Diagnosing Earth’s Energy Pathways in the Climate system (DEEP-C): Case for Support

Part 1: Previous Track Record

University of Reading

The **Department of Meteorology** was the highest-graded department focusing on the fundamental science of weather and climate in the 2008 Research Assessment Exercise; 75% of its research was graded as world leading or internationally excellent. The Department hosts units from the UK Met Office, and major elements of the NERC funded National Centre for Atmospheric Science (NCAS) and National Centre for Earth Observation (NCEO).

Dr Richard Allan is Reader in Climate Science with over 16 years experience in combining Earth Observation data with climate models and atmospheric reanalyses to understand changes in Earth’s radiative energy balance, radiative feedbacks and the global water cycle, publishing over 50 peer reviewed scientific papers. He is an active member of the Geostationary Earth Radiation Budget (GERB) and Clouds and the Earth’s Radiant Energy (CERES) International Science Teams with numerous solicited contributions to international workshops and meetings and authorship on the Intergovernmental Panel on Climate Change (IPCC) 2007 report and forthcoming 2013 report.

Prof. Jonathan Gregory is a senior scientist at NCAS Reading and the Met Office Hadley Centre and is a world expert in mechanisms of global and large-scale change in climate and sea level. He is lead author of the sea-level chapter of the upcoming IPCC report and currently leads an Advanced European Research Council Grant SEACHANGE for which **Dr Till Kuhlbrodt** (Senior Research Fellow at NCAS-Climate) is project scientist. Dr Kuhlbrodt has extensive expertise in ocean modelling, in particular mechanisms of ocean heat uptake and mechanisms of deep water formation.

Relevant Publications

Loeb, N.G., J.M. Lyman, G.C. Johnson, **R.P. Allan**, D.R. Doelling, T. Wong, B.J. Soden and G.L. Stephens (2012), Observed changes in top-of-the-atmosphere radiation and upper-ocean heating consistent within uncertainty, *Nature Geoscience*, 5, 110-113.

T. Kuhlbrodt, R.S. Smith, Z. Wang and **J.M. Gregory** (2012): The influence of eddy parameterizations on the transport of the Antarctic Circumpolar Current in coupled climate models. *Ocean Modelling*, 52-53, 1-8, doi:10.1016/j.ocemod.2012.04.006

Church, J. A et al including **J.M. Gregory** (2011) Revisiting the Earth's sea-level and energy budgets from 1961 to 2008. *Geophysical Research Letters*, 38, L18601

Allan, R.P., B.J. Soden (2008), Atmospheric Warming and the Amplification of Precipitation Extremes, *Science*, 321, 1481 – 1484

Allan, R.P., A. Slingo, S.F. Milton and M.A. Brooks (2007), Evaluation of the Met Office global forecast model using Geostationary Earth Radiation Budget (GERB) data, Q. J. Roy. Meteorol. Soc., 133, 1993-2010

Bony, S., R. Colman, V.M. Kattsov, **R.P. Allan**, et al. (2006), How well do we understand and evaluate climate change feedback processes?, *J. Climate*, 19, 3445-3482.

Uppala S. et al. including **R.P.Allan** (2005) The ERA-40 Re-analysis, *QJRMS,* 131, 2961-3012.

Wielicki, B. A., T. M. Wong, **R. P. Allan**, et al. (2002), Evidence for Large Decadal Variability in the Tropical Mean Radiative Energy Budget, *Science*, 295, 841-844.

National Oceanography Centre – Southampton (NOC)

NOC is the national focus for oceanography in the UK and is home to some 520 research scientists, lecturing support and seagoing staff as well over 700 undergraduate and postgraduate students.

Dr. Elaine McDonagh is Head of the Ocean Circulation and Processes Team in the Marine Physics and Ocean Climate Research Group in NOC. She is a physical oceanographer and has eighteen years of experience of making measurements at sea and analysing data collected at sea. She is an expert in the calculation of circulation, fluxes and budgets from hydrographic data. She has recently extended this to calculate a continuous time-series of freshwater fluxes across the RAPID-MOCHA array at 26°N using King’s OI product. In addition to dynamic and budget calculations she has used in situ data to interpret changes in water mass properties in the context of a changing climate. This proposal will capitalize on her expertise in circulation, budgets, water masses, property changes and time-series.

Dr Brian King is a Senior Research Scientist in the Marine Physics and Ocean Climate Group in NOC. He is a member of the International Argo Steering Team, the GO-SHIP committee and SCOR WG127 on the Equation of State and Thermodynamics of Seawater. As a member of the Marine Physics and

Ocean Climate Research Group at NOC, he has been leader of two observation-based National Capability Work Packages; one on Argo and one on hydrographic observations of the Antarctic Circumpolar Current. He is an expert on observational physical oceanography. He has written software to optimally interpolate (OI) on density surfaces temperature and salinity data from Argo, hydrographic and mooring data for use with the 26°N RAPID-MOCHA data. His expertise in ocean observations and their quality will facilitate the global application of the OI calculations proposed herein and will underpin the observational marine aspects of this proposal.

