Impact of the new vs. old wind stress perturbations on the ocean analysis

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12 December 2005

1. “New” and “old” wind stress perturbations

Over the last years the approach to generate perturbations in the wind stress field, which forces the ocean analysis, has been revised. The “old” perturbations, used in the operational seasonal forecast system 2 and in DEMETER, were based on differences between the ERA-15 and Southampton Oceanography Centre (SOC) wind stress data sets. With the arrival of ERA-40 it was felt that the uncertainties associated with these differences would somewhat overestimate the real uncertainties in the forcing. The “new” perturbations, to be used in the new operational system 3 and already used in ENSEMBLES, are thus based on differences between the ERA-40 and CORE data sets and are in general smaller than the “old” ones.

Figure 1 shows as example the “old” zonal wind stress perturbations in the equatorial Pacific and North Atlantic from 1986 to 2001. For comparison, figure 2 has similar time series for the “new” perturbations using the same amplitude scale. Two perturbations (blue, red) are shown as differences from the unperturbed state (black). The new set of perturbations has smaller amplitude than the old set, which can be clearly seen for the two example regions in the figures. The perturbations have been selected to be symmetric with respect to the unperturbed wind stress forcing.

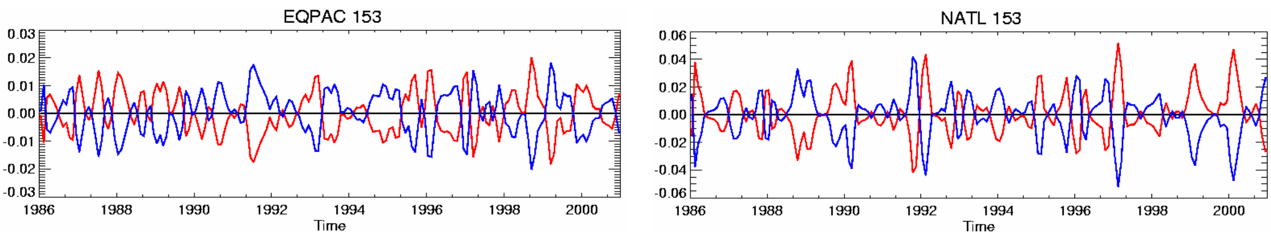

Fig. 1: “Old” zonal wind stress perturbations τ'_x for the equatorial Pacific (left) and the North Atlantic (right). The blue and red lines indicate differences from the unperturbed (black) wind stress fields.

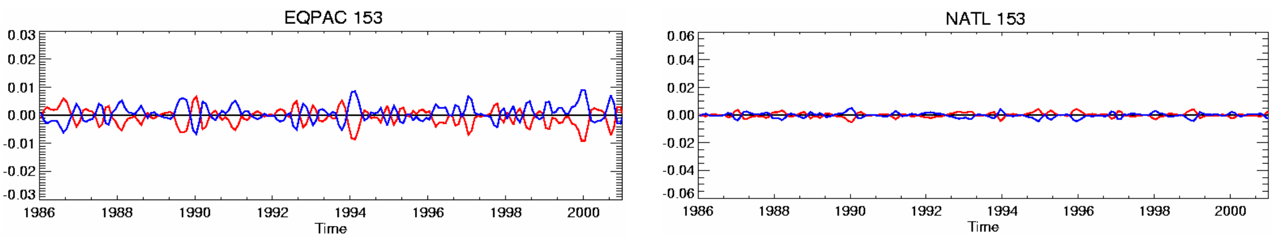

Fig. 2: “New” zonal wind stress perturbations τ'_x for the equatorial Pacific (left) and the North Atlantic (right). As in Figure 1, the blue and red lines indicate differences from the unperturbed (black) wind stress fields.

For a description of exactly how the SST and wind stress perturbations are generated and for a discussion about their global spatial distribution, please see the documentation "SST and wind stress perturbations in the ENSEMBLES seasonal and annual simulations", available from http://www.ecmwf.int/research/EU_projects/ENSEMBLES/documents/docu_perturbations.pdf.

In the following, ocean fields generated using the "old" and the "new" set of perturbations will be compared (Section 2). Here observational data have been assimilated in the ocean model. The impact of the "new" perturbations on the ocean analysis with and without data assimilation will be discussed (Section 3). Finally, the ocean analyses used in DEMETER and ENSEMBLES will be contrasted in Section 4.

2. Impact of the new perturbations on the ocean analysis

Two sets of ocean analyses have been run: one using the "old" wind stress perturbations and another one using the "new" wind stress perturbations as forcing for the HOPE (Hamburg Ocean Primitive Equations) ocean model. The analysis scheme used is OI (Optimal Interpolation), with a time window of 10 days. The first guess is provided by forcing the ocean model with daily fluxes of momentum, heat, and fresh water from the NWP atmospheric analysis system. Here only subsurface temperature observations and salinity are assimilated. Sea surface temperatures are strongly constrained by relaxation towards Reynolds OIv2 SST analysis. Three simultaneous analyses have been performed in order to sample uncertainty in the atmospheric fluxes. These simultaneous ocean analyses were created by adding the wind stress perturbations discussed above while the model is integrated forward from one analysis time to the next.

In the following we discuss some of the effects, which the use of the "old" and "new" perturbations have on the ocean fields in the assimilation analyses (expids: ep6f and enp0). We focus again on the equatorial Pacific and the North Atlantic.

