Satellite Remote Sensing and Climate Change

Rosenstiel School of Marine and Atmospheric Science

UNIVERSITY OF MIAMI

Better knowledge for better seas

With the ever growing pressures that are being put on the marine environment, Janez Potočnik Commissioner for Environment at the European Commission discusses the proposed solutions...

Europe's growth potential – and countless European livelihoods – are heavily dependent on the proper functioning of marine ecosystems. We have every interest in using these resources carefully and efficiently, in ways that safeguard them for future generations. But we can't do that effectively until we recognise and address the growing pressures that we are exerting on the marine environment today.

EU lawmakers have adopted new legislation on Maritime Spatial Planning. Competition for maritime space – for renewable energy equipment, aquaculture and other growth areas – has highlighted the need for more efficient management of such areas, to avoid potential conflict and create a stable environment attractive to investors. What we have proposed will make it easier for Member States to coordinate such activities and better manage environmental pressures from sea-based activities.

Maritime Spatial Planning is a cornerstone of the Commission's Blue Growth strategy and of Integrated Maritime Policy. Clearer rules would boost sustainable maritime growth, while also contributing to a more efficient implementation of EU environmental legislation in marine and coastal waters. It should also help establish coherent networks of Marine Protected Areas, for which cooperation on planning across borders is essential, and ensure the participation of all stakeholders in planning processes.

The EU's marine areas exceed our total land mass. In fact, almost half of the EU's population lives within 50 km of the sea, regularly using its resources. This number increases during holiday season. The seas are one of the planet's common resources, so it makes sense to have shared legislation in this area. We already do, of course, in the form of the Marine Strategy Framework Directive, the EU's flagship policy for marine protection. This ambitious legislation sets a target of "Good Environmental Status" for all of our marine waters, a target to be reached in just 6 years' time. To achieve good status, we must ensure our waters are clean, healthy and productive, and that the way we use them today does not jeopardise their use by the generations to come.

There is much to be done. It is no secret that Europe's seas are some way from good environmental status, and the latest reports from Member States make troubling reading.

Marine pollution has decreased in some places, but levels of nutrients and hazardous substances such as mercury still remain above safe levels. Damage to the sea-bed, from activities like bottom trawling, is extensive, particularly in the North Sea.

In the Mediterranean and the Black Sea, nearly 9 in every 10 species are still being overfished. Urgent action is required. If we wait too long, the greater the cost will be to our industry and we will endanger the livelihoods of the people who

depend on fishing to put food on their table. Member States must deliver on their commitment in the reformed Common Fisheries Policy not to fish beyond the Maximum Sustainable Yield and to bring our fish stocks back within safe biological limits.

To tackle the eutrophication of our seas, we need to adopt a more integrated approach to the way we manage the fertilisers and other nutrients that are at the heart of the problem.

To combat marine litter, we must go to the source of the problem, and ensure that the materials that today end up as litter are instead pumped back into our economy as the raw materials for our products. That is why I am recommending to the Commission a headline target for marine litter reduction in the circular economy and waste package to be delivered this summer.

Closer European integration is a delicate subject, but when dealing with the common resource that is our seas, there is no doubt that Europe has everything to gain from a coherent, transnational approach. It has been said that we know more about the surface of Mars than we do about the deep sea. As Member States move into the next phase of the implementation of the Marine Directive, we must develop joint monitoring programmes and improve the comparability of the data Member States invest so much in generating. That way we can also work towards a shared picture, an index of the state of our marine environment, which can tell us at a glance how far we are from genuinely healthy seas.

To date, EU Member States have set fragmented, and at times contradictory, ambitions for the marine environment. We need to align our aims if we are to achieve coordinated and adequate actions to address the key marine issues we are facing today: whether overfishing, eutrophication or marine litter.

There are global aspects too that cannot be neglected. At the United Nations' Rio+20 Conference in 2012, the EU played an important role in stepping up international marine cooperation, as outlined in the ambitious oceans chapter in the conference conclusions. A range of commitments was agreed, from reducing marine litter, curbing overfishing, mitigating sea-level rise and coastal erosion and combating ocean acidification. We are now working through the UN processes to turn these commitments into action, and to ensure that marine protection has a prominent place in the Sustainable Development Goals – the key headline targets which the international community is developing for beyond 2015.

