Climate variability from the new System 3 ocean reanalysis

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INTRODUCTION

In August 2006 a new ocean analysis (System 3 or S3) was implemented in operations at ECMWF. This is used to provide ocean initial conditions for the seasonal forecasts and, with some modifications, the monthly forecast system. Since both the seasonal and monthly forecast systems require an extensive set of hindcasts over many previous years, it is necessary to perform an ocean reanalysis as well. Currently a reanalysis has been performed back to 1959. Since the ocean reanalysis is an integral part of the operational system, the ocean model, resolution and assimilation procedure for the historical reanalysis are always the same as for the current operational analysis. Note that this is different from the approach used for atmospheric reanalyses such as ERA-40 in which the assimilation/model system is not necessarily the same as in the current operational system.

In addition to providing initial conditions for forecasts, the ocean reanalysis is an important resource for climate variability studies. We show that as well as improving the skill of seasonal forecasts, the S3 ocean reanalysis (hereafter denoted by ORA-S3) offers an interesting perspective on the earth's climate. The 48-year reconstruction is used to explore the amplitude, vertical penetration and geographical distribution of the ocean warming. It is also possible to estimate the steric changes in global sea level (i.e. changes in volume due to changes in the water density), which can be compared with the estimation of global sea level provided by the altimeter data since 1993.

A major concern for the historical reconstruction of the climate is the non-uniform observation coverage in time and space. To assess the robustness of the climate signals found in ORA-S3, we compare with those from an equivalent ocean experiment that is forced by atmospheric fluxes, but without assimilating ocean data. The consistency between ORA-S3 and this later experiment, called ORA-nobs hereafter, not only consolidates the significance of the ocean signals, but also provides an assessment of the quality of the atmospheric fluxes used to drive the ocean model.

THE ORA-S3 SYSTEM

The ORA-S3 system has several innovative features, including an on-line bias correction algorithm, the assimilation of salinity data on temperature surfaces, and assimilation of altimeter-derived sea level anomalies and global trends. A detailed description of the analysis system is provided in *Balmaseda et al* (2007). A selection of historical and real-time ocean analysis products can be seen at www.ecmwf.int/ products/forecasts/d/charts/ocean/. Monthly means from the ORA-S3 analysis are available at http://ensembles.ecmwf.int/thredds/catalog.html.

Figure 1 shows schematically the different data streams used in the production of ORA-S3. The subsurface observations come from the quality-controlled dataset prepared for the ENACT and ENSEMBLES projects until 2004 (*Ingleby & Huddleston*, 2006), and from the Global Telecommunication System thereafter (ENACT/GTS). Before the start of the Argo program in 2002, the subsurface data consist mainly of profiles of temperature from XBTs (expandable bathythermographs), CTDs (conductivity-temperature-depth profiling floats) and moored arrays (TAO/TRITON and PIRATA), and a smaller number of salinity profiles from CTDs and TRITON moorings. The implementation of the Argo program was largely completed in 2006, providing for the first time near global coverage of both temperature and salinity *(Gould*, 2005).The altimeter data used are global gridded weekly maps from 1993 onwards (*Le Traon et al*., 1998). The model sea surface temperatures (SSTs) are strongly relaxed to analyzed daily SST maps from the OIv2 SST product (*Reynolds et al*., 2002) from 1982 onwards. Prior to that date, the same SST product as in the ERA-40 reanalysis was used.

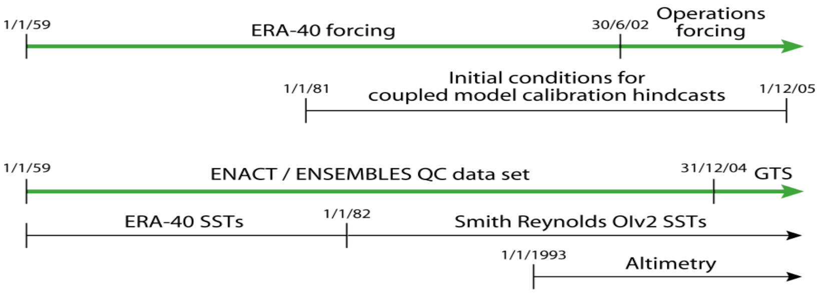

Figure 1 Data streams used in the S3 ocean reanalysis.

The ocean data assimilation system for ORA-S3 is based on the HOPE-OI scheme. The first guess is obtained by forcing the ocean model with daily fluxes of momentum, heat and fresh water from the ERA-40 reanalysis for the period January 1959 to June 2002 and from the NWP operational analysis thereafter; the fresh water flux in ERA-40 has been corrected according to *Troccoli & Kållberg* (2004).