<u>Relevant recent publications on property changes and circulation by McDonagh and King:</u>

McCarthy, G.D., **B. A. King**, P. Cipollini**, E. L. McDonagh**, J. R. Blundell, and A. Biastoch, On the sub-decadal variability of South Atlantic Antarctic Intermediate Water (2012) *Geophys. Res. Lett*., 39, L10605.

McCarthy, G.D., **E.L. McDonagh,** and **B.A. King**, Decadal variability of Thermocline and Intermediate waters at 24°S in the South Atlantic (2011) *J Phys. Oceanog.*, 41, 157-165.

McDonagh, E.L., P. McLeod, **B. A. King** and S. Torres Valdes (2010) Circulation, heat and freshwater transport at 36°N in the Atlantic, *J Phys Oceanog*, 40, 2661-2678.

Moore, C.M., et al. including **E.L. McDonagh** (2009) Large-scale distribution of Atlantic nitrogen fixation controlled by iron supply. *Nature Geoscience*, 2, 861-871.

McDonagh E.L., H.L. Bryden, **B.A. King**, and R.J. Sanders (2008) The circulation of the Indian Ocean at 32ºS. *Progress in Oceanography*, 79 20-36.

Leadbetter, S.J., Williams, R.G., **McDonagh, E.L.** and **King, B.A**. (2007) A twenty year reversal in water mass trends in the subtropical North Atlantic. *Geophys Res Lett*, 34, L12608.

B.A. King and **E.L. McDonagh** (2005) Decadal changes in ocean properties revealed by ARGO floats, *Geophysical Research Letters*, 32, L15601**.**

Bryden, H.L., **E.L. McDonagh** and **B.A. King** (2003) Changes in Ocean Water Mass Properties: Oscillations or Trends? Science, 300, 2086-2088.

Project Partners

The Met Office Hadley Centre is acknowledged as a world leader in the science of climate change and in translating that science into policy advice. **Dr Matthew Palmer** is a senior researcher, leading a team working in the Ocean Climate Processes group. His research has focussed on ocean heat content and circulation, using both ocean and climate model simulations, and analysis of observational data. Particular interests include improving our understanding of the mechanisms behind the observed heat content changes and the role of the global ocean in Earth's energy budget. He is an active member of the CLIVAR Global Synthesis and Observations Panel, the UNESCO working group for design of a global ocean deep observing array and also coordinates the assessment phase of the HadGEM3 atmosphere-ocean-ice model, which will form the basis of the UK Earth System Model.

<u>Relevant Publications</u>

Palmer, M.D. (2012), Climate and Earth's Energy Flows, Surv in Geophysics, doi: 10.1007/s10712-011-9165-8.

Robson, J., R. Sutton, K. Lohmann, D. Smith and **M.D. Palmer** (2012), Causes of the Rapid Warming of the North Atlantic in the 1990s, J Climate. dx.doi.org/10.1175/JCLI-D-11-00443.1

Palmer, M.D., D.J. McNeall and N.J. Dunstone (2011) Importance of the deep ocean for estimating decadal changes in Earth's radiation balance, Geophys. Res. Lett.. 38, L13707.

Lyman, J.M. et al. inc. **M.D. Palmer** (2010) Robust Warming of the Global Upper Ocean, *Nature*, 465, 334-337.

Palmer, M. D., S. A. Good, K. Haines, N. A. Rayner and P. A. Stott (2009), A new perspective on warming of the global oceans, Geophysical Research Letters, 36, L20709.

Palmer M.D., K. Haines (2009) Estimating oceanic heat content change using isotherms, J Clim, 22, 4953-4969.

Palmer M.D., K. Haines, S.F.B. Tett and T.J. Ansell (2007), Isolating the signal of ocean global warming, Geophysical Research Letters, 34, L23610, doi:10.1029/2007GL031712.

Gregory, J.M., H.T. Banks, P.A. Stott, J.A. Lowe, and **M.D. Palmer** (2004), Simulated and observed decadal variability in ocean heat content, Geophys. Res. Lett., 31, L15312.

Department for Energy and Climate Change (DECC) partners will develop and deliver policy that is informed by a sound scientific evidence base gained from the proposed project (see supporting Letter).

NASA Langley Research Center – Dr Norman Loeb is PI of the Clouds and the Earth's Radiant Energy System (CERES) satellite mission and will provide data and expertise to the project.

Diagnosing Earth's Energy Pathways in the Climate system (DEEP-C)
Part 2 - Description of Proposed Research

Introduction

Despite increasing greenhouse gas concentrations and rising sea level, the current rate of ocean surface warming has diminished in the most recent decade (Simmons et al. 2011). The net radiation flux into the system and the reducing observed ocean heat content change have led to the concept of 'missing energy' in the climate system (Fig. 1A). While reduced ocean heating in the upper 700m is consistent with the cessation of increasing sea surface temperature (Fig 1B) questions arise as to the potential for the deep ocean to store heat as well as the validity of the observing systems used (Palmer et al. 2011; Loeb et al. 2012). It is of crucial importance that the climate community elucidates the root cause of this current "warming hiatus" in the sea surface and upper-ocean and improves the process understanding critical for projecting climate change over the coming decades. We propose a comprehensive analysis and synthesis of complementary new satellite datasets, upper and deep ocean temperature measurements and climate model simulations, exploiting expertise across three UK institutions, to tackle the fundamental question: how is Earth currently redistributing the excess radiative energy (heating) derived from greenhouse gas forcing? We will test the following hypotheses:

