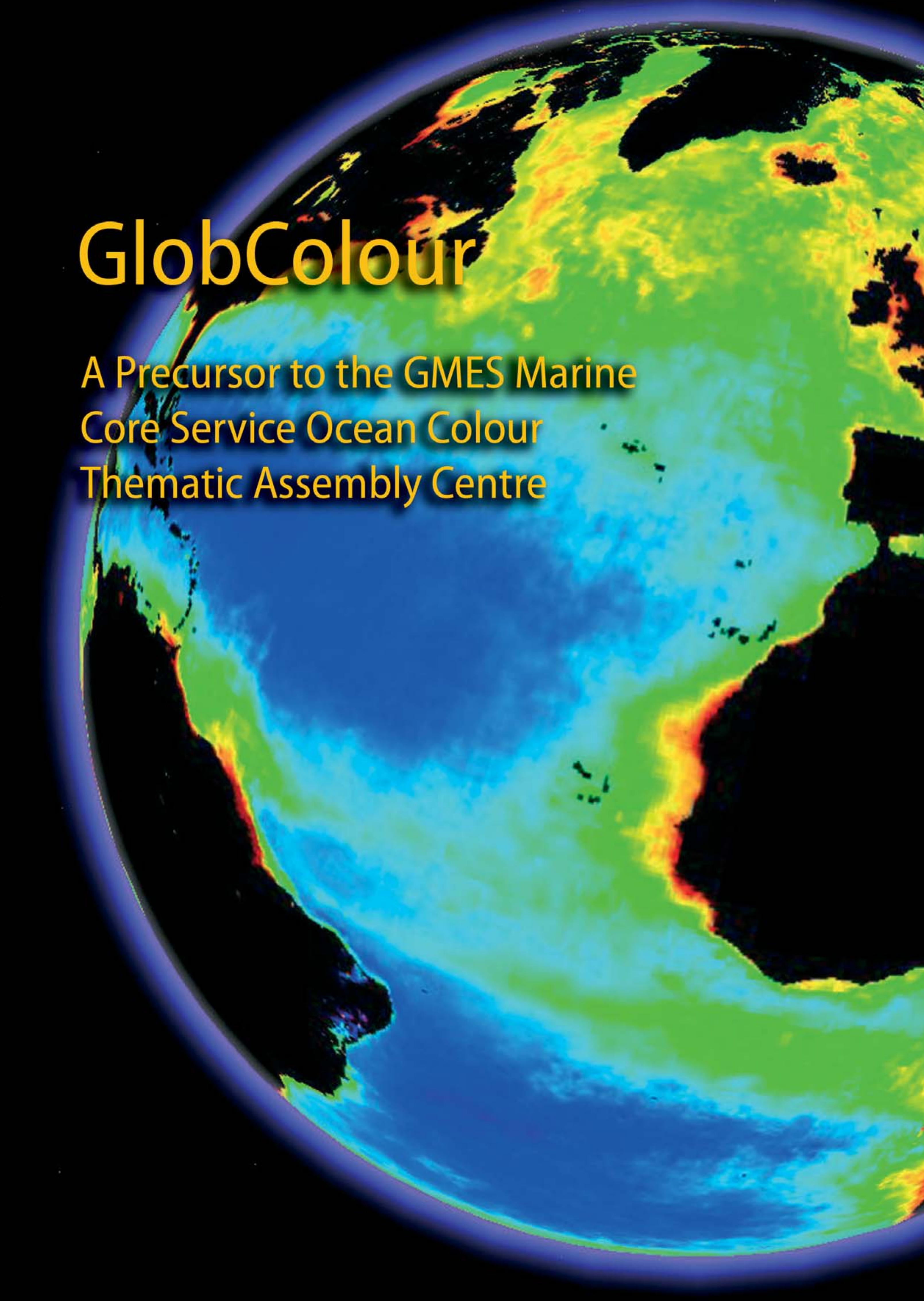
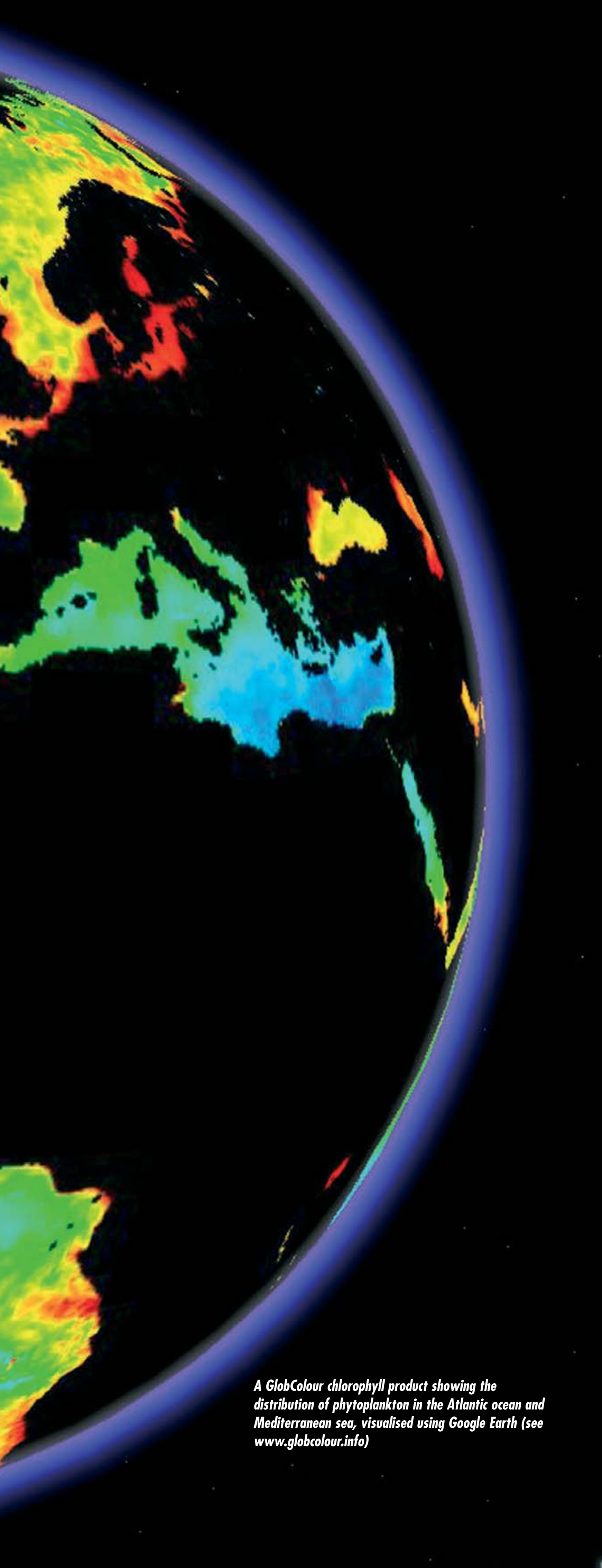
GlobColour

