National Centre for Earth Observation

NATURAL ENVIRONMENT RESEARCH COUNCIL

RESEARCH HIGHLIGHTS 2015

CONTENTS

Cover: Acknowledgement: NEODAAS/University of Dundee (Image received at Dundee from the Suomi-NPP satellite (VIIRS instrument) on 5 June 2015 at 1247 UTC).

FOREWORD

Welcome to this year's research highlights from the National Centre for Earth Observation (NCEO).

NCEO is a NERC research centre with more than 80 scientists distributed across leading UK universities and research organisations. With an annual income of over £8 million per year, half of which is derived from NERC core funding, we provide the UK with expertise in Earth observation (EO) science; data sets and data assimilation techniques; and model evaluation to underpin Earth system research. NCEO is the "heartbeat" of EO capability within NERC encouraging world-class science and underpinning the sector with respect to government and industry. We are passionate about the importance of our research to society: EO science is increasingly beneficial for a range of applications.

Within this brochure, you will find examples where NCEO scientists have worked with data from some of the latest missions and long-term analyses, produced key results in understanding carbon in the Earth system and pollutants in the atmosphere, and undertaken research which is helping to improve understanding of climate data. These illustrate our current scientific goals and structure; our topics are arranged according to science and NCEO capability areas. They also illuminate our new objectives which are:

- Derivation and science exploitation of new, quality enhanced, historical and current observations of Earth System evolution and application in operational and business services using critical long-term data sets.
- Innovative data assimilation for Earth system state representation, its model-mediated assessment and interrogation, with numerical weather prediction-related impact.
- Evaluation of global Earth System (ESMs) and component models with EO data supporting government policy through scientific research and evidence.
- Provision of instrument, data facilities and key tools for use by the wider NERC and EO community with support of applications using NERC data sets and technology.

This last year has also seen significant changes in the leadership and structure of NCEO which we hope will allow us to do an effective job of providing long-term environmental science capability whilst giving us flexibility to work proactively with the large number of organisations interested in EO. As I am based in Leicester, the Directorate is now centred in Leicester with support from Reading. We have introduced Divisional Directors, namely Peter Jan van Leeuwen (Data Assimilation); Hartmut Boesch and Helen Brindley (EO Data and Model Evaluation) and Martin Wooster (EO Infrastructure). We also have taken on management responsibility for two NERC facilities: the Field Spectroscopy Facility at University of Edinburgh and the NERC Earth Observation Data Acquisition and Analysis Service at the University of Dundee and Plymouth Marine Laboratory.

Change is always difficult and we live in a time of change so good teamwork is vital. I would particularly like to thank Peter Jan van Leeuwen who has worked hard as Interim Director and who remains at the core of NCEO. I would also like to thank Jan Fillingham and Zof Stott who have provided much needed continuity alongside Peter Jan, great advice through the transition and hard work to ensure the transition has been as smooth as possible. We are delighted that they remain key members of our Centre.

NCEO also has the remit to act as a champion for the wider academic community in its use of Earth observations. There is much work to do in this space and particularly to support the continued funding of ESA's Earth Observation Envelope Programme. Today, I would like to draw your attention to three areas: the Royal Society's project on "Observing the Earth – Expert views on environmental observation for the UK"; the successful launch of the first Sentinel satellites with a UK Collaborative Ground Segment providing access to Sentinel data; the on-going Ofcom review on the use of electromagnetic spectrum by the space community which is particularly important for the EO sector. In all of these, NCEO has worked very hard to represent, involve and benefit the community. These activities are all important to ensure a continued supply of high quality space data to study the Earth system.

As we embark on our new five year science programme, we are happy that the last year has proved very productive scientifically. Throughout the transition to new management our scientists have continued their excellent work. We hope you enjoy the highlights in this publication.

John Remedios
NCEO Director

Bob Brewin, Shubha Sathyendranath NCEO, Plymouth Marine Laboratory
Thomas Jackson, Ruth Airs, Plymouth Marine Laboratory, UK
Ray Barlow, Bayworld Centre for Research & Education, South Africa
Vanda Brotas, Universidade de Lisboa, Portugal
Tarron Lamont, University of Cape Town, South Africa

INFLUENCE OF PHYSICAL FORCING ON PHYTOPLANKTON SIZE STRUCTURE

Phytoplankton cell size influences many processes in marine biogeochemisty and marine ecology. Observations on phytoplankton size, well resolved in time and space, are required to address key questions pertaining to our understanding of marine biogeochemistry and marine ecology, and how they are likely to be influenced by climate variability.

Stimulated by the paucity of in situ observations on size structure, and by the sampling advantages of autonomous remote platforms, new efforts are being made to infer the size-structure of the phytoplankton from oceanographic variables that may be measured at high temporal and spatial resolution, such as total chlorophyll concentration. Large-scale analysis of in situ data has revealed coherent relationships between size-fractionated chlorophyll and total chlorophyll that can be quantified using a three-component model developed within NCEO. However, there are variations around these general relationships. Using estimates of the average irradiance in the mixed-layer, we investigated the influence of ambient light on the parameters of the three-component model. We observe significant relationships between model parameters and the average irradiance in the mixed-layer, consistent with ecological knowledge. These relationships are incorporated explicitly into the three-component model to account for variations in the relationship between size-structure and total chlorophyll ensuing from variations in light availability (Figure 1). The new model may be used as a tool to investigate modifications in size-structure in the context of a changing climate and may help predict future modifications in phytoplankton community structure and hence in marine biogeochemical cycles.

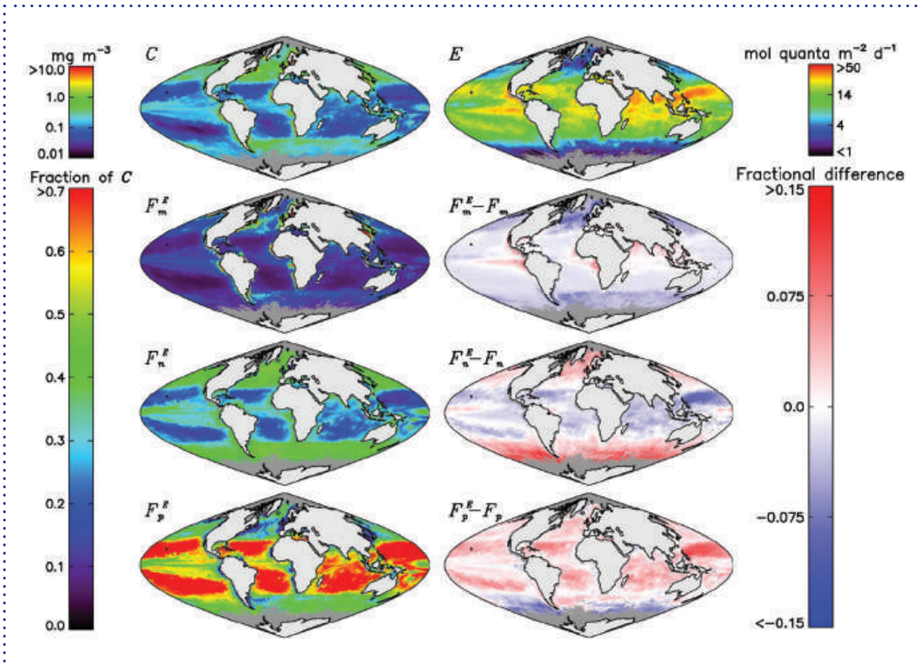


Figure 1: Monthly averages for April 2010 of chlorophyll concentration (C, top left plot), average light in the mixed-layer (E, top right plot), and the fractions of chlorophyll in the three size classes to the total chlorophyll concentration (bottom three plots on the left column, with fraction of microplankton [cells >20µm] denoted F_m, nanoplankton [cells 2-20µm] denoted F_n, and picoplankton [cells 2-20µm] denoted F_p). The superscript E denotes the model runs with light dependency. The bottom three plots on the right column show differences between the model when run with and without the light dependency. The figure is adapted from Brewin et al. (2015).

References
Brewin, R. J. W., Sathyendranath, S., Jackson, T., Barlow, R., Brotas, V., Airs, R. & Lamont, T. (2015) Influence of light in the mixed layer on the parameters of a three-component model of phytoplankton size structure. Remote Sensing of Environment, 168, 437-450, doi: 10.1016/j.rse.2015.07.004.

Stefano Ciavatta, J. Icarus Allen,
NCEO-Plymouth Marine Laboratory
Susan Kay, Momme Butenschön,
Plymouth Marine Laboratory
Stephane Saux-Picart, Meteo France/
Plymouth Marine Laboratory

OXYGEN DEFICIENCY IN THE BOTTOM WATERS OF THE NORTH WEST EUROPEAN SHELF-SEA

A large area of the North West European shelf-sea was vulnerable to oxygen deficiency during the last decade (Figure 1). This deficiency had the potential to threaten marine ecosystem services, such as trawling fishery.

This finding emerged from the reanalysis of the biogeochemistry of the North East Atlantic in the years 1998-2009, carried out by the National Centre for Earth Observation at the Plymouth Marine Laboratory, in collaboration with the ESA's Climate Change Initiative – Ocean Colour (OC-CCI) and the EC FP7 project 'Operational Ecology'. In this framework, the last generation of ocean colour released by OC-CCI (chlorophyll concentration and associated error, Version 2.0, April 2015) was assimilated into a coupled hydrodynamic-biogeochemical model of the North East Atlantic (POLCOMS-ERSEM; Artioli et al., 2012), by using a system for ocean colour assimilation based on the localised Ensemble Kalman filter (Ciavatta et al., 2011).

The reanalysis was skilled in estimating a large data set of oxygen concentrations in the study region (~60,000 data, $r = 0.72$, $p<0.01$). Thus the reanalysis was exploited to compute the minimum value of oxygen predicted by the ensemble, at the bottom of the water column up to a bathymetry of 1000m, which is of interest for trawling fishery. The oxygen concentration of 6 mg/L was used to define the threshold of deficiency, following the indications by the OSPAR Commission. We found that the Celtic Sea, Armorican shelf and German Bight were vulnerable to oxygen deficiency (Figure 1). In some instances, concentrations reached values potentially lethal for benthic species (e.g. 4.6 mg/L, Vaquer-Sunyer and Duarte, 2008).

However, daily concentrations were in all the cases above the threshold of anoxia (2 mg/L), which can trigger massive fish mortality. Previous studies had found links between oxygen deficiency and eutrophication in the region (see e.g. Claussen et al., 2009). We found in particular that the bacterial degradation of the organic matter produced by the planktonic community and exported to the bottom of the water column contributes significantly to the spatial and temporal patterns of the oxygen deficiency.

These results indicate that the novel reanalysis of the biogeochemistry of the North East Atlantic can enhance the understanding and management of the European shelf ecosystem, in relation to crucial issues such as eutrophication and fishery.

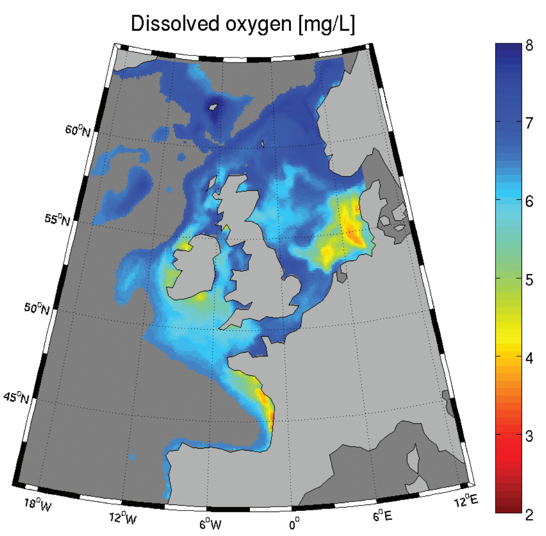


Figure 1: Oxygen concentration at the bottom of the North West European shelf-sea in the years 1998-2009.

References

Artioli, Y., Blackford, J.C., Butenschon, M., Holt, J.T., Wakelin, S.L., Thomas, H., Borges, A.V., and Allen, J.I. , 2012 The carbonate system in the North Sea: sensitivity and model validation, J. Marine Syst., 102–104, 1–13.

Ciavatta, S., Torres, R., Saux-Picart, S., Allen, I.J., 2011. Can ocean colour assimilation improve biogeochemical hindcasts in shelf seas? J. Geophys. Res. 116, C12043.

Claussen, U., Zevenboom, W., Brockmann, U., Topcu, D., & Bot, P. (2009). Assessment of the eutrophication status of transitional, coastal and marine waters within OSPAR. Hydrobiologia, 629(1), 49-58.

Vaquer-Sunyer, R., and Duarte, C. M. (2008). Thresholds of hypoxia for marine biodiversity. Proceedings of the National Academy of Sciences, 105(40), 15452-15457.

TOWARDS CLIMATE QUALITY AND DIURNALLY RESOLVED LAND SURFACE TEMPERATURE DATA

Darren Ghent, NCEO-Leicester

Key research breakthroughs in Land Surface Temperature (LST) science are being achieved within the GlobTemperature Project under the Data User Element of ESA's 4th Earth Observation Envelope Programme (2013-2017) with new datasets being delivered to users.

These include refinements to the Along Track Scanning Radiometer LST products (AATSR and ATSR-2). Key strengths of these enhanced datasets are: i) highly accurate instruments; ii) long time-series when instruments are used in conjunction; iii) full uncertainty budgets; iv) enhanced cloud detection; and v) sea-ice retrievals. A further advancement is the development of a first prototype long and stable LST time record for climate (climate data record) from single sensor types. The GlobTemperature Prototype ATSR climate data record provides monthly data on LST over land, lakes and sea-ice and its associated uncertainty with a consistent algorithm and cloud detection (Figure 1). A critical consideration has been to harmonise the temporal differences between instruments through analysis of the overlap period for the respective missions. To maximise exploitation of LST data, development of a first satellite LST product which resolves the diurnal cycle at a global level is under way. The GlobTemperature Merged LST Product is different from other LST global products because reference data is used as a common denominator between instruments to remove systematic differences. This Merged LST Product, derived in collaboration with the LSA SAF, combines the benefits of LST data from Geostationary and Low Earth Orbit satellites (Figure 2).

These datasets which advance the science in Land Surface Temperatures are freely available from the GlobTemperature Data Portal (data.globtemperature.info) which provides a "one-stop-shop" for all LST and Emissivity data products for the user community.

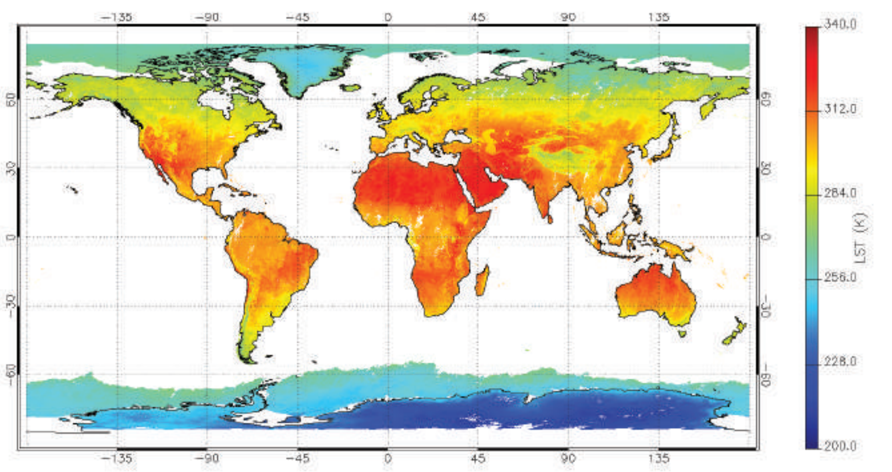


Figure 1: Monthly LST for September 2002 from the Prototype ATSR Climate Data Record

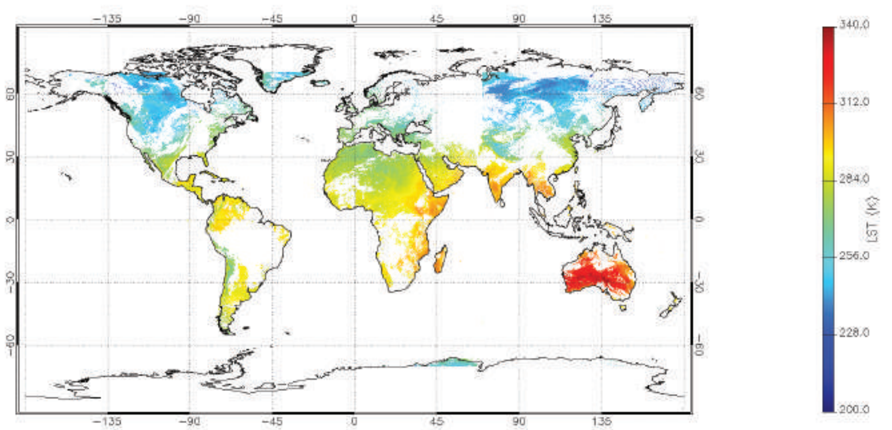


Figure 2: Prototype Merged LST Products at 09:00 UTC on 1st January 2011 combining Geostationary and Low Earth Orbit data

Martyn Chipperfield, Sandip Dhomse, NCEO-Leeds
Wuhu Feng, NCAS-Leeds
Ryan Hossaini, University of Leeds

INCREASES IN STRATOSPHERIC HYDROGEN CHLORIDE

The ozone layer shields the biosphere from harmful UV radiation and is an essential part of the climate system. Solving the problem of ozone depletion depends on the success of the Montreal Protocol, which has essentially banned the production of chlorofluorocarbons (CFC) and similar compounds globally. As a success of the Montreal Protocol their atmospheric burden has decreased during the last decade and scientists are optimistic that ozone levels will fully recover during the second half of this century.

In the stratosphere CFCs break up and release chlorine atoms which then form hydrogen chloride (HCl), the major reservoir of chlorine. Chemical processes in polar winter release the chlorine atoms from this reservoir, which then destroy ozone in polar spring. Observing the long-term evolution of the stratospheric HCl load is a key element in the coordinated effort to monitor the success of the Montreal Protocol in reducing the level of ozone-destroying chemicals.

As part of NCEO work we reported a recent and unexpected increase in atmospheric hydrogen chloride (HCl), potentially signalling a problem with the Montreal Protocol. This work made use of a network of ground-based observations along with satellite observations and global modelling. Our study showed that this unexpected increase has occurred in the Northern hemisphere since 2007, as a result of a temporary but prolonged anomaly in atmospheric circulation (see Figure 1). This circulation change has led to a transient reversal in the decline of HCl which would be expected under the protocol. The satellite observations were key to revealing the altitude dependence and global extent of the HCl changes. In the Southern Hemisphere HCl continues to decrease as expected in line with the Montreal Protocol.

In summary, we found that the increase in HCl levels above the Northern Hemisphere is related to an anomaly in atmospheric circulation, changing the balance between the CFCs and their breakdown product HCl. Therefore the HCl increase is not due to rogue CFC emissions, for example, and therefore do not challenge the general view that the Montreal Protocol is working. They rather show that atmospheric variability will modify the path towards full recovery of the ozone layer.

