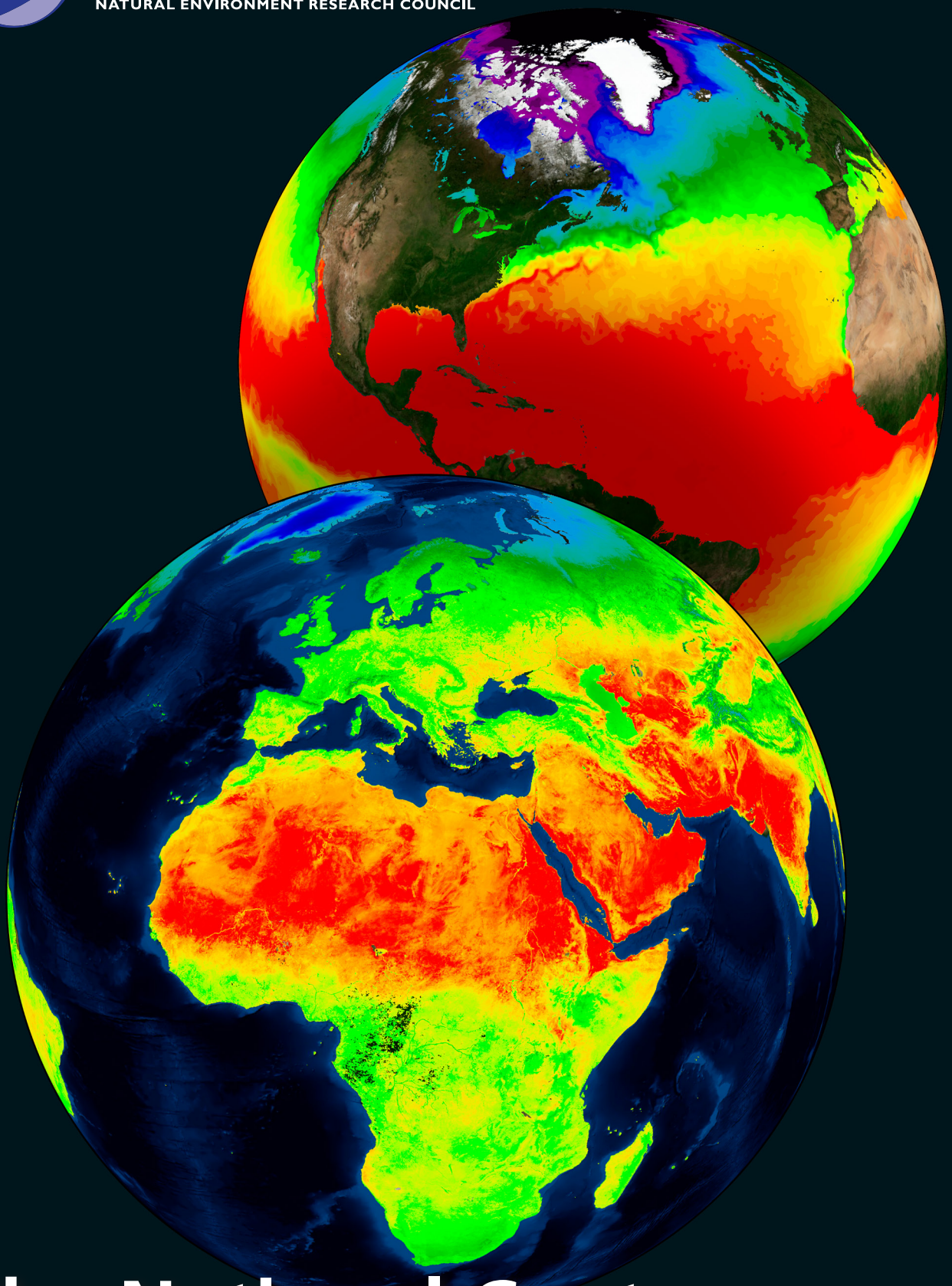
National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL



The National Centre for Earth Observation

Earth Observation Science to Understand a Changing Planet

Contents

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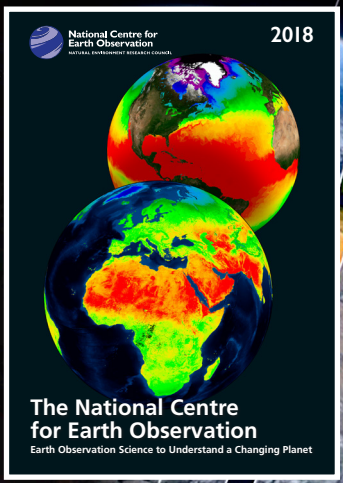


Neil Humpage (NCEO-University of Leicester) during the calibration of GHOST at STFC's UK ATC. Credit: STFC.

Group workshop at NCEO Researchers' Forum. Credit: NCEO.

Exploring enlarged images from the Astronaut or Satellite activity at an EO Detective workshop. Credit: Mark Woodward / University of York / UK Space Agency.

Our mission

Delivering transformational Earth observation science capability to meet Earth system challenges

The National Centre for Earth Observation (NCEO) has world-class capabilities in processing and analysing the vast quantities of data generated by satellites, aircraft and ground-based instruments to monitor and understand global and regional environmental change. We bring together a wide base of Earth observation (EO) data experts and scientists who model the Earth system to address key societal and environmental challenges. This remit is unique in Europe, and fuels improvements in understanding current and future environmental conditions.

Our vision is to be a globally outstanding UK scientific institution dedicated to leading EO research and its applications, encouraging, collaborating with, and building the EO community to serve science and society.

Key NCEO capabilities and expertise

- Our internationally recognised EO science covers a broad range of environmental science fields and has four principal focal points: global and regional **carbon cycles** with their complex linkages, **terrestrial–atmosphere connectivity,** from the biospheres of forests and deltas to the anthropogenic influences of agriculture and urbanisation, **physical energy and water exchanges** in the Earth system, **and observations of global climate change**.
- Our scientists have world-leading expertise in transforming raw data into high-quality EO-based **geophysical products** for cutting-edge science, operational delivery and innovation.
- Through our **innovative algorithms** we produce high-quality long-term datasets which underpin our scientific work and our collaborations with industry and the public sector. These datasets include land biomass, albedo and surface temperatures, fire data, atmospheric products including greenhouse gases and particulates, Earth radiation budget, ocean colour and phytoplankton type.
- Our Earth system research is underpinned by **evaluation** of global Earth system models (ESMs) and component models and consequent impacts on policy.
- We develop **data-assimilation** and **model-data** systems by combining data and models to optimise information outputs. Similar techniques are used by the Met Office and other services to produce daily weather forecasts.
- Our work improves **understanding, prediction and mitigation of natural hazards**.
- We **collaborate** with the UK Space Agency, the European Space Agency (ESA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), meteorological agencies, government departments and businesses nationally and internationally to support the UK's ambitions to be a leading nation in the development and exploitation of EO and meet the environmental challenges that face society.
- Our research supports the UK's **Official Development Assistance (ODA)** commitment in areas such as forestry, agriculture and air quality.
- We provide the scientific rationale and measurement experience for **new satellite missions**, working with EO academics, engineers, industry and space agencies to design next generation EO sensors.
- We host **dedicated infrastructure** for processing and storing data and performing model comparisons.
- Our scientists provide training and access to **remote-sensing instruments** on the ground and on aircraft.
- We support the use of our instruments, data facilities and key tools by the **wider community**.

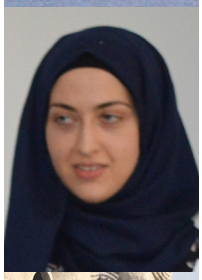
“We are passionate about the importance of our research to society; EO science is increasingly valuable for a range of applications.”

Professor John Remedios, Director of NCEO

Background

- NCEO is a **Natural Environment Research Council (NERC) research centre**, supported by and contributing to UK Research and Innovation (UKRI).
- We bring together over **100 scientists** distributed across leading UK universities and research organisations and led by Professor John Remedios at the University of Leicester.
- Our annual income is over **£10 million**.
- We generate internationally recognised datasets from more than **thirty different satellite instruments**.
- We publish over **150 research papers** every year.
- We **provide advice to government and to industry** through advisory boards, joint initiatives and projects.
- We **collaborate with the international community** through joint research, international reports and our work with space agencies. More than 60% of our papers involve international collaborations.
- Our scientists **contribute to major international environmental science** reports such as the Intergovernmental Panel on Climate Change (IPCC).
- We **work strategically at international level** through organisations such as the Committee on Earth Observation Satellites (CEOS) and the Group on Earth Observations (GEO) and through research partnerships across the globe.

> **"Over recent decades, satellite data has revolutionised our ability to monitor change on our planet. NCEO was set up to ensure that we get maximum value from that data for both the scientific community and society as a whole."**
>
> Professor Duncan Wingham
> Executive Chair, NERC



Key partnerships

Working with NERC and UKRI

As an environmental science centre, NCEO's core science is commissioned by NERC to provide a key element of national capability. NCEO supports NERC to deliver UK environmental science strategy. It works with head office staff at NERC and UKRI to enable UK leadership of and relevant contributions to the research issues of today, to provide horizon scanning, to work at high level with government and industry, to ensure connectivity to international drivers of the best research, and to articulate the research and innovation capabilities of the UK community in the EO sector. NCEO undertakes fundamental research itself, and supports the community to do the same by providing data infrastructure, access to data products and instruments and novel EO techniques such as algorithms and data assimilation.

Working with space agencies

NCEO has the responsibility, on behalf of NERC, for day-to-day interfacing with the UK Space Agency to convey the needs, successes and aspirations of the whole NERC community. NCEO ensures that the NERC community is supported by access to satellite data and that the community can articulate ambitions for new satellite missions. NCEO acts as a champion for environmental and remote sensing science in the arena of space technology and sensor development.

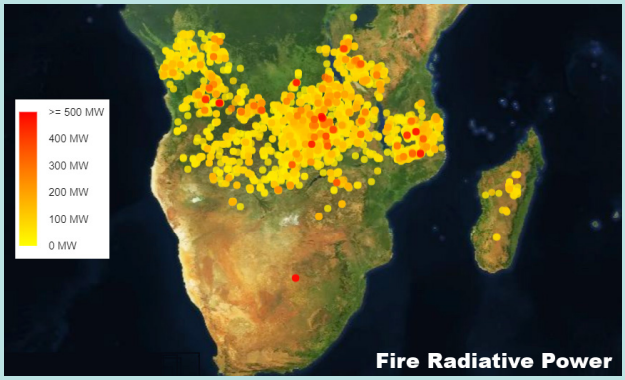
The chief UK research-satellite programme for EO is through UK Space Agency investment in the ESA Earth Observation Explorer Programme (EOEP). UK scientists from NCEO and other NERC centres and universities serve on the Advisory Committee for Earth Observation (ACEO). NCEO researchers are playing leading roles in proposing and implementing ESA missions (CryoSat currently in space, EarthCARE and BIOMASS to come).

The UK has also contributed to operational satellite systems such as those of EUMETSAT and the European Commission's Copernicus Sentinel programme. These are increasingly important for scientific research, including science campaigns and long-term observations. NCEO staff are providing scientific and expert technical support to the Sentinel missions, particularly Sentinel-3 and Sentinel-5P, including access to data through the Centre for Environmental Data Analysis (CEDA).

NCEO is leading the scientific exploitation of data from both research and operational missions through, for example, the Copernicus Climate Change and Atmosphere Monitoring Services, ESA's Climate Change Initiative (CCI), and the Glob series of projects which aim to develop global datasets of different environmental parameters. NCEO scientists are increasingly working in collaboration with EUMETSAT to apply and exploit the best scientific research algorithms.

Monitoring fires from space

NCEO staff are part of the EUMETSAT Land Surface Analysis Satellite Application (LSA SAF) project team and have responsibility for the operational, real-time fire radiative power products delivered by LSA SAF. The success of this work has led to the team specifying the scientific characteristics of a dedicated fire-measurement channel that will be placed on the forthcoming Meteosat Third Generation series of satellites. This will provide enhanced data to support applications, with improved temporal, spatial, spectral and dynamic range characteristics better focused on fire detection and more precisely quantifying fire emissions.



Radiative strength (MW) of fires burning across southern Africa on 9 August 2018 11:45 UTC, as assessed by the SEVIRI fire radiative power (FRP) product which EUMETSAT's LSA SAF produces every fifteen minutes from Meteosat data. Credit: M.Wooster, NCEO-King's College London.

Collaboration, both nationally and internationally in partnership with the UK Space Agency, is a key route to impact. Nationally, NCEO supports joint activities coordinated by the UK Space Agency, such as the Space4Climate group. Internationally, NCEO supports UK Space Agency's work with other space agencies through CEOS.

> **"I look to NCEO not only as a focal point for the community doing first class academic research involving satellite data, but also for excellent examples of innovation and data management."**
>
> Beth Greenaway
> Head of Earth Observation at the UK Space Agency

Earth observation data for Earth system science

We live on a changing planet. As the world evolves and the human population continues to expand, environmental change is being driven at an unprecedented rate. The demands on scientific research to understand these developments and provide solutions to environmental challenges are ever greater.

As humans are an important source of change, we need to learn how to consider our impact on the environment, using science to inform routes to sustainable living and improvements to health and productivity.

EO satellites deliver a unique vantage point on the world, enabling us to identify, review and track regional and global trends consistently, and to trace their influence across the planet. Satellite instruments provide direct evidence of our complex planet's evolving state, enabling us to simultaneously monitor, investigate and understand a host of key environmental markers of physical, chemical and biological processes at large scales. As new and improved research instruments become operational, our ability to observe changes to the environment will continue to grow.

Access to continuous, well-calibrated, long-term data records is increasingly important to understand environmental variations in the Earth system, especially in relation to climate science. These types of data enable scientists to identify, quantify and attribute changes to particular causes: for example, to anthropogenic emissions of greenhouse gases or to large-scale changes in land cover.