A Precursor to the GMES Marine Core Service Ocean Colour Thematic Assembly Centre





A GlobColour chlorophyll product showing the distribution of phytoplankton in the Atlantic ocean and Mediterranean sea, visualised using Google Earth (see www.globcolour.info)

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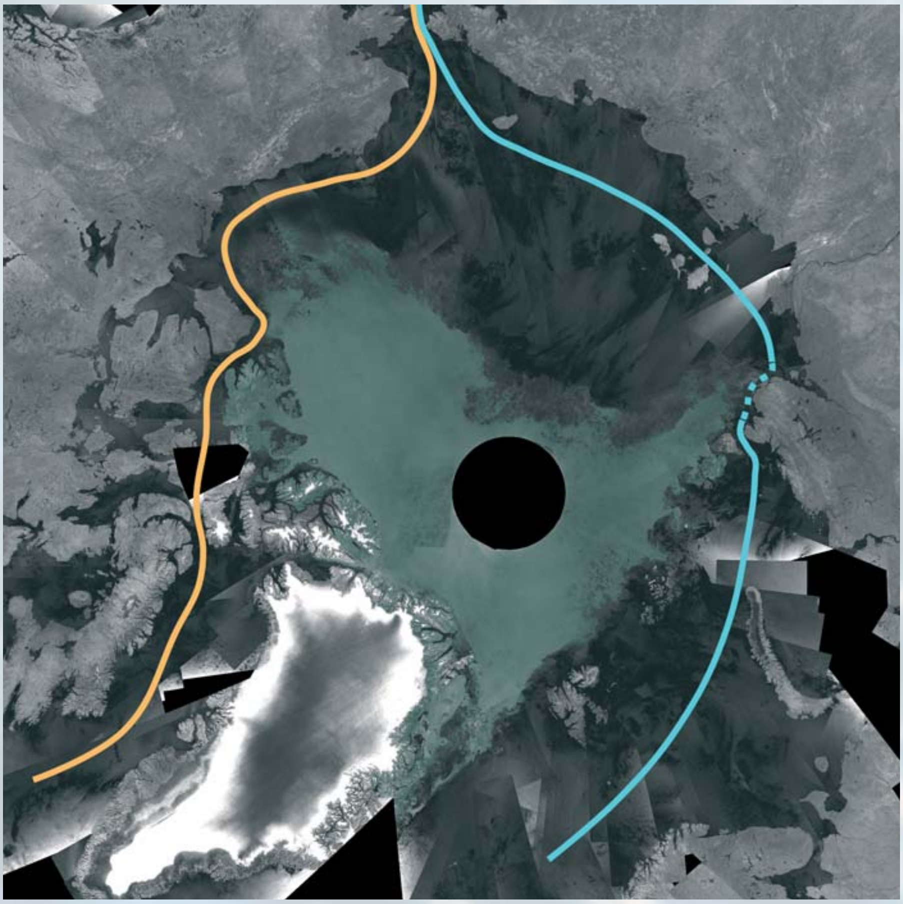
ESA's GlobColour project is providing valuable information on marine biological activity, essential for assessing the amount of carbon dioxide being absorbed from the atmosphere by the oceans, and for projecting the severity of future global warming. By merging data from three satellite sensors, GlobColour offers the most complete 'ocean colour' data covering the last 10 years. A near-real time ocean colour service is being developed to demonstrate the capability of supporting operational decision-making. Together with the Medspiration project on sea-surface temperature, GlobColour is laying the groundwork for the operational exploitation of Envisat and Sentinel-3 that will be sustained under the European Commission's 'GMES Marine Core Service'.