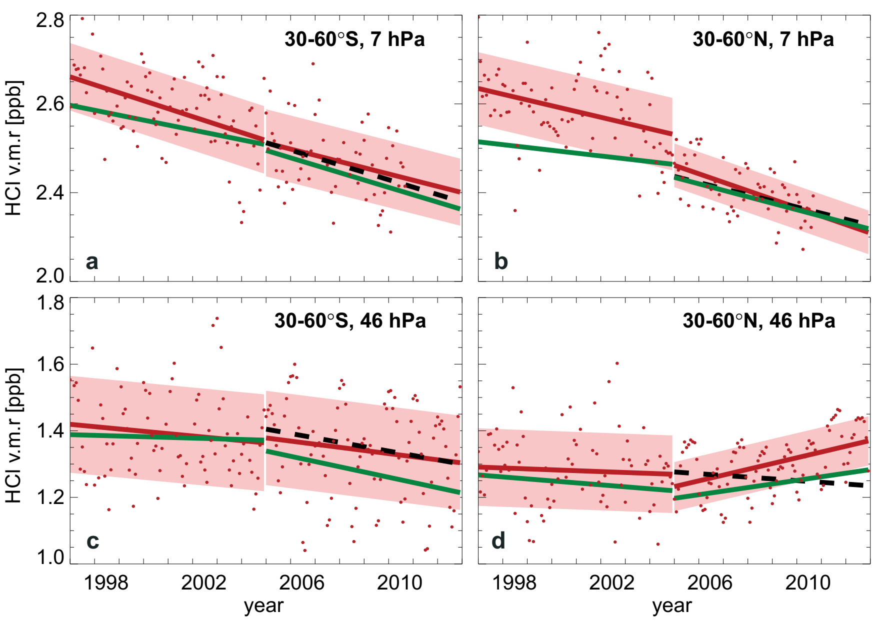


Figure 1: Evolution of stratospheric HCl (in parts per billion by volume, ppb) from satellite observations. Comparison of merged GOZCARDS satellite HCl observations (by HALOE, ACE and Aura/MLS) with SLIMCAT model runs for Northern Hemisphere and Southern Hemisphere mid-latitude lower (46 hPa) and upper (7 hPa) stratosphere. GOZCARDS monthly means are shown as red dots. Linear fits to the GOZCARDS data and standard SLIMCAT run are displayed as red and green lines, respectively, for periods before and after 2005. The dashed black line shows fits to a SLIMCAT which assumes no change in circulation. An upward trend is observed in the Northern Hemisphere lower stratosphere due to circulation changes after 2005 (d) while HCl is decreasing in the southern and northern upper stratosphere (a, b). From Mahieu et al. (2014).

References
Mahieu, E., M.P. Chipperfield, J. Notholt, T. Reddmann, J. Anderson, P.F. Bernath, T. Blumenstock, M.T. Coffey, S. Dhomse, W. Feng, B. Franco, L. Froidevaux, D.W.T. Griffith, J. Hannigan, F. Hase, R. Hossaini, N.B. Jones, I. Morino, I. Murata, H. Nakajima, M. Palm, C. Paton-Walsh, J.M. Russell, M. Schneider, C. Servais, D. Smale and K.A. Walker, Recent northern hemisphere hydrogen chloride increase due to atmospheric circulation change, Nature, 515, 104-107, doi:10.1038/nature13857, 2014.

Martyn Chipperfield, Sandip Dhomse,
NCEO- Leeds

ARCTIC OZONE HOLE AVOIDED BY THE MONTREAL PROTOCOL

The Montreal Protocol is the international treaty aimed at protecting the stratospheric ozone layer which shields life at the surface from damaging ultraviolet radiation. It came into force in 1987 and restricted the use of chlorine and bromine-containing ozone-depleting substances. The atmospheric concentrations of these harmful substances peaked in 1993 and have subsequently declined.

As part of our NCEO research we used the detailed TOMCAT/SLIMCAT 3D computer model of atmospheric chemistry to investigate what would have happened to the ozone layer if the Montreal Protocol had not been implemented. Ozone depletion in the polar regions depends on meteorology, especially the occurrence of cold temperatures at about 20 km altitude – colder temperatures cause more loss. Other studies which have assessed the importance of the Montreal Protocol have used models to predict atmospheric winds and temperatures and have looked a few decades into the future. The predictions of winds and temperatures in these models are uncertain, and probably underestimate the extent of cold winters.

Our study used actual observed meteorological conditions for the past few decades, which gives a more accurate simulation of the conditions for polar ozone loss. Without the Montreal Protocol, the model reveals that a very large ozone hole over the Arctic would have occurred during the recent cold Arctic winter of 2010/11 (Figure 1) and smaller 'Arctic ozone holes' would have become a regular occurrence.

We are already reaping the rewards of the Montreal Protocol, with the ozone layer in much better shape than it would have been without the UN treaty. Our research confirms the importance of the protocol to policy makers and society. We knew that it would save us from large ozone loss 'in the future', but in fact we are already past the point when things would have become noticeably worse.

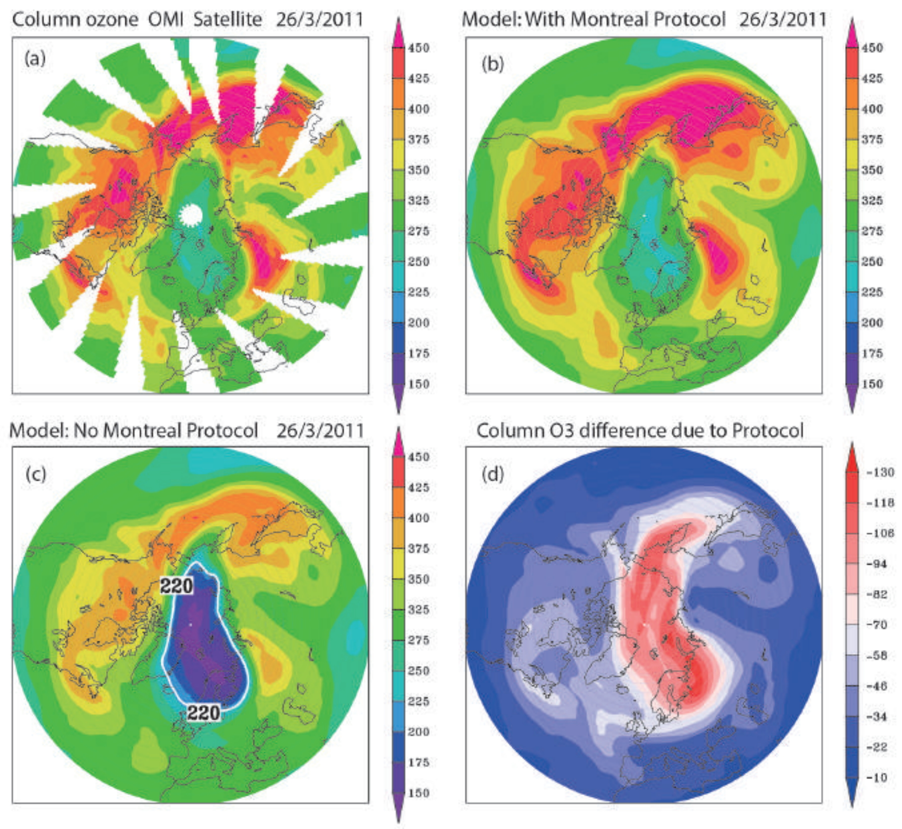


Figure 1: Observations and TOMCAT/SLIMCAT 3-D model simulations for column ozone over the Arctic in March 2011. (a) Observations from the Ozone Monitoring Instrument (OMI) onboard the NASA Aura satellite. (b) Model simulations with a chlorine and bromine scenario which follows the Montreal Protocol, showing good agreement with the observations. (c) Model simulation with chlorine and bromine continuing to increase, i.e. without the implementation of the Montreal Protocol. (d) Difference in column ozone between panels (c) and (b) – i.e. the benefit of the Montreal Protocol.

References
Chipperfield, M.P., S.S. Dhomse, W. Feng, R.L. McKenzie, G. Velders and J.A. Pyle, Quantifying the ozone and UV benefits already achieved by the Montreal Protocol, Nature Communications, 6, 7233, doi:10.1038/ncomms8233, 2015.

A PRACTICAL METHOD TO ASSESS PARAMETER SENSITIVITY AND UNCERTAINTY IN C-CYCLE MODELS

Sylvain Delahaies, Ian Roulstone, NCEO-Surrey
Nancy Nichols, NCEO-Reading

The Carbon cycle is an important component of modelling climate and the Earth system, and a variety of inverse modelling techniques have been used to combine process models with different types of observational data.

The data assimilation linked ecosystem carbon (DALEC) model is a simple box model simulating the carbon budget allocation for terrestrial ecosystems. Intercomparison experiments (Fox et al. (2009); Hill et al. (2012) have demonstrated the relative merit of various inverse modelling strategies (MCMC, ENKF) to estimate model parameters and initial carbon stocks for DALEC using eddy covariance measurements of net ecosystem exchange of CO2 and MODIS leaf area index (LAI) observations. Most results agreed on the fact that parameters and initial stocks directly related to fast processes were best estimated with narrow confidence intervals, whereas those related to slow processes were poorly estimated with very large uncertainties. While other studies (Richardson et al. (2010), Hill et al. (2012)) have tried to overcome this difficulty by adding complementary data streams no systematic analysis has been carried out so far to explain the large differences among results.

We consider adjoint based methods to investigate inverse problems using DALEC and various data streams. Using resolution matrices we study the nature of the inverse problems (solution existence, uniqueness and stability) and show how standard regularization techniques affect resolution and stability properties. Resolution matrices have been used in other areas of earth science, such as seismology, but their deployment in the climate/carbon problem appears to be new. These matrices can be visualised easily, and we have created a user interface that facilitates their application in model-data fusion experiments.

Bloom and Williams (2015) introduced a set of constraints based on *ecological common sense* as an alternative to imposing prior statistics and showed the benefit of this approach. These constraints naturally fit into a constraint optimisation framework, the efficiency and rapidity of this approach allows us to compute ensembles of solutions to the inverse problems from ensembles of perturbed observations from which we can establish the robustness of the variational method and obtain non Gaussian posterior distributions for the model parameters and initial carbon stocks.

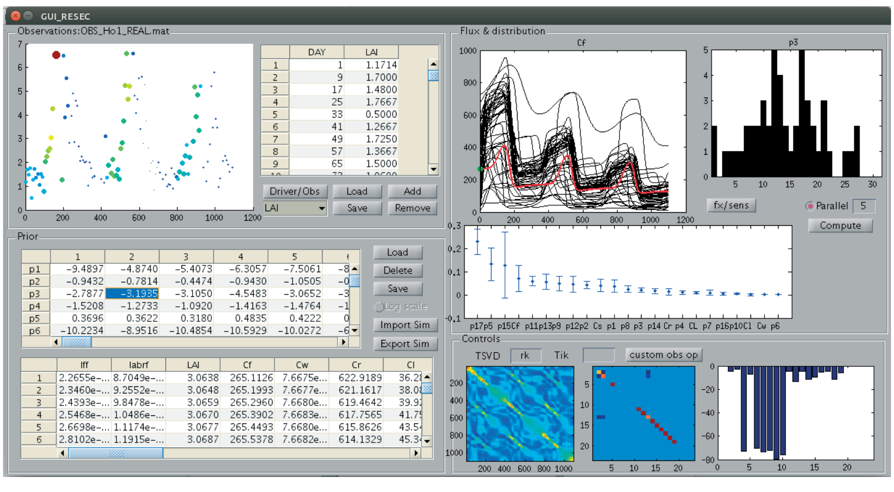


Figure 2: Graphical user interface for the OSSE (Observation System Simulation Experiment) for DALEC. We developed this MATLAB package that facilitate the analysis of the model-data fusion problem for DALEC using a collection of adjoint based tools.

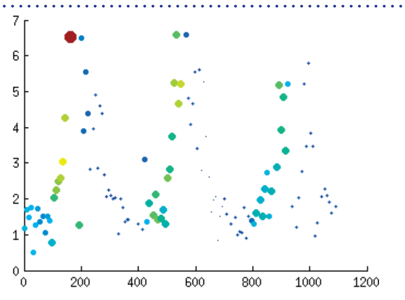


Figure 1: MODIS LAI observations at Howland forest, Maine, US, from January 2001 to December 2003. The data resolution matrix allows us to evaluate the relative contribution of each observation to the reconstruction of the LAI signal. Each observation is colourised with respect to its relative importance (the warmer the colour the more important the observation).

References

Bloom, A. and Williams, M., 2015. Estimating terrestrial carbon dynamics in a data-limited world: assimilating ecological ``common sense” in an ecosystem carbon model-data-fusion framework,Biogeosciences, 12, 1299-1

Fox, A., Williams, M., Richardson, A.D., Cameron, D., Gove, J.H., Quaife, T., Ricciuto, D., Reichstein, M., Tomelleri, E., Trudinger, C.M. and Van Wijk, M.T., 2009. The REFLEX project: Comparing different algorithms and implementations for the inversion of a terrestrial ecosystem model against eddy covariance data. Agricultural and Forest Meteorology, 149:10, 1597-1615.315.

Hill, T.C., E. Ryan and M. Williams (2012) The use of CO2 flux time series for parameter and carbon stock estimation in carbon cycle research. Global Change Biology 18: 179-193.

Richardson, A.D., M.Williams, D.Y. Hollinger, D.J.P. Moore., D.B. Dail, E.A. Davidson, N.A. Scott, R.S. Evans, H.Hughes, J.T. Lee, C.Rodrigues, and K.Savage, 2010, Estimating parameters of a forest ecosystem c model with measurements of stocks and fluxes as joint constraints, Oecologia, 164, 25-40.

Jean-François Exbrayat, Mathew Williams, NCEO- Edinburgh

USING EARTH OBSERVATION TO RECONSTRUCT THE AMAZON'S POTENTIAL BIOMASS

In recent years satellite observations have been used to monitor land-use and land cover change and provide estimates of carbon emissions from deforestation with an unprecedented degree of precision.

However, large-scale clearing and possible regrowth of parts of the Amazon Basin have started well before remote-sensing products became available. The total contribution of the Amazonian deforestation to the historical growth in atmospheric carbon dioxide therefore remains unknown.

To address this lack of knowledge we have reconstructed maps of potential biomass for the Amazon. Potential biomass is defined as the biomass there would exist if deforestation had not occurred. The difference between potential and actual biomass corresponds to the net deficit of biomass that accounts for both deforestation, regrowth and afforestation.

We first trained an algorithm to reproduce biomass in identified intact regions of the Amazon Basin as a function of local past climate. We performed this procedure using the two most recent biomass maps developed by US researchers at NASA's Jet Propulsion Laboratory (Saatchi et al., 2011) and the Woods Hole Research Center (Baccini et al., 2012) as training datasets. Then, we used climate data to apply the algorithm over non-intact regions.

Our results converge to a current biomass deficit of 11.5-12%, or 7-8 Pg C (1 Petagram = 10^{15} g, or 1 billion tonnes). Considering that about 50% of anthropogenic emissions are captured in the land and ocean sinks, we evaluate that past Amazonian deforestation has contributed about 1.8 ppm, or 1.5%, of the ongoing growth in atmospheric carbon dioxide.

The corresponding paper has been covered in worldwide media outlets and blogs and is openly available from the publisher's website.

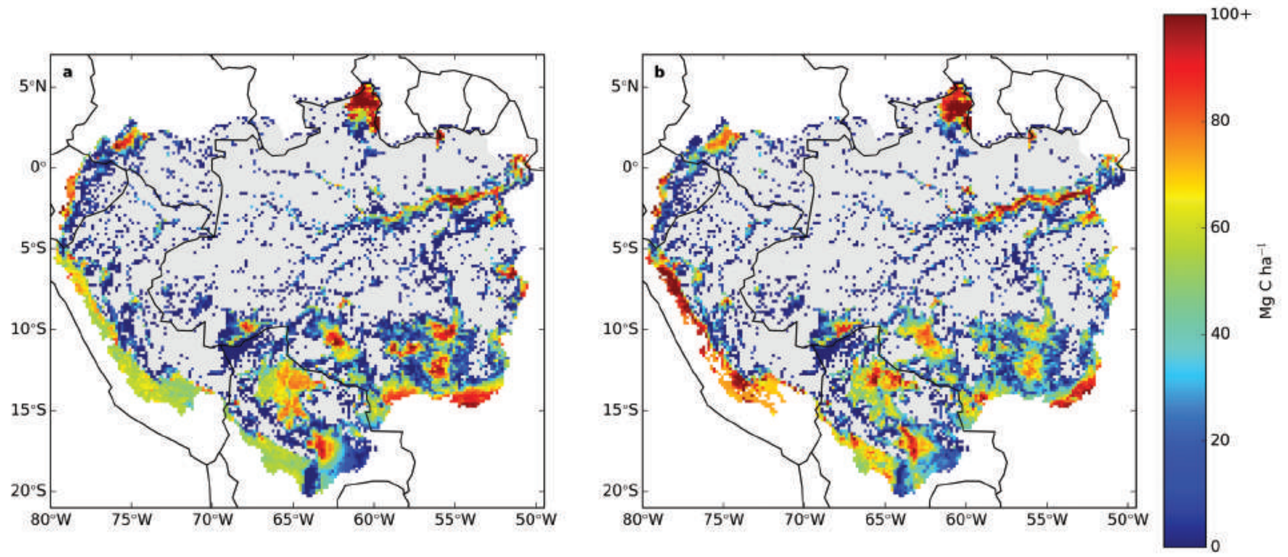


Figure 1: Difference between potential and actual biomass in the Amazon Basin. Intact regions are masked out in grey. Panel a shows results based on the biomass map from Saatchi et al. (2011) while panel b shows results based on the biomass map released by Baccini et al. (2012).

References

Exbrayat, J-F, and M Williams (2015), Quantifying the net contribution of the historical Amazonian deforestation to climate change. Geophys. Res. Lett., 42, 2968–2976. doi: 10.1002/2015GL063497.

Baccini, A., et al. (2012), Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps, Nat. Clim. Change, 2(3), 182–185, doi:10.1038/nclimate1354.

Saatchi, S. S., et al. (2011), Benchmark map of forest carbon stocks in tropical regions across three continents, Proc. Natl. Acad. Sci. U.S.A., 108, 9899–904, doi:10.1073/pnas.1019576108.

Shaun Quegan, Mark Lomas,
NCEO- Sheffield

CALIBRATING THE BIOMASS RADAR: A KEY STEP IN ACCURATE MEASUREMENTS OF FOREST BIOMASS

After a final risk assessment in February 2015, the European Space Agency (ESA) gave the go-ahead to the BIOMASS satellite, which will be the 7th Earth Explorer mission, costing around €470M and with launch around 2020.