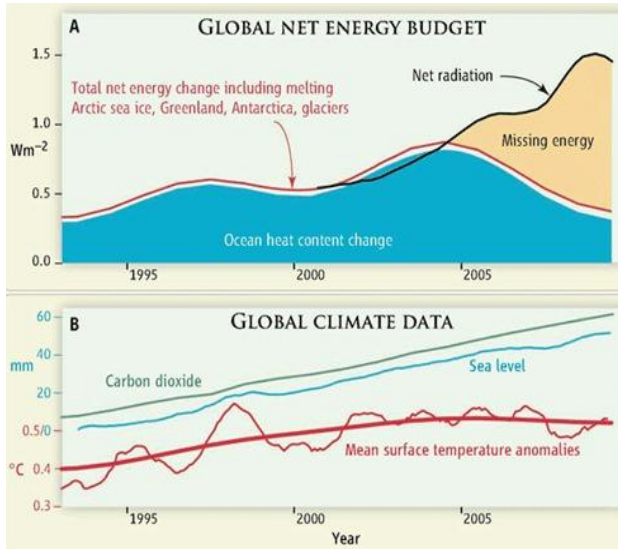

Figure 1 – Recent research by Trenberth & Fasullo (2010) suggested (A) a discrepancy between the rate of energy entering the top of the atmosphere which is rising (black line) and energy accumulating in the ocean which is declining (blue). The period is characterised by stable surface temperatures yet rising sea level (B). Our project will investigate this discrepancy using updated satellite data and improved analysis of ocean heat content data.

> ***H1*** *– The "Missing Energy" in the climate system is explained by deficiencies in the observing system and can be resolved through improved combination and analysis of updated satellite radiation budget data and in situ measurements of ocean heat content*
>
> ***H2*** *– The recent slow rates of surface warming (the so-called warming hiatus) are primarily due to an enhanced transport of heat to the deep ocean caused by natural variability in ocean circulation with changes in external forcing playing a secondary role.*

It has hitherto been problematic to observe flows of energy into and around the climate system at sufficient accuracy to address these issues (Wielicki et al. 2002; Trenberth 2009). We believe that the models are now mature enough and the observations dense enough in space and time to discern these subtle changes in Earth's energy imbalance and quantify the flows of energy through the atmosphere and into the deep ocean. This will improve our understanding of how changes in energy flows arise, are influencing climate currently and will determine changes over the coming decades.

Scientific Rationale

Current warming of Earth's climate results from a small yet persistent, positive imbalance between the sunlight absorbed by the planet and the thermal radiation emitted to space (Hansen et al. 2011). This energy imbalance is a fundamental climate variable, driving surface heating and ocean heat uptake (and thus determining how much additional warming is "in the pipeline"). On decadal and longer timescales the key balance is between: (i) the net top-of-atmosphere radiative fluxes, which determine the net input of energy to the system and (ii) changes in total ocean heat content, which is the primary energy storage term (Bindoff et al., 2007; Palmer et al., 2011; Church et al. 2011).

Recent research (Trenberth & Fasullo, 2010) has suggested a major discrepancy (Fig. 1) between changes in radiative energy fluxing into Earth's atmosphere and the energy arriving in the oceans. The oceans are by far the largest energy store in the climate system, where 90% of the energy surplus from anthropogenic radiative forcings since 1961 is thought to have accumulated (Hansen et al. 2011). New analysis by members of the DEEP-C team (Palmer et al. 2011; Loeb et al. 2012) questions the discrepancy illustrated in Fig. 1A and highlights uncertainty in current analyses of Ocean Heat Content (OHC) as potentially filling the "missing energy" gap. There is a need to move beyond a global budget, improve the accuracy of our estimates and establish the spatial patterns and mechanisms of change over the recent past. We seek resources to address this urgent need for connecting ocean, satellite and modelling communities, in which the UK is strongly placed, to tackle this discrepancy (H1).

There is also an imperative to understand the current hiatus in ocean surface warming (Fig. 1B); without improved understanding and explanation, there is a risk of loss in public confidence in climate simulations and climate science more widely. *Have radiative forcings contributed to the observed slowing of surface warming rates over the last decade (Church et al. 2011)?* While ocean surface warming has stalled, land temperatures continue to rise (Simmons et al. 2010) and the estimated net top of atmosphere (TOA) radiative imbalance remains positive (Hansen et al. 2011; Loeb et al. 2012): this implicates ocean processes as a key player in the observed slowdown of surface temperature rise. However, the possibility that changes in the *derivative* of radiative forcings with time may directly influence temperature trends (e.g. Hansen et al. 2011) must be first discounted. We will test the hypothesis that changes in ocean circulation explain the current warming hiatus (H2) using the combined ocean and satellite observing systems and modelling studies across 3 distinct and complementary workpackages.

