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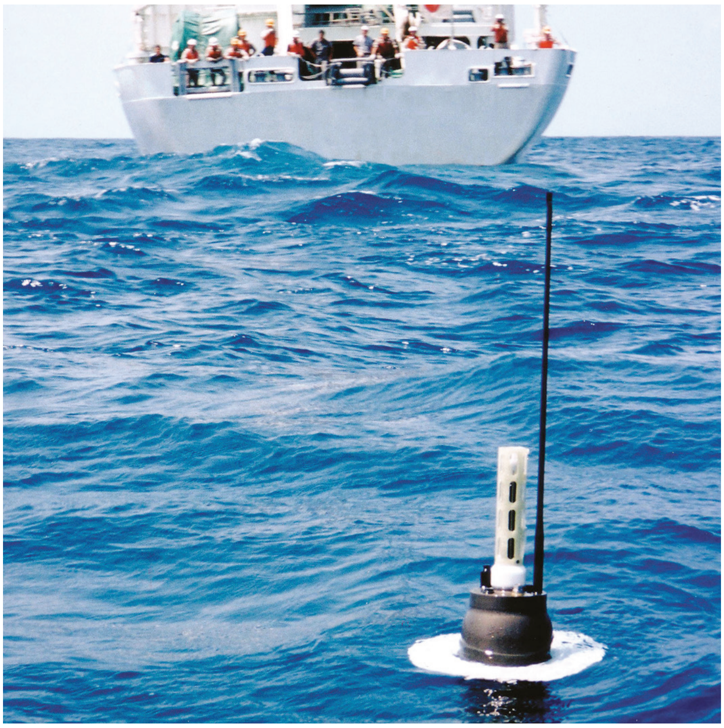

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Ocean analysis at ECMWF: from real-time ocean initial conditions to historical ocean reanalysis

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Global ocean analyses are performed daily at ECMWF to provide ocean initial conditions for both monthly and seasonal forecasts. Although the analysis systems have many features in common, they are not identical because of the greater time constraints imposed by the monthly system. Daily analyses have been produced routinely at ECMWF since 1997 as part of the seasonal forecasting system. These analyses are produced 12 days behind-real-time (BRT). The delay is required partly to allow receipt of data, and partly because the data window used in the analysis is 10 days (5 days before and after the analysis time). In 1997, an appropriate delay for receipt of data was 6 days. Now, most subsurface data are received within a day or two but there is still a delay of up to 12 days in obtaining a quality sea surface temperature (SST) analysis. While a delay of 12 days in producing initial conditions for a 6-month forecast might be quite acceptable, it is inadequate for a monthly forecast: an up-to-date analysis is required. To this end, an early delivery ocean analysis system was introduced in May 2004. It generates daily near-real-time (NRT) analyses of the ocean and runs only 8 hours behind-real-time.

Figure 1 shows schematically the schedule followed in the production of the NRT and BRT ocean analyses. Every day, the NRT ocean analysis is produced by starting from the latest BRT analysis and integrating the ocean model up to real time (i.e. 12 days forward), using all the available observations during that period. During the 12 days there are two assimilation cycles. The first assimilation takes place 12 days behind-real-time (D-12), using a 10-day window centred at D-12, and the second assimilation is performed at D-2, using observations from a 7-day off-centred window as shown in Figure 1. Except for the schedule and number of observations, both BRT and NRT products are generated with the same ocean analysis system (described below). Global three-dimensional fields of temperature, salinity and velocity for the upper ocean are produced with a horizontal resolution of approximately 1° in the extratropics, increasing to ⅓° meridionally in the equatorial region. The vertical resolution in the upper 100 m is ~10 m. In addition to the three-dimensional fields there are analyses of two-dimensional fields such as sea level and mixed-layer depth.

In addition to the ocean initial conditions for the real-time coupled forecasts, ocean reanalyses for an extended historical period are also produced at ECMWF. These are needed to initialize the retrospective coupled hindcasts that are used for the calibration of the coupled model output and for skill assessment. It is important that the historical ocean analysis provides a reliable representation of the climate variability and consistency between the historical and the “real-time” products is also required. The BRT ocean analysis can be considered as part of the historical ocean analysis that continues producing consistent analysis products close to real time, unlike the atmospheric reanalyses that generally stop production at a given date (ERA-15 products exist until 1994, and ERA-40 ended on 31 December 2002).

The rest of the article gives more detail about the ocean analysis system and ocean observations, and considers the importance of ocean initial conditions for extended range forecasts. Also the work on producing ocean reanalyses to provide initial conditions for the calibration of coupled model forecasts is described. Finally there is a description of plans to upgrade the ocean analysis system together with the seasonal forecasting system later this year.

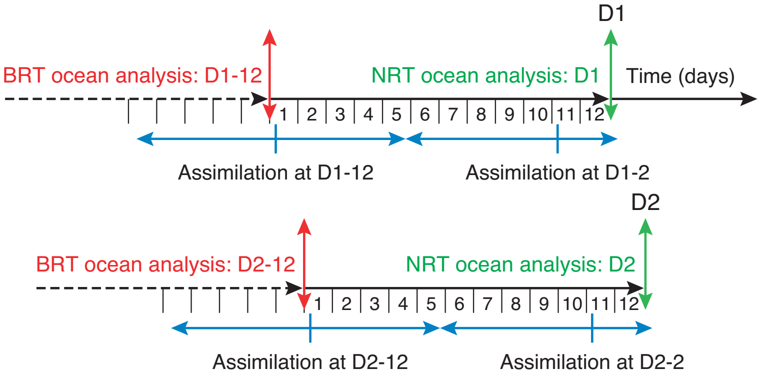

Figure 1 Schedule followed in the production of the near-real-time (NRT) and behind-real-time (BRT) ocean analysis.