Since a historical reanalysis is required to initialize the calibrating hindcasts for the seasonal and monthly forecasting systems, the quality of the reanalysis will influence the calibration process, and hence the quality of the forecasts. Ideally, the ocean reanalysis should provide a reliable representation of the inter-annual variability. Often, however, the variability can be contaminated by changes in the observing system, especially if these act to correct biases in the background. In ORA-S3, the introduction of a bias-correction algorithm with both prescribed and adaptive components has improved the representation of the inter-annual variability of the upper ocean heat content (*Balmaseda et al*., 2007). However, there may still be problems with the representation of the variability in very poorly observed areas, such as the Southern Ocean, around Antarctica, and in the salinity field.

As for the previous operational analysis system (S2), ORA-S3 consists of an ensemble of five simultaneous reanalyses. The purpose of the multiple analyses is to sample uncertainty in the ocean initial conditions, and thereby contribute to the creation of the ensemble of forecasts for the probabilistic predictions at monthly and seasonal ranges. Five simultaneous ocean analyses are created by adding perturbations to the wind stress while the ocean model is being integrated forward in time. The perturbations are commensurate with the estimated uncertainty in the wind stress product, but the ensemble does not sample uncertainties in fresh water fluxes, heat fluxes or model formulation.

IMPACT ON FORECAST SKILL

The ultimate goal of the ocean reanalysis is to improve the skill of the seasonal forecasts of SST. It is important to quantify the impact of improving the ocean initialization compared with the impact of improvements in the atmosphere model.

To this end, a coupled seasonal forecast experiment has been conducted with the atmospheric model used in S3 (*Anderson et al., 2*007), but with ocean initial conditions from the previous S2 ocean analysis. We call this experiment S2icS3m. The experiment consists of 76 ensemble forecasts, with initial conditions three months apart (January, April, July and October) spanning the period 1987–2005. For each date, an ensemble of five coupled forecasts (with perturbed initial conditions) is integrated with a lead-time of up to 7-months. The forecast SST anomalies are then computed with respect to the model climatology (which depends on the lead time).

Figure 2(a) shows the RMS error in the forecast of SST anomalies as a function of lead-time in the Niño4 area for S2icS3m, together with the results from the S3 and S2 seasonal forecasting systems which have been subsampled to cover exactly the same set of 76 forecasts as for S2icS3m. The results indicate that the impact of the improved ocean initial conditions is comparable to the impact of changing the atmospheric cycle from Cy23r4, as used in S2, to Cy31r1, as used in S3.

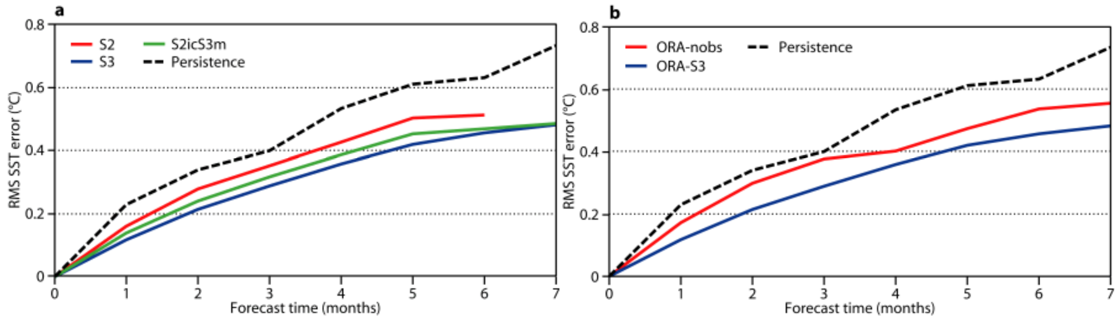

Figure 2 RMS error in the seasonal forecast of SST in the region Nino 4 (5°N–5°S, 160°E–150°W) as a function of lead-time. (a) Results from S2 (red), S3 (blue) and the hybrid S2icS3m (green). (b) Results from ORA-S3 (blue) and ORA-nobs (red) for which no ocean data has been used in the preparation of the ocean initial conditions.

