The use of Argo data in the operational ocean forecasting activities at the UK Met Office

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1. How the Argo data are used

This section gives a brief overview of each of the systems in which Argo data are used at the UK Met Office.

1.1 Operational assimilation of data

1.1.1 FOAM

The Forecasting Ocean Assimilation Model (FOAM) system is an operational short-range deep ocean forecasting system. It consists of a set of nested model configurations, ranging from a global 1° model to intermediate resolution basin-scale models down to high resolution regional models, each of which takes boundary conditions from the larger-scale models. The models are forced at the surface by fluxes taken from the operational Numerical Weather Prediction system run at the UK Met Office. Forecasts are made out to 5 days.

Various data types are assimilated into each of the configurations including in situ and satellite sea surface temperature (SST) data, along-track altimeter sea surface height (SSH) data and in situ temperature and salinity profile data, including the Argo float data. The data is assimilated using a scheme based on the Analysis Correction scheme (an iterative solution to Optimal Interpolation) in which the data is blended with model fields based on estimates of the error covariances associated with each. See Martin et al. (2007) for a description of the data assimilation scheme used in FOAM. The Argo data are quality controlled using the automatic system developed for ENACT described in section 1.2.

1.1.2 GloSea

GloSea is a coupled ocean-atmosphere modelling system which provides seasonal forecasts. The model component is based on the model used for climate predictions at the Hadley Centre (and uses the same code for the ocean model as the FOAM system).

The main data type assimilated into the ocean component of the coupled system is the in situ temperature and salinity profile data, including Argo data. The scheme used to assimilate them is the same as that used in FOAM and the data are quality controlled using the automatic system described in section 1.2. Long time-series of analyses are required in order to calibrate the seasonal forecasts produced by GloSea.
1.1.3 DePreSys

The Decadal Prediction System (DePreSys) is also a coupled ocean-atmosphere modelling system, but the focus here is on producing forecasts on longer climate time-scales. The ocean component of the coupled model is initialised with analyses of surface and sub-surface observations of temperature and salinity. These analyses are created off-line by multivariate optimal interpolation, using covariances computed directly from long integrations of the coupled model (Smith and Murphy, 2007). The effect of model biases on forecasts is avoided by initialising with observed anomalies added to the model climatology. This system is described in further detail by Smith et al., 2007. The system uses all in situ hydrographic data including Argo data to initialise the forecasts.

1.2 Production of delayed-mode quality controlled data sets

As part of the EU ENACT project, a system to quality control historical and real-time profiles of temperature and salinity was developed at the UK Met Office by Ingleby and Huddleston (2007). This has been further developed under the EU ENSEMBLES project. Once the system was developed, various versions of a comprehensive data-set containing the historical profile data, including Argo data, have been released. The latest version is available at [http://hadobs.metoffice.com/en3/](http://hadobs.metoffice.com/en3/). These are intended as a standard set of data which can be used for assimilation into the modelling systems in ENSEMBLES, but are also used elsewhere.

1.3 Analyses in delayed-mode

A modified version of the GloSea analysis procedure has been used to provide a multi-decadal objective analysis with which to compare various model/assimilation runs in ENACT/ENSEMBLES. This involves no circulation model, but instead relaxes towards climatology between analysis times, and uses the delayed-mode quality controlled data described in the previous section. These analyses have been used to assess the changes in ocean heat content over the past few decades. They have also been useful in comparing the impact of various data types on the heat content estimates, which has revealed some significant biases between different data types.

The Hadley Centre Global Ocean Analysis (HadGOA) is currently being developed to produce estimates of global ocean variability and heat content. Here, the analyses are calculated on isotherms which has potential advantages over analyses produced on depth levels. Details of the system are available from [http://hadobs.metoffice.com/hadgoa/](http://hadobs.metoffice.com/hadgoa/).

The ocean analysis used by DePreSys has also been extended to cover the historical period from 1950 onwards. Estimates of expected errors in these analyses have also been made, and show dramatic improvements since the introduction of Argo data (Fig.15 of Smith and Murphy, 2007)

1.4 Validation of analyses and forecasts

Validation of model analyses and forecasts is a vital part of any forecasting system. All profile data including Argo are used to verify the FOAM analyses/forecasts on an operational basis. This is done by comparing the model fields to the observations. The automatic verification is run as part of the operational suite. Further verification/validation tests are carried out on the system, mainly in hindcast mode, in order to check the impact of model/assimilation improvements on the verification scores.

