Impact of Ocean Observation Systems on Ocean Analysis and Seasonal Forecasts

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ABSTRACT

The relative merits of the Tropical Atmosphere–Ocean (TAO)/Triangle Trans-Ocean Buoy Network (TAO/TRITON) and Pilot Research Moored Array in the Tropical Atlantic mooring networks, the Voluntary Observing Ship (VOS) expendable bathythermograph (XBT) network, and the Argo float network are evaluated through their impact on ocean analyses and seasonal forecast skill. An ocean analysis is performed in which all available data are assimilated. In two additional experiments the moorings and the VOS datasets are withheld from the assimilation. To estimate the impact on seasonal forecast skill, the set of ocean analyses is then used to initialize a corresponding set of coupled ocean–atmosphere model forecasts. A further set of experiments is conducted to assess the impact of the more recent Argo array. A key parameter for seasonal forecast initialization is the depth of the thermocline in the tropical Pacific. This depth is quite similar in all of the experiments that involve data assimilation, but withdrawing the TAO data has a bigger effect than withdrawing XBT data, especially in the eastern half of the basin. The forecasts mainly indicate that the TAO/TRITON in situ temperature observations are essential to obtain optimum forecast skill. They are best combined with XBT, however, because this results in better predictions for the west Pacific. Furthermore, the XBTs play an important role in the North Atlantic. The ocean data assimilation performs less well in the tropical Atlantic. This may be partly a result of not having adequate observations of salinity.

1. Introduction

Several currently implemented seasonal forecast systems employ dynamical ocean models coupled to either fully dynamical or statistical atmosphere models. The ocean initial conditions are obtained by forcing the ocean with a history of the wind stress and heat flux up to the forecast start date, which is generally a few days behind real time. The skill of the forecasts relies heavily on the quality of analyses of the upper ocean (500 m). Because both ocean models and forcing data are imperfect, additional information from oceanic observation systems is used to better constrain the ocean analyses and to improve ENSO forecast skill (Kleeman et al. 1995; Fischer et al. 1997; Ji et al. 1998, 2000; Alves et al. 1999, 2004; Segschneider et al. 2000b, 2001, Balmaseda 2004).

Over the last decade the number of oceanic observations available in near–real time has increased enormously. The main data sources that are available to improve the analyses of the upper ocean through assimilation are in situ temperatures and altimeter-derived sea level anomalies. Additionally, weekly maps of sea surface temperature (SST) can be used to constrain the model surface layers close to observed values. Subsurface temperature observations that are available in near–real time are currently provided by the Tropical Atmosphere–Ocean (TAO)/Triangle Trans-Ocean Buoy Network (TAO/TRITON) and Pilot Research Moored Array in the Tropical Atlantic (PIRATA) arrays in the equatorial region (McPhaden 1995; Servain et al. 1998) and the global Volunteer Observing Ship (VOS) program, which provides expendable bathythermograph (XBT) measurements mainly along merchant shipping routes. More recently, observations are provided by the Argo network of drifting profilers. The latter frequently provide salinity measurements, also but these are not assimilated in the experiments described here and can be used as independent data for diagnostic purposes.

Because funding is always limited, the question of the relative merit of each observational system arises. This can be estimated through observation system experiments (OSEs), well known to meteorologists. In these

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experiments, permutations of combinations of the available observation systems are used in an analysis of the (atmospheric) state, in which one system is excluded from the analysis (e.g., Daley 1991; Anderson et al. 1991), so providing an estimate of the impact of the omitted system. In oceanography, this is a relatively new field, because observations have always been sparse. There are some relevant studies, however. Smith and Meyers (1996) analyzed the relative impact of TAO and XBTs on the depth of the 20°C isotherm in the tropical Pacific using an optimal interpolation (OI) scheme but no ocean model. They concluded that the observation systems were mainly complementary. In contrast, Carton et al. (1996) found only a minor role for mooring data.

Here we will gauge the relative importance of the TAO/TRITON and/or PIRATA, VOS XBT, and the Argo observation systems. The analysis of Smith and Meyers (1996) did not include altimeter data, though Carton et al. (1996) did. No altimeter data are used in this study, which mimics the system used in the European Centre for Medium-Range Weather Forecasts (ECMWF) operational ocean analysis/seasonal forecasting system, which is denoted System-2 (S2). In a later study we will discuss the importance of altimetry and in situ salinity data. While in the studies of Carton et al. (1996) and Smith and Meyers (1996), the focus was on the ocean analyses, we will additionally judge the systems by their impact on forecasts of SST anomalies.

Results from OSEs are dependent on the analysis system used and on the weight given to the data. In our case we use a system close to that of the ECMWF operational seasonal forecast S2 (Anderson et al. 2003). The basic strategy is to start from the full system and to withdraw an observing system. This is the fairest way to assess impact and should highlight redundancy between the systems. The alternative strategy of starting from a minimum system with no data assimilation and adding observation systems can give very different results. Such experiments can be used to assess the potential importance of an observing system in the absence of other observations, but the more useful approach is to start from the existing system and ask what could be withdrawn, and where and to what extent there is redundancy. It is also true that results are application dependent. In this paper we are interested mainly in seasonal forecasts. This emphasizes the Tropics over middle latitudes. For other forecast time ranges (e.g., decadal), or other objectives, different areas may be important and different conclusions might be drawn.

First we assess the impact of the TAO and XBT networks. The basic experiment, in which all observations are assimilated, is denoted MAX. Then we perform two withdrawal experiments—the first in which the moorings are withheld (denoted −AX) and the second in which XBT data are withheld (denoted MA−). These assimilation experiments span the period of 1993–2003. To assess the importance of the observing systems on forecasts, 215 six-month forecasts are made spanning the period of January 1993–July 2003 using ocean analyses from the MAX, −AX, and MA− experiments as initial conditions. Forecasts are started four times per year (1 January, 1 April, 1 July, and 1 October), and an ensemble of five members is performed.

In all of the above experiments the Argo float data are used, but we do not assess the impact of Argo floats from these experiments, because Argo is only available in the last few years and such an assessment would underestimate their impact. A special set of OSEs is conducted to evaluate the impact of Argo. From this shorter set of experiments, additional 6-month forecasts are made.

In sections 2 and 3 we will describe briefly the observation and assimilation systems used in this paper. We will assess the importance of the various observing systems on the analyses in section 4 and on the seasonal forecasts in section 5. Conclusions are given in section 6.

2. Observation systems

a. Instrumentation

The mooring array consists of TAO moorings in the central Pacific; TRITON moorings in the west Pacific, and recently in the eastern Indian Ocean; and PIRATA moorings in the tropical Atlantic. The mooring functions are broadly similar although there are differences in their operational characteristics. The TAO network provides in situ temperature observations down to a depth of 500 m on a daily basis for the equatorial Pacific. The Pacific observations are taken from moorings laid out on a grid in the equatorial Pacific between 8°S and 8°N. The longitudinal gap between buoys is typically 1500 km. In the meridional direction, buoys are located at approximately 8°, 5°, 2°, and on the equator. The buoys carry thermistor chains with sensors at fixed depth: typically at the surface, and at 25, 50, 75, 100, 125, 150, 200, 250, 300, and 500 m. Data are transmitted as daily averages from samples taken 10 min apart. The TRITON moorings, located west of the date line, are also part of the Pacific array, but their transmission characteristics are different than those of the TAO. First, they provide an additional measurement at 750 m. Second, they report hourly. Third, the profiles are not transmitted as whole profiles; partial profiles may be transmitted, which then have to be pieced together to

obtain a continuous profile and sometimes leads to incomplete profiles. There are two TRITON moorings in the Indian Ocean. The PIRATA array covers a broader latitudinal extent than the Pacific. It has largely been deployed since 1998.

The XBT network or VOS program provides measurements from XBT drops mainly along the main merchant shipping routes. These can go down to 800 m but a more typical depth is 500 m. The XBT 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 sparse. Monthly maps of measurement locations can be found on the Web pages of the Joint Environmental Data Analysis Center (available online at http://www.jedac.ucsd.edu).

Recently, Argo floats (deployment of which started in the late 1990s) provide measurements of temperature and salinity down to 2000-m depth every 10 days. About 170 floats were reporting in 2001; this increased to over 800 by mid-2003 and exceeded 1000 by the end of 2003. The expectation is to deploy 3000 Argo profiling floats distributed over the global oceans at 3° spacing by 2006.

b. Observation coverage

Figure 1 shows the available in situ observation coverage for the years 1993 (upper) and 2003 (lower) for the month of March. With respect to moorings the figures show the buildup of the PIRATA array in the Atlantic, the increase of TAO/TRITON in the Pacific, and the presence of two moorings in the Indian Ocean. On the downside, there has been a marked drop in the number of XBT lines, although the density of observation along a line has increased. However, the most striking feature of these figures is the buildup of the Argo array.

Further information on the observation coverage is given in Fig. 2. This shows the number of observations at a depth of 175 m as a function of time for two important regions: Niño-3 and the equatorial Atlantic. The regions we will use in this paper are shown in Fig. 3. Plotting observations at a given model depth such as 175 m gives a good measure of the profile data received at ECMWF. However, this number includes data that will be rejected by our analysis system, because data too close to the coast are not used. A further caveat is that in these experiments the typical reporting time for the TAO and PIRATA arrays is once per day (a daily average). However, the TRITON moorings in the west Pacific and Indian Ocean report at hourly intervals. As a result, the number of mooring observations in the Indian Ocean can appear quite high (not shown), whereas there are in fact only two moorings. In the experiments reported here we use the hourly data where available, because this is what was done in the operational ocean analysis system at the time of this work. Plotted is the number of observations in a 10-day window.

Figure 2a shows the number of TAO and XBT observations in the Niño-3 region. Although there are large swings in the number of observations in any 10-day period, overall the number of observations has held relatively constant. Likewise, the number of XBT data has remained relatively small. Figure 2b shows the growth of the PIRATA moorings in the equatorial Atlantic. Some of the spikes in the data coverage of moorings indicate glitches in the real-time acquisition of data.

3. Assimilation strategy and experimental setup

The assimilation system used in this work is the same as that used at ECMWF to provide ocean initial conditions for the S2 seasonal forecast system (Anderson et al. 2003; Balmaseda 2004; Vialard et al. 2005), except that the resolution is lower. The ocean model used here has a horizontal resolution equivalent to 2° × 2° (latitude × longitude), although at the equator the meridional resolution is finer (0.5°). The model has 20 levels in the vertical, 8 of which are in the upper 200 m, compared to 29 levels in S2. Although the resolution of the model used here is only half that used in S2, experience indicates that the relative impact of data assimilation is largely insensitive to resolution changes of this order (Stockdale et al. 2006). The background state for ocean data assimilation is provided by the Hamburg Ocean Model with Primitive Equations (HOPE) (Wolff et al. 1997) forced by daily atmospheric fluxes of momentum, heat, and freshwater. As for S2, the fluxes are derived from the 15-yr ECMWF Re-Analysis (ERA-15) atmospheric reanalysis for the years before 1994 and from the ECMWF operational system thereafter.

The temperatures are assimilated through a relatively simple univariate optimum interpolation scheme based on the work of Smith et al. (1991), and described in Alves et al. (2004). As described in Balmaseda (2004) for S2, the decorrelation scales were reduced relative to those used in Alves et al. (2004), salinity is adjusted to conserve water mass properties (Troccoli et al. 2002), and geostrophic corrections are made to the velocity field (Burgers et al. 2002).

