TECHNICAL MEMORANDUM

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Impact of ocean observation systems on ocean analysis and seasonal forecasts.

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Abstract

The relative merits of the TAO/TRITON and PIRATA mooring networks, the VOS 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 data sets are withheld from the assimilation. To estimate the impact on seasonal forecast skill, the set of ocean analyses is then used to initialise 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 initialisation is the depth of the thermocline in the tropical Pacific. This depth is quite similar in all the experiments which 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, as 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 an adequate treatment 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 (500m). As both ocean models and forcing data are imperfect, additional information from oceanic observation systems is used to better constrain the ocean analyses and thus to improve ENSO forecast skill (Kleeman et al., 1995; Fischer et al., 1997; Ji et al., 1998, 2000; Alves et al., 1998, 2004; Schneider et al., 1999, Segschneider et al., 2000, 2001, Balmaseda 2003).

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 TAO/TRITON and PIRATA arrays in the equatorial region (McPhaden 1995, Servain et al 1998) and the global Volunteer Observing Ship (VOS) programme which provides 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 and can be used as independent data for diagnostic purposes.

As funding is always limited, the question of the relative merit of each observational system arises. This can be estimated through observation system experiments (OSE), well known to meteorologists. In these 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 1992, Anderson et al 1991, Kelley et al 2004), so providing an estimate of the impact of the omitted system. In oceanography, this is a relatively new field, as observations have always been sparse. There are some relevant studies, however. Smith and Meyers (1996) analysed the relative impact of TAO and XBTs on the depth of the 20^{o} isotherm in the tropical Pacific using an 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/PIRATA, XBT/VOS and the ARGO observation systems. 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. Evaluation based on forecast skill is standard practice in meteorology and should generally be so in oceanography, even if it has not been so in the past. 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 ECMWF operational ocean analysis/seasonal forecasting system. In a later study we will discuss the importance of altimetry.

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 which is used in the ECMWF operational seasonal forecast system-2 (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 systems. The alternative strategy of starting from a 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, 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 emphasises the tropics over middle latitudes. For other forecast horizons, 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 1993-2003. To assess the importance of the observing systems on forecasts, 215 six-month forecasts are made spanning the period Jan 1993-Jul 2003 using ocean analyses from experiments MAX, -AX and MA- as initial conditions. Forecasts are started four times per year (1^{st}Jan, 1^{st}Apr, 1^{st}Jul, 1^{st}Oct) and an ensemble of 5 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, since 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 six-month forecasts are made.

In section 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 subsurface temperature and on seasonal forecasts. The impact of the various observing systems on the analyses will be given in section 4 and on the forecasts in section 5. Conclusions are given in section 6.

2 Observation systems

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 500m on a daily basis for the equatorial Pacific. The Pacific observations are taken from moorings layed out on a grid in the equatorial Pacific between 8^o S and 8^o N. The longitudinal gap between buoys is typically 1500km. In the meridional direction, buoys are located at approximately 8^o, 5^o, 2^o, and on the equator. The buoys carry thermistor chains with sensors at fixed depth: typically at the surface, 25, 50, 75, 100, 125, 150, 200, 250, 300, and 500m. 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. Firstly they provide an additional measurement at 750 meters. Secondly they report hourly. Thirdly 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 this 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 Volunteer Observing Ship (VOS) program provides measurements which can go down to 800m from XBT drops mainly along the main merchant shipping routes. 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 webpages of the Joint Environmental Data Analysis Center (*www.jedac.ucsd.edu*).

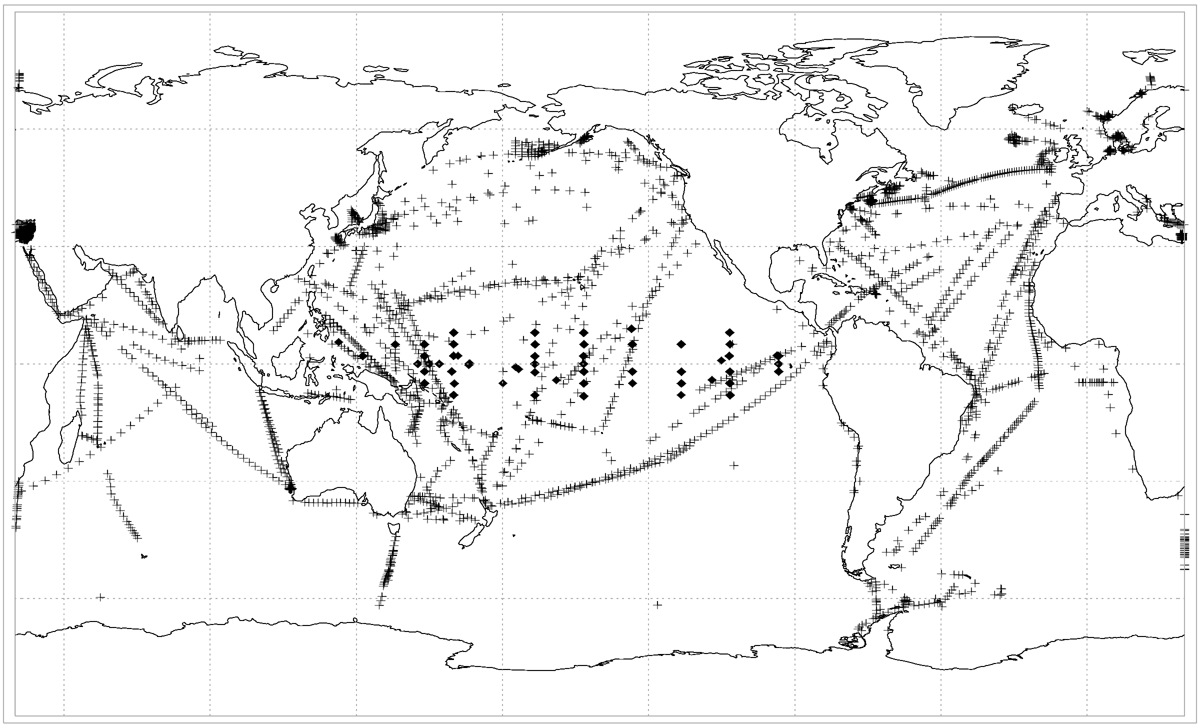
Recently, Argo floats, (deployment of which started in late 90's), provide measurements of temperature and salinity down to 2000 m depth every 10 days. About 170 floats were reporting in 2001: this increased to over 800 by mid 2003 and exceeded 1000 by the end of 2003. The expectation is to deploy 3000 ARGO profiling floats distributed over the global oceans at 3-degree spacing by 2006. The data should enhance the value of the altimeter through measurement of subsurface vertical structure (T(z), S(z)) and reference velocity, with sufficient coverage and resolution for interpretation of altimetric sea surface height variability. The interplay between altimetry and ARGO will be covered in a future work.

2.1 Observation coverage

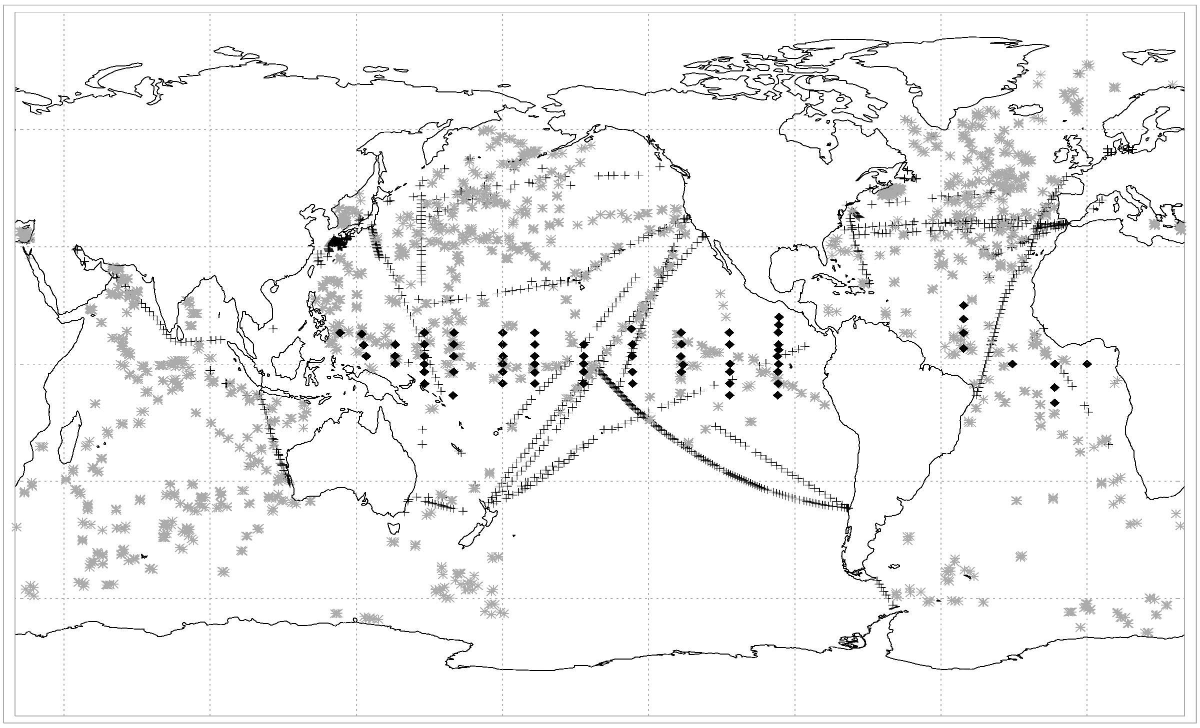
Fig. 1 shows the available *in situ* observation coverage for the years 1993 (upper) and 2003 (lower) for the month of March. With respect to moorings the figures show the build up of the PIRATA array in the Atlantic, the increase of TAO/TRITON in the Pacific and the presence of two moorings in the Indian 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 build up 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 175m as a function of time for several important regions. The regions we will use in this paper are shown in fig 3. Plotting observations at a given model depth such as 175m gives a good measure of the profile data received at ECMWF. However, this number includes data which would be rejected by our analysis system as data too close to the coast are not used in our assimilation system. 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 as this is what is currently done in the operational ocean analysis system but in the near future we plan to average the data from TRITON to daily-means before assimilation. Plotted is the number of observations in a 10-day window.

Fig 2a shows the number of TAO and XBT observations in the Niño4 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. (The TRITON moorings are all further west than Niño4 and so there are no hourly data in this figure.) Likewise the number of XBT data has remained relatively small. A similar picture applies to Niño3 (panel b). Panel c) 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.

