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Contribution of thermal expansion to present-day sea-level change revisited

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Abstract

We investigate the thermosteric (i.e., due to temperature only) sea-level change over the last 50 years using two global ocean temperature data sets recently published (Levitus et al., 2000a [Levitus, S., Stephens, C.M., Antonov, J.I., Boyer, T.P., 2000a. Yearly and year-season upper ocean temperature anomaly fields, 1948–1998, pp. 23, U.S. Gov. Printing Office, Washington, DC] and Ishii et al., 2003 [Ishii, M., Kimoto, M., Kachi, M., 2003. Historical ocean subsurface temperature analysis with error estimates, *Monthly Weather Rev.*, 131, 51–73]). These data sets which provide gridded temperatures, down to 3000 m and 500 m respectively, are based on interpolation schemes of raw historical profiles over 1950–1998. We find that the two data sets compare well over 1950–1990, both in terms of thermosteric sea-level trends and global mean. Some difference is noticed however beyond 1990, due to differences in the raw temperature data processing. Analyses based on 'Empirical Orthogonal Function' show that the interannual variability of the thermosteric sea level is dominated by the signatures of El Niño Southern Oscillation, Pacific Decadal Oscillation and influenced by North Atlantic Oscillation. As a result, regional thermosteric sea-level trends are not stationary on a century time scale and have a typical lifetime on the order of a decade. In terms of global mean, the rate of thermosteric sea-level change computed over 10-year windows displays high variability, with values reaching up to three times the 40-year (1950–1990) average at some periods. Even negative values are noticed at other periods. One important consequence is that the pattern of sea-level trends derived from Topex/Poseidon altimetry over 1993–2003, which is mainly caused by thermal expansion, is very likely a non-permanent feature. Thus past and future extrapolation based on this 10-year altimetry pattern should be considered with caution.
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Keywords: Climate change; Sea level change; Thermal expansion

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1. Introduction

Measuring the exact rate of sea-level rise over the recent decades and identifying its causes is a topic of considerable interest in the context of the current debate on global climate change. Recent results based on Topex/Poseidon altimetry for the last decade show that rates of sea-level change present great regional variability, with positive and negative trends amounting up to 10 times the global mean (Nerem and Mitchum, 2001a,b; Cazenave and Nerem, 2004). Understanding the cause of this regional variability is important, in particular for improving sea-level predictions based on climate models and mitigating potential impacts of rapid sea-level rise in vulnerable coastal areas.

On time scales ranging from years to decades, the two main causes of global mean sea-level change are steric effects (mostly thermal expansion associated with global ocean warming) and water mass exchange with continents. As we will see below, steric effects are likely an important cause of regional variability in sea-level trends. While ocean water mass change may rapidly lead to uniform sea-level change, elasto-gravity effects on the distribution of melt water from the ice sheets, in principle, also contributes to the spatially non-uniform pattern of sea-level change (Mitrovica et al., 2001; Plag and Juttner, 2001). Other causes of regional variability include wind forcing (through steric and barotropic sea-level changes) as well as potential change in the thermohaline circulation (Levermann et al., in press).

Due to the lack of 3-dimensional ocean temperature data available on a global scale, estimates of thermal expansion were until recently mainly based on Ocean General Circulation Models. For example, re-estimating the climate-related contributions to the 20th century sea-level rise, the last IPCC report (Church et al., 2001) gives a 0.5 mm/year model-based thermal expansion contribution. Since the publication of the 2001 IPCC report, a number of new results about present-day sea level have been reported, among these, the first direct estimate of thermal expansion (Antonov et al., 2002) based on historical ocean temperature observations from Levitus et al. (2000a). Antonov et al. (2002) found that thermal expansion contributes to 0.5 ± 0.05 mm/year to the rate of sea-level rise of the past 50 years. It is worth noting that this value agrees well with the IPCC value based on models.