It is also important to quantify the improvement in the forecast skill resulting from the assimilation of ocean data. To this end, another seasonal forecast experiment has been performed using ocean initial conditions from ORA-nobs, identical to the ORA-S3 ocean analysis where no ocean data, apart from SST, have been assimilated. Everything else (spin up, SST relaxation, forcing fields etc.) is the same as in ORA-S3. As before, the experiment consists of 76 different ensemble forecasts, with initial conditions from the period 1987–2005. The coupled model is that used by S3. Results displayed in Figure 2(b) show that data assimilation significantly improves the forecasts of SST: the RMS error from forecasts using ORA-S3 is substantially smaller than that of forecasts from ORA-nobs. The improvement, more noticeable in the western Pacific, is also apparent in the Indian Ocean, eastern Pacific and subtropics. However, in regions where the forecasting system has little skill, for example the equatorial Atlantic, the assimilation of data in the ocean initialization does not lead to any noticeable improvement.

CHANGES IN THE OCEAN HEAT CONTENT

We now describe the trends in the ocean heat content from ORA-S3 for the period 1959–2006 and compare the results with *Levitus et al.*, 2005 (Levitus05 in what follows) as a demonstration of the value of the ORA-S3 reanalysis for climate studies. As the variability in both Levitus05 and ORA-S3 can be affected by changes in the observing system, we also make a comparison with ORA-nobs. This comparison allows a consistency check of the climate signals in both the ocean observations and in the atmospheric forcing fluxes, as well as demonstrating the impact of assimilating ocean data.

We defined the upper ocean heat content as the average temperature in the upper 300m (T300). Differences in T300 between the 1983–2006 and the 1959–1982 averages are shown Figure 3a. The equatorial Indian and Pacific Oceans are getting colder, especially south of the equator, a feature that does not reach the surface except for an equatorially confined band in the eastern Pacific. The warming of the SST in the tropical band is therefore quite shallow. The subsurface cooling within the 10°N–10°S latitudinal band in the Pacific and at around 10°S in the Indian Ocean is also observed in ORA-nobs, implying that it is the consequence of changes in the surface forcing, most likely in the wind stress. Changes in the zonal wind stress are shown in Figure 3(b). In the Indian and Pacific basins, the equatorial easterlies are weaker in the later period, suggesting a reduction in the strength of the Walker circulation (*Vecchi et al*., 2006). The easterlies are stronger both sides of the equator, between latitudes of 5°–10°. There is a stronger convergence of the meridional component at the equator (not shown), suggestive of an intensified Hadley circulation. The weakening in the zonal winds along the equator leads to a reduced east–west slope of the equatorial thermocline and a weakening of the equatorial upwelling, mostly in the East Pacific.

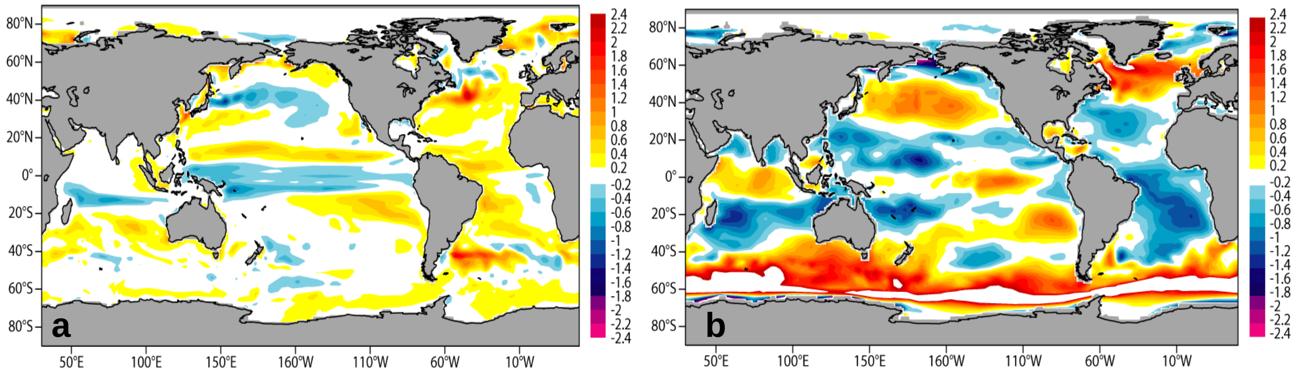

Figure 3 Difference maps of the 1983–2006 mean minus the 1959–1982 mean for (a) T300 (°C) and (b) zonal component of the wind stress (10-2 N m-2).