Introduction

The 25 000 million tonnes of carbon dioxide pumped annually into Earth's atmosphere by human activity is contributing to a global warming that is likely to make our planet less habitable. If left unchecked, the consequences could be disastrous for humanity.



A result of global warming? Shipping shortcuts between the Atlantic and Pacific are opening through the Arctic. This Envisat radar mosaic of the Arctic Ocean for early September 2007 clearly shows the most direct route of the Northwest Passage open (orange line) and the Northeast Passage only partially blocked (blue line). The dark grey represents the ice-free areas, while sea-ice and land show up as light grey

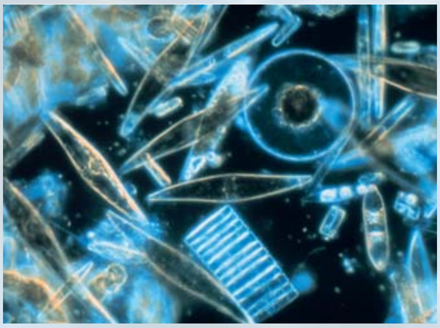
Warming seas and melting glaciers are raising the mean sea level by 2–3mm each year, increasing the risk of severe flooding in low-lying coastal cities, such as London and Amsterdam, and of the huge river delta populations of Asia and Africa. Mountain glaciers that used to be reliable summertime water sources for much of the world's agriculture are gradually disappearing, making conflicts over scarce water resources ever more likely. Changes in ocean circulation may well be disrupting fisheries and be behind some of our recent unseasonable weather. Tropical cyclones like Hurricane Katrina, which wrecked New Orleans in 2005, and Hurricane Dean in the Caribbean this year, are becoming more intense. Together with heat waves, which have killed tens of thousands in Europe in recent summers, these phenomena are linked to increases in sea-surface temperature. The fourth and latest assessment of the Intergovernmental Panel on Climate Change shows that many of the effects of global warming are already happening or are reasonably predicted to begin soon.

Optimists remind us of the benefits of global warming. Longer growing seasons in temperate regions will lead to more productive agriculture. Melting sea ice will open up global transportation shortcuts via new Arctic sea routes and allow exploitation of previously inaccessible oil reserves. But such benefits need to be weighed against the negative impacts. Whatever the outcome of that contentious debate, nobody can reasonably argue against careful management of the changes we are bringing upon the 'Earth system'. And management, if it is to be effective, starts with quantitative, accurate and unequivocal information on the state of our planet.

ESAs GlobColour project will contribute by providing scientists with a valuable new multi-satellite dataset on ocean biological activity. The colour of oceanic sea water depends largely on the number of microscopic (commonly green) phytoplankton it contains. Clear blue surface waters in the middle of ocean basins are poor in nutrients and contain relatively few phytoplankton, while regions of upwelling near continental shelves bring nutrient-rich waters from the deep ocean to the surface, enabling phytoplankton to bloom and colouring the water green. Things get rather more complicated in the coastal zones, where the seawater is also coloured by organic runoff from the land and suspended sediments, but the principle remains the same. Tiny phytoplankton are the first link in a food chain that humans also depend on for food.

As well as being fundamental for our food supply, the ocean's biological activity is worth keeping an eye on for other good reasons. It could help to mitigate climate change by absorbing carbon from the atmosphere, and turning some of it into organic detritus, which eventually sinks to become locked in sediments on the deep sea floor. This is the 'ocean biological pump'. By absorbing some of the carbon we emit into the atmosphere each year, it helps to reduce the amount of warming.

