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E-AIMS

Euro-Argo Improvements for the GMES Marine Service

Weather, seasonal and decadal forecasting: synthesis of past OSE/OSSE activities and OSE/OSSE plans

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1. Introduction

The necessity of coupling atmosphere and ocean models is accepted on seasonal to decadal prediction timescales (e.g., Kleeman et al. 1995), but the importance at the shorter time-scales relevant to Numerical Weather Prediction (NWP) has not been extensively addressed. Although existing ocean observations may be beneficial for short-term weather forecasting, they are unlikely to be optimal for both short and long timescales. With current developments in coupled prediction on both weather- and climate-related timescales, there is a need to understand how ocean, and particularly sub-surface, observations affect coupled analyses and forecasts.

There has been some work on observation impact in ocean-only analyses, and on the importance of sub-surface observations for seasonal to decadal coupled prediction, but relatively little on the importance of ocean observations, beyond sea surface temperatures, on short-term weather forecasts. Decadal forecasts have been shown to possess some skill, especially in the North Atlantic region (e.g., Robson et al. 2012, van Oldenborgh et al. 2012 [see Fig. 1], Hazeleger et al. 2013a). The skill stems from the "memory" provided by the slowly varying ocean and thus crucially depends on its correct initialization. To properly initialize the ocean enough high-quality observations are necessary. Several investigators have analyzed the impact of different observing systems (e.g., Argo) on the quality of the initial state (e.g., Oke and Schiller 2007, Balmaseda et al. 2007, Dunstone and Smith 2010) and found that Argo data have a large impact on the initial state and thus forecast skill. This importance is due to the high density of the Argo network and to the fact that it provides data down to 2000 m, instead of the 700 m of the XBT network.

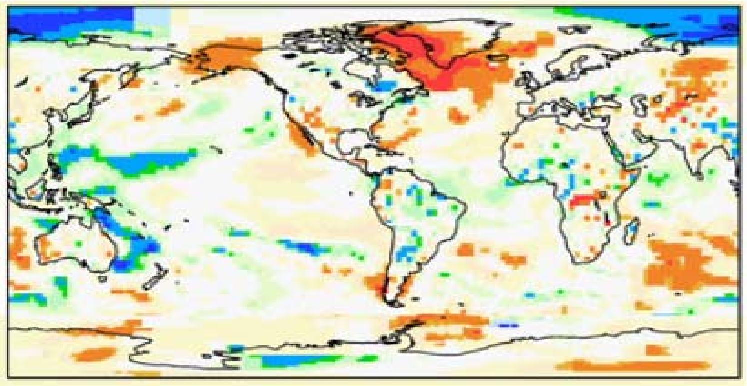

Figure 1: *Correlation skill of T2m/SST hindcasts for years 2-5 after subtracting the trend. [From Van Oldenborgh et al. 2012]*

While it is clear that Argo observations are important to obtain a good initial ocean state for long-term prediction, the question of the required density of the network and of possible geographical variations of the required density is still open. However, an answer to this question is important when one is to decide where to launch new floats. Are some areas more important than others? Are there regions which require a higher density than others? There are good reasons to believe that the answer to both questions is "yes":

- A high density may be necessary in regions of high horizontal gradients. The correct position of such fronts and the correct representation of the currents associated with it may be crucial for the subsequent redistribution of heat, which would impact SST and thus the atmosphere.

- In a region with a deep mixed layer (ML) the “memory” of the ocean is quickly eroded away by interaction with the atmosphere. A good initialization of the ocean may be less important than in a region with a shallow ML, where the deeper layers of the ocean are shielded from the atmosphere. Properties (especially temperature) are conserved and have the potential to influence the atmosphere at a later time when they somehow reach the surface.
- A good representation of the ocean initial state might be more important in (the vicinity of) regions of high predictability than in regions of low predictability. Recent experiments show that predictability is limited to certain regions, mainly the North Atlantic Ocean (see next section).

Although the effect of Argo observations on NWP forecasts has not yet been quantified, and any effects may be subtle or apparent only in specific cases, similar questions regarding the required spatial and temporal sampling apply. Observations of the upper ocean are clearly more important than the deep ocean for weather forecasting time-scales, but an important question is whether sampling the upper 100-m or so brings a significant improvement over SST measurements alone. Furthermore, it may only be during extreme weather events or in specific locations (for instance, along hurricane paths) where a knowledge of the upper ocean heat content could bring a substantial improvement in the short-term forecast.