2.1. Sea Surface Temperature

The sea surface temperature (SST) is closely linked to the wind stress forcing at the ocean's surface. In the equatorial Pacific one can observe a rather linear response to the forcing with relative symmetric fluctuations of the two perturbed analyses around the unperturbed one. This can be seen for both sets of perturbations in the left panel of figures 3 and 4. As expected, the SST fluctuations are smaller in amplitude for the "new" perturbations.

In the North Atlantic (right panel of figures 3 and 4) the response to the symmetric wind stress forcing is more strongly influenced by the non-linearities of the model. The SST differences are often not symmetric; they sometimes even have the same sign. The size of these fluctuations is much smaller in the case when the "new" wind stress perturbations had been used.

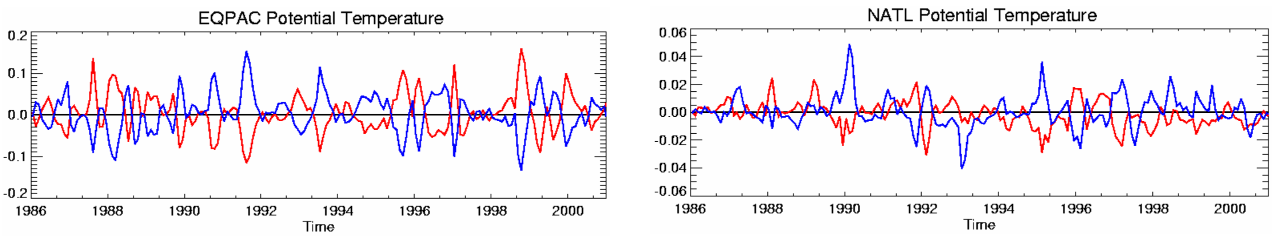

Fig. 3: Differences (blue, red) of the sea surface temperature (SST) from the unperturbed analysis (black) in the equatorial Pacific (left) and the North Atlantic (right) using the "old" wind stress perturbations in the analysis.

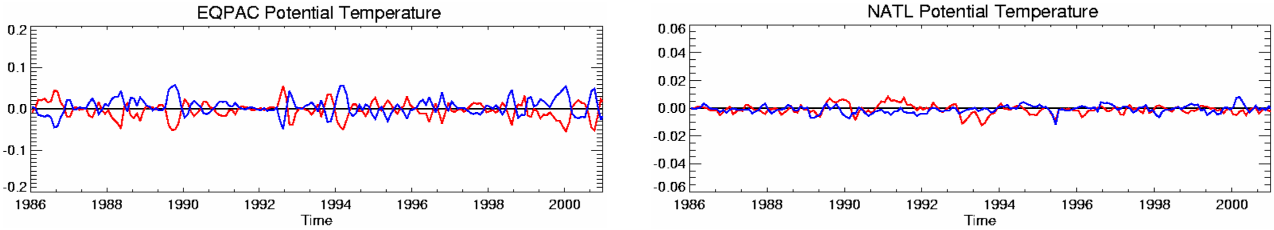

Fig. 4: As Figure 3, but using the “new” wind stress perturbations in the analysis.

2.2. Sea Level

The response of the two analyses to the different wind stress perturbations in terms of anomalies of sea level elevation (with respect to their monthly climatology) is shown in figures 5 and 6. The general evolution of sea level over the 15 years is very similar for both analyses. In the analysis using the “new” set of perturbations the ensemble has a smaller spread reflecting less uncertainty. In the North Atlantic, there is a pronounced decadal-scale component in the variability of sea level anomalies for both cases. The low-frequency variations in sea level could be interpreted as the signature of the long-term oceanic integration of the high-frequency white noise forcing imposed by atmospheric wind stress perturbations.

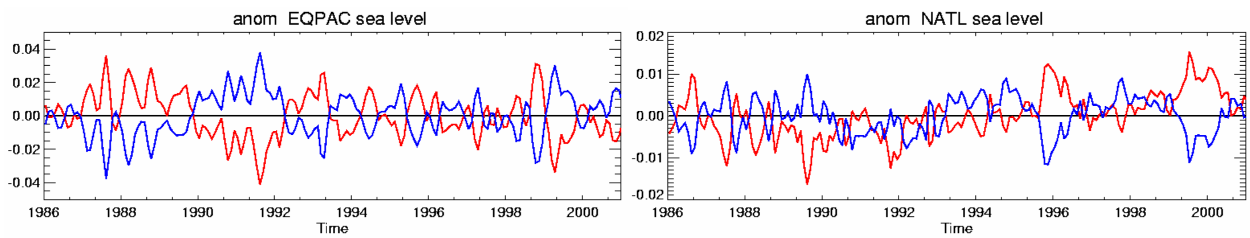

Fig. 5: Sea level elevation anomalies in the unperturbed (black) and the perturbed (blue, red) analyses in the equatorial Pacific (left) and the North Atlantic (right) using the “old” wind stress perturbations in the analysis.

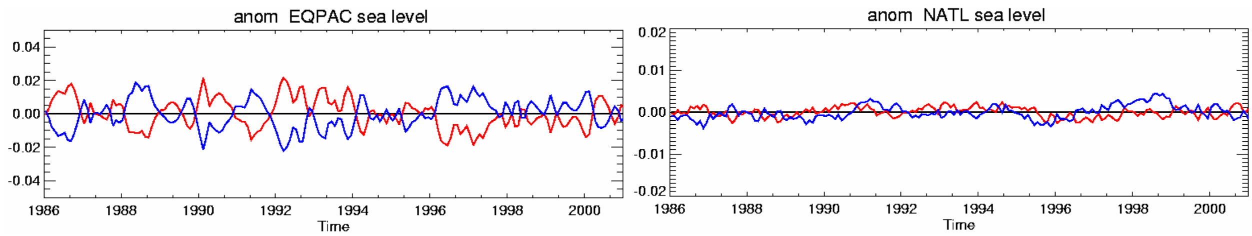

Fig. 6: As Figure 5, but using the “new” wind stress perturbations in the analysis.