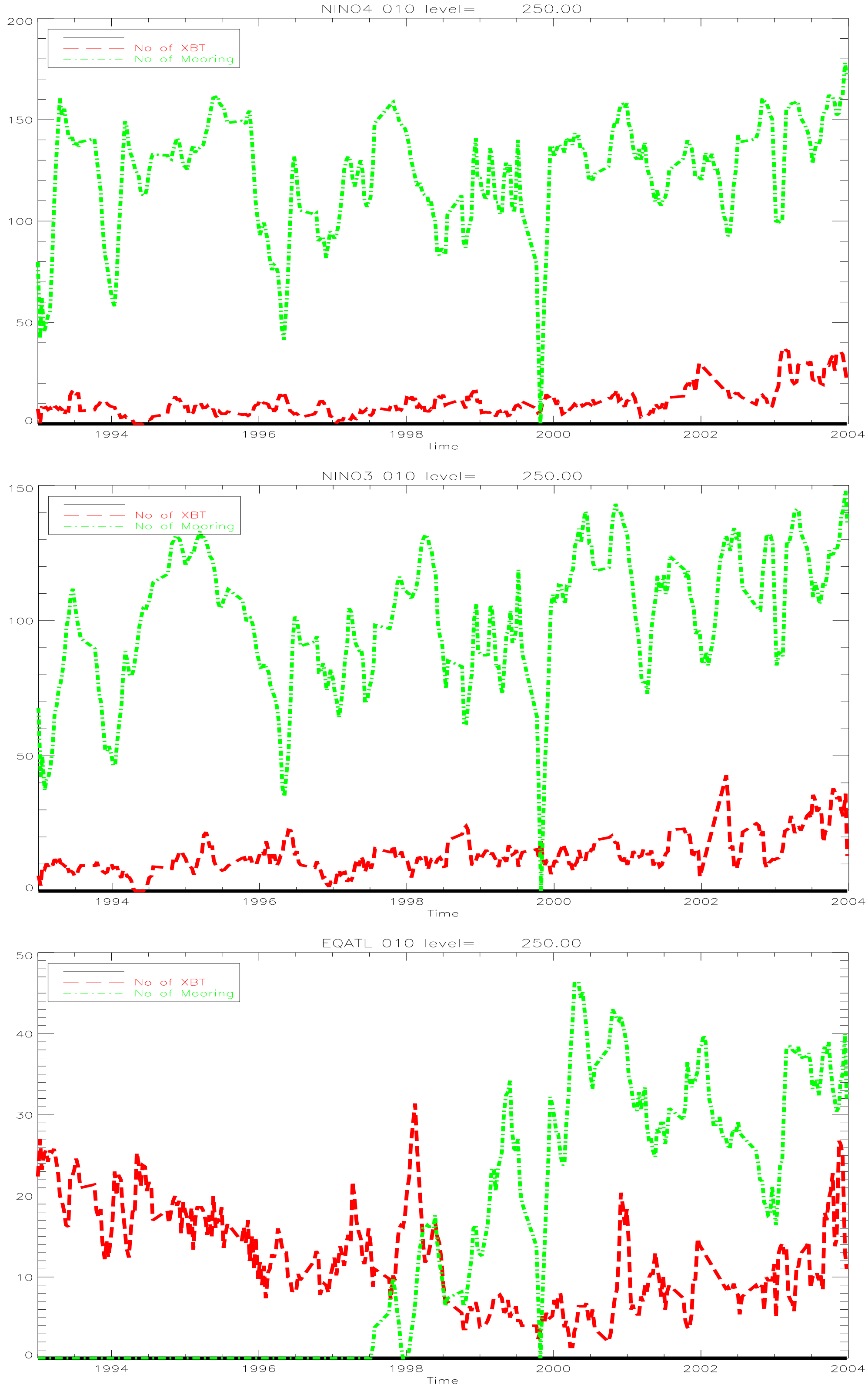


a)



b)

Figure 1: In situ *observation coverage for a) March 1993 and b) March 2003. Diamonds represent moorings, black crosses XBTs and grey stars Argo floats.*



a)

b)

c)

Figure 2: Number of observations in a 10-day period as a function of time from Jan 1993 to Dec 2003 for 3 key regions: a) Niño4, b) Niño3 and c) the equatorial Atlantic. The dashed curve indicates XBT measurements and the dash-dotted curve the number of moorings. None of these regions includes TRITON observations. The regions are shown in fig 3

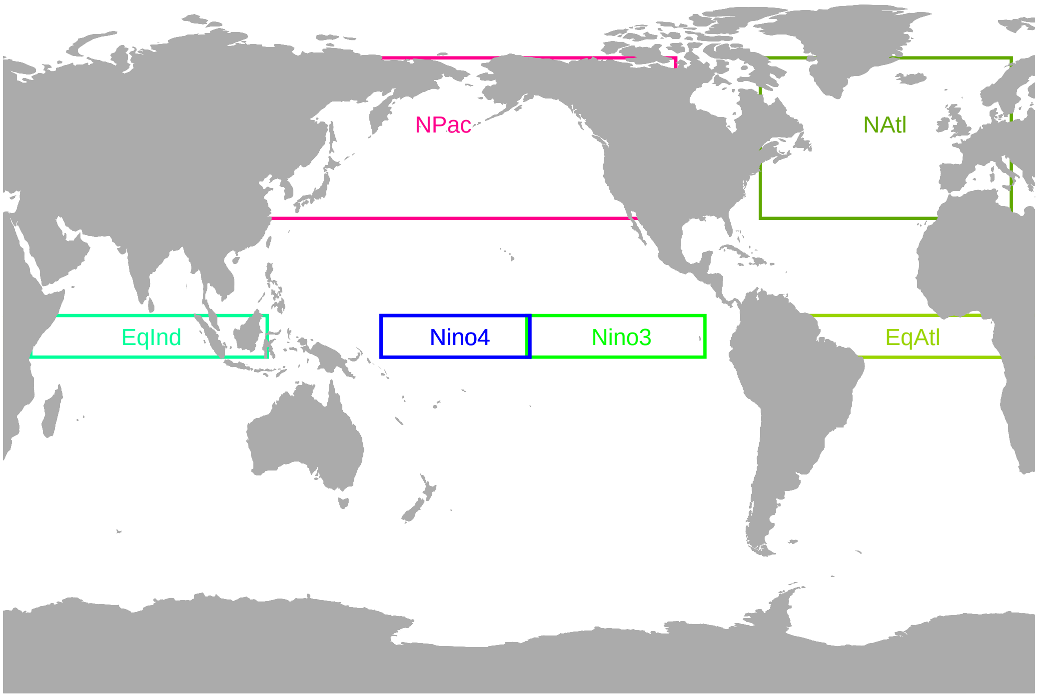


Figure 3: The regions used in this paper.

3 Assimilation strategy and experimental set-up

The assimilation system used in this work is a low resolution version of that used at ECMWF to provide ocean initial conditions for the seasonal forecast system SYSTEM2 (Anderson et al 2003, Balmaseda 2003, Vialard et al 2004); the background state for ocean data assimilation is provided by the HOPE ocean model (Wolff et al, 1997) forced by daily atmospheric fluxes of momentum, heat and fresh water. The fluxes are derived from the ERA15 atmospheric reanalysis for the years before 1994 and from the ECMWF operational system thereafter. The ocean model used here has a horizontal resolution equivalent to 2 x 2 degrees (latitude/longitude), although at the equator the meridional resolution is finer (0.5 degrees). The model has 20 levels in the vertical, 8 of which are in the upper 200m.

The temperatures are assimilated through a relatively simple univariate Optimum Interpolation scheme based on the work of Smith et al. (1995), and described in Alves et al 2004. For the system used here (SYSTEM2), the decorrelation scales were revised relative to those used in Alves et al, salinity is adjusted to conserve water mass properties (Troccoli and Haines 1999) 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 Global Temperature-Salinity Profile Program (hereafter GTSPP, http://www.nodc.noaa.gov/GTSPP/gtspp-home.html).

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, experiment MA- where no XBT data are used and experiment -AX where no mooring (TAO/TRITON/PIRATA) data are used. The experiments span the period from the 1st of January 1993 to the 31st of December 2003. Three additional experiments have been performed for the period from the 1st of January 2002 to the 31st of December 2003 mimicking the previous set but with an additional experiment M-Xs where no Argo data are used. A subscript $_s$ is used to indicate the short extent of these experiments. They can be compared with the standard experiment MAX over the common time period since they start from the MAX analysis in January 2002.

All experiments include a strong relaxation to observed SST, the time-scale being three days. We use the OIv2 SST-analyses provided by NCEP in all ocean analyses to constrain the model SST to be close to the analysed values (Reynolds *et al* 2003). This is exactly the same SST product and time-scales as used in the ECMWF operational ocean analysis system which provides ocean initial conditions for seasonal forecasts. 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 (WOA) 1998 (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 time interval as MAX and will be denoted CTL (starting with MAX initial condition for 1/1/1993) and the second will be denoted CTL_s and spans the period 1/1/2002-31/12/1003 (starting with MAX initial condition for 1/1/2002).

Experiment	Moorings	ARGO	XBT	Date
CTL	N	N	N	1/1/1993-31/12/2003
MAX	Y	Y	Y	1/1/1993-31/12/2003
-AX	N	Y	Y	1/1/1993-31/12/2003
MA-	Y	Y	N	1/1/1993-31/12/2003
CTL_s	N	N	N	1/1/2002-31/12/2003
-AX_s	N	Y	Y	1/1/2002-31/12/2003
MA-_s	Y	Y	N	1/1/2002-31/12/2003
M-X_s	Y	N	Y	1/1/2002-31/12/2003
M- -_s	Y	N	N	1/1/2002-31/12/2003
-A-_s	N	Y	N	1/1/2002-31/12/2003

Table 1: Summary of experiments showing the different observing systems used.

4 Results for the period Jan. 1993 to Dec. 2003.

4.1 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 300m of a global section along the equator, and differences of the time-mean average temperature of the upper 300m (T300), 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 years, 01/01/1993 - 31/12/2003. 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 including the XBT data is a cooling of up to 0.9K in the Atlantic. The impact in the equatorial Pacific

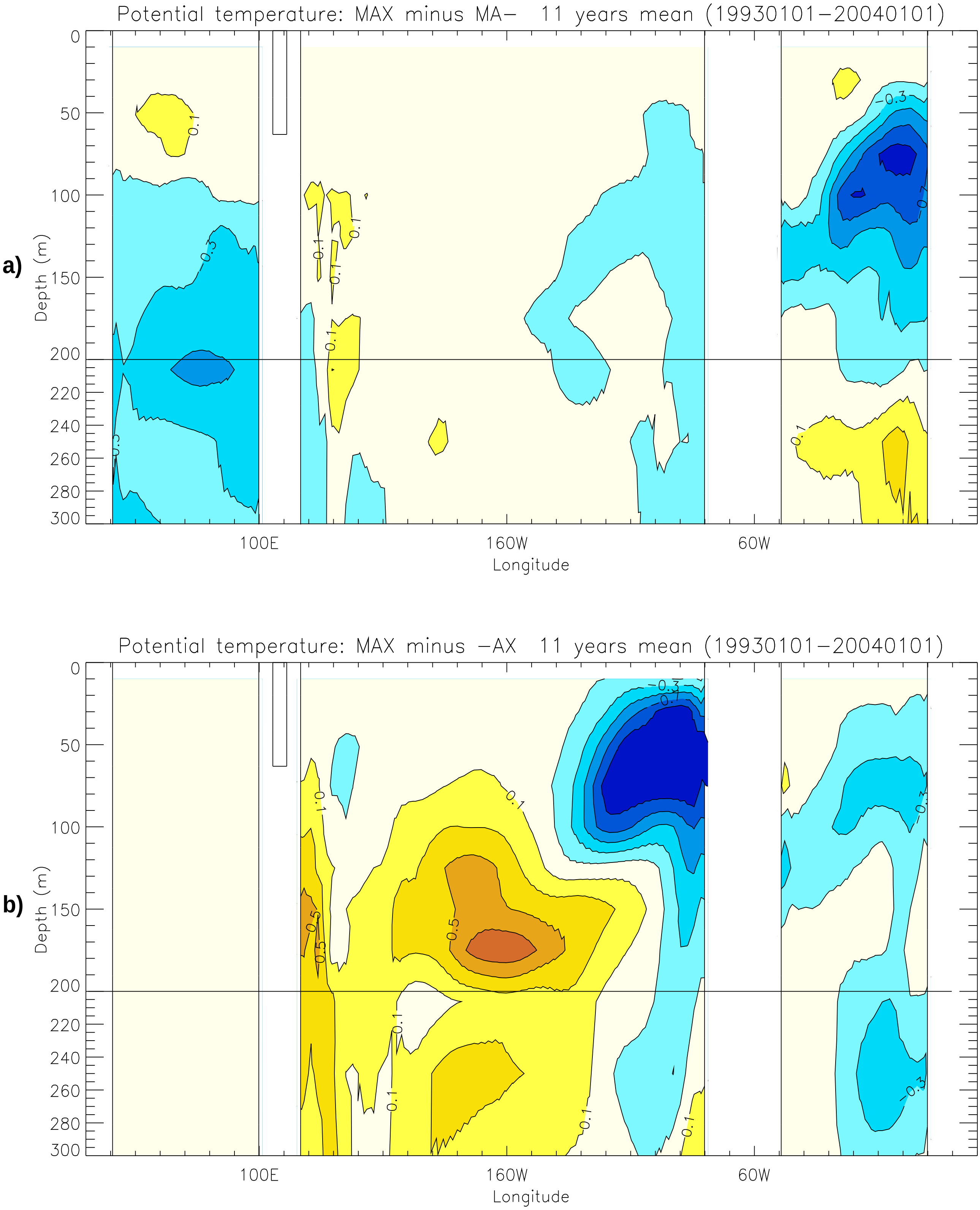


Figure 4: Impact of observation systems on time averaged temperature for a section along the equator for a) the VOS XBT-network, and b) the TAO network. The impact is shown by computing the difference between the ocean analysis using all data and the ocean analysis in which the respective data are withheld from the assimilation. Contour interval is 0.2K

is small, only about 0.1K at its maximum in a small region in the west Pacific at 200m. In the equatorial Indian ocean the impact of XBTs is smaller than in the Atlantic but larger than in the Pacific.