The in situ data used in all the experiments presented in this paper are the same as those used in the ECMWF operational ocean analysis. They are provided by The

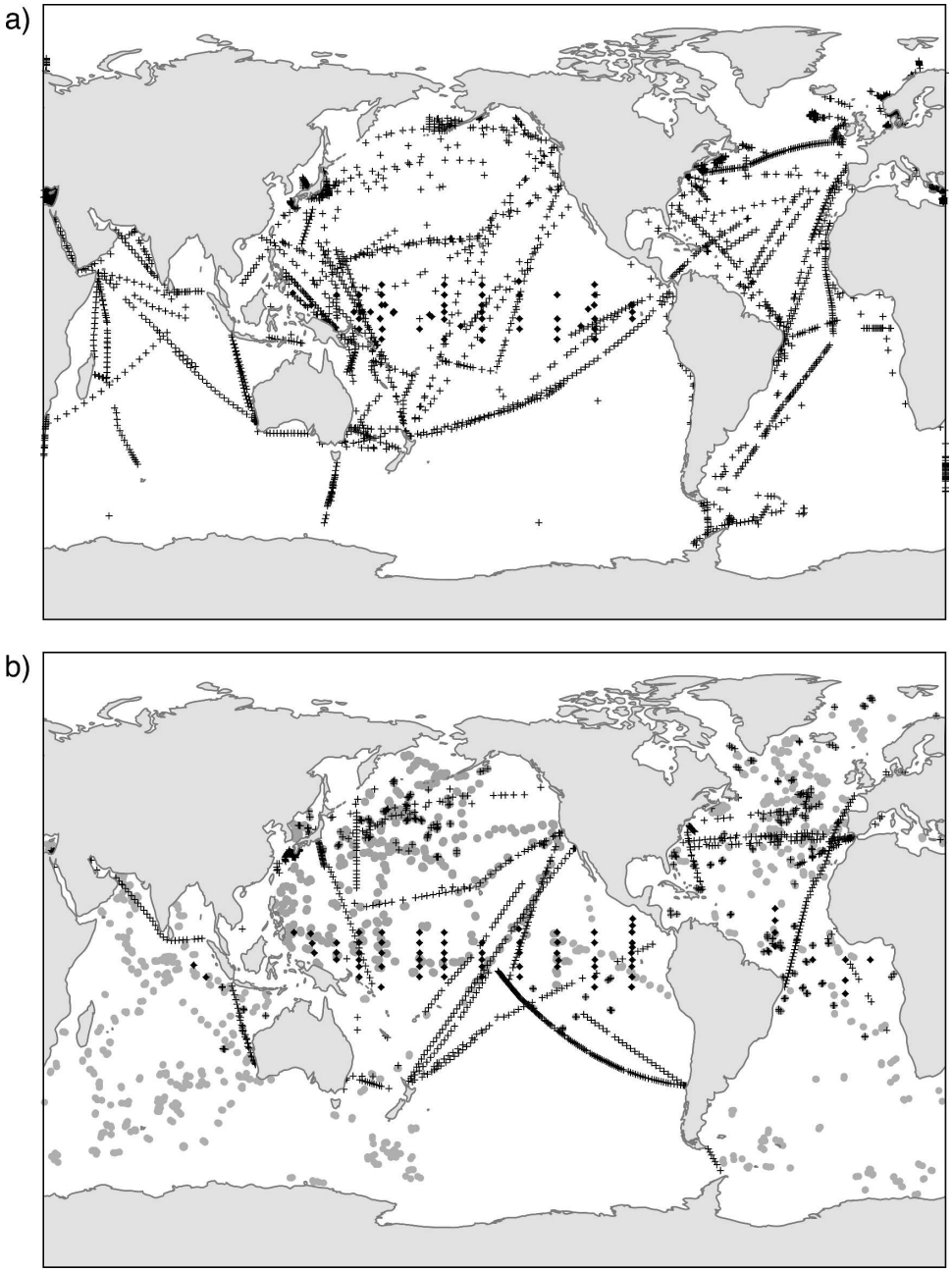

FIG. 1. In situ observation coverage for (a) March 1993 and (b) March 2003: moorings (diamonds), XBTs (black crosses), and Argo floats (gray circles).

Global Temperature-Salinity Profile Program (GTSPP; information available online at http://www.nodc.noaa.gov/GTSPP/gtspp-home.html). The system includes a built-in quality control (basically background check and cross validation) and all of the observations are given the same weight.

As mentioned earlier, three ocean analyses have been performed: the full data experiment MAX (moorings, Argo, XBTs), which makes use of all three available observation systems; MA− experiment, where no XBT data are used; and −AX experiment, where no mooring (TAO/TRITON and/or PIRATA) data are used (see Table 1). The experiments span the period from the 1 January 1993 to the 31 December 2003. Three additional experiments have been performed for the period from 1 January 2002 to 31 December 2003, mimicking the previous set but with an additional experiment M−Xs where no Argo data are used. A sub-

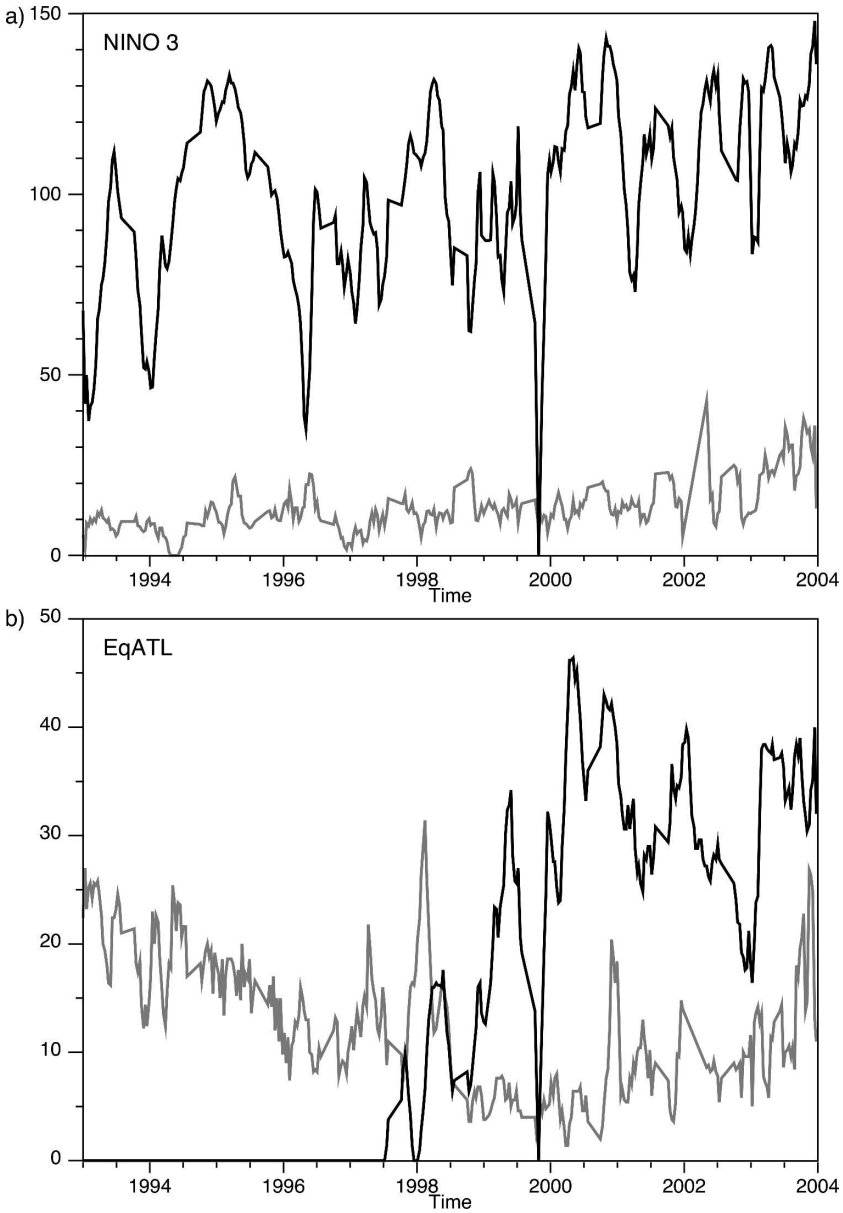

FIG. 2. Number of observations at 175 m in a 10-day period as a function of time from January 1993 to December 2003 for two key regions: (a) Niño-3 and (b) the equatorial Atlantic. The gray curve indicates XBT measurements and the black curve the number of moorings. The regions are shown in Fig. 3.

script *s* is used to indicate the short extent of these experiments. They can be compared with the standard experiment MAX over the common time period because they start from the MAX analysis in January 2002.

All experiments include a strong relaxation to observed SST, with the time scale being 3 days. We use the OI, version 2 (v2), SST analyses provided by the National Centers for Environmental Prediction (NCEP) in all ocean analyses to constrain the model SST to be close to the analyzed values (Reynolds et al. 2002). These are the same SST product and time scales as used in S2. In addition to the SST relaxation, there is a weak subsurface relaxation (time scale of 18 months) to the climatological temperature and salinity from the *World Ocean Atlas 1998* (*WOA*; Levitus et al. 1998).

For reference purposes two additional experiments have been added, which have no data assimilation but, in line with the other experiments, do have subsurface relaxation to *WOA* climatology. One spans the same

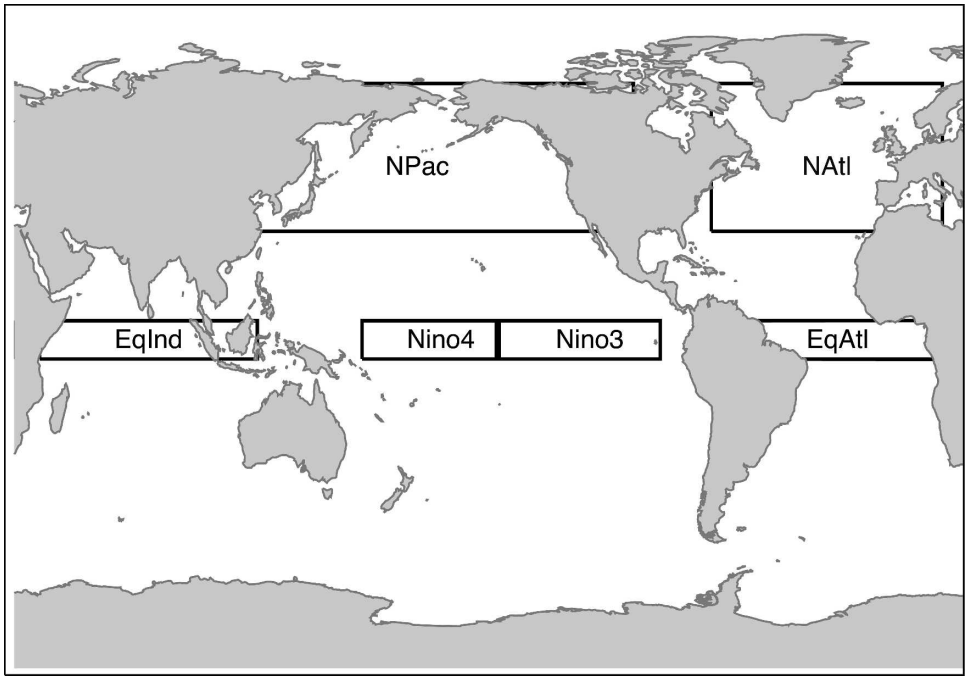

FIG. 3. The locations of regions NPac, NAtl, EqInd, Niño-4, Niño-3, and EqAtl used in this paper.

time interval as MAX and will be denoted CTL (starting with MAX initial condition for 1 January 1993) and the second will be denoted CTL_s and spans the period of 1 January 2002–31 December 2003 (starting with MAX initial condition for 1 January 2002).

