and a minimum of about 50 000 new jobs by 2030. Here, engineers working on satellite projects in Italy (above) and in France (left). © Thales Alenia Space

Another challenge, but more so an opportunity, is the broadening of its user base. The free and open Sentinel data policy has been a watershed decision by the ESA and EU Member States. This, potentially, allows a broad use of Sentinel data and derived services by an ever-increasing community. It also is the key ingredient to create real economic benefits and new jobs in a high-skill sector. Independent socio-economic studies predict an economic return of up to 10 times its original investment, but only if data and services are freely available and fully integrated into the information collection chain. However, if this process is not adequately accompanied through a regulatory and financial support framework at EU and national level, this will not only lead to a wasted opportunity, but may even lead to disappointment and disengagement of the user community and politicians. The EU has a primary responsibility, as overall programme responsible, to ensure a programmatic, financial and legislative framework that enables the full uptake of Copernicus data and services. This may seem challenging, considering that Copernicus, today, is still far away from reaching its full potential to serve all sectorial policies across the European Union.

This broadening of user base may also lead to an enlargement of today's six Sentinel lines before the next generation Sentinels is due. For example, the mid-term review of the EU Multi-Annual Financial Framework planned in 2017 could be a welcome opportunity to add one or two new Sentinel lines. As an example, users have clearly expressed a need to continue global sea-ice measurements at highest accuracy, as provided today by CryoSat, to better understand global ocean-ice interactions including a possible slowing of the Gulfstream due to climate change. Other user requests include adding low-cost free-flyer companion sensors, for example, in the thermal infrared to obtain better information for agriculture, urban planning or border control.

Likewise, there is a large political requirement for an operational carbon-monitoring constellation to support the implementation of a follow-on treaty to the Kyoto Protocol. Copernicus could be a perfect fit for such a new Sentinel series from a programmatic point of view. However, a solid user consultation process, led by the EU, is essential to determine the needs and related technologies to respond to such needs. All this requires an interactive dialogue between user and technology communities in order to fine-tune possible solutions and ensure that they are within reach of today's technology as well as within financial boundary conditions.

This requires a partnership between the key actors already in place today, the EU and EC as proxy user and political driver, ESA as technology-provider and development and procurement agency, Member

States to guide the institutional process and, obviously, industry to stimulate new ideas and implement solutions.

Finally, Copernicus is also a political tool. It provides, among others, access to global data and information for European and national governments. Considerable thought needs to be given on how to fully exploit this tool at EU and national level in order to advance domestic as well as foreign policy objectives. Again, this is primarily a challenge for the EU and national governments.

Copernicus and Climate change

Although Copernicus was, from the outset, defined to serve a large variety of domains, climate change has always been a driving force. This includes several aspects: climate research in order to better understand the status quo of our planet today and its potential future evolution, monitoring of international climate and environmental treaty obligations, and mitigating impacts of climate change through better observations and forecast models, to name a few.

GCOS, in support of the UNFCCC, has defined a number of essential climate variables, many of which can be monitored using satellite data. They include parameters such as cloud cover, aerosol concentration, greenhouse gases, vegetation fires, land cover, glaciers, sea level height and sea surface temperature. Deforestation, reforestation and forest degradation are of particular interest, since they are a rather fast changing element in the global carbon cycle.

Despite the undisputed role Copernicus will play for climate change, the Copernicus Climate Service is one of the last to become operational.

Another challenge European politicians cannot avoid to address is that Europe, being the world leader in demanding tough climate-preserving measures from the global community, has currently no concrete plans for an operational carbon monitoring satellite mission for the most significant greenhouse gas, carbon dioxide, that provides data at high temporal and spatial resolution. There are some activities, including a German-French cooperation for methane monitoring, Merlin, as well as a potential Earth Explorer science mission, Carbonsat, which could provide critical measurements, but they all have significant limitations. They are one-off missions and/or have a limited thematic focus and are not designed to monitor climate treaty obligations. The existing Sentinel missions will certainly provide some crucial climate observations, but they would need to be complemented by more dedicated climate instruments. A longtime series of such missions would need to be implemented in order to establish a fully operational carbon monitoring system.

Europe has a political responsibility, and obligation, to meet political statements with concrete action. Space-based observations are one of several, but certainly a critical, response to Europe's political ambitions in climate change leadership.

Josef Aschbacher, ESA



In 2014 the European Commission and ESA signed an Agreement of over €3 billion to manage and implement the Copernicus 'space component' between 2014 and 2021.

© Edu Van Gelder

Copernicus and Europe

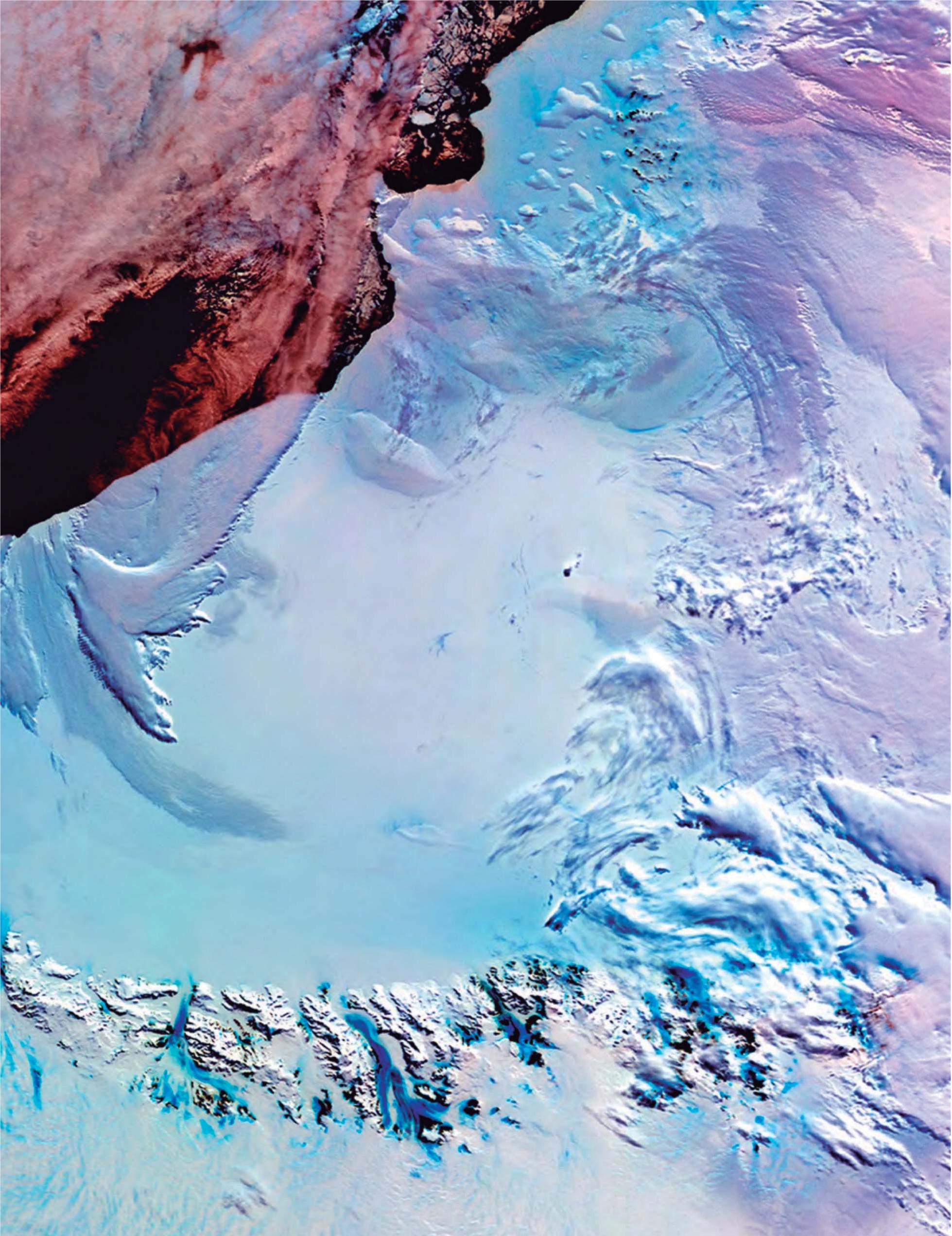
Imate change is a major global challenge with a range of potential social and economic impacts. The need for accurate information about the impacts of our changing climate for improving our capabilities to monitor, forecast and make projections about the Earth's Climate is growing increasingly urgent. The Climate Change service of the EU Earth Observation programme, Copernicus, is a direct response to the overwhelming scientific evidence confirming the existence and impacts of Climate Change. Its products are essential in order to effectively develop adaptation and mitigation strategies to reduce our vulnerability to Climate Change, and limit its amplitude.

This Copernicus Service, operated by the European Centre for Medium-Range Weather Forecasts, uses complex mathematical models that simulate the Earth components to analyze the behaviour of these systems, to generate seasonal forecasts and to provide climate projections. For example, Copernicus delivers continuous and reliable information about the extent and effects of sea-level rise in Europe's low-lying coastal areas. This monitoring is crucial if we consider that these coastal areas gather one third of the EU population and generate over 30% of the total GDP. Copernicus also allows monitoring the shrink of the polar ice cap by providing accurate topographic measurements over sea ice and ice sheets. With the deployment of its full constellation of satellites, Copernicus will ensure a systematic supply of data with rapid dissemination and short revisit time. This allows creating Climate Data Records which are a key element to better identify climate trends and to estimate Essential Climate Variables as well as Climate indices and Indicators required addressing sector specific issues.

Copernicus aims at becoming a trusted reference source for climate-related information and will become Europe's main contribution to global efforts to better understand and monitor the health of our planet.