This is the very first space mission using P-band (wavelength 70 cm) radar, which gives an unprecedented capability to provide global maps of forest biomass and height every 6 months during the 5-year mission lifetime, at 200 m resolution and with an accuracy of 20% for biomass and 20-30% for height (the accuracy in biomass may seem coarse, but it is comparable with what can be achieved on the ground in tropical forests). Unfortunately, at this long P-band wavelength the ionosphere will strongly affect the signals from the radar, and it is crucial to be able correct these effects and at the same time estimate and correct for imperfections in the radar system. This coupled problem is difficult, so previous attempts to solve it relied mainly on computer simulation and gave little insight into how well the radar must be calibrated to make sure the biomass measurements were sufficiently accurate. This is crucial to the whole design of the instrument and the strategy for monitoring its performance while in orbit. However, new mathematical analysis at the University of Sheffield, funded by NERC and ESA, explains the impact of different system imperfections on estimates of biomass, and allows their contribution to the BIOMASS error budget to be quantified. This is illustrated in the Figure, which shows how two key quantities (antenna cross-talk and channel imbalance) control the accuracy with which biomass can be estimated. This type of calculation forms the basis for the instrument performance ESA will require from the industrial consortium building the BIOMASS satellite, so has important technical and financial consequences. Significantly, design studies by industry indicate that these requirements can be met within the BIOMASS budget and hence pose no threat to the success of the mission.

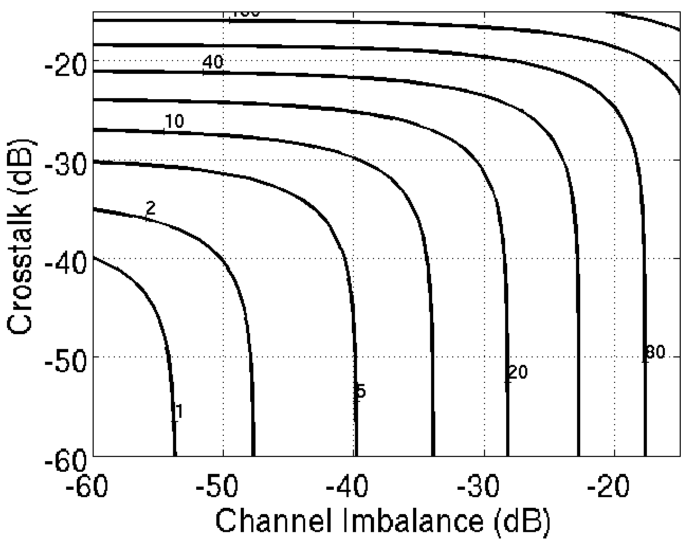


Figure 1: This contour plot shows how the maximum percentage error in biomass (the numbers labelling each contour) are affected by two basic antenna properties, cross-talk (when power leaks between different polarizations) and channel imbalance (when the transmitted powers in the horizontally and vertically polarized signal have slight differences in power or phase on transmit or receive). The key contour is that for a biomass error of 20%, which is the BIOMASS requirement. It can be seen that the channel imbalance term has to be more tightly controlled than cross-talk: it needs to be around 4 dB smaller. These provide key design constraints for industry when building the radar and for operations when the satellite is in orbit.

References

Quegan, S. and Lomas, M. R. (2015). The interaction between Faraday rotation and system effects in synthetic aperture radar measurements of backscatter and biomass, IEEE Trans. Geosci. Remote Sensing, doi: 10.1109/TGRS.2015.2395138.

Quegan, S. and Lomas, M. R. (2015). The impact of system effects on estimates of Faraday rotation from synthetic aperture radar measurements, IEEE Trans. Geosci. Remote Sensing, doi: 10.1109/TGRS.2015.2395076.

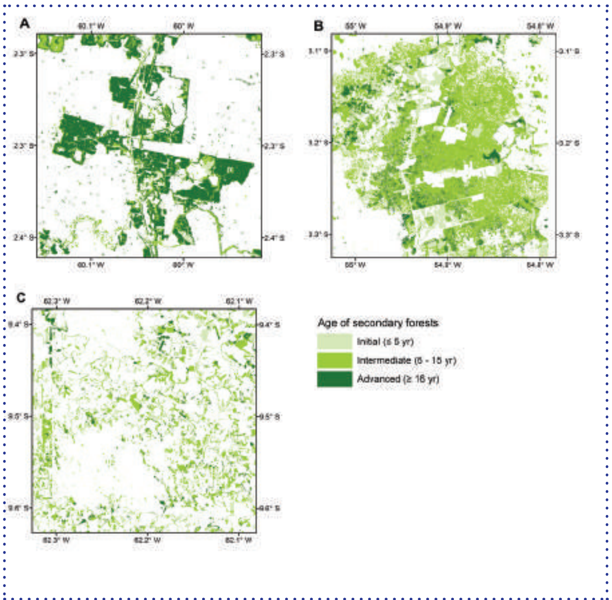
João Carreiras, NCEO- Sheffield
Isabel Rosa, Department of Life Sciences,
Imperial College London, UK

MAPPING AND MODELLING LAND COVER CHANGE DYNAMICS IN THE AMAZON: A SATELLITE CHRONOSEQUENCE APPROACH

Long time series of Landsat satellite data allow us to map major land cover types (e.g., mature forest, secondary forest, non-forest) and processes (e.g., deforestation, regrowth) over the Brazilian Amazon (Carreiras et al., 2014). This provides information about the landscape history in the region, in particular the age of secondary forests (Figure 1), the period of active land use prior to abandonment, the frequency of deforestation, and fragmentation patterns and history. Areas where deforestation started a long time ago (e.g., Manaus, Figure 1A) are characterized by higher incidence of older secondary forests; conversely, younger secondary forests are found in areas with greater frequencies of reclearance and short periods of use between deforestation events (e.g., Pará and Rondônia, Figures 1B and 1C).

Using such a chronosequence of land cover maps, we developed models that predict land cover transitions (forest to deforested, regeneration to deforested or deforested to regeneration) given values of the potential drivers of change in the region, and studied how model performance was affected by the length of the period used to train the models (Rosa et al., 2015). Deforestation of mature forests tends to occur along roads and outside protected areas, reflecting farming establishment, while regeneration tends to occur far from roads and inside protected areas, reflecting land abandonment. Most of the model parameters exhibited no significant temporal trend (Figure 2), but the agreement between model predictions and observed change depended strongly on the year used for calibration.

These studies bring home the importance of long time series of land cover data, not just for observing changes in tropical forest areas, but also for understanding why these changes are occurring and predicting how human intervention, such as road building, is likely to affect future tropical forest structure. This has important consequences for the carbon balance of these forests and for predicting biodiversity patterns, which are strongly affected by the history of landscape fragmentation (e.g., Ewers et al., 2013).



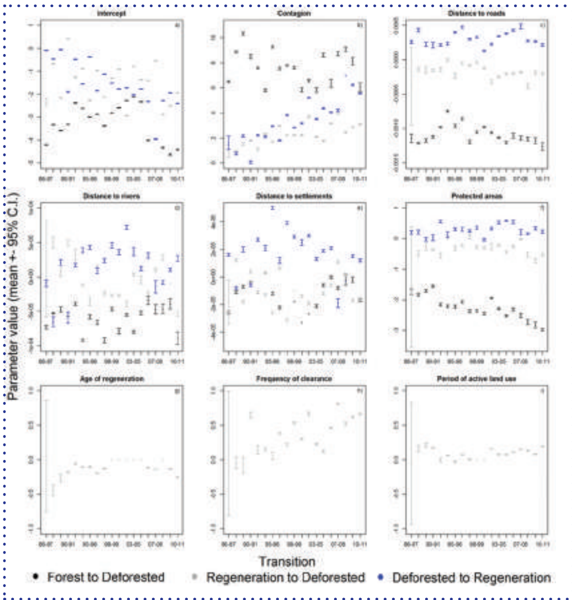


Figure 1 (above): Age of secondary forests in 2010: A) Manaus (Amazonas), B) Santarém (Pará), and C) Machadinho d'Oeste (Rondônia). Differences in the dominant age of secondary forests are clearly visible as well as patterns of landscape fragmentation.
Figure 2 (above right): Mean value of parameters associated with individual drivers of land cover transitions, for models fitted over the period 1986-2011. The ability of protected areas to prevent deforestation increased in strength by 73 % through time (from Rosa et al., 2015).

References

Carreiras, J.M.B., Lucas, R.M., Jones, J., & Gabriel, C. (2014). Land use and land cover change dynamics across the Brazilian Amazon: insights from extensive time series of remote sensing data. PLoS ONE, 9(8), e104144. doi:10.1371/journal.pone.0104144.

Ewers, R.M., Didham, R.K., Pearse, W.D., Lefebvre, V., Rosa, I.M.D., Carreiras, J.M.B., Lucas, R.M., & Reuman, D.C. (2013). Using landscape history to predict biodiversity patterns in fragmented landscapes. Ecology Letters, 16(10), 1221-1233.

Rosa, I.M.D., Purves, D., Carreiras, J.M.B., & Ewers, R.M. (2015). Evaluating the accuracy of land cover change models: sensitivity to calibration year and temporal changes to deforestation processes. Regional Environmental Change, 15(1), 123-137.

MONITORING INDONESIAN PLANTATION AND NATURAL FOREST COVER CHANGES WITH C-BAND ENVISAT DATA

Shaun Quegan, NCEO- Sheffield

Tropical forests are being cleared to provide agricultural and pasture land, but also for conversion to plantations. This has enormous consequences for carbon emissions, biodiversity and livelihoods, so needs to be monitored.

Optical data are very valuable for this purpose, but are often severely hindered by cloud cover. Hence routine monitoring may best be performed using the cloud penetration capabilities of satellite radars. Until recently, it was expected that L-band (24 cm wavelength) radar data, such as those from the Japanese PALSAR 1 & 2 missions, would be most suitable for this purpose. However, recent work carried out in cooperation with the Beijing Institute of Technology and World Wildlife Fund has shown that C-band (6 cm wavelength) may be at least as effective. Fig. 1 shows the separability of key land cover classes in Envisat ASAR (C-band) and PALSAR-1 (L-band) data using the two polarization configurations provided by these sensors (VV and VH for ASAR, HH and HV for PALSAR; HV means horizontal polarization transmitted and vertical polarization received; similarly for the other configurations). The cross-polarized (HV) signal is obviously crucial at L-band, but at C-band both the co- and cross-polarized data help in land cover classification; including L-band does not improve the C-band performance. This has become very important since the new Sentinel-1 C-band satellite will yield 4-5 dual-polarized images per year over the whole tropical belt. This should allow routine monitoring of the dynamics of tropical forests and plantations, as illustrated by Fig. 2. Here a 14-month time series of ASAR data is used to measure changes throughout the year in Riau province, Indonesia. These are dominated by rapid turnover in acacia plantations for wood-pulp; both their clearance and regrowth can be clearly seen. Sentinel-1 is likely to be equally effective in monitoring changes in natural forest.

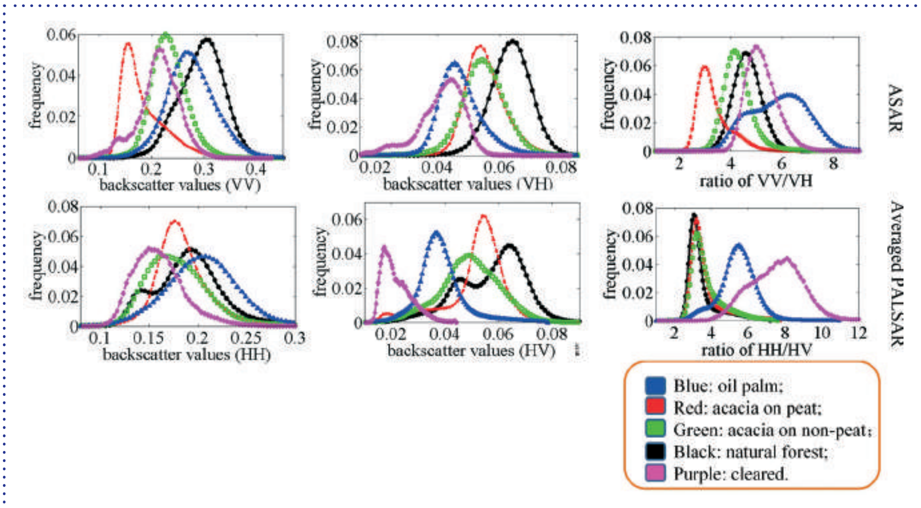


Figure 1 (left): Histograms of backscatter and backscatter ratio for oil palm, acacia growing on peat and non-peat soils, natural forest and cleared regions: (top) ASAR VV, VH and VV/VH; (bottom) PALSAR HH, HV and HH/HV.

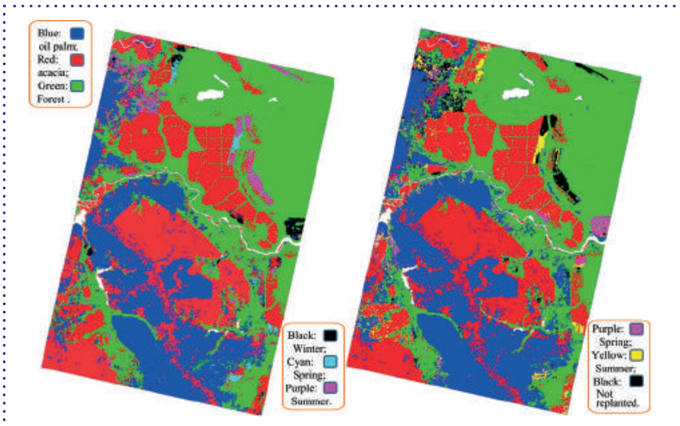


Figure 2 (left, below): Clearance (left) and regrowth (right) maps derived from classifications of an ASAR time series running from August 2010 to October 2011 for Riau province, Indonesia; these changes are dominated by the rapid turnover in acacia plantations planted for wood-pulp.

References

Zeng, T., Dong, X., Quegan, S., Hu, C. and Uryu, Y. (2014). Regional tropical deforestation detection using ALOS PALSAR 50m mosaics in Riau province, Indonesia, IET Electronics Letters, 50, no. 7, 547-549, doi: 10.1049/el.2013.4254

Dong, X., Quegan, S., Uryu, Y., Hu, C. and Zeng, T. (2015). Feasibility Study of C- and L-band SAR Time Series Data in Tracking Indonesian Plantation and Natural Forest Cover Changes, IEEE Jnl. Selected Topics in Applied Earth Observations and Remote Sensing, doi: 10.1109/JSTARS.2015.2400439

Liang Feng, Paul I. Palmer, NCEO-Edinburgh
Hartmut Boesch, Robert Parker, Will Hewson, NCEO-Leicester

ESTIMATING SURFACE FLUXES OF CO_2 FROM SPACE-BASED MEASUREMENTS OF ATMOSPHERIC CO_2

Infrared radiation emitted by the Earth's surface is absorbed by atmospheric CO_2 and other greenhouse gases. These excited gases eventually radiate energy, resulting in a warming of the atmosphere and Earth's surface. Atmospheric CO_2 concentrations are larger now than they have been for at least the past 800,000 years. Recent changes in atmospheric CO_2, attributed mostly to human activities, have led to unprecedented rates of surface warming with far-reaching implications for the future of the Earth system.

Human activities currently emit approximately eight billion tons of carbon into the atmosphere per year. About half of these emissions are removed by the terrestrial biosphere (e.g., trees and vegetation) and by the oceans. These removal processes vary with location and time, reflecting their dependence on atmospheric and land-surface climatological factors, such as solar radiation, temperature, soil nutrients, ocean acidity, and also on atmospheric CO_2 concentrations. A continued effort to observe atmospheric CO_2 is required to understand quantitatively these natural processes and to help underpin effective inter-governmental policies to monitor staged reductions in global CO_2 emissions.

We have in the past relied almost exclusively on surface networks to provide long-term measurements of atmospheric CO_2. Despite substantial investment and effort the combined surface networks currently represent a few hundred stations that are unevenly distributed across the globe, with little coverage over the tropical and polar ecosystems that are most sensitive to changes in climate.

The Japanese Greenhouse gases Observing SATellite (GOSAT) was launched in 2009 to measure atmospheric CO_2 and CH_4 concentrations from space at an unprecedented precision. We now have five years of continuous global observations with a spatial coverage that complements the surface networks (Figure 1).

Instruments aboard GOSAT measure the absorption of back-scattered solar radiation by atmospheric CO_2 at shortwave infrared wavelengths.

NCEO scientists at the University of Leicester have developed computer algorithms to model atmospheric radiative transfer in order to infer dry-air CO_2 columns (X_{CO2}) from GOSAT absorption spectra. Figure 1 shows X_{CO2} retrievals for 2010 (Cogan et al, 2010), which describe many of the large-scale variations in atmospheric CO_2 that we expect.

NCEO scientists at the University of Edinburgh have developed an ensemble Kalman filter technique (Feng et al., 2009) that fits these GOSAT X_{CO2} data to estimate regional surface fluxes of CO_2. Figure 2 shows an example distribution of net surface fluxes (emissions minus uptake) inferred from GOSAT data collected in August, 2009. The international community is still in the infancy of exploiting these satellite data.

New satellites such as the NASA Orbiting Carbon Observatory launched in 2014 will provide improved observation coverage, particularly over cloudy regions, e.g. the Amazon basin. We are working with NASA to develop better retrieval algorithms in order to improve the precision of X_{CO2} retrievals, which will help us to produce more reliable flux estimates and to learn more about the functioning of the global carbon cycle.

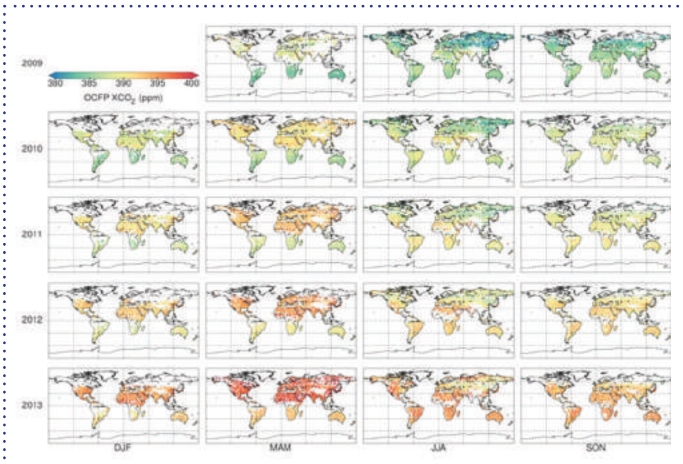


Figure 1: Seasonal mean GOSAT X_{CO2} retrievals from 2009 to 2013. Data are presented on a regular one-degree grid.

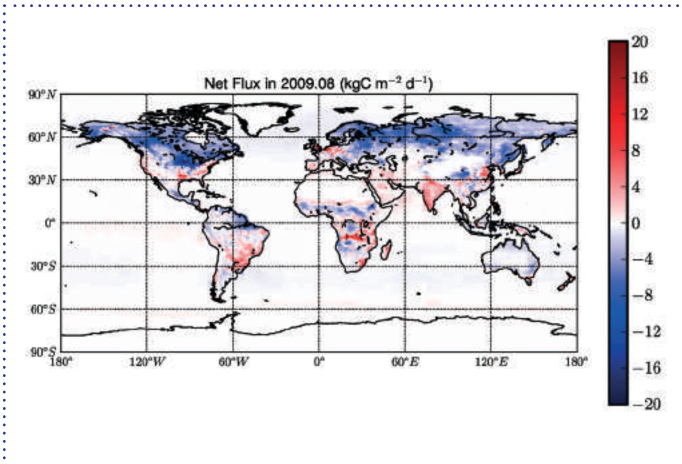


Figure 2: Monthly mean surface CO_2 fluxes for August 2009 inferred from GOSAT X_{CO2} observations using an Ensemble Kalman Filter. Fluxes are described on a 2 degree (latitude) by 2.5 degree (longitude) grid.