2.3. Averaged temperature over the top 300m

The averaged temperature anomalies over the top 300m (T300) are shown in figures 7 and 8. In the tropical Pacific, anomalies with the “new” perturbations are in general smaller than those based on the “old” perturbations, meaning that the “new” analysis is less uncertain. One can, however, also see periods with larger anomalies in the analysis using the “new” perturbations. Potential causes for this could be i) the instability of the state, ii) the larger amplitude of the perturbations during these periods, and iii) the increased temporal correlation of the perturbations. Note that the amplitude and temporal correlation of the perturbations are purely random, so that larger anomalies can occur by chance.

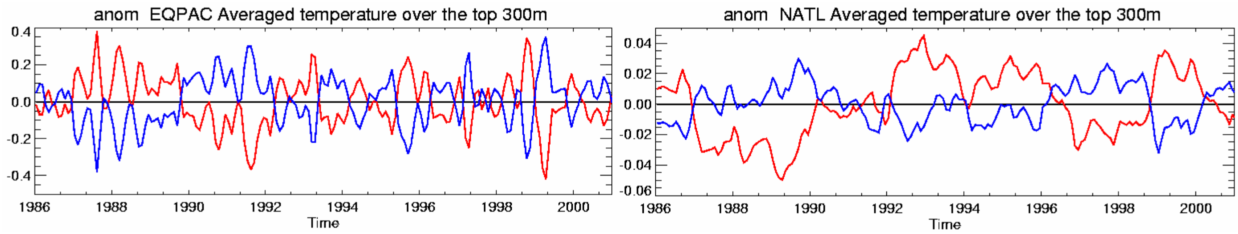

Fig. 7: Averaged temperature anomalies over the top 300 m in the unperturbed (black) and the perturbed (blue, red) analyses in the equatorial Pacific (left) and the North Atlantic (right) using the “old” wind stress perturbations in the analysis.

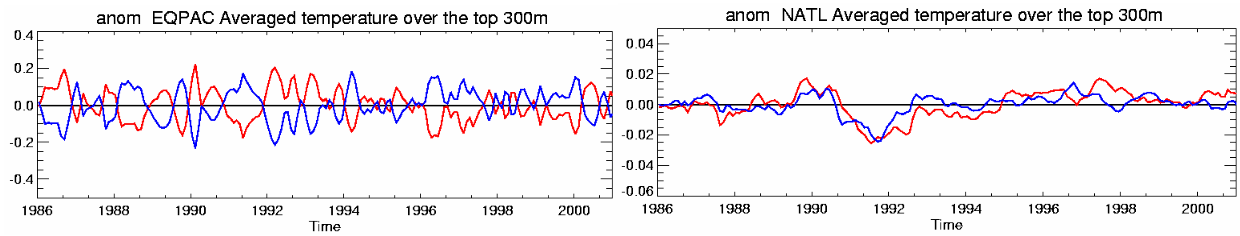

Fig. 8: As in Figure 7, but using the “new” wind stress perturbations in the analysis.

In the North Atlantic, again, the mean magnitude of the anomalies is smaller when the “new” perturbations are used. The main difference, however, is the strong nonlinear response to the symmetric “new” wind perturbations, which leads to a high correlation of the different perturbed ensemble members in terms of the averaged temperature anomalies in the top 300m (fig. 8 right). Whether this might be due to the effect of the less strong local wind stress forcing with the “new” perturbations and thus perhaps a larger contribution of any remote forcing, remains to be investigated. Note that for the absolute temperatures in the North Atlantic the uncertainty due to the wind stress perturbations is in general small compared to the pronounced mean seasonal cycle of the temperature (not shown).

2.4. Averaged salinity over the top 300m

Corresponding plots for the salinity anomalies in the top 300m (S300) are displayed in figures 9 and 10. For both regions, but most pronounced for the North Atlantic, the analysis based on the “new” set of wind perturbations seems to be more constrained and less uncertain.

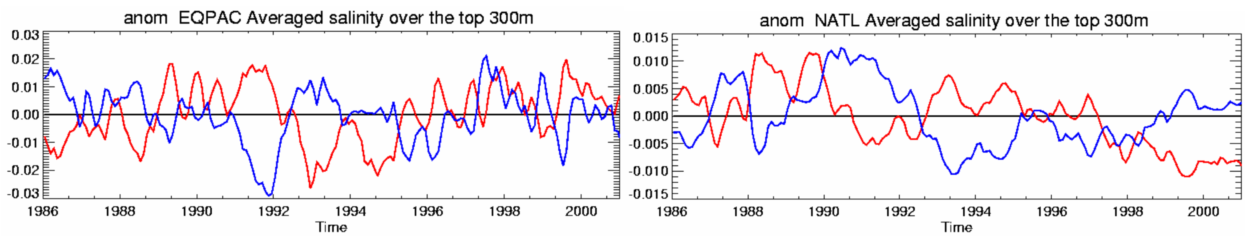

Fig. 9: Averaged salinity anomalies over the top 300 m in the unperturbed (black) and the perturbed (blue, red) analyses in the equatorial Pacific (left) and the North Atlantic (right) using the “old” wind stress perturbations in the analysis.