At NCEO we are utilising these EO capabilities to address the following areas which pose immediate challenges:

- long-term change
- connected surface–atmosphere processes for carbon
- behaviour of atmospheric gases with respect to land exchange and altered chemical composition
- physical energy and water exchanges

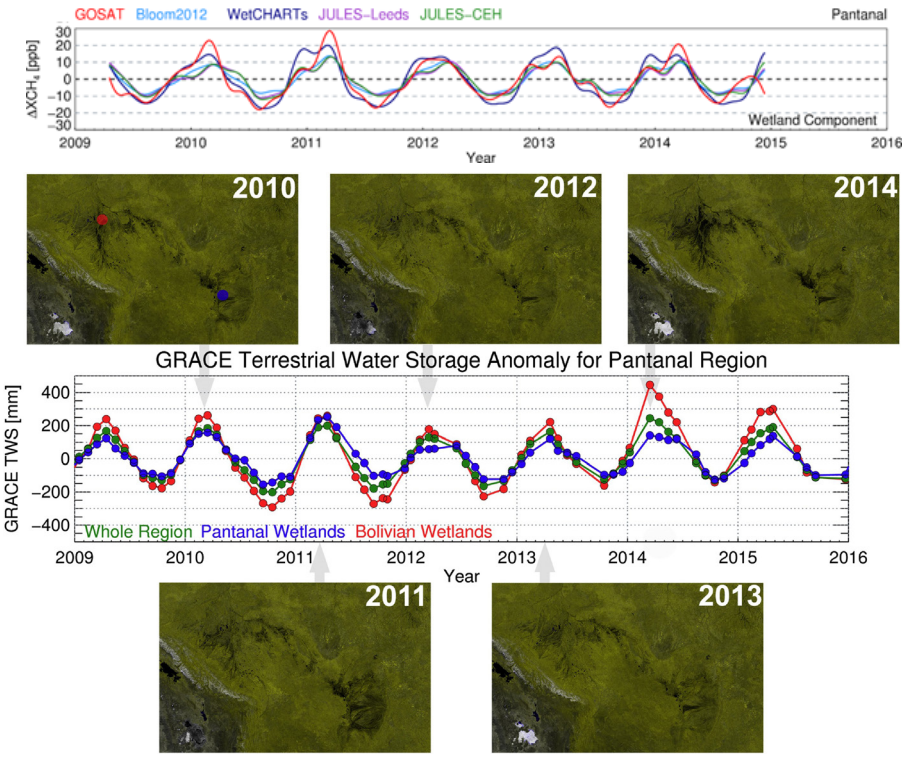
Through EO, we are also improving our understanding of disruptive events and hazards to protect against loss of life and livelihood, and access new knowledge to optimise agriculture, forest development, urban planning, ocean productivity and healthy air. The research techniques developed at NCEO are available for service providers and businesses to build into new information products for aiding society.

Contributing to climate research

NCEO aims to improve the UK's capability for climate prediction over a wide range of climate-relevant timescales, producing datasets and using models to examine changes in the atmosphere, biosphere and hydrosphere, as well as the interactions between them. There are three essential strands to this activity: production of high-quality data with uncertainties; ever-more-incisive evaluation and initialisation of environmental models, and data assimilation.

Generating long-term climate-quality data

NCEO scientists are at the forefront of producing climate datasets, working collaboratively on more than ten essential climate variables specified by the Global Climate Observing System (GCOS). With NERC support, NCEO researchers are developing novel datasets and methods using the new sensors being launched, and in response to the needs of the climate community. NCEO is a major participant in ESA's CCI programme that was set up in response to the UN Framework Convention on Climate Change's (UNFCCC) desire to support policymaking with accurate, quantifiable global evidence. NCEO researchers are producing data products for aerosols, clouds, greenhouse gases, ozone, water vapour, biomass, land surface temperature,



Methane (CH_4) is a critical greenhouse gas. The top panel shows a time series of the observed GOSAT CH_4 anomaly over the Pantanal wetlands compared to model simulations. Other satellite data (MODIS and GRACE in panels below) have shown consistently that river flooding caused by excess rain increases wetland area, leading to more methane production. None of the different modelled CH_4 emission estimates reproduce the large CH_4 anomalies observed by GOSAT in 2010, 2011 or 2014 (red line). This flooding mechanism is not included in land surface models, meaning that they miss this effect and underestimate the amount of methane being produced in these large wetlands. Credit R. Parker, NCEO-University of Leicester.

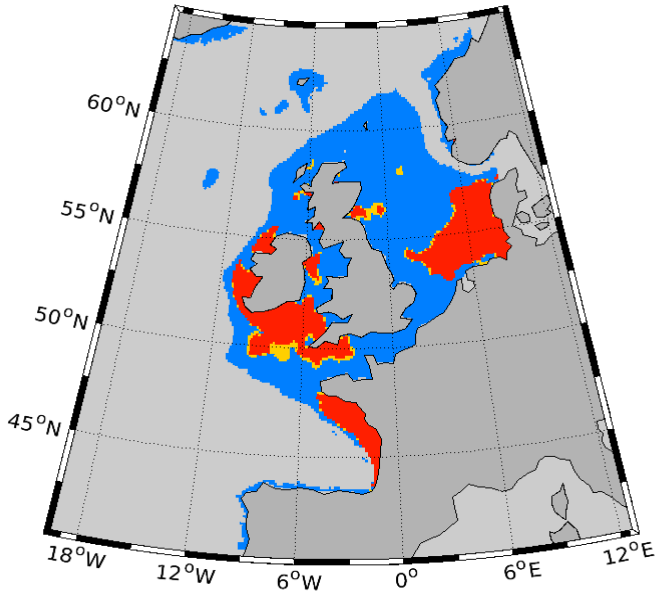
sea surface temperature and ocean colour. NCEO is using mature datasets to investigate key interactions within the Earth system, evaluate models of future climate, and constrain predictions.

Investigating processes in the Earth system

Long-term datasets are important tools to monitor change in the Earth system, and combining them allows scientists to investigate the physical processes at work. For example, NCEO researchers are working to exploit satellite observations of sea surface temperature and sea level in conjunction with in-situ datasets to constrain and understand the variability of heat uptake by the oceans. Sea surface temperature products are a key input for meteorological forecasting models, and crucial for understanding major events such as the warm phase of the El Niño Southern Oscillation that develops in the equatorial Pacific and is associated with extreme weather events. In addition to work with a global focus, our scientists are studying the North Atlantic, through the North Atlantic Climate System Integrated Study (ACSIS) programme, and the shelf seas around the UK and continental Europe. These areas are critical marine resources for the UK and important controllers for our weather and climate.

We are extending these approaches to the terrestrial surface, undertaking fundamental research into land surface temperature, soil moisture and rainfall. This work has potentially wide-reaching impact as severe floods and droughts become more common, coupled with clear trends in urbanisation and intensification of agriculture. Our scientists are leading international efforts to build accurate satellite records of land surface and lake surface temperature.

NCEO is responsible for evaluation of the first UK Earth System Model (UKESM) which is a joint venture between NERC centres and the Met Office. The work involves using EO datasets for the evaluation of both the coupled UKESM and the individual component models.

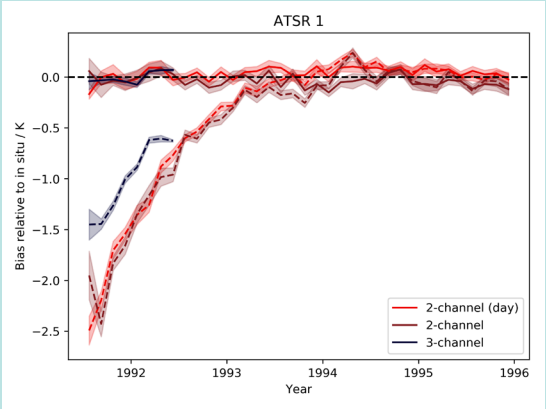


Dissolved oxygen is a critical indicator of marine-ecosystem health: excessively low levels can kill aquatic life. The map shows the bottom areas of North European shelf seas that are vulnerable to oxygen deficiency, with either 1% or 100% confidence (yellow and red areas, respectively). Here, the simulated daily oxygen concentrations were below the threshold value set by the OSPAR commission of 6 mg/l for at least one day in the years 1998–2009. These vulnerable areas were identified by assimilating EO ocean-colour data from ESA's CCI into the ERSEM ecosystem model of the Northeast Atlantic. Credit: S. Ciavatta, NCEO-PML.

In the UK, the coupled model is built on community domain models. NCEO plays a key role within the JULES land surface model community, and is increasingly working with the UKCA atmospheric chemistry and aerosol model, the Medusa marine biogeochemistry model, the ocean physics of the NEMO model and the CICE sea-ice model. NCEO scientists also work with leading offline models such as TOMCAT and GEOS-Chem for atmospheric chemistry, ERSEM for ocean biology, and DALEC for assessment of carbon pools and stocks.

ATSRs – Earth's temperature from space

NCEO is committed to building on the success of the UK's climate-quality EO instruments, the Along-Track Scanning Radiometers (ATSRs). These provide long-term measurements of the Earth radiation budget. The ATSRs are thermal-infrared and optical dual-view instruments of high enough accuracy to meet climate-data demands. NCEO staff have developed world-leading algorithms for surface temperature (including fire) and aerosol/clouds, and are now working on the challenge of extending the climate records through UK expert support to the Copernicus Sentinel-3 mission.



The importance of the dual view of the ATSRs is emphasised in this figure depicting the time period soon after the eruption of Mount Pinatubo in 1991. The figure shows the bias in various sea surface temperature retrievals from ATSR-1 relative to in-situ measurements. Before correction for the stratospheric aerosols from the eruption, the differences are large (dashed lines), particularly in 1991-1992. After correction (solid lines), the bias is very small, indicating successful use of dual-view information (shaded areas in the figure are one standard uncertainty). Credit: O. Embury, NCEO-University of Reading.

Merging observations and models for better science

Observations and computer models give us fundamental information about the Earth. But both sources of information are incomplete: there are always gaps in the measurements – a satellite might pass over a location just once per day, for example – and models are never perfect representations of reality. Data assimilation helps us make the most of our observations and models by combining the information each of them carries in optimised ways to improve representation of and confidence in our knowledge of the state of the Earth at any time and place.

> **"Improved methods of biogeochemistry assimilation are likely to lead to a step-change in our ability to monitor and predict the "green" ocean. This ground-breaking research stems from the close links between NCEO scientists at PML and the Met Office, who work jointly on a number of exciting projects."**
>
> Dr John Siddorn
> Head of the Ocean Forecasting R&D group, Met Office

Data assimilation

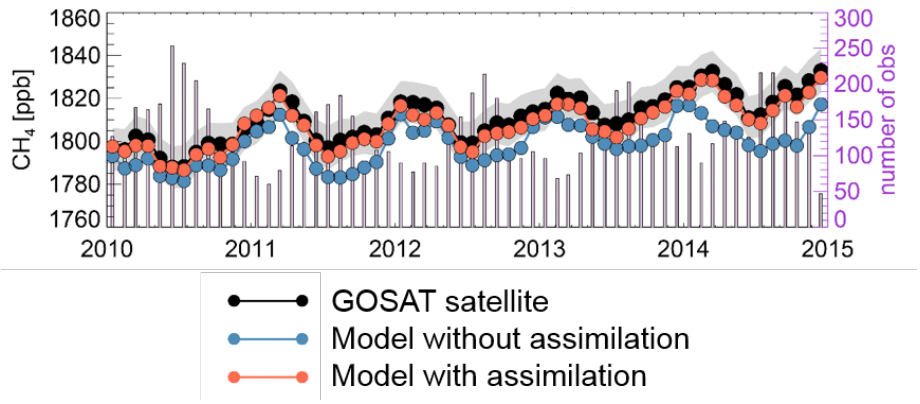
Data assimilation is used to improve forecasts, to create combined datasets of models and observations for the past (so-called reanalyses), to study environmental processes in detail, and to improve models. For example, weather forecasters collect millions of observations and assimilate them into a highly complex numerical model which has over a billion variables every six hours to estimate the best state from which to make the next forecast.

To combine data and models in the best way possible, we have to know how accurate each information source is to judge which to rely on most heavily at a particular location and time. We must take account of the distortions that can affect our observations. These can range from noise in the electronics of an instrument to a satellite's orbital characteristics. The accuracy of our model forecast depends on both the accuracy of the model itself – there may be issues due to missing physics, for example – and the accuracy of the data that drive the model. Knowing the accuracy of both we can combine observations of multiple geophysical variables with model predictions to get the best possible description of what is going on.

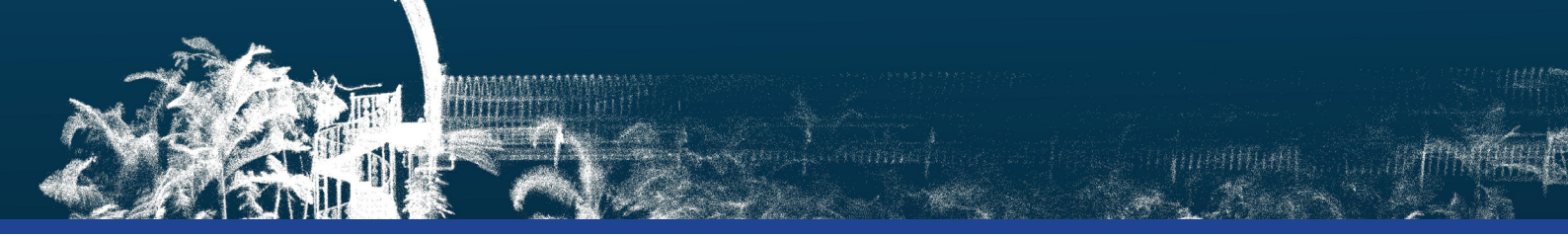
At NCEO we develop new cutting-edge data-assimilation techniques and strengthen scientific capacity in the UK for implementing the next generation of data-assimilation algorithms. We are working on accessible data assimilation for UK community models. Data assimilation helps us identify how to improve models of the Earth system by identifying mismatches between the data and the model predictions. Key challenges include how to treat uncertainty in the data and models, how to couple together systems with different scales in both time and space, how to treat highly non-linear systems such as clouds or marine biogeochemistry, and how to assess the impact of novel observing systems.

NCEO staff with data-assimilation expertise work closely with others involved in satellite retrievals and modelling across a wide range of data-model problems. We work closely with researchers at operational centres including the Met Office and the European Centre for Medium-range Weather Forecasts (ECMWF) to improve the approximations in their data-assimilation systems for future weather and climate modelling.

