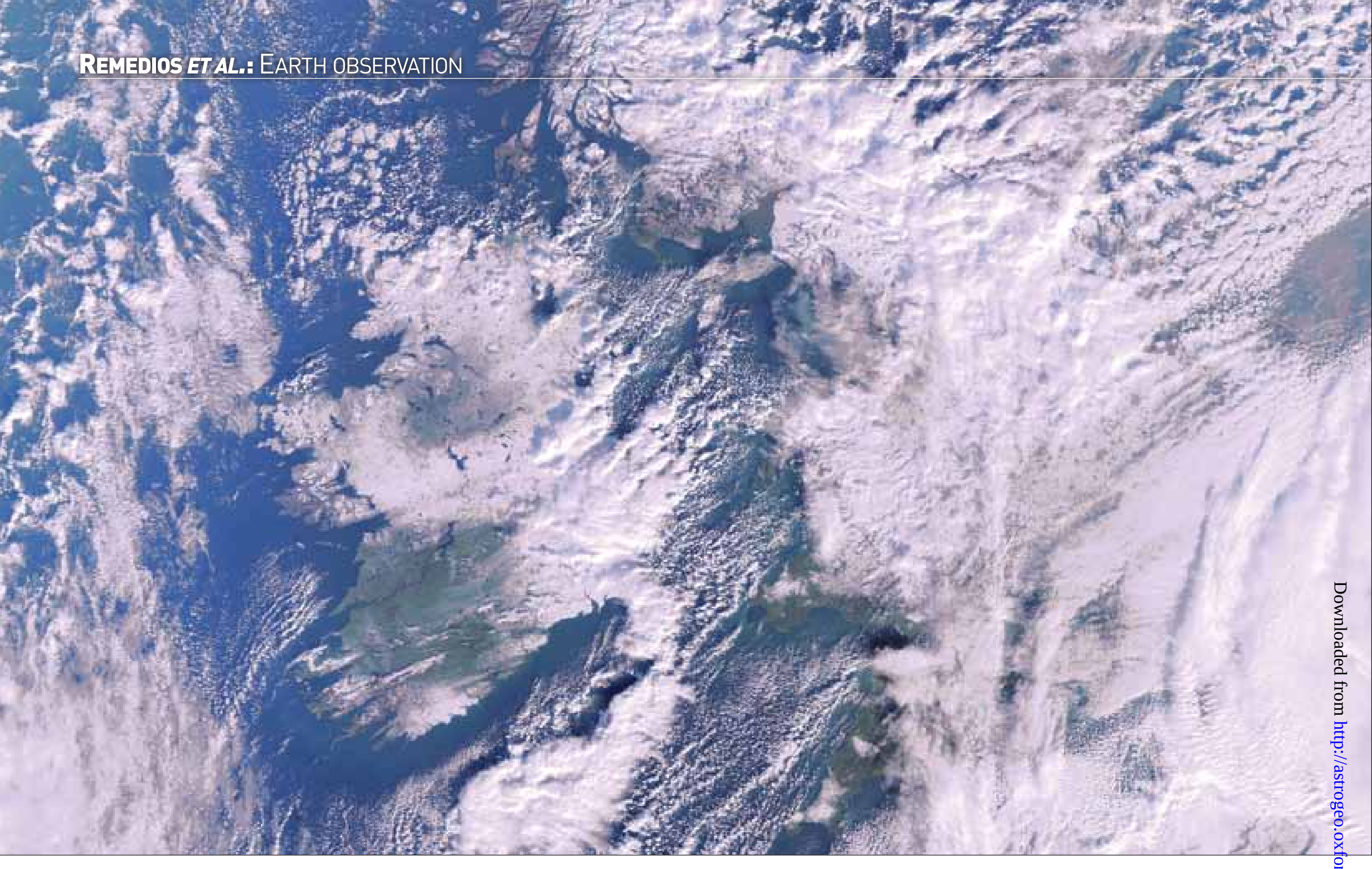


1: MERIS visible wavelength image of the UK under snow on 29 November 2010, showing also the sensitivity to fine ocean suspensions such as phytoplankton and coastal sediments. (ESA)