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The ocean analysis system

The scheme currently in operational use is OI (Optimal Interpolation), with a time window of 10 days; all the observations in the 10-day window are applied at the centre of the window. It differs from a standard OI, however, in that the resulting correction to the first guess (FG) is not applied instantaneously; rather the correction is applied incrementally during the subsequent 10 days. The FG is provided by forcing an ocean model with daily fluxes of momentum, heat, and fresh water from the NWP atmospheric analysis system. The ocean model in use is HOPE (Hamburg Ocean Primitive Equations).

Only subsurface temperature observations are assimilated presently, but corrections are applied to the temperature, velocity and salinity fields. Salinity is corrected by invoking the conservation of the water mass characteristics, in particular the relationship between temperature and salinity. The geostrophic velocity derived from the temperature and salinity increments is then applied as a correction to the velocity field.

An important feature of the ECMWF ocean analysis system is that not just a single analysis but several simultaneous analyses are performed. The purpose of the multiple analyses (five in total) is to sample uncertainty in the ocean initial conditions. The ensemble of ocean initial conditions provided by the five analyses contributes to the creation of the ensemble of forecasts for the probabilistic predictions at monthly and seasonal ranges. The five simultaneous ocean analyses are created by adding perturbations, commensurate with the estimated uncertainty, to the wind stress while the model is being integrated forward from one analysis time to the next.

The ocean observations

Over the last decade the number of oceanic observations available in near-real-time has increased considerably. Also the number of observing systems has increased.

Types of observations

Subsurface temperature observations are currently provided by the TAO/TRITON and PIRATA arrays in the equatorial region and the global Volunteer Observing Ship (VOS) programme which provides XBT (eXpandable Bathy- Thermograph) measurements mainly along merchant shipping routes. More recently, observations are provided by the ARGO network of drifting profilers. The drifters frequently provide salinity measurements and, while these are not assimilated in the current system, they will be used in the next upgrade of the operational system, due later this year. Likewise altimeter-derived sea level anomalies are not currently assimilated but will be in the next operational system. The salinity and altimeter data are currently used for validation purposes. There are no real-time measurements of velocity, except in the surface layer. Delayed mode velocity measurements are used for validation purposes. Daily SST maps, derived from the time interpolation of weekly SST products from NCEP, are used to constrain the temperature of the model surface layer.

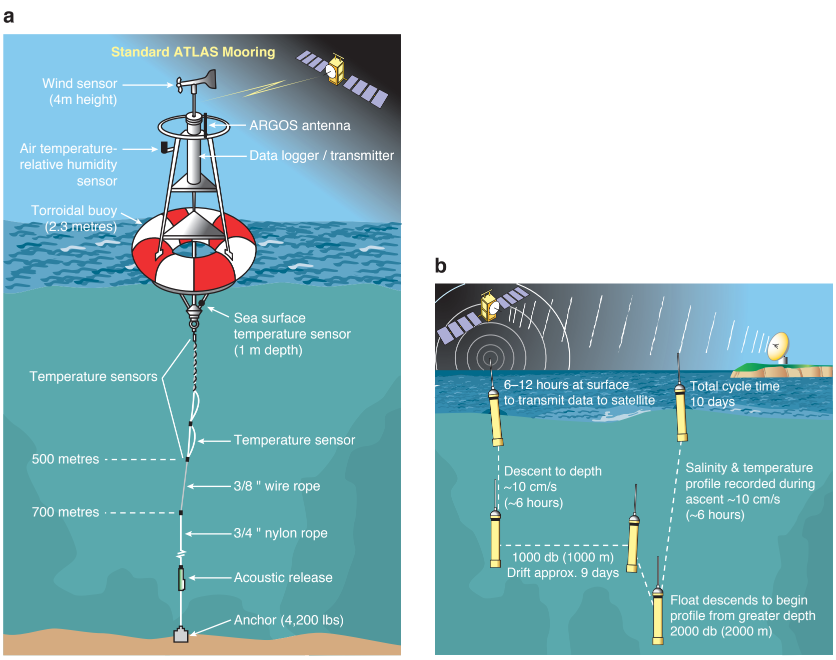

Figure 2 (a) Scheme of an ATLAS mooring (www.pmel.noaa.gov).
(b) Working scheme of the ARGO floats (www.argo.ucsd.edu).