Inferring methane emissions from tropical South America



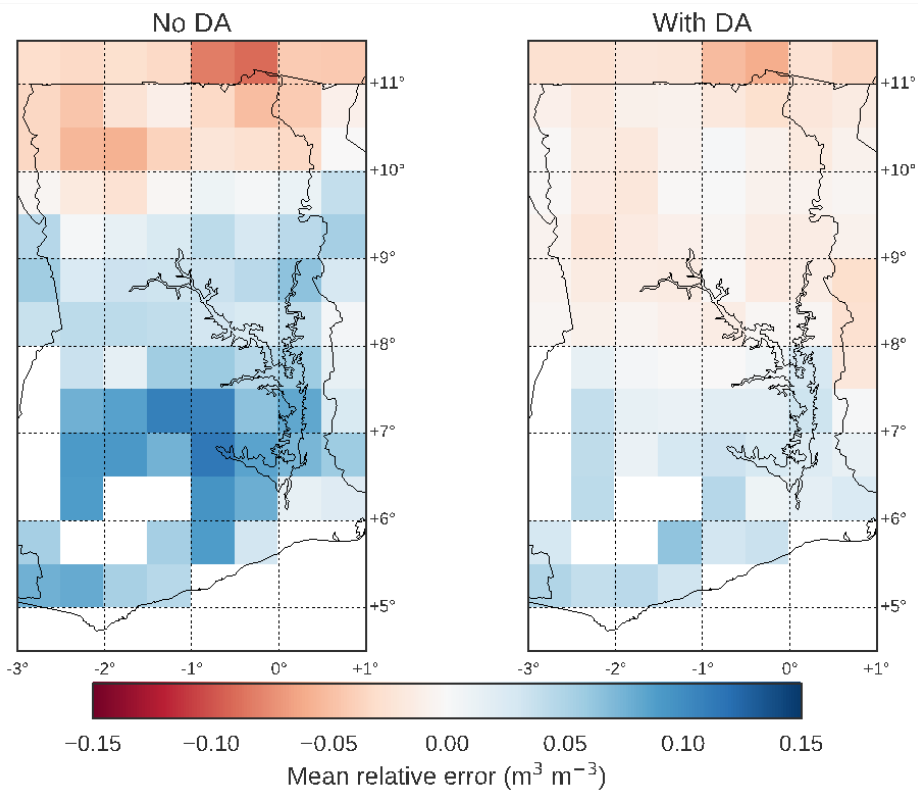
Wetland emissions account for 20–40% of total global CH_4 emissions and are thought to dominate the inter-annual variability. The majority of natural wetlands are found in tropical and sub-tropical regions. The figure compares monthly regional mean values of CH_4 over tropical South America in 2010–2014 for satellite-observed CH_4 (black circles), the TOMCAT model before assimilation of observations (blue circles) and the TOMCAT model after assimilation (red circles). The pink bars represent the number of observations assimilated in each month. The primary adjustment is to the input emissions in the Amazon wetland regions and this demonstrates the improvements that the satellite observations bring to the model. Credit: C. Wilson, NCEO-University of Leeds.



Data assimilation for soil moisture in Ghana

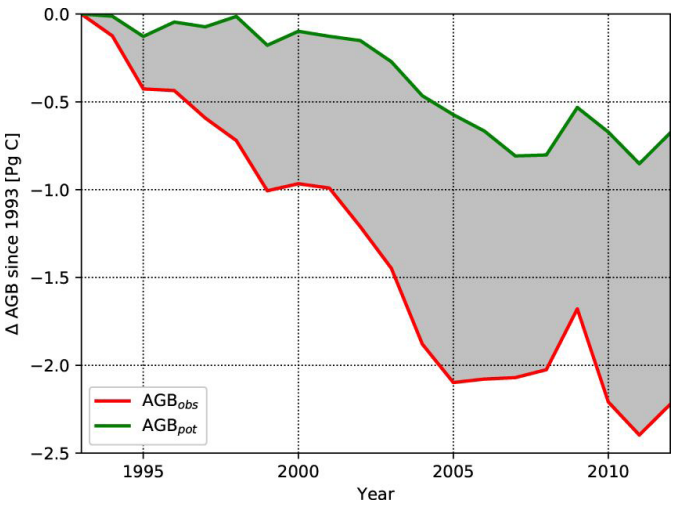
Ghana is a country with a large population where it is crucial, for agricultural productivity, to understand the soil moisture dynamics. NCEO scientists assimilated ESA CCI soil moisture satellite observations into the JULES land surface model using a scheme called 4DVar to accurately estimate soil parameters across Ghana. The accuracy of the new parameter dataset was assessed using hindcast experiments, which showed a significant improvement in model skill (see figure).

Our experiments also showed that the data-assimilation scheme was not able to remove all of the biases associated with the model-driving data, especially the onset of rains, pointing to the need for improved precipitation data. The need for such data will be fed into requirements for next-generation EO systems for soil moisture and precipitation.



Mean relative error in volumetric soil moisture predicted by JULES in a hindcast experiment for five years for Ghana. Without data assimilation (left panel) and assimilating ESA CCI data (right panel). Credit: E. Pinnington, T. Quaife and E. Black, NCEO-University of Reading.

Data assimilation for biomass variation and forest regrowth



Graph shows the difference between observed biomass (AGB_{obs} in red) and the potential for these disturbed regions to store biomass given the local climate (AGB_{pot} in green). Credit: J.-F. Exbrayat, M. Williams; NCEO-University of Edinburgh, Y. Y. Liu, NUIST.

A study by NCEO scientists indicates that land-use change has eroded above-ground biomass (AGB) stocks in the Amazon basin in the period 1993–2012 (AGB_{obs} in red in figure). They also show that climate change is reducing the forest's capacity to regrow (AGB_{pot} in green), highlighting new challenges for long-term reforestation plans. NCEO scientists used machine learning, a form of data assimilation, to derive these outputs. Based on maps of intact forest landscapes (IFL) in the Amazon, they trained an algorithm to predict variation of biomass across these undisturbed areas as a function of climate. Once trained, the algorithm can be used to estimate annual climate-driven potential biomass (AGB_{pot}) in previously disturbed regions (i.e. outside IFLs). The difference between observations of biomass (AGB_{obs}) in these disturbed regions, and the potential for these regions to store biomass given local climate (AGB_{pot}), is here plotted over time. The value of data assimilation in this study is in providing a means to infer alternate possible states for the Amazon, which informs better estimates of the effects of human disturbance in the Amazon over time.

Carbon: atmosphere, vegetation and oceans

The global carbon cycle and the impact of human activity play a central role in the Earth system. The concentration of atmospheric carbon dioxide due to anthropogenic sources is steadily increasing, which is changing the radiative balance of the Earth. Fortunately, our planet's biosphere and oceans remove a significant fraction of carbon dioxide from the atmosphere. We need to monitor these carbon reservoirs to understand their strength and vitality. At NCEO we are investigating land-based resources, in particular the storage and dynamics of carbon in forests, and the marine processes related to the biological carbon pump as well as the carbon exchanges between the land, oceans and atmosphere. We are monitoring flows of both atmospheric carbon dioxide and methane, and the roles played by fire, open-ocean and shelf-sea biology, water-vegetation interactions and soil properties.

Greenhouse gases: concentrations and fluxes

Satellite measurements of atmospheric carbon dioxide provide a unique top-down view of the integrated exchange of carbon between the atmosphere and the surface. NCEO is part of international efforts to obtain accurate measurements of greenhouse gas concentrations from space, producing datasets for the research community and beyond: for example, for the Copernicus Climate Change Service. We are using the state-of-the art data-assimilation methods developed at NCEO to derive information on carbon sources and sinks. To gain insight into the processes that govern the exchanges between the surface and the atmosphere, our researchers are generating additional EO datasets, such as carbon monoxide and chlorophyll fluorescence.

NCEO researchers are supporting the design of the Copernicus CO_2 service in preparation for the European response to complying with the Paris Agreement. We are actively engaged with the development of ESA missions; we are partners in the MicroCarb satellite mission due to launch in 2021; and we are building laboratory and aircraft demonstrators to bring mission concepts to maturity.

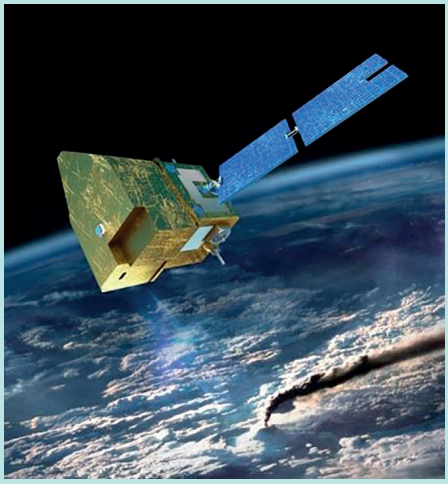
Ocean carbon: from observations to global biological reanalyses

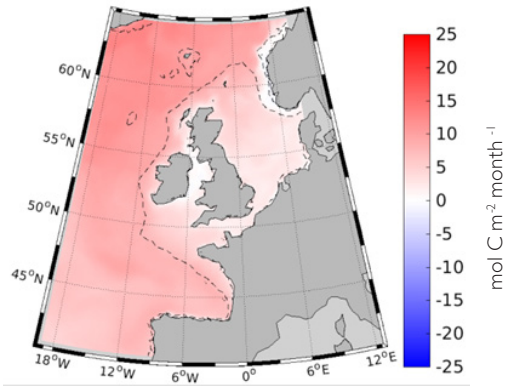
The global ocean has absorbed 30% of anthropogenic emissions of carbon dioxide to date. Whilst the rate of carbon uptake is relatively well constrained, the processes responsible for it are not so well understood. One of the processes involved is the biological carbon pump (BCP), whereby some organic carbon is produced by phytoplankton sinks and can be sequestered in the ocean over climatically relevant timescales.

NCEO research aims to improve our understanding of the magnitude and efficiency of the BCP in the global ocean, and its uptake of atmospheric carbon. We are using satellite ocean-colour datasets with in-situ measurements of ocean biogeochemistry from Argo floats to deliver and exploit novel and improved data products of carbon pools and fluxes. These products are then used to produce and assess reanalyses of carbon fluxes, using the ocean component of the UKESM model and state-of-the-art data-assimilation methods.

MicroCarb

MicroCarb will be the first dedicated European carbon dioxide mission jointly implemented by the French space agency, Centre National d'Études Spatiales (CNES), and the UK Space Agency. MicroCarb will accurately measure carbon dioxide from a microsatellite platform and features a novel city mode, which allows it to map carbon dioxide within an urban area. NCEO researchers are members of the science team working on retrieval methods, data validation and science exploitation.

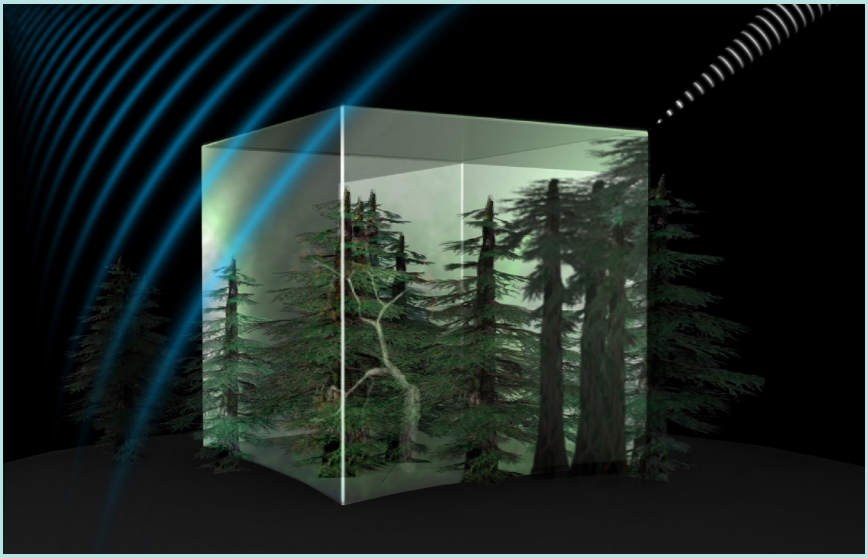




The Northeast Atlantic is a net sink of atmospheric carbon dioxide into the ocean, as shown by the fluxes mapped in this figure. The units are moles of carbon per square metre per month; positive values indicate carbon dioxide sinking into the ocean, negative values indicate carbon dioxide being released into the atmosphere. These estimates were obtained in a multi-annual reanalysis that assimilated, for the first time, phytoplankton functional type (PFT) data from ocean colour into the ERSEM marine-ecosystem model. Assimilation of PFT improved the simulation of the observed plankton community structure and CO_2 partial pressure in the water, arguably producing a more accurate picture of the simulated ocean biological fluxes of carbon dioxide and its uptake from the atmosphere. Credit: S. Ciavatta (NCEO-PML).

BIOMASS

The BIOMASS mission will provide unprecedented global measurements of biomass and tree structure in the Earth's forests, at a scale of 200 metres, to support forest management and inform climate treaties and carbon trading. NCEO researchers are working with ESA to guide the project science. We are also measuring tropical forest plots using terrestrial laser scanning techniques to validate data for the mission, due to launch in 2023. Credit: ESA.

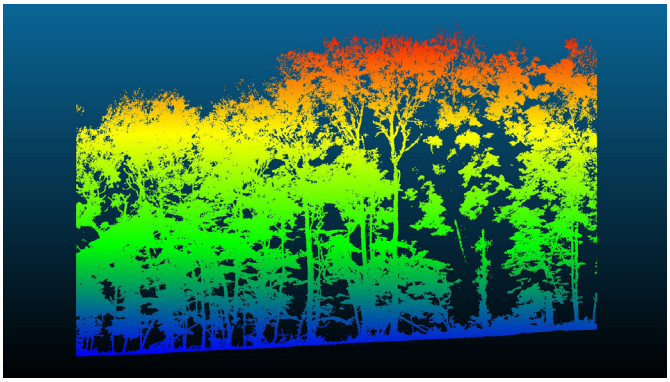


Counting carbon in forests

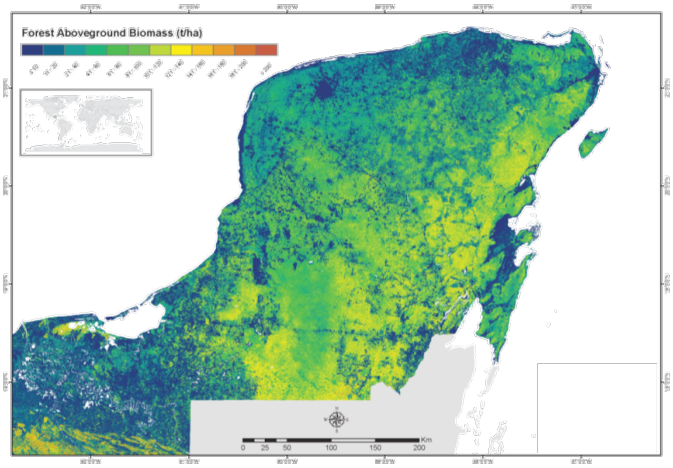
Earth observations have an increasingly important role to play in support of forest management. The data for the Essential Climate Variables that relate to forest stocks are used by the Met Office and ECMWF for climate modelling, and also by the UN, national mapping agencies, and commercial companies providing services for the carbon market.