Solving these problems is ultimately a question of political will. In March this year, marine stakeholders from all over Europe put out a declaration [1] urging policymakers to address these maritime questions as a matter of urgency, and to turn words into actions to preserve our seas. I hope they pick up that challenge.

[1] http://ec.europa.eu/environment/marine/hope-conference/pdf/HOPE%20Conference%20Declaration.pdf

Janez Potočnik
European Commissioner for Environment
European Commission
www.ec.europa.eu

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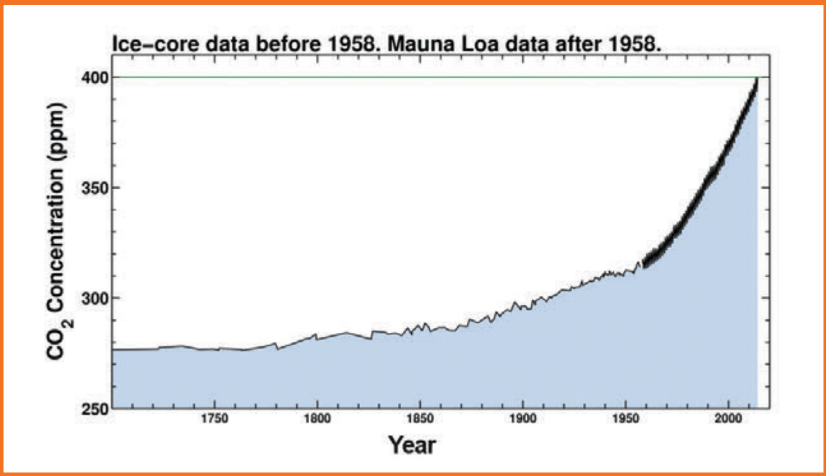
There can be little doubt that the consequences of climate change present one of the greatest challenges, if not the greatest challenge, to humanity. The climate will change in a way that is very difficult to predict on national and local levels, and on ill-defined time scales. Uncertainties pose a conundrum to politicians and decision-makers who have to formulate policies on the basis of incomplete information. Yet it is formulating the correct policies, and implementing them in a way that is acceptable to the majorities of their populations, that will mark their place in future views of history. But also our generation as a whole will be judged by our children and grandchildren, and generations into the future, on how we rise to this challenge.

The geological record tells us that there have been swings in the earth's climate in the past, but all of the indicators available to us tell of changes on longer time scales than those we can anticipate in the coming decades. The rapid increase in the concentrations of carbon dioxide in the atmosphere that have been accelerating since the start of the Industrial Revolution, caused by burning fossil fuels, is unprecedented in the history of human civilization. We have unwittingly put in motion events that will change the climatic conditions that have prevailed and been relatively stable, since the dawn of civilization. In the past ten thousand years or so, humanity developed from wandering hunter-gatherers to more stationary communities tied to a particular place by primitive agriculture. The locations where early communities were able to thrive offered specific advantages, including reliable rainfall or seasonal flooding of rivers or seasonal river flow driven by snow or glacier melt – all for the provision of drinking water and to water or irrigate crops.

Within the stable conditions of the past millennia, the weather and climate have been driven by the surplus of heat gained in the tropics from the sun; surplus in the sense that more is gained than can be absorbed or returned to space by local processes. The oceans and atmosphere work together to move the surplus of heat towards the poles where it can be lost to space by infrared radiation. The poleward movement of heat is what gives us reasonably stable and predictable weather conditions. Some of the poleward heat transfer is through the movement of water, not only in the oceans, but also in the