PIONEERING METHANE RETRIEVALS IN THE THERMAL AND SHORT-WAVE INFRARED

Richard Siddans, NCEO, STFC Rutherford Appleton Laboratory

RAL's Remote-Sensing Group has developed an optimal estimation scheme to retrieve global height resolved methane distributions from measurements in the thermal infrared (7.9 micron) band of the Infrared Atmospheric Sounding Interferometer (IASI) at relatively high spatial resolution, both day and night, over land and ocean.

The retrieval scheme extracts two independent pieces of information on the profile, with sensitivity extending into the lower troposphere. Column averaged volume mixing ratios derived from the retrieved profile have a precision of 20-40ppbv, and agree well with those from both the groundbased Total Column Carbon Observing Network TCCON and with University of Leicester's retrievals from the satellite shortwave infrared (SWIR) sounder GOSAT (see Figure 1). A paper is currently in preparation (R.Siddans et al., 'Global heightresolved methane retrievals from IASI'). A continuous series of observations are planned by IASI on MetOpA, B and -C, to be followed by IASING on MetOpSG, and monitor methane from 2007 to 2040.

Thermal infrared retrievals have limited sensitivity to methane in the boundary layer compared to shortwave infrared sounders, whereas SWIR offers only column-average information. The RAL and University of Leicester groups in NCEO plan to exploit co-located measurements at high spatial resolution by the Cross-track Infrared Sounder (CrIS) on Suomi-NPP and Sentinel-5 Precursor SWIR channel, to be launched into the A-Train in 2016, in a combined scheme to pioneer near-surface methane retrieval, for improved emissions estimates and wider science exploitation.

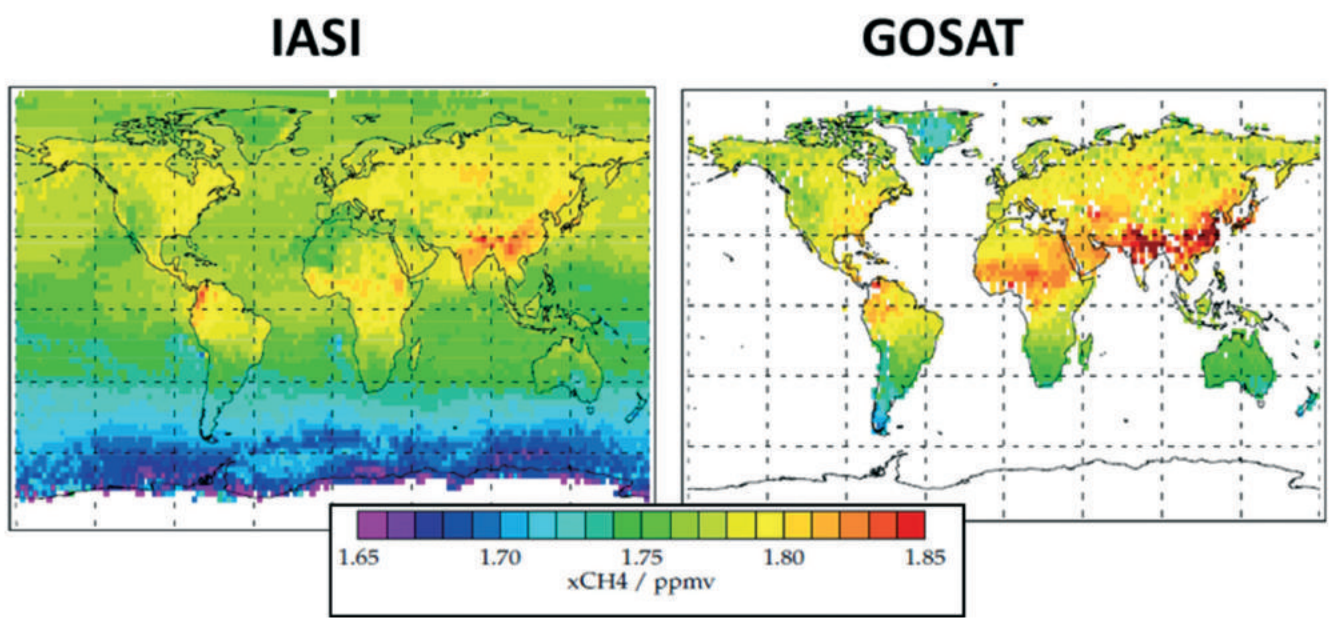


Figure 1: Global methane distribution from RAL's IASI retrieval scheme using the 7.9 micron band in the thermal infrared, compared to the University of Leicester's GOSAT retrieval at 1.6 micron (reflected solar radiation).

Phil Harris, Christopher Taylor NCEO, Centre for Ecology & Hydrology
Sonja Folwell, Belen Gallego-Elvira, Centre for Ecology & Hydrology
Darren Ghent, NCEO-Leicester

LAND SURFACE TEMPERATURE AND CONSTRAINTS ON THE SURFACE ENERGY PARTITION

Soil moisture availability exerts a strong control over land surface energy partition in many regions, affecting processes such as the initiation of convection and the intensity of summer heat waves. Global climate models disagree on when and where evaporation is limited by soil moisture rather than surface net radiation, but direct evaluation of the relevant model processes has suffered from a lack of reliable, global observations of land evaporation. Satellite observations of land surface temperature (LST), however, can provide indirect information about soil moisture constraints on the energy partition.

We have considered cases of the surface drying down through rain-free periods (dry spells), during which the LST warms faster than the overlying air if evaporation is limited by water availability. Because these periods often coincide with settled weather and clear skies, they are also relatively data rich and have less variability in solar radiation, making it easier to separate the effects of soil moisture and energy limitation. By combining observations from dry spells across large regions (Figure 1) it is possible to determine the typical surface responses under different conditions, such as season or land cover type (e.g., forest versus grassland).

In a collaboration between NCEO researchers at CEH and Leicester, we have developed a global 1 km resolution LST dataset from MODIS satellites Terra and Aqua from which we derive a diagnostic of this process suitable for comparison with output from land surface and climate models. This has been used to assess global simulations of the Joint UK Land Environment Simulator (JULES). Results indicate that JULES simulates too little soil moisture limitation in Europe, particularly in spring, and too much in Australia and other semi-arid regions (Figure 2). Similar regional temperature responses are seen when JULES is coupled to its host climate model, MetUM.

We are currently developing techniques to use these data to evaluate the behaviour of the land surface within coupled climate models from the CMIP5 archive. This use of satellite LST is emerging as a powerful tool for the evaluation of surface processes in global models.

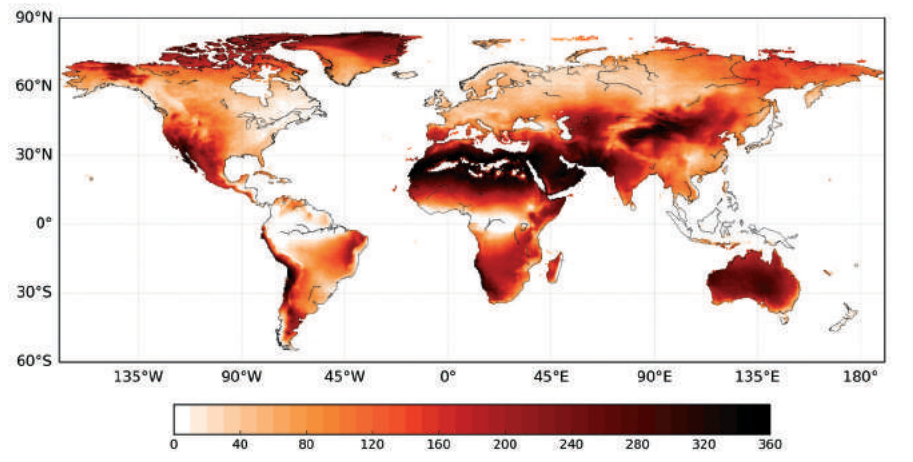


Figure 1: The mean number of days per year that are spent in a dry spell based the on WATCH-ERA Interim gridded precipitation from 2000 to 2012. A dry spell is a period of at least 10 days with less than 0.5 mm precipitation on each day.

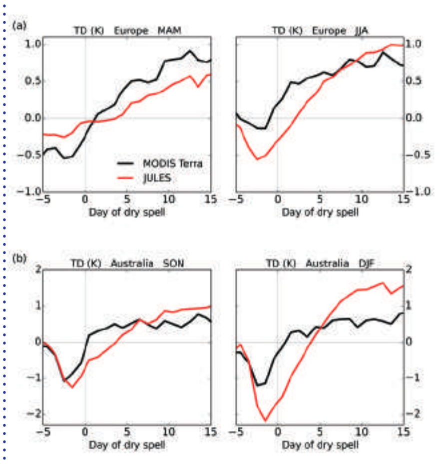


Figure 2: Dry spell composites of the difference between LST and air temperature anomalies, TD, for the spring and summer seasons in (a) Europe (Mar–May and Jun–Aug) and (b) Australia (Sep–Nov and Dec–Feb). Temperature anomalies are calculated for 1030 local time to match the MODIS-Terra overpass time and are relative to clear-sky climatologies.

References
Folwell, S.S., Harris, P.P. and Taylor, C.M. (2015), "Large-scale surface responses during European dry spells diagnosed from land surface temperature", J. Hydromet., Submitted.

URL: www.ceh.ac.uk/science/e-stress-project.html

Helen Brindley, Richard Bantges,
NCEO-Imperial College London

SPECTRAL SIGNATURES OF THE EARTH'S CLIMATE VARIABILITY

Measurements of the Earth's spectrally resolved outgoing longwave radiation (OLR) are directly related to the Earth's energy budget and simultaneously provide information concerning key atmospheric and surface phenomena. They thus represent a powerful tool that can be used to directly monitor the climatic state and detect and attribute change. However, our ability to detect robust changes in spectral OLR requires evaluation of its short-term 'natural' variability over a range of spatial scales.

With this aim, we have quantified inter-annual variability in spectral OLR at a variety of spatial scales using 5 years of observations from the Infrared Atmospheric Sounding Interferometer (IASI) flying on the MetOp-A satellite. Figure 1 shows that the spatial scale has a strong influence on both the magnitude and spectral shape of this variability. At the smallest scales investigated, maximum variability is displayed at high latitudes in regions sensitive to conditions in the low-mid stratosphere (between ~650-700 cm^{-1}). At these scales, the so-called 'atmospheric window' (800-1250 cm^{-1}), highly sensitive to surface temperature and cloud, also shows marked variability. Conversely, at the global scale, the spectral behaviour indicates that temperature and water vapour fluctuations in the mid-upper troposphere play the dominant role in determining year-year OLR variability. This finding is corroborated by observations from NASA's CERES instruments which show a more rapid reduction in inter-annual variability in window as compared to total OLR as spatial scale increases (Figure 2).

Our results, reported in detail in Brindley et al. (2015), highlight the key role that mid-upper tropospheric humidity and temperature plays in modulating the Earth's energy budget at the global scale. Moreover, they also provide an indication of the level of accuracy and length of record that planned satellite missions (e.g. CLARREO, Wielicki et al., 2013) will need to attain in order to robustly detect and attribute long-term changes in the spectral OLR.

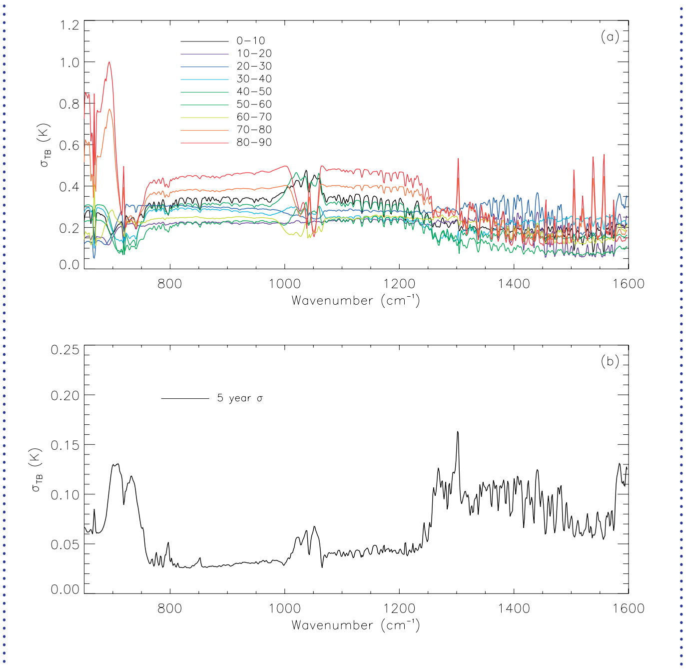


Figure 1: Standard deviation in annual mean, all-sky IASI brightness temperature spectra for (a) 10° zonal means in the Northern Hemisphere (b) Global averages over the period 2008-2012. The IASI spectral resolution has been reduced to 2.8 cm^{-1} for the purposes of related work. Note both the change in brightness temperature scale and spectral shape between (a) and (b). At the global scale, variability peaks between 700-750 cm^{-1} and at wavenumbers greater than 1250 cm^{-1}, regions sensitive to upper tropospheric temperature and mid-upper tropospheric humidity.

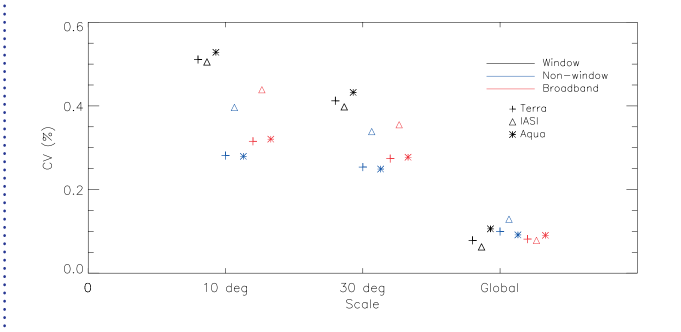


Figure 2: Dependence of the Coefficient of Variation (CV) – a measure of variability – on spatial scale (10° and 30° zonal means and global average) for different spectral regions and instruments. Terra and Aqua refer to NASA's CERES instruments flying on these satellite platforms. For each instrument, 'window' indicates measurements integrated over the atmospheric window region; 'broadband' indicates measurements representative of the full OLR spectrum (excepting IASI, where observations are integrated over the spectral range shown in Figure 1); and 'non-window' is the broadband minus window difference in each case. Note the reduction in variability as spatial scale increases for all instruments, with a faster reduction in the window compared to the broadband signal in each case.

References

Brindley, H. et al., Spectral signatures of Earth's climate variability over 5 years from IASI, J. Climate, 28, 1649-1660, 2015

Wielicki, B. et al., Achieving Climate Change Absolute Accuracy in Orbit, Bull. Amer. Meteorol. Soc., 94, 1519-1539, 2013

GPM OBSERVATIONS OF DEEP CONVECTIVE CORES: EVIDENCE OF MULTIPLE SCATTERING AND PATHWAYS FOR RETRIEVALS

Alessandro Battaglia, Kamil Mroz, NCEO-Leicester
Frederic Tridon, University of Leicester

Space-borne active systems are a unique source of information for the global monitoring of vertical profiles of atmospheric aerosols, clouds and precipitation.

The Global Precipitation Measuring (GPM) constellation of satellites is expected to significantly improve our understanding of Earth's water and energy cycle in the Tropics and the Mid-latitudes (from 65°S to 65°N).The successful launch of the core satellite in February 2014 provides an unprecedented opportunity to check the physical consistency between observations and microwave electromagnetic propagation and backscattering models in precipitating media. The GPM core satellite is equipped with the first-ever dual-frequency precipitation radar operating at Ku (13.6 GHz) and Ka (35.5 GHz) band [Hou et al, 2013] and is capable of mapping the three dimensional structure of precipitating systems (see Fig. 1.).

The interpretation of space-borne radar signal can be complicated by the presence of multiple scattering, a phenomenon well documented in the lidar community but also in CloudSat data. At the University of Leicester special attention has been paid to investigate signatures of multiple scattering enhancement in the GPM dual-frequency precipitation radar signal. Examples of such signatures are the absence of surface reflectivity peaks and anomalously small reflectivity slopes in the low troposphere at Ka with respect to Ku [Battaglia et al., 2015]. Anomalous sloping appears because the attenuation at Ka band is partly compensated by second and successive orders of scattering caused by the highly scattering ice layer in the high troposphere (see Fig. 2.).

Unfortunately the currently implemented precipitation algorithms do not account for multiply scattered radiation which introduces a significant bias in rainfall estimates in deep convective systems. Our current study is focused at including multiple scattering effects into Level 2 products. We developed an optimal estimation microphysical retrieval [Battaglia et al. 2015] that is intended to be applied to convective cores. The algorithm is currently being tested for several cases over the continental United States and is believed to significantly improve rainfall estimates for heavy precipitation compared to the at-launch version of the standard algorithms.

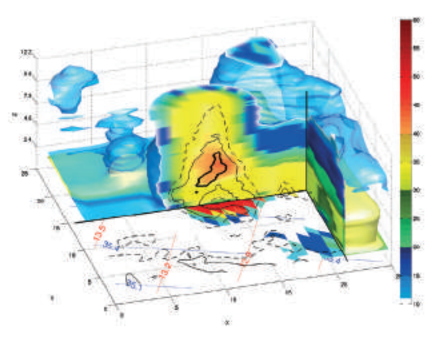


Figure 1: Three dimensional structure of a convective event observed by the Dual-Frequency Precipitation Radar on 9 September 2014 at 17:58Z over 13.1oN, 35.75oE over the eastern edge of the clay plains in Sudan. The colour modulates measured radar reflectivity factor at Ku band in dBZ (see colour bar). The black dash, thin and thick solid contour lines correspond to 10, 16 and 22 dB differences between Ku and Ka reflectivities, respectively. Note the region in the lower troposphere where such difference is increasing (instead of decreasing) with height, a signature of multiple scattering. The colour map at the surface shows the Ku-band path integrated attenuation in dB (doubled). Blue and red texts indicate the latitude and longitude coordinates.