Mauro Facchini, European Commission







Samantha Cristoforetti is flying on the International Space Station as an ESA astronaut for Italy's ASI space agency under a special agreement between ASI and NASA. © NASA

Earth Observation Innovative applications

OOKING AT THE BLUE SPHERE of the Earth from space gives us a unique view of the immediate beauty of our planet, in its protective atmosphere. At the same time it shows us how fragile it is. Astronauts or cosmonauts since Gagarin have been amazed by their first view of the Earth: what a spectacle it offers from up there! Space is the perfect vantage point for gaining a total understanding and overall vision of what happens on our planet. Like astronauts, the 'eyes' of satellites keep watch over the evolution of our fragile environment. A telescope's view of the world shows us how human beings are influencing the environmental situation on Earth, often rapidly and continuously. The information that we obtain from satellites is comprehensive, rapid, precise and extensive. Seeing climatic variations from on high offers a privileged field of study that is easier to understand and brings countless benefits for everyone. It can be argued that space activities have changed the reference system of the science of monitoring climate change. The growing awareness of environmental protection finds therefore a precious support in space acti-

vities. Satellite systems and their applications are crucial to the development of best practices for monitoring the environment, and have an impact on every aspect of ecosystem protection, the fight against climate change and the general observation of the health of the planet. Satellite data offer a valuable archive of recent years of climatic and environmental history. They help us discover what is still unknown in the field of climate change, acting as a powerful, effective tool that can provide information on the evolution of environmental conditions and the effects of disasters occurring on Earth. The information we receive from Earth observation satellite systems forms a vast wealth of data that we must to be able to exploit directly and rapidly. We can then act quickly on several fronts to mitigate, delay or better understand the various situations that we encounter. The Italian Space Agency is in the front line with Italy in the field of Earth observation. First of all, we benefit from the capabilities of the dual satellite system with four COSMO-SkyMed satellites that have been used on numerous occasions to monitor international emergencies. The Copernicus and Galileo



The mission of the Italian astronaut inspired young artists of the «Bambino Gesù Scuola» in Rome.

programmes also underline the importance that Europe attaches to Earth observation. It is globally acknowledged that satellite data are a unique resource. COSMO-SkyMed's performance in recent years has enabled us to observe the vital role space plays in this field. The extreme precision with which the four Italian satellites can 'see' the Earth opens up commercial and industrial applications in the fields of monitoring and protection of the environment.

COSMO-SkyMed free data

One example comes from the analysis of a rail accident in Andora (Liguria) that occurred in January 2014. We all remember the pictures of the train travelling along the railway line a few meters from the sea when it was derailed by a landslide and almost causing a human disaster. Several months after that episode, technicians at the Geophysical Applications Processing, a spinoff from the Politecnico di Bari that works with the ASI Centre for Interpreting Earth Observation Data in Matera, launched a study to analyse the archival interferometric images acquired by Cosmo-SkyMed. A comparison with the images of previous months clearly shows that just above the point where the train was derailed there were signs of a landslip that caused a landslide of one centimetre per year. It does not sound very much, but in the end it was enough to cause a disruption. These archives can offer enormous benefits to environmental protection of all kinds.

That is why the Agency has recently made data from Cosmo-SkyMed freely available to the public. This project will be implemented through two Open Calls targeting not only the international scientific community, but also the national private sector of SMEs, start-ups and university spin-offs. The aim is to make satellite data more widely usable. And to deliver tangible results in fields like environmental resource management and services to citizens. We are therefore "promoting the development of new algorithms" to help "improve existing products and services" and also to invent "innovative technology applications". We all have a responsibility to take better care of our Pale Blue Dot - our Earth - which is still the only possible world on which we humans can live. Space will become increasingly critical to the protection and monitoring of this remarkable planet.

Roberto Battiston President of the Agenzia Spaziale Italiana

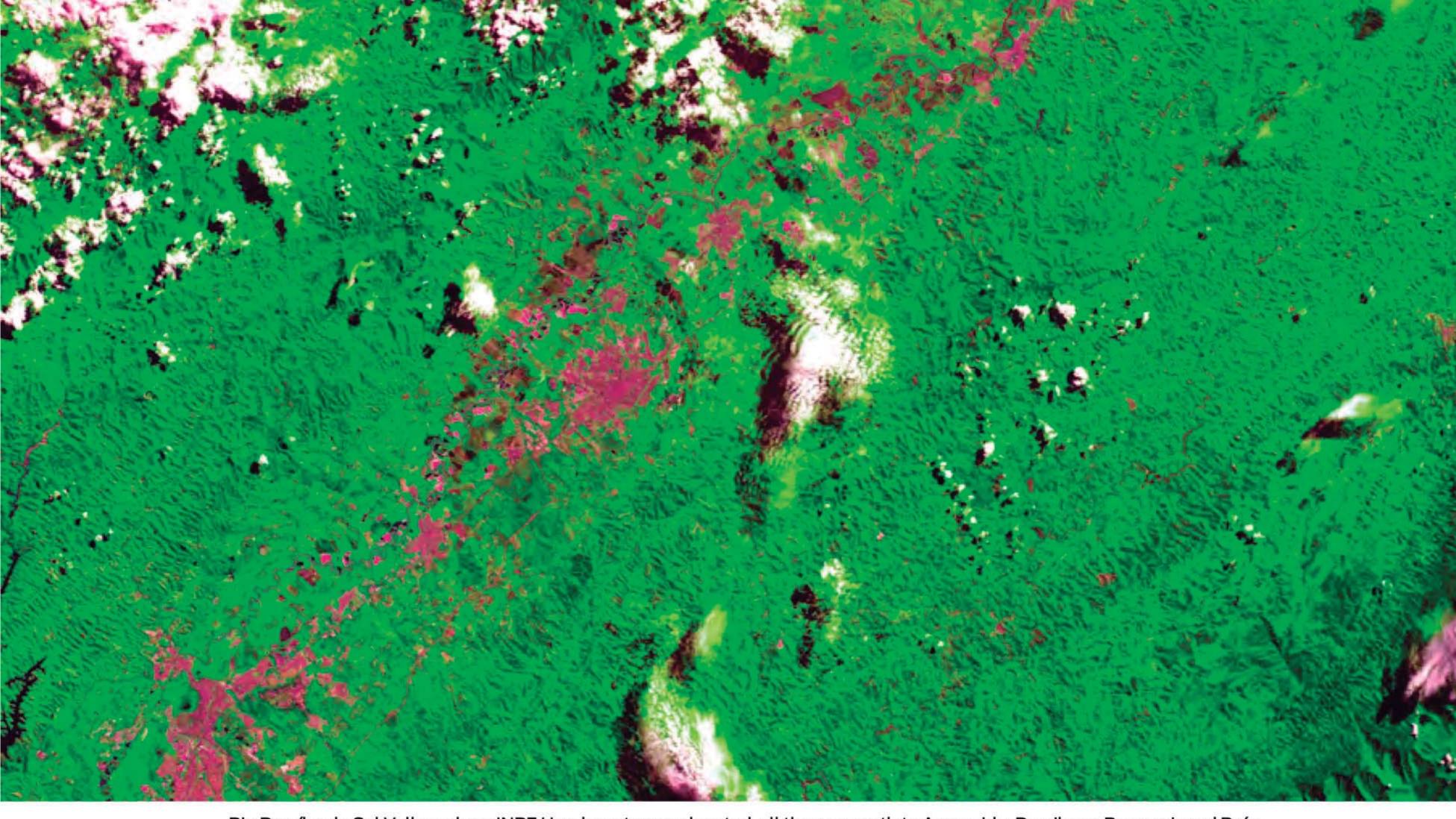
Climate data and services

limate data records, based on the essential climate variables (ECV), originating from the Italian Air Force Meteorological Service (ITAF-MS) network, date back to the middle of the 20th century. At present, the synoptic ITAF-MS network is made up of about 100 surface and 6 upper-air (through radio-sounding) meteorological stations, that operate and are certified according to WMO standards. Observational bulletins are regularly transmitted in real-time via the Global Telecommunication System (GTS) and feed international databases (ECA&D, ECMWF-MARS).

Networks devoted to special observations (such as long-term time series of CO₂, O₃, visible and UV solar radiation, acid rain, etc.) and to electrical discharges detection (Lampinet) are also currently employed for climate monitoring. ITAF-MS's official duties include the provision. mostly on-demand, of the basic in-situ. reanalysis, and satellite data, and of their statistical processing. At the international level, reference climate-related activities are carried out, within the WMO Region VI, by the Regional Climate Centers (RCCs) located in Offenbach (node on climate monitoring), De Bilt (node on climate data) and Toulouse/Moscow (node on Long-Range Forecasting).

The Italian Air Force weather Service represents Italy in many international contexts such as WMO CCI (Commission for Climatology), the IPCC (Inter-governmental Panel for Climate Change), the GFCS (Global Framework for Climate Services).

The NCSNI (National Climate Services Network of Italy) is being built up with the purpose of providing a coherent set of climate services for national objectives and to participate in international programs, such as the Copernicus Climate Change Services and other European initiatives, e.g. within the EUMETNET framework. It is constituted by the Institute for Environmental Protection and Research, ISPRA, the Italian Air Force services, meteorological regional agencies and research institutions and consortia (CNR-ISAC, ENEA, CMCC), all of them active in operational climatology. Availability of in-situ long-term data time series is a prerequisite for the evaluation of current climate variations and trends through highresolution reanalysis and calibration of seasonal/ climate models and satellite data (such as, for example, CM-SAF datasets). That is the rationale for the crucial importance, in our view, of investing on data rescue and quality control. Col. Leonardo Musulmano Ufficio Generale Spazio Aereo e Meteorologia



Rio Paraíba do Sul Valley, where INPE Headquarters are located, all the way north to Aparecida, Paraibuna Reservoir and Baía de Caraguatatuba. © Brazilian Chinese CBERS image acquired at INPE. Processed by Oton Barros, OBT Rapid Response.

Education first

Raising awareness

LIMATE CHANGE has become a major issue for Brazil. Extreme events such as droughts, landslides and floods have increased, taking their toll on the population across the country, including in urban centers and affecting our economics. We have to cope with these events, whether they are direct or side-effects of climate change, and improve alert and prevention mechanisms. Brazil has a well-structured scientific network, relying on space-based and in situ data. In 2011, in response to extreme events, the Science, Technology and Innovation Ministry decided to set up the National Center for Alerting and Monitoring of Natural Disasters (CEMADEN).