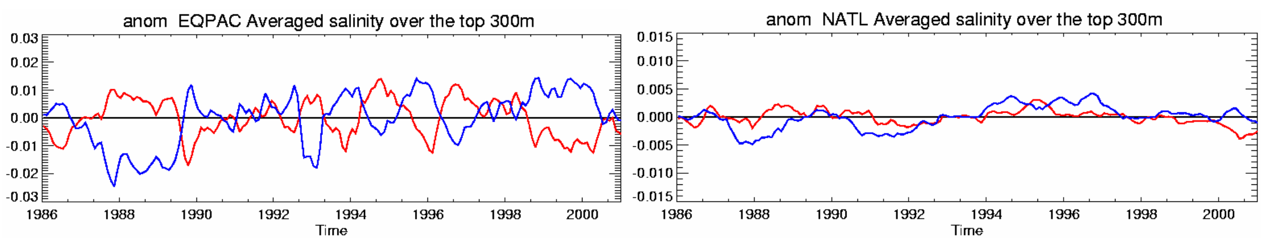

Fig. 10: As in Figure 9, but using the “new” wind stress perturbations in the analysis.

To summarise, it was demonstrated that the “new” set of wind stress perturbations leads in general to a decreased level of uncertainty in the ocean analysis, especially with respect to the SST and the sea level elevation. The tendency of producing a more constraint analysis with the “new” perturbations can also be seen in the averaged temperature and salinity anomalies over the top 300m.

3. Impact of ocean data assimilation using the “new” perturbations

In this section the impact of assimilating sub-surface ocean observations compared to a no-assimilation analysis, - in the following referred to as control analysis -, will be discussed briefly (expid: enp0). In both cases the “new” wind stress perturbations were applied. The assimilation scheme has been briefly described in the beginning of Section 2. Note that although for the control analysis there is, in general, no constraint by observational data, the SSTs are strongly relaxed towards Reynolds OIv2 SSTs. The assimilation analysis discussed in the following is the same analysis as used in the comparison between the “new” and “old” wind stress perturbations in Section 2 above.

3.1. Averaged temperature over the top 300m

In figure 11 the evolution of the differences of anomalies in the averaged temperature in the top 300m in the equatorial Pacific and North Atlantic is shown for the control analysis. Here ‘anomaly’ refers to the long-term mean value and ‘difference’ means the difference between the perturbed (blue and red curves) and unperturbed (black) analysis member. The corresponding plots for the assimilation analysis are displayed in figure 8 above. The amplitude of the temperature anomalies in both regions is reduced when the assimilation scheme is applied, which leads to a decrease in the uncertainty of the resulting analysis.

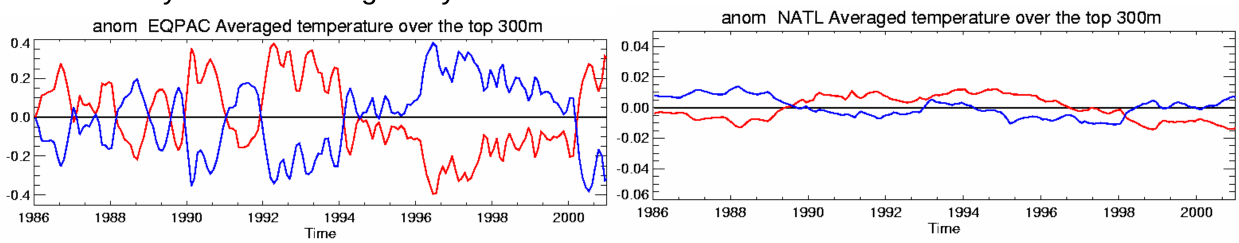

Fig. 11: Differences (blue, red) of the averaged temperature anomalies in the top 300 m from the unperturbed analysis (black) in the equatorial Pacific (left) and the North Atlantic (right) using the control analysis.

3.2. Sea level

The strong constraint of the assimilation analysis is also to be seen in the time series of sea level elevation anomalies in figure 12. In the case of ocean data assimilation (figure 6), the analysis in the equatorial Pacific is less uncertain or better constrained, which can be seen by the much reduced magnitude of the anomalies. In the North Atlantic, such a pronounced impact has not been found.

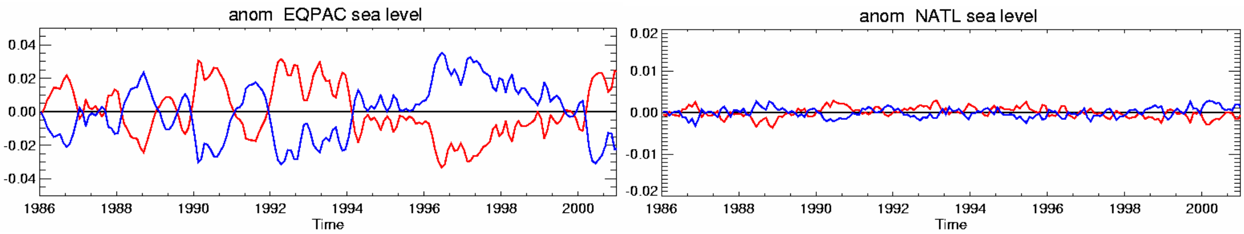

Fig. 12: Sea level elevation anomalies in the unperturbed (black) and the perturbed (blue, red) analyses in the equatorial Pacific using the control analysis.