4. Results for the period from January 1993 to December 2003

a. Impact on the mean state

In this section we will discuss the impact of the different datasets on the ocean analyses. In particular, we will discuss differences in the mean state of the temperature fields of the upper 300 m of a global section along the equator, and the differences of the time-mean average temperature of the upper 300 m (T 300), which is a good proxy for upper-ocean heat content.

The differences of the temperature fields along the equator between experiments MAX and MA−, and MAX and −AX are shown in Figs. 4a,b respectively. The differences are averaged over the 11 yr (1 January 1993–31 December 2003. The figures show the mean impact of the observation system that has been withheld from the assimilation.

Figure 4a shows that the impact at the equator of the XBT data is mainly confined to the Atlantic Ocean. The effect of withdrawing the XBT data is a warming of up to 0.9 K in the Atlantic. The impact in the equatorial Pacific is small, only about 0.1 K at its maximum in a small region in the west Pacific at 200 m. In the equatorial Indian Ocean the impact of XBT is smaller than in the Atlantic, but larger than in the Pacific.

Figure 4b shows the average impact of the mooring array. This is largest in the equatorial Pacific. TAO/TRITON data are responsible for warming the analyses of the central, and to a lesser degree the west, Pacific, that is, the analysis with the moorings is warmer than that without them. In contrast, they create a cooling of up to 1.4 K in the eastern Pacific thermocline. In the Atlantic the effect of PIRATA shows most strongly in the east. It is again a cooling, but extends considerably deeper than in the case of XBT. In fact, the moorings and XBTs seem to be in opposition below 200 m.

TABLE 1. Summary of experiments showing the different observing systems used; N: no, Y: yes.

Expt	Moorings	Argo	XBT	Date
CTL	N	N	N	1 Jan 1993–31 Dec 2003
MAX	Y	Y	Y	1 Jan 1993–31 Dec 2003
−AX	N	Y	Y	1 Jan 1993–31 Dec 2003
MA−	Y	Y	N	1 Jan 1993–31 Dec 2003
CTL_s	N	N	N	1 Jan 2002–31 Dec 2003
$-AX_s$	N	Y	Y	1 Jan 2002–31 Dec 2003
$MA-_s$	Y	Y	N	1 Jan 2002–31 Dec 2003
$M-X_s$	Y	N	Y	1 Jan 2002–31 Dec 2003
$M- -_s$	Y	N	N	1 Jan 2002–31 Dec 2003
$-A-_s$	N	Y	N	1 Jan 2002–31 Dec 2003

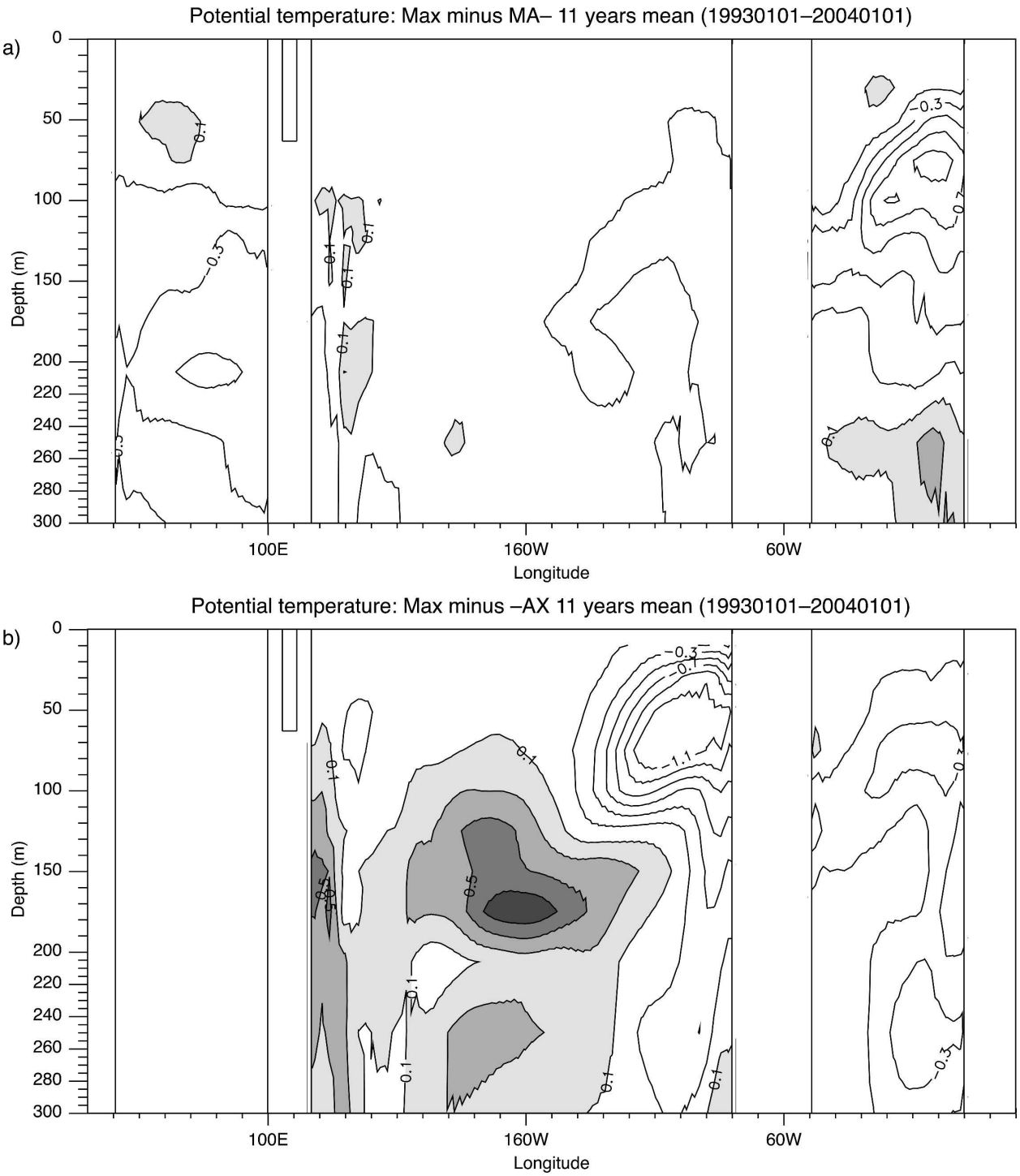

FIG. 4. Impact of observation systems on time-averaged temperature for a section along the equator for (a) the VOS XBT network and (b) the TAO network. The impact is shown by computing the difference between the ocean analysis using all data and the ocean analysis in which the respective data are withheld from the assimilation. Shading indicates that the analysis with XBT (moorings) is warmer than the analysis without. Removing the moorings results in a flatter thermocline. Contour interval is 0.2 K.

In the equatorial Pacific, the small impact from XBTs compared to that of moorings might imply that there is substantial redundancy between the XBT and the TAO/TRITON observing systems, at least in terms of defining the mean state.[1] This is thought to be mainly because the TAO/TRITON moorings give good coverage of the equatorial Pacific, leaving little scope for the XBTs. The relative importance of XBT versus PIRATA is not easily determined from Fig. 4 because PIRATA was only implemented toward the end of the period (see section 5 for results focused on the 2002–03 period). There is little impact of moorings in the Indian Ocean because there are few data there.

The main impact of TAO/TRITON in the equatorial Pacific is to correct the slope of the thermocline, as seen by Balmaseda (2004) and Vialard et al. (2003). They show that changing the slope of the thermocline by assimilation of temperature data only can give rise to spurious vertical circulations. The introduction of multivariate relationships in salinity and velocity can mitigate, but apparently not remove, this undesirable feature (Burgers et al. 2002; Balmaseda 2003; Ricci et al. 2005). Adequate treatment of bias may be required in these cases (Bell et al. 2004).

We now turn to the mean values of temperature averaged over the upper 300 m. Figures 5a and 5b show horizontal maps of the differences between experiment MAX and MA−, and between experiment MAX and −AX, respectively. Figure 5a shows that in the equatorial Pacific, within the domain covered by the TAO/TRITON array, the impact of the XBT data is small. In the subtropical Pacific, poleward of the TAO/TRITON area, the impact of the XBT data is mainly a warming of up to nearly 1 K (i.e., the analysis without XBTs is cooler than that with them), with a strengthening of the meridional gradients associated with the North Equatorial Countercurrent [as seen in Alves et al. (2004) and Vialard et al. (2003)]. Further poleward, cooling is observed especially in the region of the Kuroshio. In the Indian Ocean removing the XBT data leads to a general warming of over 0.6 K, mainly concentrated along the path of the Indonesian throughflow. In the equatorial Atlantic the mean effect of XBT data is a cooling within 10° of the equator and a slight warming in the northern subtropics. The effect in the equatorial Atlantic takes place mainly at the beginning of the period when there were no PIRATA data, as will be discussed in the next section. At higher latitudes (40°–50°N), the impact of XBT data is quite large in the vicinity of the Gulf Stream. As for the Kuroshio, the data can act to modify the path of the Gulf Stream. A much higher resolution than that used in these studies is required to correctly model the meandering and separation of such boundary currents.

The impact of the TAO/TRITON array (Fig. 5b) is naturally mainly restricted to the equatorial Pacific, although there is some impact on the eastern Indian Ocean via the Indonesian throughflow. The mean impact is a large-scale warming in the west and central Pacific, and a stronger cooling in the eastern Pacific. The net effect of these changes is to adjust (steepen) the slope of the thermocline along the equatorial Pacific. The impact of PIRATA on the Atlantic thermal field is a cooling. It does adjust the thermocline slope but mainly shallows the thermocline. The amplitude appears smaller than that of the TAO/TRITON because PIRATA data are only present in the later period.

The observing system is not stationary and it is quite likely that the different components would have had different impacts at different stages in the development of the observing system. For example, the PIRATA array was first deployed in late 1997 and therefore comparing the mean impact on the period of 1993–2003 with that from TAO or XBT will underrepresent its impact. This can be seen by calculating the same figures as for Fig. 5, but for different periods (results concentrating on the latter period will be shown in section 4d). An alternative is to look at the temporal evolution of some quantity in the different experiments, as will be done in the next section.

b. Temporal variability

Figure 5 shows the mean impact of components of the observing system but gives no information on the temporal behavior. However, time series such as that of the depth of the 20° isotherm (D20) in selected regions are shown in Fig. 6. There is a clear post-ENSO effect in Niño-4 compared to CTL; all data assimilation experiments show a significantly deeper thermocline in this region after the 1998 El Niño. Comparison with sea level estimates (not shown) indicates that the impact of TAO is beneficial for the representation of the post-ENSO era in the equatorial Pacific regions. The impact of XBT is smaller than that of TAO throughout.

In the equatorial Atlantic (5°S–5°N), there are substantial differences between the pre- and post-PIRATA periods (before and after 1998). Pre-1998, MAX and −AX are essentially the same because there are no moorings data, and CTL and MA− are also the same because removing the XBT data is equivalent to no assimilation for this period. After 1998, the PIRATA array is introduced and the four experiments differ. The

[1] We will consider variability later.