One of AEB's missions is to make sure that data is available to monitor the shifts in climate patterns over time, as data continuity is instrumental to understand climate change and reduce risks, through more efficient forecasts. Brazil has its own earth-observation satellites, such as the CBERS series in cooperation with China. The Amazônia's family will be, in the next future, the first Earth Observation satellites built entirely in Brazil. Obviously, we also work with international institutions and data from satellites such as Jason whenever we need to call upon additional knowledge or to

mutualize our data. Early 2015, Omnisys and Thales Alenia Space set up a technological center in San José where students and scientists will be able to use climate change data coming from Copernicus.

Investing in education is key

In addition to technology, what we need is to educate people, to change their mindset and create a culture of readiness and fast response. With more commitment, many local actions could be implemented, improving and even saving the lives of many people in Brazil.

I believe young generations are more eco-conscious. I would like our young people to go abroad, see how other countries are dealing with the environment, and bring back best practices to our country. Investing in education programs and providing young people with the means to get involved is key.

This, together with better alert mechanisms, and the implementation of many local actions would drastically improve our ability to deal more efficiently with the impact of climate change, it would improve and even save the lives of many people in Brazil. Awareness, education and technology have a crucial role to play.

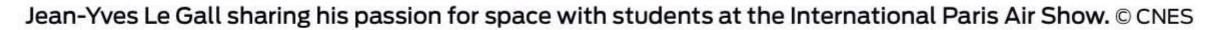
> José R. Coelho, President Agência Espacial Brasileira

Global efforts

Scientific and technological excellence

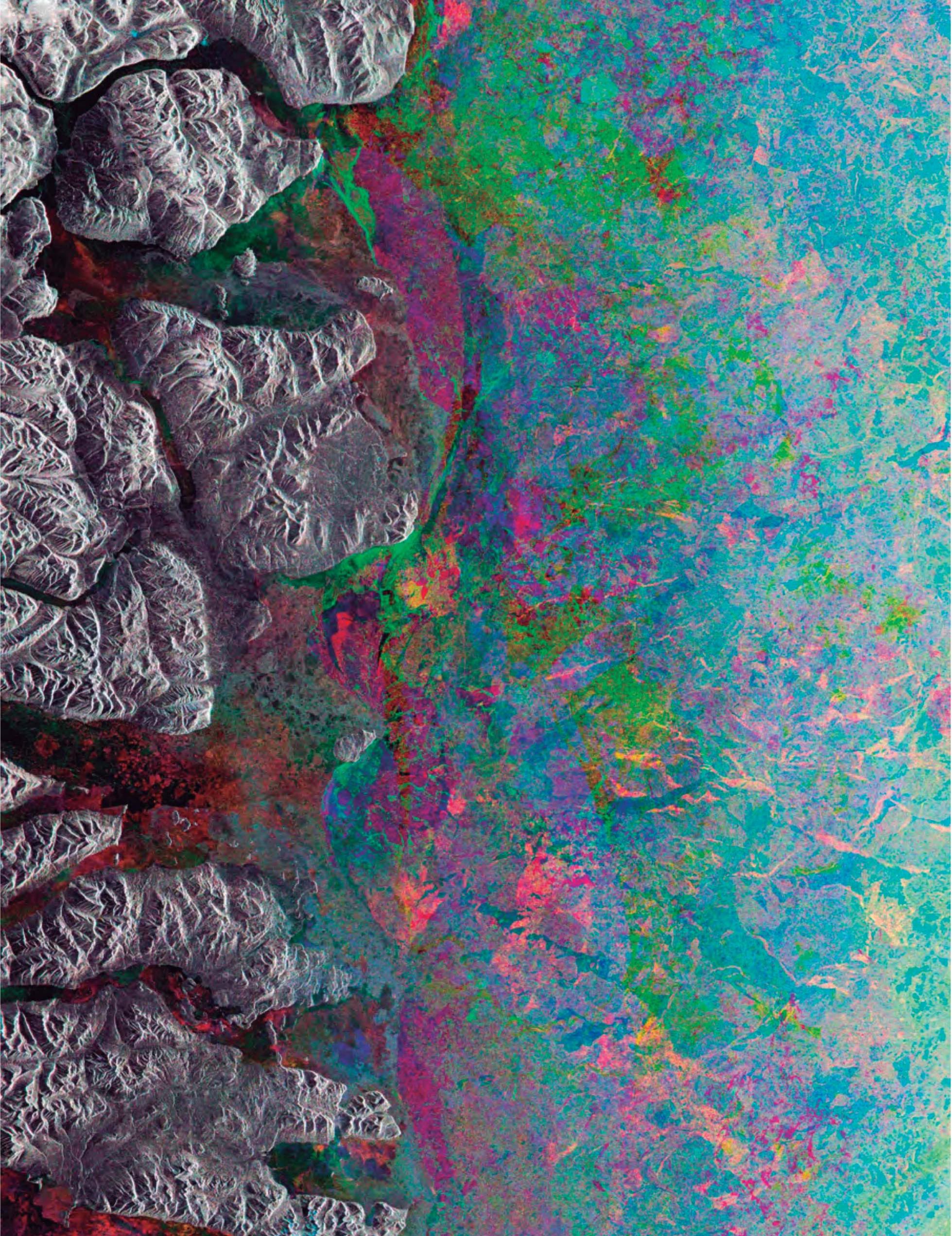
LIMATOLOGY has become a priority research focus, given the demand for a greater understanding of the mechanisms behind climate change and a strategy that will allow us to limit and adapt to these changes. The challenge is to develop increasingly accurate climate models, which in turn requires measurements and observations to validate or invalidate the proposed climate models, theories and hypotheses. A global climate observation system should enable us to answer these questions. There are many climate variables, of course, but also a very wide range of observation systems. Ground-based systems, as well as those mounted on airplanes, balloons or buoys, provide observations that are often incomplete, because of the few measurement points. And that's where space comes in! A number of operational or climate research satellites would provide the parameters needed to estimate 50 essential climate variables (ECV) for our entire planet, with spatial and temporal resolution tailored to requirements. Out of the 50 essential climate variables, 26 are under observation from space, using about 50 different satellites. They feed models with data on land and sea temperatures, icecaps, sea levels, clouds and aerosols, greenhouse gases, etc. And that, in a nutshell, is why the climate is at the heart of French space policy and a number of space programs we have been working on for many years that contribute to this global effort. In the future, Jason 3, IASI NG, Merlin, SWOT and Copernicus will take over to push French and European scientific and technological excellence to an even higher plane.

Jean-Yves Le Gall, President CNES









EUMETSAT

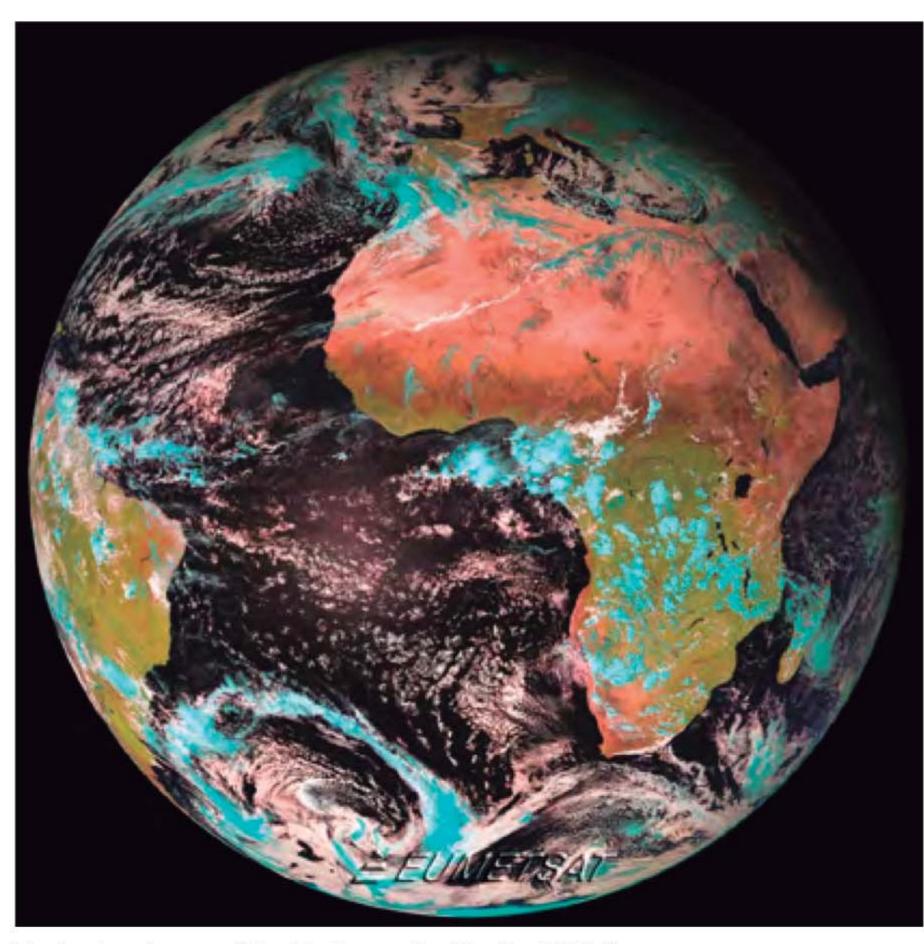
Grand Challenges

LIMATE CHANGE is undoubtedly a reality and the younger generation, especially, will be confronted with its impact in their day-today lives, as the effects of climate change become more and more tangible in the decades to come. Unfortunately it is the price to pay for the continuous growth of carbon emissions in the past decades.

Climate change is also a "grand challenge" of unprecedented scope and complexity for our society. Unlike the destruction of the ozone layer, its causes are as multiple as its consequences are multifaceted. In fact, climate change calls for difficult decisions, as the necessary adaptation and mitigation policies involve large and sustained public and private investments, which in many cases will pay off only in the long term. To be acceptable for society, such decisions must be well informed and well communicated, with due consideration being given to uncertainties, risks, costs and expected benefits. The emerging climate information services combine observations and modelling of the Earth system with information on vulnerability and socio-economic data to fulfill this requirement. However, in order to be credible, they require a solid scientific foundation. We therefore need to tackle the "Grand Science Challenges" identified by the World Climate Research Programme (WCRP) as the climate research priorities and ensure that the knowledge gained is shared globally, in particular through the IPCC assessment reports.