Fig. 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. In contrast they create a cooling of up to 1.4K 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 200m.

In the Pacific, the small impact from XBTs compared to that of moorings may imply that there is substantial redundancy between the XBT and the TAO/TRITON observing systems, at least in terms of defining the mean state. (We will consider variability later). In the presence of TAO/TRITON, it would appear that XBTs could comfortably be withdrawn from the equatorial Pacific but this will be discussed later. 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 v PIRATA is not easily determined from figure 4 as PIRATA was only implemented towards the end of the period (see section 5 for results focused on the 2002-2003 period). There is little impact of moorings in the Indian ocean since 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 2003 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 2004). Adequate treatment of bias may be required in these cases (Bell et al 2004).

We now turn to the mean values of temperature over the upper 300m. Figs.5a and b show horizontal maps of the differences a) between experiment MAX and MA-, and b) between experiment MAX and -AX. Panel a) 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 1K 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, which can not be well represented, given the model resolution. In the Indian Ocean the XBT data cause a general cooling of over 0.6K, mainly concentrated along the path of the Indonesian throughflow. In the equatorial Atlantic the mean effect of XBT data is a cooling within 10 degrees 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 (40N-50N), the impact of XBT data is quite large in the vicinity of the Gulf Stream. As for the Kuroshio, the data can act to correct the path of the Gulf Stream. Much higher resolution than 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

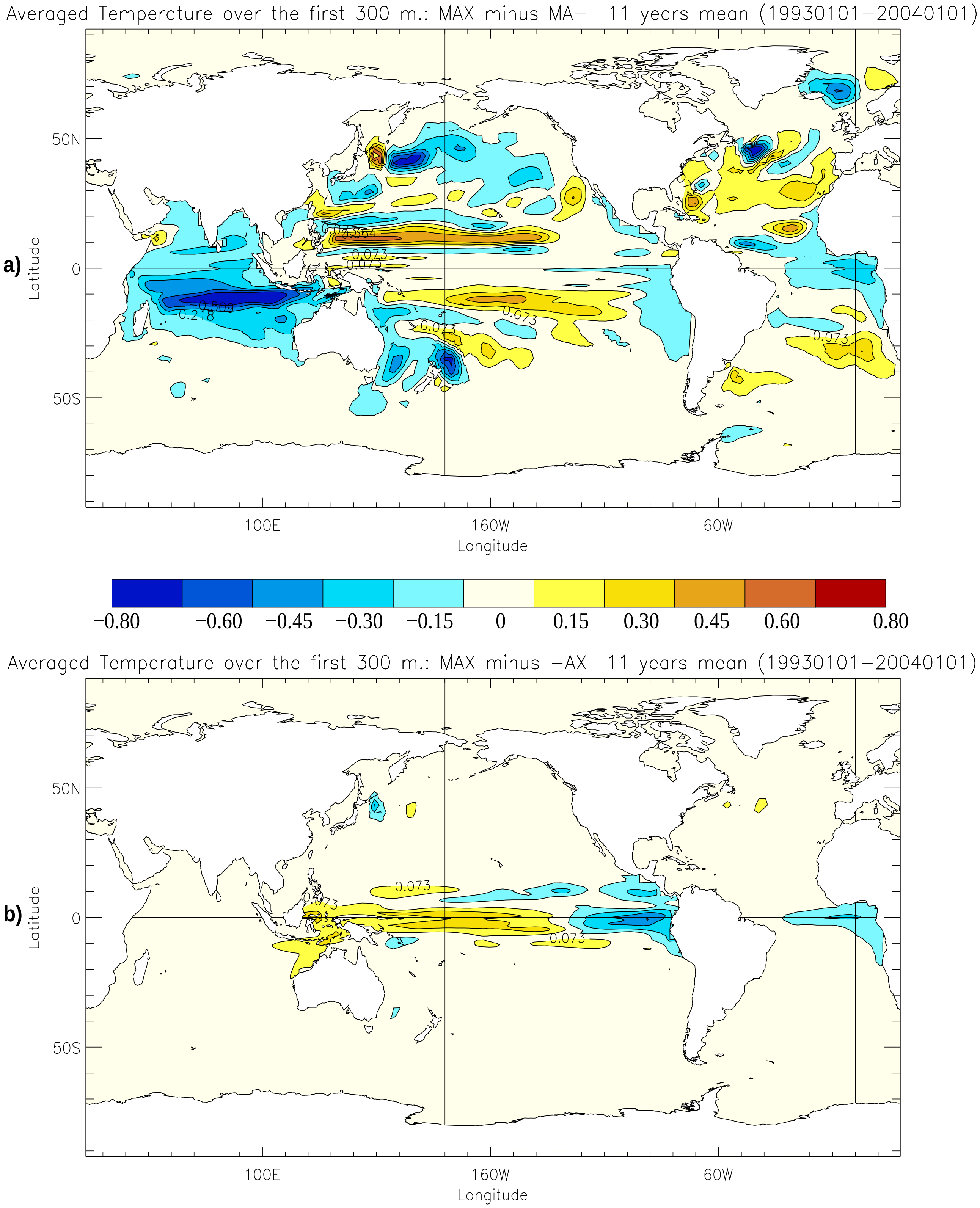


Figure 5: Impact of observation systems on time-averaged upper 300m heat content for a) the VOS XBT-network, and b) the TAO network. The impact is shown by computing the difference between the ocean analysis using all data and the ocean analysis in which the respective data are withheld from the assimilation. Contour interval is 0.15K.

array was first deployed in late 1997 and therefore comparing the mean impact on the period 1993-2003 with that from TAO or XBT will under-represent 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 4). An alternative is to look at the temporal evolution of some quantity in the different experiments, as will be done in the next section.

4.2 Temporal variability

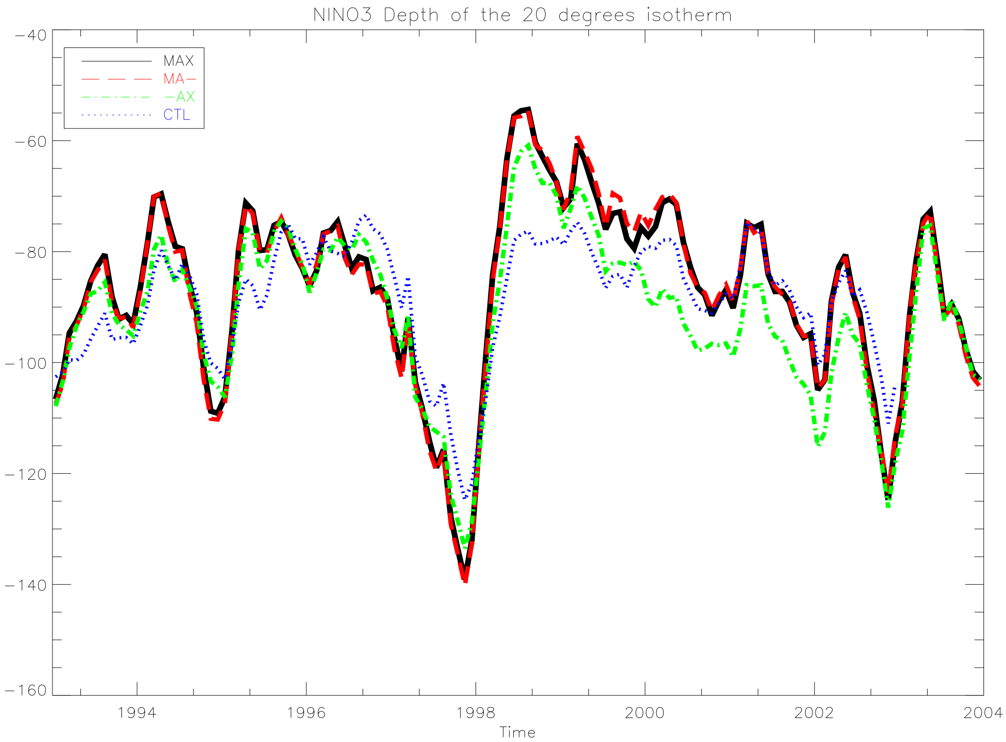
Fig 5 shows the mean impact of components of the observing system but gives no information on the temporal behaviour. However, time series such as that of the depth of the 20 degree-isotherm (D20) in selected regions, are shown in Fig. 6 and 7. Fig. 6 indicates that in Niño3 the strong cooling observed in figs 4b and 5b is not present throughout the analysis period but in fact develops after the 1997 El Niño (compare MAX and -AX curves). Without TAO data, D20 is too deep by some $\sim 10-20m$. This post-ENSO effect is not present in the Niño4 region, however, where TAO has an impact throughout the analysis period. Typical amplitudes of impact in Niño4 are $\sim 5-10m$. There is a clear post-ENSO effect in Niño4 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 cold era in both regions. The impact of XBT is smaller than that of TAO throughout.

In the Equatorial Atlantic (5S-5N), fig 7 shows that there are substantial differences between the pre- and post-PIRATA periods (before and after 1998). Pre-1998, MAX and -AX are essentially the same since there are no moorings data and CTL and MA- are also the same since 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 differences between MAX and -AX are typically 2-3 m though occasionally can reach 5m. 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 assimilation and the no-assimilation case (*i.e.* between MAX and CTL) is typically 15-20m. 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 sometimes acts not just to correct a mean bias but also influences the variability. Apparently PIRATA and XBT often disagree in this region for instance during the period 1998-2002 when MA- is mainly above MAX and -AX mainly below. However this is mostly an artefact of the area averaged as will be shown in section 4.4.

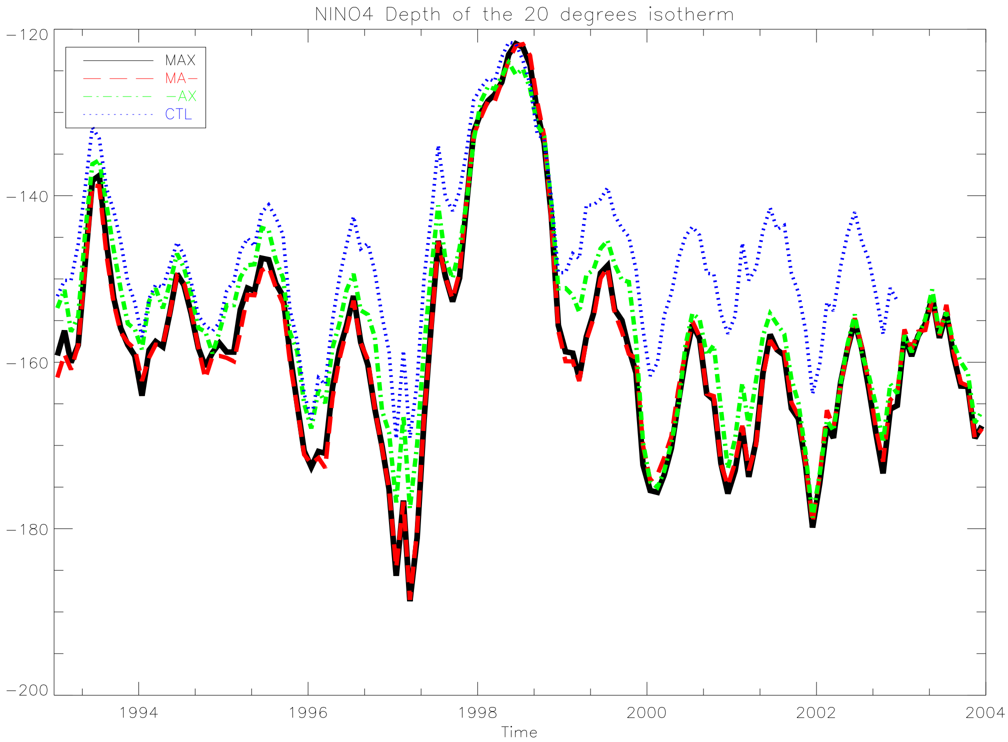
For the 1993-2003 period, the Indian ocean (fig 7b) is almost entirely observed through XBTs, and therefore there is no impact from moorings in the equatorial Indian ocean. (There is some influence on the Indonesian Throughflow but that is from moorings in the west Pacific). There are now a few TAO/TRITON 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 the moorings but we will look at the impact of ARGO floats in a later section.