Such a hiatus in global surface temperature change is not uncommon in the climate record (Easterling and Wehner, 2009) and such episodes are also seen in projections of future climate change (Easterling and Wehner, 2009; Knight et al., 2009). Recent climate model analysis shows that during decades of stalled or decreasing surface temperature the ocean deeper than 300m to have increased heat content whilst the energy in the upper 300 m has decreased (Meehl et al, 2011). They identified the TOA energy budget and deep-ocean (in this context usually deeper than a typical Expendable Bathythermograph sampling depth of 700m) as the most likely components to account for the "missing energy" described earlier. The project proposed herein will quantify the contributions of each of these components and identify whether or not they can account for the "hiatus". We will also establish the robustness of the Meehl et al. (2011) findings over a range of CMIP5 models.

The explanations offered so far on the "hiatus" have been based on modelling results or statistical analysis of global-integrated time series. Importantly, our analysis will be rooted in the observations and will identify the spatial structures of change that are necessary to draw robust conclusions on the underlying causes. Meehl et al. (2011) find that the oceanic heat re-arrangement is mainly across the 300m isobath and mostly in the Pacific. We know that the upper 700 m cannot account for all the heating, so we must look deeper, and in different ocean basins. A combination of modelling and observations will be necessary to diagnose the spatial pattern of energy redistribution and whether this conforms to an internal component of variability (H2). Preliminary climate model analysis indicates episodes of substantial heat transfer across both the 700 m and 1800 m isobaths with the North Atlantic as a key player (Figure 2).

Our proposal will deliver a 2-dimensional (2D) observed estimate of Earth's TOA energy imbalance, and atmospheric/surface energy flows (WP1), a 3-dimensional (3D) estimate of ocean heating (WP2)

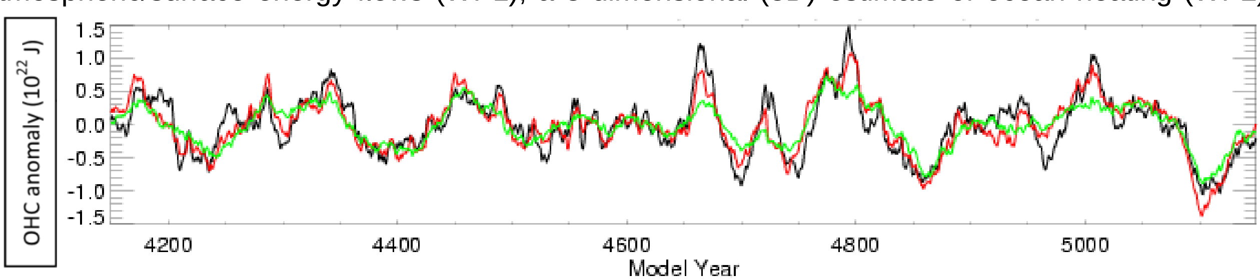

Figure 2 – Ocean heat content variations (high pass filtered) in the 1800-6000 m layer from the HadCM3 pre-industrial control run for: Global ocean (black), Atlantic (red) and North Atlantic (green). The results show episodic large heat exchange with the deep ocean that tends to be dominated by the North Atlantic basin.

and will elucidate processes fundamental for ocean heat redistribution using a detailed modelling approach (WP3). The resulting analyses and data sets, including comprehensive error estimates, will be of enormous value to the international climate research and oceanographic community.

Scientific Objectives

The primary goal of this project is to close the planetary energy budget using observations and to elucidate energy transport mechanisms through detailed simulations. This will meet key challenges of the NERC climate theme including providing accurate observations of the climate system, improving understanding of the physical climate system and its representation in models and increasing knowledge of natural climate variability. The *primary* project objectives, testing hypotheses H1 and H2 using techniques described in four work-packages (WP1-4), are as follows:

O1. Combine satellite radiation budget measurements with atmospheric reanalyses, providing improved 2D estimates of surface heat fluxes across the ocean surface (WP1)

O2. Calculate global 3D ocean heat content and its changes since 2003 using ARGO and ship-based observations, leading to improved understanding of energy propagation through the climate system (WP2)

O3. Investigate spatial patterns of surface and sub-surface temperature changes in distinct hiatus decades using simulations and observations (e.g. Fig. 4); evaluate the processes fundamental for ocean heat uptake and redistribution (WP3)

O4. Combine ocean and satellite data (from O1-2) to provide new estimate of Earth's net radiative energy balance (2000-2015) and compare with CMIP5 climate simulations (from O3) (WP1-4)

O5. Monitor co-variations in net radiative energy imbalance and ocean heating (from O1,O2,O4); quantify and understand lags between OHC and TOA radiation (WP1-4)

O6. Characterise spatial signatures and mechanisms of ocean and atmospheric heat re-distribution (from O4-5) during the hiatus period 2000-2015 using observations and simulations (WP1-4)

The powerful combination of observations and modelling will also allow us to compute ocean-basin scale estimates of energy budget, identify key regions of energy subduction into the ocean on interannual-decadal time-scales. Our observational focus on the Argo era avoids pitfalls due to changing observing systems. While ambitious, we consider the objectives to be achievable: the combined observational and modelling expertise offered by the project team will contribute toward a vibrant inter-disciplinary research community, contributing to the UK's position as a world leader in environmental sciences.