The mooring array consists of TAO moorings in the central Pacific, TRITON moorings in the west Pacific, and PIRATA moorings in the tropical Atlantic. In the different regions the moorings are broadly similar although there are differences in their operational characteristics. Figure 2(a) shows a TAO/ATLAS mooring. The TAO network provides in-situ temperature observations down to a depth of 500 m on a daily basis for the equatorial Pacific. The moorings are arranged on a grid spanning the equatorial Pacific between 8°S and 8°N, and the longitudinal gap between buoys is typically 1500 km. In the meridional direction, buoys are located at approximately 8°S, 5°S, 2°S, 0°, 2°N, 5°N and 8°N. Thermistor chains with sensors at fixed depth are carried by the buoys: typically at the surface, 25, 50, 75, 100, 125, 150, 200, 250, 300, and 500 m. Data are transmitted as daily averages from samples taken 10 minutes apart. The TRITON moorings, located west of the date line, are also part of the Pacific array but their transmission characteristics are different to TAO. Namely they provide an additional measurement at 750 metres, they report hourly, and the profiles are not always transmitted as whole profiles. There are some TAO and TRITON moorings in the Indian Ocean with planned extensions. The Atlantic array covers a broader latitudinal extent than the Pacific.

The XBTs provide measurements which can go down to 800 m. These observations provide better vertical resolution than the TAO data, but are irregular in space and sparse in time. The network is not specially designed to observe the equatorial Pacific, and the number of frequently-observed tracks crossing the equator is relatively low. In the last few years the number of XBTs lines has been decreasing.

The ARGO profiling floats are the most recent of the observing systems. Deployment started in the late 1990s. About 170 floats were reporting in 2001: this increased to over 800 by mid 2003 and currently the number of floats is close to 2,000. It is expected that by 2006 there will be 3,000 floats distributed over the global oceans at three-degree spacing. Measurements of temperature and salinity down to 2000 m depth are provided every 10 days. The buoys drift at ~1000 m for 9 days, and on the 10th day they descend to 2000 m before starting to rise to the surface, measuring temperature and salinity on their way up; they then transmit the information via satellite (Figure 2(b)).

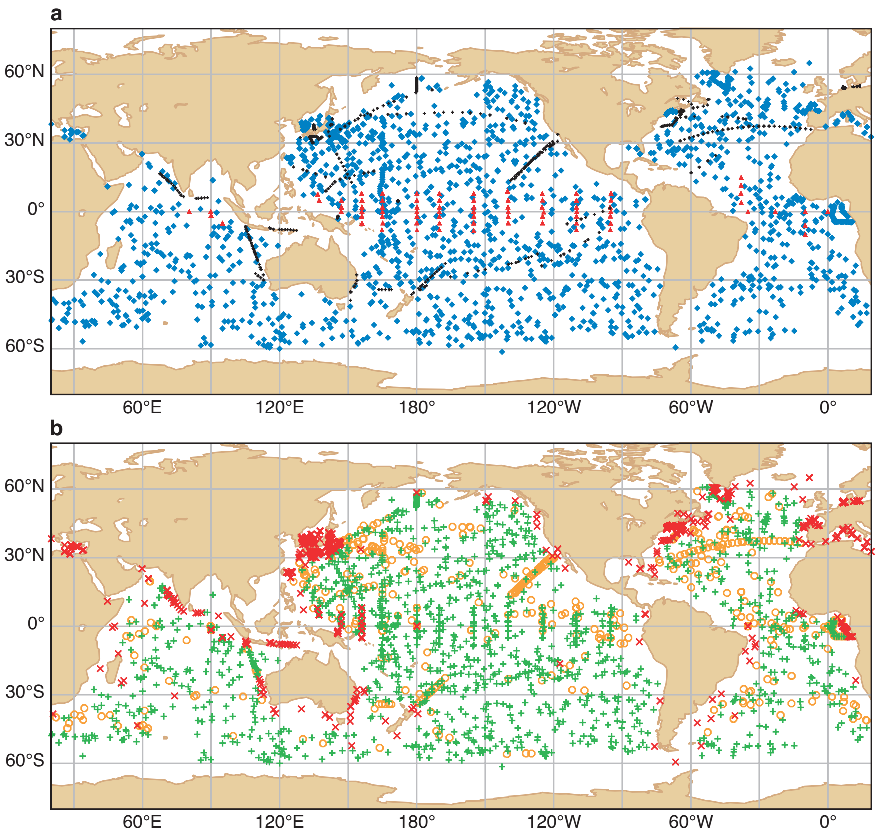

Figure 3 (a) Spatial coverage of the observations used in the delayed ocean analysis for a typical 10-day period, showing the TRITON/TAO/PIRATA mooring array in the Pacific/Atlantic oceans (▲), the XBT network (+) and the ARGO floats (◆). (b) Profiles that have been accepted after the quality control procedure are marked as + and those that are rejected as **X**. Profiles where part was accepted and part rejected are marked as **O**. Data close to coasts are rejected automatically.

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Distribution and number of observations

Figure 3(a) shows the spatial coverage of subsurface temperature observations used by the delayed analysis in a typical 10-day window. The TRITON/TAO/PIRATA mooring array is represented as red triangles, the XBT network as black crosses and the ARGO floats as blue diamonds. Most of the data are now received at ECMWF within one day or so, through the Global Telecommunications System (GTS). When data are received they are subjected to an automatic quality control procedure: each individual observation is checked and compared against the model first guess and also with an analysis performed without the datum being checked (buddy check). Figure 3(b) shows the quality control decisions: the rejected data appear in red, the accepted data in green and partially accepted in orange. Since coastal areas are not well represented by the ocean model the data near the coast are rejected. In open ocean some profiles are partially rejected; at some depths the model and observations differ too much and the data are rejected, but data from the same profile above or below might be used. The quality control also has a super-obbing scheme: if there are many data points in close proximity in space and time, they are combined into a "super-observation" and given increased weight. After the quality control, about 15% of the profiles are rejected, 15% partially accepted and 70% fully accepted, of which more than 50% are super-obbed.

