Argo – a cornerstone of earth observation and UK climate science

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Executive summary

In its short life the Argo profiling float array has become the essential core element of the in-situ monitoring system for the sub-surface ocean and has led to a revolution in our ability to understand key climate-relevant ocean processes and to run predictive climate models used to inform government policies on climate change mitigation and adaptation. Since the publication of the IPCC's fourth assessment report, the emphasis of UK climate research has shifted from global to regional spatial scales, in order to deliver the information needed to evaluate the socio-economic impacts of climate change (NERC, 2007; Defra/DECC/MoD Integrated Climate Programme). There is a growing requirement for skilful seasonal-to-decadal forecasts of climate in addition to the routine operational land and ocean weather forecasts. There is strong evidence that the global ocean observations delivered by Argo are fundamental to meeting these scientific challenges. Therefore, the long-term funding of the Argo array of profiling floats is of highest priority for UK climate science and to ensure that the best climate science is used to inform government policies on climate change mitigation and adaptation.

Facts

- In October 2007 Argo reached its goal of 3,000 active floats, able to deliver 100,000 surface-to-depth observations of temperature and salinity annually in real-time. This is an order of magnitude greater than in the pre-Argo era and includes observations from previously unobserved regions and seasons.

Argo has revolutionised our ability to observe the sub-surface ocean. For the first time, we are able to resolve the seasonal cycle in all ice-free areas of the deep ocean. Argo is rapidly advancing our knowledge of climate variability and change in the oceans.

Key findings

- A key uncertainty highlighted in the 2007 IPCC Fourth Assessment Report (AR4; Solomon et al., 2007) is in the ability of climate models to **predict sea-level changes**. A major contributor to sea level is change due to thermal expansion. Argo profiles are essential to distinguish between this contribution and those due to changes in the hydrological cycle or to ice sheet melting. Hence Argo provides an essential data set both for climate monitoring and for climate model development and assessment.

- If sustained, the Argo array of profiling floats can help to **improve predictions of climate change**, by providing an observational constraint on the rate of ocean uptake of heat and fresh water. This will help to reduce uncertainty in climate model projections of surface temperature rise and other important climate variables.

- The Met Office Decadal Prediction System has shown that the sub-surface observations from Argo are essential to **provide skilful seasonal-to-decadal predictions**. In order to further improve the accuracy and usefulness of seasonal-to-decadal climate predictions we require the continuing collection of the high quality global data set of sub-surface temperature and salinity observations from Argo for model initialisation and validation.

- Argo observations have dramatically improved the accuracy of **ocean analysis and forecast systems**. Argo is now a cornerstone of UK operational oceanography and is fundamental to the ocean forecasting and environmental support activities provided to the Royal Navy by the National Centre for Ocean Forecasting and the UK Hydrographic Office.

- Data from the Argo array are used by climate and ocean researchers in UK universities and research institutes. The outcomes of much of this research ultimately feeds in to operational forecasting and analysis activities.

Relevant key uncertainties from IPCC AR4 Technical Summary

Here we list some of the key uncertainties documented in the IPCC AR4 technical summary (Solomon et al., 2007) that a sustained Argo observing array will help to address.

1. "Limitations in ocean sampling imply that decadal variability in global ocean heat content, salinity and sea-level can only be evaluated with moderate confidence."

2. "There is low confidence in observations of trends in the meridional overturning circulation." (See Appendix A.)

3. "Global average sea level rise from 1961 to 2003 appears to be larger than can be explained by thermal expansion and land ice melting".

4. "Despite improved understanding, uncertainties in model simulated internal climate variability limit some aspects of attribution studies. For example, there are apparent discrepancies between estimates of ocean heat content variability from models and observations".

5. "Systematic biases have been found in most models' simulations of the Southern Ocean that are linked to uncertainty in transient climate response".

Another key issue is the assessment of heat uptake in the Southern Ocean. This is an important area in the model simulations and where it is essential to have adequate observations. Argo is really the only option for continuous monitoring of such a large area since regular research cruises would be prohibitively expensive.

1. What is Argo?

Each of the 3,000 or so autonomous profiling floats in the Argo array measures the temperature and salt content (salinity) between the surface and a pre-determined depth (typically 2,000m) every 10 days and transmits this information via satellite. The floats drift freely in the ocean and have an average separation of 3° in latitude/longitude. Sub-surface ocean currents can be determined using the float displacements between data transmissions. Argo float deployments started in 2000 and by November 2007 reached the target of 3,000 operating floats. Each float typically has a lifetime of 4-5 years and so the array must be replenished at a rate of about 800 floats per year. The Argo array is a collaboration with contributions from 23 countries, all of which share their data freely in real-time and without restriction. The data are also available in a slower “delayed mode” with more rigorous scientific quality control applied, necessary for climate monitoring.