3.3. Averaged salinity over the top 300m

The evolution of the averaged salinity in the first 300m is shown in figure 13; for the corresponding assimilation analysis compare with figure 10. In the equatorial Pacific the impact of the sub-surface data assimilation concerns mainly the amplitude of the anomalies with smaller values, i.e. reduced uncertainty, in the assimilation analysis. In the North Atlantic, however, the control analysis reveals a pronounced low-frequency component of variability (fig. 13 right), whereas the assimilation analysis has more variability on shorter time scales (fig. 10 right). In both cases the amplitude of the anomalies is roughly the same.

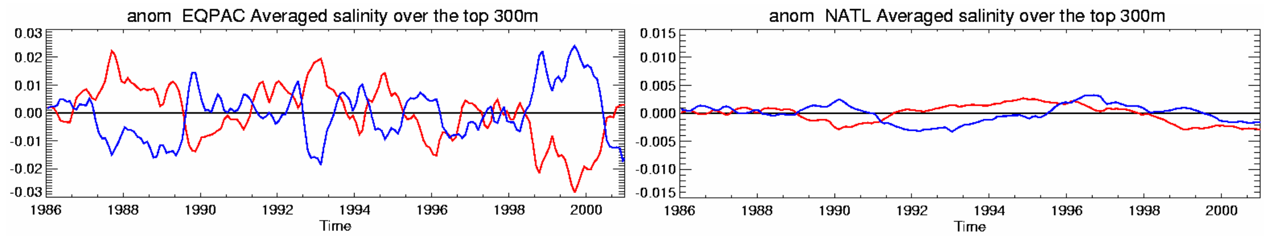

Fig. 13: Differences (blue, red) of the averaged salinity anomalies in the top 300 m from the unperturbed analysis (black) in the equatorial Pacific (left) and the North Atlantic (right) using the control analysis.

To briefly summarise, assimilating subsurface observations leads to decreased uncertainty and can modify the internal variability on shorter and longer time scales.

4. The ocean analyses in DEMETER and ENSEMBLES stream 1

This section gives a summary of the main differences in the ocean analyses applied in the DEMETER (expid: e722) and ENSEMBLES projects (stream 1, expid: 0001). Beside the fact that over time from DEMETER to ENSEMBLES both the ocean model and the assimilation scheme have been further developed, there are two main differences between the DEMETER and ENSEMBLES analyses: the ocean analysis in DEMETER used the “old” set of perturbations with the sampling of the perturbations being done in a non-symmetric way (figure 14). Second, the “old” perturbations are based on differences between the ERA-15 and SOC data sets. This analysis is similar, although not exactly the same as the analysis used in the operational seasonal forecasts of System 2. For the ENSEMBLES stream 1 simulations the “new” set of perturbations are used and applied to the model in a symmetric way (cf figure 2). The “new” perturbations, however, are based on differences between the ERA-40 and CORE data sets.

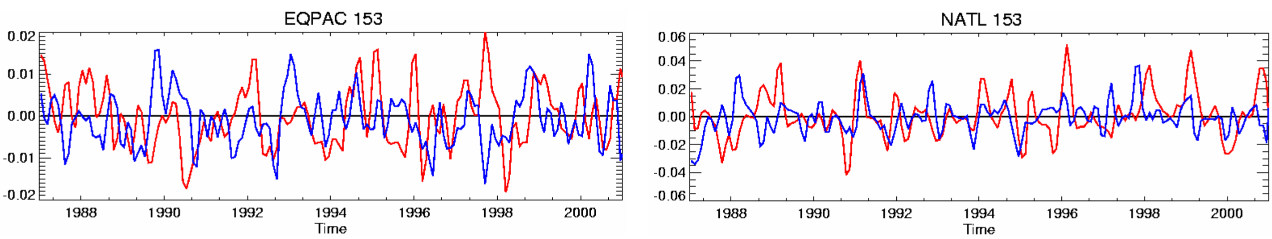

Fig. 14: Zonal wind stress perturbations τ'_x for the equatorial Pacific (left) and the North Atlantic (right) as used in DEMETER. The blue and red lines indicate differences from the unperturbed (black) wind stress fields.

As discussed in Section 2, the “new” perturbations are in general smaller in amplitude than the “old” perturbations. This becomes especially striking in the North Atlantic. At the time of writing it is assumed that the ocean analysis used in the ENSEMBLES simulations is similar to the future operational analysis of System 3. For a more detailed discussion on how the perturbations have been generated the reader is referred to the documentation “SST and wind stress perturbations in the ENSEMBLES seasonal and annual simulations”, available from http://www.ecmwf.int/research/EU_projects/ENSEMBLES/documents/docu_perturbations.pdf.

4.1. Sea level

A comparison of the sea level elevations in figures 15 and 16 shows that the temporal evolution is, broadly speaking, rather similar. For the equatorial Pacific region, the sea level appears slightly lower on average in the ENSEMBLES analysis. In the North Atlantic, the seasonal cycle is the most obvious signal, superposed by a longer-term upward trend. It can be seen that the ocean analysis, which has been used for the ENSEMBLES project, generates larger amplitudes of the seasonal cycle and a stronger trend.