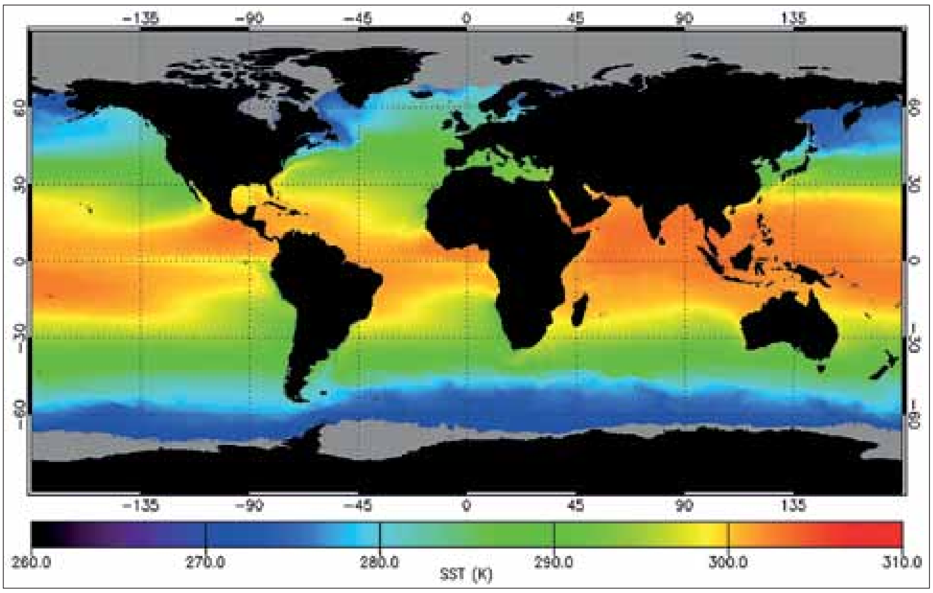
# Earth observation: a revolutionary leap into the future

**MEETING REPORT John Remedios and fellow meeting presenters look forward to the prospects for Earth observation in the coming years.**

At a recent meeting in Leicester (Observing the Earth and Planets: the Next 50 Years, Sims *et al.* 2012), there was an interesting and vigorous discussion on Earth observation (EO) from space over the next five decades. This article is an outcome and development of those conversations and presentations, reflecting on the themes that emerged and on the future of EO science with its enduring power to inform society from government policy to personal information and commercial applications. The heart of this EO transformation lies in "upstream" applied physics, technology and engineering exploited through "downstream" nonlinear mathematics and computer technology; noting also the closeness of EO applied physics to fundamental physics in spectroscopy, semiconductor physics and interferometry (optical and microwave; in the future potentially cold atom interferometry). The next 50 years are likely to demand more attention to the fundamental science and also that we move well beyond science into services and environmental sustainability.

In the past 50 years, EO missions have travelled a long way, albeit around the same planet. The first images of the Earth from Explorer VI in 1959, more a grainy picture than an image, have given way to high spatial resolution images (of less than 1 m for commercial imaging systems) at a few wavelengths and hyperspectral images at scales of a few hundred metres with many wavelengths (see figure 1 for an example of research-quality image data). State-of-the-art interferometers record highly resolved spectra of the Earth thousands of times a day with resolving powers sufficient to distinguish individual Doppler or Lorentz-broadened lines originating from atmosphere absorption or emission. Lasers and radars actively probe the atmosphere, vegetation canopy, surface height and sea-ice thickness. The power of our remote sensing systems has improved with every decade.

Scientifically, these observations have enabled critical issues in our understanding of the Earth system to be identified, monitored and diagnosed. The most complete story is clearly that of ozone depletion where satellite observations of ozone and the reactive chlorine species provides a long time series of observations (e.g. Randel and Wu 2007) and identification of major episodes of ozone loss. The severe loss of ozone over the Arctic in winter/spring of 2010/2011 has been described as the first Arctic winter displaying characteristics of the Antarctic ozone hole (Manney *et al.* 2011). Similarly, long-term observations of pollutant nitrogen dioxide have dominated our understanding of global air quality and its change over time, confirming strong increases in Asia (Richter *et al.* 2005), and decreases in Western Europe (Konovalov *et al.* 2006). These atmospheric observations are complemented by long-term, high-quality measurements of sea-surface temperature, sea-surface height, phytoplankton biomass (chlorophyll-a) and polar sea ice for the ocean. Although the first steps in constructing such series for land have been made in radiative surface temperature and vegetation indices, time series for land observables is clearly one of the next challenges; we foresee very strong progress in this area in the next decade.




**2: Sea surface temperatures from AATSR (EnviSat) and ATSR-2 (ERS-2). Data are nighttime, dual-view, three-channel SST averaged for May from 1997 to 2011. (K Veal/University of Leicester)**

**3: Artist's impression of ENVISAT in orbit providing 10 years of data to 8 April 2012. (ESA)**

The challenges have, if anything, grown with our increased understanding. How does planet Earth work as a complex, coupled, nonlinear system (which includes life)? If we are to understand what is happening to the Earth's climate and associated natural systems, and be able to describe it, we need to determine whether we have the processes and feedbacks right in numerical models of the Earth. We also have to be able to identify natural and anthropogenic contributions and quantify them. Better knowledge of these factors will enable us to predict the future state of our planet with confidence (good understanding of uncertainty). But we need to go beyond the science too and in this article we consider the strategic dimensions propelling EO science forward at the same time as societal drivers.