Whilst cloud frequently obstructs satellite views of tropical forests, relatively new radar instruments can 'see through' mist and cloud, giving scientists unrestricted views of forest cover, tree carbon and changes due to forest logging and afforestation. NCEO researchers are working with international partners such as ESA to map global forest biomass stocks from optical and radar satellites.

NCEO work monitoring the impacts of fire, deforestation and degradation has been critical to plans for a new purpose-built satellite to measure the carbon stocks contained in the Earth's forests with unprecedented sensitivity. Through a proposal led by Professor Shaun Quegan (NCEO-University of Sheffield), BIOMASS has been selected as the seventh ESA Earth Explorer satellite.



Banner at top of page. Credit: ESA.



Above-ground biomass maps at 25 m spatial resolution for the reference year 2010 for the Yucatan peninsula produced by the University of Leicester team within the GlobBiomass project. Credit: P. Rodriguez-Veiga and H. Balzter, NCEO-University of Leicester.

> **"We can turn highly-accurate laser measurements, comprising millions of 3D laser points, into estimates of tree size, shape and mass."**
>
> Professor Mat Disney
> NCEO-UCL

A profile of terrestrial laser scan data, coloured by height, from Wytham Woods near Oxford, UK. The NCEO-UCL team, in conjunction with the NPL and the University of Oxford, have scanned 6 ha of this woodland, winter and summer. This is the largest snapshot of a forest that has ever been captured like this, and the data are being used to test new satellite-derived estimates of forest properties. Credit: M. Disney, NCEO-UCL and K. Calders, UGhent and NPL.

Understanding large-scale biosphere–atmosphere exchange

The atmosphere is central to Earth system dynamics, integrating varying surface emissions spatially and temporally on time scales from weeks to years. Consequent disturbances and trends in atmospheric constituents, such as aerosols and greenhouse gases, affect weather, climate and air quality, and result in feedbacks to surface processes such as primary productivity of vegetation.

NCEO scientists offer the community new and improved EO datasets that provide insights into the couplings between the atmosphere and biosphere at large scales across Earth domains. We collaborate internationally to obtain accurate measurements of carbon dioxide, methane, ozone, ammonia and a range of organic compounds from visible, shortwave/near-infrared (SWIR/NIR) and thermal-infrared (TIR) instruments. These data will, for example, help inform decision-making on emission reductions to mitigate the worst impacts of climate change. They are also utilised to improve component models describing biosphere responses to climate change within the UKESM.

NCEO scientists are using these EO datasets alongside observations from ground and aircraft to explore the manifold links between surface fluxes that drive the system. This work includes the interactions of mingled urban and rural emissions and their large-scale consequences for atmospheric composition variations and trends. This work enables other communities to explore links between air pollution, human health, food security and ecology. It also provides greater insights into changes in land surface characteristics.

EO datasets and derived downstream data products developed within NCEO continue to contribute directly to international assessments such as the World Meteorological Organisation (WMO) and United Nations Environment Programme (UNEP) Scientific Assessments of Ozone Depletion, Tropospheric Ozone Assessment Report, and ESA CCI. We also contribute to pan-Europe activities such as the Copernicus Atmospheric Monitoring Service (CAMS).

Observed variations of atmospheric composition

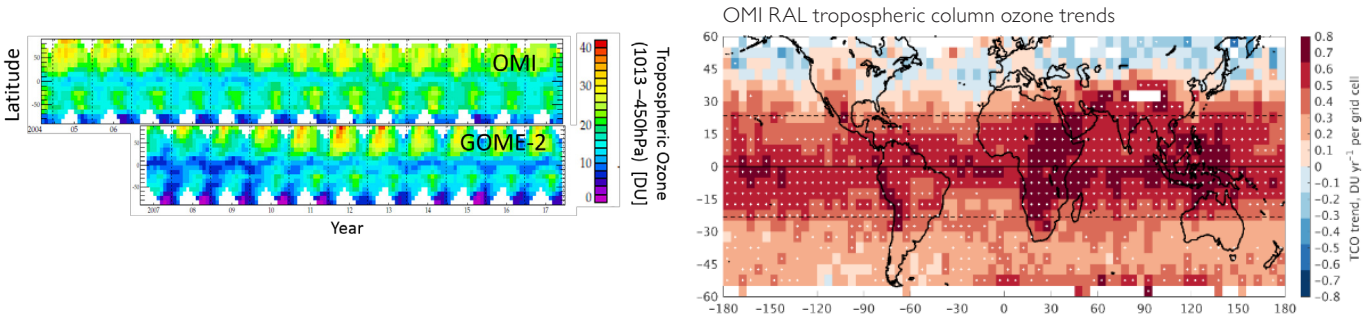
Non-CO_2 greenhouse gases, such as methane and tropospheric ozone, play a significant role in radiative forcing and the oxidising capacity of the global troposphere. Elevated concentrations of particulate matter and some reactive trace gases can impact human health.

NCEO uses atmospheric trace gas and land surface EO to improve understanding of observed non-CO_2 greenhouse gas variations in terms of physical, chemical and biological drivers. We reconcile these 'top-down' emission estimates with 'bottom-up' inventories. NCEO develops and interprets long-term, self-consistent records that allow us to study changes in the magnitude and distribution of emissions.

> **"Earth observations underpin the Met Office's operational weather forecasting services and are vital for our weather and climate research. NCEO provides expertise and a strong national capability in Earth observations which is of great benefit for organisations such as the Met Office and many others in the UK that are working to better understand and protect our natural environment."**
>
> Professor Stephen Belcher
> Met Office Chief Scientist

Exploiting long-term records of tropospheric ozone has enabled NCEO scientists to understand regional variations of ozone and to link them with changes reported by the surface ozone data. We continue to benefit from our collaboration with the Japanese GOSAT team to understand regional inter-annual variations of methane column, particularly during the 2015/2016 El Niño event.

Looking to the high spatial resolution observations provided by the TROPOspheric Monitoring Instrument (TROPOMI) and upcoming geostationary sensors such as TEMPO (Tropospheric Emissions: Monitoring of Pollution), we are investigating how urbanisation trends will impact the nature of regional emissions within the context of natural drivers. This builds on ongoing work within NCEO that has used statistical approaches to explore city-scale distributions of reactive gases, such as formaldehyde, over India.



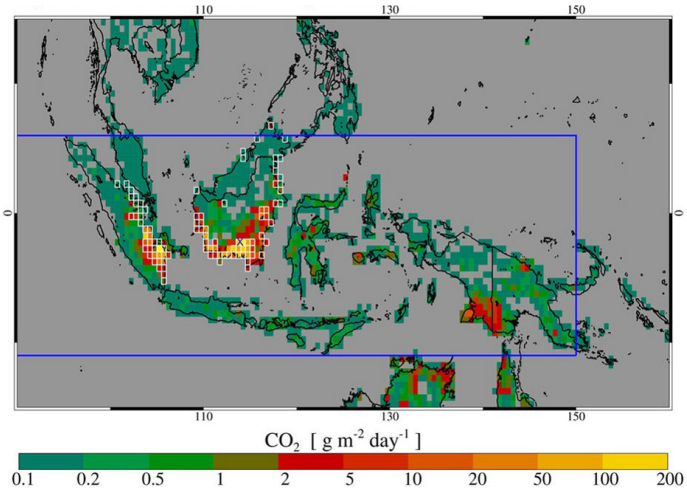
Tropospheric ozone is a significant greenhouse gas and at surface level affects air quality and plant health. It is therefore important to monitor its changing global distribution. This is possible from satellites, though challenging because there is ~10 times more ozone in the stratosphere above. The left figure shows consistent seasonal and year-to-year variations of tropospheric ozone observed from two satellites. The right figure shows a significant underlying increase at low latitudes in the decade 2005-15 derived from OMI observations. Credit: NCEO-RAL/TOAR-Climate.

Landscape fires and their Earth system impacts

Landscape fire is our planet's greatest terrestrial disturbance agent. On average it burns across an area approaching that of the EU's land area every year, affecting almost every vegetated biome worldwide. Fire's influence extends to the atmosphere, where it is a major source of many trace gases and aerosols and a dominant source of species such as carbon monoxide and black carbon.

Compared to most other sources of atmospheric emissions, landscape fires also show extreme and often unpredictable spatial and temporal variability, including regional order-of-magnitude inter-annual variations. Because of this extensive nature, landscape fire plays a key role in many Earth system processes, from the natural carbon cycle to anthropogenically driven land use and land cover change. Satellite remote sensing is key to its quantification and investigation because of the extreme spatial and temporal variability involved.

NCEO works to develop improved methods for quantifying the extent and type of area affected, the composition of the smoke released, and the rate at which the fires release radiated energy, combing these to study local to global land and atmospheric impacts of fire events. Our research in this field of Earth system science is cutting edge: NCEO scientists are the world-leading experts on fire radiative power.



Daily mean CO_2 emissions from peat and vegetation fires burning across maritime Southeast Asia in September and October 2015, presented in 0.5° × 0.5° grid cells (figure from Huijnen, V. *et al., Sci. Rep.* 6, 2016). In 2015, widespread forest and peatland fires over large parts of maritime Southeast Asia, most notably Indonesia, released large amounts of terrestrially stored carbon into the atmosphere, primarily in the form of CO_2, CO and CH_4. Although seasonal fires are a frequent occurrence in the human-modified landscapes of Indonesia, the extent of the 2015 fires was greatly inflated by an extended drought period associated with a strong El Niño. Estimates of carbon emissions were made using satellite observations of the fire's radiative power output and atmospheric CO concentrations, and processed using the CAMS modelling and assimilation framework combined with measurements made in Kalimantan, including some by NCEO scientists.

Professor Martin Wooster (NCEO-King's College London) deploying ground-based instrumentation and a drone to examine fire and haze properties – Indonesia 2015. Credit: NCEO.

Diagnosing physical energy and water exchanges

Energy flows between the surface, atmosphere and space are fundamental in establishing the circulation patterns that drive weather and climate. Our ability to quantify these flows has advanced through the combination of satellite and in-situ observations; however, significant discrepancies still exist, even at the global scale. Climate models show marked variations in the atmospheric and oceanic energy and water transports that create this global picture. These variations correspond to major differences in regional radiative exchanges, leading to gross biases in their depiction of the water cycle. Understanding how clouds, precipitation and land surface influence the circulation, and improving the link with water, is a current World Climate Research Programme (WCRP) Grand Challenge. NCEO researchers are playing an active role in meeting this challenge.

> **“NCEO provides the platform for creative, inter-disciplinary work, coupling expertise to tackle current ‘big science’ questions within the Earth system.”**
>
> Dr Helen Brindley
> NCEO-Imperial College London

Clouds, aerosols and precipitation

One of the largest sources of uncertainty in predicting future climate is related to the interplay between clouds and aerosols – tiny liquid droplets or particulates in the atmosphere that act as condensation nuclei for cloud-formation. As well as directly reflecting and absorbing radiation, aerosols can also affect the reflectivity and lifetime of clouds. Indeed, aerosol–cloud interactions are implicitly linked to cloud-precipitation lifecycles via a number of complex microphysical processes. Climate models struggle to match historical precipitation records at the regional scale and show large variability in their future predictions.

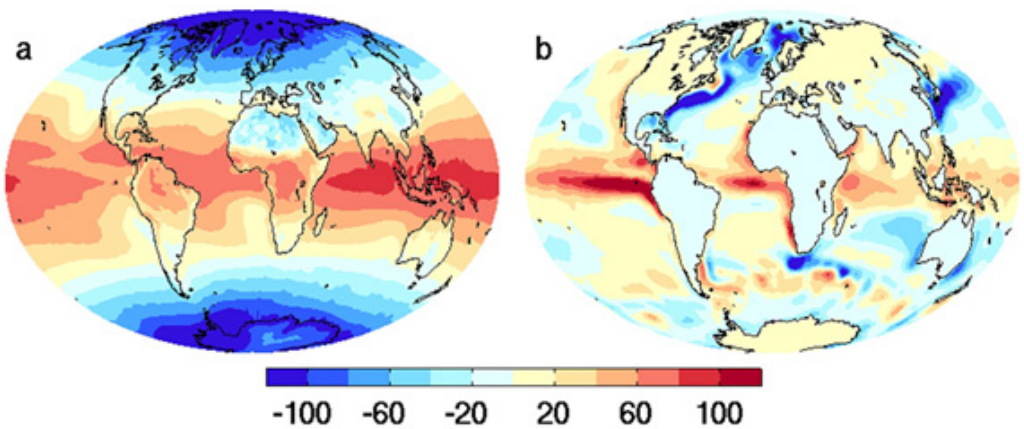
NCEO researchers are using the emerging ESA CCI records to evaluate the strength of observed aerosol–cloud interactions. We are playing a leading role in deriving state-of-the-art precipitation records from the Global Precipitation Measurement (GPM) mission and in assessing the potential of the future EarthCARE mission to improve our understanding of key microphysical processes. We will combine these insights with work on the large-scale coupling of the energy–water cycle and measurements from instruments such as the Geostationary Earth Radiation Budget (GERB) experiment, with the ultimate aim of better constraining predictions of future climate.

Diagnosing physical energy and water exchanges

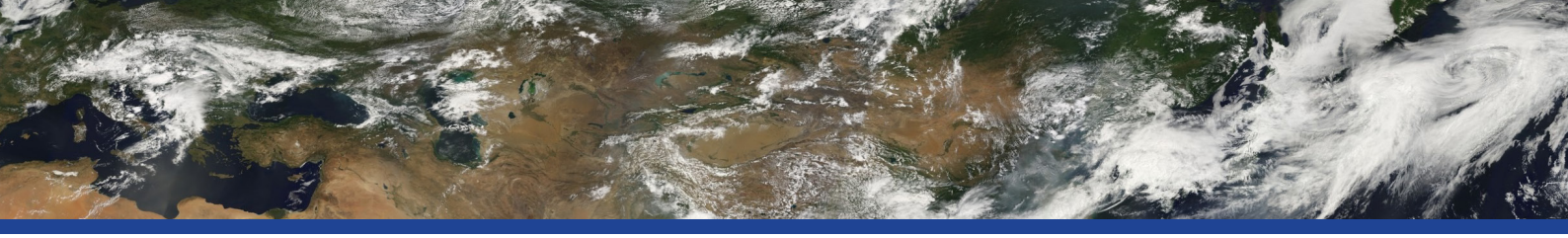
Energy is accumulating in the climate system at around 0.7 Watts per square metre, due primarily to the inexorable increases in greenhouse gas concentrations caused by human activities. Where this energy accumulates in the ocean determines the rate of surface temperature rise as well as how atmospheric circulations and precipitation patterns evolve over time.