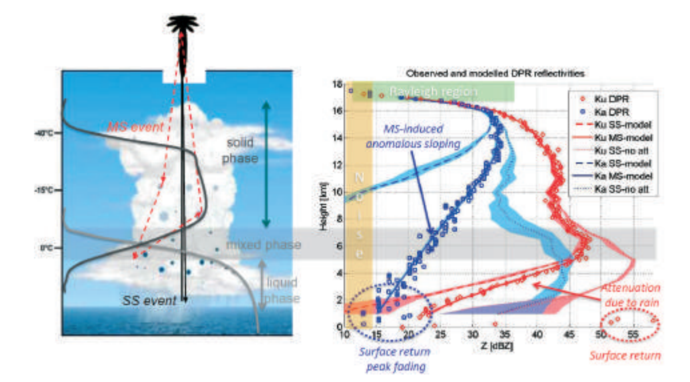


Figure 2: Left: schematic of the multiple scattering mechanism in a convective cloud. Radar echoes are typically interpreted by single-scattering theory with a direct conversion of the time delay between emission and reception of the energy backscattered by hydrometeors into target range. In presence of multiple scattering the power received after two or more scattering orders (red arrows) is misplaced and appears at ranges larger than those characteristic of the illuminated targets (black arrows). Hence, a scattering layer high up in the atmosphere can significantly modify the radar return further down in the profile. Right: measured and modelled dual-frequency precipitation reflectivities for the profile in the core of a convective system. Red and blue colours correspond to Ku and Ka reflectivities in dBZ. Circles represent the measurements, dashed (dotted) lines correspond to the (non-) attenuated single scattering forward-modelled profiles. Two main characteristics of multiple scattering affected profiles can be highlighted: 1) at Ka band, below 6 km, multiple scattering enhancement partly compensates for attenuation. As a result the reflectivity signal appears to decrease at a rate lower than at Ku (anomalous sloping pinpointed by the arrows) while the presence of high rain rates is predicted by single scattering theory to produce Ka attenuation seven times larger than at Ku; 2) while the signal is above the noise level down to the surface, the surface return at Ka band is not as clear as at Ku band (blue and red ellipses), a sign that attenuation is very strong and that the signal in the lower levels is primarily coming from multiple scattering.

References

Hou, A. Y., R. K. Kakar, S. Neeck, A. A. Azarbarzin, C. D. Kummerow, M. Kojima, R. Oki, K. Nakamura, and T. Iguchi, 2013: The Global Precipitation Measurement (GPM) Mission. Bull. Amer. Met. Soc., 95, 701–722, doi: http://dx.doi.org/10.1175/BAMS-D-13-00164.1.

Battaglia, A., S. Tanelli, K. Mroz, and F. Tridon, 2015: Multiple scattering in observations of the GPM dual-frequency precipitation radar: evidence and impact on retrievals. J. Geophys. Res., 10.1002/2014JD022866

Battaglia, A., K. Mroz, F. Tridon, S. Tanelli, P.-E. Kirstetter, 2015. Multiple-scattering-induced "ghost echoes" in GPM-DPR observations of a tornadic supercell. J. Appl. Meteor. Climatol. Submitted.

Richard P. Allan, NCEO-Reading

CHANGES IN EARTH'S HEATING RATE BETWEEN 1985 AND 2013

Understanding how Earth is currently heating up now helps us to gauge how much the planet is going to warm in the future. This is vital for making decisions on how to adapt to and mitigate climate change. We collaborated with NASA and the Met Office to analyse computer simulations and satellite measurements from the Earth Radiation Budget Satellite wide field of view instrument (ERBS WFOV) and the Clouds and the Earth's Radiant Energy System (CERES) instrument (on the Terra satellite) combined with ocean observations to assess how Earth's heating rate has varied.

Earth is heating up since it is absorbing more sunlight energy than it is losing to space through emitted heat. Energy is currently building up at the rate of 0.6 Watts for each square metre of the globe (equivalent to every person currently alive on Earth using about 20 kettles each to slowly and continuously boil the oceans!). We found that climate simulations are able to capture variations in this heating rate due to natural factors such as volcanoes (which cool the planet) and changes in the ocean relating to El Niño/ La Niña (which have both cooling and heating effects).

The results also show that while surface warming rates decreased between the 1985-1999 and the 2000-2013 periods, heating of Earth actually increased. This is consistent with the rising concentrations of greenhouse gases and indicates that more of the accumulating energy is heating deeper layers of the ocean in the recent period due to natural oscillations in the oceans. We therefore conclude that heating of the oceans and rapid warming of the surface is likely over the coming decades.

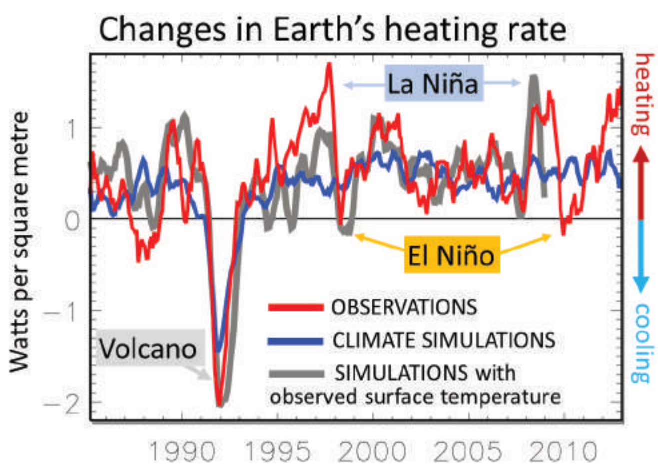


Figure 1: Changes in Earth's yearly average heating rate (absorbed sunlight minus outgoing infrared radiation) from observations and simulations 1985-2013. Shown here are observations based on satellite data and ocean measurements and averages of 9 coupled atmosphere-ocean simulations applying realistic radiative forcings (CMIP5) atmosphere-only climate model (AMIP5) simulations which applied observed sea surface temperatures and realistic radiative forcings. These were adjusted to match the observed average heating rate over the 2005-2010 period to focus on comparing the variability in heating rate. Earth loses heat following large volcanic eruptions such as Mt. Pinatubo in 1991 and during the strongest El Niño events such as 1998 while the heating rate becomes larger during La Niña episodes when the ocean surface is relatively cool. The coupled CMIP5 simulations are not designed to simulate the timing of El Niño and La Niña but all datasets simulate the response to Mt. Pinatubo and a slight increase in Earth's heating rate over the whole period.

References

Allan, R. P., C. Liu, N. G. Loeb, M. D. Palmer, M. Roberts, D. Smith and P.-L. Vidale (2014) Changes in global net radiative imbalance 1985-2012, Geophysical Research Letters, 41, 5588-5597, doi:10.1002/2014GL060962

Smith, D., R. P. Allan, A. C. Coward, R. Eade, P. Hyder, C. Liu, N. G. Loeb, M. D. Palmer, M. Roberts, and A. A. Scaif (2015) Earth's energy imbalance since 1960 in observations and CMIP5 models, Geophysical Research Letters, 42, 1205-1213, doi:10.1002/2014GL062669

Additional communication:

ENSO blog: https://www.climate.gov/news-features/blogs/enso/role-ocean-tempering-global-warming

Conversation: http://theconversation.com/heat-accumulating-deep-in-the-atlantic-has-put-global-warming-on-hiatus-30805

Departmental Blog: http://blogs.reading.ac.uk/weather-and-climate-at-reading/2014/has-global-warming-taken-a-holiday/

Carbon Brief: http://www.carbonbrief.org/blog/2014/07/slow-surface-warming-since-1998-is-not-exceptional-say-scientists/

J. Christine Chiu, NCEO-Reading
Matthew Young, University of Reading
Charles Williams, NCAS-Climate, University of Reading

WARM RAIN DETECTION FROM GEOSTATIONARY SATELLITE OBSERVATIONS

Rainfall information is extremely vital for the African continent. It is a key element for monitoring flood and drought, and for understanding how precipitation patterns might change in a warmer climate. Consequently, this has a huge impact on rain-fed agriculture, food security and climate adaptation. Unfortunately, the African continent has the lowest rain-gauge density in the world, and thus monitoring rainfall must rely on satellite observations.

Satellite observations, however, have limitations. They have difficulty in detecting rain from shallow, warm, low-topped clouds, because distinguishing signals from warm land surface and warm clouds is challenging, and because thick clouds aloft often obscure the signal from below. Thanks to spaceborne radar measurements from the CloudSat mission that started in 2006, we now have the ability to probe vertical structures of precipitating clouds and detect warm rain. However, on their own these radar measurements are not suitable for rainfall monitoring due to limited swaths and infrequent temporal sampling.

To better monitor warm rain and enhance temporal resolution from twice a day to hourly sampling, we develop a new warm rain delineation method that uses geostationary shortwave radiation measurements. Focusing on southern West Africa which is experiencing unprecedented population and economic growth (Knippertz, et al., in press), our results show that warm rain dominates in August and is frequent during June–October. Warm rain also occurs more frequently from late morning to afternoon in hills, highland regions, and along the Guinea coast, as depicted in the figure.

Although we can now monitor warm rain frequency much better, warm rain amounts are still a huge challenge. Interestingly, we found that, the warm rain regions mentioned above are coincident with those where satellite-based rainfall estimates are significantly underestimated compared to rain gauge measurements; much more research is needed to make robust and reliable estimates for these problematic regions.

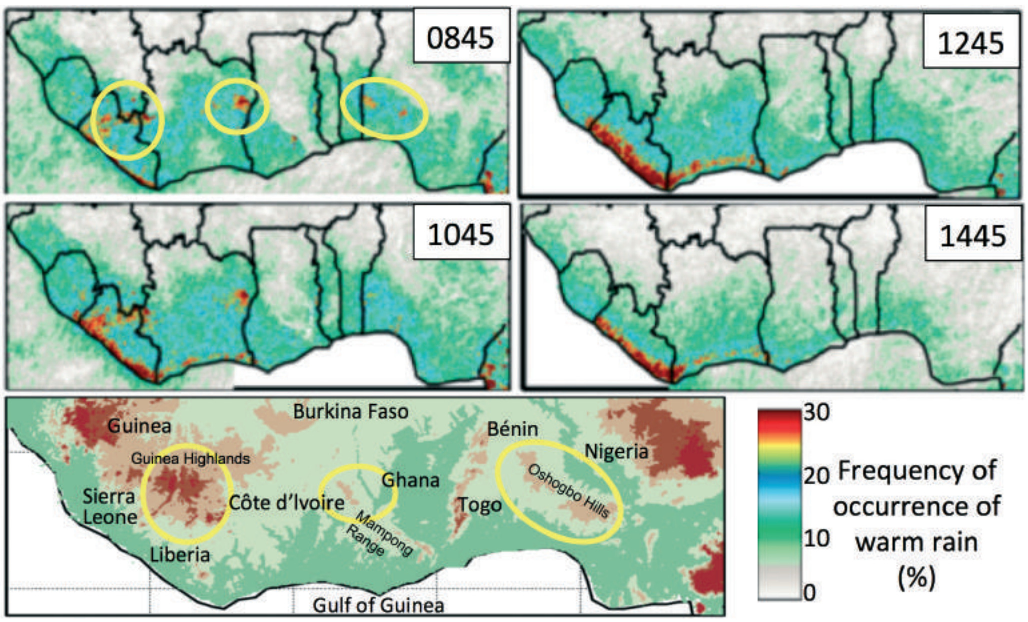


Figure 1: Frequency of warm rain occurrences during 0845 – 1445 UTC in August for southern West Africa. Warm rain is frequent along the coast in the entire time period, while it is most frequent in hills and highland regions (yellow circles) in early mornings. How southern West Africa will respond to climate change remains uncertain, knowledge of warm rain location and frequency will greatly help constrain models and improve representation of warm rain processes.

References
Knippertz, P., H. Coe, J. Chiu, M. Evans, A. Fink, N. Kalthoff, C. Liousse, C. Mari, R. Allan, B. Brooks, S. Danour, C. Flamant, O. Jegede, F. Lohou, and J. Marsham, 2015: The DACCIWA project: Dynamics-aerosol-chemistry-cloud interactions in West Africa. Bull. Amer. Meteor. Soc. doi:10.1175/BAMS-D-14- 00108.1, in press.

Phil M Browne, David Livings, Peter Jan van Leeuwen, NCEO-Reading

THE EMPIRE DATA-ASSIMILATION SOFTWARE SYSTEM

Data assimilation is a tool to combine observations of a system with a numerical computer model of that system. It is a technique used in all geoscience fields, and gaining popularity rapidly as it allows for better forecasts, but also better understanding of the system at hand. In weather forecasting the system is the atmosphere, the observations consists of millions of local and satellite observations of the atmosphere, and the model is a highly sophisticated numerical computer code that describes the evolution of the atmosphere. Large parts of the data-assimilation code are independent of the model, and can be generalized. NCEO is developing a data-assimilation framework, or rather software package, called EMPIRE that can be coupled easily to any geoscience model of choice, making data assimilation a mainstream tool in geoscience research.

The basic strategy of EMPIRE relies on keeping the model separate from any data assimilation code, and coupling the two through the use of Message Passing Interface (MPI) functionality. The figure shows the structure of the coupling.

In practice the coupling is such that the whole state vector of the model is sent to the data-assimilation code, changed there by incorporating observation information, and sent back to the model. This strategy limits the changes necessary to the model and as such is rapid to program. Also, because the code changes are minimal and logical, researchers can do this themselves, or with little technical support.

We studied the performance of the coupling in detail. The table gives an example of the performance reduction from the MPI communication overhead for the climate model HadCM3, with over 2 million variables. The times relate to one day, which consists of 72 model time steps.

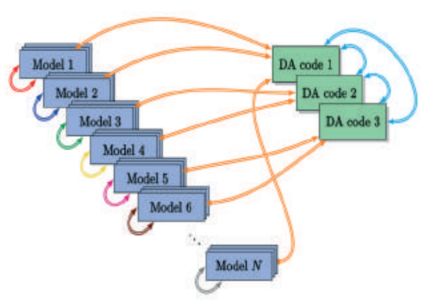


Figure 1: Communication structure of the data-assimilation with the EMPIRE system. The left-hand side of the figure depicts the copies of the model used in the ensemble data-assimilation method. The almost closed circular arrows denote internal MPI communication as happens in any large-dimensional model. On the other side is the data-assimilation code with its internal communication. The new element is the coupling of the two directly via MPI. This allows the model and the data-assimilation code to be separate executables, which allows for minimal changes to the model.

Number of ensemble members	Number of cores used	Model only time (s)	Model plus MPI communication time (s)
1	36	4.6	5.5
3	108	4.6	5.5
7	252	4.6	5.5
15	540	4.6	5.5
31	1116	4.6	5.5
62	2332	4.6	5.5

The coupling adds an extra 20% compute time, and the good news is that it scales perfectly with increasing number of model copies and number of compute cores. The implementation technique is applied in different models with state dimension up to 2.7 108. The latter is the operational weather prediction model used by the Met Office, the Unified Model. The overhead was only 7% in that case, showing that the larger the model the smaller the MPI overhead.

We have coupled the system to several models, including the climate model HadCM3, the weather prediction Unified Model, the ocean model NEMO, the solar wind model ENLIL, the shallow-water finite element model TELEMAC (used e.g. for storm surge forecasting in the North Sea), a 1-dimensional version of the bio-geochemistry model ESRIM, the land-surface evolution model JULES, and others.

Concluding, the data-assimilation software system EMPIRE contains state-of-the-art data-assimilation methods and models, and will revolutionize the way data assimilation supports the UK geoscience community.

Tristan Quaife, NCEO-Reading

IMPROVING ESTIMATES OF SOIL MOISTURE IN AFRICA USING THE JULES-EMPIRE DATA ASSIMILATION SYSTEM

The EMPIRE software, developed by NCEO, is an ensemble based Data Assimilation system designed to be easily coupled with complex dynamic models (Browne and Wilson, 2015). We have integrated EMPIRE with JULES, the land surface scheme of the UK Met Office, to enable the assimilation of Earth Observation data so as to provide optimal estimates of the true state of land surface based on our knowledge of uncertainties in both the model and the observations.

One application which we are using the JULES-EMPIRE system for is to improve estimates of the soil moisture in sub-Saharan Africa to provide better information to weather-index based insurance firms. Such firms provide a cost effective means of insuring the least well-off farmers as they rely only on readily available precipitation data. However the relationship between precipitation and crop failure is not always very accurate; there are many other factors which affect the amount of water available to plants. Our solution is to apply a combination of models and satellite data.

For a site near Tamale in Ghana for 2008 the figure shows an ensemble of JULES model estimates of soil moisture (blue lines and shaded area) and the JULES-EMPIRE predictions which have been produced by assimilating observations from the European Space Agency (ESA) Climate Change Initiative (CCI) Soil Moisture data set (green lines and shaded area). The CCI observations themselves are shown as red dots.
The high frequency (spikey shaded areas) low frequency (smooth lines) components have been separated out to ease interpretation. The JULES-EMPIRE system captures the variability in the ESA data better than the JULES model running on its own. We are currently working on using this system to produce large scale maps of soil moisture for countries in Africa as well as efforts to provide independent validation of the method.

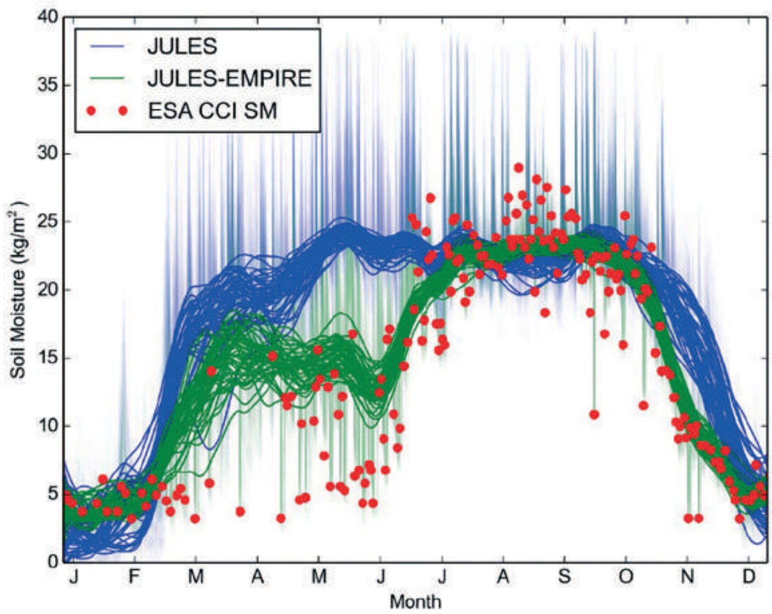


Figure 1: For a site near Tamale in Ghana for 2008 the figure shows an ensemble of JULES model estimates of soil moisture (blue lines and shaded area) and the JULES-EMPIRE predictions which have been produced by assimilating observations from the European Space Agency (ESA) Climate Change Initiative (CCI) Soil Moisture data set (green lines and shaded area). The CCI observations themselves are shown as red dots.

References
Browne P.A. and Wilson S. (2015) A simple method for integrating a complex model into an ensemble data assimilation system using MPI. Environmental Modelling & Software. 68, pages 122–128.

Mengbin Zhu, University of Reading
Peter Jan van Leeuwen, Javier Amezcua,
NCEO-Reading

TOWARDS ROBUST FULLY NONLINEAR DATA ASSIMILATION

Data assimilation is the science of combining observations of a system with a numerical model of that system. It is used extensively in weather prediction, where atmospheric models are informed by observations of the atmosphere every 6 hours about the actual state of the atmosphere, before actual forecast are made. It has been known for centuries how to do data assimilation, following a Theorem by Bayes, but, unfortunately, that theorem can only be applied to very small systems. This means that for large geophysical systems approximations have to be made. Present-day data-assimilation methods as used in for instance weather prediction are based on simplifications, in which nonlinear relations are approximated as being linear. While this procedure has been hugely successful its limitations are starting to become visible in highly nonlinear systems, such as accurate prediction of convective systems.