4.3 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 T with CTD data and S with all available salinity observations and compare 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 ENACT data set (Ingleby and Huddleston 2004) 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 as 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

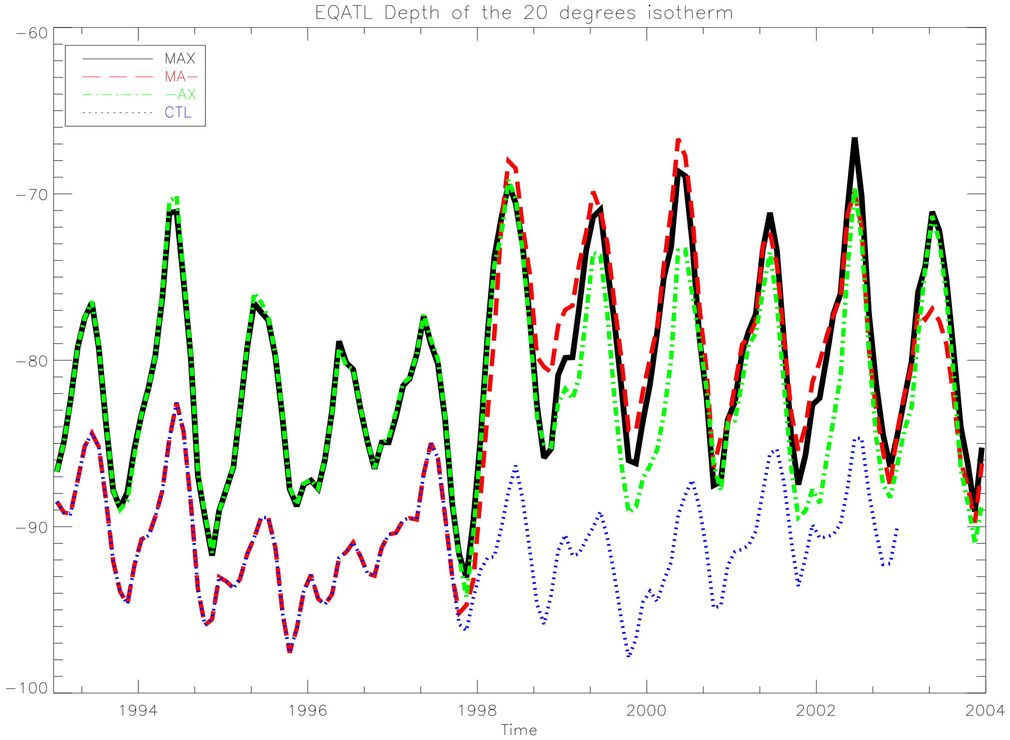


a)

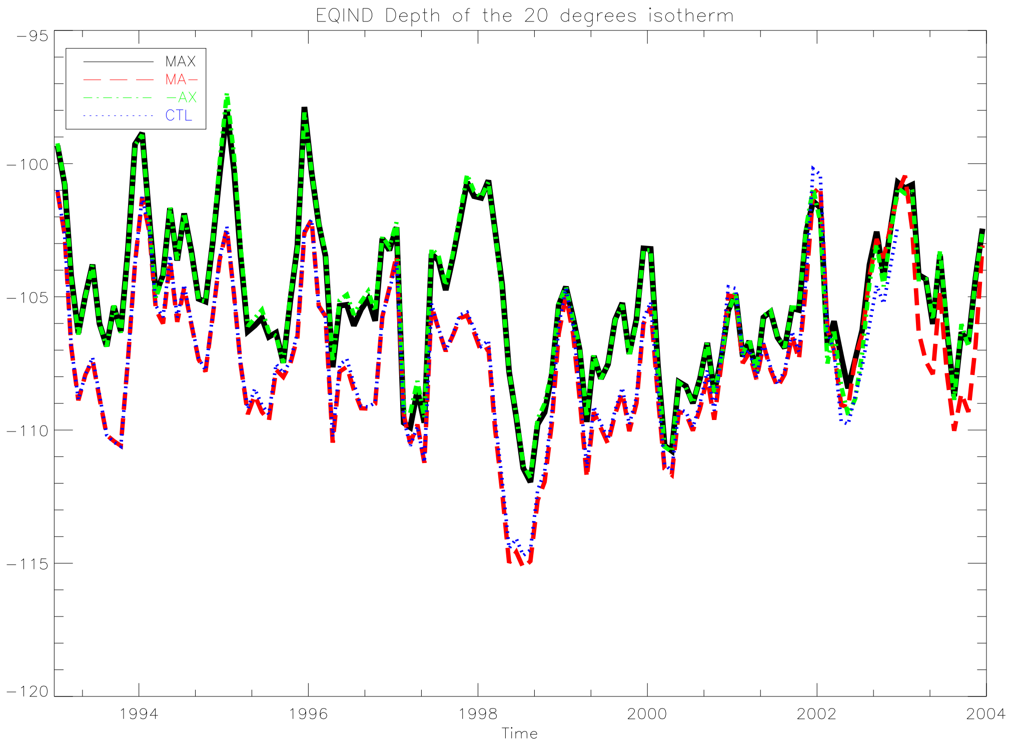


b)

Figure 6: Time series of area-averaged depth of the 20º C isotherm for a) the Niño-3 region and b) the Niño-4 region. In experiment MAX (plain curve) mooring and XBT data are assimilated, whereas in experiment -AX (dot-dashed) the mooring data are withheld from the assimilation, and in experiment MA- (dashed) the XBT data are withheld from the assimilation. ARGO data, when available are used in all experiments. The CTL experiment with no data assimilation is shown in dotted.



a)



b)

Figure 7: As for previous figure but for the equatorial Atlantic, EqAtl (a) and equatorial Indian regions, EqInd (b).

tested but is not used in these experiments (Haines et al 2005). 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 modelled salinity against the independent observations allows some assessment of the performance of this approach. Others have tried different approaches e.g. Vossepol et al 2001, Maes and Behringer 2000. In these cases an attempt is being made to perform a multi-variate analysis, but one should not expect to be able to fully correct salinity without using any salinity observations.

4.3.1 Comparison with temperature from CTDs

Conductivity-Temperature-Depth (CTD) instruments measure three important parameters directly - conductivity (hence salinity), temperature and pressure. Accuracy of the salinity measurement is generally better than 0.005 psu for a standard CTD profiler. A CTD instrument usually uses a thermistor, a platinum thermometer, or a combination of these to measure the temperature of the water to an accuracy of greater than 0.005K (sampling errors are likely to be larger than this).

In fig 8 six regions are compared: Niño3, Niño4, EqInd, EqAtl, NAtl and NPac. Fig 8 shows the profiles (from the surface down to 1000m) of RMS differences between the various experiments and the temperature as measured by CTD devices for the period from 1993 to 2003 at the location of the observations in the chosen regions. In all these areas, the assimilation improves the fit of temperature to the independent CTD data. In the upper ocean of regions Niño3, Niño4, and EqAtl, most of the improvement comes from the assimilation of mooring data and in EqInd, NAtl and NPac the main contributor is the XBT Network. In EqAtl, the assimilation without moorings degrades the fit to CTD at about 250m compared to the control, further illustrating the importance of the moorings in that area.

Argo temperature data are assimilated as well and may have an impact on these diagnostics. In NAtl for instance, since 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 be coming 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. Apart from the Niño3 and Niño4 regions, most of the CTD temperature measurements take place at the end of the period. This may explain why the impact from PIRATA is noticeable even if they were not present at the beginning of the period.

4.3.2 Comparison with salinity observations

Fig 9 shows the profiles from the surface to 300m of the RMS differences between the experiments and the salinity data from CTD and Argo measurements. In the Niño3 region, both XBT and mooring temperature measurements help to improve salinity (XBTs in the lower part, moorings in the upper part). In Niño4, 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 has been decided not to apply it in the top 50m. However in region such as Niño4 where the mixed layer extends deeper this exclusion zone may be inadequate.

In EqAtl, the salinity of the upper 200m is significantly improved by the assimilation of temperature. Here, however, the temperatures from the PIRATA array do not seem to have a significant effect on salinity (MAX

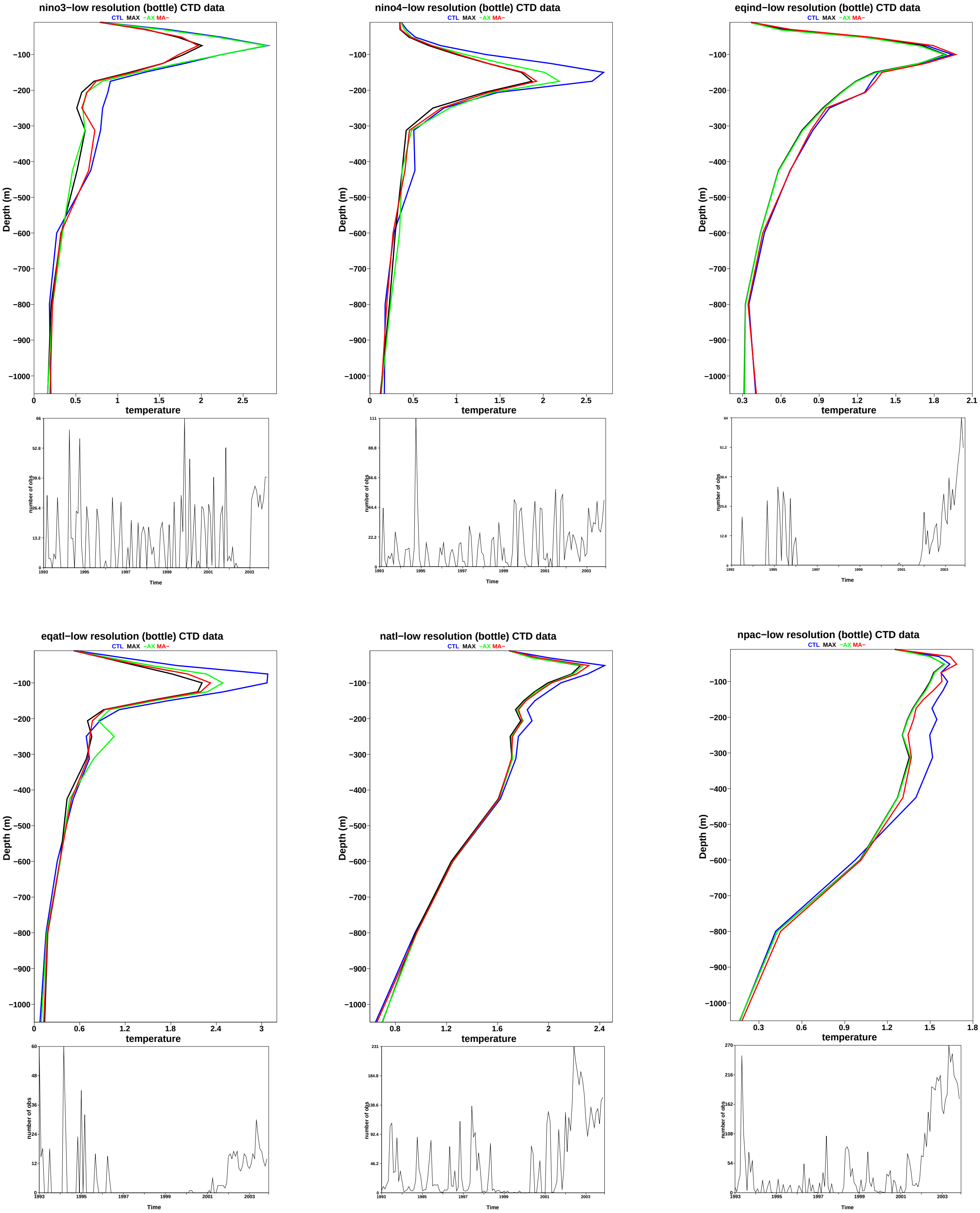


Figure 8: Profiles of RMS differences from CTD temperature data for the six regions Niño3, Niño4, equatorial indian (EqInd), equatorial Atlantic (EqAtl), North Atlantic (NAtl) and North Pacific (NPac). The second panel shows the number of observation in the given region.