## Driving progress

A strategic dimension has clearly been the growth of the space technology industry in EO and the increase in access to space in recent times. Allied to the power of the remote sensing techniques themselves, it has been the ability to build series of instruments to exacting designs that has been essential in enabling the EO community to derive data sets of value for example in describing variations in recent (decadal) climate. In the UK, leadership of the Along Track Scanning Radiometers (ATSRs) has enabled the EO community to develop insight into the quality of calibration and instrument performance required for climate observations (Smith *et al.* 2012) and the detailed understanding of radiative physics necessary to derive accurate geophysical quantities from measured radiances (calibrated signal counts) at the instrument (Embury *et al.* 2012a). The instruments rely on fundamental instrument attributes: high accuracy on-board blackbodies at 263 K and 305 K, low noise detectors cooled to low temperatures near 80 K by novel Stirling cycle space coolers, dual-view geometry to allow accurate atmospheric correction for its thermal infrared channels. The UK strength in calibration is leading to mission proposals for spaceborne systems dedicated to calibration of other satellite sensors!

The challenges of deriving climate data from satellite instruments have also had consequences for scientific research into the remote sensing problem. In the case of the ATSRs, the detailed consideration of retrieval theory for sea-surface temperature and its application for high-accuracy climate has been improving for as long as the ATSR series of instruments (ATSR-1, ATSR-2 and the Advanced ATSR or AATSR) have been in operation. The result (see figure 2) is an SI-traceable time series of sea-surface temperature (Llewellyn-Jones and Remedios 2012, and references therein) with arguably equivalent accuracy to the *in situ* record of sea-surface temperature, with well understood global uncertainties. The accuracy of ATSR SSTs, designed to be of order 0.3 K per single measurement, are probably better with estimated random errors of 0.16 K and relative, inter-ATSR instrument biases of less than 0.1 K (Embury *et al.* 2012b).

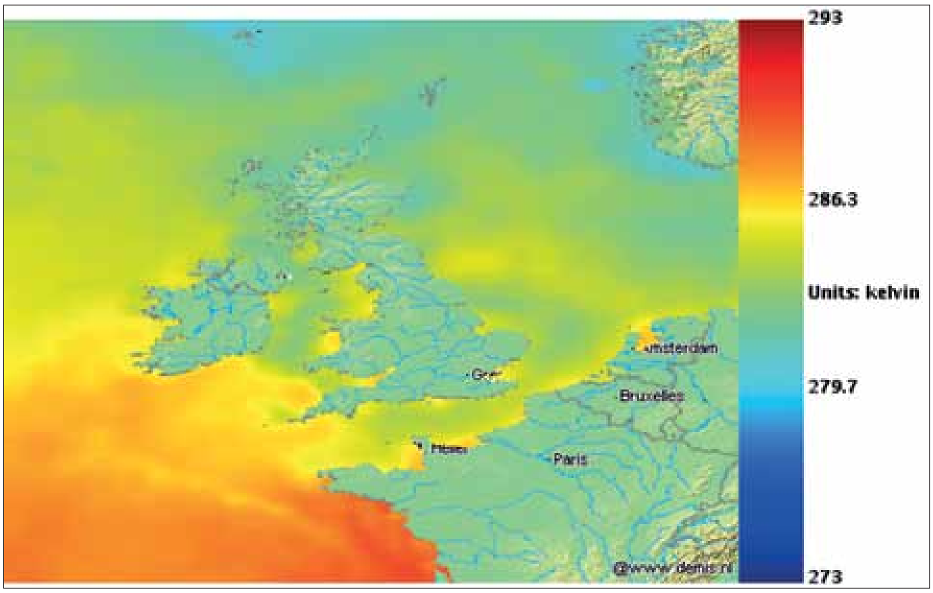
Such a time series of data for 60% to 70% of the globe is delivering timely insights into the global temperature record and new data sets to test climate models. Such tests may prove important in understanding the range of climate model predictions for the future decades and century. Hence the climate imperative has really driven state-of-the-art knowledge of the physical basis (radiative physics and molecular spectroscopy) and mathematical techniques (nonlinear inverse theory) through which EO data are derived. But most importantly, the increasing success of EO climate-related observations has been to drive awareness of the timescales of natural variability, anthropogenic perturbations and feedback in the Earth system. Long-term data (over decades) provide monitoring but also observations of "natural experiments" that give us new information.