Nonlinear data-assimilation methods are available but typically too expensive to be used in high-dimensional systems. This is sometimes called the curse of dimensionality. However, funded by NCEO, we recently managed to produce methods that are fully nonlinear and cure the curse. An example is the so-called Equivalent-Weights Particle Filter, which we are using now even on systems as complex as climate models, as reported elsewhere in this brochure. The method is based on ensemble integrations of the model, in which several copies of the model with slightly different starting points and forcings are run in parallel to explore the model space, allowing us to focus on those model copies that are closest to all observations.

As issue with these new methods is that they have several tuning parameters, and the tuning takes time and is expensive. This motivated the search for more robust particle filters with less, or even no tuning parameters. A step in that direction is the so-called Implicit Equal-Weights Particle Filter. What it essentially does is it changes the model slightly so that it forces the model towards the observations. To compensate for these model changes the model states are slightly displaced at observation times. Interestingly, this whole process is well defined mathematically, and it can be shown that we do solve the original full nonlinear data-assimilation problem.

The figures show results of experiments in high-dimensional linear and nonlinear systems using only 20 particles, so only 20 model runs. These results show that we can beat the curse of dimensionality, and that without tuning we achieve consistently good results in very different systems, demonstrating the robustness of this new method.

The new nonlinear data-assimilation method is much more robust than previous variants and opens the road to efficient data-assimilation in real geophysical systems.

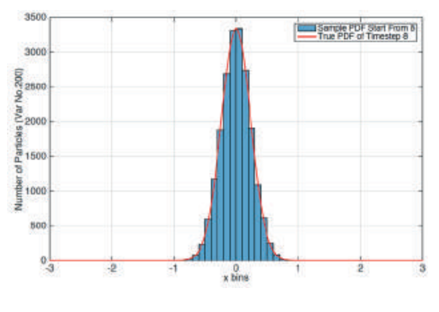


Figure 1: A probability density function (pdf) at a certain gridpoint in a 1000-dimensional linear system. The red line denotes the true pdf, and the blue histogram the estimated pdf using only 20 particles, so 20 model runs, accumulating statistics over a large number of time steps. This shows that we can beat the curse of dimensionality and perform robust nonlinear data-assimilation.

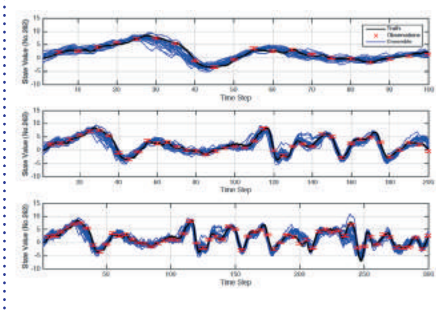


Figure 2: Results of the new particle filter on the 1000 dimensional Lorenz 1996 model, using again only 20 particles. Only the first 500 grid points are observed, the other 500 are not observed. Shown is the time evolution of the truth in black, and the 20 particles in blue, with observations and their errors in red. Note the different horizontal time axes in the three plots. The particles follow the truth faithfully, and their spread is close to observational errors, demonstrating good performance of the new filter in this highly nonlinear high-dimensional system.

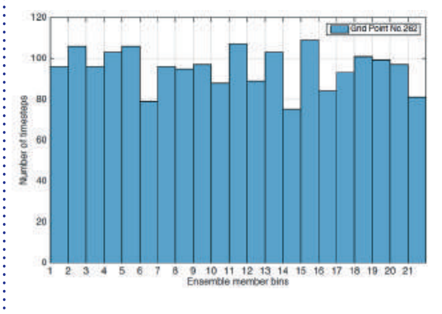


Figure 3: Similar to figure 2, now showing a rank histogram at one observed grid point. A rank histogram depicts the accumulated statistics of where the observation ranks in the 20 particles. If the quality of the data-assimilation scheme is good the rank histogram is flat, with some noise on top of that, as indeed we find in our experiment, again showing that the new method is doing a good job.

References

Zhu, M., P.J. van Leeuwen, and J. Amezcua, Implicit Equal-Weights Particle Filter, Submitted to Quarterly J.Royal Meteorol. Soc. 2015.

Phil Browne, Peter Jan van Leeuwen, NCEO- Reading

CLIMATE MODEL INITIALISATION USING FULLY NONLINEAR DATA ASSIMILATION

Climate models have been used extensively to predict our future climate. For prediction a few decades or more ahead one focuses on the statistics of the models to infer for instance rain frequency in a certain area. However, on the shorter timescales from seasons up to a decade, the starting point of the climate model is of importance for these statistics, related to the correct representation of larger-scale patterns in ocean and atmosphere. To this end the models are informed of the real state of the ocean-atmosphere system via observations. Combining the models with observations is called data assimilation, in which the models assimilate the observational data.

Present-day data-assimilation methods are based on simplifications, in which nonlinear relations are approximated as being linear. This procedure has been hugely successful in weather prediction, at least for the larger scales, but climate models are so nonlinear that these linearisations can fail significantly.

Here we report on using a fully nonlinear data-assimilation method, a so-called particle filter, to perform the data assimilation. Particle filters tend to be very expensive for high-dimensional systems like climate models, but a recent breakthrough, funded via NCEO, has allowed us to develop particle filters that are efficient even in very high dimensional systems.

We successfully used the so-called Equivalent-Weights Particle Filter on the climate model HadCM3.

A crucial aspect is a proper statistical modeling of the errors in the model equations. The first figure shows a small part of the covariance we used, between the atmospheric and oceanic velocities. It shows that in most places the correlation between the two is plus or minus one, consistent with known ocean-atmosphere interactions.

We then proceeded by testing the data-assimilation experiment using observations generated by the model itself. Only the temperature of the sea-surface was observed at all ocean grid points of the model, once every day. We investigated how this information spreads through the rest of the climate model during the fully nonlinear data assimilation run. The second figure shows how the observation information from the upper surface of the ocean is spread into the deep ocean by the data-assimilation scheme. Visible is that the signal is lost at depth greater than 100 meter.

The newly developed fully nonlinear data-assimilation methods are successful on climate models, demonstrating that fully nonlinear data-assimilation is possible in very high-dimensional systems.

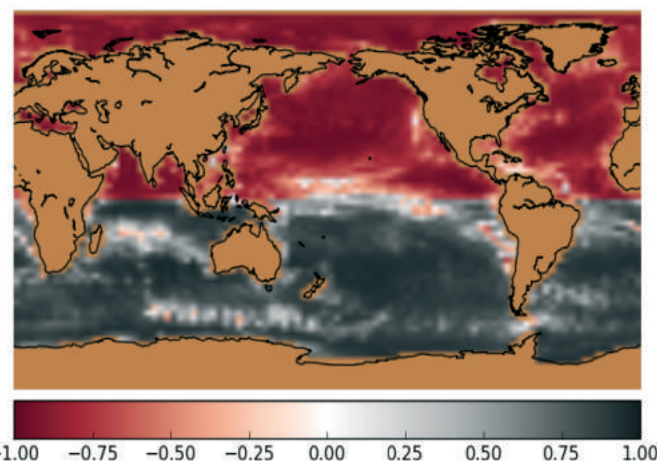


Figure 1: The point-wise correlation between the zonal atmospheric velocity and the meridional ocean velocity for the climate model HadCM3. These correlations are used to describe errors in the model equations in the nonlinear data-assimilation scheme. The strong positive (southern hemisphere) and negative (northern hemisphere) correlations are related to well-understood Ekman dynamics. The white areas denote areas where the ocean velocities are highly nonlinear and the linear Ekman theory does not hold.

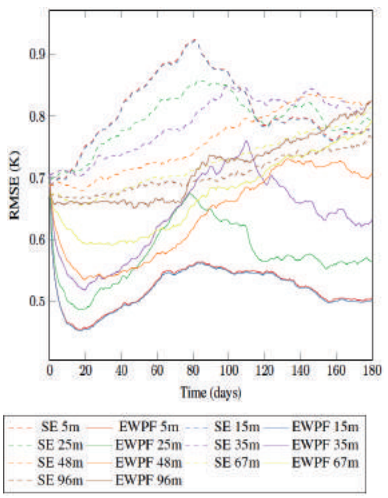


Figure 2: The solid lines are the root-mean-square differences between the ocean temperature after the nonlinear data assimilation and the true ocean temperature, averaged at different depths. The dashed lines are the root-mean-square differences of the free model run and the true temperatures. This shows that 1) the assimilation successfully constrains the ocean temperature when only the temperature at the surface is observed, but 2) the effect is limited to about 100m. To constrain the deeper ocean other observations are needed.

References

Browne, P.A., and P.J. van Leeuwen, Twin experiments with the Equivalent-Weights Particle Filter and HadCM3, Q.J.Royal.Meteorol. Soc., In Press, 2015.

TOWARDS A PRACTICAL LAND SURFACE MONITORING SCHEME IN THE SENTINEL ERA

Jose Gómez-Dans, Philip Lewis, NCEO-UCL

The ESA Sentinels present a challenge: various sensors with different properties require robust approaches to combining and interpreting the resulting data, exploiting the contrasting characteristics of each sensor to provide the best estimate land surface state. Part of this challenge is to develop models that are consistent across the thermal, optical and microwave domains, ensuring that assumptions about e.g. vegetation structure are coherent. The large data volumes from the Sentinels and other missions require methods that are not only robust, but also applicable to large volumes of data in a practical way.

NCEO scientists at UCL with colleagues in the Netherlands and Germany, have used funding from NERC and ESA to develop methods to interpret observations from different sensors in a consistent way. Core to this is the EO Land Data Assimilation System (EO-LDAS) developed at UCL. EO-LDAS is a set of tools for estimating biophysical parameters from EO data based on the classic variational (4DVAR) approach. EO-LDAS is implemented in Python, using radiative transfer (RT) models to interpret EO data. A limitation of this approach is the requirement of running computationally expensive RT models many times, as well as evaluating their partial derivatives for efficient optimisation. A pragmatic approach is to use Gaussian Process (GP) emulators, where a very fast surrogate function that provides the same mapping from input parameters (LAI, leaf chlorophyll,...) to model output (directional surface reflectance) as the RT model, quantifying the error. GPs also estimate the model gradient directly, opening the door to fast local linearisations to the non-linear DA problem. NCEO researchers at UCL have developed new GP applications that are enabling DA methods to be applied to large, multi-sensor datasets of the sort provided by the ESA Sentinels.

Fig. 1 depicts reconstructions of top-of-atmosphere reflectance from a soil-leaf-canopy RT model (PROSAIL) coupled to an atmospheric RT model (6S). The full model evaluation takes around seven minutes on a modern workstation, whereas the GP emulation of 1000 input parameters takes 4 seconds, a massive speedup, and also produces an approximation to the gradient. Fig. 2 shows the results of validating the emulator output with a set of one thousand independent full model runs. The plot shows a spectral distribution of the mismatch between the emulator and the full model output, where we note the small error in the emulation.

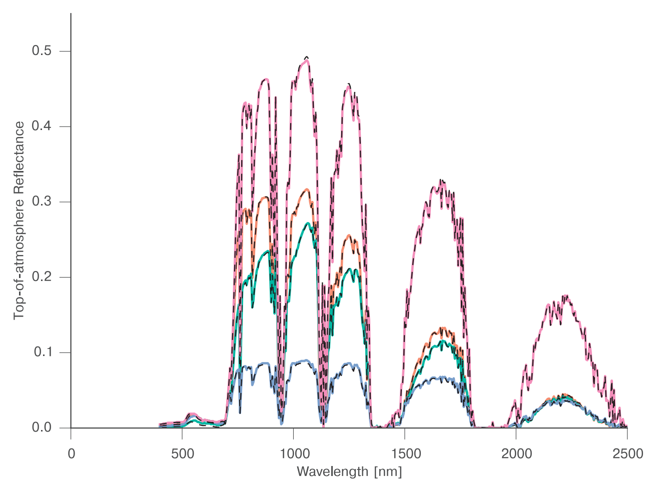


Figure 1: Four sample realisations of the coupled PROSAIL+6S canopy and atmosphere RT models (full lines) and the emulated model (dashed lines). The emulator required only 200 forward model runs.

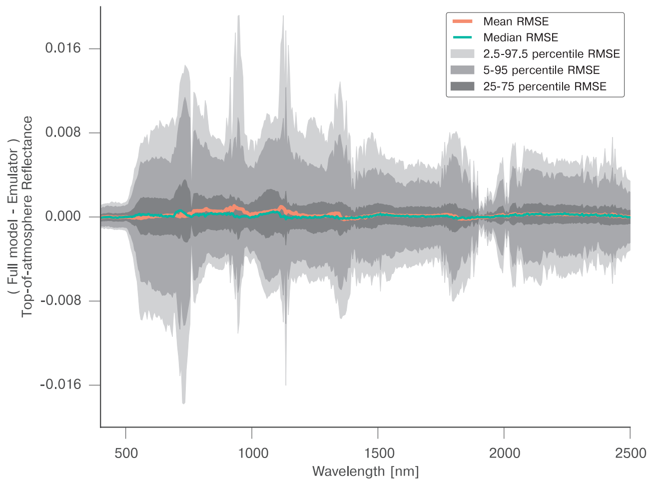


Figure 2: Spectral distributions of the mismatch between the full PROSAIL+6s full model and its emulator for 1000 independent input parameter sets.

BALANCE AND LOCALIZATION IN THE ENSEMBLE KALMAN FILTER FOR DATA ASSIMILATION

Ross Bannister, NCEO-Reading

Data assimilation (DA) is an essential tool used to combine information from observations of planet Earth with models. The ensemble Kalman Filter (EnKF) is a promising method of doing DA which allows model uncertainty to be quantified, and hence correctly matched against observations.

The EnKF relies on multiple realisations of model states (an ensemble). Since the number of model realisations in the ensemble is finite, the ensemble's estimate of the uncertainty statistics is affected by sampling errors. Without fixing this problem, the EnKF fails. A 'fix' for sampling errors is called localization where spurious error correlations between distant points are artificially suppressed – Fig. 1.

Localization allows the EnKF to be a competitive DA method for operational weather forecasting applications but this 'treatment' usually has the 'side-effect' of introducing another kind of noise in subsequent forecasts by introducing geophysical imbalance.

Localization is usually done using fixed functions that damp sampling noise as a function of the distance between two points. We have studied new methods of doing localization, each of which adapts with the flow. For each adaptive method we test (i) how effective it is at suppressing spurious sampling noise and (ii) how this affects geophysical balance (geostrophic and hydrostatic balances). Two adaptive methods are named SENCORP (Bishop and Hodyss 2007) and ECORAP (Bishop and Hodyss 2009) (the meanings of these acronyms are not important here). Compared against a non-adaptive scheme the ECORAP method was found to be best at doing (i) and (ii) – Fig. 2. This work (Bannister 2015) may help guide weather forecasting centres choose an effective localization method for EnKF applications.

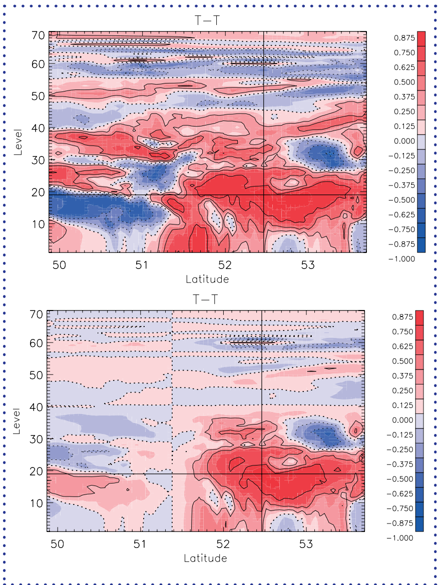


Figure 1: Forecast error correlation function between temperature at the crosshair with temperature at field locations in the latitude/height slice. Top: correlations found from the unlocalized ensemble showing features far from the crosshair that resemble sampling noise. Bottom: the same correlations but localized with a fixed localization scheme. The ensemble used has 24 forecast members for a high-resolution convection permitting version of the Unified Model for the Southern UK.

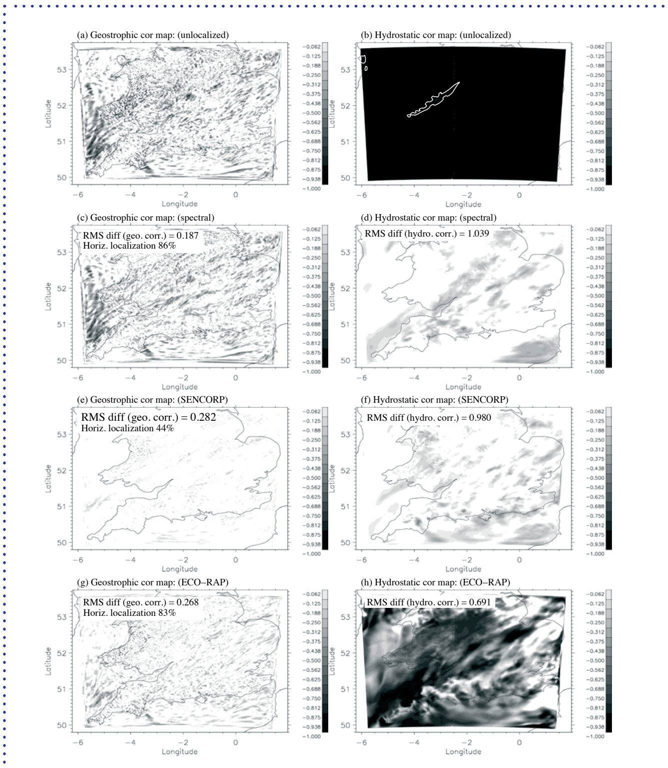


Figure 2: Maps with shading showing the degree that geostrophic (GB, left) and hydrostatic (HB, right) balances are obeyed (heavier shading implied higher balance). From the top, the rows are for the unlocalized ensemble, localized with a fixed scheme (labelled as 'spectral'), localized with SENCORP, and localized with ECORAP. The unlocalized values are regarded as those that should be matched (the 'target') by the localized ensembles. The fixed scheme does best at matching the target for GB , but is poor for HB; SENCORP is poor for GB and HB; ECORAP is reasonable for both. (Note: HB is so well obeyed in the unlocalized system that the shading is dark everywhere and the contour of a feature where HB is slightly less obeyed – otherwise invisible – has been added to aid comparison.)

References

Bannister R.N., How is the balance of a forecast ensemble affected by adaptive and nonadaptive localization scheme, Mon. Wea. Rev. in press.

Bishop C.H., Hodyss D., Flow-adaptive moderation of spurious ensemble correlations and its use in ensemble-based data assimilation, Q.J.R. Meteorol. Soc. 133, 2029-2044 (2007).

Bishop C.H., Hodyss D., Ensemble covariances adaptively localized with ECO-RAP, Part 1: tests on simple error models, Tellus 61A, 84-96 (2009).