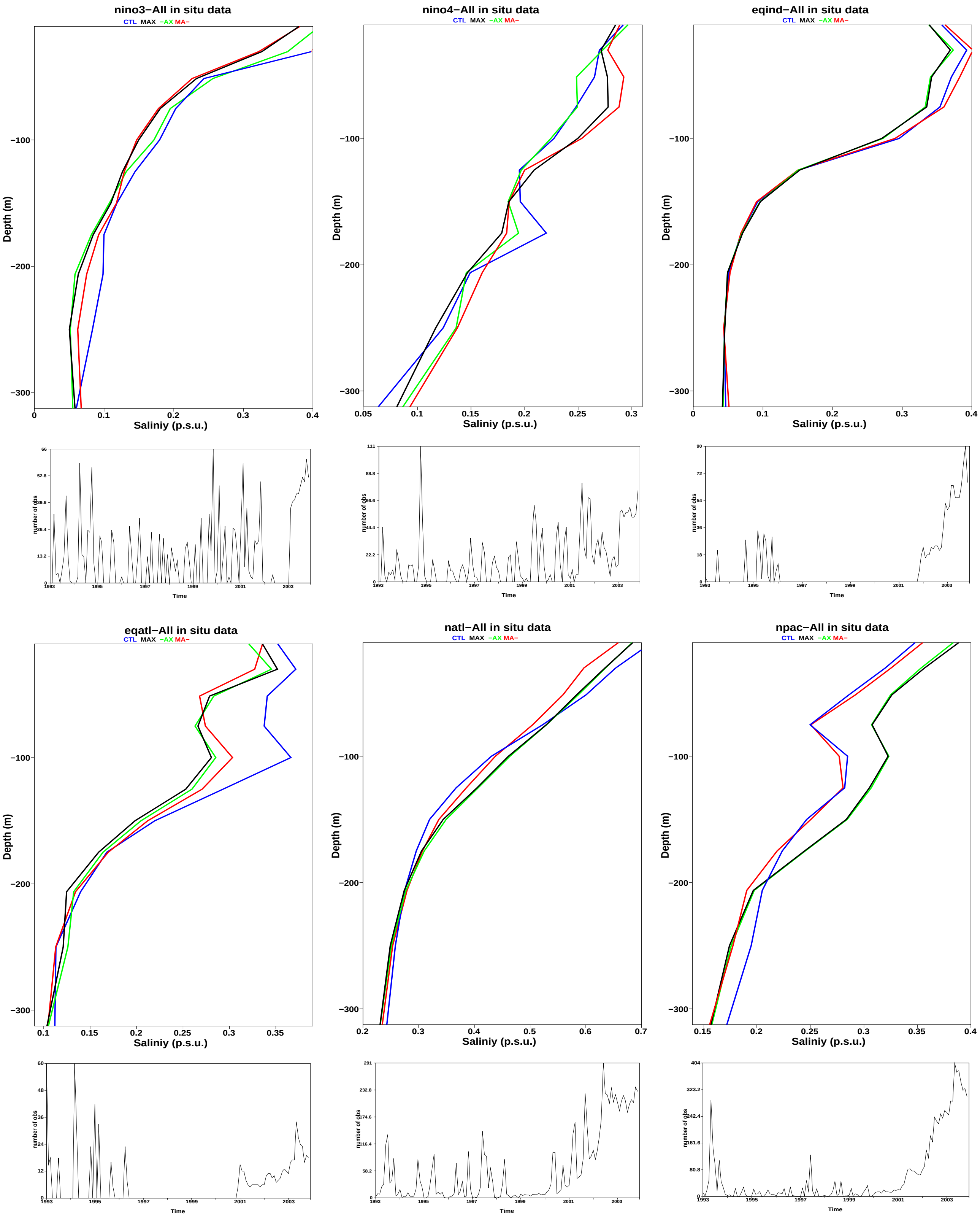


Figure 9: Profiles of RMS differences salinity data from ARGO and CTD for the six regions Niño3, Niño4, equatorial indian (EqInd), equatorial Atlantic (EqAtl), North Atlantic (NAtl) and North Pacific (NPac). The second panel shows the number of observation in the given region.

and -AX are close to each other).

In higher latitude the salinity correction from S(T) is reduced linearly to 0 from 30^o to 60^o and therefore the potential to correct salinity is much reduced. This explains why the impact of assimilation of T on salinity is pretty neutral in NAtl and significantly damaging in NPac.

The vertical scale for salinity extends to 300m as only salinity data to this depth were archived, whereas for temperature it extends to 1000m. It is expected that the RMS error in salinity would decrease at depths greater than 300m in much the same way as for temperature, but this can not be confirmed.

4.3.3 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 SSALTO/DUACS as part of the Environment and climate European ENACT project (EVK2-CT2001-00117) and distributed by AVISO with support from CNES. These are monthly mean maps coming from the delayed-mode high-quality merged satellite product from CLS, denoted HH (Historical Homogeneous) (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 60N. This data set was only available from Jan 1993 to May 2003. First we calculated the correlation of the various analyses with the CLS HH monthly-mean fields. As the altimetry provides only anomalies relative to the 7 year mean 1/1/1993-31/12/1999, 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, typical differences being a few centimetres. However, as we have no satellite equivalent we will not assess these mean states but concentrate on the anomalies.

Fig. 10 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 degrees of the equator) is more modest, since the correlation is already high (comparison of MAX and MA-)[1] . The effect of XBTs is more noticeable in the Pacific ocean poleward of 10 degrees: the area with correlation above 0.5 is consistently greater in panel b than in panel c. In the Atlantic, the assimilation of XBT in the presence of moorings significantly and consistently improves the sea level (compare MAX/panel b and MA-/panel c) whereas the impact from PIRATA is much less clear (compare MAX/panel b and -AX/panel d). In fact the assimilation of moorings without XBTs (panel c) seems to degrade the correlation with respect to CTL (panel a). This is consistent with Segschneider et al. 2000 who reported the occurrence of spurious signals in the model sea level following the introduction of PIRATA in 1998. It is also consistent with figure 7 which showed 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 (panel b and c).

[1] The effect of XBTs in the absence of the TAO/TRITON array is larger, as could be inferred by comparing CTL and -AX (since the effect of ARGO during the long period is negligible)

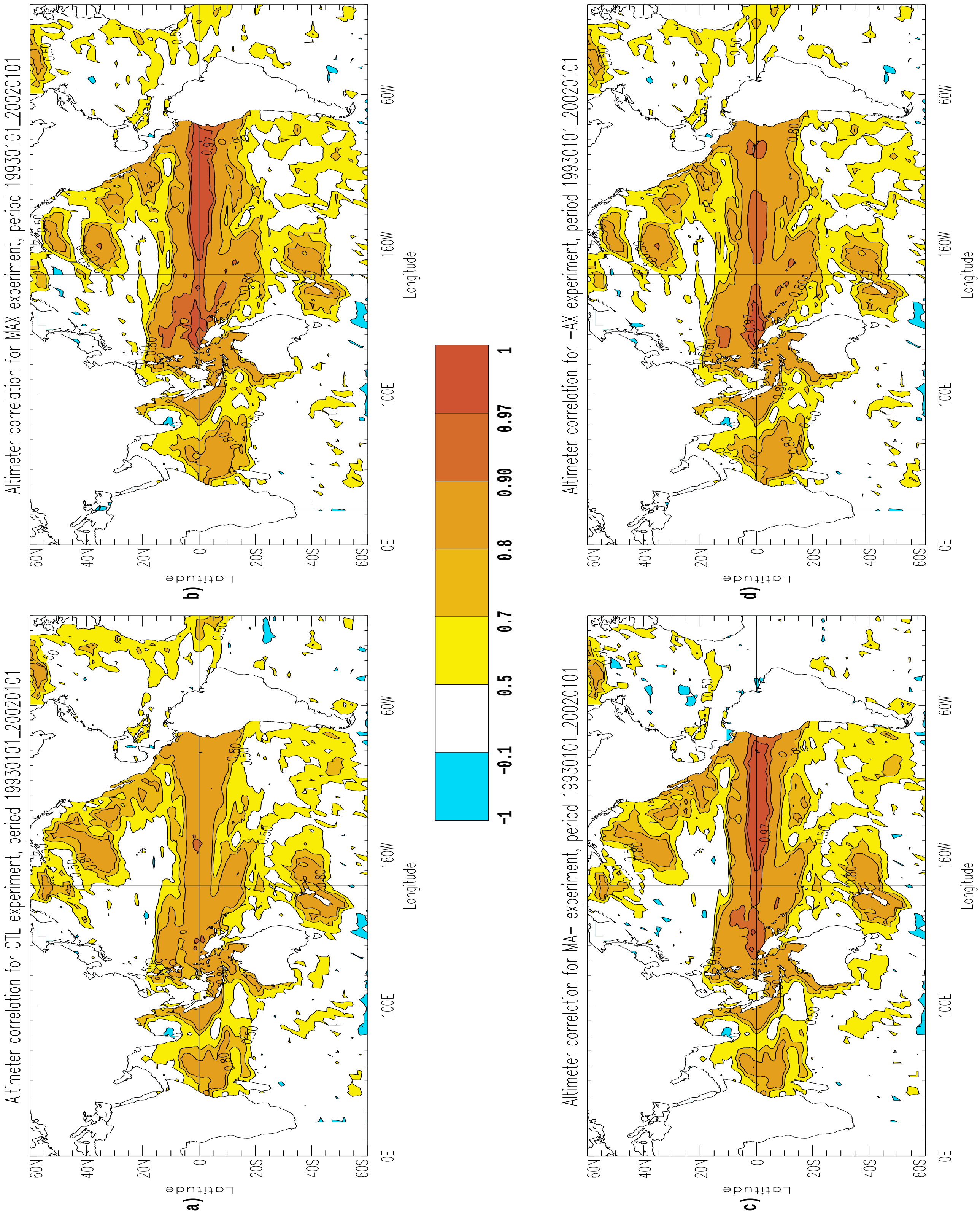


Figure 10: Correlation with altimeter SLA for experiments CTL (a) MAX (b), MA- (c) and -AX (d) for the period from January 1993 to May 2003.

4.4 Development of the Argo system

A more recent change in the observing system has been the spin-up of the ARGO float network. It has been proposed as a major contribution to the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS). It is expected that Argo will provide significant benefits for seasonal forecasting, climate prediction and operational oceanography. The float technology was demonstrated during WOCE (World Ocean Circulation Experiment) and shown to offer a viable alternative means of making near-real-time ocean measurements at a reasonable cost.