The off-equatorial intensification of the trades increases the latitudinal extent of the meridional circulation cell in the ocean, with increased divergence either side of the equator and increased convergence at around 15°N/S. The net effect is an export of heat from the equator towards 15°N/S within the depth of the wind-driven meridional cell (~300 m). The cooling in the Indian Ocean south of the equator is produced by a similar mechanism. The changes in the wind stress lead to a weakening of the northern branch of the South Equatorial Current and the North Equatorial Countercurrent. That the 10°N–10°S cooling appears in ORA-nobs suggests that the signal is caused by the surface forcing.

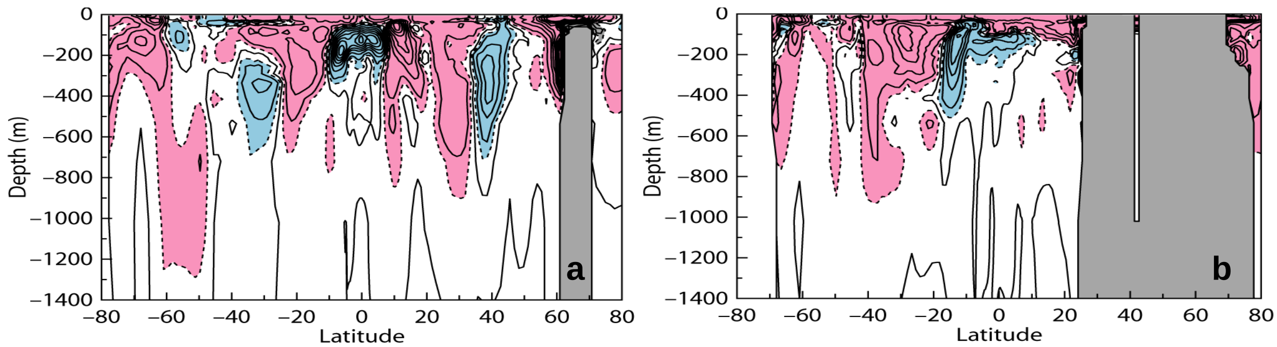

Figure 4 Latitude-depth sections of the linear trends in temperature over the period 1959–2006 in ORA-S3 for the (a) Pacific, and (b) Indian Oceans. The contour interval is 0.05 degrees/decade. Values above 0.025 degrees/decade are shaded in pink, and those below -0.025 degrees/decade are shaded in blue.

A better insight into the vertical distribution of the changes in temperature is given in Figure 4. This shows a depth-latitude map of the zonally averaged temperature trends over the period 1959–2006 in ORA-S3 for the Pacific and Indian Oceans. The figure is directly comparable with Figure 5.3 of the IPCC AR4 (*Bindoff & Willebrand*, 2007), using the same contour interval and shading convention. The spatial patterns in ORA-S3 are largely consistent with Levitus05, although exhibit sharper vertical and meridional structures, probably because the resolution used in ORA-S3 is higher, and no smoothing has been applied. Most of the changes in Figure 4 indicate warming, except for the pronounced equatorial cooling and the occurrence of cold/warm dipoles, possibly associated with the displacement of the gyres. The equatorial cooling is also present in ORA-nobs, indicating that the signal is wind-driven. That the cooling appears in ORA-nobs and Levitus05 independently is indicative of a consistency between ocean observations and surface fluxes.

SEA LEVEL AND THERMAL EXPANSION

Figure 5 shows the evolution in global steric height from the ORA-S3 ocean analysis and for ORA-nobs. The global sea level from altimeter data is also shown starting in 1993. The minimum in the mid 1960's is present in both ORA-S3 and ORA-nobs, while the fluctuation during the 1970's and 1980's are only apparent in ORA-S3. This could be partially due to problems with XBT's fall rate corrections (Gouretsky and Koltermann, 2007). For the period 1993–2002 the sea level evolution and the steric height in ORA-S3 exhibit rising similar trends, larger that those in ORA-nobs. After 2002, the steric height drops considerably in ORA-S3, stabilizes in ORA-nobs, whereas the altimeter sea level keeps rising.