1.5 Aid to model and assimilation development and tuning

The depth of the well-mixed layer at the ocean surface is an important output from the FOAM model. A realistic representation of vertical mixing is also required to correctly represent the effects of surface fluxes of heat, momentum and moisture. Argo data enable vertical mixing models to be tuned and validated over an annual cycle with an unprecedented geographical
A tuning and validation study of FOAM using Argo data was performed by Acreman and Jeffery (2007).

The observation and background error covariances are a crucial part of any data assimilation scheme as they determine both the relative weight given to the observations and model background field, and also the way in which the information is spread into the model. There are various ways in which these error covariances can be estimated. The method previously used in FOAM was based on collocated observation and model values. This method requires large numbers of observations in order to make the statistics robust, and so was unfeasible before the Argo array was in place. For more information see Martin et al. (2002).

2. Source of Argo data for each application

The main source of Argo data for near-real time applications at the Met Office is the Global Telecommunications System (GTS). The data from the GTS is kept in a database from which it can be retrieved and processed. The data for both the FOAM and GloSea systems are obtained in this manner.

The data-sets described in section 1.2 were based on data from various sources, including the Argo GDACs, GTSPP and WOD05. Once this data has been processed, it is used to produce the delayed-mode reanalyses for ENSEMBLES, the DePreSys analyses and the HadGOA analyses.

3. Timeliness of Argo data for each application

3.1 FOAM

The FOAM system runs at 05:00 UTC every day and produces an analysis using data which is valid up to midnight the previous day, as shown in Fig. 1. The data valid at midnight therefore has 5 hours to reach the model before it is used. The data valid just after midnight on the previous day has 29 hours to reach the model before it is used. Data which is not available for assimilation on the day in which it is valid is still used in the assimilation, as long as it arrives within 10 days of its validity time. However, the longer it takes to reach the assimilation system, the less weight it is given.

The number of float reports which were obtained from the GTS in January 2007 is 10,035. Out of these, 91.2% reported within 24 hours of their validity time and so would have been given full weight in the FOAM assimilation system. The timelines of all the reports is shown in Table 1. Less than 1% of the float reports were not available for assimilation at all in FOAM, i.e. take longer than 10 days to be received. It would however improve the utilisation of the Argo floats if an even higher percentage of reports were obtained within 24 hours of their validity time.
<table>
<thead>
<tr>
<th>Timeliness of reports (days)</th>
<th>0&lt;t&lt;1</th>
<th>1&lt;t&lt;2</th>
<th>2&lt;t&lt;4</th>
<th>4&lt;t&lt;6</th>
<th>6&lt;t&lt;8</th>
<th>8&lt;10</th>
<th>t&gt;10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of reports</td>
<td>9154</td>
<td>431</td>
<td>256</td>
<td>78</td>
<td>31</td>
<td>28</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 1: Difference between validity and receipt times (days) for all Argo reports over the GTS in January 2007.

3.2 GloSea

The GloSea operational system is currently run once each week, 10 days behind real-time. It uses the data obtained over the GTS and so will assimilate almost all of the Argo data (over 99%), given the figures in Table 1. In the near future, the system will be changed to run 6 days behind real time.

3.3 HadGOA

The HadGOA system is currently under development and so does not run operationally. When it does start running, it will produce a gridded monthly anomaly field once each month about 10 days after the end of the month for which the analysis is produced.

3.4 DePreSys

DePreSys typically runs a month or two behind real-time, for which the present delivery of Argo data is suitable.

4. Assessment of the quality of the Argo data for each application

4.1 Quality issues from the FOAM perspective

As described in section 1.1, FOAM uses an automatic quality control system. This includes various checks such as track checks, spike checks, background check, stability checks, duplicate checks and buddy checks. If more than half of a report is flagged as having failed one or more of the checks, then the whole report will be rejected. Figure 2 shows the percentage of whole reports which were rejected in the operational FOAM system for the first 34 days of 2007. The number rejected is generally quite small and always less than 1%. Of the whole profiles which pass the quality control, a similar percentage (~1%) of individual levels of profiles are also flagged by the quality control.

Overall, the data quality of Argo is good, but some floats have caused problems in the operational FOAM system, particularly with bad salinity data. The main problem is with the specification of the error variances used in the background check. In areas of high variability the error variance will be relatively high and so it is more difficult to distinguish bad data (for instance a salinity offset or drift) from the natural variability. On one or two occasions, bad data have passed the quality control and have been assimilated into the model. This has then adversely affected the model’s salinity, but has also been transferred into other model fields by the dynamics. These problems are solved by tightening the background check so that there is less chance of bad observations getting through the quality control. However, this does result in a slightly larger number of good floats being rejected.