Marine phytoplankton seen through a microscope. (N. Sullivan, US National Oceanic & Atmospheric Administration/Department of Commerce)



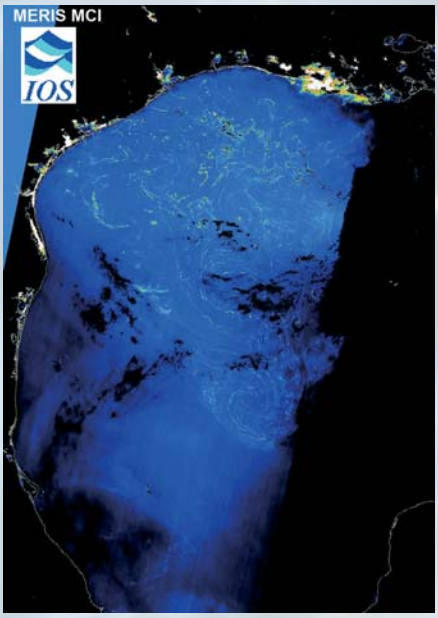
As the concentration of carbon dioxide in the atmosphere increases, some of it also dissolves chemically in the oceans, making seawater more acidic. Together, these two processes are estimated to be about equivalent to the terrestrial carbon sink. One problem, however, is that this gradually increasing acidification of the oceans could eventually reduce the ability of coral and some types of plankton to build their skeletons and shells, slowing biological activity, and reducing the amount of carbon absorbed by the oceans. Monitoring the evolution of the biological pump as atmospheric carbon dioxide increases is therefore essential for accurate projections of future climate change.

This kind of frailty means that information on ocean biology can also be a useful indicator of climate change. It can help scientists to check the predictions of their highly complex models, and to give early warning of things they didn't expect.

History

The science of measuring ocean colour from space began in 1978 with the launch of NASA's Coastal Zone Color Scanner (CZCS). This highly successful proof-of-concept mission exceeded its one-year design lifetime by almost a factor of eight. More importantly, it helped to realise the potential for measuring chlorophyll concentration in the oceans by providing scientists with the necessary data to develop effective retrieval algorithms.

Spurred on by this success, several agencies began planning new global ocean colour missions. The DLR German space agency developed the Modular Optoelectronic Scanner that flew on India's IRS-P3 satellite 1996–2004, and on Russia's Mir space station. The Orbital Sciences Corporation in the USA developed GeoEye's SeaWiFS mission with the primary goal of providing commercial services to the fisheries industry. Thanks to both NASA's Earth Science Programme and ESA's Earthnet, these commercial data



Sargassum in the Gulf of Mexico. First seen from space with the help of MERIS by Jim Gower and Stephanie King of the Canadian Institute of Ocean Sciences, and Chuamin Hu of the University of South Florida

were also made widely available to the science community, which has made SeaWiFS the workhorse scientific ocean colour instrument for the last ten years. Japan's JAXA launched the Ocean Colour and Temperature Scanner on ADEOS-1, and the ocean colour-capable Global Land Imager on ADEOS-2. Both were accompanied by the POLDER instrument from France's space agency CNES. Unfortunately, they were all lost less than a year after launch through failures in the solar panels of both ADEOS satellites.

In 2004, CNES flew a third POLDER-type instrument on the Parasol mission. Although intended to monitor global dimming owing to anthropogenic aerosol emissions, Parasol has recently started to provide ocean colour data. In the meantime, NASA followed the success of CZCS with two sophisticated and multi-purpose Moderate Resolution Imaging Spectrometer (MODIS) instruments. While the first MODIS, launched on the Terra satellite in 1999, has suffered from unstable calibration making ocean colour retrievals difficult, the second, launched on Aqua in 2002, provides high-quality observations.

Since 1999, several other missions which do not provide global data have been launched by China, Japan, Taiwan, India, Korea and Argentina.

ESA's first ocean colour instrument, the Medium Resolution Imaging Spectrometer (MERIS), was launched on Envisat in 2002. MERIS provides high-quality ocean colour data at both global (1 km) and coastal (300 m) resolutions, and has improved retrieval capabilities for coastal waters. Specialised narrow spectral bands allow not only the possibility to monitor phytoplankton in the oceans, but also to monitor biological activity in the much more complex coastal zones. MERIS' enhanced capabilities are opening up new possibilities for monitoring the marine environment, such as the recent detection in the Gulf of Mexico of vast thick beds of floating 'sargassum' seaweed, the first time this phenomenon has been observed by satellite.

User Needs

In 1996, the International Ocean-Colour Coordinating Group (IOCCG) was established to facilitate coordination between the science community and space agencies. Specialised scientific working groups of recognised world experts were set up to build consensus, such as providing recommendations on satellite sensor specifications and documenting scientific best practice.