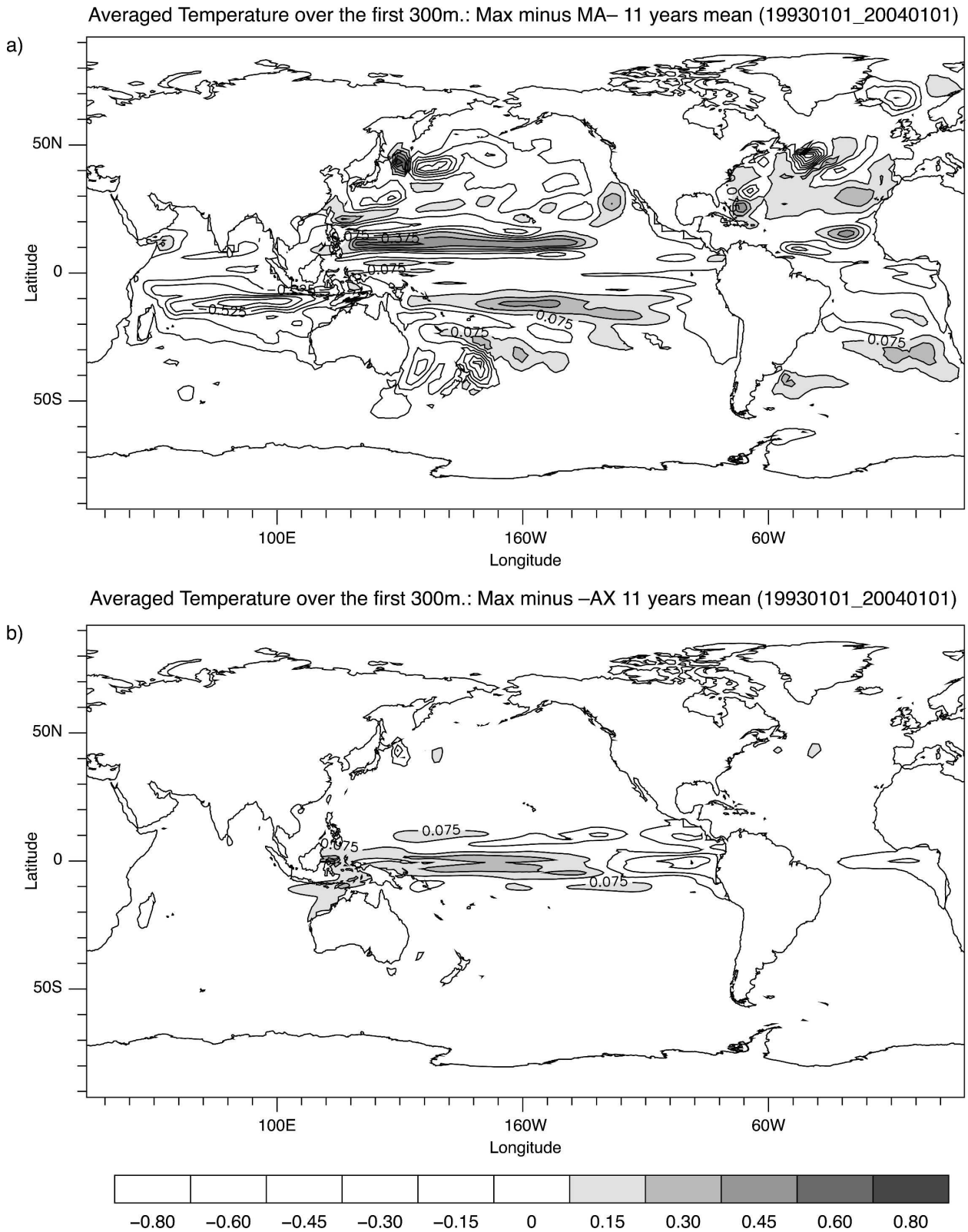

FIG. 5. Impact of observation systems on time-averaged upper-300-m temperature for (a) the VOS XBT network and (b) the TAO network. The impact is shown by computing the difference between the ocean analysis using all data and the ocean analysis in which the respective data are withheld from the assimilation. Shading indicates that removing the XBTs (moorings) reduces the heat content of the upper ocean. Contour interval is 0.15 K.

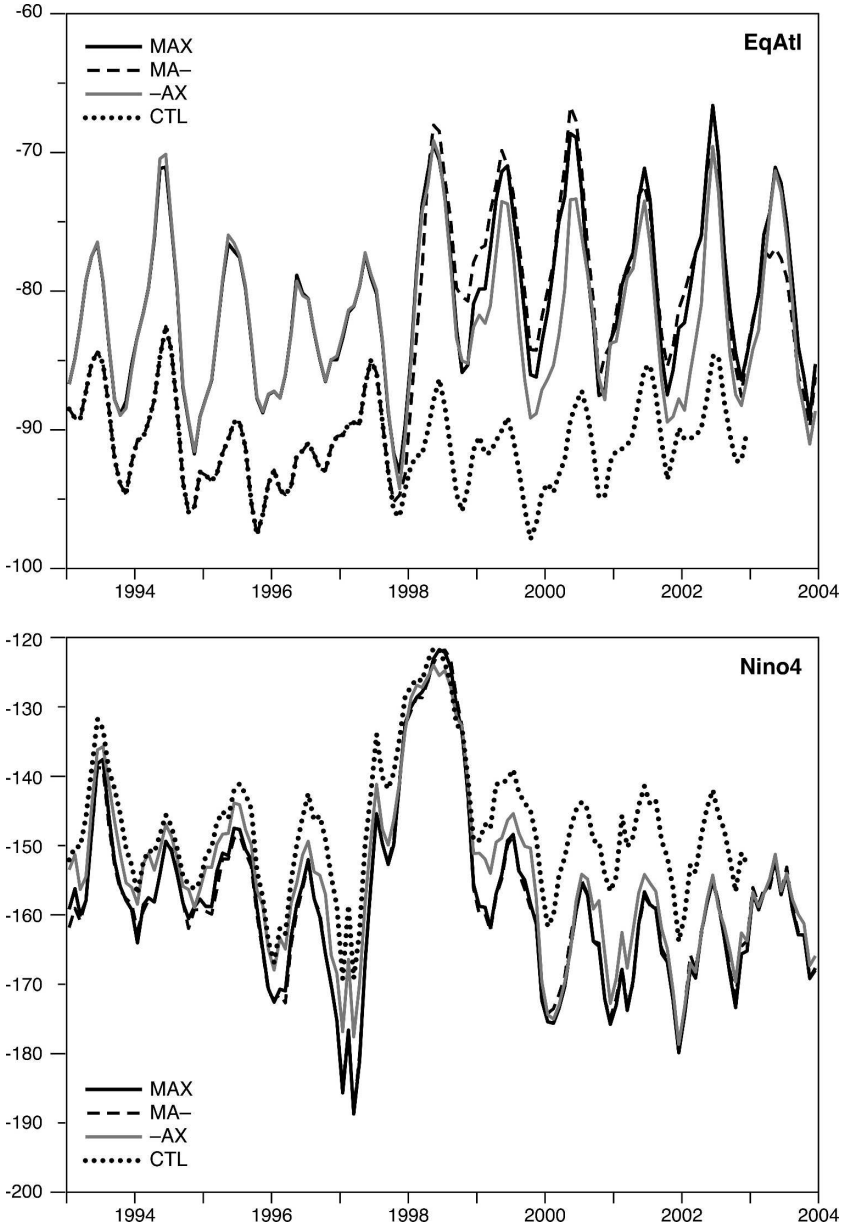

FIG. 6. Time series of area-averaged depth of the 20°C isotherm for the equatorial Atlantic and the Niño-4 region.

differences between MAX and −AX are typically 2–3 m, though occasionally can reach 5 m. The differences between MAX and MA− are typically a bit smaller than this. The smaller impact of XBT compared with mooring data may in part reflect the smaller number of XBTs in the years immediately following 1998. The differences between the assimilation and the no-assimilation cases (i.e., between MAX and CTL) are typically 15–20 m. It is not just the mean offset that is of interest, but also the size of the variability. The annual cycle is considerably larger in the case of data assimilation so assimilation acts not just to correct a mean bias but also to influence the variability. Apparently PIRATA and XBT often disagree in this region, for instance, during the 1998–2002 period when D20 in MA− is mainly above MAX and in −AX is mainly below. However, this is mostly an artifact of the area averaged as will be shown in section 4d.

For the 1993–2003 period, the Indian Ocean (not shown) is almost entirely observed through XBTs, and therefore there is no impact from moorings in the equatorial Indian Ocean. (There is some influence on the

Indonesian throughflow, but that is from moorings in the west Pacific.) There are now a few TAO/TRITON buoys in the eastern part of the equatorial Indian Ocean as well as an increasing number of Argo floats. We will not specifically look at the impact of these moorings but we will look at the impact of Argo floats in a later section.

c. Comparison with independent data

One way to assess the quality of analyses is to compare them with independent data. In this section we will compare analyzed temperature (T) with CTD data, analyzed salinity with all available salinity (S) observations, and the model sea level with altimeter data. The former were not distributed in real time and therefore were not entered in the GTSPP near-real-time data stream, but have been included in the recently compiled Enhanced Ocean Data Assimilation and Climate Prediction (ENACT) dataset (Ingleby and Huddleston 2006) that is used in the next two subsections. Both T and S from CTDs are therefore independent data. In addition, Argo floats measure salinity, but because salinity data are not currently assimilated into the analysis system Argo salinity data can be treated as independent. A strategy for assimilating salinity is being tested but is not used in these experiments (Haines et al. (2006). Likewise, a strategy for using altimetry is being tested but altimetry assimilation is not part of the current system.

Salinity is adjusted, however, following T assimilation. The method, described in Troccoli et al. (2002), preserves the model $T(S)$ relationship during T assimilation [except near the surface where $T(S)$ is not conserved]. Comparing the modeled salinity against the independent observations allows some assessment of the performance of this approach. Others have tried different approaches (e.g., Vossepol and Behringer 2000; Maes and Behringer 2000). In all of these methods an attempt is being made to perform a multivariate analysis, but one should not expect to be able to fully correct salinity without using any salinity observations.

1) COMPARISON WITH TEMPERATURE FROM CTDS

The root-mean-square (RMS) differences between the various analyses and the temperature as measured by CTD devices at the location of the observations were evaluated for several regions for the period from 1993 to 2003. In all the areas considered, the assimilation improves the fit of temperature to the independent CTD data. Figure 7 shows the profiles (from the surface down to 1000 m) for the two regions of Niño-3 and EqAtl (locations shown in Fig. 3). In the upper ocean of the two regions shown, most of the improvement comes from the assimilation of mooring data, but in other regions such as EqInd, Natl, and NPac (not shown) the main contributor is the XBT network. In EqAtl, the assimilation without moorings degrades the fit to CTD at about 250 m compared to the control, further illustrating the importance of the moorings in that area. In Ninõ-3, in the part of the profile between 250 and 600 m, MAX is worse than the two other assimilation runs and not much better than CTL. That is probably due to applying increments that are not completely balanced in velocity or salinity.

Argo temperature data are assimilated as well and may have an impact on these diagnostics. In NAtl (not shown), for instance, because there is no mooring in the region, MAX and −AX are almost the same but MA− is closer to the CTD observations than CTL. Although this can be due to some remote effect of the assimilation of moorings, it is more likely to come from the assimilation of Argo data. The temporal evolution of the number of data used for this diagnostic is shown in the panel below the profiles. In EqAtl many of the CTD temperature measurements take place at the end of the period, which may explain why the impact from PIRATA data is noticeable even though they were not present at the beginning of the period.

2) COMPARISON WITH SALINITY OBSERVATIONS

Figure 8 shows the profiles from the surface to 300 m of the RMS differences between the experiments and the salinity data from CTD and Argo measurements for the same regions as the previous figure. In the Niño-3 region, both XBT and mooring temperature measurements help to improve salinity (XBTs in the lower part, moorings in the upper part). In Niño-4 (not shown), the assimilation of temperature data from moorings seems to degrade the salinity mostly in the upper part. The $S(T)$ adjustment scheme is not valid in the mixed layer and therefore it is not applied in the top 50 m. However, in regions such as Niño-4 where the mixed layer extends deeper than 50 m, this exclusion zone may be inadequate.

In EqAtl, the salinity of the upper 150 m is significantly improved by the assimilation of temperature relative to CTL. Here, however, the temperatures from the PIRATA array do not seem to have a significant effect on salinity (MAX and −AX are close to each other).