In this paper, we revisit the estimate of thermal expansion over 1950–1998 using a new ocean temperature data set (Ishii et al., 2003), in addition to the Levitus one. The Ishii data set consists of gridded temperature data down to 500 m for the historical period (1950–1998). We compare the Ishii and Levitus data sets and their contribution to thermal expansion, in order to describe the spatial and temporal structure of thermosteric sea-level patterns. We also focus on the last half decade by comparing Topex/Poseidon and Ishii-derived sea-level variations over 1993–98.

2. Data description

Subsurface temperature data are stored in various formats with respect to different vertical levels. In addition, from one measurement date to another, site locations often vary. Thus for easier handling of these observations, data interpolation at standard ocean depths and geographical positions is indicated. Recently, Levitus et al. (2000a) and Ishii et al. (2003) provided global gridded temperature data sets for the last 50 years based on objective analysis methods applied to the raw temperature profiles. These objective analyses are usually used to interpolate scattered data onto regular grids. Since ocean sampling is strongly inhomogeneous in time and space, and very incomplete over large regions of the global ocean (e.g., Southern Ocean), the resulting maps must be, however, interpreted with caution.

2.1. World Ocean Atlas and Database 1998 (Levitus et al., 2000a,b)

The Levitus et al. (2000a) data set consists on $1°\times1°$ gridded temperature anomalies given as yearly means for the upper 500 m from 1945 to 1998 and 5-year means down to 3000 m for 1947–1994. Using the raw temperature profiles, Levitus et al. computed gridded time series at non-uniformly spaced depth levels, based on an objective analysis scheme. Using this data set, Levitus et al. (2000b) reported that globally averaged ocean heat content increased by 2×10^{23} J between the mid-1950s and the mid-1990s, corresponding to a net ocean warming of 0.06 °C during the past 50 years. In

the Pacific Ocean, warming significantly increased in the early 1970s and in the mid-1980s. The Indian Ocean also warmed significantly since the 1960s. The Atlantic Ocean showed a somewhat different behaviour, with a rather monotonic warming trend since 1950 to the early 1990s, then a steep increase thereafter. In addition, only the Atlantic Ocean showed substantial warming at depths below 1000 m, unlike the Pacific and Indian Oceans, where change in heat content mainly occurred in the upper 300 m. The steep warming reported during the 1990s has been recently questioned and attributed to an error in the data processing (S. Levitus, personal communication, 2003). The problem arises from the depth correction which needs to be applied to XBTs (Expandable Bathy Thermographs) temperature profiles (Hanawa et al., 1995). Applying this correction results in an 'apparent' warming of the temperature profile compared to uncorrected data. Applying it twice leads to overestimating the temperature. Note that the data prior to 1990 are unaffected by this correction error.

2.2. Historical ocean subsurface temperature analysis by Ishii et al. (2003)

The Ishii et al. (2003) data set consists of monthly $1° \times 1°$ gridded temperature fields given as monthly means down to 500 m from 1950 to 1998. As for the gridded Levitus data, the Ishii data set is produced by a so-called objective analysis, but their methodologies are totally different. One difference is to explicitly consider background errors and observational errors in the Ishii analysis through variational methods (e.g., Derber and Rosati, 1989; Ghil and Malanotte-Rizzoli, 1991). An optimal solution is then computed in the sense of least squares. In general, this approach is thought to be superior than other methods, since observational noise is effectively filtered out. Ishii et al. chose a 600-km spatial de-correlation scale in order to efficiently remove the meso-scale noise. Thus temperature fields produced by Ishii et al. are smoother than Levitus et al. ones (which are based on a distance-weighted interpolation scheme). One problematic consequence is that Ishii-based temperature variations (hence rates of sea-level change) are probably underestimated.