In their second report, in 1999, IOCCG analysed user needs for global ocean colour monitoring. As well as the need to quantify the global ocean carbon flux, these requirements included monitoring fisheries and coastal zones, and providing ocean forecasters with essential information on the way light and heat are absorbed by the upper layers of the ocean. IOCCG combined these user needs to derive specific requirements for satellite missions, which showed that global coverage is needed at least every 3 days. The report considered the complementarity between different satellite missions, and pointed out that, owing to interference from Sun glint and cloud cover, no single instrument would be capable of meeting this requirement. The report also noted, however, that by combining observations from multiple sensors, a significant increase in coverage would be achieved. For instance, SeaWiFS, with the widest swath (2800 km) can provide only 60% global coverage in 8 days. But by combining data from the three currently flying sensors, it is possible to achieve the same coverage in only 4 days.

As well as improving spatial coverage, merging data from different satellite missions can provide improved temporal coverage. Thanks to the natural variability in the Earth system, the only way to detect the subtle signals of climate change is to average many measurements over a long time period. This is rather like your car's fuel gauge, which has to average measurements made over several minutes in order to read the true depth of petrol in a tank that is being sloshed about as you drive along. This leads to a strong need for multi-decadal ocean colour time series for global change monitoring. The only way to produce such a dataset is to string together the multi-annual time series from different sensors into a consistently calibrated data set spanning a time period much longer than the lifetime of any single satellite.

Combining data from several satellites brings several extra benefits. As different satellites usually fly over the same area at different times, combining the data leads to a better sampling of the daily variability. As well as getting a result with a smaller random error simply because of the larger amount of data, since all sensors are built differently, the intercalibration step required before the data can be merged tends to reduce instrumental biases. Merging also highlights suspicious regions where retrievals differ more than expected, which can be missed when data are compared with the very few 'ground-truth' measurements available. Erroneous temporal trends in the time series from individual sensors can also be more easily corrected.

For these reasons, and the fact that they are based on all the available information, scientific analyses built on a merged dataset have the highest possible credibility. This is an important criterion when governments need to use these analyses to make decisions with potentially huge social and economic implications.

The GlobColour Project

ESA's Data User Element (DUE) is building the user community for Earth observation data by running projects to develop and demonstrate user-driven applications. In so doing, it helps to transfer research techniques into viable applications, and puts Earth observation to work for the benefit of Europe's citizens. Since 1996, almost 90 projects have been kicked-off involving more than 180 formally committed user organisations and 150 European and Canadian companies. Several projects have pioneered applications that are being developed into operational services by the European Commission under the Global Monitoring for Environment and Security (GMES) initiative.

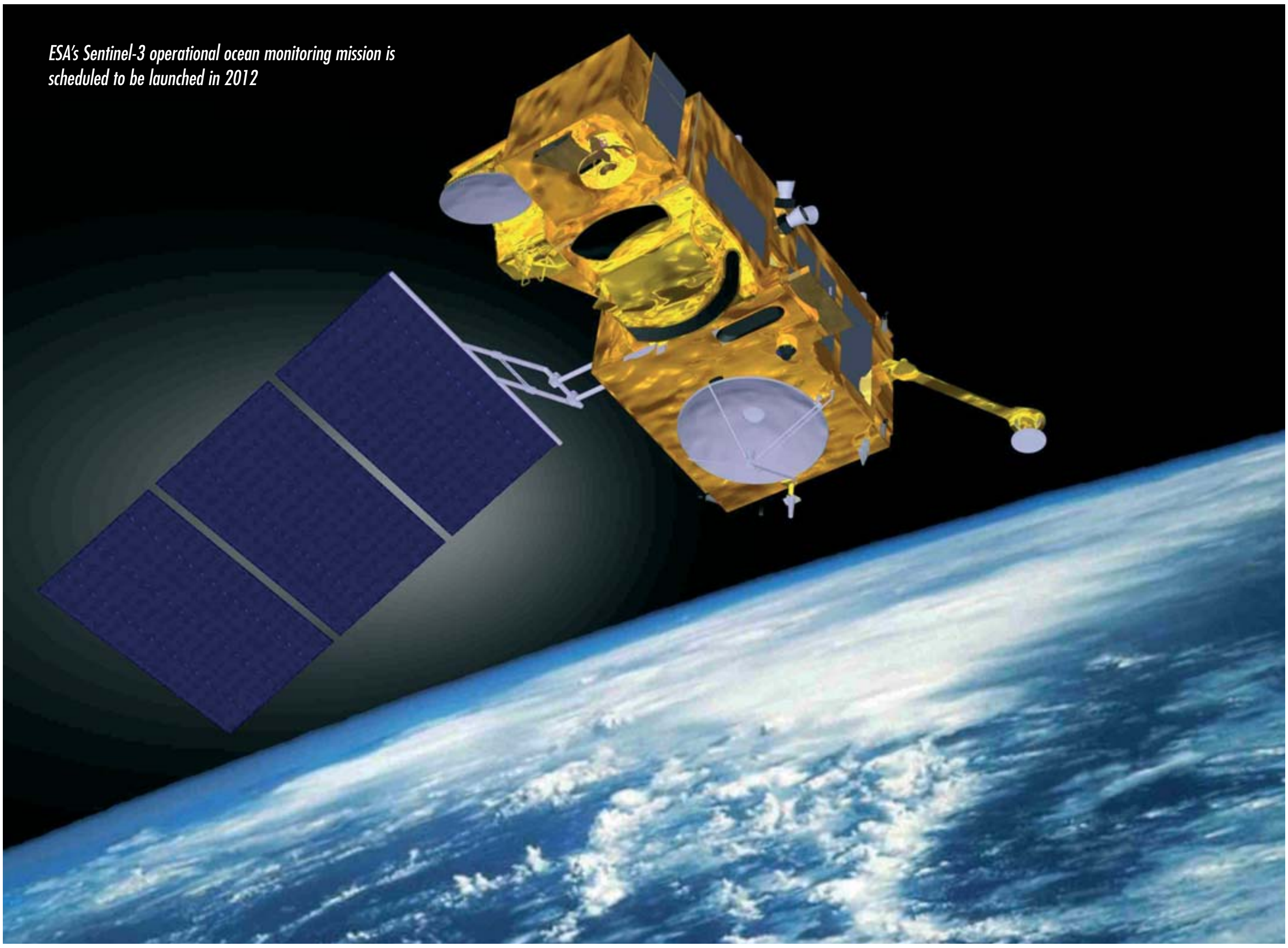
The DUE also supports scientific programmes and international environmental conventions, such as the United Nations conventions on climate change, desertification and biodiversity, by providing large-scale satellite-derived information for global change research and monitoring.