The FOAM quality control has the facility to blacklist certain float identifiers and this has been used in the past to prevent bad data from being assimilated. However, this can only be done after the event, once the adverse effects on the model fields have already been established. It would be useful to have access to a blacklist which was updated frequently. The frequency of updating the blacklist in the FOAM operational system is likely to be about once per month.
4.2 Quality issues from the delayed-mode processing perspective

During recent work on the delayed-mode quality control many more instances of "bad" Argo data were observed than expected. In part this is due to the large (by ocean standards) data volume available in recent years. Most Argo data are generally of good quality but a significant minority have data quality problems. Table 2 gives an idea of the scale of profile rejections from the ENSEMBLES quality control.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total number rejected</th>
<th>Profiling floats (Argo and pre-Argo)</th>
<th>XBT</th>
<th>CTD</th>
<th>Argo T</th>
<th>Argo S</th>
<th>Number of Argo floats</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
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<td>1991</td>
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<td>0</td>
<td>4</td>
<td>2</td>
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<td>0</td>
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<td>2</td>
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<td>1</td>
<td>4</td>
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<td>1</td>
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<td>3</td>
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<tr>
<td>1997</td>
<td>5</td>
<td>4</td>
<td>1</td>
<td>2</td>
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<td>18</td>
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<td>6</td>
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<td>16</td>
<td>0</td>
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<td>14</td>
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<td>14</td>
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<td>0</td>
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<td>17</td>
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<td>13</td>
<td>0</td>
<td>1</td>
<td>14</td>
<td>572</td>
<td>572</td>
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<tr>
<td>2002</td>
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<td>2004</td>
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<td>78</td>
<td>37</td>
<td>1855</td>
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<td>164</td>
<td>1</td>
<td>111</td>
<td>54</td>
<td>2555</td>
<td>2555</td>
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</tbody>
</table>

Table 2. Summary of suspect cruises rejected 1990-2005

Some issues were found with frozen profiles where in some cases identical (or almost identical) temperature and salinity profiles are reported month after month from the same float (the latitude/longitude change). In a few cases there is an intermittent update: one particular profile is repeated several times, then a different profile is repeated several times. It is fairly obvious that this is happening if a sequence of reports from a float are examined but if single
reports are examined separately the problem can easily be undetected. This is a particular problem because if the profile is recently "frozen", it can look quite good by comparison with the background and so will be accepted by the quality control. Approximately 40-50 floats have been afflicted by this problem, some of which have stopped reporting now.

Whilst salinity biases have been recognised (and to some extent addressed) for a number of years, it is now clear that a few floats have temperature biases. In the quality control system, "large" biases tend to be rejected and pose less of a problem than "moderate" biases. It is usually easiest to detect biases at lower levels in the profile where variability is less (sometimes our system rejects these lower levels, if more than half of the profile is flagged the whole profile will be rejected). In poorly observed or very variable regions it is sometimes difficult to decide if there is a measurement bias or not.

Some other issues include:

- Pressure sensor problems: there can be "junk" values, sometimes in the middle of an otherwise sensible profile. There can also be more subtle problems including apparent biases. Of course the T-S relationship is unaffected and it can be difficult to decide if an apparent upwards/downwards shift is physical or erroneous.
- A few floats had wild temperature zig-zags in the top 100m or so and apparently reasonable values below. (In our system, and in the greylist, it is not currently possible to reject part of a profile so the whole profiles were rejected.)
- There was one apparent position error from float 3900077 in January 2005.

The Argo greylist is available from either ftp://ftp.ifremer.fr/ifremer/argo/ar_greylist.txt or ftp://usgodae2.usgodae.org/pub/outgoing/argo/ar_greylist.txt. Recent experience suggests that the greylist is useful but incomplete. However, the greylist has not been updated for the last six months - a disincentive to operational use. A significant number of float problems are not included in the greylist (between about one third and one half), including some "frozen profiles". There are also instances where the rejection should start a few months earlier or should include temperature as well where the greylist just indicated a salinity problem.

5. Suitability of Argo data coverage for each application

It is difficult to objectively quantify the Argo coverage required by the various applications. This section therefore gives a more subjective view on the suitability of the Argo array. More quantitative statements could be made about the impact of the resolution of the data by running observing system simulation experiments.