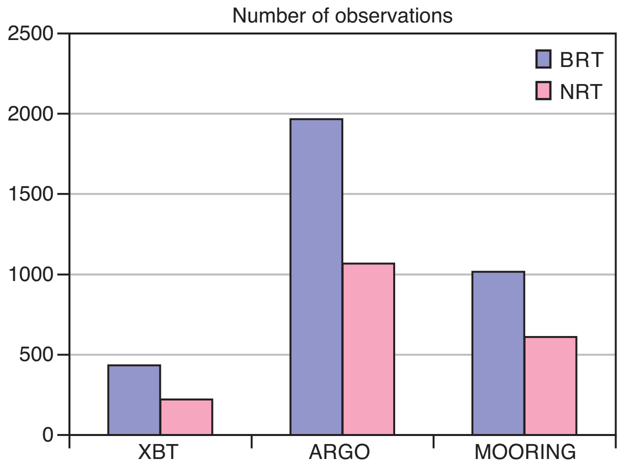

Figure 4 Number of observations received in a standard 10-day window of the BRT ocean analysis and in the 7-day window of the second assimilation cycle of the NRT analysis.

Timeliness of observations

As mentioned earlier, during the 12 days that it takes to bring to real time the NRT ocean analysis, there are two assimilation cycles. The first is at the beginning of the 12-day integration, i.e. 12 days behind-real-time (D-12). This analysis uses the observations in a centred 10-day window. The data in this first assimilation window is about the same as that used in the delayed analysis centred on the same date. The second assimilation is performed 2 days behind-real-time (D-2). For this cycle, the observation window spans a 7-day range, and is off-centred (5 days before, 2 days after the analysis time). Figure 4 shows the number of observations used in this second assimilation, classified by observing system and compared with the number of observations for the same date in the delayed analysis. The number of observations in the second assimilation of the NRT analysis is smaller, as expected from the shorter window, but the number of observations is more or less proportional to the number of days since most observations are now received within one day.

The arrival of SST information is one of the major factors for introducing a delay in the analysis. Global SST maps from NCEP are received every Monday at midday, representing the average of the previous week SST values. For the delayed ocean analysis, daily SST maps are obtained by interpolation of the weekly products, which requires the existence of two consecutive weekly values. This can introduce a delay of up to 12 days. The NRT analysis does not wait for the second map of SST to be available. Instead, a daily SST product is created by adding the latest SST anomaly to the daily climatology. The importance of representing daily variations of the annual cycle in SST is illustrated in the next section.

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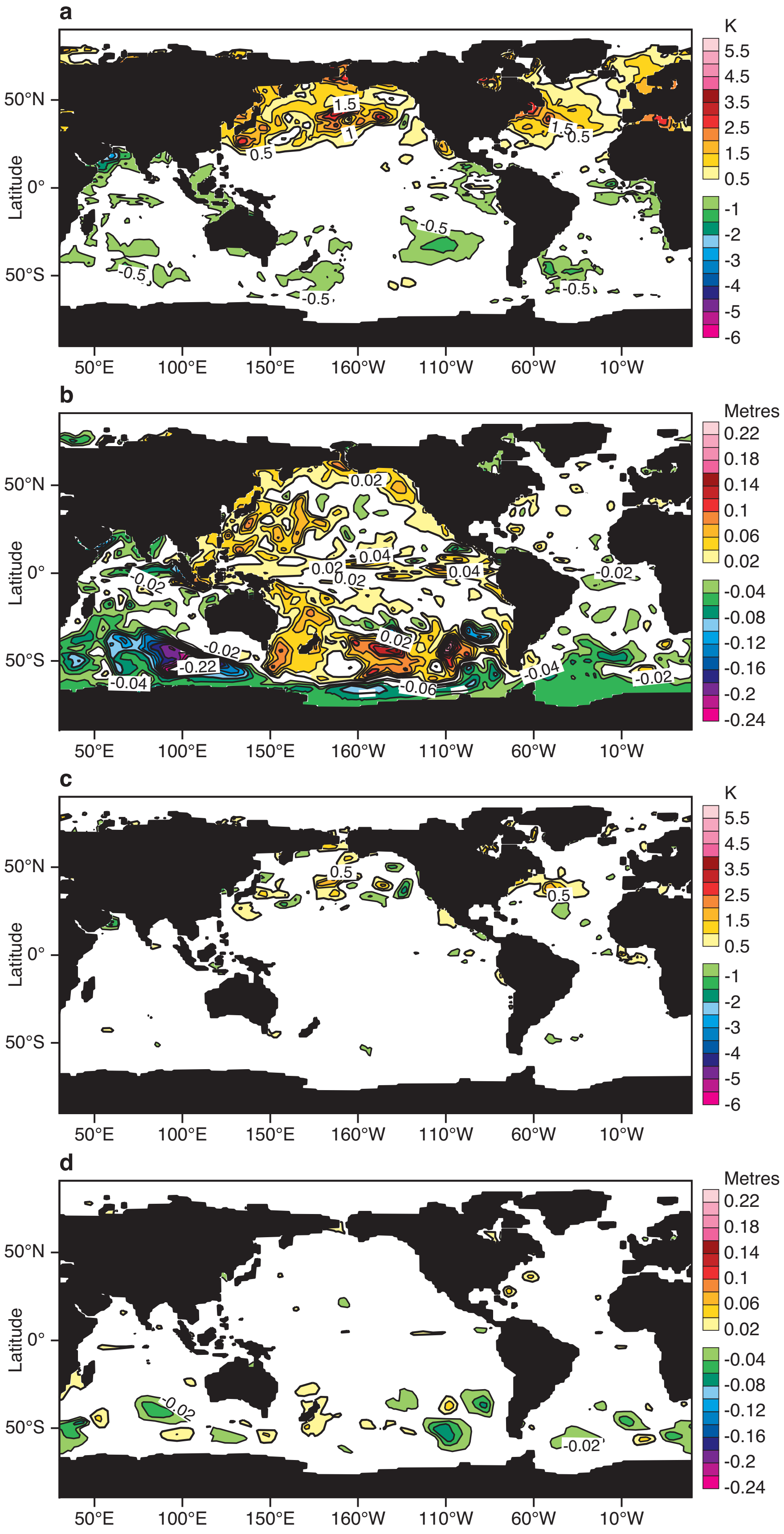