NCEO researchers have been able to reconstruct the energy balance at the top of Earth’s atmosphere: the absorbed fraction of sunlight arriving and the emitted thermal-infrared radiative energy leaving to space. In addition, by combining the satellite records with novel reanalyses of the atmosphere and its flows of energy, we have developed a new realisation of the critical energy flux at the planetary surface.

New satellite-based products can diagnose systematic biases in climate-model simulations, particularly over the turbid and climatologically crucial Southern Ocean, the North Atlantic Ocean conveyor and the region straddling the hemispheres. Looking forward, we will apply new variational inverse methods to Earth radiation budget measurements from existing missions as well as future initiatives such as EarthCARE. The resulting realisation of energetic flux transports will provide a key tool for exploring the role of energy and water cycles in driving and modulating current climate change.



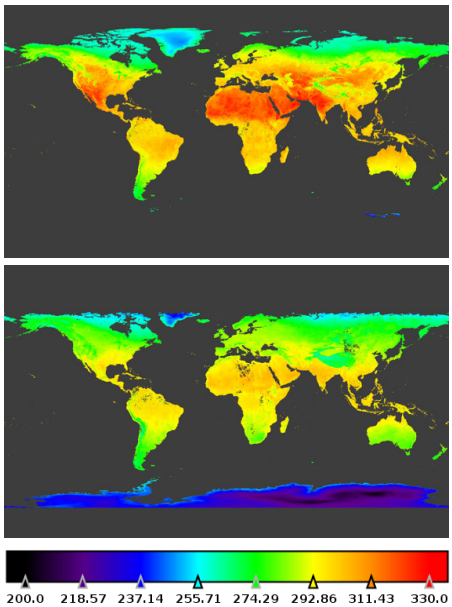
Energy fluxes are critical for weather and climate change forecasting. The figure shows mean downward energy flux at the top of atmosphere (a) and at the surface (b) over the period 1985–2015 in W m^{-2}. Credit: C. Liu and R. Allan, NCEO-University of Reading.



Surface radiation and moisture

Moisture in the soil influences regional weather and climate via exchanges of heat and water with the atmosphere. When the land is wet, energy from solar radiation is primarily used to evaporate moisture, either directly from the soil surface or via transpiring plants. During drier periods, moisture in the soil may not be sufficient to maintain high rates of evaporation, and the energy switches towards extra heating of the surface and atmosphere, raising temperatures. Knowledge of the moisture state of the soil in regional terms is limited, specifically how moisture affects the balance between heating and moistening of the atmosphere. This is partly because landscapes are so diverse in terms of vegetation, land management and soil type, and partly due to a lack of accurate estimates of surface–atmosphere exchanges of heat and moisture.

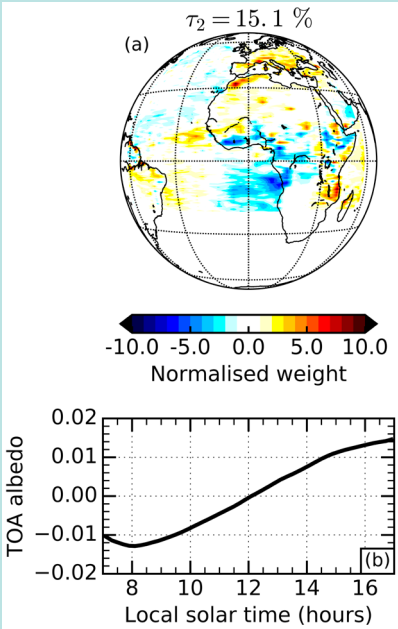
Within NCEO, we are creating high-quality long-term global datasets of land surface temperature, advancing research on how soil moisture affects the atmosphere. We are using these data to see how rapidly different landscapes warm up during dry spells. We can compare these measurements with simulations of the land surface within weather and climate models. This novel methodology facilitates the identifying of unphysical aspects of models, provides a focus for new model developments and, ultimately, reduces uncertainty in weather forecasts and climate projections.



Daytime (top) and night-time (bottom) land surface temperature from Sentinel-3A for May 2018. Developments initiated in NCEO, such as full uncertainty characterisation and enhanced probabilistic cloud clearing, have led to improvements in the operational land surface temperature data from Sentinel-3A and ESA GlobTemperature and CCI datasets. Credit: D. Ghent, NCEO-University of Leicester.

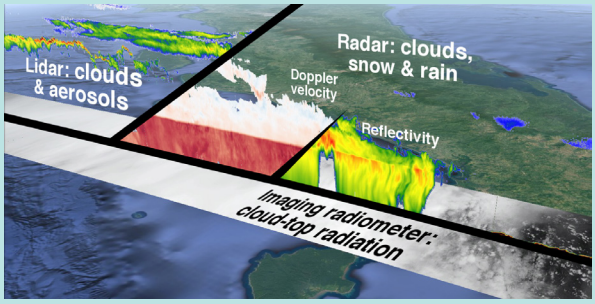
The Geostationary Earth Radiation Budget (GERB) experiment

The GERB sensor is the first instrument designed to measure Earth radiation budget parameters from a geostationary satellite. It provides measurements of reflected shortwave and outgoing longwave radiation over a disc of the Earth every fifteen minutes. Recent work by NCEO staff has seen the development of a new high-resolution product, designed specifically for climate-model evaluation. The data have already been used to assess patterns of variability in the Met Office Unified Model, providing insight into the realism of rapid cloud-radiation interactions. Dr Helen Brindley (NCEO-Imperial College London) is the GERB principal investigator.



Variability in monthly mean reflected shortwave energy as observed by GERB (a). The pattern associated with the development and decay of marine stratocumulus and deep convection through the day (b). Credit: J. Gristey, NCEO-University of Reading.

EarthCARE



Interactions within the atmosphere between clouds, precipitation, aerosols and radiation are critical to global energy and water cycles. The ground-breaking Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) mission is being developed as a joint venture between ESA and the Japan Aerospace Exploration Agency (JAXA) with the goal of observing and characterising these interactions. EarthCARE will use synergistic measurements to observe the vertical distribution of clouds, rain and snow, and aerosols through the atmosphere, in conjunction with top-of-atmosphere radiative fluxes. NCEO scientists are working with ESA to prepare and evaluate retrieval algorithms which will provide official EarthCARE data products after launch.

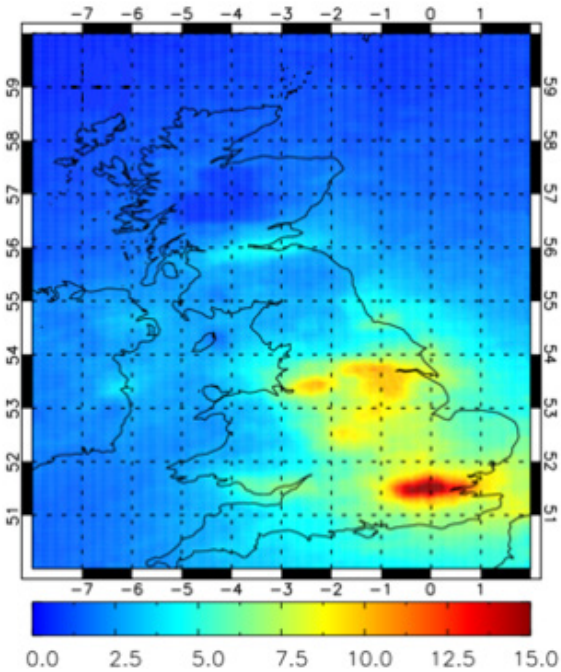
Representation of EarthCARE measurements. Credit: Shannon Mason, NCEO-University of Reading (data supplied by L. Tian and D. Hlavka).

Monitoring and characterising hazards

Each year hundreds of millions of people around the world are affected by severe environmental hazards and natural disasters. These include weather-related extreme events such as cyclones, droughts, floods and poor air quality, as well as earthquakes, tsunamis and volcanoes.

According to the IPCC Fifth Assessment Report, climate change is already affecting the nature of natural weather-related hazards, leading to more frequent, extreme events, and will likely exacerbate natural hazards in the coming decades. Economic losses regularly exceed £65 billion annually and are projected to double by 2030.

Mapping large-scale air quality



Satellite observations of pollutants provide a country-scale picture of changes in air quality. Here, a high-resolution map of OM tropospheric column nitrogen dioxide over the UK (10^{15} molecules/cm^2) shows improvements in national air quality (2005–2015). Credit: R. Pope, NCEO-University of Leeds.

Urban growth can create its own problems, including an increased risk of air pollution. By 2050, seventy per cent of the world's population is expected to live in urban areas. The impact on air quality depends not only on direct emissions of pollutants but also on how these emissions interact with atmospheric circulation and chemistry.

Improvements in EO systems for observing atmospheric composition mean that regional air quality can now be observed from space. NCEO staff, working in collaboration with the UK Met Office, have used measurements of the air pollutant nitrogen dioxide to examine how large-scale weather systems affect air quality and give insight as to how model improvements can be used to improve daily forecasts for the UK. NCEO scientists are working with regional and local organisations, particularly in Asia, to improve near real-time observations of large-scale air-quality events for warning systems and scientific assessment of their magnitude, evolution and frequency.

New data from Sentinel-5P and, later, from geostationary orbit will allow NCEO scientists to examine pollutant emissions, pollution transport and chemistry at finer scales and to deliver better characterisation of pollution variability as observed from space.

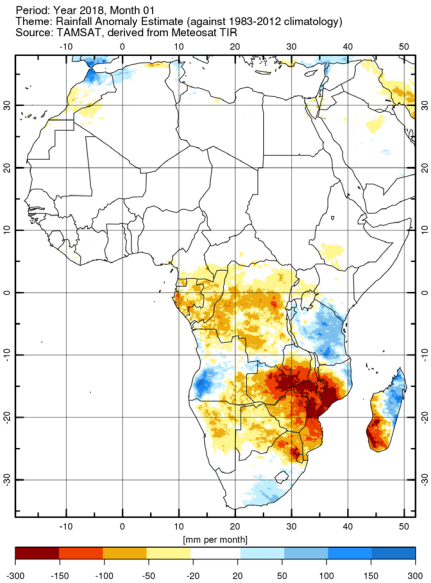
Volcanic impacts on the atmosphere

NCEO scientists operate a range of sophisticated algorithms for determining atmospheric gas and particle concentrations globally. These have been implemented specifically for monitoring volcanoes, forming part of a regular volcano watch, and can be deployed when required for urgent events or events of special interest. Our staff support the use of thermal-infrared spectral data (IASI) to monitor sulphur dioxide and ash in near-real time. We also analyse the use of dual-view and geostationary observations to estimate ash location and height. With the advances in meteorological satellite capabilities, the EO community will be able to provide much more timely information on volcanic eruptions for aviation.

Smoke rises from Mt. Etna, Italy photographed from the International Space Station by Tim Peake. NCEO scientists work to understand the effects of volcanic activity and enable responses to these. Credit: Tim Peake, ESA/NASA.

Drought

Drought is a hugely significant but variable hazard to food security. New datasets for precipitation, soil moisture and land surface temperature are already proving to be scientifically valuable in constraining changes in surface condition during drying events. NCEO staff are using improved observations and model-data techniques to develop drought information in, for example, the University of Reading Tropical Applications of Meteorology using SATellite data and ground-based observations (TAMSAT) system operated with the National Centre for Atmospheric Science (NCAS) and NCEO.



The figure above from the University of Reading TAMSAT (https://www.tamsat.org.uk/) team working within NCAS and NCEO highlights a very large negative rainfall anomaly experienced in Zambia in January 2018. TAMSAT data are at the heart of a new government insurance scheme in Zambia which protects small-scale farmers from highly variable and damaging weather. Those affected by the severe dry spell benefited from more than $2 million in payouts from this scheme in 2017 and 2018. In addition to NERC, this investigation was supported by the European Commission's Monitoring of Agricultural Resources (MARS) unit at the Joint Research Centre (JRC). Credit: TAMSAT, derived from Meteosat TIR.

Monitoring harmful algal blooms

Harmful blooms of algae in the seas around the UK and Europe can cause significant economic losses to the aquaculture industry and present a threat to human health. The Scottish Executive estimated that 2.2 million salmon were killed by algal blooms between 1999 and 2002. Research algorithms developed by Plymouth Marine Laboratory (PML) and NCEO staff and ocean-colour images produced in near-real time by the NERC Earth Observation and Data Acquisition and Analysis Service (NEODAAS) contribute to research efforts into these blooms. This scientific supply chain is being explored through innovation initiatives in aquaculture as part of food security research.

Impact of wildfire

Wildfires have significant impacts on the economy and human health. Economic costs range from direct costs associated with firefighting to loss of income from the land following wildfire incidents, and damage to property, local businesses and communities. Wildfires create safety issues for those who live and work in isolated areas, as well as endangering people who use and enjoy the countryside. Wildfire also has the potential to affect the lives of people well outside the immediate area of any incident. Smoke can travel many miles on prevailing winds, affecting air quality and visibility in areas far away. This can have public health implications, especially for people with respiratory problems, as well as causing disruption to traffic.

Rapid response

NCEO has a growing capability for near real-time (NRT) data, with bespoke offerings for volcanic eruption monitoring, tropospheric ozone, and ocean parameters such as colour. These are provided through a number of facilities, including NEODAAS. NCEO algorithms are also used in a number of NRT data streams operated by agencies, such as the EUMETSAT-supported LSA SAF. NCEO staff contribute to the scientific characterisation of significant events perturbing the Earth system, such as large-scale fires and air-quality episodes. Increasingly, NCEO is joining efforts aiming to engender rapid scientific response and provide appropriate information for wider decision-making.

The Saddleworth Moor fire (June 2018) imaged by Landsat 8. NCEO scientists used satellite images to monitor the effects of the fire. Credit: NCEO/USGS/Synergise.

Growing the market

Working with business

Satellite data are increasingly important in modern and emerging economies to support economic development and inform decision-making. The Space Innovation and Growth Strategy, an industry-led strategy supported by NCEO, sets the UK the ambitious target of capturing ten per cent of the world market in satellite systems and services by 2030. This share of the market is worth £40 billion and equates to 100,000 new jobs. Services based on EO are key to this growth strategy. With its first-class scientific expertise, NCEO works with stakeholders nationally and internationally to support the UK's ambitions. The director of NCEO, Professor Remedios, works within strategic initiatives connected with industry, such as the Space Sector Council and Space Growth Partnership, developing action plans for business growth in space data and satellite platforms.