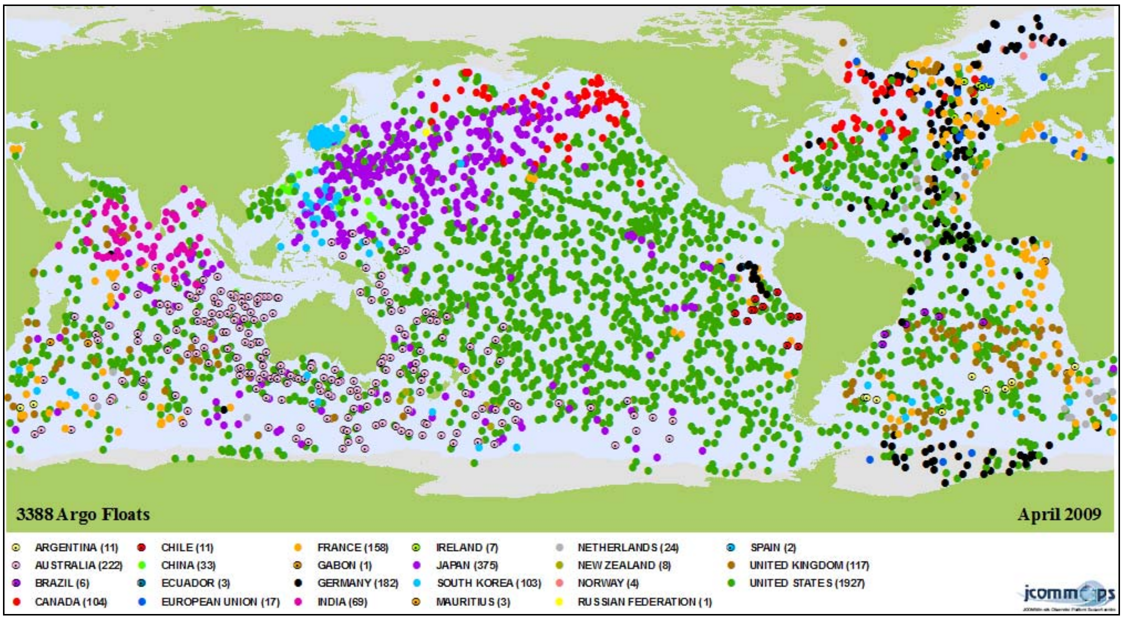

Figure 1: Argo coverage at end April 2009, showing the contributions of the various countries.

2. The UK contribution to Argo

The UK was in the first group of countries to contribute to Argo and this support has continued, as shown in Table 1. The number of UK floats deployed has varied from year to year depending on funding levels, although the number operating has steadily increased as float lifetime and reliability has improved. At the end of April 2009 there were 117 UK floats operating out of a total of 3,388 thus contributing about 3.5% of the global array.

	2001	2002	2003	2004	2005	2006	2007	2008
Number of floats deployed	29	38	38	47	28	26	33	29
Number operating at end of year	19	43	59	81	86	86	95	108

Table 1: Number of UK floats deployed each year that contribute to Argo and the number operating at the year end.

Funding for UK Argo has, to date, been provided from research budgets from Defra (now DECC), MoD and NERC. At current funding levels the UK contribution is likely to decline to around 2% of the global array by 2012, which would be well below the original commitment made by the Government's CSA in 1999 that the UK would contribute to at least a GNP level (about 5% of the global array).

Currently, there is no long-term commitment by the UK funding agencies to maintain a national contribution to Argo despite the fact that the UK has taken a leading position in the application of Argo for climate prediction, climate research and operational ocean forecasting. Overall the cost of maintaining the entire global array is approximately $20M per year, such that a 5% contribution (40 floats per year) would be about £800k per annum.

3. Overview of Argo use in UK and international climate science

In the short time for which global Argo data have been available it has made possible revolutionary developments in a number of areas of climate science. Many of these are areas of research in which the UK has a leading position. In the following sections we give examples of the importance of Argo temperature and salinity data with a particular emphasis on contributions from the UK.

3.1 Constraining climate predictions using Argo data

Most of the uncertainty in climate predictions at timescales of decades and longer, results from the spread in the different models' simulated responses to anthropogenic climate forcings (Hawkins and Sutton, 2009). Argo measurements of the sub-surface ocean have great potential to reduce uncertainties in climate predictions, by providing an observational constraint on the rate of ocean heat uptake. There is some evidence to suggest that climate models have overestimated how rapidly heat has penetrated below the ocean's mixed layer (Forest and Stott, 2007). Continuing sub-surface temperature data will better constrain to what extent climate models could be under-estimating the near-surface temperature response by exporting too much heat to the deep ocean.

Further, sub-surface salinity observations made by Argo will aid an improved quantification of observed changes in the strength of the hydrological cycle. Observed precipitation trends over land demonstrate that the predicted signal of climate change of reductions in the sub-tropics and increases at high latitudes has begun to emerge, although there are also some indications that climate models could underestimate the observed rates of change (Zhang et al., 2007). Ocean salinity acts as an integrator of differences between precipitation and evaporation at the ocean surface and continued data from Argo as the climate signal strengthens will provide important information of changes in the hydrological cycle over the poorly-observed ocean.

3.2 Monitoring the ocean state: heat and freshwater content, and global sea level

The fact that Argo provides temperature and salinity information from the upper 2km of almost all areas of the global ocean has made it possible, for the first time, to monitor the global ocean state. This includes the detection of temperature and salinity change and the possibility of attributing the patterns of change to anthropogenic influences (King and McDonagh 2005; Stark et al. 2006). There are numerous publications relating to the ability of Argo data to document year-to-year changes in the properties of mode waters (water masses modified by energetic wintertime exchanges of heat and fresh water with the atmosphere). Our understanding of the processes involved and the significance of changes will be greatly enhanced as the length of the Argo record is extended.