The ARGO deployment started in 1998 but the number of active floats before 2002 was relatively small. In order 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 two-year period 01/01/2002-31/12/2003. 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 period as ARGO and are indicated with a subscript $_s$ in table 1. All experiments start from the MAX analysis in Jan 2002 and can therefore be compared with MAX.

The impact of the mooring and ARGO data during this reduced period can be seen in figure 11 (upper and lower panels respectively), that shows equatorial cross-sections of the mean temperature differences in the upper 300m. The upper panel shows that the impact of PIRATA in the Atlantic is comparable to the impact of TAO/TRITON in the Pacific, suggesting that the weaker impact observed during the longer period 1993-2003 (lower panel of figure 4) was a consequence of the long averaging period. Another difference between the two periods is the west Pacific, where the moorings are linked to a cooling during the short period, as opposed to the warming shown for the longer period (fig 4). The difference could be due to a change in systematic error. It can also be an indication of the presence of the additional TRITON measurements in a region that was not covered before by the TAO moorings. Or it can reflect that our system gives too much weight to the hourly reports of the TRITON moorings. Comparison with an experiment where the TRITON data are daily-averaged shows that this may be the case. The relative importance of XBT data in this region has declined (not shown).

The lower panel of figure 11 shows that in the presence of other data, the impact of ARGO in the equatorial temperature field is small. 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 13 shows the time series of the global number of observation entering into 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. One can also see that for recent dates Argo has become the main contributor to ocean in situ observations in term of numbers.

To see if the small impact of ARGO is just an equatorial problem or if it is true more generally, we plot global maps of heat content. A global view of the impact of ARGO on heat content is shown in fig 12 (lower panel), and for XBTs in the upper panel. 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 300m. At higher latitudes (40N-50N), the impact of XBT data is large especially north of the Gulf Stream and in the Kuroshio, two boundary currents that can not be well represented in the model given its coarse resolution. In the Indian ocean, the assimilation of XBTs 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

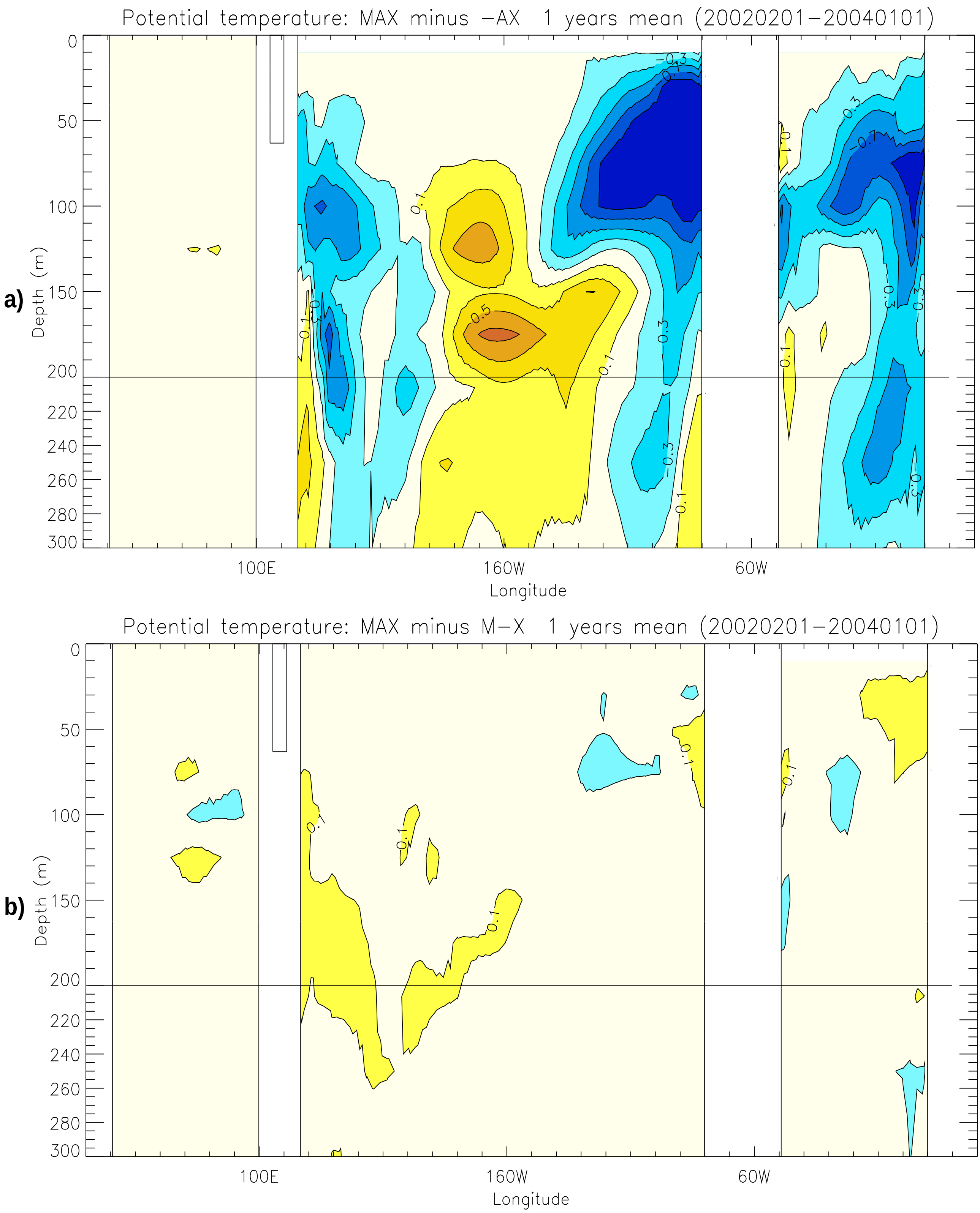


Figure 11: Impact of observation systems on time averaged temperature for a section along the equator for the TAO network (top), and the ARGO network (bottom). The impact is shown by computing the difference between the ocean analysis using all data and the ocean analysis in which the respective data are withheld from the assimilation. Contour interval is 0.2K

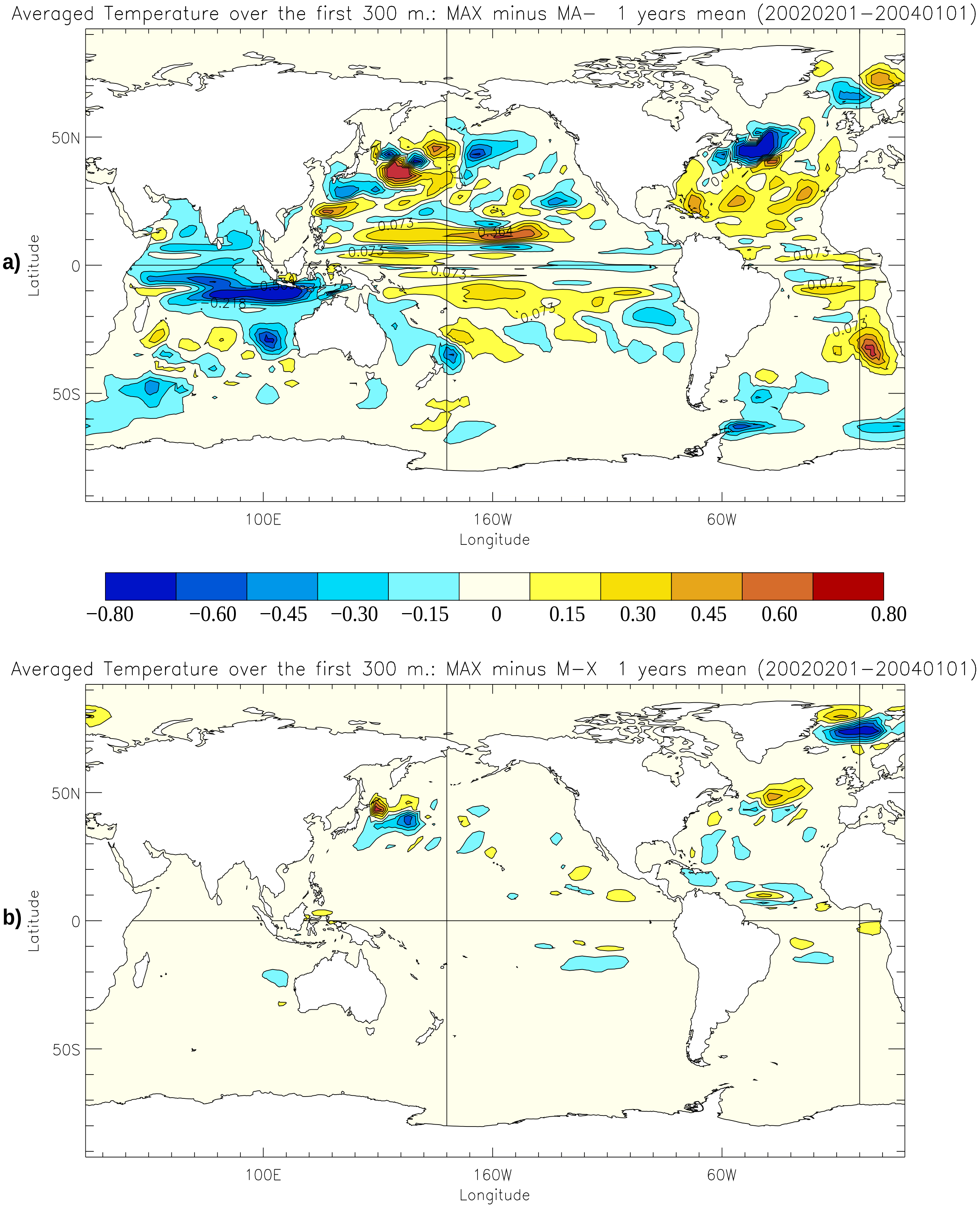


Figure 12: Impact of observation systems on time-averaged upper 300m heat content for the VOS XBT-network (top), and the ARGO network (bottom). The impact is shown by computing the difference between the ocean analysis using all data and the ocean analysis in which the respective data are withheld from the assimilation. Contour interval is 0.15

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 figure 1 show the persistent presence of XBT lines in the neighbourhood 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 is the case, an isopycnal formulation of the background covariance matrix would be beneficial.

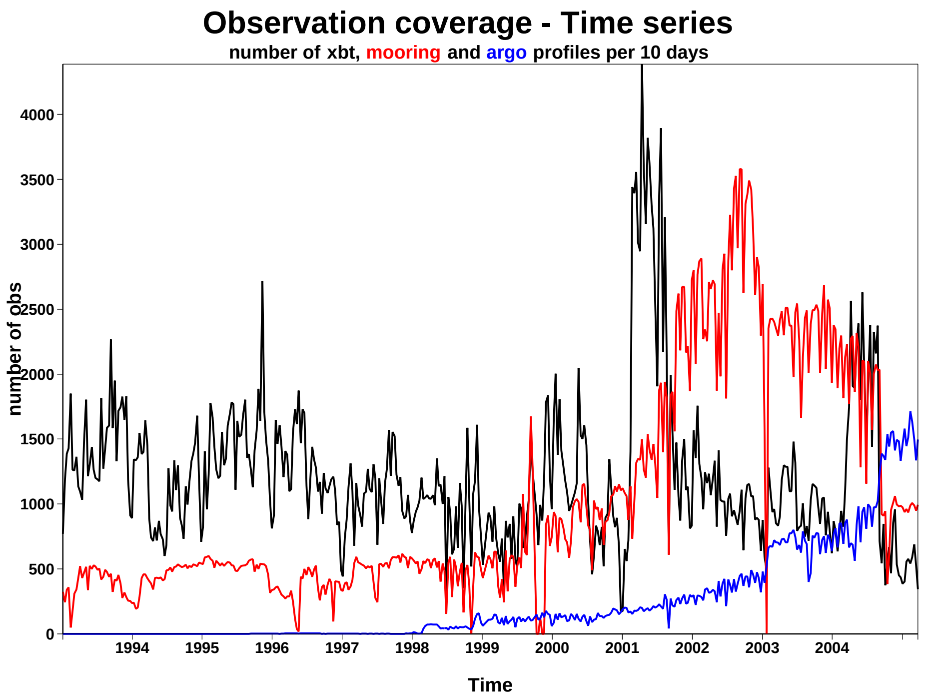


Figure 13: Number of observation used in the operational ECMWF ocean analysis for the XBTs (black), Moorings(red) and Argo floats (blue) from 1993 to the beginning of 2005.