NCEO supports the exploitation of NERC EO research by industry, often through collaborative projects initiated by space agencies, EC and government departments, including:

- Providing advice on the expert use of NERC EO data by key industrial sectors: for example, applications for climate services, forestry and agriculture, and cities.
- Supporting expert use of NERC EO techniques including improved algorithms, quality control, and data assimilation.
- Defining scientific requirements and advising on operational specifications for new EO missions and instruments, working closely with the Centre for Earth Observation Instrumentation (CEOI).
- Working jointly with industry to develop data products, data systems and services.

We build 'impact alliances' working in strategic partnerships; these include the Satellite Applications Catapult, the East Midlands Centre of Excellence in Satellite Applications led from the University of Leicester, the University of Reading Institute for Environmental Analytics, the British Association of Remote Sensing Companies, and Space4Climate.

Innovation with companies

NCEO is keen to build on its partnerships with individual businesses. It does so through fellowships, PhD and MSc projects, and knowledge-exchange mechanisms including Innovate UK, strategic partnership projects and UKRI Research Councils. It also works collaboratively on research and development projects with national companies and SMEs; NCEO is involved in a number of business-led projects supported by the UK Space Agency and ESA. Areas of activity include forestry, fires, agriculture, ocean behaviour, satellite-mission design and instrument technology.

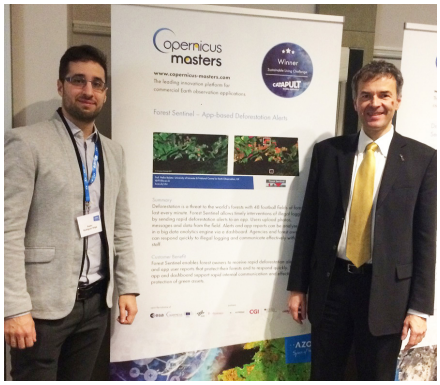
Satellite Applications Catapult: East Midlands Centre of Excellence

East Midlands
Centre of Excellence in Satellite Applications

The Satellite Applications Catapult's vision is to support industry and the science base across the UK to accelerate the growth of satellite applications.

Regional Centres of Excellence support work with local communities to achieve this aim. They create focal points of activity linking the science base with large industry and SMEs around the UK, to enable the development of applications and solutions, as well as to engage the wider end user market. The Centres of Excellence act as representatives and ambassadors for the Catapult in their local region.

NCEO is a partner in the East Midlands Centre of Excellence, led by the University of Leicester. From urban monitoring to agritech solutions and decarbonising future energy – satellite enabled products and services play a key role in achieving sustainable economic development.



NCEO-University of Leicester researchers Dr Pedro Rodriguez-Veiga and Professor Heiko Balzter, winners of the prestigious Copernicus Masters Sustainable Living Challenge 2017 awarded by the Satellite Applications Catapult. They received the accolade for their pioneering research to reduce the devastating effects of deforestation and development of an innovative mobile app for accessing the data. Credit: NCEO.

Space4Climate

SPACE4CLIMATE

NCEO is a steering-board and founding member of the Space4Climate group. Space4Climate is a public–private–academic partnership working to raise the profile of, and support, the UK's world-leading climate community in delivering, sustaining and making use of trusted climate information from space. Space4Climate builds on the UK and NCEO's expertise in climate datasets. The group's activities enable a seamless supply chain of climate data from space assets, help identify climate services' user requirements and facilitate development of climate services for global economic and societal benefit.

> **"The Satellite Applications Catapult regularly partners with the world-class community of scientists and technical specialists from NCEO to develop leading edge innovations - most recently, in our work on Analysis Ready Data."**
>
> Professor Nick Veck MBE
> Special Advisor to the CEO, Satellite Applications Catapult

Societal benefits

Working with public-sector agencies and government

The societal impact of applying the knowledge gained from EO is huge, encompassing evidence of challenges and solutions in areas ranging from ozone depletion to deforestation. Consequently, the public-sector use of EO data is large and increasing. The meteorological agencies, the Met Office and ECMWF, already have major interests in using EO techniques to underpin and improve weather forecasting and broader environmental services, including climate, ocean forecasting and analysis of atmospheric composition. The Met Office is a major NCEO partner in evaluating Earth system and climate models and driving forward improvements to these models using satellite data. The NERC-Met Office Joint Weather and Climate Research Programme (JWCRP) facilitates this partnership. Advice for government from NCEO is a significant activity.

> **"At BEIS we value NCEO's role in advising on the latest developments in Earth observation of tropical forests, and convening the UK's EO community to inform our investment decision-making."**
>
> Selina Newell
> Department for Business, Energy and Industrial Strategy

NCEO is playing a proactive role assisting policymakers and their agencies to use EO to achieve a range of outcomes:

- Evidence-based policymaking: creating and maintaining a strong base for environmental decision-making.
- Policy delivery and evaluation: developing monitoring and surveillance capability to deliver policy goals.
- International engagement: supporting, representing and promoting UK policy interests in international EO fora.

The advent of the European Copernicus programme has provided a wealth of opportunities that support the UK government's Department for Environment, Food and Rural Affairs (Defra) and its network of partners in areas such as biodiversity, agriculture, catchment management and water quality. NCEO is supporting Defra to realise open access to satellite data and make the most of EO-related capabilities.

Copernicus has also led to the development of core services to support government and industry use of EO data and information. Of these, NCEO staff are funded to work in the areas of land, marine environment, atmosphere and climate as well as being integrated into mission performance centres, particularly for Sentinel-3, in respect of algorithms and data quality.

Other UK government departments with growing interests in and responsibilities for EO products and services include:

- The Department for Business, Energy and Industrial Strategy (BEIS) with respect to national inventory reporting to the UNFCCC and international climate monitoring, reporting and verification.
- Cabinet Office with its cross-government remit to consider and develop a UK Government EO Service (UK-GEOS).

BEIS and UK-GEOS both look to NCEO for strategic advice based on the best science.

Participants at the AFOLU (Agriculture, Forestry and Other Land Use) Monitoring Reporting and Verification Workshop hosted by NCEO (University of Leicester, May 2018) in support of the International Climate and Energy Directorate at BEIS.

International

NCEO activities abroad

International work is a very important dimension of NCEO's remit. We value international collaborations and recognise they are vital in EO and environmental science. At present, publicly funded UK missions in EO are entirely international, almost wholly through European partnerships. Many businesses working with NCEO have activities in multiple countries. NCEO connects internationally through:

- **Major international scientific bodies**. NCEO staff contribute to the IPCC, GCOS, WMO/UNEP Scientific Assessments of Ozone Depletion, Global Energy and Water Cycle Experiment (GEWEX), Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS) and more.
- **Major international groupings**. NCEO staff play roles in CEOS and GEO (see below).
- **International and bilateral science projects, including ODA-compliant activities**. This includes NERC-funded activities, Newton projects and International Partnership Programme case studies.
- **Collaboration on in-flight and new EO missions**. NCEO works on European missions as well as UK bilaterals with other countries and collaborates on international missions where it has staff on the science team.
- **Working with businesses overseas**. NCEO works both with companies based in the UK who are wanting to develop business overseas, and with international companies wishing to improve their global or regional products. NCEO staff are involved in the UK Space Agency's International Partnership Programme, particularly in Africa and Central America.

The UK GEO/CEOS office

NCEO is working on behalf of the UK EO community to interface to two major international initiatives: GEO and CEOS.

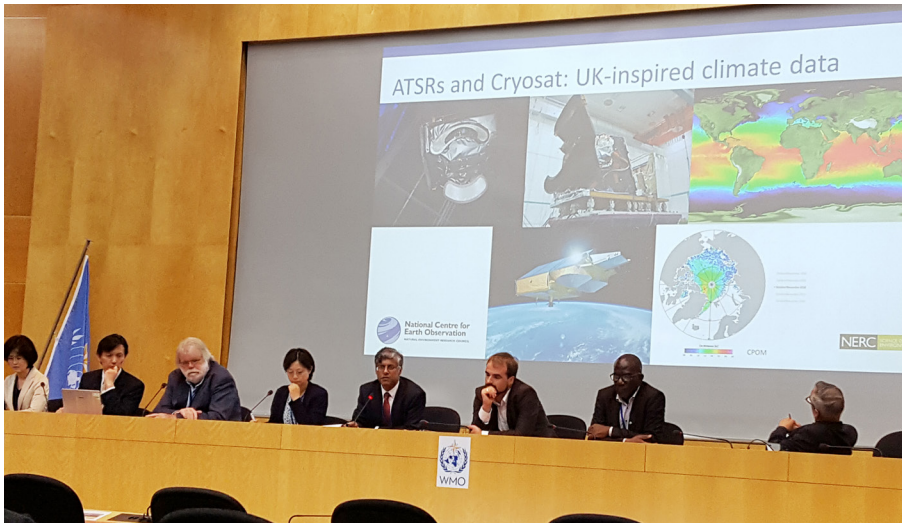
GEO is a voluntary partnership of over 100 governments and the European Commission, plus a similar number of participating organisations, working to make EO data and resources freely available for societal benefit. GEO is leading a worldwide effort to create a data portal called the Global Earth Observation System of Systems (GEOSS) to link EO resources worldwide across multiple areas of societal benefit. Defra is the UK policy lead for GEO.

The UK stand at GEO plenary in Washington, October 2017 with delegates from left to right Martin Jones (Cabinet Office), Zof Stott (NCEO), Robert-Jan Smits (EC co-chair, EXCOM).

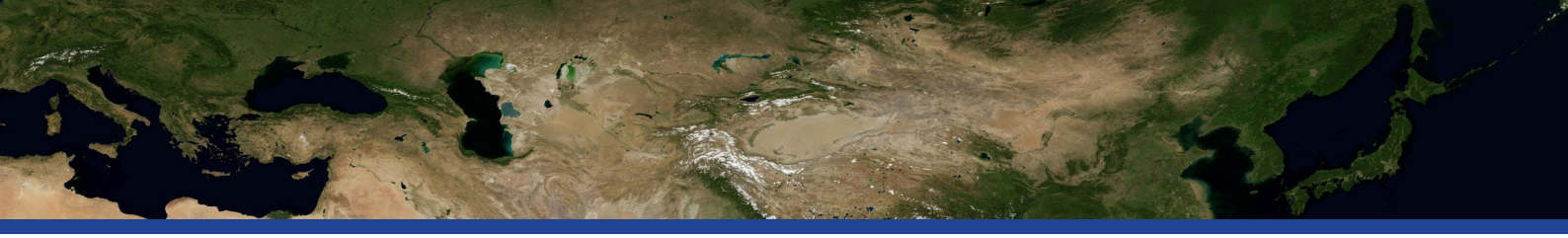
CEOS is GEO's sister coordination body, and aims to coordinate civil space-based EO programmes across the globe. The UK Space Agency has responsibility for leading UK engagement with CEOS.

In 2016 NCEO, Defra and the UK Space Agency set up a joint UK GEO/CEOS Office to coordinate UK activities relating to these two initiatives. This office supports the UK's strategic international ambitions to take a leading role in EO policymaking and standard-setting, promotes UK EO priorities, showcases UK capabilities and expertise on a global stage, and consolidates the UK's position as a world leader on addressing global challenges.

For example, the UK works closely with the GEO and CEOS communities on deforestation and climate change. Deforestation and forest degradation are the second leading cause of global



Professor John Remedios, Director of NCEO, presents the UK national perspectives on EO for the Paris Agreement at the GEO Symposium in Geneva, June 2018. Credit: M.F. Racault, NCEO-PML.



warming, responsible for about 15% of global greenhouse gas emissions. GEO's Global Forest Observations Initiative (GFOI) is helping developing countries measure, report and verify forest areas and carbon stocks using systematic and agreed methodologies. The UK's BEIS is a member of the GFOI Leads Group and NCEO scientists support research and the CEOS Ad Hoc Space Data Coordination Group.

International science collaborations

NCEO scientists are valued internationally for their expertise. At least 60% of NCEO papers have international co-authors. Collaborations take many forms: working with fellow scientists, supporting operational agencies, and providing capacity building and upskilling through ODA projects.

We collaborate effectively through EO-related activities with many universities and research centres across Europe, the United States, Canada, Australia, Southeast Asia and, increasingly, with India and China. Our aim is to grow science partnerships in Africa and South America to complement these. Often the academic relationships, such as those with NASA centres, are focused on fundamental EO science but collaborations are also built around applications, for example, in agricultural projects between NCEO-UCL and the Chinese Academy of Agricultural Sciences. A growing area of strength is partnership with key technical and scientific government-related agencies including meteorological agencies, forestry and carbon centres and services, and space-agency centres. For example, NCEO staff led by Professor Martin Wooster (NCEO-King's College London) work with the Canadian Forest Service, and NCEO-University of Leicester are co-developing applications with the Kenyan Forestry Service. Key goals are to extend the use of satellite remote sensing in regional and national forest services for fire risk and to validate satellite data products.

NCEO has a formal ODA programme commissioned by NERC as well as roles in short-term projects funded by the UK Space Agency International Partnership Programme. The NCEO ODA programme focuses on forest carbon stocks and change in Kenya, on soil moisture in Ghana and on large-scale air quality in Southeast Asia including Indonesia.

Collaborating in EO space missions

As well as contributing to national and European (ESA, EUMETSAT and Copernicus) satellite missions, NCEO scientists engage in world-leading, internationally recognised research by providing fundamental input into a range of other international missions focused on Earth's most vital processes. We believe that UK science is best served by expert cooperation with the world's leading space agencies, scientists and missions. Current NCEO collaborations include missions from the US (for example, GPM to measure global precipitation), Japan (for example, GOSAT to measure greenhouse gases) and China (for example, TanSat to measure carbon dioxide).

NCEO also supports the community to make best use of international missions, sometimes in conjunction with technology investment from the UK Space Agency. An example is the Surface Water Ocean Topography mission: UK marine and inland-water scientists are members of the science team and intend to support validation of the data.

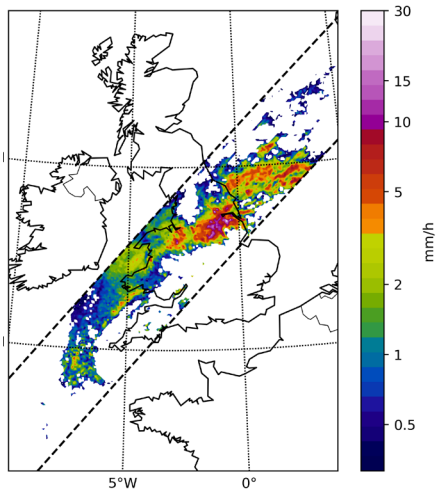
We also add to the scientific quality and applications of datasets and research papers from a wide range of existing missions. Examples are given below.