Meteosat Second Generation (MSG) testing at ESTEC (1998). © ESA



First colour image of the Earth acquired by the MSG-2 satellite in 2006. © EUMETSAT

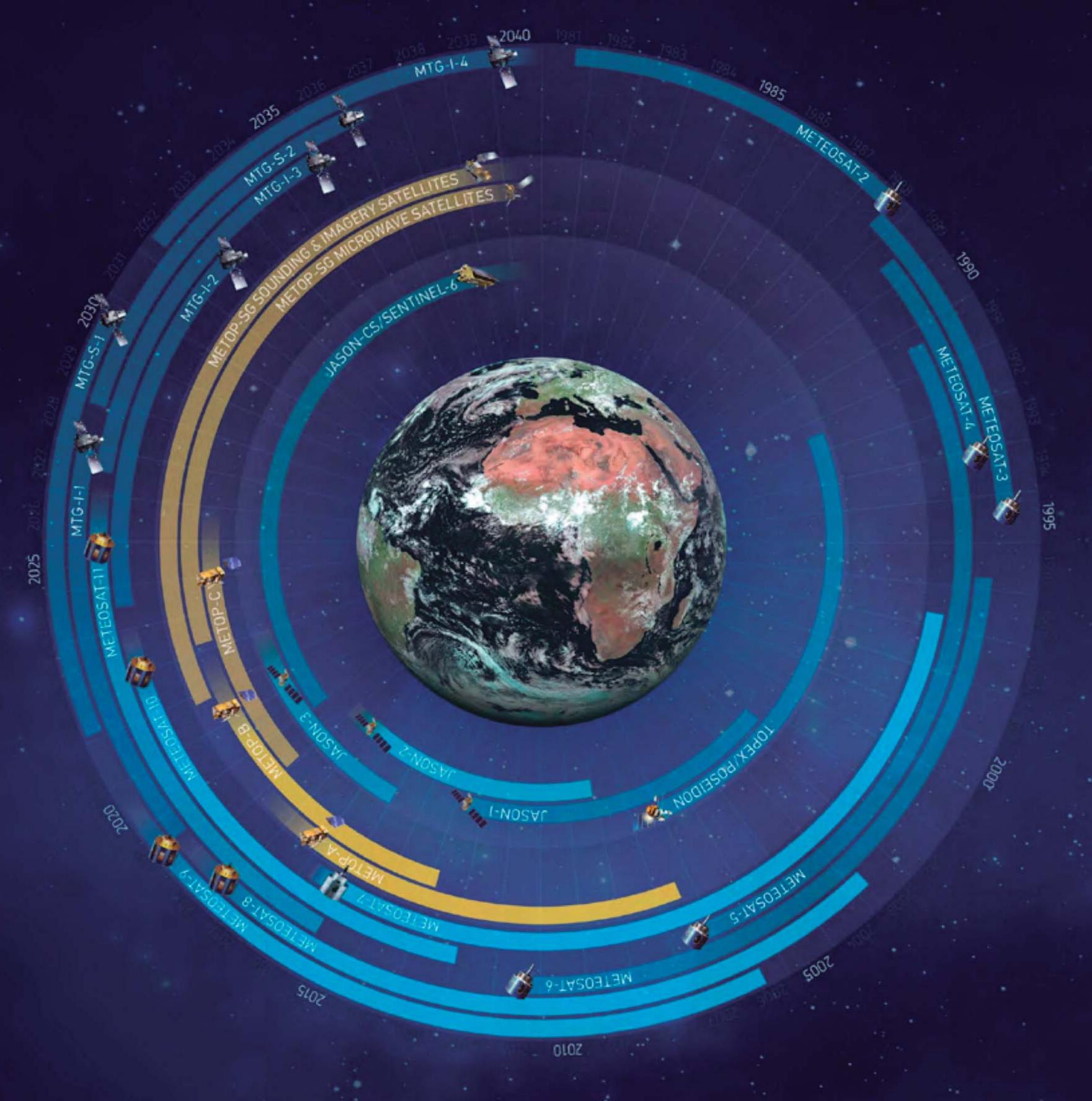
Grand Science Challenges

Observations from space are one of the essential ingredients of climate research - i.e. for collecting evidence on climate change, understanding the complex processes in action and improving their reflection in climate models.

In particular, observations from space, being global, repetitive and achievable over any territory of our Planet are crucial to address the Grand Science Challenges. Those challenges are:

- "Clouds, Circulation and Climate Sensitivity"
- "The Changing Water Cycle"
- "Cryosphere in a Warming World"
- "Ocean Circulation and Regional Sea Level Rise"
- "Prediction and Attribution of Extremes: from Climate to Weather"
- "Regional Climate Variability and Change: Enabling Climate Services."

All were discussed in depth by the international symposium "Climate Research and Earth Observations from Space: Climate Information for Decision Making", organised in October 2014 by EUMETSAT and the WCRP, in Darmstadt, Germany, just after the publica-





METEOSAT THIRD GENERATION

Among the operational multi-satellite programmes of EUMETSAT, the Meteosat Third Generation (MTG) twin satellite system will offer new opportunities for climate monitoring. For example, the thermal infrared imagery of the MTG-I satellites will improve high-frequency measurements of the radiative power of forest fires associated to large emissions of greenhouse gases, some of which (CO, CH $_{\!_{4}}$, SO $_{\!_{2}}$) will be measured at the same time and for the first time from the geostationary orbit, by the IRS infrared hyperspectral sounder and the Copernicus Sentinel-4 ultraviolet sounder embarked onboard the MTG-S satellites. The new Lightning Imager of MTG-I will also monitor the evolution of thunderstorm activity over the tropical Atlantic and Indian oceans in our changing climate, an important factor for future aviation safety.

© ESA

tion of the Fifth Assessment Report of the IPCC and one year before the 21st Conference of the Parties to the UN Framework Convention on Climate Change.

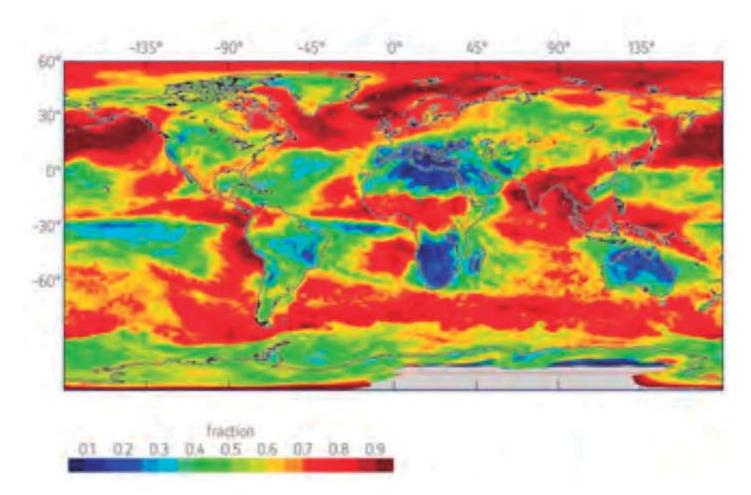
The symposium acknowledged "an unequivocal need for sustained long-term space-based observing systems provided by operational satellites". It recommended 'science theme' oriented space missions proposed by the research agencies take benefit from the core observations produced by these operational meteorological satellites". Another finding stated that "combining multi-sensors/satellite operational and research missions should be considered to address science questions across the multiple Grand Science Challenges."

From weather to climate

When it was created in 1986, EUMETSAT's mission was to "establish, maintain and exploit European systems of meteorological satellites". In 2000, the Convention of the organisation was amended to add the objective to "contribute to the operational monitoring of the climate and the detection of global climatic changes".

This was in recognition that modern meteorology, like climate monitoring, requires global space-based observations of the atmosphere, but also of the ocean, the land surfaces and the cryosphere, and that the operational multi-satellite programmes of EUMETSAT are building unparalleled climate records, with already 35 years of Meteosat observations. The new Convention also created the possibility of optional programmes and programmes implemented on behalf of third parties. Not surprisingly, the first EUMETSAT optional programmes were its contributions to the Jason high precision altimeter missions dedicated to the monitoring of ocean circulation and sea-level. Likewise, third party programmes funded by ESA and the European Union, provided the framework for EUMETSAT's role as the operator of four out of the six Copernicus Sentinel missions, namely the Sentinel-3 and Sentinel-6 marine missions and the Sentinel-4 and Sentinel-5 air quality monitoring missions, both implemented as part of EUMETSAT's future Meteosat Third Generation and EPS-Second Generation systems.

Today, EUMETSAT provides a substantial European contribution to the operational backbone of the global architecture for climate monitoring from space established by the World Meteorological Organisation, the Committee for Earth Observation Satellite (CEOS) and the Coordination Group for Meteorological Satellites (CGMS). The organisation achieves this through its contributions to the Jason cooperative missions and its series of Meteosat and Metop satellites. In addition, the Metop satellites add value to the full architecture because they fly some of the highly accurate instruments required as a reference for climate monitoring and an anchor for less accurate measurements. The Metop GRAS temperature profiles using the self-calibrated GNSS radio-occultation technique may serve as one example; another example would be the extremely stable IASI hypers-



AVHRR Climate Data Record. Mean cloud fractional coverage for July 2007, extracted from a 10-year long climate record. Source: CM SAF

pectral infrared sounder, which is used for cross calibration of many infrared observations.