At higher latitudes the salinity correction from $S(T)$ is reduced linearly to zero from 30° to 60° and therefore the potential to correct salinity is much reduced and the risk of producing unbalanced increments is higher. The impact of assimilation of T on salinity is pretty neutral in NAtl and damaging in NPac.

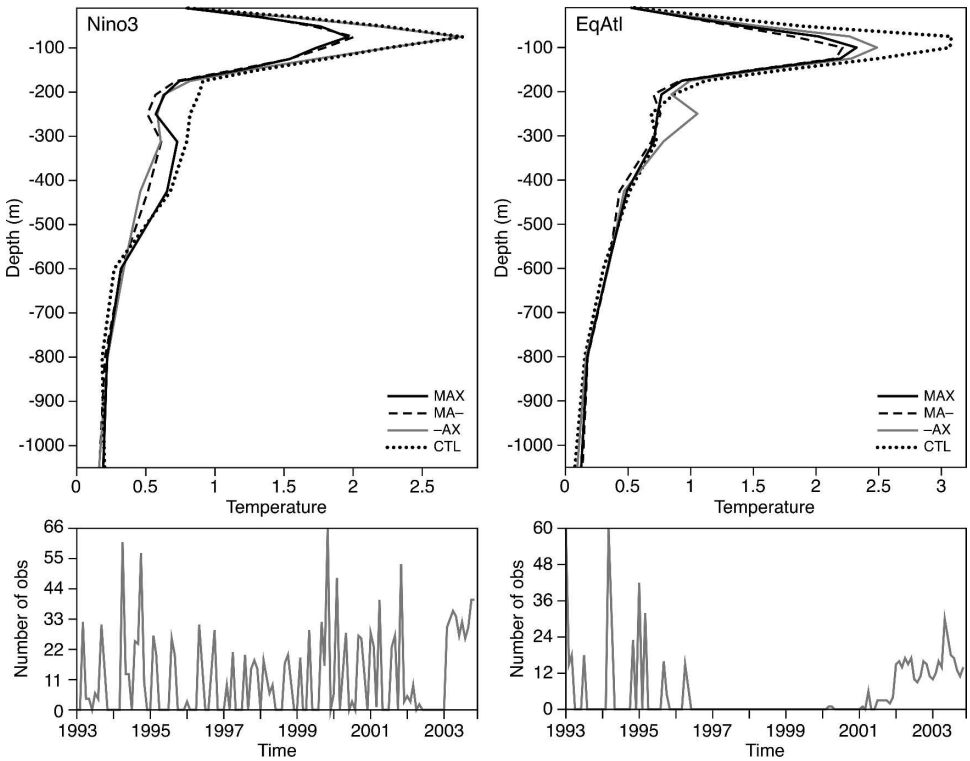

FIG. 7. Profiles of RMS differences from CTD temperature data for the Niño-3 and EqAtl regions for CTL, MAX, MA−, and −AX experiments. The lower panels show the number of observations in the two regions.

3) COMPARISON OF MODEL SEA LEVEL ANOMALIES WITH ALTIMETRY SEA LEVEL ANOMALIES

In this section we will compare the various analyses with sea level data from altimetry that were produced by Segment Sol Multimissions d'Altimétrie, d'Orbitographie et de Localisation Précise (SSALTO)/Data Unification and Altimeter Combination System (DUACS) as part of the Environment and Climate European ENACT project (EVK2-CT2001–00117) and distributed by Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO) with support from Centre National d'Etudes Spatiales (CNES). These are monthly mean maps coming from the delayed-mode high-quality merged satellite product from CLS, denoted historical homogeneous (HH) (Le Traon et al. 1998). The altimeter data have been interpolated onto the ocean grid and the small scales have been filtered out using a loess filter, which is equivalent to a 2° filtering at the equator and 1° at 60°N. This dataset was only available from January 1993 to May 2003. First we calculated the correlation of the various analyses with the CLS HH monthly mean fields. Because the altimetry provides only anomalies relative to the 7-yr mean of 1 January 1993–31 December 1999, we calculated the corresponding anomalies from the model analyses and in both cases the seasonal cycle was removed. The mean sea level from the various experiments have different mean states, with typical differences being a few centimeters. However, because we have no satellite equivalent we will not assess these mean states but concentrate on the anomalies.

Figure 9 shows the correlation of CTL, MAX, MA−, and −AX with the altimeter. The level of correlation is generally very high, especially in the tropical Pacific where data assimilation increases the correlation even further, as can be seen by comparing CTL and MAX. In the equatorial Pacific, a region dominated by the TAO/TRITON array, the increase in correlation is due to the assimilation of mooring data. In the presence of the moorings, the effect of XBT in this region (within 10° of the equator) is more modest, because the correlation is already high (cf. −MAX and MA−).[2] The effect of

[2] The effect of XBTs in the absence of the TAO/TRITON array is larger, as could be inferred by comparing CTL and −AX, because the effect of Argo during the long period is negligible.

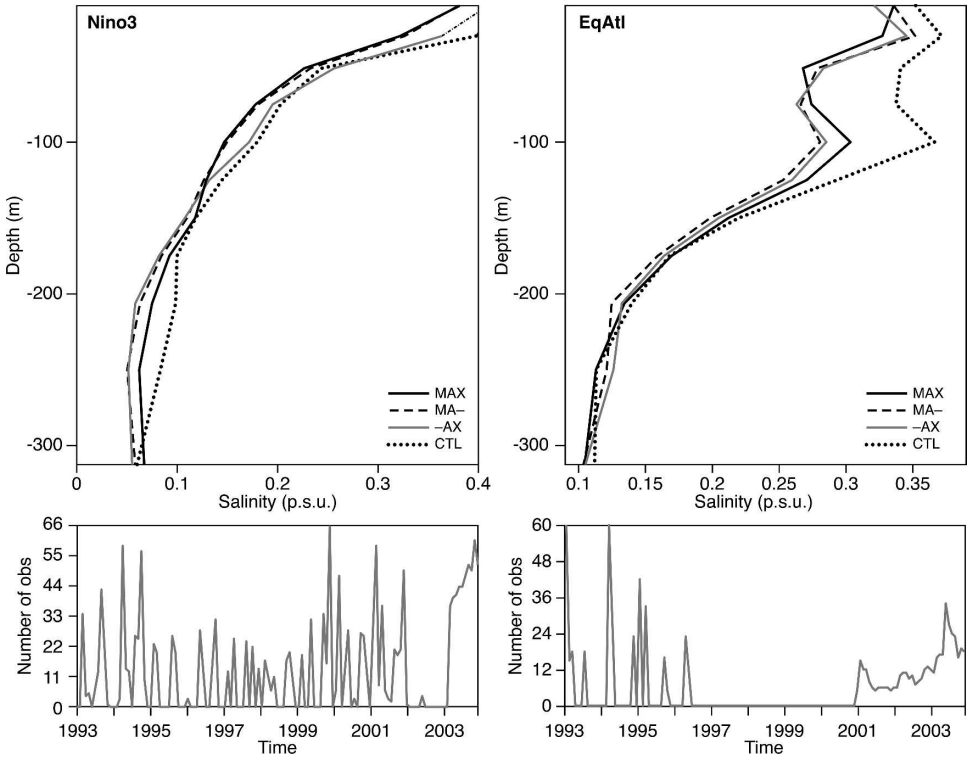

FIG. 8. Profiles of RMS differences in salinity data from Argo and CTD for the Niño-3 and EqAtl regions for CTL, MAX, MA−, and −AX experiments. The lower panels show the number of observations in the two regions.

XBTs is more noticeable in the Pacific Ocean poleward of 10°; the area with correlation above 0.5 is consistently greater in Fig. 9b than in Fig. 9c. In the Atlantic, the assimilation of XBT in the presence of moorings significantly and consistently improves the sea level (cf. Figs. 9b and 9c) whereas the impact from PIRATA is much less clear (cf. Figs. 9b and 9d). In fact, the assimilation of moorings without XBTs (Fig. 9c) seems to degrade the correlation with respect to CTL (Fig. 9a). This is consistent with Segschneider et al. (2000a) who reported the occurrence of spurious signals in the model sea level following the introduction of PIRATA in 1998. It is also consistent with Fig. 6, which shows the differences in the thermal mean state before and after the introduction of PIRATA. This difference in the mean state leads to an artificial variability in the sea level, and therefore an apparent degradation in the correlation with the altimeter. If the statistics are computed only for the PIRATA period (1998–2003) the moorings have a positive impact on the correlation, although with such a short sample it may not be statistically significant and it is not shown. In the tropical Indian Ocean the assimilation of XBT slightly improves the sea level (Figs. 9b and 9c).

d. Development of the Argo system

A more recent change in the observing system has been the spinup of the Argo float network. Deployment started in 1998 but the number of active floats before 2002 was relatively small. To see the impact of this array we performed an additional experiment called $M-X_s$ in which we withheld Argo float data. This experiment is for the 2-yr period of 1 January 2002–31 December 2003. To assess the relative importance of Argo versus the mooring and XBT networks, we performed two further experiments in which we withheld XBT (denoted $MA-_s$) and mooring data ($-AX_s$). These cover the same 2-yr period and are indicated with a subscript *s* in Table 1. All experiments start from the MAX analysis in January 2002 and can therefore be compared with MAX.

In the presence of other data, the impact of Argo on the equatorial temperature field is small (not shown). This could be because the observing systems for the equatorial Pacific and Atlantic are sufficient and Argo has little role to play there. Alternatively, it could simply be related to the number of observations. Figure 10 shows the time series of the global number of observa-

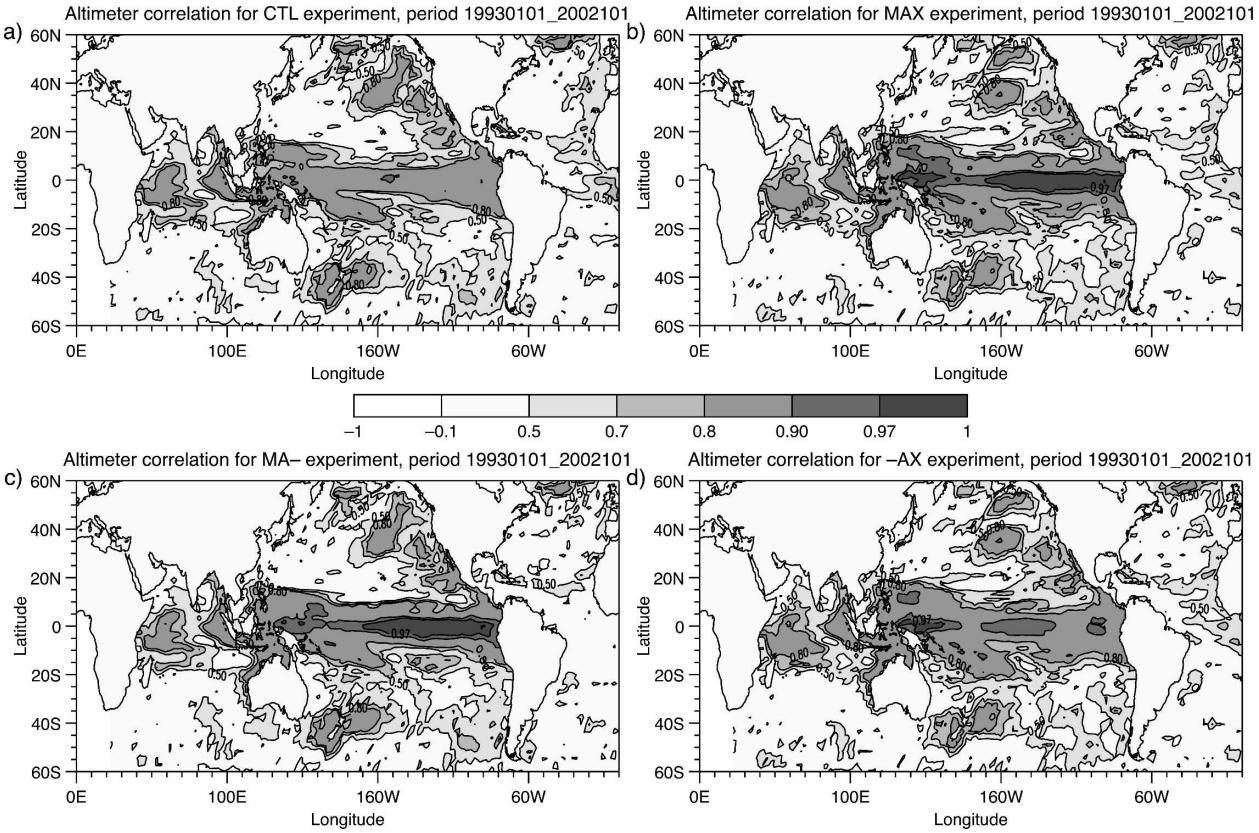

FIG. 9. Correlation with altimeter SLA for (a) CTL, (b) MAX, (c) MA−, and (d) −AX experiments for the period from January 1993 to May 2003. Note the highly nonlinear contour interval.

tions entering the ECMWF operational ocean analysis. The same data has been used in the experiments presented in this paper. One can note that the number of Argo measurements only reaches the number of XBT data after the end of the considered period. For recent dates Argo has become the main contributor to ocean in situ observations in term of numbers.