Figure 5 Differences between two BRT ocean analysis 12 days apart (1 July minus 19 June) in (a) SST (K) and (b) sea level (metres). The corresponding differences between the BRT and the NRT ocean analysis for 1 July are shown in (c) and (d).

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The importance of the NRT ocean analysis

Figures 5(a) and 5(b) show the difference between two BRT ocean analyses 12 days apart (1 July minus 19 June) for (a) SST and (b) sea level. The differences are indicative of the errors in the initial conditions that would be present if the BRT analysis were used to initialize the monthly forecasts. Positive differences larger than 1 K occupy most of the Northern Hemisphere (boreal summer), with peak differences occurring around northern Europe, in the Mediterranean, and along the path of the Gulf Stream and Kuroshio currents. Negative differences larger than 0.5 K are apparent in large areas of the tropical and southern oceans. Especially noticeable are the large differences in the Arabian Sea, which may be the result of the onset of the monsoon at the end of June. The value of SST may in turn be of importance for the monsoon prediction.

The differences in sea level in Figure 5(b) are large scale, and are apparent all over the world. They are most pronounced in the Southern Hemisphere, around the northern edge of the Antartic Circumpolar Current (ACC). These differences are largely due to fast moving weather systems, which are stronger in the winter hemisphere. The basin-wide sea level differences everywhere else are mainly the result of the propagation of these barotropic disturbances. The barotropic disturbances will have a signature in the velocity field, but the vertical thermal structure is not affected. There are also some differences of a baroclinic nature confined to the Equatorial Indian and Pacific Ocean, which have an impact on the depth of the thermocline. For instance, the increased upwelling caused by the onset of the monsoon winds is visible in the Indian Ocean sea level, which is lower after the onset of the monsoon.

Figures 5(c) and 5(d) show the corresponding differences between the NRT and the BRT ocean analysis for 1 July 2005. The differences in both SST and SL are greatly reduced. In SST most of the differences are now located in the northern hemisphere, and are much smaller scale. The negative differences in the Mediterranean and North Eastern Atlantic have been eliminated. Only some negative differences remain in the extension of the Gulf Stream and the Kuroshio currents. In the tropical and southern oceans, differences in SST rarely exceed 0.5 K. The differences in sea level have almost disappeared and there are no longer basin-wide. Only some differences remain in the area around the edge of the ACC, but they are much smaller than those shown in Figure 5(b).

The importance of ocean initial conditions for extended range forecasts

Forecasts for the extended range (monthly and seasonal time scales) are made with coupled ocean-atmosphere models. These forecasts require information about the state of the ocean as well as that of the atmosphere. The relative importance of oceanic versus atmospheric initial conditions increases with the forecast range. As the atmosphere behaves in a chaotic manner beyond timescales of days, it is mainly the ocean initial conditions that carry the potential for seasonal predictability. For the monthly range, atmospheric, soil and ocean initial conditions are possibly all important.

For the monthly forecasts, initialization of the upper 100 m of the ocean may be sufficient in many places. For seasonal forecasts the ocean needs to be initialized deeper (~300–400 m) since the potential for predictability at seasonal range is thought to lie in the waters around and above the ocean thermocline. Special attention is paid to the initialization of the Equatorial Pacific, where equatorially trapped Kelvin waves can travel long distances along the equator. In general, the longer the forecast range the deeper one needs to initialize the ocean. In the eventual case of multi-annual or decadal forecasts, there may be a need to initialize the deep ocean. The predictability at multi-annual time scales is being assessed within the European projects ENSEMBLES and ENACT. On the other side of the spectrum, the short- and medium-range weather forecasts do not currently use any information from the ocean analysis (they use persisted SST). In the future they may also benefit from having an active ocean, as rapid changes of the SST associated with tropical cyclones and storm tracks may be important. The initialization of so many different time scales poses a problem for the ocean analysis system. The current set up of BRT and NRT analysis streams has potential for tailoring the assimilation parameters to allow the initialization of different time and spatial scales in the different analysis streams. However, for the time being we are using the same analysis system for monthly and seasonal forecasts (except for the operational schedule).