An Observing System Experiment (OSE) provides a method by which to determine the impact of specific observations on a resulting analysis and forecast. This is a conceptually straight-forward experiment which can elucidate the consequences when an observation type is added to, or lost from, the current mix. However, an OSE is expensive as it involves re-running the assimilation and forecast system without the selected observations. Also, the differences found in the analysis and forecast will be due to a combination of the assimilation system used, the time over which the OSE is run and the range of diagnostics chosen, in addition to the observations.

While OSEs allow the impact of existing observations to be quantified, an Observing System Simulation Experiment (OSSE) uses simulated observations to quantify the benefits of a modified/extended observing system, by for example increasing the spatial or temporal resolution of an existing observation type. These are generally performed as identical twin experiments where a run incorporating the existing system provides the truth against which improvements are judged.

Additionally, techniques based on diagnostics of the assimilation system can be used to quantify the impact of observations on the analysis and forecast. Analysis sensitivity techniques allow the determination of the influence of individual observations on the resulting analysis (e.g., Rodgers, 2000; Cardinali et al., 2004; Desroziers et al., 2005; Todling, 2013). On the other hand, forecast error sensitivity techniques employ the adjoint of the data assimilation system to quantify the contribution of all observations to the analysis and forecast (e.g., Langland & Baker, 2004; Moore et al., 2011). Although this can quantify the impact of an observation on the forecast as well as the analysis, the assumption of linearity necessary to use the adjoint means that this technique may not be valid beyond short-term forecasts. Moreover, the adjoint is not readily available in most systems and so this is an expensive prerequisite.

2. Synthesis of past OSEs

The complementarity of different ocean observation types was demonstrated by Oke & Schiller (2007) in OSEs where the relative impacts on an eddy-resolving ocean analysis of the Australian region were assessed. More recently, Lea et al. (2013) performed near real-time OSEs with the global configuration of FOAM, the Met Office operational short-term ocean forecasting system. Over a six month period, they withheld a different observation type each month, including temperature and salinity profiles, satellite altimetry, SST measurements and Argo profile data. For the Argo withholding experiment, they concluded that exclusion of Argo caused an increase of 5% in temperature and salinity innovations along with up to 5cm changes in the sea surface height.

Sea Surface Temperature (SST) measurements are routinely used in models from short-term weather prediction to multi-decadal climate prediction and also supply the lower boundary for atmospheric sounder retrievals which are then assimilated into atmospheric models. OSTIA, the Operational SST and Sea-Ice Analysis system, provides the boundary condition for weather forecast models at the Met Office and ECMWF. The positive influence of SST observations on the short-term forecasts, through the use of OSTIA, was demonstrated by Donlon et al. (2012). Specifically, they found that during the Arctic sea-ice retreat of summer 2007, the previous SST system defaulted to climatology due to the large changes, but the OSTIA system resulted in a significant reduction in forecast error.

Ocean observations are heavily used in the initialization of coupled models for seasonal to longer-term prediction. Vidard et al. (2007) investigated the relative impact of various ocean observing systems, including Argo, and although they found that TAO/TRITION observations substantially improve seasonal forecast skill, they did not reach any firm conclusions regarding the Argo array as it was still in its early stages when the array was being rapidly expanded. Later, Balmaseda & Anderson (2009) investigated various initialization strategies for seasonal prediction with a coupled atmosphere-ocean model in a weakly-coupled data assimilation scenario. They concluded that when initializing the atmosphere and ocean separately, the assimilation of all available observations had a greater positive impact on the forecast skill than either the assimilation of SST alone, or of both SST and atmospheric observations. Fully-coupled data assimilation where atmosphere and ocean observations are assimilated together to produce a balanced atmosphere-ocean initial state has not yet been demonstrated.

Balmaseda & Anderson also investigated the relative impact of various ocean observations and found that, as with the ocean-only OSEs discussed earlier, there is little redundancy between observations types, but the dominant contributor changes from region to region. In particular, observations from the Argo array were most constraining in the Central-Western Pacific and the Indian Ocean. Similarly, Balmaseda et al. (2010) found that the assimilation of all available ocean observations improves the skill of the ECMWF coupled seasonal forecasting system. Importantly, they noted that the maintenance and extension of the current ocean observing system was crucial in sustaining progress in seasonal forecasting and that a long continuous observing record is a requirement for historical ocean initial conditions needed for seasonal to multi-decadal prediction.