In these analyses based on statistical approaches (rather than data assimilation into a dynamical model), the quantity and quality of number of raw observations are crucial factors. Levitus et al. used WOD98 (Levitus et al., 1998; Antonov et al., 1998; Boyer et al., 1998) data while Ishii et al. used a previous version WOD94 (Levitus and Boyer, 1994; Boyer and Levitus, 1994; Levitus et al., 1994). Differences between the two data sets mainly affect the 1990s. Because WOD94 contains too few data in the 1990s, Ishii et al. used GTS (Global Telecommunication System) data instead of the former data set. As far as the WOD98 database is concerned, its spatial coverage is superior to that of the GTS one. The replacement of WOD94 data by GTS data as of January 1st, 1991, may lead to some discontinuity in the Ishii et al. gridded data set. Another potential discontinuity may arise from the replacement of GISST (Global Sea Ice and Sea Surface Temperature data set) by Sea Surface Temperature data from the Japan Meteorological Agency as of January 1st, 1995. On the other hand, the use of TOGA–TAO (Tropical Ocean Global Atmosphere–Tropical Ocean Array buoys) data, abundant in the tropical Pacific, may somewhat mitigate the abovementioned data processing drawbacks for the last decade.

2.3. The problem of the XBT depth correction

XBTs data comprise a large fraction of the overall data used both by Levitus et al. and Ishii et al. Ignoring or wrongly applying the XBT depth correction may result in a bias in the estimated temperatures which can be as large as the decadal variability of thermal expansion itself. However, its effects on climate-related signals have been largely ignored in the scientific literature. While Levitus et al. applied the correction twice to XBT data on the 1990s, Ishii et al. did not apply it at all to the GTS data (while they applied it to the WOD94 data, i.e., before 1991). XBT data whose depths should be corrected amount to 30 to 40% of all XBT observations used by Ishii et al. since 1991. We do not know how many XBT data were over-corrected by Levitus. In summary, the correction was not applied in Ishii et al.'s data while it was doubled in Levitus et al.', during the 1990s. Hence some difference between the two data sets is expected over this period compared to the previous 40 years.

3. Ocean data analyses (1950–1998)

3.1. Subsurface temperature mean field over 1950–1998

Fig. 1 shows depth versus time diagrams of the geographically average ocean temperatures anomalies down to 500 m since 1950, computed with the global gridded data of Levitus et al. (2000a) and Ishii et al. (2003) respectively (the Ishii monthly data have been averaged on a yearly basis for comparison with the Levitus data). Comparing the two panels shows that temperature anomalies compare well, both in terms of amplitude and temporal variations for 1950–1990: warming is observed between 1970 and 1985 in all layers, beginning at depth and propagating upward until the mid-1980s. Since the end of the 1980s, ocean warming has been increasing, especially in the surface layers, compared to the previous decades. However positive temperature anomalies of the intermediate layers (100–500 m) seen in Levitus data, are not observed in Ishii data. This certainly results from the differences in temperature data processing by the two groups (see Section 2).
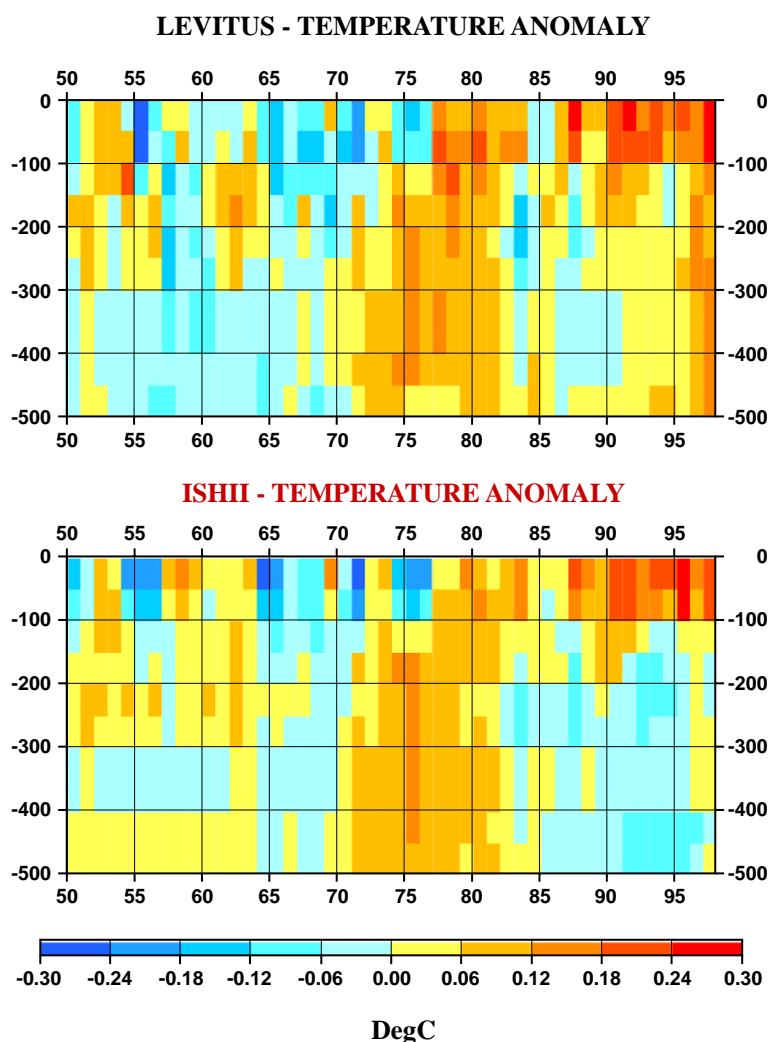