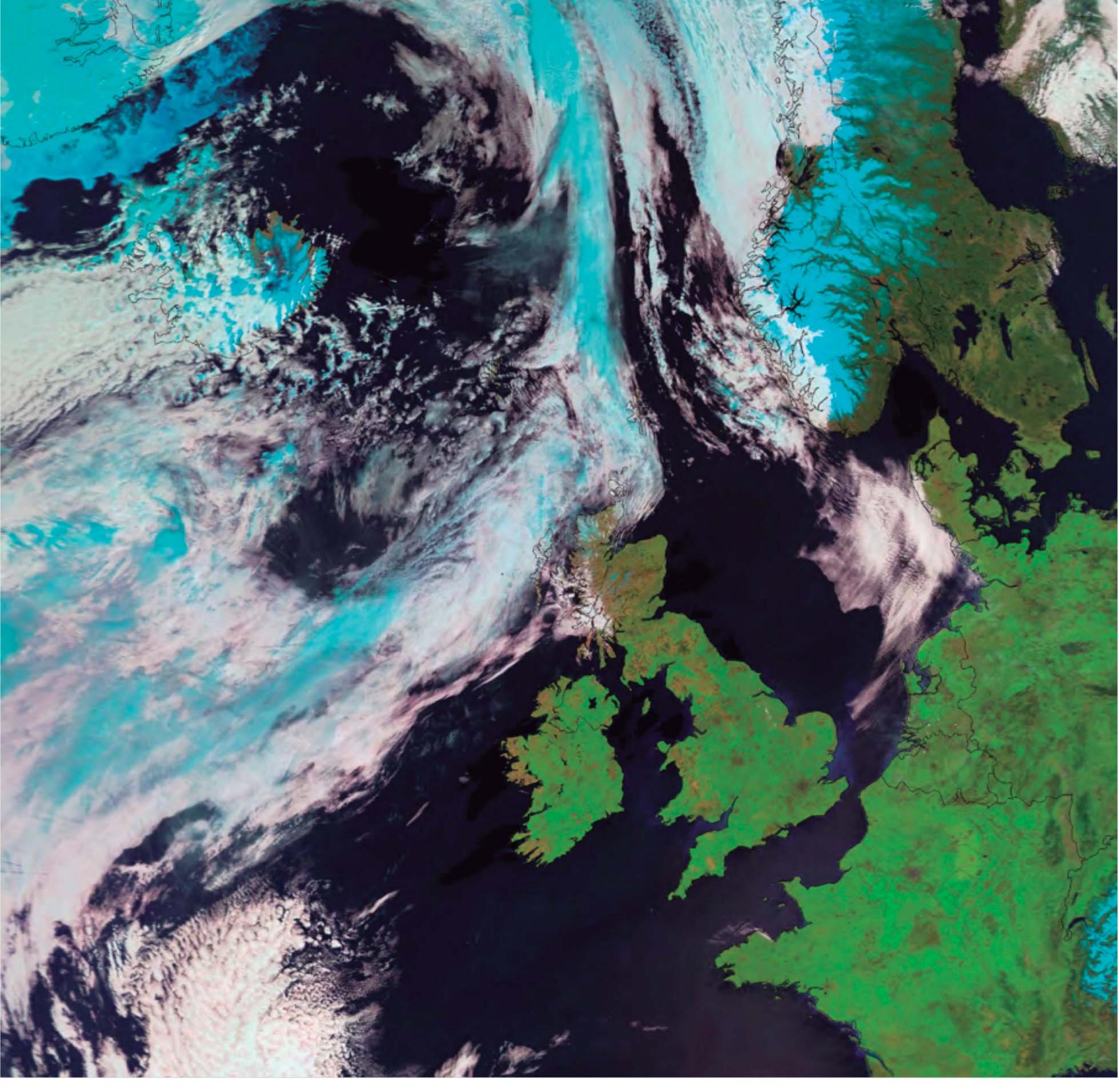
The innovative instruments of the future Meteosat Third Generation (MTG) and EPS-Second Generation (EPS-SG) systems will further expand the current climate records and reference measurements into the period 2020-2040.

They will also offer new opportunities for climate monitoring, through observations of additional Essential Climate Variables expected to span over decades. For example, the microwave Ice Cloud Imager of the Metop-SG-B satellites will observe for the first time the thin ice clouds that enhance the greenhouse effect. In line with the conclusions of the Climate Symposium, EUMETSAT considers "the broad range of scientific challenges and priorities formulated by the research community for space-based observations can only be fulfilled through international cooperation". The organisation therefore harmonises the planning of its future missions with those of other CEOS and CGMS agencies, as part of "an integrated observational approach that is strategically designed to be cost effective and sustained over decades, yet remains targeted on key challenges and promotes the fusion of theory, models and observations". At European level, one key objective is the maximum synergy between EUMETSAT and Copernicus missions.

From climate to weather

The titles of two of the WCRP Grand Science Challenges, "Prediction and Attribution of Extremes: from Climate to Weather" and "Regional Climate Variability and Change: Enabling Climate Services" point to another form of relationship between observations of weather and climate. Indeed, the likely increase of both the frequency and intensity of extreme events being an attribute of climate change, efficient early warning systems for high impact weather will be at the core of any credible adaptation policy.

Developing resilience to these extremes will therefore become a key requirement. All this will increase the value of the observations of operational meteorological satellites like those of EUMETSAT, which feed early warning systems and at the same time build long-term



Clear skies over Europe as seen from MetOp on 21 April 2015. Further north, snow (cyan colour) can be seen on mountain regions of Scandinavia and sea ice is visible off the coast of Greenland. © EUMETSAT

climate records of Essential Climate Variables. In the future, observations of high impact weather by these satellites may be compared in real time to climate records established by previous satellites over the same region, the "climatology" of numerical prediction model outputs and even the scenarios available from regional climate projections. These comparisons will help to qualify extremes, e.g. in terms of probability of occurrence and similarity with past events, and support their possible attribution to climate change, thus

possibly closing the loop between observations, weather prediction and climate projections for the benefit of decision makers.

These are all reasons to believe that the relationship between observations of weather and climate and the integration between weather and climate information services will become increasingly important, as adaptation to climate change becomes a daily concern in many parts of the world.