On shorter time-scales, there has been more limited work on the impact of ocean observations. While the impact will not be as widespread, there are specific cases where a significant effect may be expected. Goni & Trinanes (2003) and Scharroo et al. (2005) have shown that the predictability of hurricane intensity could be improved by using observations to constrain the heat content of the ocean mixed layer. Although in general the deeper the ocean layer considered, the longer is the time-scale on which it will influence the atmosphere, energetic phenomena can cause increased upwelling which increases the short-term atmospheric connection to deeper layers in the ocean. Indeed, Sriver et al. (2010) found that tropical cyclones could have a significant effect on the temperature profile and circulation in particular regions.

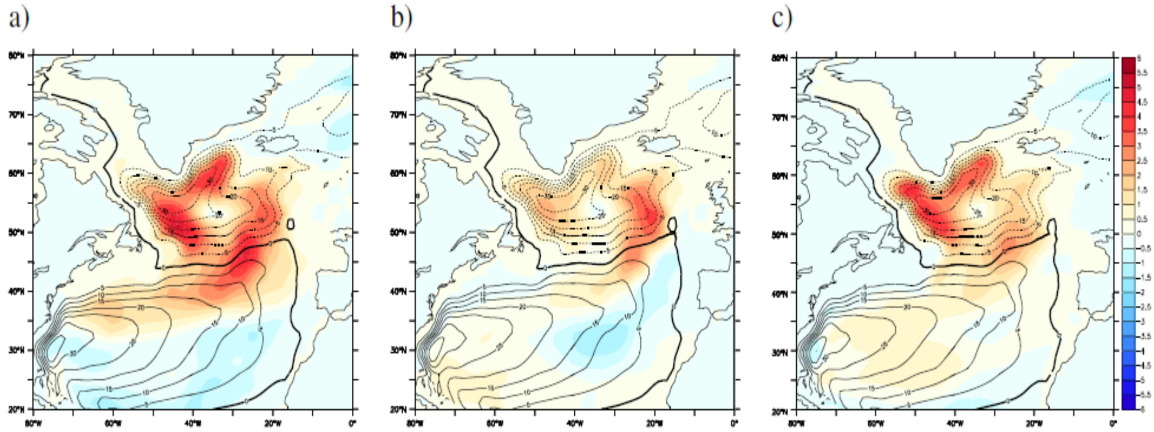

Figure 2: (a) Leading mode of variability in the North Atlantic barotropic stream function in the control run, obtained from an empirical orthogonal function analysis in the first year after the six start dates of the perfect model hindcasts.(b and c) Same as Figure 2a but for the hindcasts initialized using the 1990 and 2008 pseudo-observations, respectively. A normalization has been applied so that the standard deviation of the associated principal components equals 1 Sv. [From Wouters et al. 2013]

Seasonal to decadal predictability was addressed in the EU FP7 projects THOR and COMBINE. KNMI participated in these projects, by, among others, performing decadal forecasts with the climate model EC-Earth (Hazeleger et al. 2012). Both CMIP5-style hindcasts and OSE/OSSE runs were carried out. The hindcasts were evaluated together with similar experiments performed by other project partners by Hazeleger et al. (2013a). They find predictive skill after accounting for the forced signal originating from the increasing greenhouse gas burden. The skill beats damped persistence and is significant for several (6-9) years ahead in the sub-polar gyre of the North Atlantic. This skill stems from a proper initialization of the ocean. The effect of initialization was further investigated by Hazeleger et al. (2013b), who compared decadal prediction runs performed without initialization, with full-field initialization, and with anomaly initialization. The two initialized ensembles show comparable skill, albeit with regional differences. In the North Atlantic region, their skill is higher than that of the uninitialized run, and the fully initialized run performs slightly better than the anomaly initialized run.

In a follow-up research, Wouters et al. (2013) investigated the impact of data availability on forecast skill in the sub-polar gyre (SPG). In a “perfect model” setting they generate ocean initial states by extracting pseudo observations from a long model run and combining them with the model climatology to fill in the gaps in the observations. They do so for the observational densities of 1990 and 2008, respectively representing the pre-Argo and Argo eras. The SPG strength is predictable a few (~ 3) years ahead when Argo data are present, but only one year ahead without Argo data (see Fig. 2). Subsequently, Wouters et al. (2013) investigate whether their results carry over to the real world. Over a period of 20 years they start 10 year hindcasts from ECMWF’s operational NEMOVAR-ORAS4 analysis. The hindcasts for the first two years reproduce the general features of the observations well. Significant positive skill is found for two years ahead and a comparison with uninitialized runs shows that the skill stems from the initialization.