A global view of the impact of Argo on heat content (lower panel) and for XBTs (upper panel) is shown in Fig. 11. Argo does have some impact but it is considerably smaller than that of XBTs in much of the ocean. Globally the XBT network has a significant effect. However, in the equatorial Atlantic and Pacific (where the moorings are located) the mean effect of XBTs is relatively small compared to other areas. In the subtropical region of the Atlantic and Pacific Oceans the effect of XBTs is a slight warming of the upper 300 m. At higher latitudes (40°–50°N), the impact of XBT data is large especially north of the Gulf Stream and in the Kuroshio, two boundary currents that cannot be well represented in the model given its coarse resolution. In the Indian Ocean, the assimilation of XBT_s induces an overall cooling strongest south of the equator. This is all very similar to Fig. 5.

The assimilation of Argo floats has a rather small impact on our system compared to XBT and moorings except in the far North Atlantic. The main effect of floats is a warming north of the Gulf Stream that is in contradiction with the cooling from the XBTs. This could be due to the different locations of the floats and the XBT lines in regions of large spatial gradients. The observation coverage maps in Fig. 1 show the persistent presence of XBT lines in the neighborhood of the Gulf Stream. In areas of large gradients the correlation scales used in the assimilation may be too broad, spreading the information too far. If this were the case, an isopycnal formulation of the background covariance matrix would be beneficial.

The previous results are not an entirely fair way to measure the impact of Argo because the network is still building up and has significantly increased in size during the years of 2002–04 (see Fig. 10). This may explain the small impact of Argo in the Southern Ocean. Most of the Argo floats in the South Pacific were deployed after late 2003. Moreover, only the temperature coming from Argo has been used in these experiments, whereas most of the floats measure salinity as well. Knowing both quantities is of importance and allows for assimi-

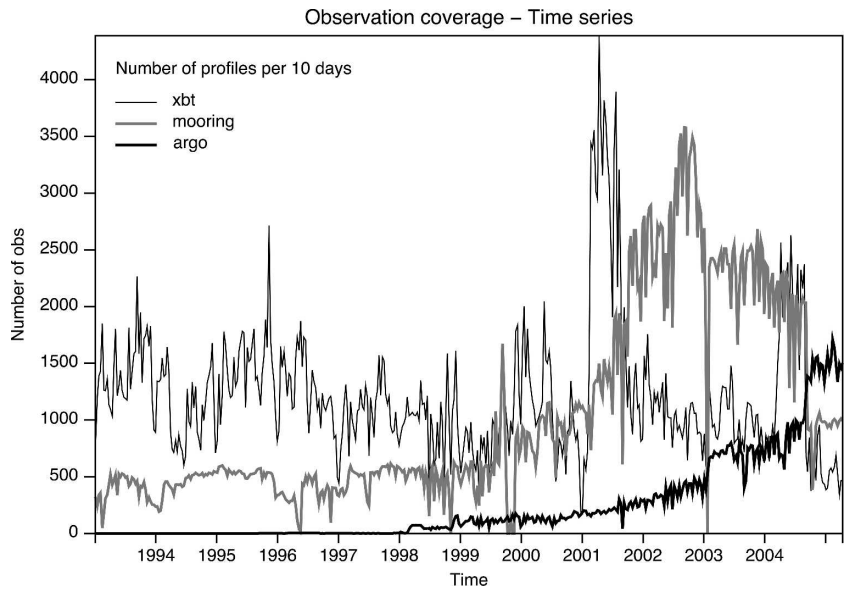

FIG. 10. Number of observations used in the operational ECMWF ocean analysis for the XBTs, moorings, and Argo floats from 1993 to the beginning of 2005.

lation of salinity data on temperature surfaces (Haines et al. 2006).

Resulting from their respective spatial and temporal coverage, the XBT and Argo floats will have very different impacts and their error characteristics should probably have different specifications. This is not the case in our system. In fact, the current values of errors and decorrelation scales are such that they favor observations that are dense in time and space, and will bias the results toward the XBT data. To have an idea of the impact of Argo in the opposite scenario, we conducted experiments where the XBT data are given zero weight. Such experiments can be justified, because there is no guarantee that the XBT network will be maintained. If the XBT network were discontinued, is Argo a suitable replacement? To assess this, two additional experiments have been performed without any XBT data, $M--_s$ and $-A-_s$, and have been compared with $MA-_s$. The two experiments cover the same 2 yr (2002–03) and have the same initial conditions as experiments $-AX_s$ and $MA-_s$, described above. All of these experiments start from MAX analysis of 1 January 2002 and so can be compared with MAX.

Figure 12 shows the impact on heat content from both moorings and Argo floats in the absence of XBTs. As expected, PIRATA data mainly affect the equatorial and subtropical Atlantic (the PIRATA array spans 10°S–15°N) and their mean effect is a cooling, with a maximum in the eastern part of the basin. This feature is consistent with the sudden shallowing of the thermocline (D20) after the introduction of PIRATA data, observed in experiment MA− and shown in the upper panel of Fig. 6. The upper panel of Fig. 6 also showed a disagreement between the impact of XBT and PIRATA data in the EqAtl region, as discussed in section 4b. By inspecting the spatial maps (upper panels of Figs. 11 and 12) one can see that the disagreement is only apparent: the effect is indeed of an opposite sign but it occurs at different locations, with the main effect of the XBTs outside the equatorial strip while the effect of PIRATA is centered on the equator (east of the basin).

There are, as well, small, unexpected remote effects of PIRATA in the higher latitudes, mainly in the Gulf Stream region. It might seem odd to have an impact so far from the region where the data are assimilated. However, in an assimilation system, information can propagate through the quality control decisions. The propagation speed is not related to any physical process. It is likely to show in regions where there are strong gradients. The impact of the TAO/TRITON array is naturally mainly restricted to the Pacific, within 15° of the equator. The mean impact is a fairly strong warming in the central Pacific, a very equatorially confined cooling (barely visible at the resolution of Fig. 12a) in the western Pacific, and a wider cooling in the eastern Pacific. A basin-wide cooling around 10°N is also apparent in the Pacific and to a lesser degree in the Atlantic Ocean.

In the absence of XBT, the impact of Argo is important and even as strong in intensity, if not in spatial coverage, as that of XBT (Fig. 12b). This does not mean

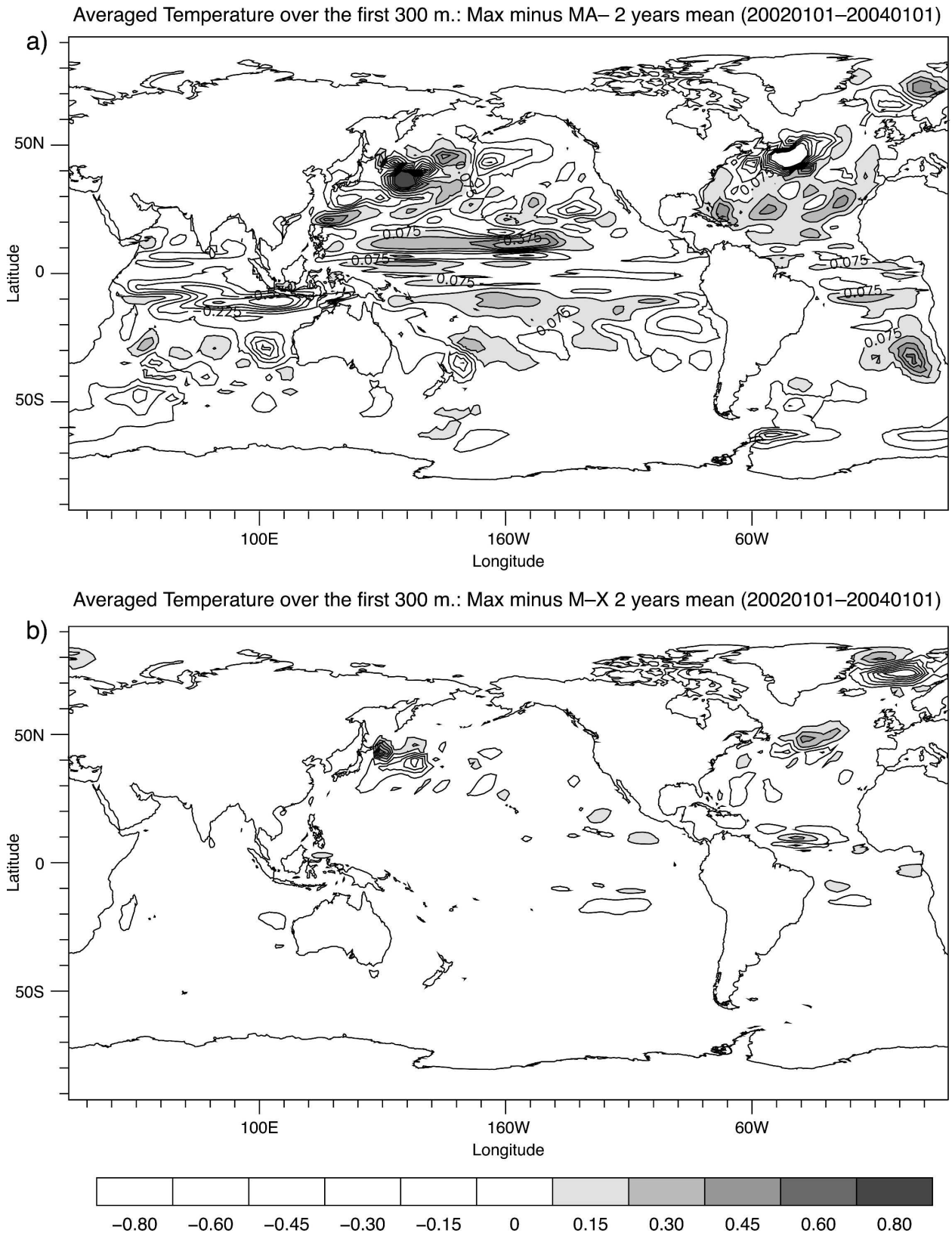

FIG. 11. Impact of observation systems on time-averaged upper-300-m temperature for the (top) VOS XBT network and (bottom) the Argo network. The impact is shown by computing the difference between the ocean analysis using all data and the ocean analysis in which the respective data are withheld from the assimilation. Shading indicates that the analysis with the XBT (mooring) data is warmer than that without. Contour interval is 0.15 K.