The previous results are not an entirely fair way to measure the impact of Argo as the network is still building up and has significantly increased in size during the years 2002 to 2004 (see fig13). 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 assimilation of salinity data on temperature surfaces (Haines et al 2005).

Due to their respective spatial and time coverage the XBT and ARGO floats will have very different impact, and probably their error characteristics should 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 favour observations that are dense in time and space, and will bias the results towards the XBT data. To have an idea of the impact of ARGO in the opposite scenario, we could conduct experiments where the XBT data is given zero weight. Such experiments can be justified, since there is no guarantee that the XBT network will be maintained. If the XBT network were discontinued, is Argo a suitable replacement? To assess that, two additional experiments have been performed without XBT data at all : M- -$_s$ and -A-$_s$ and compared with MA-$_s$. The two experiments cover the same 2 years (2002-2003) and have the same initial conditions as experiments -AX$_s$ and MA-$_s$ described above. All these experiments start from MAX analysis of 1/1/2002 and so can be compared with MAX.

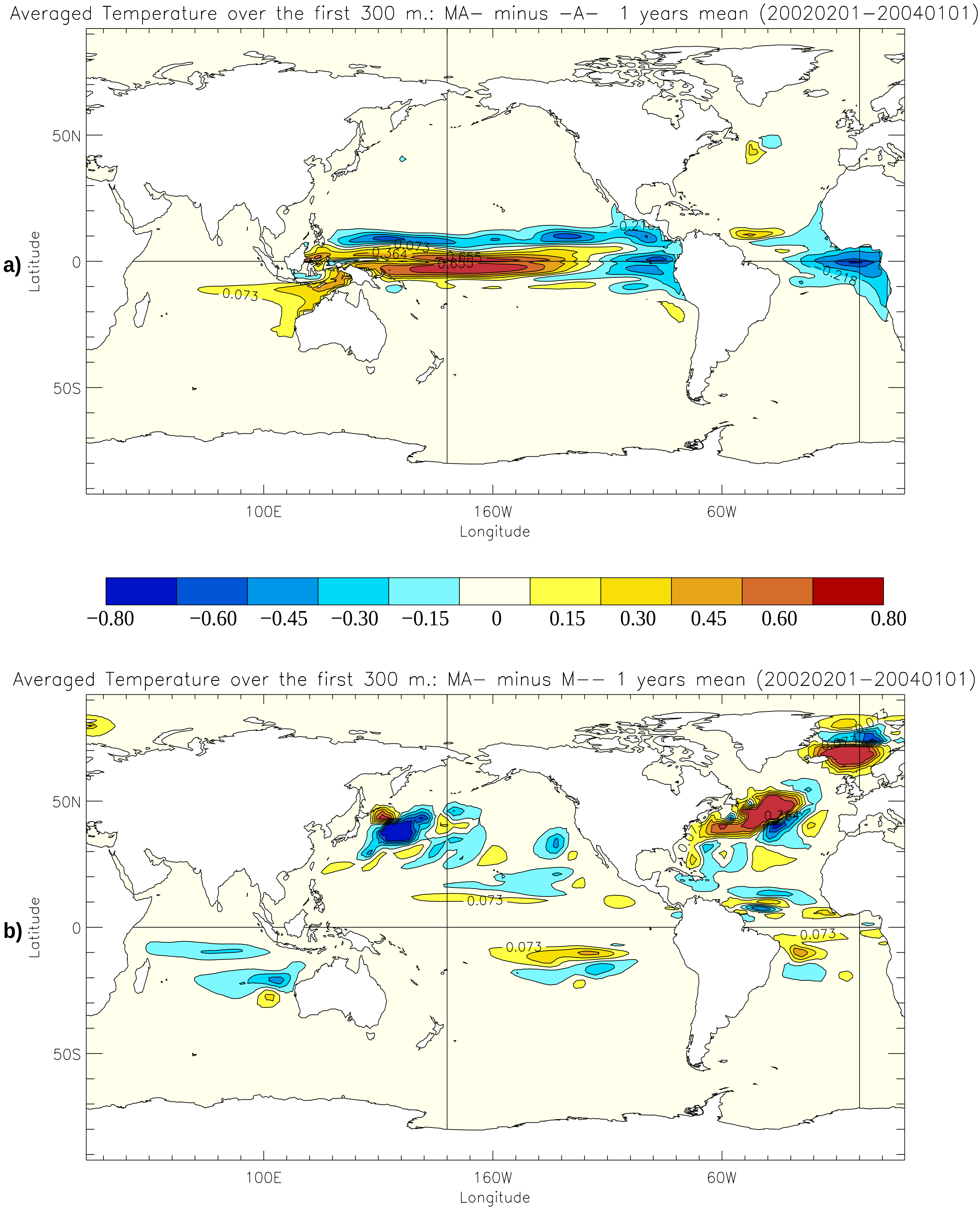


Figure 14: Impact of observation systems on time-averaged upper 300m heat content in the absence of the VOS XBT-network for the TAO network(top), and the ARGO network (bottom). The impact is shown by computing the difference between the ocean analysis using all data and the ocean analysis in which the respective data are withheld from the assimilation. Contour interval is 0.15K

Fig. 14 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 sub-tropical Atlantic (the PIRATA array spans 10S-15N) 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 figure 7. The upper panel of figure 7 also showed a disagreement between the impact of XBT and PIRATA data in the EqAtl region, as discussed in section 4.2. By inspection of the spatial maps (upper panels of figures 12 and 14) one can see that the disagreement is only apparent: the effect is indeed of 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, where the model has some instabilities. The impact of the TAO/TRITON-array is naturally mainly restricted to the Pacific, within 15 degrees 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 14a) 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 Atlantic oceans

In the absence of XBT, the impact of Argo is of importance and even as strong in intensity, if not in spatial coverage, as that of XBT (fig 14b). This does not mean that their respective impacts are equivalent since the impact of XBTs is large even in the presence of Argo floats. One of the reasons why fig. 12b shows such a small impact might be that XBTs outnumber the Argo floats.

One can notice in fig. 14b some cooling-warming oscillations between 0 and 10N in the Atlantic at about 40W. This feature can be seen but with lower amplitude in Fig 14a, Fig 12b and is present in MAX minus -AX$_s$ (not shown). It is close to the location of four PIRATA moorings (38W / 4N, 8N, 11.5N and 15N). To have a closer look at the origin of this small scale cold-warm dipole, fig. 15 shows meridional cross sections of the three experiments CTL$_s$ (a), MAX (b) and M- -$_s$ (c) spanning 0-50N at 38W, the four North Tropical Atlantic PIRATA positions being marked as vertical thick black lines. The changes to the 11 degree-isotherm between the 2 moorings at 8N and 11.5N can be taken as an illustration of the small scales of the features we want to correct for. Compared to the control (top) the effect of assimilation (bottom) is to shift the top of the isotherm southward. At mooring locations this is translated into a shallowing of the isotherm at 8N and a deepening at 11.5N. Indeed, that is exactly what M- -$_s$ tends to do at both locations but it keeps the 'summit' of the isotherm in between. This leads to an increase of the topography of the isotherm. Additional information is needed to do the proper correction and may be provided by Argo floats (MA-$_s$ (not shown) and MAX are pretty similar in this area). This lack of nformation 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 (aliasing). In our system, only the second point is addressed, by superobbing 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). The XBTs are dense in space and time but only along a given track; they provide a 'slice' of the ocean thermal field.

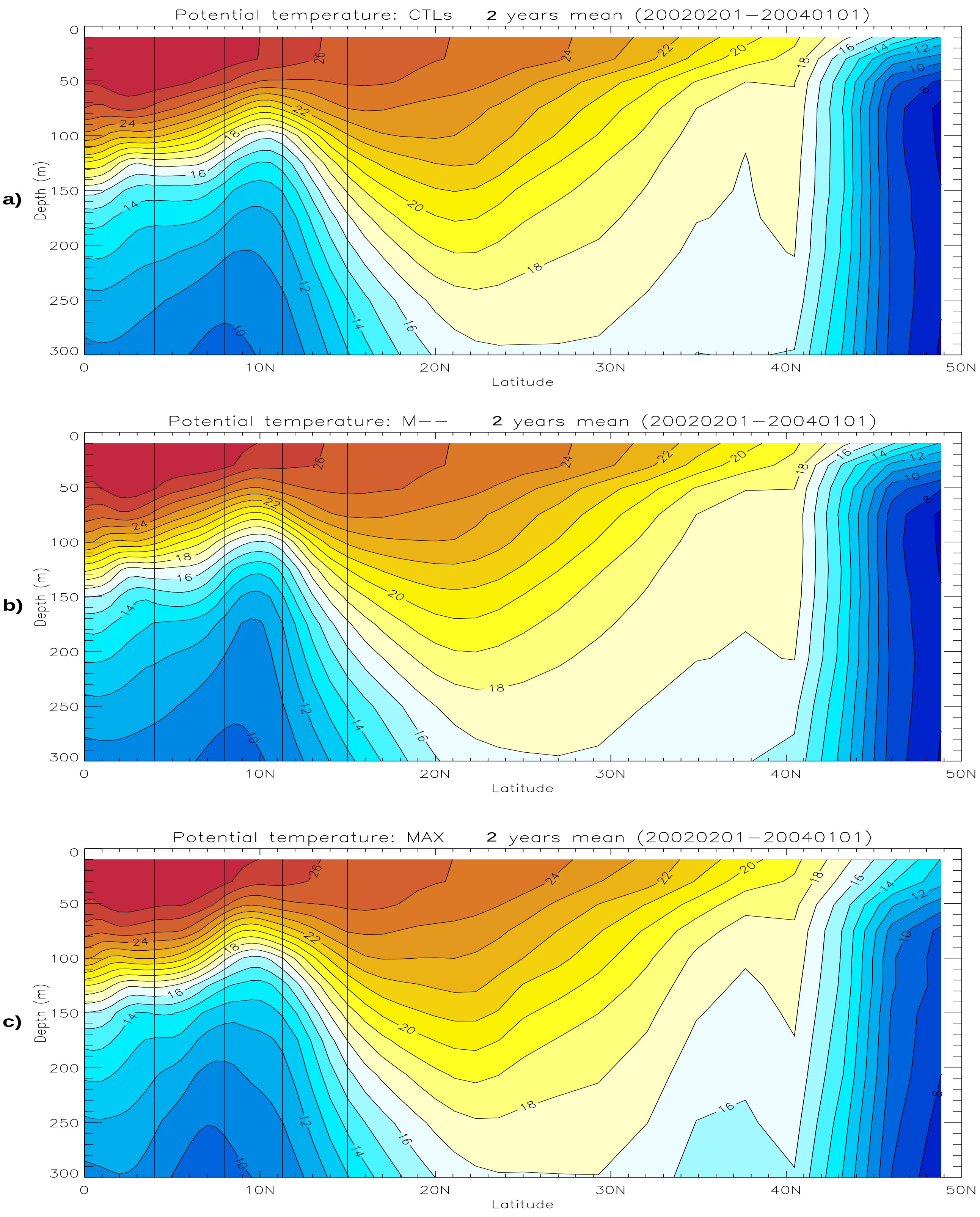


Figure 15: Cross section of the temperature field at 38W for the three experiments (a) CTL$_s$ (b) M- -$_s$ and (c) MAX. The thick vertical lines represent the PIRATA locations.

5 Impact on coupled forecasts

In order 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, initialised from the ocean analyses described previously. The coupled forecasts are started on the 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 5-member ensemble. This strategy for generating an ensemble is discussed fully in Vialard et al 2005. The coupled model employed is the HOPE ocean model as used above, coupled to the same version of the atmospheric model (IFS, Cy24r1) as is used in the operational ECMWF seasonal forecast system.