Methodology

We will combine complementary and independent datasets with detailed modelling over 4 work-packages. CERES satellite data provide more than 10 years of stable measurements of TOA radiative energy. While CERES cannot provide absolute accuracy to within the required precision, the Argo OHC record provides a means to “anchor” this time series. In addition, variation in both records provides an indicator of fidelity (Fig. 3). The model simulations allow us to test hypotheses, improve process understanding and explore the importance of the ocean below 2000m, which Argo observations cannot reach.

WP1 – Observed TOA Radiative Imbalance and Atmospheric Energy Transports (Reading)

WP1 will combine TOA observed net radiation (R_T) from Edition 3 CERES (1x1^o grid) data (Loeb et al. 2012) with state-of-the-art atmospheric reanalysis simulations (ERA-Interim) of atmospheric energy content (Fig. 2) and its transports (Berrisford et al. 2011). Total energy divergence per unit area in each atmospheric column is defined as:

$$\frac{\partial E_{ATM}}{\partial t} = -\underline{\nabla} \bullet (1/g) \int_0^{p_s} \underline{v}(Lq + C_p T + \phi_S + k) dp + R_T - F_S, \qquad (1)$$

where L is the latent heat of vapourization, q is the specific humidity, T is temperature, Φ_s is surface geopotential, k is kinetic energy, p is pressure and $\underline{v}$ is vector velocity (Berrisford et al. 2011). Surface fluxes (F_S) from reanalyses are prone to error (Allan et al. 2004) since energy and moisture conservation is not ensured (Trenberth et al. 2012). ERA-Interim displays an improved energy budget over older reanalyses (Berrisford et al. 2011) although it is susceptible to spurious trends relating to the observing system (Fig. 3). However, we will exploit the strength of ERA-Interim (wind fields and transports of dry and moist static energy and moisture) to compute lateral transports of energy. Combining ERA-Interim lateral energy transports with R_T from CERES will provide an independent estimate of F_S calculated as a residual from Eq (1). Our new estimates of F_S will be of substantial utility to the surface flux community (e.g. Stephens et al. 2012), allowing a valuable assessment of uncertainty. We will compare these estimates with current reanalysis estimates and evaluate where possible with surface radiation measurements. Minor energy terms (e.g. land heating, ice melt) will be estimated (e.g. Trenberth 2009) such that 2D energy flows into the ocean can be computed. Loeb et al. (2012) derived an uncertainty in R_T of ±0.43 Wm^{-2} with stability (relevant for changes) within 0.2 Wm^{-2}. Combining datasets with WP2-3, and based on previous analysis by Lyman et al. (2010), we aim to achieve absolute accuracy better than ±0.2 Wm^{-2}.

A further aim of WP1 will be to quantify the influence of natural variability on Earth's energy flows. Fig. 3 shows changes in global R_T observed by CERES (black) and simulated by ERA Interim (green) *but lagged by 6 months* in relation to changes in the ocean heating rate from an Argo-only estimates (PJJ 0-1800m) and a combined estimate (PJJ 0-700m) based upon data used by Loeb et al. (2012). The agreement over the period 2007-2010 provides tantalizing evidence for a delay between energy released from the ocean to the atmosphere and its appearance in the satellite record (Dessler 2011). In this case, the *ocean* changes force responses in global R_T rather than the other way around. Accounting for components of Earth's energy stores will enable these lags to be quantified for the first time; this is an exciting research problem that will be undertaken in year 2 of the project (Table 2).

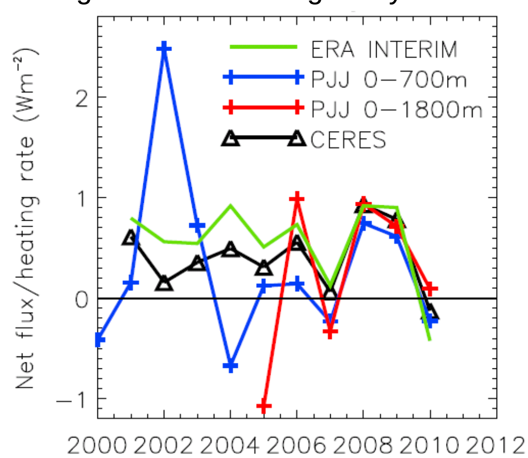

Figure 3 – Changes in energy entering top of Earth's atmosphere observed by CERES (black) and simulated by ERA-Interim (green) and observed heating of the upper ocean (blue, red). CERES and ERA-Interim estimates are "anchored" to the 2006-2010 mean ocean heating rate over this period but lagged by 6-months.

Key to this proposal is linking WP1 results with WP2-3, enabling current capabilities for assessing global quantities to be extended to a regional perspective, more relevant for understanding physical mechanisms of ocean heat uptake. Close contact with the CERES PI (see Letter of Support) will ensure the most accurate products and additional provision of near-real time estimates of R_T (FLASHFlux); combined with current ERA Interim data, this will allow monitoring of regional changes in energy entering or leaving the system to improve understanding of interannual climate variability and of utility to the decadal climate prediction community.