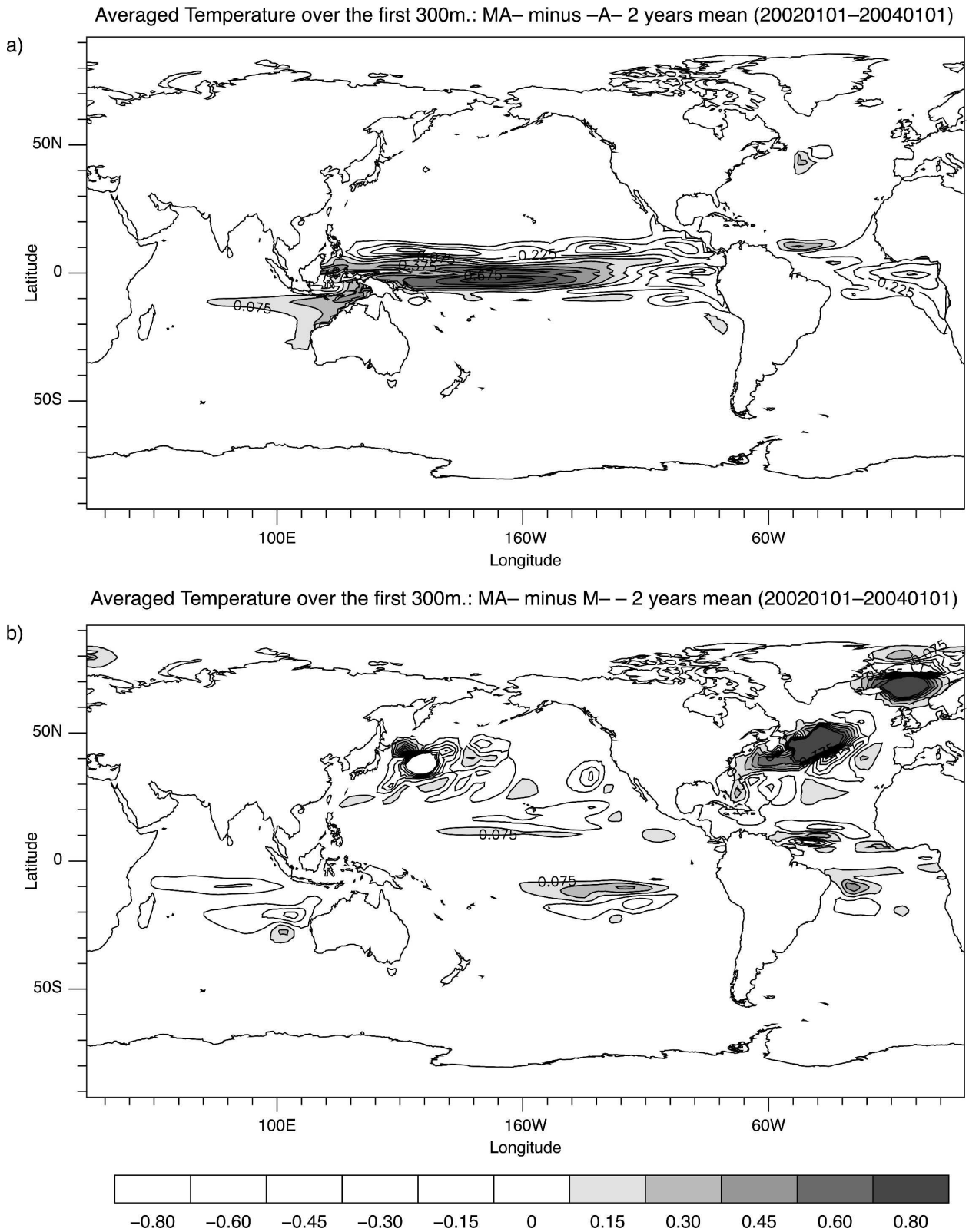

FIG. 12. Impact of observation systems on time-averaged upper-300-m heat content in the absence of the VOS XBT network for (a) the TAO network and (b) the Argo network. The impact is shown by computing the difference between the ocean analysis using all data and the ocean analysis in which the respective data are withheld from the assimilation. Contour interval is 0.15 K.

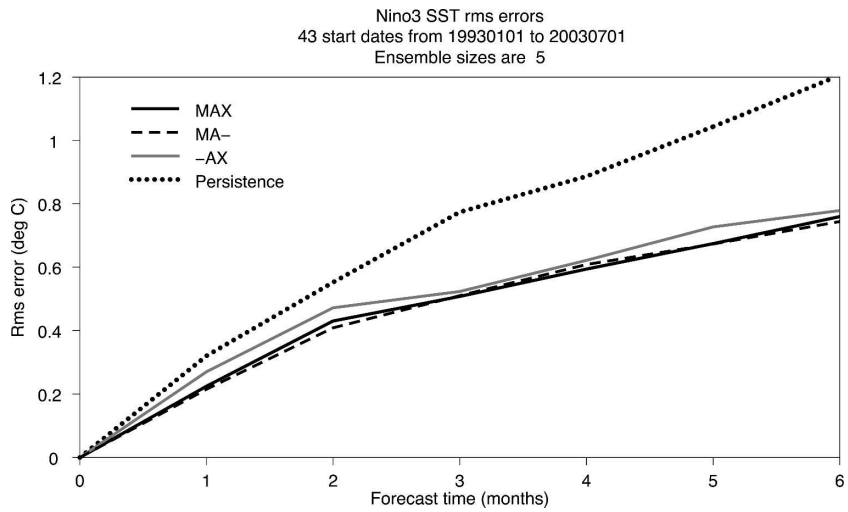

FIG. 13. SSTA forecast skill measured by RMS error for coupled experiments in Niño-3. The dotted curve is a measure of skill for persistence.

that their respective impacts are equivalent because the impact of the XBTs is large even in the presence of Argo floats. One of the reasons why Fig. 11b shows such a small impact might be that the number of observations from XBTs outnumbers those from Argo floats.

One can notice in Fig. 12b some cooling–warming oscillations between 0° and 10°N in the Atlantic at about 40°W. This feature can be seen, but with a lower amplitude in Fig. 12a and Fig. 11b, and is present in MAX minus $-\mathrm{AX}_s$ (not shown). It is close to the location of four PIRATA moorings (4°, 8°, 11.5°, and 15°N, 38°W), and a closer investigation (see Vidard et al. 2005) showed that in the absence of other data, the assimilation of these four moorings by this system can be damaging: additional information is needed to do the proper correction and may be provided by Argo floats [$\mathrm{MA}-_s$ (not shown) and MAX are pretty similar in this area]. This lack of information can be reduced by better background error statistics, such as flow-dependent error covariance matrices.

The above paragraph illustrates the importance of the specification of the representativeness error. If the observation coverage is too coarse it will not capture small-scale phenomena that may be present in the model, and the assimilation of these observations can be damaging. On the other hand, a too-dense dataset may be able to capture scales that are not resolved by the model and their assimilation may be damaging as well. In our system, only the second point is addressed, by forming superobservations; that is, regrouping observations in the horizontal and temporal dimension and by projecting onto model levels for the vertical dimension. The former point is still an issue in not-so-well observed areas (mainly the southern oceans).

In that sense the three types of data are different: the moorings are somewhat sparse in space and dense in time, the Argo floats are becoming quite dense in space but stay sparse in time (unless several floats are launched at the same place), and the XBTs are dense in space and time along a given track, providing a "slice" of the ocean thermal field.

5. Impact on coupled forecasts

To further assess the quality of the analyses discussed above, we will consider their impact on forecast skill. We will discuss four sets of forecasts, initialized from the ocean analyses described previously. The coupled forecasts are started on 1 January, 1 April, 1 July, and 1 October from January 1993 to July 2003 (inclusive). For each of these dates, SST perturbations are used to create a five-member ensemble. This strategy for generating an ensemble is discussed fully in Vialard et al. (2005). The model employed is the HOPE ocean model as used above, coupled to the same version of the atmospheric model [Integrated Forecast System (IFS), Cy24r1] as is used in the operational ECMWF seasonal forecast system S2.

To evaluate the impact of the OSEs on coupled forecast skill, results for several area-averaged SST forecast anomalies (SSTAs) are considered. Figure 13 shows the RMS error for the SSTA forecasts started from the MAX, −AX, and MA− experiments for the Niño-3 area. The RMS error is about the same for MAX and MA−, but when the mooring data are excluded from

TABLE 2. Mean absolute error in the first 3 months of SST forecast for the whole period of 1993–2003 averaged over the selected regions for experiment CTL, MAX, −AX, and MA−.

Region	CTL	MAX	−AX	MA−
Niño-3	0.335	0.299	0.319	0.305
Niño-4	0.223	0.211	0.234	0.224
NPac	0.128	0.126	0.127	0.125
NAtl	0.139	0.134	0.138	0.160
EqAtl	0.163	0.163	0.161	0.165
EqInd	0.133	0.123	0.122	0.126

TABLE 3. Mean absolute error in the first 3 months of SST forecast for the reduced period of 2002–03 averaged over the selected regions for experiment MAX, $-AX_s$, $MA-_s$, $M-X_s$.

Region	MAX	$-AX_s$	$MA-_s$	$M-X_s$
Niño-3	0.213	0.276	0.230	0.230
Niño-4	0.236	0.294	0.236	0.254
NPac	0.067	0.078	0.117	0.079
NAtl	0.215	0.218	0.243	0.249
EqAtl	0.112	0.141	0.118	0.138
EqInd	0.081	0.091	0.061	0.098

the ocean analysis (−AX) the skill is reduced, especially in the first 2 months. All forecasts, however, are more skillful than persistence for all lead times. These results show that forecasts of Niño-3 are mainly constrained by the assimilation of TAO/TRITON data and the XBTs have a rather small impact on forecast skill on this region, consistent with expectations based on the comparisons of ocean analyses.

If one considers the mean absolute error (MAE) in SSTAs averaged over the first 3 months of the forecast in the selected regions and the different experiments, for the whole period (1993–2003), one finds that moorings are the most important source of information in the equatorial Pacific (Table 2). In Niño-4 the predicted SST is worse in the absence of moorings than without assimilation at all; the system seems to be unable to make good use of XBTs, perhaps because there are too few of them.

In the North Atlantic it is hard to beat the skill of persistence (not shown). Assimilation of all data (MAX) improves the forecast skill very little relative to persistence. This skill is significantly degraded by the withdrawal of XBTs when it becomes worse than persistence. For further details, see Vidard et al. (2005).

In EqAtl, no observing system improves the forecast. This area is known to be difficult for current systems. Tropical Atlantic predictability is discussed further in Stockdale et al. (2006). Overall, the impact of assimilation on MAEs of SST forecasts seems quite small, indicating that the error in ocean initial conditions may not be the main error in the coupled system (see Stockdale et al. 2006 for more consideration on this topic). However, the total number of observations has significantly increased since the late 1990s (see Fig. 10) and therefore the impact of assimilation on forecast skill could be larger in the latter period.