Numerous examples exist that illustrate the importance of the ocean initial conditions for seasonal forecasts, especially in the prediction of an El Niño event. Here we have chosen instead to present an example from the monthly forecast. Figure 6(a) shows a time-longitude section along the equator depicting the evolution of the sea level anomalies from the NRT ocean analysis, followed by the prediction from the monthly forecasting system (ensemble mean). The analysis and forecast anomalies are referred to the climatology of the analysis and coupled model respectively. For comparison the evolution of the delayed analysis is shown in Figure 6(b). The differences between Figures 6(a) and 6(b) in the period 14 March to 14 April are the differences between the NRT and BRT analysis. These differences are small.

A positive anomaly in sea level is seen propagating in the analysis as a Kelvin wave during the month prior to the start of the forecast. The positive sea level anomaly is associated with a warm temperature anomaly in the subsurface. The warm anomaly will surface after a few days into the forecast, producing a warm anomaly in SST in the Eastern Pacific that was observed (not shown). The forecast was able to capture the rapid change in SST during the first days into the forecast (more than 2 K in 10 days), and the change of sign (from negative to positive anomalies, not shown).

The other feature visible in Figures 6(a) and 6(b) is the response of the ocean to the successful prediction of the westerly wind event in the Western Pacific, probably linked to a Madden Julian Oscillation (MJO): a warm anomaly is generated in the subsurface, that travels eastward as an equatorial Kelvin wave and can be seen in the evolution of sea level. The response in the forecast is slightly weaker than in the analysis, as can be expected from using the ensemble mean. As a consequence of the westerly wind burst, the SST at ~140°E cooled down by about 0.5 K (not shown). This cooling was well captured by the model.

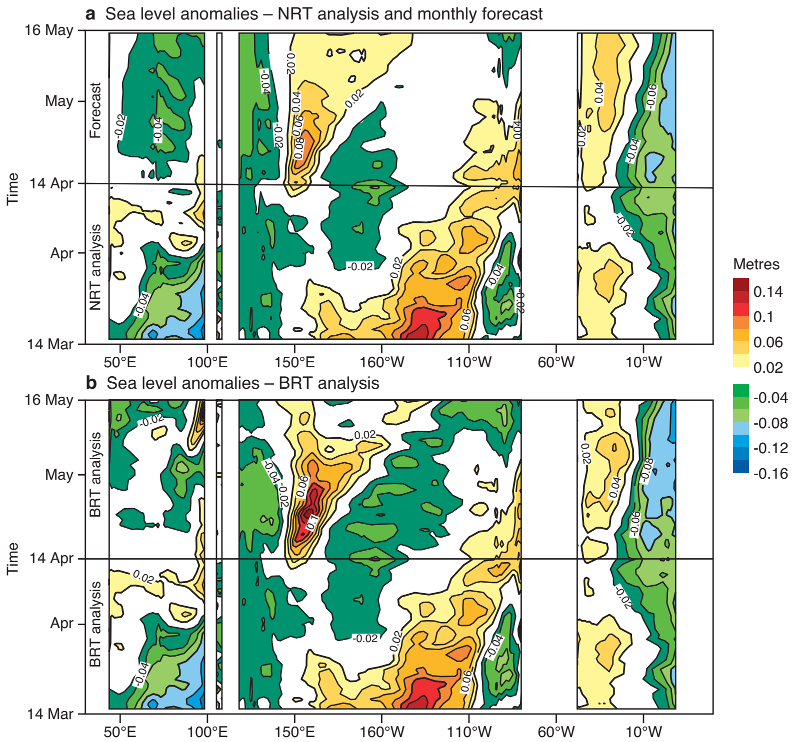

Figure 6 Time evolution of the sea level anomalies (metres) along the equator during the period 14 March to 16 May 2005. (a) The NRT analysis from the 14 March to 14 April, followed by the ensemble mean of the monthly forecast initiated on 14 April. (b) As (a) but using the BRT ocean analysis for the whole period.

Historical ocean reanalysis

ECMWF is heavily involved in ocean reanalysis. The main motivation for the ocean reanalysis at ECMWF is the provision of initial conditions for the calibration of coupled model forecasts. In these extended-range forecasts, model error becomes large and can not be ignored. One way to cope with model error is to refer the real-time forecasts to the model climatology. For example, the forecast anomalies in Figure 6 were computed with respect to the model climatology which is obtained by performing an extensive set of past integrations or hindcasts (commonly referred to as "back-integrations"). This in turn brings the need for extended ocean analysis into the past to provide ocean initial conditions for the calibrating hindcasts. In what follows we will refer to the historical ocean reanalysis as OR, as opposed to the ocean analysis used for the real-time forecasts, that will be referred as RT (real-time) ocean analysis, this latter encompassing both the BRT and NRT systems. Figure 7 shows schematically a summary of the components of the OR for System 2 (currently in operations) and of the future OR for System 3 (to be implemented later in the year).