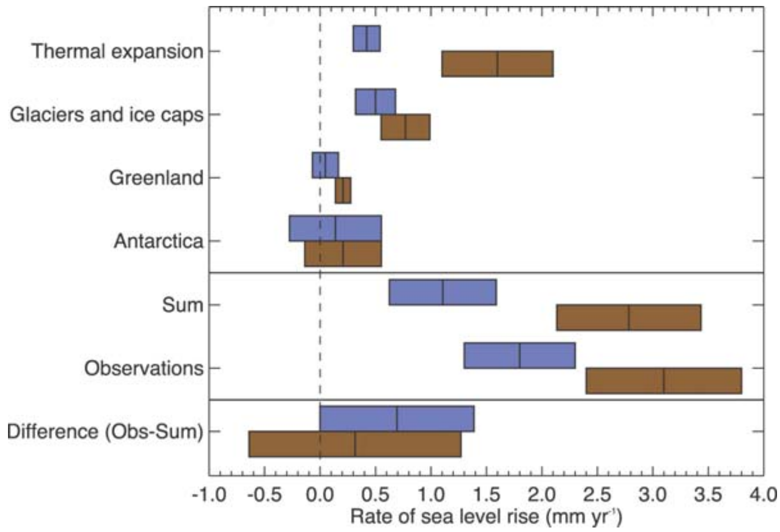

Figure 2: Estimates of the various contributions to the budget of the global mean sea level change (upper four entries), the sum of these contributions and the observed rate of rise (middle two), and the observed rate minus the sum of contributions (lower), all for 1961 to 2003 (blue) and 1993 to 2003 (brown). The bars represent the 90% error range. For the sum, the error has been calculated as the square root of the sum of squared errors of the contributions. Likewise the errors of the sum and the observed rate have been combined to obtain the error for the difference. Reproduced from IPCC AR4 (Bindoff et al., 2007).

The 2007 IPCC report provided a breakdown of the contributions to sea level made by the main factors involved (Figure 2). Thermal expansion of the ocean water column is a major contributor and one that, thanks to the combination of Argo and satellite radar altimetry, it is now possible to quantify with some accuracy (Domingues et al., 2008; Church et al. 2008; Wijffels et al. 2008). As the Argo record is extended and the accuracy of its data improves it will be possible to better quantify the other contributions to sea level variations especially those due to changes in air-sea fluxes (atmospheric aerosols from volcanic activity, changes in cloudiness).

3.3 Seasonal-to-decadal prediction

An area of climate prediction with the most immediate socio-economic applications (e.g. in the areas of agriculture, energy strategy, water supply, coastal protection, insurance) is that of seasonal-to-decadal forecasting. A major challenge in climate research is to develop skilful capability on these timescales and with useful spatial resolution. Representing the influence of the oceans is vital since they have a much larger capacity to store heat and freshwater than the atmosphere and also have much slower modes of propagating climate anomalies. These factors result in the oceans having a much longer "memory" in the climate system and thus the potential for longer forecast lead times when models are initialised with an estimate of ocean state.

Argo is essential for providing the sub-surface observations required to initialise and validate both seasonal (Balmaseda et al., 2007)) and decadal climate forecasts (Smith et al., 2007). The delivery of both collocated temperature and salinity is required to gain skill in forecasting the time evolution of the climate system, including the meridional overturning circulation (MOC, e.g. Bryden et al., 2005), which is the focus of the NERC RAPID program. Model studies suggest that a collapse of the MOC due to additional freshwater input associated with global warming could cause a rapid regional temperature change of -2°C over Western Europe (Vellinga and Wood, 2002). See appendix A for a case study on decadal forecasts of the MOC using simulated Argo observations in the Met Office decadal prediction system (Smith et al., 2007).

3.4 Operational ocean forecasting

Operational oceanographic analysis and forecasting systems, including the UK Met Office's FOAM (Forecasting Ocean Atmosphere Model), provide estimates of the ocean state. The FOAM system produces high resolution realisations that are used by the Royal Navy. The outputs also support public and commercial services for ship routing, offshore industry, fisheries, oil-spill monitoring applications as well as for science research. In FOAM, both in-situ and satellite ocean observations are assimilated into the models to produce the best analyses. Significant degradation of the performance of the FOAM ocean forecasting system occurs when Argo data are omitted from the assimilation scheme. This results in significant large-scale errors in both the temperature and salinity of the ocean, which means that the models then fail to correctly utilize the high resolution surface information provided by satellite altimetry (see appendix B for further details).

3.5 Use by the academic research community

The ready availability of Argo data has been a valuable asset for Universities and research Institutes and has already been the basis of a number of MSc and PhD projects. UK researchers are authors or co-authors on 6% of the peer-reviewed publications in the Argo bibliography maintained by the international Argo project. In addition to research on decadal scale changes in water mass properties and changes in ocean heat storage and the MOC a notable PhD project (Matthews et al 2007) used Argo data to show the deep penetration of the Madden-Julian Oscillation in Indian Ocean. This deep ocean sink of energy input from the wind is potentially important for understanding climate phenomena such as El Niño–Southern Oscillation. Other papers have studied deep winter convection in the N Atlantic and Mediterranean (Hadfield et al 2007, Smith et al 2008). Argo data are of considerable value in setting the wider-scale context of data collected on research vessel cruises.