3. Synthesis of past OSSEs

The capabilities of the full Argo array, and adaptions to the current Argo array, in terms of improving seasonal to decadal prediction skill have been investigated by a number of authors. Schiller et al. (2004) used an ocean-only model to investigate sampling strategies to resolve intra-seasonal oscillations in the upper Indian Ocean. They concluded that the current sampling strategy is adequate for seasonal and longer term variability down to 2000m, but to capture Monsoon related activity they advocated a sampling resolution of ~500km (longitude) by ~100km (latitude) - approximately twice the 3º x 3º resolution. They also suggest sampling down to 500m every 5 days and down to 2000 m only every 20 days. An important caveat to this result is that their model was not capable of directly comparing the current and proposed sampling strategies due to their use of 3-day mean model fields.

However, Vecchi & Harrison (2007) performed similar OSSEs with a higher resolution version of the same model, but also had daily fields rather than 3-day mean fields and used a parameterization of the sub-daily variability. They found that while an Argo array with 10 day, 3º x 3º sampling could enable the prediction of the inter-annual variability in the temperature of the upper ocean, this capability was reduced with a 5-day sampling strategy and sub-seasonal predictability did not benefit substantially. This difference compared to the results of Schiller et al. was in part due to the model differences described above and the increased advection of Argo floats when a shorter repeat cycle is used. This degradation in the predictive capability with increased temporal sampling may be limited by recent improvements which restrict the time floats spend at the surface.

Kamenkovich et al. (2009) also used global OSSEs to demonstrate that the Argo array has significant skill in predicting annual variations in temperature and salinity and heat content of the upper ocean. More recently, Dunstone & Smith (2010) showed that, in an idealized experiment, the assimilation of sub-surface observations can allow the initialization of the Meridional Overturning Circulation (MOC) and has useful skill in predicting global ocean heat content on decadal prediction time-scales. As Balmaseda & Anderson (2009) had demonstrated for seasonal prediction timescales, Dunstone & Smith found that the assimilation of SST alone is insufficient, and although the assimilation of atmospheric observations improves the forecast skill initially, after the first year it has a negligible effect. They also demonstrated a need for temperature and salinity profiles down to ~2000 m depth as provided by the Argo array and suggest that more, deeper observations may be advantageous, particularly in a more realistic scenario where the distribution of Argo floats impact on the data coverage.

4. Plan for coupled OSE/OSSEs

4.1. Weather forecasting timescales – Met Office

The OSE/OSSEs planned for this work to assess the requirements of the Argo array for NWP prediction will make use of the coupled atmosphere-ocean model developed at the Met Office. In this weakly-coupled data assimilation (WCDA) system, a coupled model is used to provide background information for separate ocean/sea-ice and atmosphere analyses, and the resulting increments are used to adjust the coupled model ready for the forecast.

Our coupled system uses the Unified Model (UM) with ~60km horizontal resolution and 85 vertical levels for the atmosphere component, and NEMO/CICE with ~25km horizontal resolution and 75 vertical levels for the ocean component. These are coupled hourly. There is 4D-VAR data assimilation for atmospheric observations, 3D-VAR assimilation of ocean observations (including temperature and salinity profiles, SST, SLA and sea-ice concentration), and assimilation of land surface observations. This is run with a 6-hour analysis cycle.

This WCDA system is currently being used to perform a series of experiments to ascertain the impact of coupling the data assimilation, as opposed to the impact of a coupled forecast. To do this, two experiments are performed: the first uses a coupled atmosphere/ocean background, performs the data assimilation separately for the atmosphere and ocean, and then runs a coupled forecast; the second (control) experiment uses separate atmosphere and ocean backgrounds, performs the data assimilation separately and then runs a coupled forecast. Both experiments are run over two separate 1-month periods (December 2011 and June 2012) with a 5-day forecast produced every 12 hours.