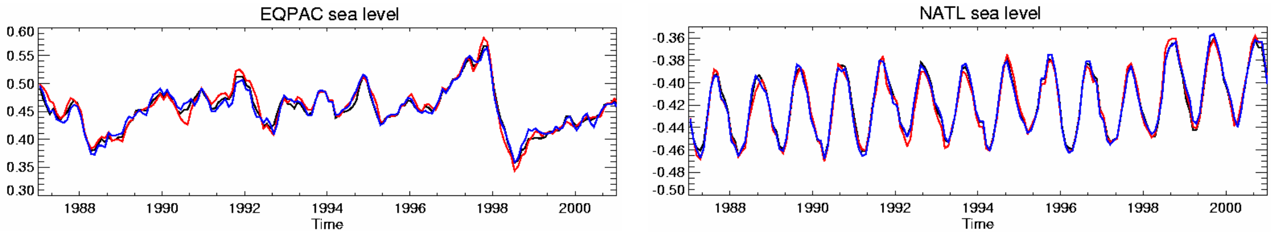

Fig. 15: Sea level elevation in the unperturbed (black) and the perturbed (blue, red) analyses in the equatorial Pacific (left) and the North Atlantic (right) as used in DEMETER.

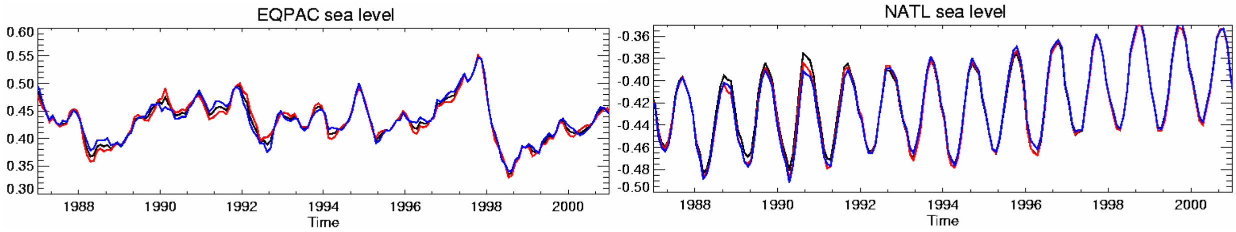

Fig. 16: As Figure 15, but for ENSEMBLES.

A more detailed look at the uncertainties related to the two sets of analyses, as shown in figures 17 to 19, reveals that the magnitude of the differences in the equatorial Pacific is somewhat smaller in ENSEMBLES compared with DEMETER. Note that in these figures, different from before differences, rather than anomalies, of the total sea level elevation are plotted. For DEMETER the impact of the non-symmetric wind stress perturbations can be clearly seen. In the North Atlantic the perturbed analysis in ENSEMBLES shows well pronounced low-frequency variability with negative differences in the beginning of the simulations and positive differences in the mid 1990s (figure 18 right). There is no such trend in the corresponding DEMETER analysis (figure 17 right). Comparing the magnitude of the differences in DEMETER and ENSEMBLES reveals that the uncertainty in ENSEMBLES sea level is larger in the beginning of the analysed period and decreases towards the end of the period.

In figure 19 a comparison of the unperturbed analysis members in DEMETER and ENSEMBLES, plotted as differences of DEMETER minus ENSEMBLES, is shown. Over the full period the sea level elevation in the equatorial Pacific used in ENSEMBLES is substantially smaller than the corresponding one in DEMETER, as already pointed out in the discussion of figures 15 and 16 above. Interestingly, the difference between DEMETER and ENSEMBLES in the two selected regions is approximately twice as large as the uncertainty within any of the two experiments.

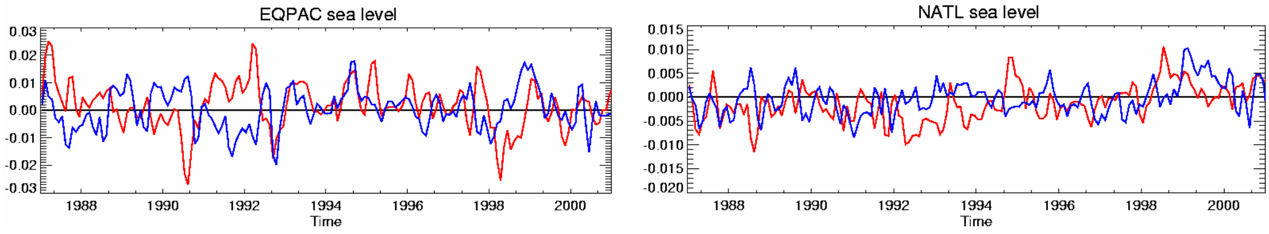

Fig. 17: Differences of sea level elevation in the unperturbed (black) and the perturbed (blue, red) analyses in the equatorial Pacific (left) and the North Atlantic (right) as used in DEMETER.

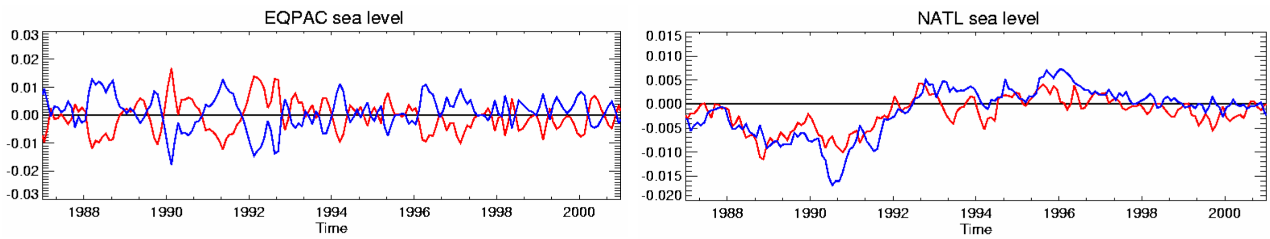

Fig. 18: As Figure 17, but for ENSEMBLES.