4. Synergies between Argo and other observing platforms

The in-situ observations provided by Argo have some important synergies with other components of the global climate observing system. Here we highlight some of those relationships and the fundamental scientific questions that Argo is helping to address.

4.1 Satellite measurements of sea surface height

While Argo is a vital new contributor to monitoring of the state of the global ocean, in order to realise its full potential it has a degree of interdependence with other observing system elements. Foremost among these is Argo's link with high precision satellite altimetry, which measures sea surface height. Since the early 1990s there has been continuous quasi-global altimetry coverage, starting with ERS-1 and 2 and the remarkable 13-year (1992-2005) Topex-Poseidon satellites, continuing to the present day with Jason-1 and 2. (The name of the Argo project reflects its synergy with the Jason satellite series. Argo was the ship in Greek mythology in which Jason sought the Golden Fleece.)

Satellite altimetry provides accurate estimates of both global and regional sea-level changes. However, both thermal expansion (from global warming) and addition of freshwater (from terrestrial ice-melt and water storage changes) contribute to sea-level changes. Argo observations provide estimates of the thermal expansion component, which is crucial to understanding the mechanisms behind observed sea-level changes. The higher resolution of the satellite altimeter data help to reduce uncertainties in estimates of ocean heat content change, using relationships between sea surface height and column-integrated ocean temperature (e.g. Willis et al., 2004; Lyman and Johnson, 2008). It has also been demonstrated that altimetry provides a means of identifying previously undetectable anomalies in the performance of individual floats, which will help to ensure that Argo data is of the highest quality.

4.2 Satellite gravity field observations

The Gravity Recovery and Climate Experiment (GRACE) and the Gravity field and steady-state Ocean Circulation Explorer (GOCE) missions[*] will map Earth's gravitational field. Variations in Earth's gravitational field arise from: changes due to surface and deep currents in the ocean; runoff and ground water storage on land masses; exchanges between ice sheets or glaciers and the oceans; and variations of mass within the Earth. Argo estimates of ocean thermal expansion in combination with altimeter data, will provide an independent estimate of ocean freshwater input to cross-validate with GRACE and GOCE. Argo observations of changes in sub-surface temperature and salinity will also combine with gravity field observations to aid our understanding of changes in ocean circulation, using geostrophy.

4.3 Satellite measurements of radiation

It was recently estimated that over 80% of the Earth's radiation imbalance manifests in warming of the subsurface ocean (Levitus et al., 2005). Therefore, estimates of ocean heat uptake based on Argo observations provide a powerful constraint for efforts to close the Earth's radiation balance. Similar to the gravity measurements described above, the combination of Argo and satellite estimates of top-of-atmosphere radiation provides a means to cross-validate two independent measurements and better understand the capabilities of

[*] http://www.csr.utexas.edu/grace/ and http://www.esa.int/esaLP/LPgoce.html

the current observing system (e.g. Wong et al., 2005). Closing Earth's radiation balance is a priority for climate research and Argo observations will play a key role in realising this goal.

4.4 Improving our understanding of sea surface temperature

Typically Argo floats measure temperature to within about 5m of the ocean surface. Comparisons with drifter data show that the 5m Argo temperatures agree well with nearby (in space and time) drifter sea surface temperatures (SST). Significant differences are observed only in low-wind daytime conditions where surface heating can cause large temperature variations in a thin near-surface layer over the day. Recent developments now permit floats to measure temperatures all the way to the surface thus providing a valuable complement to traditional SST data (from satellites, drifters and ships) and helping to better elucidate the effects of temperature variability in the surface layer.

4.5. Research ship measurements of temperature and salinity

There is another important link between Argo and traditional research ship measurements of temperature and salinity. The link is two-fold; the first being that ship-based measurements provide, albeit sparse, observations of changes in the deeper ocean, where Argo floats cannot sample (though this may be possible in future). The second is that research ship measurements provide independent and verifiable calibration data for the salinity sensors of Argo floats. This helps to ensure that Argo data are of the highest possible quality for use in climate change research.

5. Conclusions

This report provides strong evidence of how ocean observations made by Argo underpin improved understanding of climate change, facilitate development of key climate services and provide valuable new insights into climate-relevant ocean processes. Argo must be sustained in order to:

1. Develop and verify operational ocean forecasts and seasonal-to-decadal climate forecasts.
2. Improve our understanding of regional climate change and impacts.
3. Better understand and predict future sea-level change.

4. Reduce the uncertainty in long-term climate change projections by providing an observational constraints on ocean heat uptake.
5. Provide real-time monitoring of sea-level, ocean heat content, changes in the ocean circulation and hydrological cycle.

Hence, the long-term funding of the Argo array of profiling floats is of highest priority for UK climate science and to ensure that the best climate science is used to inform government policies on climate change mitigation and adaptation. This will require sustained funding from those countries who have contributed to building the Argo array. A continued and sustained contribution from the UK is critical to this, particularly given the UK's world-leading position in climate science.