The provision of initial conditions for the calibration of coupled model output sets strong constraints on the development of the ocean analysis system. Consistency between the OR and the RT systems is needed if the back integrations are to be used to calibrate the real-time forecasts. Major upgrades in the RT would have an impact on the real-time forecasts and the quality of the calibration. Therefore, the RT analysis is not changed unless a retrospective OR is performed and the back-integration recalculated. The expense of this exercise means the upgrades to the ocean analysis system are not gradual; rather, the upgrades are step-like: infrequent but substantial.

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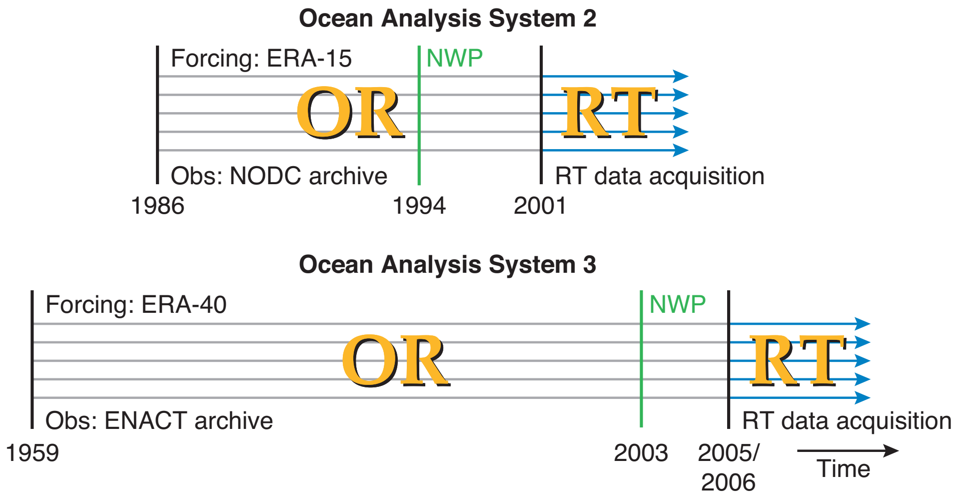

Figure 7 Schematic summary of the ocean reanalysis (OR) and real-time (RT) analysis in the current operational System 2, and planned OR and RT for System 3. The next reanalysis will use forcing fields from ERA-40 and will start in 1959. System 3 will produce an ensemble of five ocean analyses, as did System 2.

As the back-integrations from the OR ocean initial conditions are often used for skill assessment, the representation of the interannual and climate variability in the OR should be reliable. This is a tremendous challenge for any reanalysis system, subject to discontinuities due to the ever-changing nature of observing system. This is for instance the reason why altimeter data are not used in the current ECMWF ocean analysis system: by the time of its operational implementation back in 2001, the assimilation of altimeter data (available since 1993) was found to change the mean state of the ocean analysis, which would have implied limiting the extent of back-integrations to 1993. Since it is important that the back-integrations sample a wide range of climate situations, it was decided to leave the altimeter data aside. Assimilation of altimeter data is planned in the next ocean analysis system (System 3), since the assimilation will include a procedure for online estimation and correction of the bias, and the method to assimilate altimeter has been revised to ameliorate the impact on the mean state. Hopefully the benefits of using the altimeter data will outweigh the possible draw-backs.

As a result of the extended range forecast activities, ECMWF can offer to the climate community ocean reanalysis products of high quality that can be used in the study of climate variability. Figure 8 shows the evolution of upper 300 m ocean temperature, (T300) in three different regions: Eastern Pacific (Figure 8(a)), North Atlantic (Figure 8(b)) and Global (Figure 8(c)). The time series, which spans the period 1962–2002, is from a prototype of the next operational system. The evolution of T300 in the Eastern Equatorial Pacific is dominated by ENSO interannual variability, which is by no means periodic. ENSO variability in the Eastern Pacific has an amplitude ranging from 1 K to more than 3 K. The unprecedented amplitude of the 1997/8 El Niño can be appreciated, as well as the large 1982/3 event. These large events not only dominate the variability in the Eastern Pacific, but they also affect the three tropical oceans (not shown).

In the North Atlantic, the evolution of T300 shows an obvious warming trend of about 0.6 K from 1987 to 2002. The variability in T300 here relates well to the North Atlantic Oscillation (NAO) index: peak cold events during 1962/4, 1969/70, 1979, and 1995 all follow negative peaks of the NAO index. The evolution of the global temperature in the upper 300 m of the ocean since the late 1980s is clearly dominated by a large warming trend, to which the temperatures in the North Atlantic are a major contributor. There is some interdecadal variability, with the 1960s and 1980s being colder than the 1970s. The information contained in the ocean reanalysis can help to quantify and understand the role of the ocean in a changing climate.