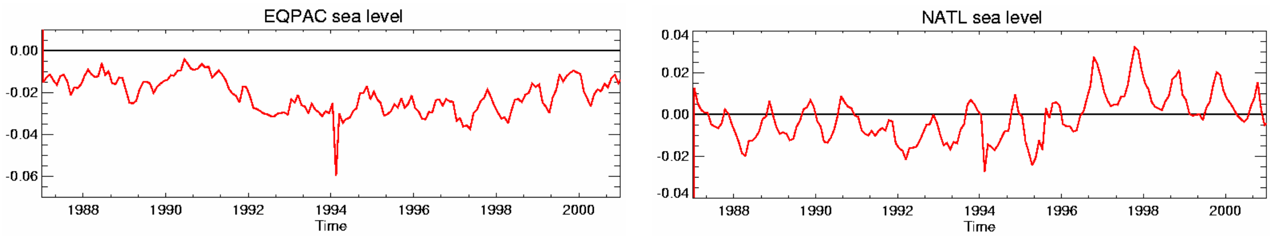

Fig. 19: Difference DEMETER - ENSEMBLES of sea level elevation in the equatorial Pacific (left) and the North Atlantic (right) for the unperturbed analysis.

4.2. Averaged temperature over the top 300m

Broadly similar conclusions hold for the case of the temperature in the top 300m, displayed in figures 20 - 22. The uncertainty in the ENSEMBLES analysis in the equatorial Pacific is slightly reduced compared to the DEMETER analyses (figures 20 and 21 left). However, the differences between the DEMETER and ENSEMBLES analyses are double the size than the uncertainty within each of the two systems, as seen in figure 22 left, with the temperatures in ENSEMBLES on average being smaller than in DEMETER. The difference between DEMETER and ENSEMBLES is decreasing over time, which may reflect the better constraint of the analysis as more temperature observations in the Pacific became available.

In the North Atlantic there are again more low-frequency fluctuations in ENSEMBLES producing rather strong trends in the beginning of the 1990s. Again, the amplitude of the annual cycle is larger in ENSEMBLES. On average, temperatures in the North Atlantic were higher in DEMETER then they are in ENSEMBLES, which is especially the case in the second half of the analysed time period.

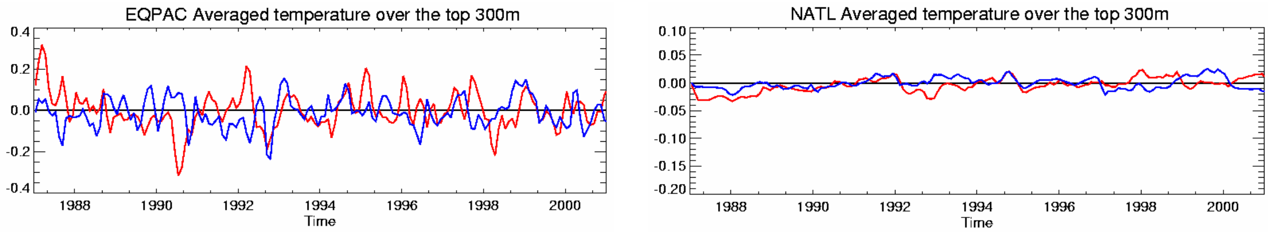

Fig. 20: Differences of the top 300m temperature in the unperturbed (black) and the perturbed (blue, red) analyses in the equatorial Pacific (left) and the North Atlantic (right) as used in DEMETER.

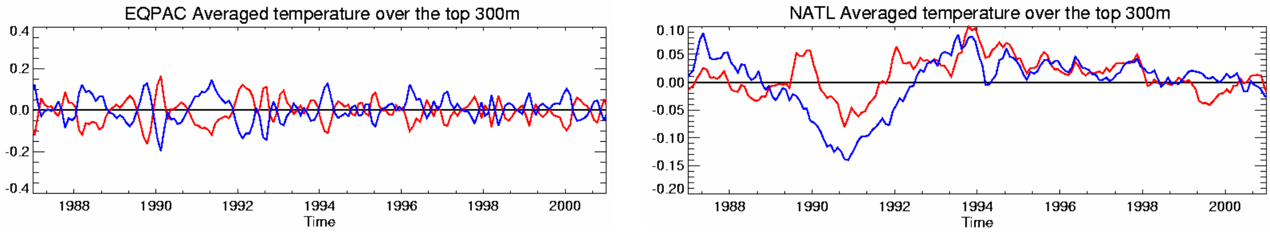

Fig. 21: As Figure 20, but for ENSEMBLES.