Carbon dioxide with OCO-2

The Orbiting Carbon Observatory-2 (OCO-2) mission is NASA's first dedicated remote-sensing satellite measuring atmospheric carbon dioxide from space. The NCEO team involved in OCO-2, led by Professors Paul Palmer (NCEO-University of Edinburgh) and Hartmut Boesch (NCEO-University of Leicester), are contributing to the OCO-2 initiative as science team members in the areas of data quality and data interpretation.

Measuring rainfall from space

Global Precipitation Measurement (GPM) is an international mission designed to use a constellation of space-borne microwave sensors to advance precipitation measurements. The GPM core satellite carries the first dual-frequency radar in space and measures the three-dimensional structure of storms along its orbit track. The NCEO-University of Leicester team is part of the GPM International Collaborator Team and is actively contributing to improving the accuracy of the mission's rainfall product by providing expertise in radiative modelling of cloud/precipitating particles, and by carrying out ground validation activities focused on precipitation in mid latitudes.



UK rainfall rate at the surface measured by GPM (21 November 2016). Credit: K. Mroz, NCEO-University of Leicester.

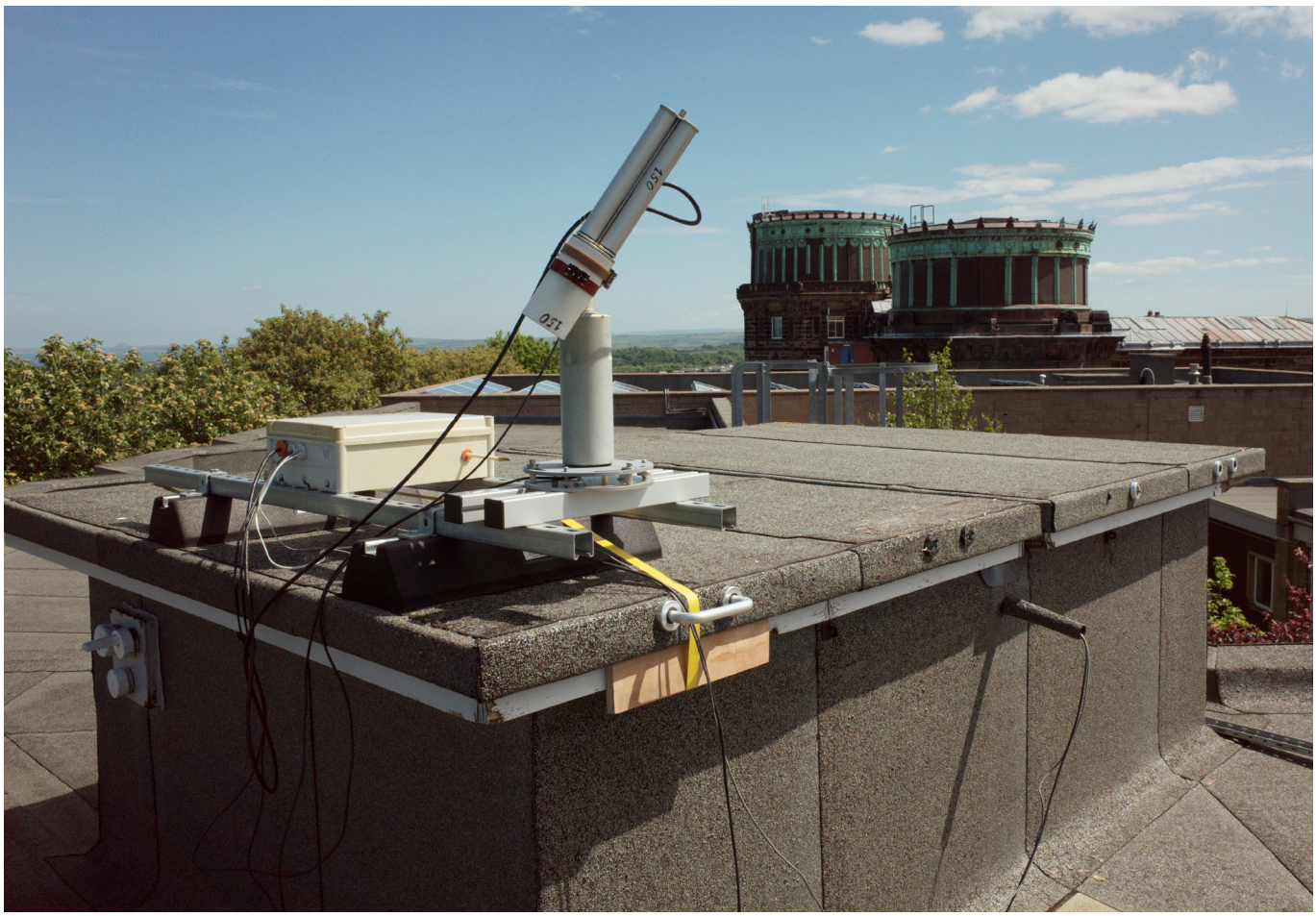
> **"Ecometrica is working with leading experts from NCEO to develop practical, scaleable solutions for monitoring forest condition from EO satellites. Improved methods are being tested and scaled up to cover over 300 million hectares of forest in 6 tropical countries. This project is supported by the UK Space Agency's International Partnership Programme."**
>
> Dr. Richard Tipper FRSA
> Executive Chairman, Ecometrica

Our dedicated infrastructure

NCEO provides scientific oversight, governance and coordination of a series of NERC-funded facilities, data centres and computing infrastructures focused on EO. These facilities are available for the entire NERC and wider UK science communities to access via grant awards or direct access proposals, and external steering committees are involved in the governance to ensure state-of-the-art capabilities are evolved to support developing science areas beyond solely the focus of NCEO.

NERC Field Spectroscopy Facility

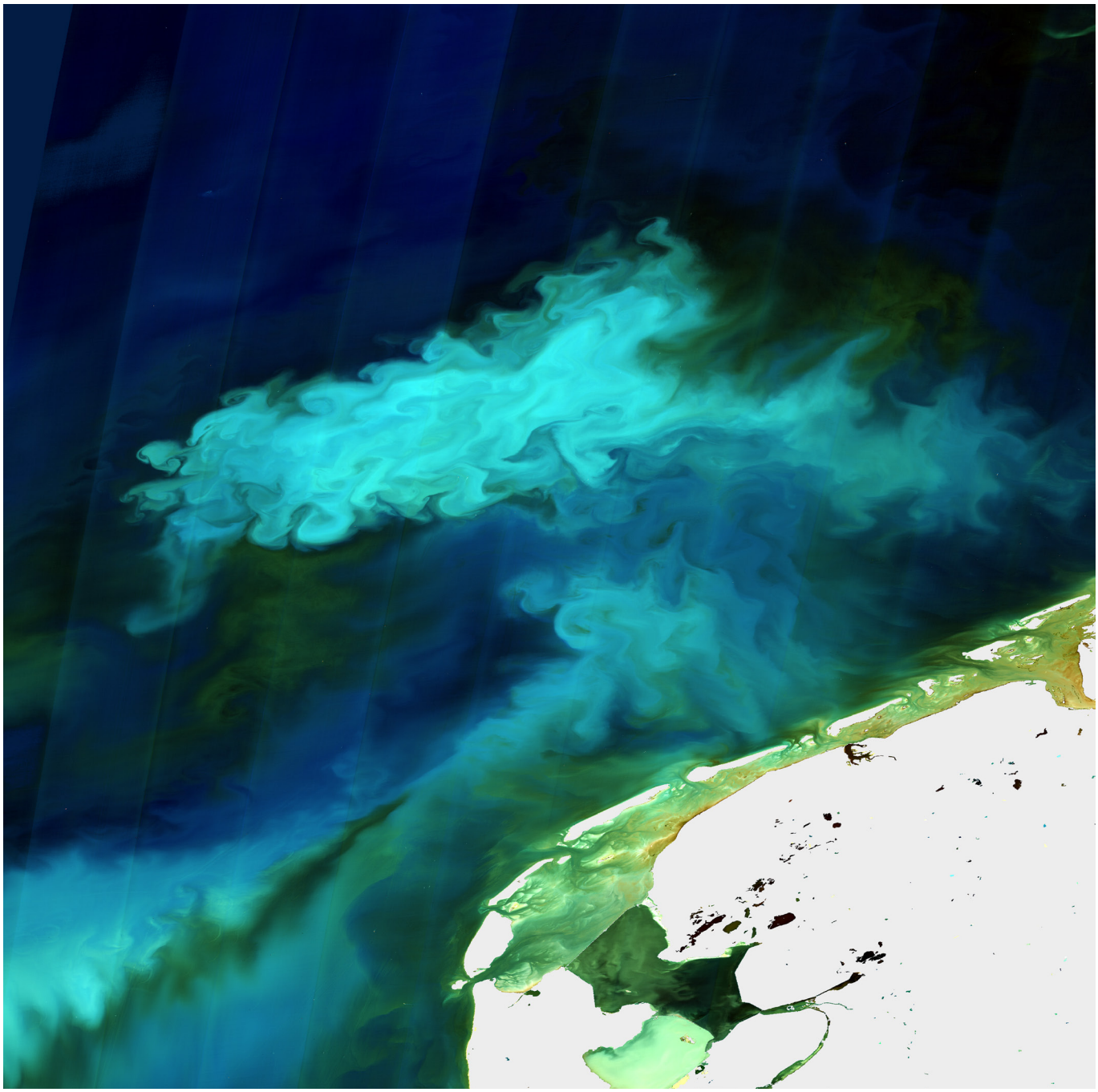
NERC's Field Spectroscopy Facility (FSF), hosted by the University of Edinburgh, offers expertise and equipment for high-performance optical remote sensing, both in the field and in the laboratory. Ground-based spectral measurements are used to study environmental phenomena such as the photosynthetic activity of vegetation, the albedo of snow and ice, the gases and particulates contained in polluted plumes, and the detailed spectral reflectance and emittance properties of vegetation, rocks, soil and water under a host of observing conditions. These measurements are also used to develop and evaluate EO algorithms and data products coming from a wide variety of satellite, aircraft and unmanned aerial vehicle (UAV) missions. All FSF equipment is calibrated and quality-assured using a dedicated calibration laboratory, which external scientists can access to characterise their own instrumentation. FSF's instruments available to the community currently include field spectroradiometers measuring from the visible to the shortwave infrared, portable and fixed sun photometers and an open-path Fourier-transform infrared (FTIR) spectrometer, along with equipment for measuring underwater inherent and apparent optical properties. A regular programme of instrument renewal and expansion ensures quality, state-of-the-art observation capabilities are maintained.



One of FSF's CIMELs, an automatic tracking sunphotometer that provides information on atmospheric aerosol compositions as part of a global network of instruments (AERONET), seen here in its most recent installation on the roof of the Royal Observatory in Edinburgh. This instrument can be used by atmospheric modellers, or by researchers analysing satellite data, to remove the atmospheric effects from their images. Credit: A. Gray, NERC-FSF.

NERC Earth Observation Data Acquisition and Analysis Service

NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS) is a 24-hour / 7-day per week satellite data-processing and analysis facility based in the Remote Sensing Group of PML. NEODAAS provides NRT information where required, for anywhere in the world and derived within minutes of satellite-data arrival, forwarding targeted information to those in need. The facility regularly supports NERC's marine cruises and aircraft research campaigns, notably by identifying the most scientifically valuable locations to sample. NEODAAS can also respond rapidly to disruptive events, from algal blooms to volcanic eruptions, with its data and imagery regularly appearing in the UK media. NEODAAS supports NERC scientists to better identify, understand and monitor rapid changes and advise governments, the public and other stakeholders on the nature and impact of the phenomena.



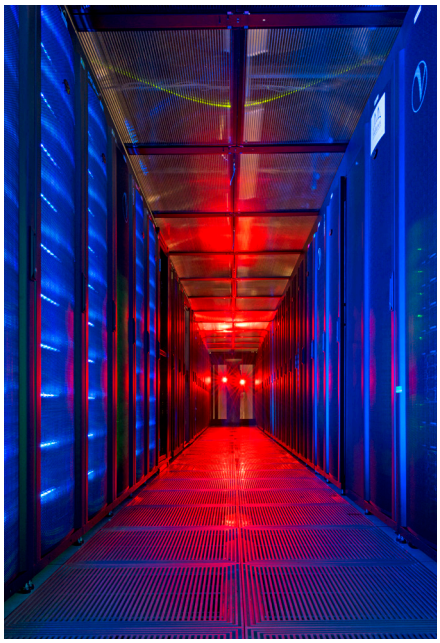
Coccolithophore bloom, likely to be of the species Emiliania huxleyi, in the southern North Sea on 5 May 2018 from Sentinel-2. Blooms can be observed from satellites as they develop and decay, since they release external calcite plates or liths which strongly backscatter light in the water. Research at PML has investigated how the latitudinal distribution of these blooms has changed over the last few decades; the NCEO NEODAAS service processes ocean-colour images to guide research-vessel sampling whilst at sea. Credit: NEODAAS-PML.

Our dedicated infrastructure

Centre for Environmental Data Analysis and JASMIN

NCEO offers access to data, alongside massive storage, processing and analysis capabilities, through the Centre for Environmental Data Analysis (CEDA), hosted on the high performance JASMIN computing infrastructure. These infrastructures support a range of activities which aid the analysis requirements of the UK and European climate and environmental science communities.

CEDA hosts and operates a series of NERC environmental data centres for Earth Observation, atmospheric, and solar system science. In terms of EO, the CEDA data centre holds and provides online access to new datasets created by NCEO and other NERC supported scientists, and maintains copies of large datasets produced by other agencies, such as ESA, EUMETSAT, NASA and NOAA. CEDA holds key climate data sets from the UK and from the ESA Climate Change Initiative (CCI) programme, opening up extensive possibilities for the evaluation of Earth system models.



JASMIN computing cluster.
Credit: STFC; NERC; NCAS; NCEO.

The CEDA EO data collection on JASMIN is the largest EO data archive in the UK. Over 4 Petabytes of satellite data and related products from a range of satellite missions extend back nearly three decades, whilst data from NERC Airborne Remote Sensing campaigns extend back to 1982. CEDA is the UK academic data hub for ESA's Sentinel missions, with responsibility for storing Sentinel data and providing access to the UK science community. Sentinel data volumes are significantly higher than previous satellite missions: up to 9 Terabytes per day, and these data feeds increase the CEDA archive volume by several Petabytes per year.