Melanie Ades, Peter Jan van Leeuwen, NCEO-Reading
Andrew M. Stuart, University of Warwick
Kody J. H. Law, KAUST, Saudi Arabia

EVALUATING THE PERFORMANCE OF ADVANCED DATA-ASSIMILATION METHODS

Because of computational limitations all present-day data-assimilation schemes are approximations of the full solution of the data-assimilation problem. We have investigated in detail how the different schemes perform in both linear and nonlinear situations, by comparing them to a 'gold standard', a method that gives the full solution. This allows us to understand the limitations of the different methods, and will provide guidance on improving them.

Unfortunately, we cannot perform these comparisons on real systems, as finding the full solution would be way too expensive. Instead, we use the 40-dimensional Lorenz 1996 model over 40 time steps, so a full system dimension of 1600. We observe the first 20 grid points, allowing for the development of nonlinear dynamics. As gold standard we have chosen Metropolis-Hastings with a large number, 1 million, of model runs. We compare a standard data-assimilation method, 4DVar, a simple particle filter, called Sequential Importance Sampling (SIR), and three sophisticated methods, namely the Implicit Particle Smoother, the Equivalent-Weights Particle Filter, and the Equivalent-Weights Particle Smoother, with this gold standard.

Figure 1 concentrates on the limit of a large number of model runs, a 100,000. This limit is not realistic for geophysical applications, but tells us about the convergence of the methods. Clearly visible is that the standard 4DVar is missing the structure of the solution, but also that the advanced methods converge slower than the simple particle filter. However, the advanced methods are developed to be useful with a small number of model runs.

Figure 2 shows the behaviour of the methods as function of the number of model runs. As realistically we can run only 10-100 model runs, it is clear that the advanced methods have much smaller errors than the simpler ones. Especially the two methods developed via NCEO funding, the EWPF and the EWPS outperform the other methods in this small runs limit.

We can conclude that when comparing the performance of several advanced data-assimilation methods with a gold standard the new methods developed by NCEO outperform all other methods in the realistic limit of a low number of model runs.

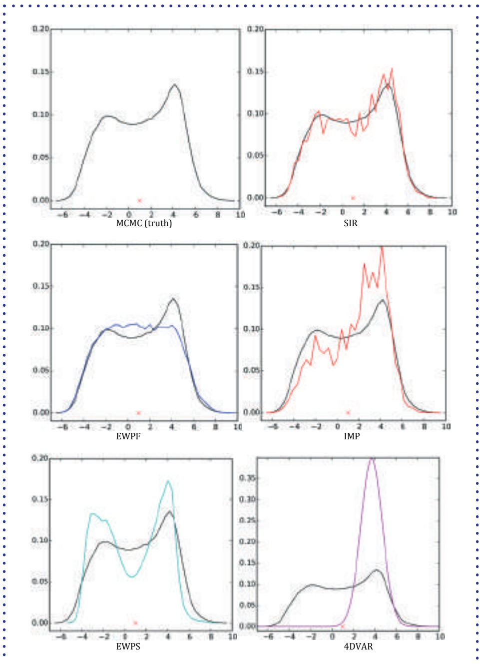


Figure 1: The performance of each data-assimilation method compared to the 'gold standard' MCMC. Note the two peaks in the probability density fuction, indicative of a nonlinear data-assimilation problem. The MCMC uses 1,000,000 model runs, and has converged to the true solution. The other methods use 100,000 model runs. The standard particle filter SIR shows good performance, although some statistical noise is still visible. The standard 4DVAR, a method used in present-day weather forecasting, shows the worst performance, completely missing one of the peaks. The more sophisticated particle filters all show reasonable behaviour. Note that these are developed especially for situations in which only a small number of model runs can be afforded.

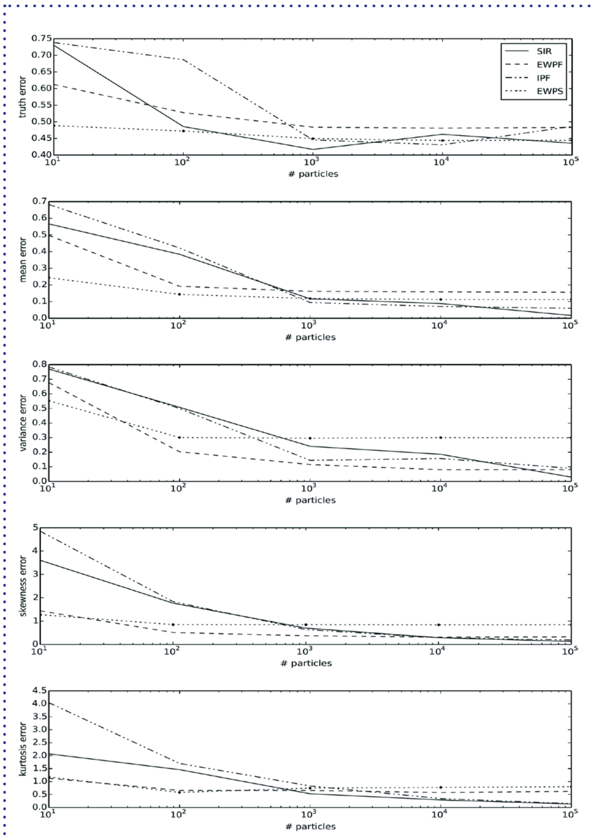


Figure 2: Difference of the nonlinear data-assimilation methods with the gold standard MCMC, for different numbers of model runs. Shown are the errors in the mean compared to the truth, and compared to the mean, variance, skewness, and kurtosis of the MCMC posterior. Note that the methods developed by NCEO, the EWPF and the EWPS perform best when the number of model runs is in the realistic 10-100 regime.

Hartmut Boesch, NCEO-Leicester
Neil Humpage, University of Leicester
Paul Palmer, NCEO-Edinburgh
Martin Wooster,
NCEO-Kings College London

DEMONSTRATING UK AIRBORNE REMOTE SENSING CAPABILITIES FOR ATMOSPHERIC MEASUREMENTS OF CO_2, CH_4 AND CO

It is well established that increases in atmospheric abundances of key greenhouse gases (GHGs) such as carbon dioxide (CO_2) and methane (CH_4) are due to human activities, and that they are the main driver of observed increases in global mean surface temperatures over the last century. Atmospheric concentrations of CO_2 and CH_4 are governed by natural and human fluxes (emission minus uptake), and by atmospheric chemistry and transport. Reliably forecasting future levels of atmospheric CO_2 and CH_4 remains difficult because of our incomplete knowledge of the magnitude, location and processes involved in GHG emission and removal, in part due to lack of data, particularly over remote ecosystems.

A new remote sensing capability for observing atmospheric CO_2 and CH_4 from airborne platforms has been developed by the UK Astronomy Technology Centre and the Universities of Leicester and Edinburgh. The instrument is called GHOST (GreenHouse Observations of the Stratosphere and Troposphere), and was jointly funded by NERC and STFC. GHOST is a spectrometer similar to the instruments carried by NASA's Orbiting Carbon Observatory (OCO-2) and the Japanese Greenhouse gases Observing SATellite (GOSAT) missions. GHOST is able to observe GHGs in much greater spatial detail than OCO-2 or GOSAT because it flies lower down in the atmosphere. GHOST can also observe other atmospheric pollutants such as carbon monoxide (CO), which is a tracer of incomplete combustion and a key air pollutant.

As a contribution to the international CAST-ATTREX campaign, GHOST was deployed on the NASA Global Hawk large unmanned aerial vehicle from NASA's Armstrong Flight Research Center in California. GHOST took part in regional surveys over the eastern Pacific during early spring 2015, which included coincident overpasses from GOSAT and OCO-2. These data are being used to test atmospheric transport models over remote regions, and to help validate the satellite GHG observations over the oceans.

In late spring 2015, GHOST was installed on the Dornier 226 research aircraft operated by the NERC Airborne Remote Sensing Facility (ARSF) as part of a project funded by the UK Space Agency. The main objective was to collect local-scale measurements of significant emission sources including Leicester city centre, a major power plant, and a controlled UK heathland fire. Ground-based spectrometers measuring CO_2, CH_4, CO and other pollutant gases were deployed during the controlled burn to help validate the GHOST measurements in heavily aerosol laden plumes, such as those from wildfires.

Figure 1: David Pearson (UK ATC) refilling liquid nitrogen during the GHOST installation into the NASA Global Hawk.

Figure 2: NASA Global Hawk during a flight of the CAST-ATTREX campaign in spring 2015. The GHOST instrument is installed in the belly of the aircraft.

Figure 3: Deployment of GHOST on the NERC ARSF aircraft to probe the greenhouse gas and carbon monoxide emissions from a controlled heathland fire.

Figure 4: Ground-based Fourier spectrometer deployed to measure the greenhouse gas and reactive gas composition of the heathland fire plume for comparison to the measurements from GHOST.

Alasdair MacArthur, NERC/NCEO Field Spectroscopy Facility, GeoSciences, University of Edinburgh
Jose Gomez-Dans, NCEO-UCL
Gary Llewellyn, BAS-ARSF
Ben Taylor NEODAAS, Plymouth

NERC ATSC FIELD SPECTROSCOPY, AIRBORNE OPTICAL IMAGING AND PROCESS MODELLING FOR ENVIRONMENTAL SCIENCE

The NERC/NCEO Field Spectroscopy Facility (FSF), in collaboration with scientists from the NERC/BAS Airborne Research and Survey Facility (ARSF), their Data Analysis Node (ARSF-DAN), and University College London (UCL), organised a NERC funded Advanced Training Short Course for PhD students and Early Career Researchers in the use of field spectroscopy, hyperspectral airborne imaging, and related advanced analytical techniques.

Near-ground and airborne hyperspectral Earth observations (EO) are of increasing interest to Earth system, global change and environmental scientists. Hyperspectral measurements provide quantitative information on Earth surface biogeochemical cycling and biophysical state variables and their dynamics. However, collection and analysis of these measurements requires consideration and care at all stages to ensure the most useful information with minimum uncertainties is obtained.

The course, attended by 11 trainees from the UK, provided a unique opportunity to gain both theoretical and practical 'hands-on' experience in hyperspectral field data acquisition and analysis to infer key ecophysiological parameters and for the validation of airborne observations. The course was held at the ITAP Las Tiesas Experimental Farm, near Barrax, southern Spain. Las Tiesas is an established and well characterised agricultural site frequently used for EO research and one where weather conditions were expected to be very suitable for optical measurement field work that relies in part on stable solar illumination conditions. Lectures, desktop demonstrations, and computer-based practical exercises were provided, and trainees required to develop appropriate science hypotheses to test and be supported by field and airborne measurements. A unique opportunity was provided to visit the NERC Dornier research aircraft, and the trainees given an introduction to the instrumentation and capacity of NERC airborne Earth observation (Figure 1). Fieldwork was then conducted making use of state-of-the-art field spectrometers provided by FSF (Figure 2), as well as the airborne EO capability provided by ARSF, and with instruction by NERC-funded experts. Post processing and analysis was then conducted on these data, leading to each trainee group reported their finding as a 'conference' presentation at the end of the course. All the materials from the short course are being collated into an online training module that will be available to all via the NCEO website.

Figure 1: Course attendees with NERC/BAS Airborne Research and Survey Facility (ARSF) Dornier aircraft.

Figure 2 (above): Students being instructed in the use of state-of-the-art field spectrometers provided by FSF, here used for making ground-based spectral measurements simultaneous with the ARSF aircraft overflight. The large tarpaulin seen on the ground is a target of known spectral reflectance that will appear in the airborne imagery and which will be used for atmospheric correction purposes.

Figure 3 (left): FluoWAT leaf clip (insert) and ASD FS spectrometer, both provided by FSF, being used by students to measure sun induced fluorescence in a maize field.

References
Photos by Mat Walsh, matt@visualpersistence.com

Ben Taylor, Silvana Mallor Hoya, Steve Groom NEODAAS Plymouth

NEW LANDSAT-8 AND SENTINEL-2 PRODUCTS FOR NEODAAS

NEODAAS has been working with the Royal Belgian Institute of Natural Sciences (RBINS) to acquire the ability to process Landsat-8 Ocean Land Imager (OLI) data, exploiting research funded by the EC FP7 INFORM project. The 30m ground resolution of Landsat 8 gives a significant improvement over other sensors such as NASA's Moderate Resolution Imaging Spectrometer (MODIS) at 0.25/0.5/1 km resolution. The RBINS software allows NEODAAS to atmosphere-correct Landsat-8 and produce Suspended Particulate Matter (SPM) concentration imagery, a non-standard product for Landsat (Vanhellemont & Ruddick, 2014). This allows investigation of processes in inland waters or near-shore environments that cannot be resolved at lower spatial resolution, such as wind-turbine wakes or coastal sediment plumes. Figure 1 and 2 show OLI SPM images of the Thames estuary and the Plymouth area.

The capability will be extended to the MultiSpectral Instrument (MSI) on-board ESA's Sentinel-2 satellite (launched in June 2015) which will provide data at 10-20m with more spectral wavebands. NEODAAS will further benefit from results from on-going research projects at PML funded by NERC (such as GloboLakes), EC FP7 (such as Earth2observe) and internally by PML focussing on lakes and coastal waters, atmosphere correction and algorithm development for Sentinel 2. This will allow exploitation by the NERC community and provide impact beyond those projects.

NEODAAS have already provided OLI data to one user from NOC and will be offering OLI and MSI imagery as standard products in the near future making a powerful new tool available to our users, expanding our user base in disciplines that previously might not have been able to benefit from NEODAAS.

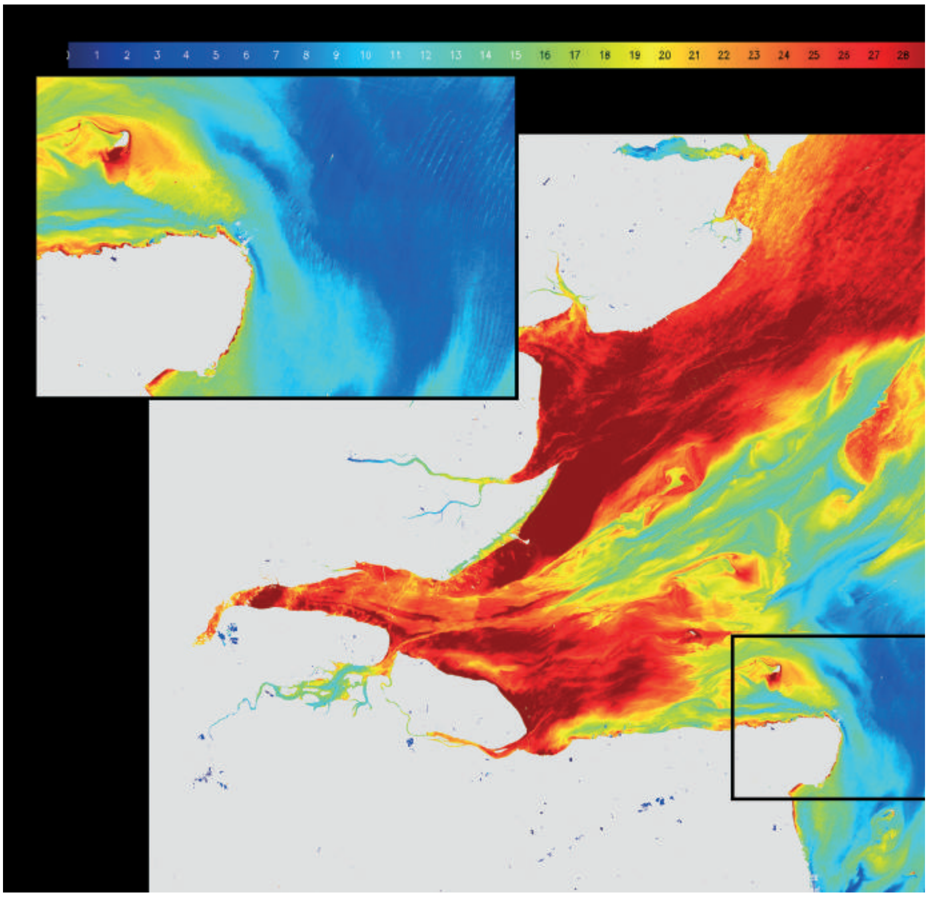


Figure 1: Landsat SPM image of the Thames Estuary and coast of South-East England from 29th April 2013, with section zoomed in. Wind turbine and ship wakes can be clearly seen in the SPM field.

References
Vanhellemont, Q. & Ruddick, K. (2014), Turbid wakes associated with offshore wind turbines observed with Landsat 8, Remote Sensing of Environment, 145, pp. 105-115, doi: 10.1016/j.rse.2014.01.009

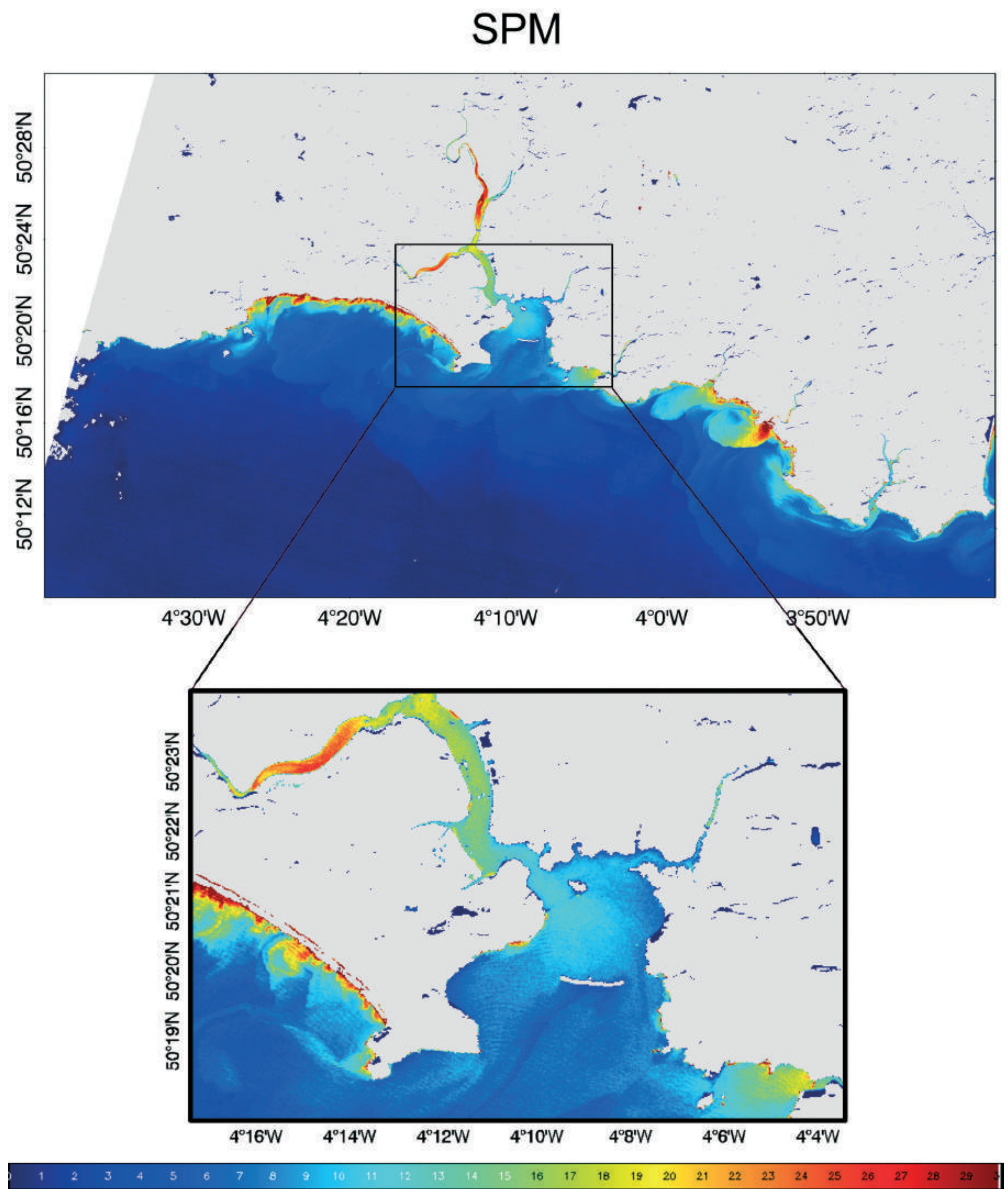


Figure 2: Landsat SPM image of Plymouth Sound and the surrounding area from 4th November 2013, with section zoomed in. Waves and sediment patterns are clearly visible.