In 2005, the IOCCG convened a working group to examine the state-of-the-art in ocean colour data merging. It showed that the research techniques had matured sufficiently and the time was now ripe for putting them to work. This effectively threw down the gauntlet for attempts to be made to merge large quantities of global satellite data to provide the consistent high-quality long time series that the user communities are asking for. ESA took up the challenge by initiating the GlobColour project, and NASA started the Ocean Color Time-Series, which builds on their earlier Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies programme. Comparisons between these merged datasets will help to refine the techniques. GlobColour is the only one that so far includes MERIS.

In setting up GlobColour, three user organisations were invited to help. Their roles are to specify the detailed user requirements, act as a channel to the broader end user community, and to provide feedback and assessment of the results. The International Ocean Carbon Coordination Project based at UNESCO in Paris provides direct access to the carbon cycle modelling community's requirements and to the modellers themselves who will use the final products. The UK Meteorological Office's National Centre for Ocean Forecasting provides an understanding of the requirements of operational users. The IOCCG brought its knowledge of the global user needs and valuable advice on best practice within the ocean colour science community.

The 3-year project began in November 2005 under the joint leadership of ACRI (F) and the University of Plymouth (UK). The objective is to produce the best possible global daily ocean colour data set by merging data from the three most capable sensors: SeaWiFS, MODIS on Aqua, and Envisat's MERIS, and to process all available data from them to produce a consistently calibrated time series covering from 1997 to 2008.

The first year of work, 2006, was devoted to development and prototyping. Four months of merged global data were produced with each of three merging methods. Validation and intercomparison of this prototype dataset, and consideration of these results in terms of how best to meet the user requirements provided the basis on which the final merging methodology was selected. The results of this first year of work were presented at a user consultation workshop organised by the Laboratoire d'Océanographie de Villefranche in France, in December 2006. This was an opportunity for the wider global user community to hear about


ESA's Sentinel-3 operational ocean monitoring mission is scheduled to be launched in 2012

the results and to influence the direction of the project. It also provided the final stamp of approval on the merging methodology before large-scale processing began in 2007.

Almost the full 1997–2007 set of global daily merged ocean colour products has been processed. An intensive phase of validation was also undertaken to assess the quality of the dataset. As it is based on a much larger set of *in situ* data than could be used for the validation of the prototype data set, it provides significantly clearer results. Both the final products and the quality assessment will be presented at a second user consultation in Oslo, organised by the Norwegian Institute for Water Research (20–22 November 2007). The data will then be made freely available for use by the worldwide science community via the project's web portal: at *www.globcolour.info*

Of course, GlobColour will not stop there. In 2008, the project will continue merging ocean colour data, but with a new twist. Having demonstrated the means to provide the global change community with a long-term global dataset for ocean carbon cycle research, the project will attempt to reuse what it has developed to support operational oceanography. Like weather forecasters, operational oceanographers need near-real time observations to assimilate into predictive ocean models in order to forecast the future ocean state. Ocean colour can provide forecasters with the information they need to generate forecasts of, for example, water clarity for naval mine-clearing operations, and biological activity for fisheries and aquaculture industries. As always with computers: 'garbage in, garbage out', so the accuracy of these forecasts depends critically on the quality of the input data. Hence using GlobColour's 'best possible' multi-sensor ocean colour products should ensure the best possible ocean forecasts can be made.