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Appendix A: Impact of Argo on forecasts of the meridional overturning circulation

Western Europe's mild climate is sustained by high poleward heat transport by the global meridional overturning circulation (MOC). The large and rapid transitions between glacial and interglacial periods have been linked to changes in the MOC and in the location and intensity of deep winter convection at high latitudes. Model studies suggest that a collapse of the MOC due to addition of freshwater under global warming could cause a regional temperature change of -2°C over Western Europe (Vellinga and Wood, 2002). The NERC RAPID[†] programme is studying the stability and variability of the MOC. The fact that Argo measures both salinity and temperature (and therefore density can be derived) makes the data particularly valuable for understanding and predicting changes of the MOC (e.g. Bryden et al., 2005).

Validating decadal forecast systems, using "hindcasts", is currently very difficult due to the extremely limited coverage prior to Argo. Idealised (or "Perfect model") predictability studies enable us to cleanly separate the affects of assimilating different observations without having to take external forcings or observational uncertainty into account. As a basis for our experiments we use a long control run of the Hadley Centre Coupled Model, version 3 (HadCM3, Gordon et al., 2000). All our assimilation experiments start using model conditions taken from a distant part of the control run. We focus on four different assimilation schemes:

1. 'Perfect' - uses conditions from the original control run
2. 'Full-Depth' - ocean temperature (T) and salinity (S) are assimilated to full depth
3. '2000m' - ocean T and S are assimilated to 2,000m (c.f. Argo)
4. 'SST Only' - sea surface temperature (SST) is assimilated

For the 'Full Depth' and '2000m' experiments we use the same, relatively strong, relaxation to assimilated data as in Smith et al. (2007). Similarly, both experiments assimilate six-hourly atmospheric data. In the case of the 'SST Only' experiment we follow the assimilation method of Keenlyside et al. (2008). This has a weaker and latitude dependent relaxation timescale and also does not assimilate the atmosphere. The assimilation runs provide the initial conditions for the forecasts.

[†] http://www.noc.soton.ac.uk/rapid/rapid.php

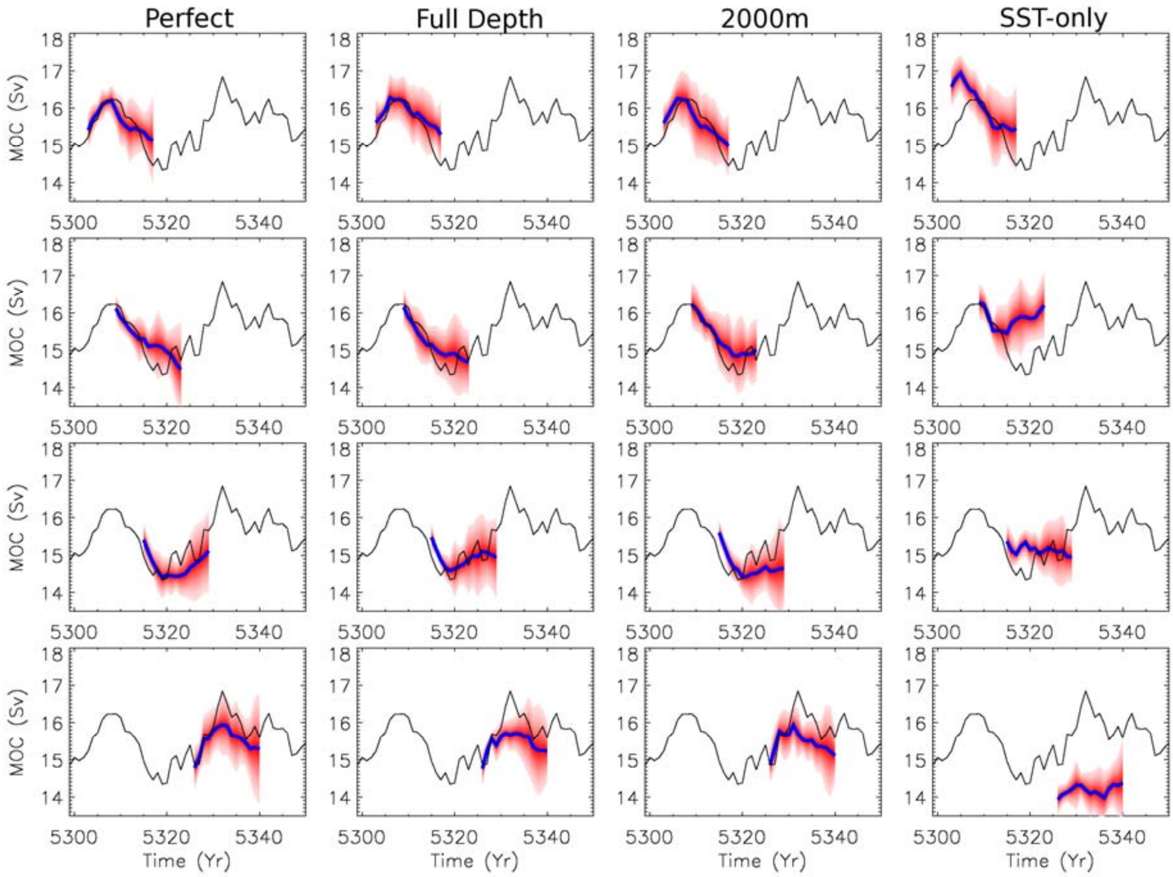

Figure A1: Forecasts of the MOC for the four experiments (each with different ocean initialisation) and for four start dates. The thick blue lines are the ensemble means and the red shading indicates the 90% confidence region.