Indeed, for the recent period (Table 3) the impact of assimilation is larger but represents only a limited number of cases (35 six-month forecasts[3]) and may not be statistically significant. Wherever the moorings are present (i.e., Niño-3, Niño-4, EqAtl, and to a lesser extent EQInd) the impact of their assimilation on forecast skill is considerable. Moreover, they seem to have a small remote beneficial impact in NPac. In the equatorial Atlantic, in the presence of PIRATA and Argo, the XBTs have very little impact. Here both PIRATA and Argo have about the same level of beneficial impact. Because we can see this impact in both $M-X_s$ and $-AX_s$, these two observing systems seem to be complementary. In NAtl, assimilation of both XBTs and Argo floats seems to be of importance, whereas in NPac the influence of XBTs is dominant. In EqInd the results are more puzzling: while the beneficial impact from assimilation of Argo floats and moorings is plausible, the withdrawal of XBTs leads to an unexpected and significant improvement in SST forecast. However, because the number of forecasts used here is relatively small this result may not be significant.

In summary, there seems to be a clear signal that withdrawing the TAO/TRITON mooring data leads to a significant reduction in the skill with which we can predict El Niño–related SSTs. In the Atlantic where the PIRATA mooring data are available for a shorter period there is also a suggestion of a reduction in the skill of predicting tropical Atlantic SSTs, when the data are withheld but the period is too short to be sure that this result is statistically robust. The impact of the XBTs on forecast skill is difficult to determine. A longer period should produce more reliable statistics, but in such an event it is unlikely that the observing system would remain stable over the whole period. Changes in the observing system can lead to spurious low-frequency variability. So it is probably difficult to determine the relative importance of components of the observing system unless they significantly alter the analyses. One should also remember that errors do not come only from ocean initial conditions but from imperfect models and coupling as well. Vialard et al. (2005) show that model error is a significant cause of forecast error, especially as the forecast lead time increases. This probably reduces the sensitivity of forecasts to initial condition errors.

[3] There are seven start dates and five ensemble members.

6. Conclusions

A set of observation system experiments was performed with a global ocean data assimilation system. Seasonal forecasts with a coupled ocean–atmosphere model were then used to evaluate the impact on SSTA forecast skill. The observation systems that were evaluated were the TAO/TRITON moorings in the equatorial Pacific and PIRATA moorings in the equatorial Atlantic, the global VOS XBT network, and the global Argo network. The impact on the analyzed state of the ocean was evaluated for a time-averaged temperature section along the equator, the time-averaged upper-ocean heat content, and the area-averaged time series of D20. The quality of the analyses was assessed using comparison with independent data and SST forecast skill.

In the equatorial Pacific, the impact of the XBTs is very small in the TAO/TRITON region. The TAO/TRITON data tend to warm the subsurface water in the west and most strongly in the central equatorial Pacific and to cool the eastern equatorial Pacific. This is consistent with the need of steepening and tightening of the thermocline in the equatorial Pacific. In this area our conclusions differ markedly from those of Carton et al. (1996). They concluded that TAO was of little importance, indeed, that the XBT network was much more valuable than the TAO network, although altimetry had the greatest impact of all. We find TAO to be the most important in the tropical Pacific though XBT can contribute; we have not evaluated altimetry in this article because it is not yet part of our operational system. In the case of Carton et al. (1996) the metric for impact was based on RMS variability. In our case one major reason for data assimilation is to provide improved ocean initial conditions for seasonal forecasts. One of our metrics for assessing the importance of an observing system is its impact on forecast skill. Using this metric, we find the TAO array to be the most important and to have a significant impact on ENSO forecasts for such regions as Niño-3.4.

In the post-1998 equatorial Atlantic, the PIRATA array has a significant and dominant impact but benefits from the presence of XBTs. The PIRATA array may not be dense enough to be sufficient on its own because the signals in the Atlantic are of a smaller scale than those in the Pacific. In mid- and high latitudes in the Atlantic and the Pacific and in the Indian Ocean, the XBT network was the most important source of information during the period considered.

It is probably too early to assess the importance of Argo floats even though it is now the largest in situ observing system, but it seems that they bring useful additional information to complement the PIRATA array and may be a good complement/alternative to the XBT network whose maintenance is not fully assured.

One should also remember that some redundancy is desirable, partly to guard against failure of one of the observing systems, but also to allow calibration of the observing systems. There is scope for improvement in the use of all the data, however, because a full multivariate specification of the background error covariance has not yet been developed to assimilate in situ data. Likewise, satellite data could be assimilated. Further studies using altimetry and salinity data will be reported in a subsequent paper.

It is quite a difficult task to draw a clear conclusion from OSEs in the ocean (at least for seasonal time scales) because of the need for long integration periods. During this time the observing system can evolve. Such low-frequency variability in the observing system makes it difficult to assess the importance of individual parts. An exception is the TAO array where withdrawing these data significantly degrades the forecasts.

REFERENCES

Alves, O. J., D. L. T. Anderson, T. N. Stockdale, M. A. Balmaseda, and J. Segschneider, 1999: Sensitivity of ENSO forecasts to ocean initial conditions. *Proc. The Int. Symp. TRIANGLE 98*, Kyoto, Japan, JAMSTEC, 21–30.

Alves, O., M. Balmaseda, D. Anderson, and T. Stockdale, 2004: Sensitivity of dynamical seasonal forecasts to ocean initial conditions. *Quart. J. Roy. Meteor. Soc.,* **130,** 647–668.

Anderson, D., A. Hollingsworth, S. Uppala, and P. Worceshyn, 1991: A study of the use of scatterometer data in the ECMWF Operational Analysis–Forecast model. Part II. Data impact. *J. Geophys. Res.,* **96** (C2), 2635–2649.

——, and Coauthors, 2003: Comparison of the ECMWF seasonal forecast Systems 1 and 2, including the relative performance for the 1997/98 El Niño. ECMWF Tech. Memo. 404, 93 pp.

Balmaseda, M. A., 2004: Ocean data assimilation for seasonal forecasts. *Proc. of the Seminar on Recent Developments in Data Assimilation for Atmosphere and Ocean,* Reading, United Kingdom, ECMWF, 301–326.

Bell, M. J., M. J. Martin, and N. K. Nichols, 2004: Assimilation of data into an ocean model with systematic errors near the equator. *Quart. J. Roy. Meteor. Soc.,* **130,** 873–893.

Burgers, G., M. Balmaseda, F. Vossepoel, G. J. van Oldenborgh, and P. J. van Leeuwen, 2002: Balanced ocean-data assimilation near the equator. *J. Phys. Oceanogr.,* **32,** 2509–2519.

Carton, J. A., B. S. Giese, X. Cao, and L. Miller, 1996: Impact of altimeter, thermistor and expendable bathythermograph data on retrospective analyses of the tropical Pacific Ocean. *J. Geophys. Res.,* **101,** 14 147–14 159.

Daley, R., 1991: *Atmospheric Data Analysis.* Cambridge University Press, 457 pp.

Fischer, M., M. Flügel, M. Ji, and M. Latif, 1997: The impact of data assimilation on ENSO simulations and predictions. *Mon. Wea. Rev.,* **125,** 819–829.

Haines, K., J. Blower, J.-P. Drecourt, A. Vidard, C. Liu, I. Astin,

and X. Zhou, 2006: Salinity Assimilation using $S(T)$ relationships. *Mon. Wea. Rev.,* **134,** 759–771.

Ingleby, B., and M. Huddleston, 2006: Quality control of ocean temperature and salinity profiles—Historical and real-time data. *J. Mar. Sci.,* in press.

Ji, M., D. W. Behringer, and A. Leetma, 1998: An improved coupled model for ENSO prediction and implications for ocean initialization. Part II: The coupled model. *Mon. Wea. Rev.,* **126,** 1022–1034.

——, R. W. Reynolds, and D. W. Behringer, 2000: Use of TOPEX/Poseidon sea level data for ocean analyses and ENSO prediction: Some early results. *J. Climate,* **13,** 216–231.

Kleeman, R., A. M. Moore, and N. R. Smith, 1995: Assimilation of subsurface thermal data into an intermediate tropical coupled ocean atmosphere model. *Mon. Wea. Rev.,* **123,** 3103–3113.

Le Traon, P. Y., F. Nadal, and N. Ducet, 1998: An improved mapping method of multisatellite altimeter data. *J. Atmos. Oceanic Technol.,* **15,** 522–534.

Levitus, S., and Coauthors, 1998: *Introduction*. Vol. 1, *World Ocean Database 1998,* NOAA Atlas NESDIS 18, 346 pp.

Maes, C., and D. Behringer, 2000: Using satellite-derived sea level and temperature profiles for determining the salinity variability: A new approach. *J. Geophys. Res.,* **105,** 8537–8547.

McPhaden, M. J., 1995: The Tropical Atmosphere-Ocean Array is completed. *Bull. Amer. Meteor. Soc.,* **76,** 739–741.

Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang, 2002: An improved in situ and satellite SST analysis for climate. *J. Climate,* **15,** 1609–1625.

Ricci, S., A. T. Weaver, J. Vialard, and P. Rogel, 2005: Incorporating temperature–salinity constraints in the background error covariance of variational ocean data assimilation. *Mon. Wea. Rev.,* **133,** 317–338.

Segschneider, J., D. L. T. Anderson, and T. N. Stockdale, 2000a: Toward the use of altimetry for operational seasonal forecasting. *J. Climate,* **13,** 3115–3138.

——, M. Balmaseda, and D. L. T. Anderson, 2000b: Anomalous temperature and salinity variations in the tropical Atlantic: Possible causes and implications for the use of altimeter data. *Geophys. Res. Lett.,* **27,** 2281–2884.

——, D. L. T. Anderson, J. Vialard, M. Balmaseda, T. N. Stockdale, A. Troccoli, and K. Haines, 2001: Initialization of seasonal forecasts assimilating sea level and temperature observations. *J. Climate,* **14,** 4292–4307.

Servain, J., A. J. Busalacchi, M. J. Mc Phaden, A. D. Moura, G. Reverdin, M. Vianna, and S. E. Zebiak, 1998: A Pilot Research Moored Array in the Tropical Atlantic (PIRATA). *Bull. Amer. Meteor. Soc.,* **79,** 2019–2032.

Smith, N. R., and G. Meyers, 1996: An evaluation of XBT and TAO data for monitoring tropical ocean variability. *J. Geophys. Res.,* **101,** 28 489–28 502.

——, J. Blomley, and G. Meyers, 1991: A univariate statistical interpolation scheme for subsurface thermal analyses in the tropical oceans. *Progress in Oceanography,* Vol. 28, Pergamon Press, 219–256.

Stockdale, T. N., M. Balmaseda, and A. Vidard, 2006: Tropical Atlantic SST prediction with coupled ocean–atmosphere GCMs. *J. Climate,* **19,** 6047–6061.

Troccoli, A., and Coauthors, 2002: Salinity adjustment in the presence of temperature data assimilation. *Mon. Wea. Rev.,* **130,** 89–102.

Vialard, J., A. Weaver, D. Anderson, and P. Delecluse, 2003: Three- and four-dimensional variational assimilation with a general circulation model of the tropical Pacific Ocean. Part II: Physical validations. *Mon.Wea. Rev.,* **131,** 1378–1395.

——, F. Vitart, M. A. Balmaseda, T. N. Stockdale, and D. L. T. Anderson, 2005: An ensemble generation method for seasonal forecasting with an ocean–atmosphere coupled model. *Mon. Wea. Rev.,* **133,** 441–453.

Vidard, A., D. L. T. Anderson, and M. A. Balmaseda, 2005: Impact of ocean observation systems on ocean analysis and seasonal forecasts. ECMWF Tech. Memo. 460, 32 pp.

Vossepoel, F. C., and D. W. Behringer, 2000: Impact of sea level assimilation on salinity variability in the western equatorial Pacific. *J. Phys. Oceanogr.,* **30,** 1706–1721.

Wolff, J., E. Maier-Reimer, and S. Legutke, 1997: The Hamburg Ocean Primitive Equation Model. Deutsches Klimarechenzentrum Tech. Rep. 13, 98 pp.