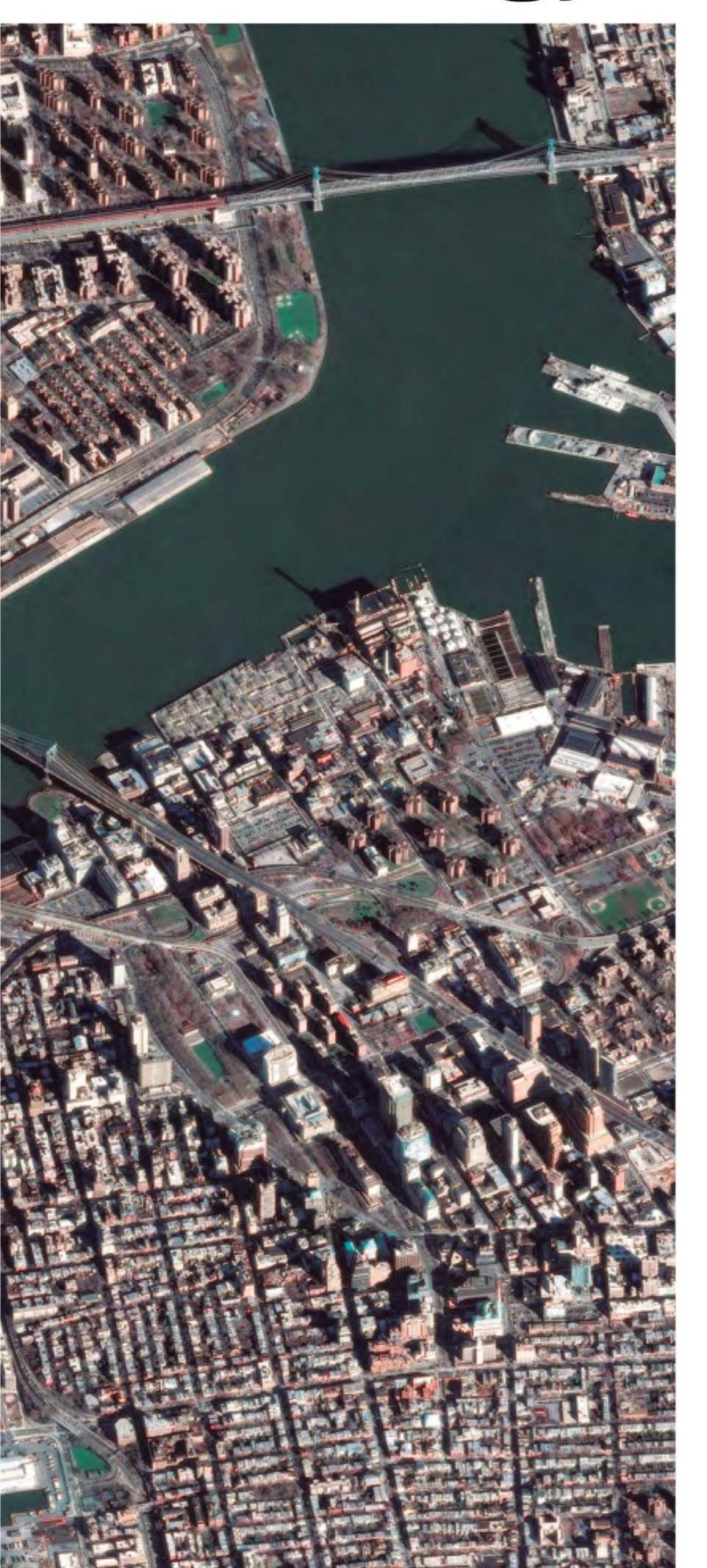
Alain Ratier, Director-General EUMETSAT

New missions

2040: a space



technology scenario



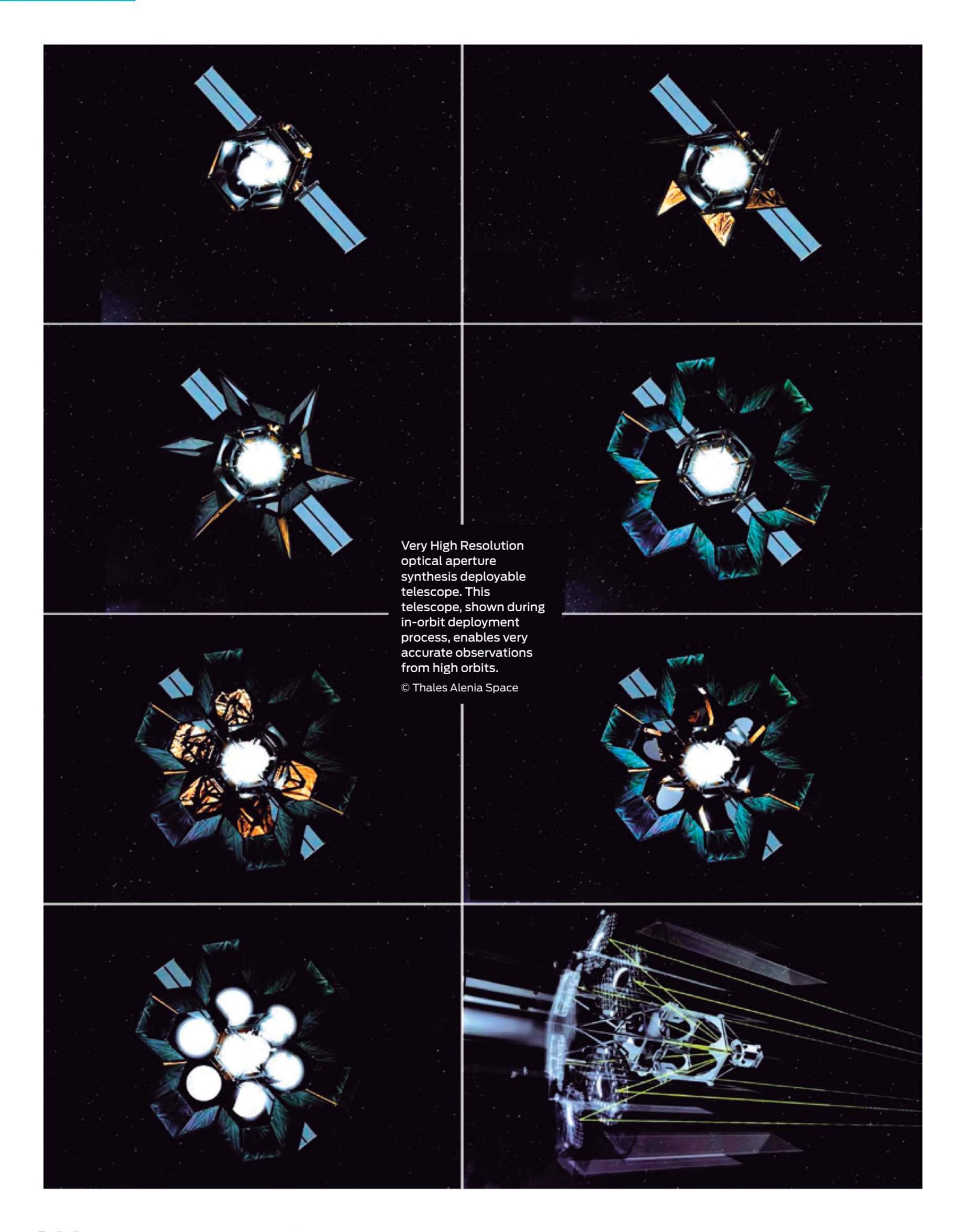
NE OF THE MAJOR CHALLENGES facing society in the coming years is undoubtedly climate change. By 2040, space-based technologies will have already played a fundamental role in meeting this challenge, and they will have probably undergone deep changes to deal with the booming demand for data. Spaceborne systems are real decision-aid tools that have to deliver huge volumes of data to the scientific community, almost instantaneously, to better understand and control the impact of climate change, deal with pollution and manage natural resources. In short, these systems will influence our ability to protect the fragile balance that characterizes life on our planet.

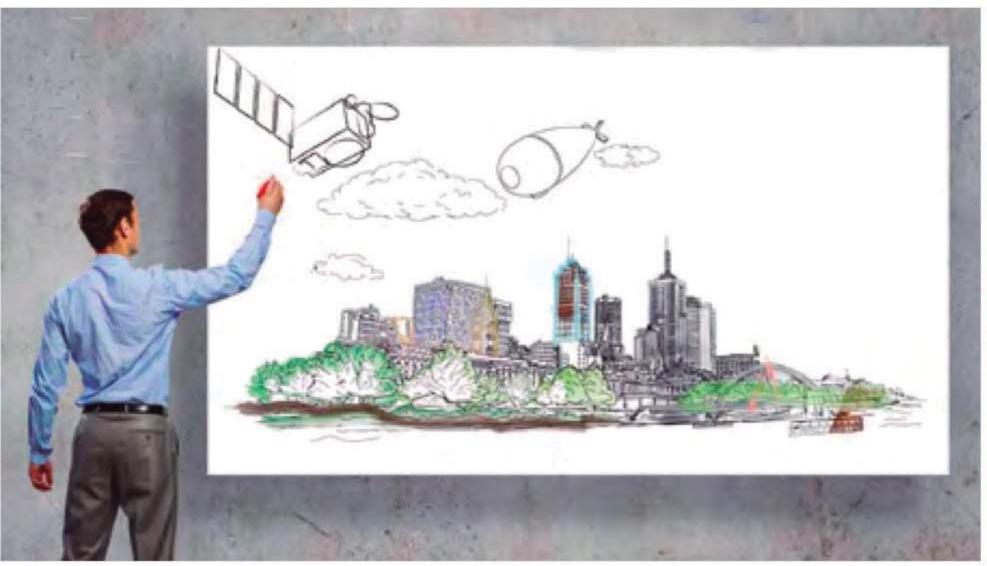
The technology scenario for 2040 has to be planned starting today. In fact, one of the major characteristics of our industry is a need to anticipate trends. We generally say that the «spatialization» of technologies (i.e., their adaptation to the space environment) takes about a dozen years. This is due in large part to the time needed to qualify new technologies for the constraints of the space environment, as well as reliability and lifespan requirements, plus the hefty investments needed.

However, the steady growth of new market segments is in the process of upsetting the apple cart. Given this new framework, we could predict that the time needed to nurture and spatialize new technologies will decline significantly in the coming years. Which means that the space industry will make more extensive technological leaps more quickly, which will in turn open new possibilities in terms of mission shape, content and cost.

Constellations, clusters, swarms

By 2040, large-scale conventional systems will probably co-exist not only with a multitude of small, low-cost systems, but also with non-orbital systems, especially geostationary stratospheric airships. Many missions previously carried out by medium-size platforms in low Earth orbit, or large platforms in geostationary orbit, will instead be performed by constellations, clusters or swarms of very small platforms in low orbit, for applications including telecommunications, observation, sounding, navigation, weather forecasting, etc. Stratospheric platforms will provide regional warnings for local weather phenomena, and they will also participate in specific territorial surveillance operations. New missions based on these small platforms will certainly take shape. Constellations of small satellites with diverse instrument suites will be able to enhance the study of the constituent components on the Earth's surface or in the atmosphere, as a complement to other systems, or via data fusion. Small satellites flying in formation and equipped with very-high-precision devices for angular measurement and ranging will support observation missions based on very long focal lengths, synthetic apertures or radio-frequency.





Thales Alenia Space's Innovation Cluster fosters innovation at all levels. Brainstorming sessions are organized to tackle climate change and societal issues and to shape the future of spacebased applications. © Thales Alenia Space



Halfway between a drone and a satellite, Stratobus is a multimission autonomous stratospheric platform. It can handle environmental missions, including marine pollution, deforestation, humanitarian aid ... © Thales Alenia Space

More conventional large-scale systems will perform missions requiring higher precision, greater computing power or high RF transmission power; in short, missions demanding large observation or scientific instruments, large antennas and large solar arrays. These large-scale systems will benefit from appendage deployment technologies making them feasible, and decreasing production and launch costs. In particular, large observation instruments will comprise very light optical components, some deployable, and with controllable shapes and positions. This will provide an optimum tradeoff between instrument stability in an aggressive thermal environment and the operational complexity of very-high-precision regulation mechanisms controlling several tens of degrees of freedom. Active optics systems, based on the use of deformable or repositionable optical components, would enable us to eliminate part of the stability requirement for the materials used in opto-mechanical structures, and thus pave the way for the use of materials less specifically designed for the space environment, as well as new production techniques, such as additive manufacturing. By combining these techniques with topological optimization, we will make lighter, less expensive structures.

Cost reduction, an imperative in large constellations, will also inevitably depend on the use of commercial off-the-shelf (COTS) technological components, instead of special hardened components. This would enable the deployment of much more advanced functions, similar to those available on the ground - but provided we make the intellectual step implicit in revising our ideas about reliability. Onboard computers, for instance, will be incomparably more powerful than those now used on satellites, including memory storage. Scientific and observation instruments will also benefit from this trend, insofar as they will be under active control to restore performance, or they will include processing algorithms to offset the loss of optical quality due to lower manufacturing costs.

Another possibility is the ability to process data onboard that is usually processed on the ground, meaning that spaceborne platforms could directly deliver products, and not just raw data. In 2040, space will move closer to end-users with their smartphones, tablets and laptops. End-users won't even realize that the information they receive comes via space, since the space segment and the terrestrial network will be so intertwined. We could even dream that weather and environmental satellites will be part of a global space network by then, pooling its computing power so that satellites can directly transmit maps ready for the end-user.

In 2040 all these space systems will exchange and transmit huge volumes of data, and the ground infrastructures will have to keep pace. The watchwords 25 years from now will be «cloud», «big data» and «deep learning». The champion technologies of 2040 will be those that are able to combine the huge volumes of data with powerful learning methods that support automated interpretation. Another key factor will be predictive maintenance on constellations, swarms and other systems with hundreds of platforms, because mission reliability will be based on system redundancy (i.e., the satellites) and no longer solely on component redundancy. Under these conditions, we will use machine learning techniques, and we will be able to anticipate performance degradation or platform failures so they can be replaced in timely fashion, or to reconfigure the constellation to maintain the requisite service quality.