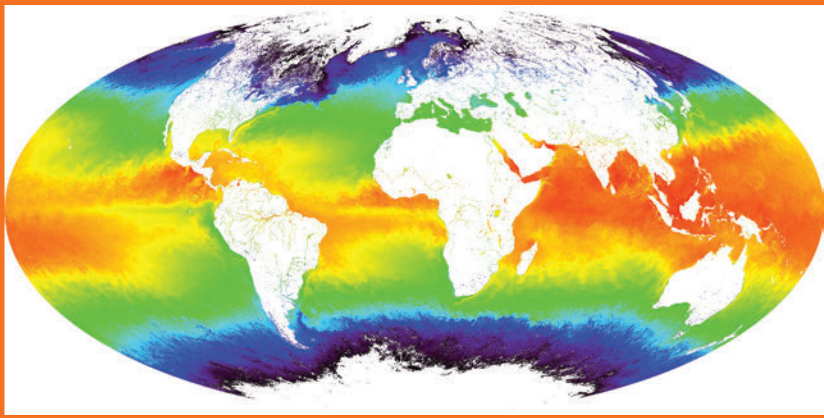
1. The concentration of atmospheric carbon dioxide since the start of the Industrial Revolution. Early measurements are from ice-cores, and those after 1958 from direct measurements taken on the mountain Mauna Loa in Hawai'i. The direct measurements resolve the seasonal cycle of atmospheric carbon dioxide concentration, which leads to the fine temporal structure to the curve. From Scripps Institution of Oceanography, University of California San Diego (**http://keelingcurve.ucsd.edu/** *).*

atmosphere in the form of water vapor, clouds and precipitation – the hydrological cycle.

While it is difficult, if not impossible, to lay the blame of any unusual weather event on climate change, the number and intensity of extreme events in the past decade, whether flooding, severe storms or extended droughts, are a likely indication of the early symptoms of global change. Of course it is inevitable that people view the state of the climate by their own recent experience, but the issues of climate change are indeed global. Several areas in the northern hemisphere have just experienced a very severe winter, but elsewhere in the northern hemisphere the winter has been anomalously mild; very hot conditions have prevailed at the same time in the southern hemisphere summer, and there are regions where droughts have become persistent. And sea-level continues its slow but accelerating rise, to the consternation of forward-looking coastal communities and the governments of low-lying countries.

The oceans play an extremely important role in the climate system. They cover about three-quarters of the earth's surface, contain about 97% of the earth's

2. New ice beginning to form in open water of the Arctic Ocean. The photograph was taken from the Russian icebreaker Kapitan Dranitsyn on September 12, 2005, at 80° 47.59' N, 103° 47.687' E during a research expedition of the Nansen and Amundsen Basins Observational System (NABOS) program. © Peter J Minnett.



3. Monthly averaged global sea-surface temperature derived from infrared measurements of the MODerate-resolution Imaging Spectroradiometer (MODIS) on the NASA satellite Terra. The data were taken during May, 2001, using cloud screening and atmospheric corrections developed at the Rosenstiel School of Marine and Atmospheric Science of the University of Miami, USA.

water, provide about 85% of evaporation into the atmosphere and receive about three-quarters of the global precipitation. They provide much of the energy to drive the atmospheric circulation, which gives us weather, and have their own circulation patterns that are part of the poleward transport of heat. The oceans, sometimes referred to as the "flywheel" of the climate system, control the timing and influence the magnitudes of changes in the global climate. Without better understanding of the properties and behavior of the oceans, and how they interact with the overlying atmosphere, progress in improving our knowledge of the climate system, and in producing better climate forecasts will be hindered.

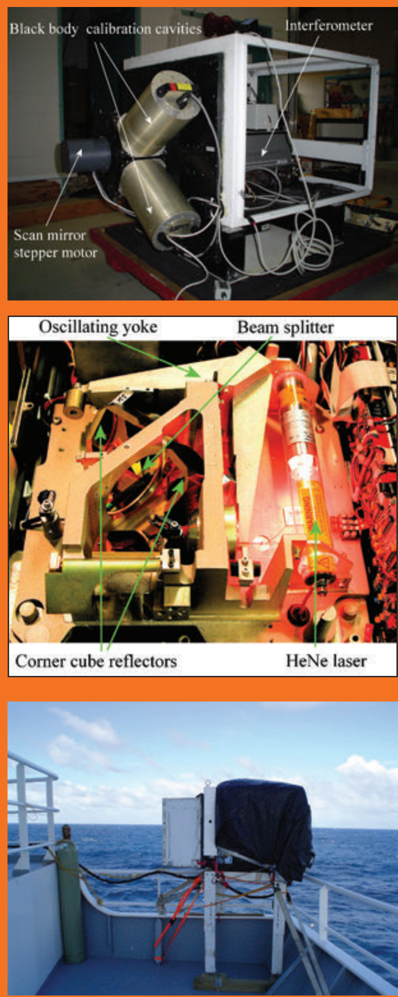
Despite remarkable progress in our ability to measure some of the properties of the oceans made in the last decade or so, exploiting new technologies such as autonomous underwater vehicles (gliders) and autonomous profilers (Argo), properly sampling the relevant oceanic variability is extraordinarily difficult. And it is instruments on earth-observation satellites that can provide important information about the ocean, atmosphere and climate system.