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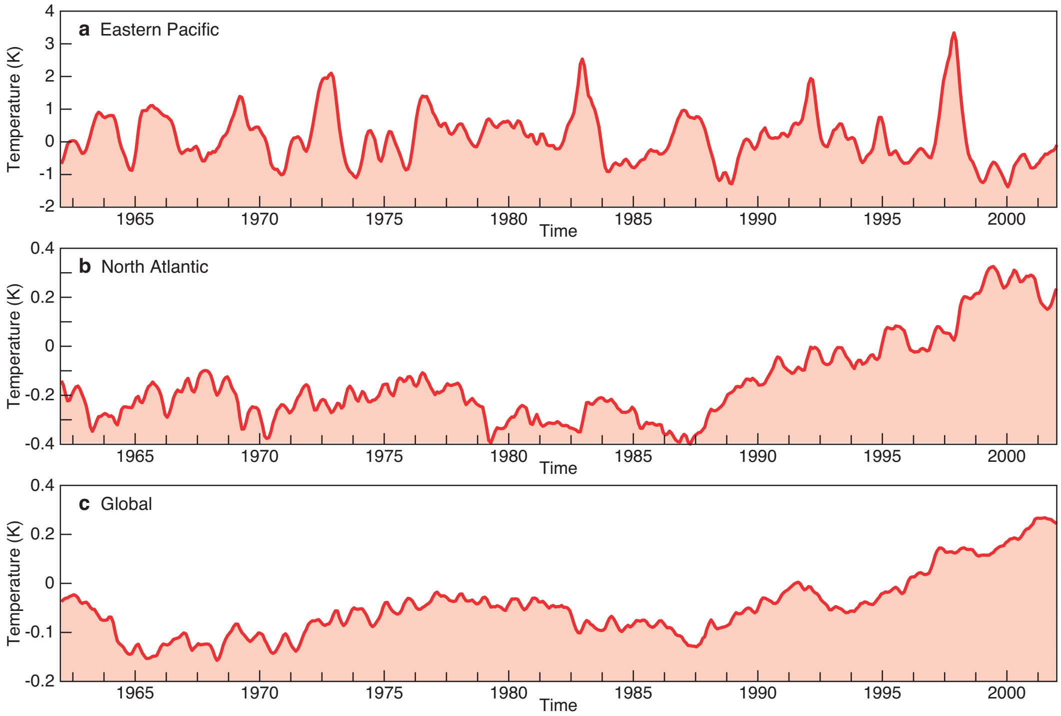

Figure 8 Time evolution of the ocean temperature averaged over the upper 300 m (T300) in three different regions: (a) Eastern Pacific, (b) North Atlantic and (c) global. ENSO variability dominates the Eastern Pacific, with the NAO impact visible in the evolution of T300 in the North Atlantic. A strong warming trend is apparent after 1987 in the global T300. The time series are from a prototype of the next operational system, and is a contribution of ECMWF to the ENACT project.

Future developments

Later this year, the ocean analysis system will be upgraded together with the seasonal forecasting system (System 3). The new system will provide retrospective ocean analysis back to 1959 (the reanalysis for the current System 2 started in 1986). Two main developments have made this extension possible: the availability of quality forcing fields back to 1959 from the ERA-40 atmospheric analysis, and the existence of a comprehensive quality-controlled observational archive compiled as part of the ENACT project. Salinity and altimeter-derived sea level anomalies will now be assimilated as well as subsurface temperature. The possibility of using the geoid information provided by GRACE is currently being assessed. Major developments in the assimilation systems have been made to be able to assimilate salinity data, which involved the formulation of isopycnal covariances of the background error. The method to assimilate altimeter data has also undergone major revision in order to avoid discontinuities in the ocean analysis mean state. There is a multivariate scheme for online estimation and correction of the bias that aims to make the ocean analysis less vulnerable to changes in the observing system. The wind perturbations used to create the ensemble of analyses have also been revised to allow for increasing uncertainty as we go further into the past.

The ECMWF ocean products, from the historical reanalysis to the real-time products, are a valuable contribution to a wide community. The historical ocean reanalyses provide a rich data set for the study and understanding of climate variability. Climate diagnostics of the historical ocean reanalysis will provide feedback about the strengths and weaknesses of the products, setting in this way the path for future development. Real-time ocean analysis products, used to initialize coupled forecasts (monthly and seasonal), are also used to monitor the state and evolution of the global oceans. Real-time ocean analyses of the subsurface are used together with the seasonal forecasts of SST to produce the routine statements needed by the WMO ENSO advisory committee. The SST forecasts from the seasonal forecasting system can be used as boundary conditions to produce seasonal forecasts with atmosphere-only models. Finally, the monthly forecasting system produces an ensemble of global ocean forecasts every seven days. The timeliness of the monthly system can assist decision makers involved with the latest SST forecasts and ENSO related problems.

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System 3 will be probably the last operational system that uses the HOPE model and the OI assimilation system. The new ocean component will use the OPA ocean model developed at the Laboratoire d'Océanographie Dynamique et de Climatologie in Paris, and the assimilation will be variational, based on the OPAVAR system developed at CERFACS in Toulouse. Changes in the horizontal and vertical resolution are also planned. In the next few years major development is need to prepare a reliable operational system based on these components. Strong collaboration with external partners will be required.

A final remark on the importance of atmospheric reanalysis: the quality of the ocean analyses is determined by the quality of the forcing fields. ERA-40 has made possible the extension of the ocean reanalysis back to 1959. For the same reason, it would be desirable that the production of atmospheric reanalyses were not conceived with a specific end date, but were kept nearly up to real time. This has the potential of improving the skill of the extended range forecasts by improving the consistency between the historical and the real-time products needed in the calibration process.

Further reading

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