WEIGHING TREES WITH LASERS: MEASURING FOREST CARBON FROM GROUND AND SPACE

Mathias Disney and Andrew Burt
NCEO-UCL Geography
Kim Calders UCL Geography and NPL

Measuring forest carbon (C) is vital to quantifying forest response to climate and anthropogenic pressures. Current estimates of global forest C stocks and fluxes largely rely on empirical (allometric) relationships between tree size (diameter and height) and mass, due to the difficulty of making direct measurements, particularly of large tropical trees. We are pioneering new measurements of forest canopy structure using terrestrial laser scanning (TLS) to capture very detailed (mm to cm) 3D information on tree size, crown shape and the size and location of branches and leaves. These measurements allow us to estimate of tree above ground biomass very accurately, independent of allometric assumptions and across a much larger range of tree sizes than possible for empirical methods.

Recent work in the Brazilian Amazon is allowing us to estimate how tree structure and forest composition can change in response to climate impacts such as severe drought. The 3D measurements are also allowing us to quantify the close relationship between tree structure and function. Our TLS-derived 3D tree structural measurements are also being used to test new satellite-based estimates of forest biomass and structure from the forthcoming ESA BIOMASS and NASA GEDI missions, both due to be launched by 2020. Both instruments will depend on allometric height-to-mass relationships, as well as assumptions regarding tree structure. We are providing 3D tree data to both mission teams to enable testing of the satellite retrieval algorithms and validation of the retrieved biomass estimates once they are in production. We have recently received funding from NERC to apply our methods across the tropics over the next 3 years, including in Malaysia, W. Africa, and Peru; ESA are also funding us to scan a BIOMASS-related experimental plots in Ghana and Gabon. Closer to home, we are scanning the largest area measured like this to date, 6 ha of UK deciduous forest at Wytham Woods near Oxford. This is part of an EU-funded project to develop modelling tools for tracing uncertainty in satellite retrievals of canopy properties.

Figure 1: UCL's Riegl VZ400 terrestrial laser scanner operating in Wytham Woods, Oxfordshire, UK, during the 2015 field campaign.

References

Calders, K. et al. (2015) Non- destructive estimates of above-ground biomass using terrestrial laser scanning, Methods in Ecol. and Evolution, 6, 198-208, DOI: 10.1111/2041-210X.12301

Calders, K. et al. (2015) Reducing uncertainties in above-ground biomass estimates using terrestrial laser scanning, Silvilaser 2015, Sept 28-Oct 2 2015, La Grande Motte, France.

Disney, M. I. et al. (2015) New approaches to assessing tropical forest biomass and structure using terrestrial laser scanning, RSPSoc, NCEO and CEOI-ST Joint Annual Conference, Southampton, UK, September 9-11 2015.

Blog: http://disneytls.blogspot.co.uk/

Brazil expedition: http://disneytls.blogspot.co.uk/2014/12/new-results-from-caxiuana.html

Wytham: http://disneytls.blogspot.co.uk/2015/06/wytham-woods-summer-2015.html

UCL press release on Calders et al. paper: http://www.ucl.ac.uk/news/news-articles/1114/211114-laser-scanning-weighs-trees

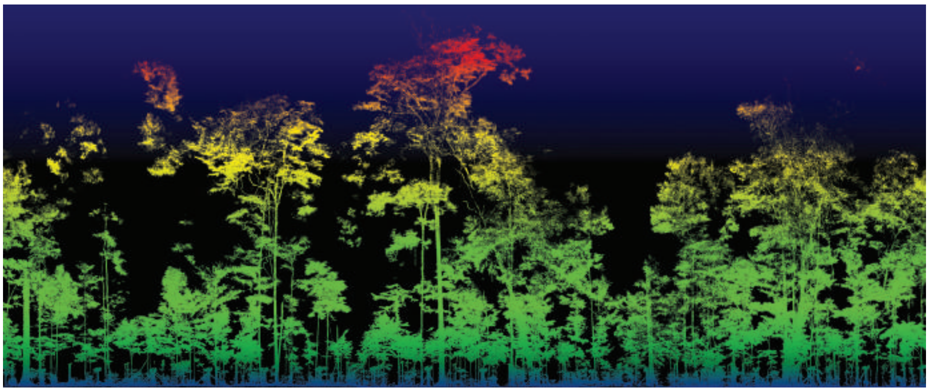


Figure 2: An example slice through a TLS point cloud from Caxiuaña, Brazil. This is a 100 x 50 x 5 m section through the full 1 ha point cloud, which contains over ~0.5bn lidar points. Colour represents height, with the largest tree in the centre ~ 45m. Figure credit: M. Disney, UCL.

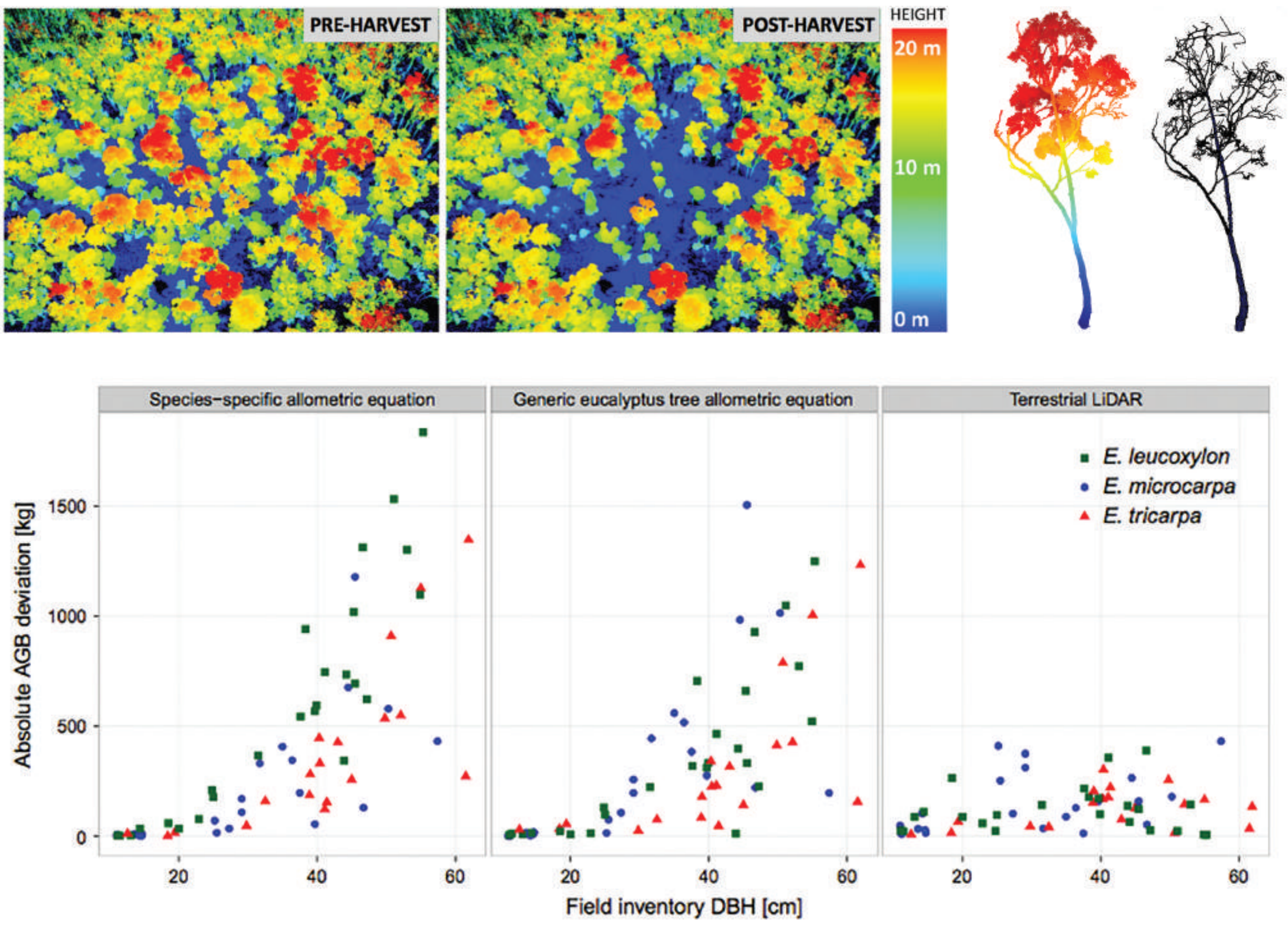


Figure 3: Testing our TLS-derived estimates of biomass. Top row, left: pre- and post-harvest Eucalyptus forest in Victoria, Australia; right: a tree point cloud, and the corresponding derived tree structure. Bottom row: comparison of biomass estimates from TLS and empirical allometric equations (y axis) as a function of tree diameter-at-breast height (DBH) (x axis). Left to right: species-specific allometry, generic Eucalypt allometry, TLS comparison with harvest data. This shows the increasing uncertainty in the allometric estimates as a function of tree size, while the uncertainty in the TLS-derived values is constant with size. Figures from Calders et al. (2015), K. Calders, UCL/NPL.

Victoria Bennett, NCEO-Centre for Environmental Data Analysis, STFC

MIRRORING SENTINEL DATA FOR UK RESEARCHERS

The first of the European Sentinel series of satellites, Sentinel-1A was launched in April 2014, followed by Sentinel-2A in July 2015. The data product archive volumes are unprecedentedly large: around 1 terabyte per day from Sentinel-1A, with similar expected soon from Sentinel-2A.

The data are made available for all users to download from the European Space Agency's (ESA) scientific data hub, but for global or long time-series scientific processing and analysis the data transfer speed, and users' own local storage and processing resources, can be insufficient to meet the needs.

In the UK, the Centre for Environmental Analysis (CEDA) provides infrastructure to support the analysis of such data. CEDA will provide both a mirror archive of Sentinel data, and an environment to exploit that data alongside other datasets. Sentinel-1A Level 1 products (Single Look Complex (SLC) and Ground Range Detected (GRD)) from April 2015 onwards (10's TB) are already available in the archive and the data volumes will continue to rise considerably as more data are acquired.

The data are stored on, and made accessible to the UK science community via the JASMIN super data cluster, and the academic CEMS(Climate Environment and Monitoring from Space) facility which is hosted on JASMIN. JASMIN incorporates over 17 PB of disk, co-located with tape and computing facilities for data analysis via batch, hosted and cloud computing. Recent data are stored on-line for direct access to users; older data will be moved to a near-line tape archive, reinstating it for users on demand. It is expected that most UK science users will access, process and analyse the data in the JASMIN-CEMS hosted environment avoiding the need to download and store data on their local machines. Sentinel 2 and Sentinel 3 data will follow soon.

CEDA are part of the UK Collaborative Ground Segment for Copernicus, collaborating with the Satellite Applications Catapult and Airbus-DS in Farnborough to ensure Sentinel data access for UK users in academia, government and the private sector.

The UK academic community has already achieved impressive science results using Sentinel 1 data. Applications of the data so far include earthquake mapping, monitoring of land cover changes in cloud-covered regions, global forest biomass mapping to constrain and validate climate models, observations of ice loss in polar regions and the detection of deforestation in the tropics.

Figure 1: Artists impression of Sentinel-1A satellite (credit: ESA)

Figure 2: JASMIN super data cluster (credit: Stephen Kill, STFC)

Jan Fillingham, NCEO Training, Communications and Events Manager

NCEO EXTERNAL EVENTS

UK Earth Observation Applications Conference, London

On 23 March 2015, on behalf of Defra, the UK Space Agency, and the Natural Environment Research Council, NCEO held a one day conference on the applications of Earth Observation technology. The conference focussed on the EU Copernicus Programme, one of the EU's space flagship programmes. Over the next 7 years, the EU will invest €3.8Bn in Copernicus, primarily on operational Earth Observation satellites, including €800m on information services targeted at environmental policy makers. On the 3rd April 2014 Copernicus entered its operational phase with the launch of the first satellite called Sentinel. Data from Sentinel-1 became publically available in October. Sentinel-2 launched in May 2015 and Sentinel 3 is due to be launched late 2015. The conference coincided with an announcement of the UK Space Agency and European Space Agency's agreement for UK to host a data facility at CEDA to give full access to EO data from Europe's Copernicus programme.

The conference brought together 180 people from the UK public sector, industry including SMEs and academia to network and identify opportunities for EO technology to deliver better environmental policy and to stimulate the UK EO and other business sectors. 43% of attendees came from industry; 31% from government; and 26% from academia. The European Commission, European Space Agency and EUMETSAT articulated their vision for Copernicus, and the Copernicus service providers/operators demonstrated their implementation approaches. The conference also addressed related initiatives such as the UK's Space for Smarter Government Programme and international collaborations such as the Group for Earth Observations. A common theme was how best to manage, analyse and interpret large data volumes to get the maximum benefit for the UK across the public, commercial and academic sectors.

UK Meeting on GEO (Group on Earth Observations)

NCEO helps to coordinate UK interests in GEO on behalf of lead government department Defra, NERC and UK Space Agency. GEO is a voluntary partnership of governments and organizations that envisions "a future wherein decisions and actions for the benefit of humankind are informed by coordinated, comprehensive and sustained Earth observations and information." GEO Member governments include 96 nations and the European Commission, and 87 Participating Organizations comprised of international bodies with a mandate in Earth observations. Together, the GEO community is creating a Global Earth Observation System of Systems (GEOSS) that will link Earth observation resources world-wide across multiple Societal Benefit Areas – agriculture, biodiversity, climate, disasters, ecosystems, energy, health, water and weather – and make those resources available for better informed decision-making.

On 23 June 2015, NCEO organised a meeting at Defra's offices in London to identify UK interests in GEO such as data access, data sharing and global initiatives such as the Global Forest Observations Initiative (GFOI) .

UK Space Conference

NCEO with colleagues from the National Oceanographic Centre exhibited Earth Observation science at the UK Space Conference in Liverpool in July 2015. Over 700 people attended the conference. NCEO launched its new Corporate Brochure and John Remedios was filmed by the Institution of Engineering and Technology for their website.

NCEO's Catherine Fitzsimons introduced the Tim Peake EO Detective project to school teachers at the 2015 UK Space Conference's convention for schools (see following page for more details).

Figure 1: UK Space Conference, Liverpool, 2015. John Remedios talking to the Institute of Engineering and Technology on the NCEO stand.

MOOC

NCEO Scientists, led by Martin Wooster and Mat Disney, were contributors and lead educators on a European Space Agency-funded massively open online course (MOOC) on "Monitoring Climate from Space". Developed by Imperative Space and delivered by FutureLearn, the course attracted over 8000 participants worldwide on its first run in June 2015. The course proved so popular that it is likely to be repeated.

Jan Fillingham, NCEO Training, Communications and Events Manager

NCEO EVENTS AND OUTREACH

NCEO Researchers' Forum, Leicester

New staff members, researchers and students met in Leicester on 10-11 March 2015 to present their science and expand their knowledge of NCEO. They each gave talks and presented posters on their science. They learned about NCEO's international connections and current science disciplines. External speakers from NERC and the Satellite Applications Catapult gave presentations on Impact and Careers in Earth Observation in Industry. And delegates took part in a workshop to develop a new inter-disciplinary research project.

NCEO's Tim Peake Project – "EO Detective"

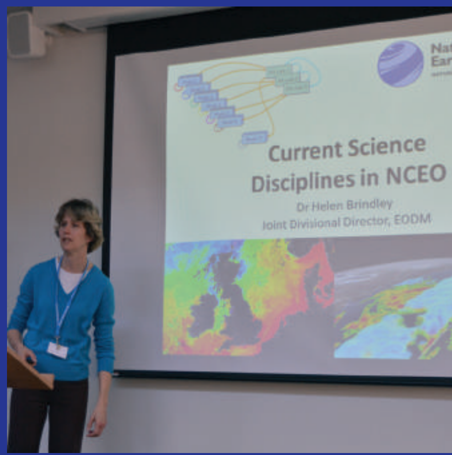
In December 2015 Britain's first European Space Agency astronaut Tim Peake will start his six-month mission to the International Space Station. His exciting mission presents a unique opportunity to use space as an inspiring context for learning in the classroom. "Earth Observation Detective" is a cross-curricular activity supporting aspects of science, geography, maths and computing at key stages 2-4. Students will be given access to photographs taken by astronauts and to images and data collected by Earth Observation satellites during fifty years of observing the Earth from space. Using these, they will be able to observe and quantify the effects of phenomena such as volcanic eruptions, floods and seasonal changes in vegetation and surface temperature; investigate changes and identify trends in land use and the extent of forests, sea-ice and glaciers; and evaluate the impact of human activity. Materials will be available at www.esero.org.uk/timpeake.

2015: NERC's 50th Anniversary

NCEO has presented its science at a number of outreach events celebrating NERC's 50th, including the British Geological Survey Open Day and "Summer of Science" events.

Figure 1: Attendees at NCEO Researchers' Forum, Leicester, 10-11 March 2015.


National Centre for
Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL


Current Science
Disciplines in NCEO
Dr Helen Brindley
Joint Divisional Director, EODM


NATIONAL CENTRE FOR
EARTH OBSERVATION
NATIONAL CENTRE FOR
EARTH OBSERVATION
NATIONAL CENTRE FOR
EARTH OBSERVATION
planet works


INNOVATION


EO Instrumentation & Facilities Division
Vision for EOIF Division:
Strategic Areas:
University of
Leicester

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

NERC SCIENCE OF THE ENVIRONMENT

John Remedios, NCEO Director
jjr8@leicester.ac.uk
National Centre for Earth Observation,
Michael Atiyah Building, University of Leicester,
University Road, Leicester, LE1 7RH, UK
Tel: +44 (0)116 252 2016
Fax: +44 (0)116 252 2464

Jan Fillingham, NCEO Training,
Communications and Events Manager
jan.fillingham@nceo.ac.uk
University of Reading, Earley Gate,
Building 58, Reading, RG6 6BB, UK
Tel +44 (0)118 378 6728
Fax: +44 (0)118 378 5576

Email info@nceo.ac.uk
Twitter @NCEOscience

www.nceo.ac.uk