In addition to hosting the CEDA data archive, the JASMIN computing infrastructure also supports NERC scientists through access to collaborative workspaces, hosted processing, high-performance computing, and a cloud-computing environment that can be accessed remotely. Its performance is key to the ability of NCEO and the UK community to undertake leading science using big data processing techniques. It also offers opportunities for scientists and industry to work together in testing new systems for EO data.

CEDA is located at the Science and Technology Facilities Council's Rutherford Appleton Laboratory in Oxfordshire and is supported by NCAS and NCEO jointly.

NCEO instrumentation suite

NCEO itself maintains and operates a series of state-of-the-art remote-sensing instruments and associated calibration and environmental measurement equipment, aiding and supporting its national-capability science.

Our instrumentation suite includes ground and upward viewing spectrometers and spectroradiometers utilised to probe the greenhouse gas, aerosol, and pollutant constituents of the atmosphere; a total carbon column observing network (TCCON) station based around a highly precise ground-based FTIR spectrometer that records direct near-infrared solar spectra for validation of satellite-derived total column atmospheric greenhouse gas measures; field and laboratory infrared thermal imagers, high accuracy radiometers and FTIR spectrometers which can be used to validate land surface temperature retrievals and assess the spectral emissivity of solid and liquid samples for support to land surface temperature retrieval; and radiometers capable of being operated in marine environments to measure ocean-leaving spectral radiance alongside a series of other field spectroradiometer equipment.

NCEO refreshes and adds to parts of this instrument suite annually, and operates a series of integrating sphere and blackbody radiance sources, high-quality Differential GPS systems, ground-based LiDAR, high-capacity UAV systems and other field-measurement infrastructure that together provide the necessary companion data to remote-sensing measurements.

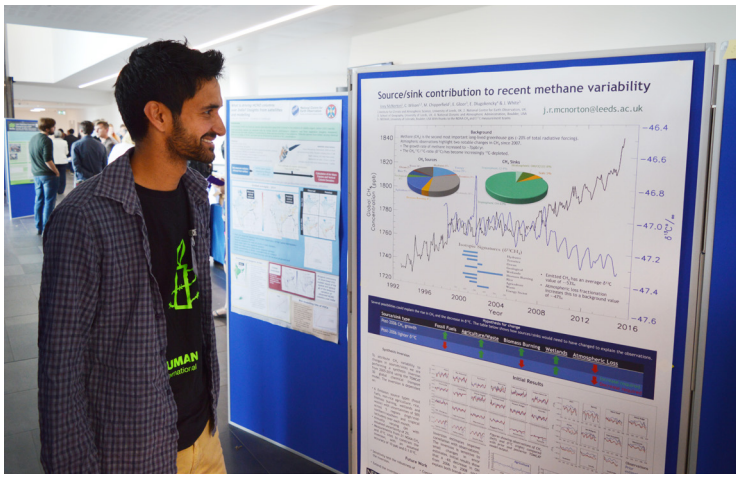
NCEO-UCL's Riegl VZ-400 terrestrial laser scanner (TLS). The instrument sends out hundreds of thousands of laser pulses per second to make an extremely detailed 3D picture of these 200-year-old oaks in Hampstead Heath. These measurements are used to help estimate the atmospheric CO2 absorbed by urban trees during photosynthesis. Credit: M. Disney and P. Wilkes, NCEO-UCL.

Keeping the UK at the forefront of world-class research

NCEO conferences, workshops and engagement

NCEO recognises that a vibrant UK science community benefits from national and international networking and collaborations. NCEO hosts annual conferences for its staff and the EO community, usually in collaboration with CEOI. Biennially, the two centres work with the Remote Sensing and Photogrammetry Society (RSPSoc) to organise the UK National Earth Observation conference for academia, industry and government attendees. We also organise the annual EO Researchers' Forum for early-career scientists, EO Applications conferences, and foster community-dedicated science meetings on topics from agriculture to ocean remote sensing. We regularly contribute to important showcases, such as UK Space Conference and GEOBusiness, involving the community in organisation and delivery. Further afield, we are very much engaged in international conferences such as the ESA Living Planet Symposium, the European Geophysical Union meetings and GEO/CEOS events.

> **"NCEO provides excellent support for early-career scientists. The Researchers' Forum gave me the opportunity to improve the communication of my PhD research."**
>
> Michael Cartwright
> NCEO-University of Leicester



Poster Session at the NCEO Science Conference June 2017. Credit: NCEO.

The NCEO team at the Royal Albert Hall Big Space Day 2018. Credit: NCEO.

NCEO training

NCEO has a suite of training opportunities to support the use of world-class EO. We provide a range of short classroom-based training courses, online training and a range of tools for EO users across the globe. Our short training courses include how to use EO data, data assimilation and field spectroscopy. In addition, NCEO is a Copernicus Academy and works to train people in the use of Copernicus Sentinel data.

NCEO/Mathematics of Planet Earth Centre for Doctoral Training PhD Student Jemima Tabeart presents her team's workshop project at the NCEO Researchers' Forum 2018. Credit: NCEO.

The NCEO website has online training in radiative transfer and data assimilation. We are a partner in Data Tree – a free online course for research-data management.

Our researchers teach at EO summer schools run by ESA and contribute to massive open online courses (MOOCs) in climate data from space and atmospheric science developed by the company Imperative Space.

NCEO has trained over sixty PhD students in projects ranging from studying greenhouse gases to understanding climate variability. NCEO can host MPhil and PhD students in collaboration with doctoral training partners and centres for doctoral training. NCEO is a partner in the Scenario, Centa, Edinburgh E3, Oxford, Imperial SSCP and London doctoral training partnerships as well as the Maths of Planet Earth Centre for Doctoral Training.

Working with the public and schools

Public engagement

NCEO and its staff are absolutely committed to interacting with the public to convey the excitement of EO, share information on the significant science that we do and receive feedback on the most valued activities and challenges. NCEO organises and takes part in large open events, such as NERC's UnEarthed event at Dynamic Earth in Edinburgh. We recently simulated the challenges of space photography at the Royal Albert Hall's Big Space Day.

NCEO researchers also frequently take part in open days, festivals and other events designed to showcase the work of scientists. We offer talks, demonstrations and activities suitable for a wide range of audiences and participants. Examples of these include exploring how non-visible light can provide valuable information through remote sensing and explaining how EO data is gathered, stored and used.

NCEO is also working with NERC and the UK Space Agency to develop innovative engagement practices. Most recently, NCEO has partnered with NCAS and others in the NERC-funded Climate Communication Project. Focusing on the issue of climate change, the project is looking at engendering high-impact public partnerships and digital platforms communicating to the public about climate change on a national scale. NCEO supports the UK Space Agency in communications to the public on the occasion of major satellite launches and worked closely with the agency during British ESA astronaut Tim Peake's Principia mission to the International Space Station (ISS), particularly in associating fifty years of environmental change with changes observed in astronaut photographs throughout the space age. During Tim's visit to the ISS, NCEO worked with ESA and NASA to arrange for photographs of the Earth to be taken by astronauts targeting features identified by UK schoolchildren.

EO Detective

NCEO's schools project, EO Detective, was launched in 2015 with funding from the UK Space Agency and NERC.

The core strand is a suite of classroom activities that place aspects of the UK national curricula for students aged 5 to 16 in EO contexts. Teacher notes and the resources for each activity, which can be downloaded free of charge, are created to be usable regardless of previous EO knowledge. As a result, the materials have been used by tens of thousands of children in the three years since their publication. The activities have also been adopted by a variety of organisations including ESERO-UK (Tim Peake Primary Project), STEM Learning (Polar Explorer Programme), NERC and the Association of Science and Discovery Centres (Operation Earth), The Scout Association (Astronautics badge supporting materials) and the Institute for Research in Schools (MELT project).

These curriculum-focused activities are supplemented by a careers resource, Meet the EO Detectives, which is linked to a website that hosts additional materials such as downloadable games and a blog, and our Leicester-based researchers regularly support careers events at the National Space Centre. One of the people featured in the careers activity is Tim Peake, whom we interviewed about photographing the Earth from the ISS. A video of the interview, along with a presentation featuring individual images discussed during it, forms part of the resource collection.

EO Detective teaching materials: www.stem.org.uk/resources/collection/4356/eo-detective

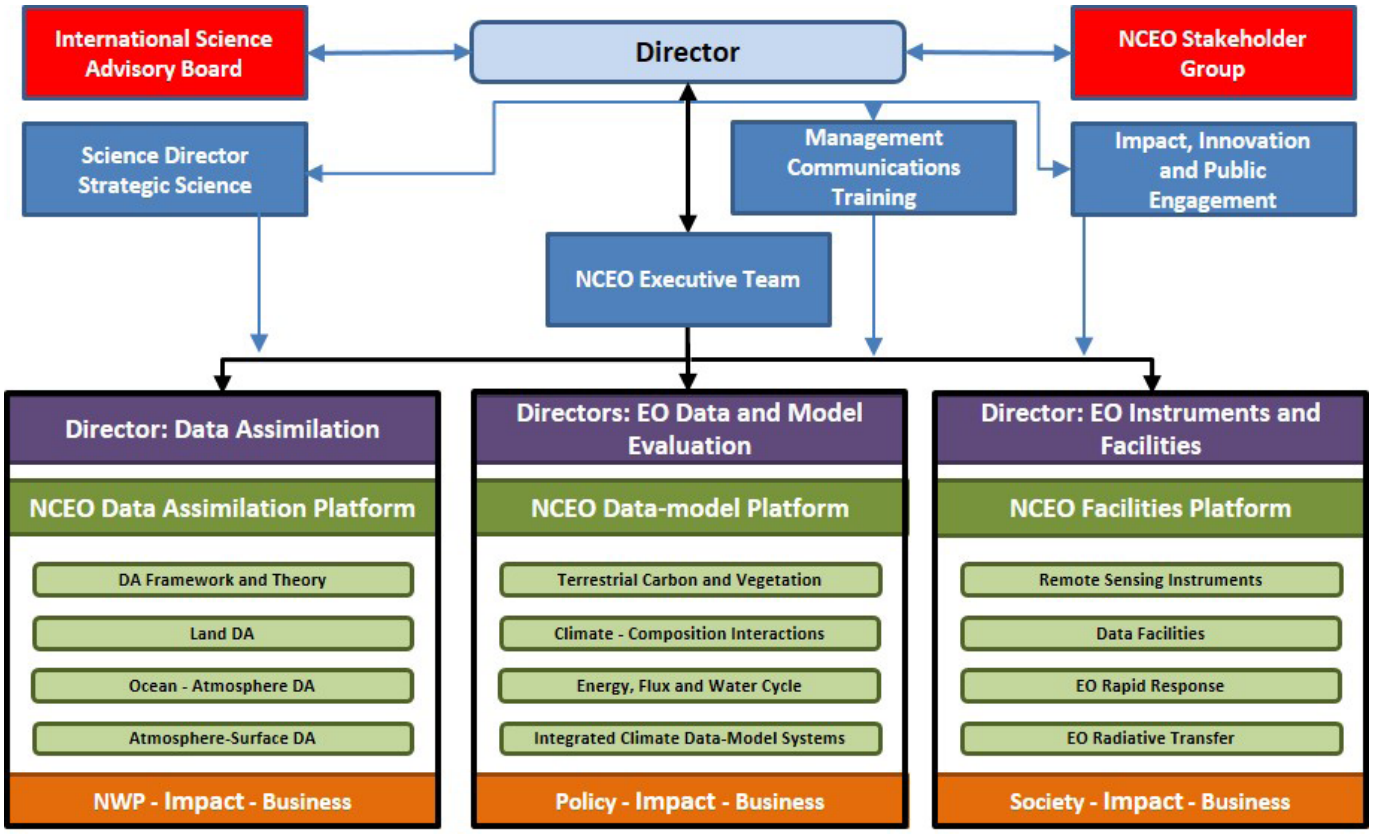
EO Detective blog: www.eodetective.wordpress.com

Primary school children try to match up photographs taken 'from the ground and from the sky'. Credit: Colette Godfrey/NCEO.

The winners and runners-up in the EO Detective Competition display their prizes at the National Space Centre. Credit: National Space Centre.

How we are organised

NCEO's structure is shown below. NCEO's core management and support team is located with the director, Professor John Remedios, at the University of Leicester, and at the University of Reading. We are organised in divisions according to three broad scientific activities – data assimilation, EO data-model evaluation, and EO instrumentation and facilities – each with a divisional director and associated key capabilities and infrastructure (the platforms). The platforms serve as vehicles for interactions within NCEO and with the wider NERC science community. The NCEO director, science director and divisional directors together form the NCEO executive team. The NCEO director is advised by an international science advisory board and a stakeholder group.



Sentinel 3. Credit: ESA/ATG MediaLab.

NCEO Directors			
Professor John Remedios	NCEO Director	University of Leicester	john.remedios@nceo.ac.uk
Dr Amos Lawless and Professor Sarah Dance	Directors of Data Assimilation (data assimilation software systems and theory)	University of Reading	a.s.lawless@reading.ac.uk s.l.dance@reading.ac.uk
Dr Helen Brindley	Co-director of EO Data and Model Evaluation (energy, water cycle and integrated climate-data models; radiation budget)	Imperial College London	h.brindley@imperial.ac.uk
Professor Hartmut Boesch	Co-director of EO Data and Model Evaluation (climate-composition interactions; terrestrial carbon and vegetation)	University of Leicester	hartmut.boesch@le.ac.uk
Professor Martin Wooster	Director of EO Instrumentation and Facilities	King's College London	martin.wooster@kcl.ac.uk
Professor Paul Palmer	Science Director	University of Edinburgh	pip@ed.ac.uk
Data Centre			
Dr Victoria Bennett	Division Head, Centre for Environmental Data Analysis	STFC Rutherford Appleton Laboratory	victoria.bennett@stfc.ac.uk support@ceda.ac.uk
Facilities			
Mr Steve Groom	Director of NEODAAS-Plymouth	Plymouth Marine Laboratory	SBG@pml.ac.uk
Mr Chris MacLellan	FSF Manager	University of Edinburgh	chris.maclellan@ed.ac.uk
Science Support			
Tara Thompson	NCEO Communications Manager	University of Leicester	tara.thompson@nceo.ac.uk
Sharon North	NCEO Special Projects Manager	University of Leicester	sharon.north@nceo.ac.uk
Zee Shabbir	NCEO Centre and Programme Manager	University of Leicester	zee.shabbir@nceo.ac.uk

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

Natural Environment Research Council

National Centre for Earth Observation
Space Park Leicester
Corporation Road
Leicester LE4 5SP
United Kingdom

Front cover: global sea surface temperature and land surface temperature.
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