The forecasts are nine-member initial condition perturbed ensembles and are run for 15 years. In figure A1 we show the forecasts of the MOC for all experiments and four start dates which were chosen to sample a range of phases of the MOC. The Full depth and 2000m experiments show a similar level of skill to that of the Perfect experiment. This is particularly encouraging as it suggests that assimilating 2,000m T and S data (as provided by the Argo array) has the potential to provide skilful forecasts of the MOC. In contrast, when we only assimilate SST the model does a relatively poor job at reproducing the evolution of the original MOC.

In figure A2 we look at the skill of forecasting SST. Here we correlate anomaly maps of five year mean forecast SST against the truth from each forecast start date. We calculate an average correlation from all start dates and then plot this as a function of forecast lead time for each of the four experiments. Figure A2 clearly illustrates that the forecast skill is dependent upon the amount of information that we assimilate. The Perfect experiment, having full knowledge of all variables (including ocean currents), gives the highest skill at all lead times. Initially the Full depth and 2000m T and S experiments show only slightly less skill than the Perfect experiment. At longer lead times the skill of the 2000m experiment starts to decrease more rapidly than that of the Perfect and Full depth experiments. This suggests that initialising the deeper ocean is starting to have a surface impact after a couple of years. The skill of the SST Only experiment, while positive, is very much less than the experiments that assimilate sub-surface temperature and salinity data. This simple experiment illustrates the potential of Argo data to successfully initialise decadal climate models.

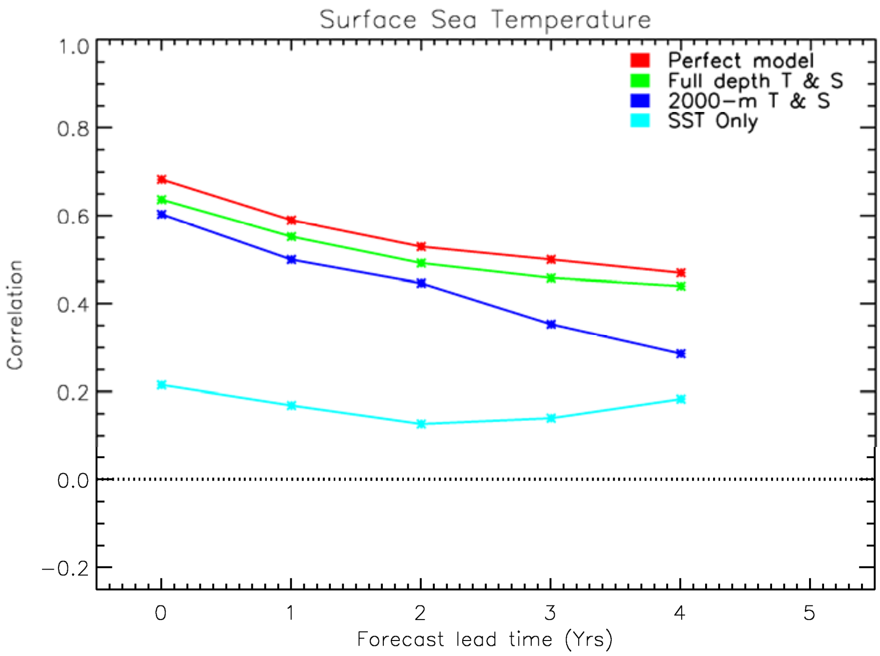

Figure A2: The skill in forecasting 5 year SST anomalies is shown for the four different experiments. Note that the skill in these idealised experiments depends upon the amount of information assimilated. The Argo like 2000m T & S experiment compares favourably to the Perfect and Full depth experiments, although skill does drop off quicker at longer lead times. The experiment that assimilates SST only shows relatively poor skill at all lead times.

Appendix B: Impact of Argo data on short-range ocean forecasts

The Met Office Forecasting Ocean Assimilation Model (FOAM; Martin et al., 2007) system provides operational analyses and 5-day forecasts of ocean temperature, salinity, currents and sea-ice on a daily basis. It assimilates Argo data as well as other data types including satellite altimeter sea surface height data and sea surface temperature data. The main aims are to analyse and forecast the mesoscale structure of the ocean and to use the analyses produced by FOAM to monitor the climate of the oceans. For both of these aims, the Argo data are crucial. The only data available which can directly resolve the dynamical structure at the mesoscale is the satellite altimeter sea surface height data. The method used to assimilate the altimeter data makes no changes to the water mass properties of the model and so the only way in which these can be altered is through direct assimilation of in situ profile data, such as from Argo.