The Future

Having reached its 5-year design life in March 2007, Envisat is still going strong, but even the most optimistic of ESA engineers knows the satellite is on borrowed time. It has to be deorbited when its fuel runs out about 5 years from now. SeaWiFS is already 10 years old and showing signs of age, and Aqua too will reach its design life in 2008. So what about the future?

Following the last 30 years of research

MERIS reduced-resolution image from 3 May 2007 showing a bloom of phytoplankton (primarily coccolithophores) along the edge of the continental shelf south west of Ireland and to the west of the English Channel, and suspended sediments in the Irish Sea, Bristol Channel and English Channel

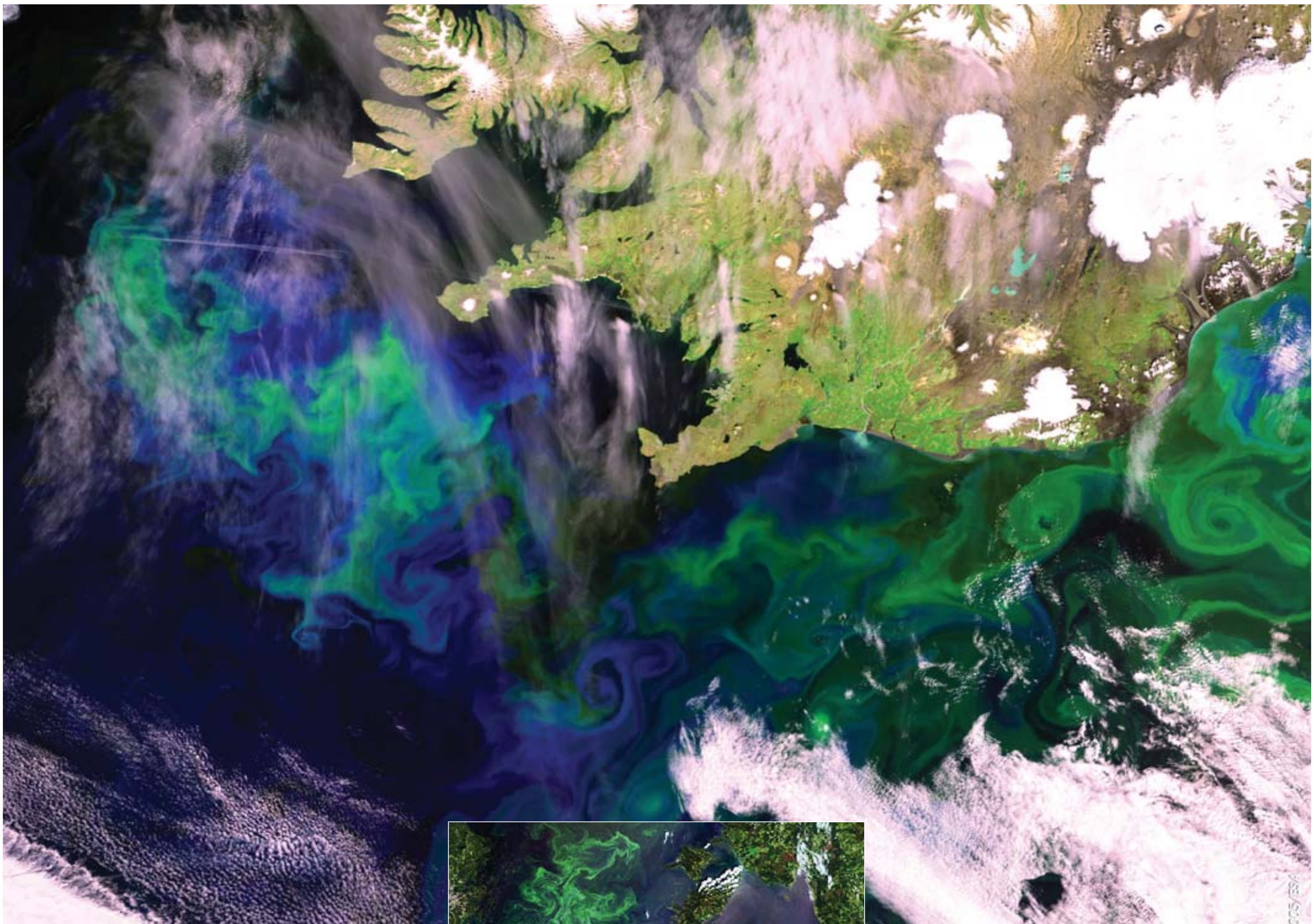
and development since the launch of CZCS, the age of sustained operational ocean colour monitoring will finally begin with the launch of ESA's Sentinel-3 and the joint NASA-NOAA NPOESS (National Polar-orbiting Operational Environmental Satellite System) satellites. The The Visible/Infrared Imager/Radiometer Suite (VIIRS) on NPOESS will provide basic capabilities to monitor global ocean chlorophyll, while Sentinel-3 will carry the Ocean and Land Colour Instrument (OLCI), partly based on MERIS. Thanks to this heritage, OLCI will have significantly enhanced capabilities to provide both more accurate chlorophyll retrieval, not only in the open ocean, but also, like MERIS, in coastal waters, by providing operational monitoring of other optically active marine components such as dissolved organic material and suspended sediments.