Our planned OSE will use the first experiment described above as our control run and we will use the same system to run an Argo-withheld experiment. A general assessment of the impact on upper-ocean and near-surface atmospheric variables will be performed, followed by targeted assessment of specific phenomena, e.g., hurricanes. There is potential to extend the forecast range to examine the impact of Argo on forecasts out to ~15 days, and if time permits we will also include observation impact diagnostics in the OSE (e.g., Todling 2012).

For the OSSEs we intend to perform two experimentsinvolving an increased sampling of the upper 100m of the ocean. The first will simulate an order-of-magnitude increase in both the spatial and temporal sampling of the upper ocean by Argo, while the second will simulate a doubling of the spatial and temporal resolution. We will refer to these as 10x-OSSE and 2x-OSSE, respectively.

The details may be adjusted based on the results of the OSE, but for the 10x-OSSEour current plan is to retain the current vertical resolution and increase the horizontal resolution from one float every 3º x 3º box to 1 every square degree. Additionally, we will increase the temporal resolution by sampling every day rather the current 10-day sampling strategy. We appreciate that this represents an optimistic expansion of the current Argo array, but to address the question of whether knowledge of the state of the upper ocean can positively impact the skill of NWP forecasts, we are likely to be dealing with subtle effects.

The results of this order-of-magnitude sampling increase (10x-OSSE) will inform the choice of sampling strategy for the second experiment (2x-OSSE), but our current plans are to have a horizontal resolution of approximately 1 float every 2º x 2º with each float sampling to the surface every 5 days.

The control run OSE will provide the ‘truth’ run for these OSSEs from which our simulated Argo observations will be sampled. These will have appropriate noise added to better approximate the assimilation of real Argo data, including incorporation of the representativeness error. To introduce perturbations between the control run and the runs assimilating simulated observations, we will use initial conditions for the OSSEs from runs a few days from the intended start dates. A similar assessment will be performed as for the OSE, but for the OSSEs we will also have the truth run for comparison.

Combined, these experiments will allow us to determine if the current Argo array has an impact on coupled forecasts on short-timescales, and also address the extent to which this can be improved by extensions to the Argo array. These results will written-up for submission to a peer-reviewed journal.

4.2. Seasonal to decadal prediction timescales - The KNMI

Our work in E-AIMS will build on the results and knowledge gained within THOR and COMBINE as outlined above. These results show that ocean initialization is important, but they also show that predictability is limited to (parts of) the North Atlantic Ocean. For a proper initialization Argo data are needed (see also Balmaseda et al. 2007; Dunstone, Smith 2010). Within E-AIMS we want to investigate the optimal Argo density to obtain a proper ocean initial state, and whether this density varies geographically.

Our experiments will be performed with EC-Earth in its standard form which uses the ORCA1 configuration for the ocean component (Hazeleger et al. 2012; Sterl et al. 2012) with a horizontal resolution of approximately 1º.

We will follow the "perfect model" approach of Wouters et al. (2013). Instead of using actual observation densities, we prescribe the observational network. This makes it possible to change the density systematically and with geographic variations. The planned experiments are

1. Use a complete ocean restart file from the model, but different atmospheric states. This base experiment defines the predictability limit which is set by the chaotic behaviour of the atmosphere.
2. As 1, but with the ocean restart file degraded: Assuming that ocean observations are available at every second grid point only (in both horizontal directions), ocean restart files are constructed following the procedure of Wouters et al. (2013). Given the 1º resolution of ORCA1 this corresponds to one observation (Argo float) in any 2º x 2º box, which is higher than the current aim for the Argo array (one float per 3º x 3º box).
3. As 2, but with pseudo observations every third grid point, corresponding to the current 3º x 3º Argo aim.
4. Geographical variation in observational density: High (1º x 1º) in the northern North Atlantic (poleward of 40º), low (3º x 3º) elsewhere.
5. Depending on time left, variations of 4: high density in different geographical regions.

To obtain robust statistical results an ensemble of runs will be performed for each experiment. Ensemble members will be generated either by taking the initial states and pseudo observations from different years of a control run, or by using slightly different atmospheric initial states.

Note that following the "perfect model" approach is different from what we suggested in the DOW. There we proposed to perform "real world" experiments with initial states taken from ECMWF's NEMOVAR system. However, this would put an extra burden on the project as NEMOVAR would have to be run for every degraded set of observations. Furthermore, we regard the idealized "perfect model" setting to be better suited to answer the basic question of what the optimal Argo density would be.

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