WP2 – Ocean heat content (OHC) from observations (NOC)

WP2 is the analysis of ocean observations to determine the evolution of OHC during the period 2000 to 2015. Different strategies are required for the upper 2000m, measured by Argo, and the deep ocean, below 2000m, sampled by research cruises. OHC will be examined on a global and regional basis, and the relative contributions of the upper and deeper ocean quantified. We will analyse model output to establish the representativeness of our results. We will undertake an analysis focussed on the N. Atlantic which, of all deep basins, has the best sampling. The RAPID-WATCH/MOCHA mooring array at 26°N will be used to give insight into the mechanisms of OHC change in the N. Atlantic.

<u>2.1 Global ocean heat content and 3D OHC structure</u>

Upper ocean (top 2000m): We will use Optimal Interpolation (OI) of the Argo dataset on density surfaces to produce global gridded ocean temperature (T) and salinity (S) every 10 days. Software already written at NOC maps anomalies of Argo data relative to climatology. We will extend the OI and use the global Hydrobase3 climatology that is due for release in mid-2012 (R. Curry, WHOI, pers comm). We will produce global maps of upper-ocean heat content and quantify its variability between 2000 and 2015. Mapping on density levels allows longer decorrelation scales to be used, and preserves the T-S structure of the water column with smaller uncertainty. These better T-S properties will improve our ability to distinguish underlying mechanisms of change. In addition we will assess which water mass property changes predominantly account for variation of OHC.

Our runs in the N. Atlantic show that the mapping error of T on density is (on average) half the mapping error of T on pressure. However, when returning temperature maps from density to pressure coordinates (for OHC calculation), the uncertainty is dominated by heave of the isopycnals. Thus the uncertainty of the density-mapped data increases to close to that of the pressure-mapped data. We expect the error introduced by transient heave to be reduced by averaging, so that the total uncertainty of the density-mapped data approaches just the mapping error on density surfaces. This is equivalent to about 0.8 $\times 10^9$ J/m^2 or 1.9$\times 10^{21}$ J for random errors and 300 independent mapped points in the N Atlantic. We can therefore determine changes in the N. Atlantic with an uncertainty equivalent to 0.15 W/m^2 over a 10-year interval: this is half the uncertainty from data mapped on pressure surfaces.

Deep ocean (below 2000m): We will examine heat and other property changes on pressure surfaces deeper than 2000m using repeat sections of ship-based hydrography. All data are available at CCHDO. Some sections have a repeat-interval close to 5 years; where possible we will attempt to interpolate changes to each pentad (bounded by 2000, 2005, 2010, 2015). For each basin and pentad we will estimate the rate of warming/cooling. We will use literature estimates where possible and reanalyse section data where necessary. We will relate heat content changes to the water masses that exhibit those changes, whether by changing volumetric census, or by property changes.

The uncertainty in each basin will be estimated from the structure of variability along the sections. An additional means of estimating the uncertainty of the reported changes will be to subsample a numerical model. We will choose an appropriate GCM running a climate change scenario. We will subsample model basins with a space and time resolution equivalent to our in situ observations, and compare pentadal changes inferred from analysis of these simulated sections with full-basin results on heat content change calculated from the complete model fields.

<u>2.2 Focussed study of the North Atlantic</u>

We expect the N. Atlantic to transmit energy fluctuations to the deep ocean because it contains sites of Deep Water formation. Model results in Fig. 2 suggest that global variability in deep heat content is dominated by the variability in the Atlantic and in particular the N. Atlantic. The N. Atlantic contains a high density of hydrographic data, making it the best-sampled deep ocean in the world, as well as the property measurements and circulation estimates from the 26°N mooring array.

While the western N. Atlantic warmed (along with the majority of the global abyssal ocean) between the 1990s and 2000s, the eastern N. Atlantic was the only abyssal (> 4000m) ocean basin to significantly cool (Purkey and Johnson, 2010). Analysis of new data at 20°W collected in 2011 by co-I King shows that the reported cooling has reversed. The mooring array at 26°N provides twice-daily estimates of overturning circulation, and T-S profiles at moorings since 2004. With this time series, we will assess whether abyssal variability is due to changes in the quantity and properties of the northward-flowing Antarctic Bottom Water, or the southward-flowing North Atlantic Deep Water.

WP3 – Climate Model Simulations and Process Understanding (Met Office, Reading)

WP3 will exploit climate model simulations to investigate the relationships between TOA, surface flux variations and changes in ocean heat content and uncertainties, aiding interpretation of observations in WP1 and WP2. Specific aims include: (i) investigating whether knowledge of the upper 2000 m can inform deeper ocean changes; (ii) establishing the key spatial patterns and modes of variability that generate “hiatus” decades; (iii) identifying the key regions and processes where substantial transfer of heat to the deep ocean can occur.

These aims will be achieved primarily through analysis on long control simulations (Table 1). Control simulations provide many realisations of internal variability with which to compare with the observations. Initial findings suggest a “hiatus” episode occurs in the control simulations about twice per century; so many centuries are needed to span the potential range of behaviours.