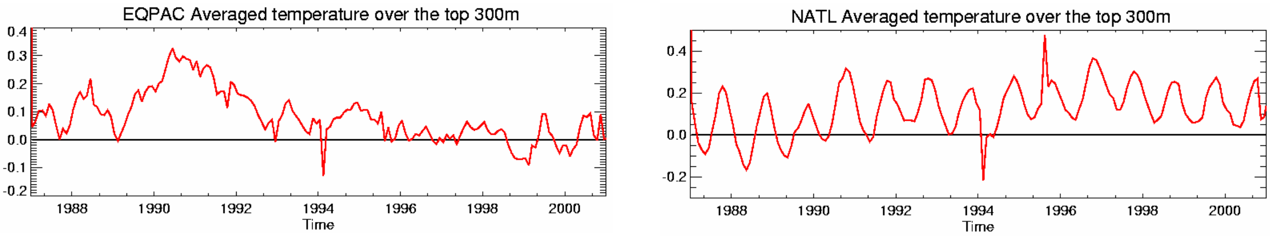

Fig. 22: Difference DEMETER - ENSEMBLES of top 300m temperature in the equatorial Pacific (left) and the North Atlantic (right) for the unperturbed analysis.

4.3. Salinity

Similar diagnostics for the averaged salinity in the top 300m is shown in figures 23 - 25 below. The ENSEMBLES uncertainty in the equatorial Pacific is somewhat reduced compared to DEMETER (figure 23 and 24 left). However, the mean differences in the equatorial Pacific between DEMETER and ENSEMBLES are approximately 5 times as big as the average spread from either DEMETER or ENSEMBLES (figure 25 left). There is an increasing trend in these differences with less salinity in the ENSEMBLES analysis. This probably reflects the impact of including the assimilation of salinity observations in the latest ocean analysis system that has been used for ENSEMBLES.

In the North Atlantic, both sets of analyses show long-term fluctuations; larger amplitudes of which occur in the ENSEMBLES runs (figures 23 and 24 right). Different from the equatorial Pacific, there is no trend in the differences between DEMETER and ENSEMBLES (figure 25 right). The magnitude of the differences between the two systems is similar or a little larger than the uncertainty in either DEMETER or ENSEMBLES.

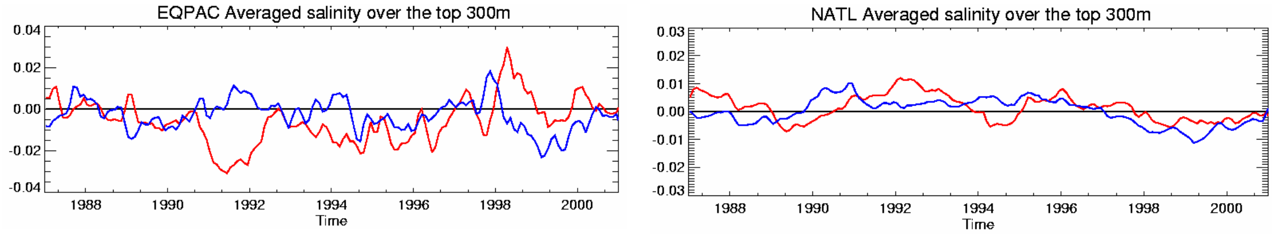

Fig. 23: Differences of the top 300m salinity in the unperturbed (black) and the perturbed (blue, red) analyses in the equatorial Pacific (left) and the North Atlantic (right) as used in DEMETER.

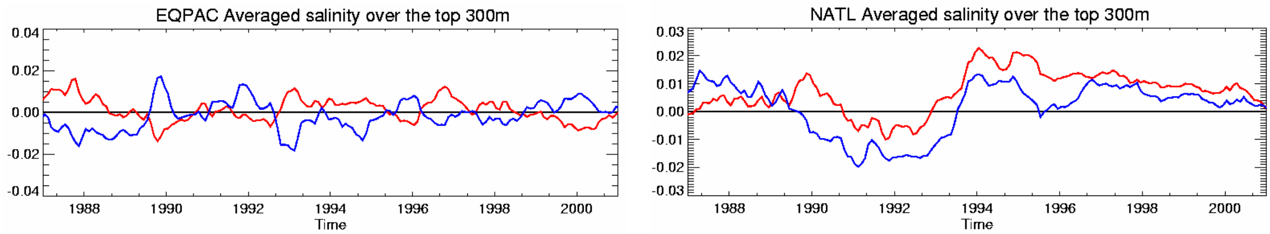

Fig. 24: As Figure 23, but for ENSEMBLES.

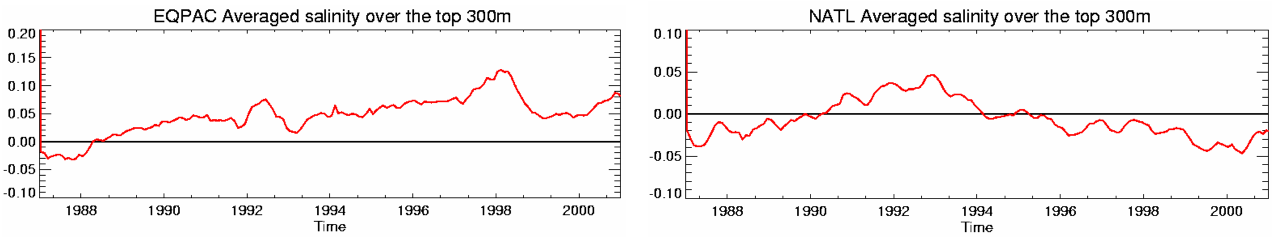

Fig. 25: Difference DEMETER - ENSEMBLES of top 300m salinity in the equatorial Pacific (left) and the North Atlantic (right) for the unperturbed analysis.

We have seen that the differences between the two analysis schemes have in general a larger impact than the wind stress perturbations, i.e., the uncertainty in the initial conditions. In order to better understand the physical impact of the different sources of uncertainty on the ocean analysis, more detailed investigations and sensitivity studies are planned for the future.