In the FOAM system, one of the main aims is to analyse and forecast the mesoscale structure of the ocean. The only data available which can directly resolve the dynamical structure at these scales is the satellite altimeter SSH data. Another aim is 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 method used to assimilate the altimeter data is the Cooper and Haines scheme. This scheme 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 Argo.

The target horizontal resolution of the Argo array is 3˚×3˚ and in general this is probably sufficient to capture the large scale changes in temperature and salinity. The data assimilation scheme puts the information from the observations into the model at two separate length scales, one at about 40km and one at about 400km. This is done in order to separate out the information contained in the data about the mesoscale ocean and that of the larger scale features. The Argo data can initialise these larger scales, whereas the altimeter data will resolve the mesoscale features. As well as these two phenomena, there is the mixed layer initialisation and forecasting. Here, the initial density structure is important but it is probably sufficient to initialise the large scale density structure and use the surface fluxes to capture the small scale variations in the mixed layer.

In the vertical, the model resolution is generally coarser than that of the Argo data and so the vertical resolution of the data is adequate as it is. The impact of the vertical extent of the data
is more difficult to ascertain. For the longer time-scale applications, particularly the decadal prediction system, it is useful to observe the deeper ocean down to 2000m. For the FOAM system, it is probably not necessary to have data down to these depths however.

Improved skill of decadal forecasts has been traced to the initialisation of decadal variability of ocean heat content (Smith et al., 2007). However, further analysis is required to understand the mechanisms causing this variability, and hence to provide more guidance on the suitability of the Argo coverage for decadal predictions.

6. Impact of Argo data on analysis/forecast skill

6.1 Example of the impact of Argo on FOAM analyses

An observing system experiment has been performed using the FOAM system. Two integrations were 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.

In order to evaluate the impact of the Argo data, both runs have been compared with in situ temperature and salinity observations before they were assimilated into the model (which are valid within 24 hours of the model analysis). Figure 2 shows the root mean square errors for temperature and salinity as a function of depth, averaged over the 5 year integrations. It is clear from this that the Argo array has a significantly 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 data sources are assimilated.

![Figure 2: Root mean square errors vs. in situ observations for the run without Argo data assimilated (orange) and the run with all data assimilated (black) (a) temperature errors (°C) (b) salinity errors (psu/1000).](image)

As well as the overall errors, regional variations in the impact of the Argo observing network can be seen by comparing the average fields from the 5 year integrations with a climatology. Figure 3 shows the anomaly from the Levitus climatology of the average salinity fields at 1000m depth from the two integrations. It is clear from this that there is a freshening of the waters to the east of the North Atlantic whilst those to the west are more salty than the climatology when the Argo data are not assimilated. Assimilating the data reduces these errors significantly. This information, together with insights as to the processes involved, can help in improving the modelling of certain processes. In this example, the errors were found to
be largely the result of the type of vertical advection scheme used in the model. Improving the vertical advection scheme has led to smaller errors in the temperature and salinity fields at depth (not shown here).

![Figure 3](image)

**Figure 3:** Average salinity difference (psu/1000) between Levitus climatology and the model at 1000m depth for (a) run with no Argo data and (b) run with all data assimilated.

### 6.2 Impact of Argo data on seasonal forecasts

Six ocean analyses have been generated using the GloSea seasonal forecasting system and are described in table 3. The control (CNTL) experiment is an ocean model forced with heat and momentum fluxes from the ECMWF ERA40 reanalyses and ECMWF real time NWP products but has no assimilation of observations. The five remaining analyses use the same ocean model and surface fluxes as the CNTL with the addition of data assimilation. The data-withholding experiments are labelled with a minus sign before the names of the excluded data: no XBT (-XBT), no moored buoy data (-TAO), no Argo (-ARGO) and no salinity assimilation (-SAL). All available data were assimilated in the final analysis (ALL). Note that the –ARGO analysis excludes Argo temperature and Argo salinity data, whilst –SAL excludes all salinity data and not just those from Argo.

<table>
<thead>
<tr>
<th>Data \ Experiment</th>
<th>CNTL</th>
<th>-XBT</th>
<th>-TAO</th>
<th>-ARGO</th>
<th>-SAL</th>
<th>ALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>XBT</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>Moored buoy</td>
<td>•</td>
<td></td>
<td>•</td>
<td>•</td>
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<td></td>
</tr>
<tr>
<td>Argo</td>
<td>•</td>
<td>•</td>
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<td>•</td>
<td></td>
</tr>
<tr>
<td>Salinity</td>
<td>•</td>
<td>•</td>
<td></td>
<td>•</td>
<td></td>
<td>•</td>
</tr>
</tbody>
</table>

Table 3: Experiment design for the data-withholding ocean analyses. See text for definitions.