Space engineering will have changed its paradigm by 2040, by more fully integrating information technology and mathematics, which will take a more important role in certain areas than the equipment per se. Primary candidates include artificial intelligence, mathematical optimization of platform and instrument functions, onboard data processing in high-dimensional spaces, etc.

It seems likely that far more space technologies will exist in 2040, and that they will be much more powerful, and more than ever at the service of scientific disciplines that seek to understand and predict the impact of climate change, to measure air and water pollution, and to better manage our precious natural resources.

Frédéric Falzon, Thales Alenia Space

From observations to decisions International collaboration

HE EARTH'S CLIMATE IS CHANGING, but in different ways in different parts of the world. In some areas, temperatures are higher than ever; other regions are experiencing recordbreaking lows. In some regions, the amount of rainfall is at never-seen levels, in other regions, snowfall is the lowest on record. Lakes and rivers are drying up, while higher than normal flooding is creating havoc and destruction. Many experts are studying these phenomena from a multitude of disciplines and perspectives to understand the causes. But an important question is: what are we, as a global ociety, doing to prepare for and mitigate the impacts of climate change? Of equal importance, do we have - and are we using properly - all of the available tools to understand, predict and prepare for the impacts of our changing environment? The answer to the first question is: plenty of people are talking about the need to prepare, and a number are trying to convince political leaders and policy makers of the need to take action. To the second question, the answer is that we have many of the tools, but we are not using all to their greatest potential.

Earth observations - from satellites, aircraft and land and marine-based sensors - provide an inestimable wealth of data and information that can be transformed into tools, products and services to help all of us understand what is happening to our planet. With this essential information, we can make wise, informed decisions about how to protect the lives and livelihoods of our peoples, especially those with the fewest resources of their own. However, those observation resources, often captured through publiclyfunded equipment and processes, must be brought more fully into the discussion and decision-making process to best prepare for and mitigate the impacts of climate change.

Vulnerability and resilience

According to the Intergovernmental Panel on Climate Change Fifth Assessment Report Working Group II (Field et al., 2014), the impacts attributed to climate change are related to the physical system (glaciers, snow, ice, permafrost, rivers, lakes, floods, droughts, coastal erosion, sea level), the biological system (terrestrial ecosystems, wildfires, marine ecosystems) and the human and managed systems (food production, livelihoods, health, economics). The 2014 UN Human



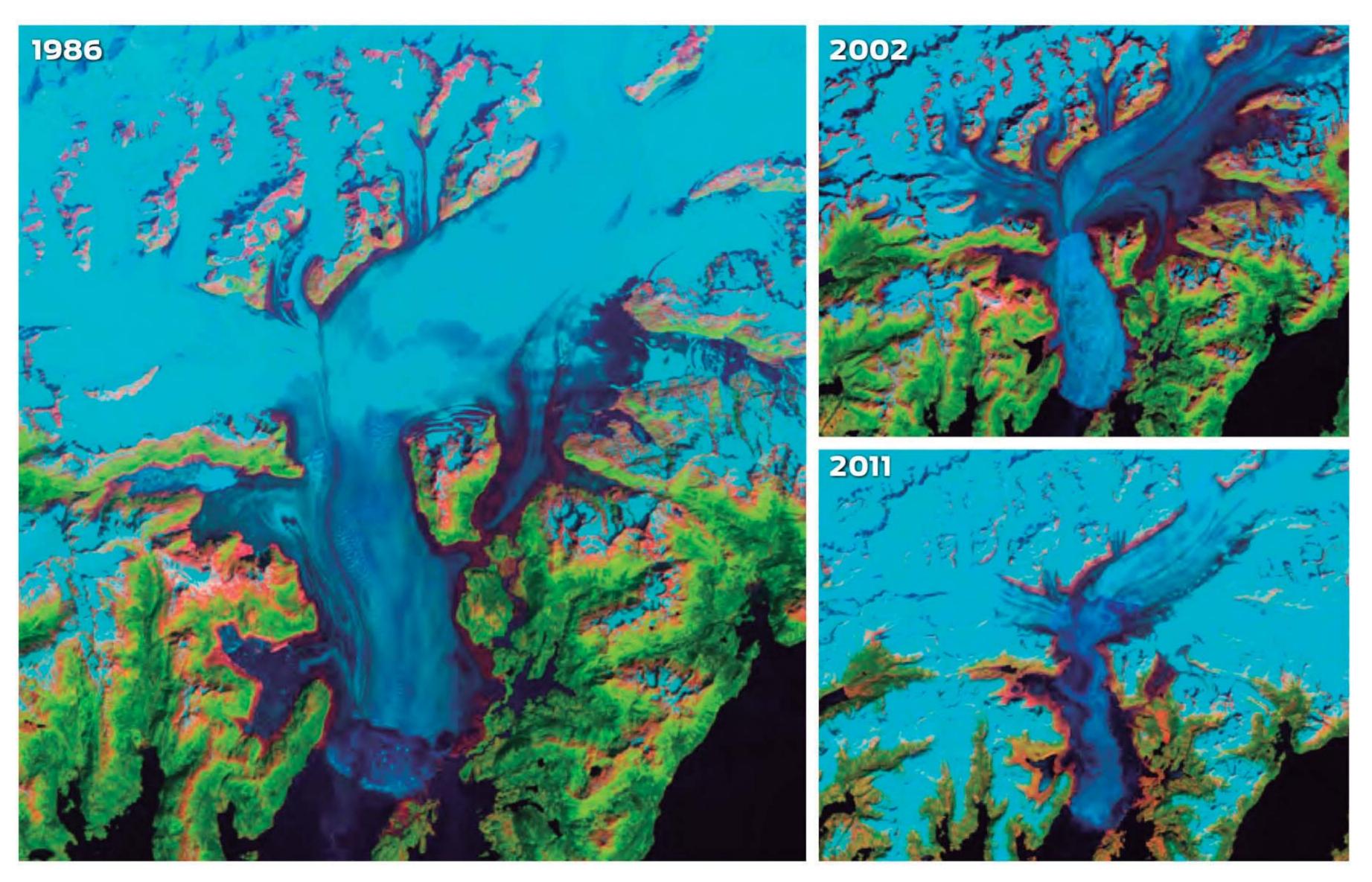
Jordanian UN peacekeepers rescue children from a flooded orphanage after the passing of hurricane Ike, a powerful tropical cyclone that swept through portions of the Greater Antilles and Northern America in September 2008. © UN Photo/Marco Dormino

Development Report on vulnerability and resilience warns that climate change could be one of the most critical factors to achieve the global sustainable development goals. However, many aspects of the global climate system are still not fully understood. Key uncertainties involve clouds and aerosols, sea-level rise and the carbon cycle.

The systematic and sustained observation of the climate system in its entirety, and the provision of reliable climate data, are of paramount importance to solve these uncertainties. Climate data are an invaluable asset to understand climate variability and change, as well as to predict future climate. Both are needed to strengthen the ability of governments to adopt more effective policies for mitigating and adapting to climate change.

Integrated Earth observations from diverse sources can provide powerful tools to understand the present status of each of Earth's systems, as well as the interplay among them. These tools may also be used to predict the future behaviour of those systems, thereby allowing potential consequences of human activities on the planet to be understood and anticipated.

The intergovernmental Group on Earth Observations (GEO) is a global partnership of 100 governments



Alaska's Columbia Glacier descends through the Chugach Mountains into Prince William Sound, but has retreated significantly over the past two decades. Source: NASA Earth Observatory, using data from the U.S. Geological Survey.

and 87 international, scientific and technical organizations that envisions "a future wherein decisions and actions for the benefit of humankind are informed by coordinated, comprehensive and sustained Earth observations." GEO is working through voluntary best efforts to create the Global Earth Observation System of Systems (GEOSS) from among thousands of individual Earth observation, information and processing systems. GEO is a unique organization that occupies a key, strategic, upstream coordination position in the international community. This position enables GEO to improve the quality, timeliness, range and availability of Earth observations, data, information and knowledge about the Earth system to improve the observational foundations of decisionmaking globally.

End-to-end value chain

Climate is one of nine Societal Benefit Areas that have framed GEO's work during its first decade, with the strategic target of achieving effective and sustained global climate observations and reliable delivery of quality climate information needed to predict, mitigate and adapt to climate variability and change. For example, a multiplicity of data producers around the

globe have contributed to extend the climate record by producing high-quality, temporally-homogeneous estimates of past and current climate to better detect climate variability and change. Datasets include reconstructions of the past climate, model-based reanalyses, satellite-based climate data records and in situ based datasets. The Global Climate Observing System (GCOS) constitutes the climate-observing component of GEOSS. GCOS coordinates climate observations on a global scale and has a critical role to ensure the sustained provision of reliable physical, chemical and biological observations and data records for the total climate system, across the atmospheric, oceanic and terrestrial domains, including hydrological and carbon cycles and the cryosphere. In addition, GEO is urging its members to coordinate their Earth observation efforts through National GEO Offices, which would create closer collaboration among the various space, scientific and observational organizations and agencies within government. This comprehensive approach to monitoring the Earth's climate would enhance access to the additional climate relevant data and products which are essential to mitigating the impacts of a changing climate. GEO also focuses on advancing Earth-system prediction



Women attend a course in Minima, Burkina Faso. Supported by IFAD, the International Fund for Agricultural Development, PDRD (Programme de Développement Rural Durable) provides farmers, women and youth with training and support in its effort to bring sustainable rural development in Burkina Faso. ©IFAD/Aubrey Wade

and strengthening the ability worldwide to deliver new and improved climate, weather, water and environmental services. In the next GEO decade (2016-2025), climate will be a cross-cutting issue of crucial importance affecting most, if not all, future Societal Benefit Areas in GEO, such as Food Security and Sustainable Agriculture, Disaster Resilience, Health Surveillance and Water Management. GEO will increasingly focus on the integration of climate products and services into adaptation processes and encourage the use of this information by policy and decision makers at all levels, thereby addressing the entire end-to-end value chain of turning observations into decisions.