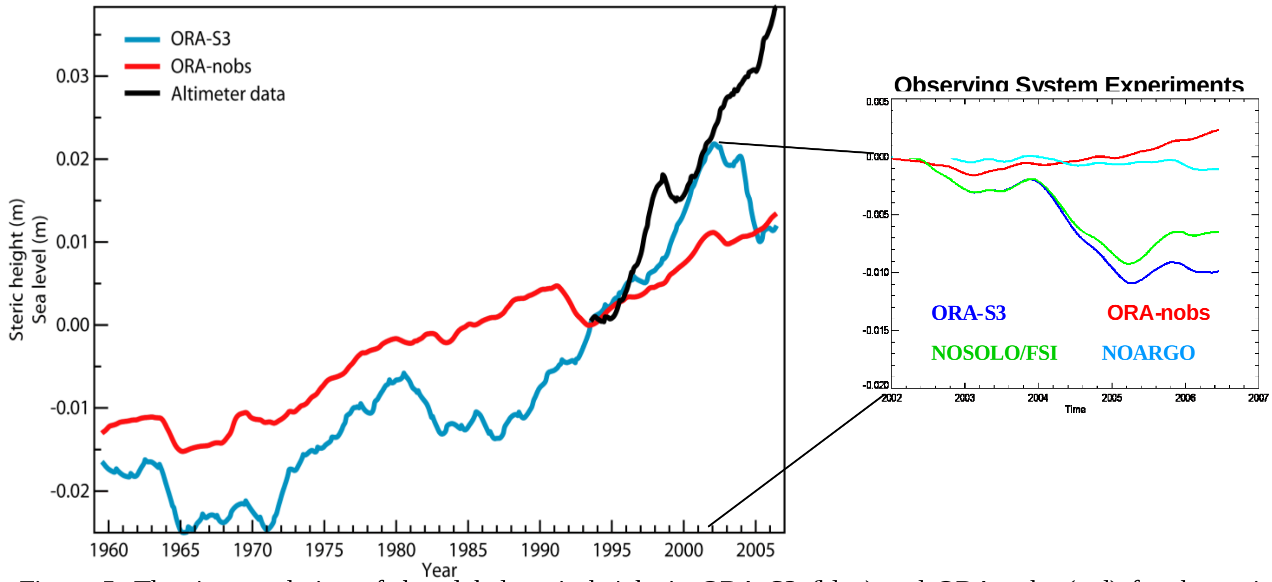

Figure 5: The time evolution of the global steric height in ORA-S3 (blue) and ORA-nobs (red) for the period 1960–2007, and the global sea level from the altimeter data (black) for the period 1993–2007 are shown on the left. The results from observing system experiments for the period 2001-2006 are shown in the right, where the curves have been offset as to have the same origin.

The widening gap between the evolution of sea level and steric height after 2002 is worrying. The difference is even larger after 2004. The origin of this mismatch is unknown. One possibility is the underestimation of the volume increase by the ocean analysis. Observing system experiments we have performed indicate that the post-2002 sharp decline in ORA-S3 is not due to the reported problems with the SOLO/FSI floats *(Lyman et al 2006)*, which seem to have little effect in the ORA-S3. The decline is probably due to sampling error: the advent of Argo implies that for the first time there is a uniform distribution of temperature and salinity observations in the oceans of the southern hemisphere. However, the widening gap between sea level and steric height occurs even without Argo. The mismatch could be real reflecting an increase in the mass of the oceans from the melting of glaciers and continental ice sheets. Understanding the origin of the widening gap between sea level trends and steric height trends is of paramount importance for the monitoring of the earth system and its response to global warming.

SUMMARY AND CONCLUSIONS

We have shown that the initial conditions from the ORA-S3 ocean reanalysis produce better forecasts of SST than those from the previous operational system (S2). It is found that the effect of better ocean initialization in the forecasts of SST is of comparable magnitude to the effect of changing the atmospheric model cycle in the coupled system from that used in S2 to that used in S3.

The ORA-S3 provides a historical reconstruction of the ocean since 1959. The 48-year record has been used to investigate the distribution of the warming trends in the oceans. The consistent results between ORA-S3, ORA-nobs which has no assimilation of ocean data, and the Levitus05 analysis based solely on ocean observations, indicate the robustness of the cooling of the equatorial Indian and Pacific Oceans, resulting from the constructive synergy between the information provided by the ocean observations and atmospheric fluxes. The equatorial meridional cell has intensified, apparently a consequence of changes in the winds, leading to a net cooling of the equatorial ocean in the upper 300 m.

Large uncertainties remain in the attribution of sea level change: for the period 1961–2003, the rates of sea level rise given by historical reconstructions based on tide gauge and altimeter data are higher than the estimates of the steric effect from ocean temperature and salinity observations. The difference appears to be too large to be accounted for by an increase in mass due to melting of the continental ice. The steric height trends from ORA-S3 for the period 1961–2003 are 0.9 mm/yr, higher than existing reconstructions based on ocean and salinity observations, higher than in the experiment with no data assimilation, and closer to the trends in sea level from tide-gauges. ORA-S3 also captures the increase in steric height from 1993 to 2003. After 2002, the gap between sea level and steric height widens considerably for reasons that are not understood.

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