Hindcasts were produced, starting from these analyses, using the coupled ocean-atmosphere model. The forecast range was six months and 15 member ensembles were generated by applying a range of SST perturbations derived from temporal and areal differences in SST climatologies (see Graham et al., 2005). The SST perturbations are reduced from the surface to zero influence at 40m depth. No other subsurface ocean perturbations were made. The four start dates for each year were 1 February, 1 May, 1 August, 1 November for 2000-2004.

It is important to make clear that with only 5 hindcasts for any one season, the observation record is very short and results may not be robust, especially since the Argo observing system changed dramatically during this period. Also, there were no significant El Niño or La Nina events during the period, and so performance is likely to be lower. Forecasting systems work best when there is a strong signal to propagate and El Niño is the primary mechanism for long-lead seasonal forecast skill. As such, these experiments can be viewed as indicative of the impact of each observing system rather than providing definitive estimates of seasonal forecasting skill.
Table 4 summarises diagnostics on the impact of observing systems on forecast skill using anomaly correlation coefficients of the dynamical forecast initialised with the respective analysis against a persistence forecast. The persistence forecast uses the mean anomalies from the previous month to the start date (i.e. January anomalies for a 1st February start date) and projects those anomalies onto the mean seasonal cycle for 2000-2004. The persistence and dynamical forecasts can then be compared against the best analysis available (i.e. one with ALL data).

<table>
<thead>
<tr>
<th></th>
<th>Persistence</th>
<th>CNTL</th>
<th>ALL</th>
<th>-SAL</th>
<th>-ARGO</th>
<th>-TAO</th>
<th>-XBT</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.39</td>
<td>0.64</td>
<td>0.57</td>
<td>0.55</td>
<td>0.62</td>
<td>0.56</td>
</tr>
<tr>
<td>Feb 4-6</td>
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<td>0.24</td>
<td>0.44</td>
<td>0.39</td>
<td>0.38</td>
<td>0.43</td>
<td>0.38</td>
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<td>May 2-4</td>
<td>0.59</td>
<td>0.37</td>
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<td>0.49</td>
<td>0.62</td>
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<tr>
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<td>Mean</td>
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</tbody>
</table>

Table 4: Global mean forecast anomaly correlation coefficients of 360m vertically averaged temperature for various start dates in comparison to an ocean analysis using ALL data. A lead time of 2-4 indicates the mean of five forecasts initialised 1st Feb for 2000-2004 for the forecast months 2 to 4 (March, April and May).

Forecasts of 3 month mean vertically averaged temperature (VAT) for leads times of 1 and 3 months do show a clear positive impact from data assimilation and a negative impact from the withdrawal of the various observing systems. Persistence forecasts give a baseline predictability of about 0.5. The CNTL is disadvantaged in the comparison as forecasts with no prior knowledge of real anomalies are compared against observations – the CNTL will show however anomalies that are derived from atmospheric forcing of the ocean state and then propagated into the forecast. The best performance is from a forecast containing ALL data in the initial conditions – with reductions on that performance when any of the observing systems are removed. The –TAO forecasts show a smaller impact as the TAO/PIRATA moorings affect a relatively small area of the globe. Removing XBT also negatively impacts the forecast.

Importantly for this report, the removal of Argo data in the –ARGO experiment clearly shows a negative impact on forecast skill for forecasts initialised in any season and for any lead time.

### 6.3 Impact of Argo data on decadal forecasts

Assessment of decadal hindcast experiments indicate that initial conditions, particularly in the ocean, significantly increase forecast skill at all lead times up to, and beyond, a decade (Smith et al, 2007). Accurate initialisation of the ocean is therefore crucial for decadal climate prediction. The expected accuracy of the ocean analyses used to initialise DePreSys shows a dramatic improvement following the introduction of Argo data (Smith and Murphy, 2007). Argo data would therefore be expected to have a significant impact on the skill of decadal climate predictions. However, a more direct assessment of this impact would require additional experiments in which the Argo data are withheld.

### 7. Other potential requirements of Argo

FOAM is developing a coupled biological-physical ocean modelling and data assimilation system. As part of this it would be useful to include additional sensors on Argo floats which measure biogeochemical variables.
A high resolution SST analysis system called OSTIA is being produced operationally at the UK Met Office. It would be useful for the validation of this analysis to be able to compare it with data from Argo floats which observe temperature closer to the surface than is currently obtained.

References