## New missions

Alongside these challenges of long-term climate data, there are also new types of research missions that will shape our understanding of the Earth system and our interpretation of long-term records. In turn they are likely to become operational themselves, bringing new qualities to the information that EO can provide; the Envisat satellite (figure 3) has showcased research into operational EO across a range of domains leading to the successor Sentinel satellites. Measuring carbon biomass and the extent, structure and activity of vegetation are the subject of current mission studies. The ability of P-band synthetic aperture radar to address the former (Le Toan *et al.* 2011) and the use of spectrally resolved vegetation fluorescence to determine the latter (Guanter *et al.* 2012) are the results of innovative experiments on aircraft and in space. Pollution transport and global atmospheric chemistry models have been significantly augmented in the past decade by the new observations of reactive chemistry, particularly of organic compounds that indicate active carbon. These scientific innovations will push current technology to the limit; there are particular benefits in the long term for new techniques in laser technology in space, for more sophisticated versions of synthetic aperture radar (e.g. NovaSAR S-band) and for clever spectrometric techniques. They will also return to the forefront the need to study fundamental molecular physics at very high spectral resolutions, of the order of $0.001\,cm^{-1}$ or better, in order to describe complex phenomena such as line mixing and detailed molecular lineshapes.

Technology skills are critical for both short-term research and long-term climate missions.

The second strategic dimension relates the challenge of climate data sets with the growth of operational EO. The necessity of continuous long-term records of data for understanding climate has a surprising consequence for EO in that it strongly intertwines climate with other rationales for long-term EO data sets including environmental monitoring, policy, public and commercial services; figure 4 shows climate SST incorporated into a daily analysis for operational weather forecasting and oceanography. In other words, data for climate serves other scientific or societal needs and vice versa if such data are properly constituted and calibrated. The cross-over is similar to that which has been well established for many years in the study of atmospheric science with operational EO systems designed to service the numerical weather assimilation systems producing weather forecasts. The National Research Council's Decadal Survey (NRC 2007) identified strong mappings between Earth system science, accessible through EO, and societal drivers such as water and food, energy and security, early warning of hazards, ecosystem services and public health/environmental information. The European Commission's Global Monitoring for Environment and Security (GMES) programme recognizes the significant impact of EO in these areas, and is beginning to understand the dual service of public EO data for impact beyond science and for long-term change problems such as climate. The Sentinel series of satellites will provide a vital step in securing EO for science and society into the next decade and likewise should prove an excellent source of data for climate.




**4: High-resolution analysis produced by the Met Office Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system, which uses AATSR data and supports the weather forecast. (Met Office)**

## New systems

The third strategic dimension is based on science and society's need for information in near real time and with fine sampling of the global planet on a daily basis. The consequence for both operational systems and new research missions is for detailed sampling in both time and space. New systems are needed to observe variables that change at diurnal timescales and provide such coverage both in geostationary view and at polar latitudes. The leap forward in information content for Earth system models is huge if the requisite scales can be bridged. This may seem fanciful but already the power of geostationary systems is increasing, multiple instruments of wide swath are bringing increased sampling of the poles and there are investigations of specific polar systems with diurnal capabilities. There are already realizable systems likely to come to fruition in the next decade. The big opportunities though are represented by the increasing potential in constellations of satellites. The two most likely forms are multiple, low mass, agile platforms in low Earth orbits, and constellations of low to medium Earth orbit communication systems. The low-mass platform is already proving a considerable success with increasing numbers of satellites in place and offers a scalable model so even here there are realistic possibilities. These opportunities would require very different industrial models with larger numbers of instruments produced at one time and with repeat business requiring production-run facilities that have not previously been possible or strongly considered. We need to study these opportunities and develop bespoke instrument systems with well understood capabilities in order to be ready and to be able to demonstrate these systems in space at an early stage.

The EO community is realizing that, over the next 50 years, new EO systems will liberate operational streams of data covering oceanographic, terrestrial and cryospheric services in the way that has already happened for atmosphere studies with operational meteorology systems. As for the weather forecast, the EO satellite data will be embedded within the service structure and almost invisible to the user. Already EO data have ceased to be simply the prerogative of scientists and government, but have been transformed into a source of personal information expected to be online 24 hours a day. In this sense, one is reminded of the "computer revolution" which has shaped our society. The challenges in terms of launch availability, cost and development of the skills base are huge, but the vision is there and from our perspective the potential gains demand that we consider such developments as not just desirable but mandatory. The corollary is a vastly improved science base with which to tackle the Earth system and its changes. Such a science drive will have the added benefit of demanding extant *in situ* systems and very strong development of next-generation Earth system models.

The past 50 years have seen huge advances in EO science and technology. The next 50 may well be seen as the maturing of a scientific revolution with strategic dimensions of mission build capability, operational EO for science and society, and observations of the global planet daily. The stage is set and we expect the UK to play a central role in the capabilities for science and society of the new EO systems. ●

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*Ackowledgements. The author gratefully acknowledges the authors of the contributing presentations for their insights and David Moore, Harjinder Sembhi and Karen Veal for recording the EO sessions at the 50 year meeting in Leicester in September 2011. John Pye and Mark Sims provided close support to the organization of the meeting and its consequent success.*

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