Another major objective of GEO's climate work is to improve understanding of the global carbon cycle. Increasing CO₂ levels in the atmosphere is the primary cause of climate change, and of ocean acidification. CO₂ emissions are accelerating every year, and the CO₂ growth rate in the atmosphere is higher every decade. Any solutions relating to climate change must, therefore, involve fossil fuel emissions, biomass burning and the carbon cycle.

Integrated Carbon Observation

In 2010, the GEO Carbon Community of Practice, comprised of scientists, research and operational

agencies, and also practitioners, published the GEO Carbon Strategy, outlining the vision, progress to date, and additional needs to implement an Integrated Global Carbon Observation System. In response, the Committee on Earth Observation Satellites (CEOS) developed a Strategy for Carbon Observations from Space, while in Europe, a GEOCARBON project has made significant progress towards a sustained and operational Integrated Global Carbon Observation and Analysis System. Lastly, an essential ingredient to successfully coping with climate change is the broad availability of data from all sources, especially government data resources. Based on its full and open Data Sharing Principles, GEO has been coordinating international, regional and national efforts to improve the discoverability, accessibility and usability of diverse Earth observations.

While much has been accomplished in GEO's first decade, more needs to be done. Understanding, preparing for and mitigating the impacts of climate change is a global challenge. GEO is committed to contributing its resources and expertise to addressing this challenge through the work of its member governments and partners.

Barbara J. Ryan, André Obregón GEO Secretariat



To get the best yields from cereal, oilseed and protein field crops, farmers have to pay very close attention to weather and soil parameters, while optimizing the resources they use. © iStock

Satellite Services Protecting the Earth

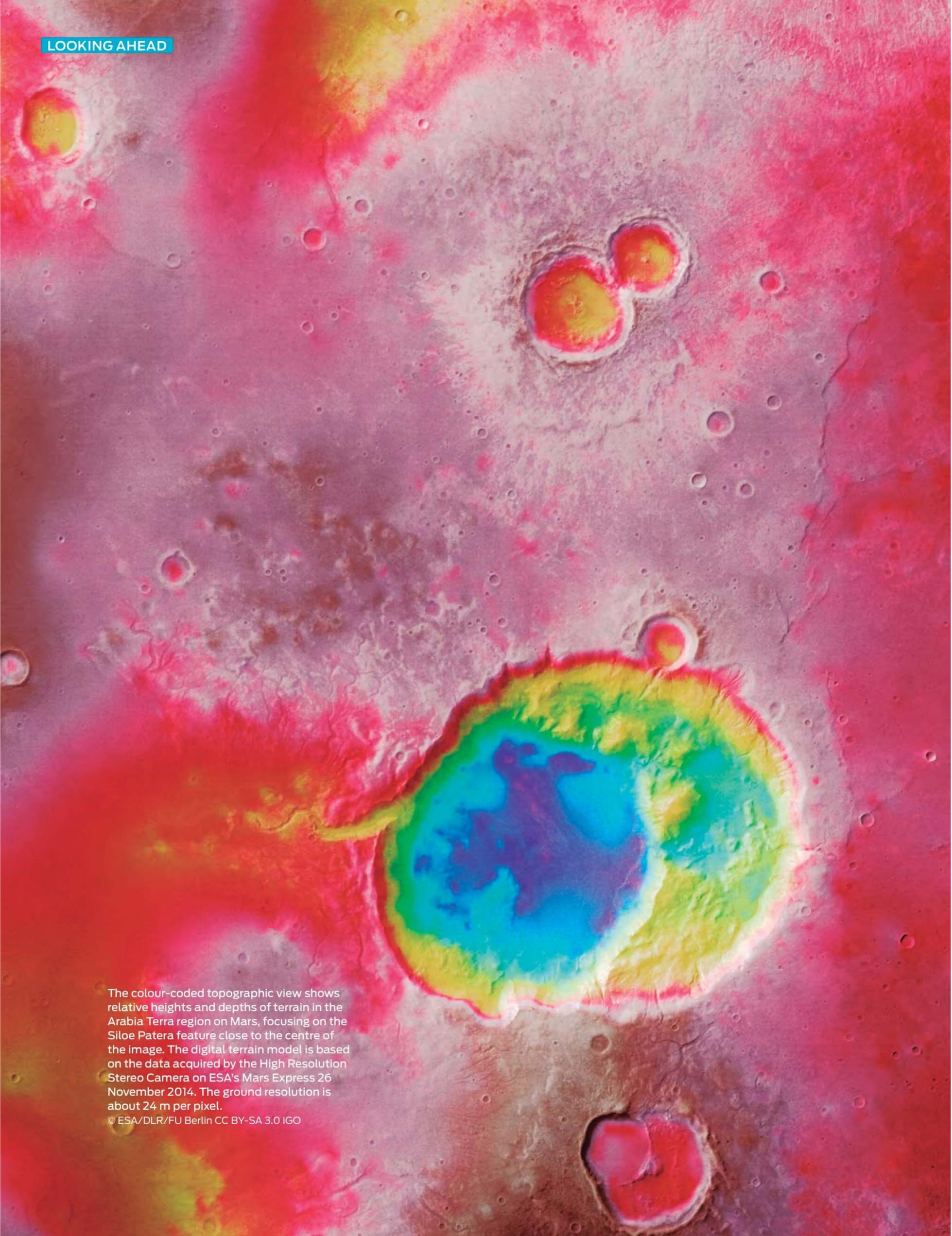
ROVIDING HIGH-ADDED value satellite and geoinformation services to a very wide public can help prepare our children's future, and is key for the well-being of its habitants and the sustainable development of our regions. This implies adequate policies for Greenhouse Gas Emissions abatement and low carbon trajectories as well as the effective capacity to independently measure our environmental status and verify the effectiveness of adaptation and mitigation actions implemented under climate policies framework worldwide.

Meanwhile, the digital disruption and big data phenomena are changing the way societies relate to information, the way they interact with it and creating expectations for instant, high added-value content. Space technologies can be a driving force in the creation of wealth and of new links mobilizing the best of public institutions and private organizations. In this context, the development of user-friendly envi-

ronmental surveillance capabilities, available to the greatest number, is becoming a critical issue. Connecting experts, sharing best practices and making sure that field knowledge is taken into account are essential to build sustainable environmental and land management policies.

The EarthLab Galaxy relies on the combination of local knowledge and cross-disciplinary know-how. It was created to foster the emergence of services integrating the most advanced observation, navigation and communication means into sound environmental practices. It is the first global geoinformation cluster bringing together space and image processing software experts along with local specialists and researchers. Its objective is to implement products and services which answer both high-stakes environmental and economic challenges. Ultimately, the EarthLab Galaxy will bring together a worldwide network of some 10 to 15 centers.

Didier Rigal, EarthLab/Telespazio France



Mars and Venus Testimony to our own future?

OW MIGHT THE STUDY of Mars and Venus help us to apprehend the future climate of the Earth, or at least give us fresh insight into what is happening on our beloved planet? Mars, Venus and the Earth were probably very similar planets in the beginning, but they ended up with very different climates. The principal reason was their distance from the Sun and thus their difference in temperature. But there might be other explanations, and that is why many scientific teams are studying these two planets and, in particular, Mars.

Mars has an atmosphere which, although rarefied, has meteorological phenomena and seasons; it has a day of roughly 25 hours, and a year whose duration is 687 terrestrial solar days. Mars has a complex geological history and may well have had in the distant past a few lakes and oceans. The planet has icy polar caps (of CO₂ and water), canyons (maybe pertaining to fluvial beds), volcanoes, sand dunes and mountains (Olympus Mons is three time higher than Everest and has the same area as France, while Valles Marineris is three times deeper and ten times longer than the Grand Canyon).

Now, the temperature on Mars can oscillate between -125°C and +23°C, and the annual average is only –53°C (+14°C for the Earth). The Martian climate may have changed drastically during its history. Temperatures fell to below 0°C, and the water froze and went underground. It is probably still there. In addition, Mars has a large quantity of natural resources that can be utilized to produce, on the spot, everything necessary to support human exploration. These are powerful reasons for carrying out space missions to the red planet.

Concerning Venus, which has almost the same mass as Earth but a thicker atmosphere, there was also probably water in the beginning. But temperatures became so high (460° C) that it was impossible for this water to condense, which is why this planet did not have an ocean. After the

water evaporated, the water vapour and CO₂ in the atmosphere produced what is called a runaway greenhouse effect. This atmosphere is now very hot and dry. On the surface, temperatures can reach 500°C.

To understand how and why the climates of Mars and Venus have changed can help us to understand the Earth's climate and the way it may change in the future. For example, the general circulation models used for these planets could provide an interesting insight into climate change on Earth.

Studies of these parent planets have paved the way to revolutionary techniques to modulate Earth's climate that now are called geoengineering. These techniques born with the name terraforming had been seen more in the science fiction realm. For Mars, it could mean creating an artificial greenhouse effect to raise the surface temperature and then possibly evaporate some of its water. This could help human exploration and settlement. The trilogy by Stanley Robinson on Mars, describes this hypothesis. There are also several proposals to mitigate the greenhouse effect on the Earth inspired by the volcanic eruptions. They are based on the idea of injecting in the terrestrial stratosphere large quantities of dust that could reflect solar energy and so decrease the surface temperature. This might have happened on Venus, even though this cooling effect of solar reflection on aerosols was outweighed by the greenhouse effect.

The previous considerations show that studying the climate of other planets could help to understand the evolution of the Earth's climate. This is a good example of convergence of studies between two communities, one of scientists exploring the solar system and the other of those studying Earth's climate. With one common goal: keeping our planet habitable.

Text based on an interview with Guido Visconti, professor (now retired) at University of L'Aquila, former Director of the Cetemps, Centre of Excellence (Italy).

Climate Change & Satellites

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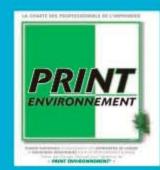
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Bora Bora captured by Pléiades. This island in the Society Islands of French Polynesia is surrounded by a lagoon and a barrier reef. Adapting to climate change will be unavoidable for all South Pacific nations.

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