To evaluate the impact of the OSEs on coupled forecasts, results for several area-averaged SST forecast anomalies (SSTAs) are considered. Fig. 16 shows the RMS-error for the SSTA forecasts started from experiments MAX, -AX, and MA-. For the Niño-3 area the RMS-error (Fig. 16a) is about the same for MAX (black) and MA- (red), but when the mooring data are excluded from the ocean analysis (experiment -AX, green curve) the skill is reduced, especially in the first two months. All forecasts, however, are more skillful than persistence for all lead times. These results show that forecasts for this area are mainly constrained by the assimilation of mooring data and the XBTs have a rather small impact on forecast skill, consistent with expectations based on the comparisons of ocean analyses. The importance of the TAO/TRITON array is clearly demonstrated.

In the North Atlantic (Fig. 16b) it is hard to beat the skill of persistence. Assimilation of all data (MAX, black) shows very little improvement relative to persistence. This skill is significantly degraded by the withdrawal of XBTs when it becomes worse than persistence.

Fig 16 shows the Mean Absolute Error 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). As expected, moorings are the most important source of information in the equatorial Pacific. In Niño4 the predicted SST is worse in the absence of moorings than without assimilation at all; the system seems not to be able to make good use of XBTs. This may be because there are too few of them.

In NAtl, the forecasts are degraded by the withdrawal of XBT's. In fact the results in NAtl are significantly worse in the case of MA- than CTL. This might be the result of the small remote effect of the mooring assimilation that can (hardly) be seen in fig 5b. This area shows some instabilities in our system; it is possible that the assimilation of moorings excites some of those.

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 2005. Overall, the impact of assimilation on mean absolute errors (MAE) 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 at al, 2005 for more consideration on this topic). However, the total number of observations has significantly increased since the late nineties (see fig 13) and therefore the impact of assimilation on forecast skill could be larger in the latter period.

Indeed, for the recent period (fig 18) the impact of assimilation is larger but represents only a limited number of cases (35 6-months forecasts[1]) and may not be statistically significant. Wherever the moorings are present (i.e. Niño3, Niño4, 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. Since 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:

[1] 7 start dates, 5 ensemble members

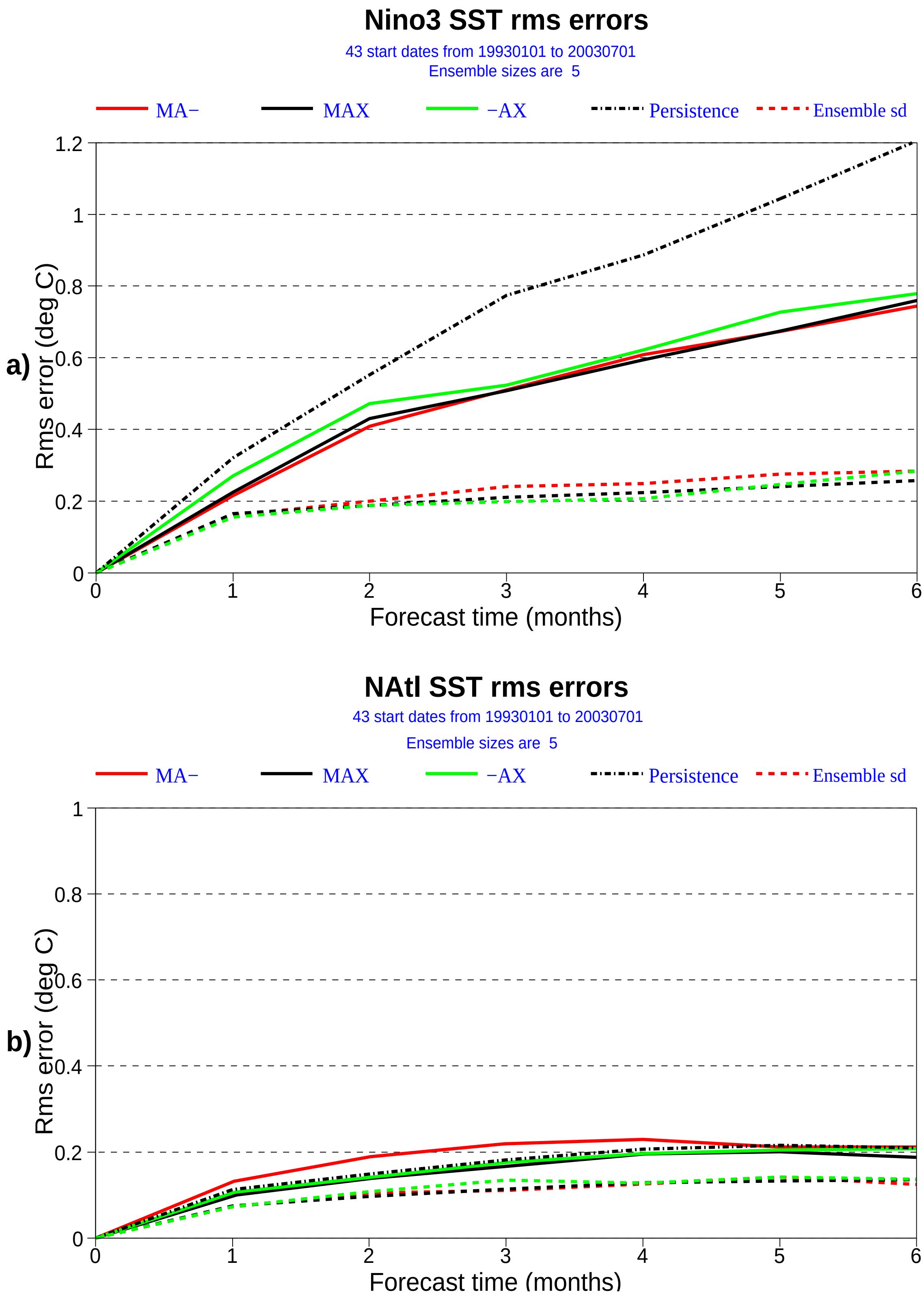


Figure 16: SSTA forecast skill measured by RMS-error for coupled experiments in two region: Nino3 (a) and NAtl (b). The dot-dash curve is a measure of skill for persistence.

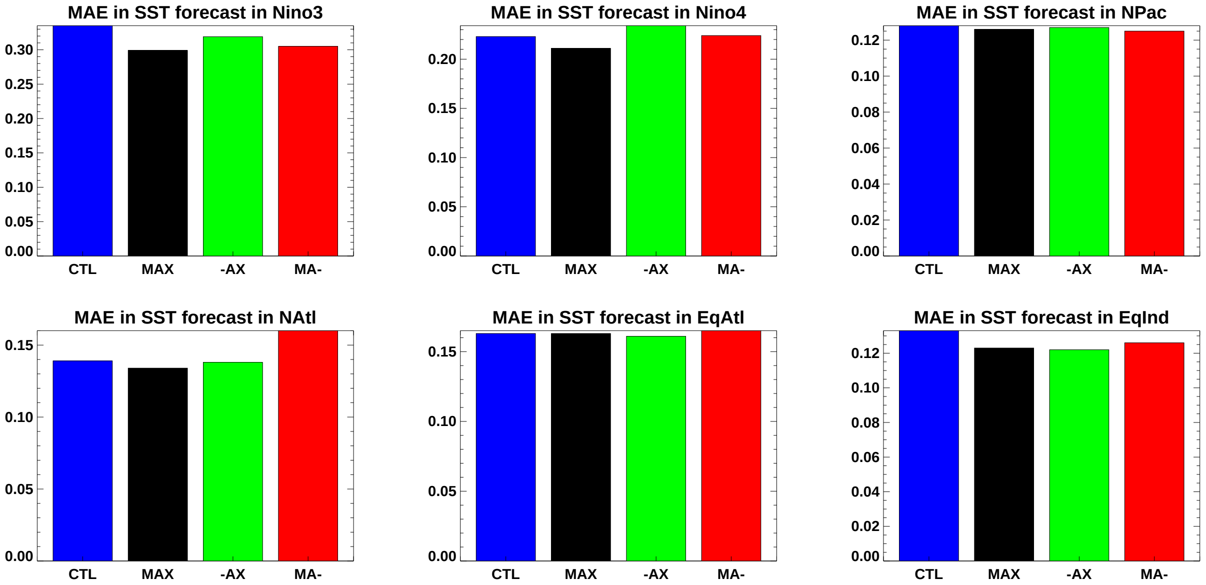


Figure 17: Mean Absolute error in the first three month of SST forecast for the whole period 1993-2003 averaged over the selected regions for experiment CTL (blue), MAX (black), -AX (green) and MA- (red)

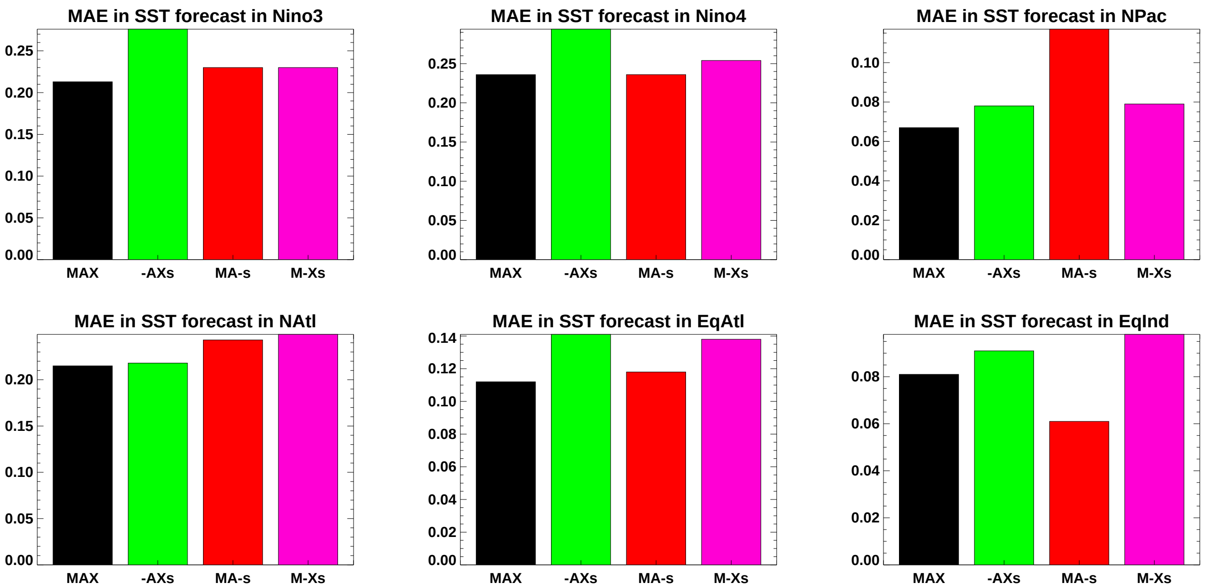


Figure 18: Mean Absolute error in the first three month of SST forecast for the reduced period 2002-2003 averaged over the selected regions for experiment MAX (black), -AX_s (green), MA-$_s$ (red) and M-X_s (purple)

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, since the number of forecasts used here is relatively small this result may not be significant.

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 analysed state of the ocean was evaluated for a time-averaged temperature section along the equator, the time-averaged upper ocean heat content and area-averaged time series of D20. The quality of the analysis was assessed using comparison with independent data and SST forecast skill.

In the Equatorial Pacific, the impact of the XBTs in 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 XBT was much more valuable than TAO 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 the paper as 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 TAO to be clearly the most important.

In the post-1998 equatorial Atlantic, the PIRATA have a significant and dominant impact but can benefit more from additional information than the TAO/TRITON array. The PIRATA Array may not be dense enough to be sufficient on its own as the signals in the Atlantic are smaller scales 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 considered period.

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.

It is a quite 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.

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, since a full multi-variate 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 will be reported in a subsequent paper.

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