The impetus of developing earth observations satellite instruments was originally for weather forecasting and for military purposes. In concert with the provision of satellite data, rapid advances in computing capabilities led to the growth of numerical models for weather forecasting. And it was only later that these two resources were applied to the challenges of understanding longer term variability, that is, to understanding the internal workings of the climate and to attempting to forecast climate change.

A critical component of the climate system is the interaction of radiation, visible radiation from the sun and infrared radiation from the atmosphere and the surface, with the atmosphere. It was in the 1890's that a Swedish scientist, Svante Arrhenius, conducted the first study of the likely consequences of increasing the levels of carbon dioxide in the atmosphere by burning coal. Arrhenius concluded that a warmer climate would be the outcome. This was an impressive intellectual feat, given the limited information and tools at his disposal, rendered even more remarkable by his prediction that the first area of the globe to reveal signal of a changing climate would be the Arctic. Arrhenius's prescient conclusion has since been borne out by all computer models that are used to predict future climates, as they all indicate the temperature rises in the Arctic will be larger than the global average in a world with increased levels of greenhouse gasses. The models may not agree in the magnitude of the changes, or when certain warming thresholds will be passed, but they all indicate "Arctic amplification" of the climate change signal.

Another convincing confirmation of Arctic amplification is in the measurements from satellites of Arctic sea ice extent. Before the satellite era, that began in the late 1970's, information about the extent of Arctic sea ice was very sparse and incomplete, being derived from few ship observations and from aircraft patrols designed to monitor the positions of icebergs that might present a hazard to shipping in the North Atlantic. Since late 1978, a series of imaging microwave radiometers have flown on satellites in polar orbit, providing measurements of the entire Arctic region on a daily basis. The contrast in the signal in the microwave emission from ice and sea water is very large, and so the distinction between areas covered by sea ice and open water is relatively easy to measure. There is a seasonal cycle to the Arctic sea ice extent, increasing in the autumn and winter when the sunlight is weak or absent, and the surface loses heat to space by infrared radiation. The extent begins to diminish in late spring when solar heating begins to dominate the surface heat budget and the sea-ice begins to melt, leading to a minimum in the extent in mid-September each year. In the first two decades of the satellite era, the seasonal cycle was more-or-less stable, with some years showing more ice in September than in others, but in the late 1990's the trend changed with an acceleration in the reduction of the annual minimum sea-ice extent. This acceleration has continued, with some year-to-year variations, through the last decade with the minimum ice extent in 2012 being about half of that in 1980.

Another climate-relevant variable measureable from space is the surface temperature of the oceans, commonly referred to as sea-surface temperature (SST). Images of the global SST can be derived from space by both infrared and microwave radiometers on satellites. The microwave signal can propagate through most clouds, so can give a more complete picture of the SST patterns than those taken by infrared imagers, for which clouds obscure the surface. However, infrared imagers produce information at a much higher spatial resolution, and therefore complement the microwave data. The time series of infrared-derived SST equals that of the microwave sea-ice extent, going back to 1978, whereas accurate SSTs from microwave instruments began in the early 2000's. Because the thermal capacity of water is so high, taking about 3500 times more heat to raise the temperature of equal volumes of water and air (at average conditions at



4. The Marine-Atmospheric Emitted Radiance Interferometer (M-AERI) is a key instrument for the assessment of the uncertainties in satellite-derived SSTs. It is a Fourier-Transform Infrared interferometer that measures spectra of emitted radiation from the ocean and atmosphere in the 3-18µm wavelength range. Figure 4a shows it being prepared for at-sea deployment, with the side panels of the protective enclosure removed and some components labelled. The internal parts of the interferometer are presented in Figure 4b, and Figure 4c shows the M-AERI deployed in the South Pacific Ocean on the New Zealand research vessel Tangaroa.

the surface), the anticipated temperature change in the ocean temperature is small, making it a very difficult proposition to measure such small signals from space (or by any means).