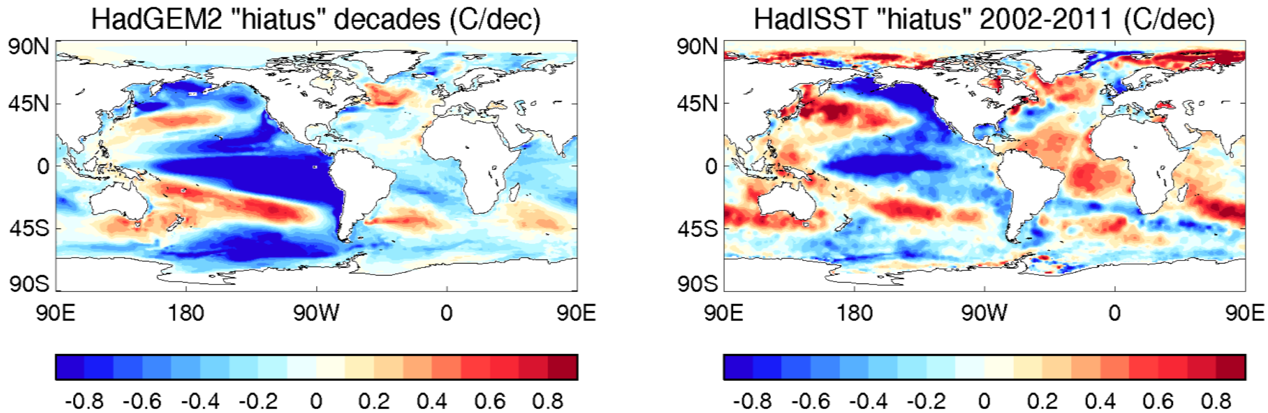

Figure 4 - Spatial map of the surface temperature changes associated with hiatus periods in (left) HadGEM2 model simulations and (right) HadISST observations for the current decade.

Recent analysis of a number of Hadley Centre climate models show a similar IPO-like pattern to that reported by Meehl et al. (2011) during model analogues of warming "hiatus" decades (Fig. 4, left). The SST trend from the observations over the period 2002-2011 (Fig. 4, right) is remarkably similar to the simulations, which suggests that greater insight will be gained by further process-based analysis of climate model output. The spatial patterns of change identified in WP1 and WP2 (e.g. Fig. 4, right) will allow us to search for model analogues of the recent "hiatus" period and conduct analysis of the simulations in a case-study approach.

In-depth analysis of mechanisms and processes will be limited – at least initially – to Met Office systems, where existing infrastructure and code will help with handling the large control run data sets (Table1). There is also a wealth of expertise to draw on within the Hadley Centre in conducting and interpreting the analysis results. Later in the project, analysis will be extended to include HadGEM3 configurations with an "eddy-permitting" ocean resolution.

Simulations from the CMIP5 archive will be used to investigate the relative roles of temporary changes in TOA radiative fluxes and ocean heat re-arrangement during "hiatus" decades across a large range of models. We will test the robustness of the simulated spatial patterns and use the model ensemble to improve the error estimates for total ocean heat content from Palmer et al. (2011).

System	Type	Atmosphere	Ocean	Data
HadCM3	Climate Model	N48	1.25° × 1.25°	3,000 year control simulation
HadGEM1	Climate Model	N96	1° × 1°	1,500 year control simulation
HadGEM2	Earth System Model	N96	1° × 1°	1,000 year control simulation
HadGEM3	Climate Model	N216/N144/N96	0.25° × 0.25°	Multi-century
GloSea5	Ocean analysis	ERA-Interim	0.25° × 0.25°	1989-present
FOAM	Ocean analysis	NWP Fluxes	0.25° × 0.25°	2-3 yr simulations

Table 1: Overview of the Met Office systems for analysis under WP3 and WP4. The numbers prefixed with "N" refers to the highest wavenumber that can be resolved in a latitude circle in the atmospheric model.

WP4 – Synthesis: Tracking Earth's Energy Flows (All)

All partners will work on combining datasets and results from WP1-3 to meet objectives O4-6. A new estimate of Earth's energy imbalance will be constructed over the period 2000-2015 (<±0.2 Wm^{-2}) combining data from WP1-2 and improving on previous estimates (Lyman et al. 2010) through techniques described in WP2. This estimate and its variability will be published in a high impact journal (D4). The new dataset will be combined with detailed modelling to elucidate mechanisms of energy redistribution by the ocean and identify model deficiencies in ocean heat uptake leading to a further high impact publication (D5). Co-Is Gregory and Kuhlbrodt, specializing in climate modeling, sea level and heat uptake globally and in the Southern ocean, will bring additional expertise to fully exploit the project datasets, software and results and enable dissemination to a wide community. Partner PI Palmer will ensure that monitoring and process understanding is capitalized on within the Met Office including their ocean modeling system. Additional tasks that will be addressed during the synthesis phase of the project are as follows:

- The observed atmospheric and oceanic energy flows over the period 2000 to 2015 will be compared with Met Office simulations to evaluate their fidelity and identify any missing processes (O4). These simulations will include the new HadGEM3 model that is currently under development, and is the first to include an ORCA025 eddy-permitting ocean.
- CMIP5 climate model simulations (control runs and simulation of the recent decades) from WP3 will be used to inform (i) the uncertainty on the observations of using the upper 2000m OHC changes as our estimate of total ocean heat content changes, (ii) the significance of the changes in deep water mass properties in the deeper N. Atlantic (WP2.2), (iii) the influence of realistic radiative forcings (e.g. Church et al. 2011) on surface warming.
- Development of a modeller-accessible data set to describe Earth's energy flows with appropriate error bars, to be produced in CF-compliant NetCDF and following CMIP5 protocols. This will permit the global climate modelling community to exploit estimates developed under our proposal.
- Ocean state estimates provided by the FOAM and GloSea5 seasonal forecast systems (Table 1) will be used to aid interpretation of the observed OHC changes in the upper 2000m, as estimated by WP2. These data assimilation systems will use historical observations and an eddy-permitting global ocean model to create a three-dimensional ocean state estimate of the recent decades. In particular, this will aid us in tracing back observed deep energy anomalies to their surface origins.
- Observational insight into the implications of model energy subduction into the deeper ocean for regional sea level changes. How much heat could be buried, especially at higher latitudes, and still evade detection in the satellite altimeter record?
- Application of the Palmer and Haines (2009) method for diagnosing heat content change mechanisms to the isopycnally-averaged analyses developed in WP2. The new WP2 products will provide the cleanest possible separation between changes arising due to air-sea heat fluxes and those arising due to changes in ocean transport/circulation and can potentially pave the way for detection and attribution studies of the recent warming "hiatus"

Deliverables

The following primary outputs relating to project objectives will be delivered. All partners will contribute toward publications to encourage cross-WP collaboration (the lead WP is denoted):

D1. Combined satellite-reanalysis atmosphere/surface energy flows: methodology, uncertainty and exploring lags in the climate system (paper 1,2; WP1, O1,4)

D2. Global 3D OHC and comprehensive uncertainty estimates (paper 3,4, WP2, O2)

D3. Multi-model comparison of variability in ocean heat content, freshwater content and spatial signatures (paper 5, WP3, O3)

D4. Characterization and integrated monitoring of Earth's radiative energy imbalance 2000-2015 from observations and simulations (paper 6/software, WP4, O4,5)

D5. Mechanisms of energy redistribution during hiatus decades (paper 7, WP4, O6)

Project Management and Wider Applications

PI Allan will manage overall running of the project with close involvement from joint PI McDonagh and Partner PI Palmer (with substantial in-kind co-funding of 3 years FTE over 4 years). WP1-3 will run in unison over 36 months from month 6 while project administration and integration under WP4 will run throughout the project. An experienced PDRA is required at Reading to process satellite data and reanalysis fields and develop software. A PDRA at Southampton NOC will develop 3D OHC estimates; Co-I King will provide expertise in Argo data, hydrographic observations, and on the Optimal Interpolation of observations. Reading Co-Is Gregory and Kuhlbrodt provide expertise in ocean heat uptake, including the Southern Ocean, and regional sea level patterns; they will contribute towards the synthesis of results from WP 1-3. Effective collaboration will be ensured through regular project meetings (3 each at the Met Office, Southampton and Reading); a Kick-Off (KO) meeting will be held in early 2013 to discuss project management, administration and initiation of the work-packages, thereafter project meetings will be held every six months.

Project results will be of wide value to the scientific community (see Academic Beneficiaries), in particular regional sea level patterns and radiative forcing (through Co-I Gregory) and in ocean modelling (through Met Office partner). Strong links through the Met Office partner will ensure new knowledge of ocean processes are incorporated into improved model physics and decadal climate simulations. The relationship between land and ocean warming and implications for the hydrological cycle will be of interest to the climate community, including the Changing Water Cycle (CWC) program of which PI Allan has strong links. Results will also be of interest to the international community (e.g. NASA project partners) and will also be of substantial public interest and policy makers including DECC project partners (addressing why there are decades of slow warming rate despite increasing greenhouse gas concentrations).

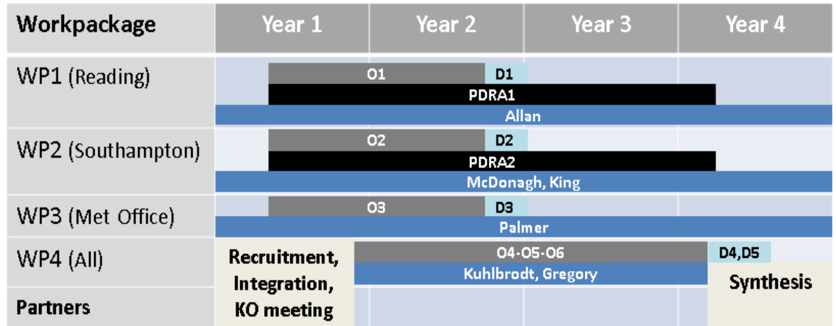

Table 2 - Management timeline for DEEP-C.

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