Observing system experiments have been performed using the 1/9° resolution North Atlantic FOAM configuration: one in which all the available temperature and salinity data were assimilated, and one in which the Argo data were withheld from the assimilation. Both of these integrations were started from the same initial conditions on 7th January 2001 and run for 5 years. The average impact of the data on the model is shown in figure B1 for temperature and figure B2 for salinity, both at 1,000m depth. These figures show that with the Argo data included, there is a much larger impact on the model from the data assimilation. Without Argo data, the data assimilation is unable to constrain the salinity field in particular and also has a large impact on the analysed temperature. The overall root-mean-square errors from these integrations are presented in figure B3 which shows that the Argo array has a significant positive impact on the overall errors in the FOAM system. Without the Argo data the temperature errors are up to 40% larger and the salinity errors near the surface are over twice as large, even when the other in situ data sources are assimilated.

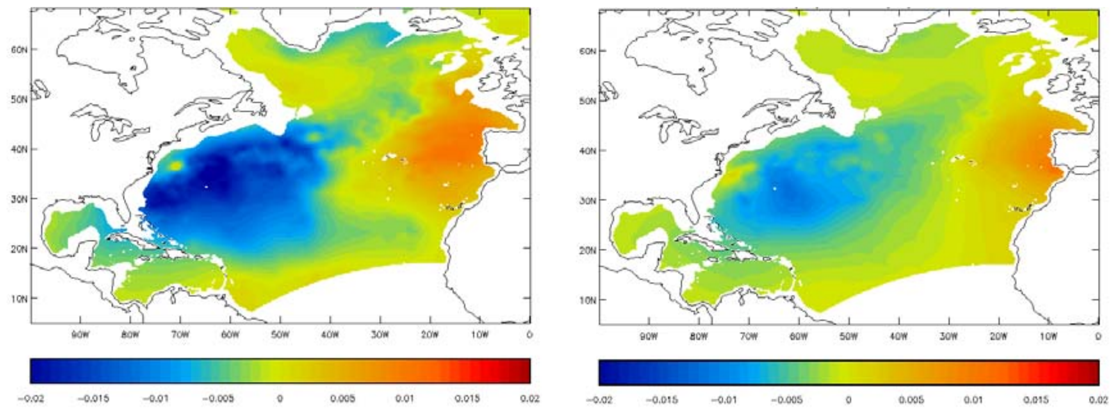

Figure B1: Average temperature changes (˚C per day) made to the model by the data assimilation at 1,000m depth when (left) all data are assimilated and (right) all data except Argo profiles are assimilated.

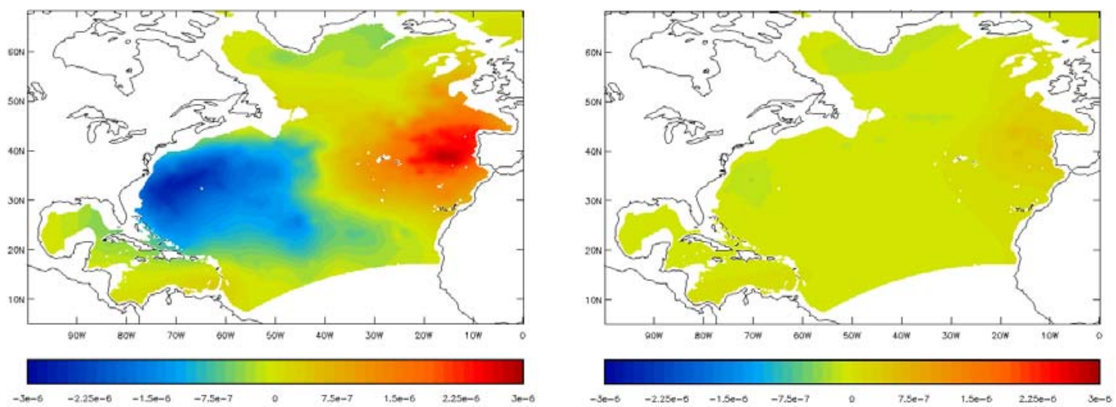

Figure B2: Average salinity changes (psu/1000 per day) made to the model by the data assimilation at 1,000m depth when (left) all data are assimilated and (right) all data except Argo profiles are assimilated.

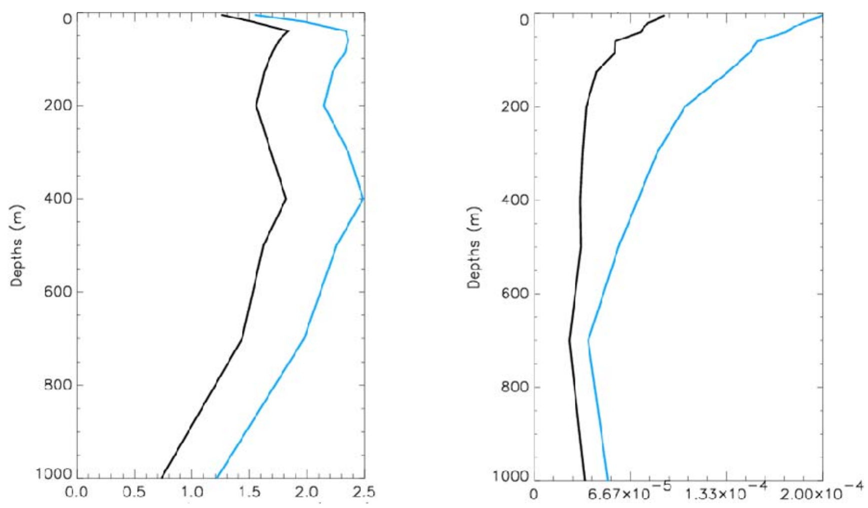

Figure B3: Root-mean-square errors as a function of depth over a 5-year reanalysis of the FOAM system for (left) temperature (˚C) and (right) salinity (psu/1000). The black line shows the errors when all *in situ* data are assimilated, and the blue line shows the errors when all data except Argo data are assimilated.