SST is a very variable quantity, reflecting changes caused by the absorption of solar radiation, by heat loss to the overlying atmosphere, and by the surface currents of the ocean itself. The time scales of these variations range from hours to decades, and in themselves may not have anything to do with climate change. Perhaps the most widely recognised SST anomalies are those associated with the El-Niño – Southern Oscillation (ENSO) events that occur in the Pacific Ocean a few times per decade and have wide-ranging influence on atmospheric circulations and therefore global weather patterns. The peak amplitudes of the ENSO signals in parts of the equatorial Pacific Ocean are 3-4 °C, whereas a climate change signal might be an order of magnitude smaller. Furthermore, a climate change signal in SST need not simply be a uniform increase in global surface temperatures, but some areas will exhibit enhanced warming, such as in the Arctic, while others could cool. Thus a climate-change signal in SST would be small and spatially varying and set against a background of larger signals that are not necessarily related to the effects of increased levels of greenhouse gases, or other factors causing the climate to change. A "Climate Data Record" was formally defined in the early 2000's and it was stipulated that time series of measurements have to be long enough and sufficiently accurate to be able to identify a small climate change signal in the "noise" of natural variability unrelated to global change. In the case of SST, this requires measurement uncertainties of <0.1°C and stability of those measurements of better than 0.04°C per decade.

The current generation of satellite infrared imaging radiometers are capable of reaching the absolute accuracy requirement through careful pre-launch calibration and characterisation. However, once launched they are never retrieved to check how their performance has degraded over the years of their mission. Furthermore, the post-launch temperature measurements are made at about 800km above the sea surface, and to derive a good estimate of the SST requires a very accurate correction for the effects of the intervening atmosphere. Corrections include reliable identification of clouds and aerosols, such as Saharan Dust outbreaks and those from volcanic eruptions, and then a correction for the clear sky effects which result from the interactions of the infrared photons emitted from the sea-surface and the molecules of the atmosphere, particularly those of water vapor. Over the years several approaches to cloud screening and atmospheric corrections have been developed. But demonstrating whether the required accuracies have been achieved is a demanding task.

Assessing the uncertainties in the derived SSTs requires comparisons with independent temperature measurements, and these have to be of higher quality than the satellite measurements. For the past decade and more, determining the uncertainties in satellite-derived SSTs has been one of the foci of my research group at the Rosenstiel School at the University of Miami. Part of our effort has been to mount very accurate infrared spectro-radiometers on ships. These instruments measure SST in the same manner as the satellite infrared radiometers. Thus we make a "like-with-like" comparison with the satellite measurement. We use both research vessels and commercial ships. Through a series of workshops involving the US National Institute of Standards and Technology (NIST), these ship radiometric measurements have calibration traceability to international temperature standards. This allows measurements from multiple ship-board radiometers to be combined in a rigorous fashion, and equally to assess in a defensible manner the characteristics of multiple satellite instruments. This activity is shared with other researchers around the world and is coordinated though the Group for High-Resolution Sea Surface Temperature (**see www.ghrsst.org**).

Satellite instruments take a long time to develop and therefore are very expensive. However, once launched they often operate for many years, even more than a decade, before failure or significant degradation and therefore the data sets they produce are of exceptionally good monetary value. Rarely are such instruments developed solely for climate research, but are multi-purpose, often primarily intended for weather forecasting. However, the full impact of the satellite data cannot be fully realised without painstaking research over many years to improve the accuracy of the measurements, and to demonstrate the characteristics of the residual uncertainties in the SSTs.

In the past couple of years, the first of a new generation of infrared radiometer with SST capability has been launched by the USA, and an improved model of microwave radiometer by Japan. The first of a new type of infrared radiometer, optimised for the measurement of SST, will be launched by ESA next year, and a new infrared radiometer is being developed for the next generation of EUMETSAT polar-orbiting weather satellites, the first of which is planned of launch in 2021. These are all excellent indicators of a promising future for studying the climate system from earth observation satellites. But this promise will not be realised without increased investment in the research groups around the world endeavoring to improve the accuracies of satellite-derived ocean variables, including SST, to ensure they are “fit for purpose” for climate research and monitoring.

Peter J Minnett

Ocean Sciences
Rosenstiel School of Marine and Atmospheric Science
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149, USA

Tel: +1 305 421 4104
Email: pminnett@rsmas.miami.edu