With operational satellite missions in place, ocean colour data merging also needs to continue on an operational basis. The initial 12-year GlobColour time series will need to extend well into the future to allow scientists to continue to monitor and more fully understand the sea's role in the carbon cycle. But whereas ESA programmes such as DUE can develop and demonstrate new Earth observation-based services, the implementation of long-term operational services has to be sustained by the user communities themselves. As a major user of environmental information, the European Commission is putting in place this long-term operational capacity through its GMES initiative. In 2008, the EC-funded Marine Core Service will start to provide a suite of operational services to support Europe's decision-makers. As one of these services, GlobColour's merged ocean colour dataset will continue to support the global change research community well into the future within the Ocean Colour Thematic Assembly Centre (OC TAC).

The main objective of OC TAC is to bridge the gap between space agencies providing ocean colour data and GMES marine applications. It will deliver core ocean colour products, annotated with quality control flags and reliable error estimates at pixel level at global to regional European scales, consolidating European efforts and maximising their impact. The aim is to integrate the best components of existing pre-operational systems developed in the last few years by national, ESA and European projects like GlobColour, MarCoast and Mersea into a common European system, filling gaps and creating a common external interface.

Having focused this article on the global oceans, we should not forget that MERIS and OLCI were also designed for monitoring the coastal zones. Coastal waters are rich in nutrients and support a much more active biology than the relatively barren surface waters of the open oceans. They could account for a significant fraction of the carbon absorbed by the sea, but assessment of the fluxes of carbon between coastal waters and the atmosphere is still a topic of research. Apart from helping to monitor and understand the carbon cycle, MERIS and OLCI coastal capabilities open up whole new domains where ocean colour information can be put to good use.

Coastal waters are vitally important as sources of wealth, but they are also where mankind's impact on the marine environment is greatest. Warmer seas and increasing levels of nutrients from agricultural runoff can give rise to more frequent algal blooms, which in turn can suffocate marine life by mopping up all the available oxygen. Some blooms give off neurotoxins that damage fish stocks, can make seafood and shellfish unsafe to eat, and can even be directly harmful to swimmers. The total socio-economic impact of such harmful algal blooms in Spain, Italy and Greece alone is estimated at €329 million each year. Predictive models are under development with the aim of forecasting algal blooms, to allow action to be taken to



MERIS image over Iceland, 21 June 2004. Phytoplankton play an important role in the Earth-system: they could help to reduce the amount of carbon dioxide in the atmosphere, and are a useful indicator of changes in ocean productivity

Ocean colour data are important for predicting harmful algal blooms. Envisat/MERIS recorded this Baltic scene in July 2005

minimise the risks to commercial operations and human health. But the accuracy of these forecasts will depend critically on the availability of high-quality satellite-based observations.

Governments are already obliged by the European Water Framework directive to monitor harmful discharges from rivers into their immediate coastal environments. In the future European Maritime Policy these obligations are likely to be enlarged to include areas further offshore where, to be cost-effective, monitoring will have to rely on a combination of *in situ* sampling and Earth observation. The increased temporal sampling resulting from data merging will be invaluable when put to work in monitoring these rapidly changing coastal zones.

Through GlobColour, ESA is currently providing scientists with the best possible ocean colour data set for carbon cycle research, allowing politicians to make informed decisions on climate change mitigation and adaptation policies. Just as importantly, it is also laying the groundwork for valuable information services that will be needed to support Europe's Maritime Policy and the well-being of her citizens well into the future.

Acknowledgements

The authors would like to acknowledge the hard work and dedication of the GlobColour project team (ACRI, University of Plymouth, Laboratoire d'Océanographie de Villefranche, Norwegian Institute for Water Research, University of California Santa Barbara, Brockmann Consult, Deutsche Zentrum für Luft- und Raumfahrt, ARGANS Ltd), the enthusiastic participation of the champion users (IOCCG, IOCCP and the UK Met Office), as well as NASA and GeoEye for access to MODIS and SeaWiFS.