APPENDIX C: Selected Argo publications

The Argo profiling float array now provides a major observational system and has been a catalyst for a wide range of scientific studies. This fact is reflected in a bibliography compiled by Argo that grows at a rate of order 100 peer-reviewed publications per annum in which Argo data are used. The following list is some of papers in which UK based scientists have made a major contribution.

Balmaseda, M., and D. Anderson, 2009: Impact of initialization strategies and observations on seasonal forecast skill, *Geophysical Research Letters*, 36, L01701.

Balmaseda, M.A., A. Vidard, and D.L.T. Anderson, 2008: The ECMWF Ocean Analysis System: ORA-S3, *Monthly Weather Review*, 136, 3018-3034.

Boehme, L., M.P. Meredith, S.E. Thorpe et al., 2008: Antarctic Circumpolar Current frontal system in the South Atlantic: Monitoring using merged Argo and animal-borne sensor data. *Journal of Geophysical Research – Oceans*, 113 (C9).

Smith, R.O., H.L. Bryden and K. Stansfield, 2008: Observations of new western Mediterranean deep water formation using Argo floats 2004–2006, *Ocean Science*, 4, 133-149.

Acreman, D.M., and C.D. Jeffery, 2007: The use of Argo for validation and tuning of mixed layer models. *Ocean Modelling*, 19, 53-69.

Balmaseda, M., D. Anderson and A. Vidard, 2007: Impact of Argo on analyses of the global ocean, *Geophysical Research Letters*, 34, L16605.

Hadfield, R.E., N.C Wells, S.A. Josey and J.J.-M. Hirschi, 2007: On the accuracy of North Atlantic temperature and heat storage fields from Argo, *Journal of Geophysical Research-Oceans*, 112.

Ingleby, B. and M. Huddleston, 2007: Quality control of ocean temperature and salinity profiles – Historical and real-time data, *Journal of Marine Systems*, 65, 158-175.

Ivchenko, V.O., S.D. Danilov, D.V. Sidorenko, J. Schroeter, M. Wenzel and D.L. Aleynik, 2007: Comparing the steric height of the Northern Atlantic with satellite altimetry, *Ocean Science Discussions*, 4, 441-457.

Martin, M.J., A. Hines and M.J. Bell, 2007: Data assimilation in the FOAM operational short-range ocean forecasting system: A description of the scheme and its impact, *Quarterly Journal of the Royal Meteorological Society*, 133, 981-995.

Matthews, A., P. Singhruck and K. Heywood, 2007: Deep ocean impact of a Madden-Julian Oscillation observed by Argo floats, *Science*, 318, 1765-1769.

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

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.

Palmer, M.D. and K. Haines, 2009: Estimating oceanic heat content change using isotherms, *Journal of Climate*, in press.

Pollard, R.T., H.J. Venables, J.F. Read, et al., 2007: Large-scale circulation around the Crozet Plateau controls an annual phytoplankton bloom in the Crozet Basin. *Deep-Sea Research Part II*, 54, 1915-1929.

Venables, H.J., R.T. Pollard and E.E. Popova, 2007: Physical conditions controlling the development of a regular phytoplankton bloom north of the Crozet Plateau, Southern Ocean. *Deep-Sea Research Part II*, 54, 1949-1965.

Vidard, A., D.L.T Anderson and M. Balmaseda, 2007: Impact of ocean observation systems on ocean analysis and seasonal forecasts, *Monthly Weather Review* 135, 409-429

Gould, W.J. and J. Turton, 2006: Argo – Sounding the Oceans. *Weather*, 61, 17-21.

Haines, K., J.D. Blower, J.-P. Drecourt, C. Liu, A. Vidard, I. Astin and X. Zhou, 2006: Salinity assimilation using S(T): covariance relationships. *Monthly Weather Review*, 134, 759-71.

Ivchenko, V.O., N.C Wells and D.L. Aleynik, 2006: Anomaly of heat content in the northern Atlantic in the last 7 years: Is the ocean warming or cooling?, *Geophysical Research Letters*, 33, L22606.

Domingues, C.M., J.A. Church, N.J. White, P.J. Gleckler, S.E. Wijffels, P.M. Barker and J.R. Dunn, 2008: Improved estimates of upper-ocean warming and multi-decadal sea-level rise, *Nature*, 453, 1090-1093.

Wijffels, S., J. Willis, C. Domingues, et al., 2008: Changing Expendable Bathythermograph Fall Rates and Their Impact on Estimates of Thermosteric Sea Level Rise, *Journal of Climate*, 21, 5657-5672.

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

Stark, S., R.A. Wood and H.T. Banks, 2006: Reevaluating the Causes of Observed Changes in Indian Ocean Water Masses. *Journal of Climate*, 19, 4075-4086.