Fig. 1. Depth versus time diagrams of the 60S–60N geographically average ocean temperatures anomalies down to 500 m since 1950 until 1998. Upper panel—Levitus data; lower panel—Ishii data.

3.2. Global steric sea level (1950–1998)

To compute the steric sea level (more precisely the thermosteric sea level, i.e., due to temperature only), it is necessary to first convert the gridded temperature anomalies in terms of density anomalies at each standard level using the classical expression for the equation of state of the ocean (Gill, 1982; the Levitus climatology is used for salinity variations). The thermosteric sea level is further obtained by vertically integrating density anomalies at each grid point and each time step according to:

$$h_{\text{steric}}\,(x,y,t) = \int_{-H}^{0} \frac{\rho_0(x,y,z) - \rho(x,y,z,t)}{\rho_0(x,y,z)}\,\mathrm{d}z$$

(1)

where $\rho_0(x,y,z)$ is the reference density; ρ_0 is a function of the reference temperature T_0, reference salinity S_0 and depth z. $\rho(x,y,z,t)$ is a non-linear function of temperature and salinity (e.g. Gill, 1982).

Fig. 2 compares global mean thermosteric sea-level variations for 1950–1998 computed with the two data sets. While the two curves agree reasonably well between 1950 and 1990, significant difference is observed between 1990 and 1998, the Ishii-based sea level being lower than the Levitus-based one: as a result, the global mean thermal expansion over 1990–1998 amounts only 0.47 ± 0.44 mm/year with Ishii data, compared to the 1.41 ± 0.49 mm/year increase with Levitus data. As discussed in Section 2, this divergence during the 1990s is certainly due to the problem of the XBT depth correction and inhomogeneous data in the Ishii processing. In both curves, the thermosteric sea level presents large decadal/interdecadal fluctuations, in particular a long period of significant rise from the mid-1960s to the early 1980s, followed by a rapid decrease during the 1980s. In terms of trends, the thermosteric contribution of the upper 500-m layers over 1950–1990 (excluding the recent years for the reason discussed above) amounts 0.11 ± 0.04 mm/year, and 0.19 ± 0.06 mm/year for the Ishii and Levitus data respectively. Considering the associated uncertainties, this difference in trend is probably insignificant and due to differences in the computing process.

3.3. Contribution of ocean layers to the total thermosteric sea-level variations

In Fig. 2 are also presented, for both data sets, individual contributions of different 100-m-thick layers to the thermosteric sea-level change with time over 1950 to 1998. The dominant contribution arises from shallow layers, but deeper layers down to 500 m also contribute. This is especially true for the 1970s where we note a significant increase (then decrease) of the thermosteric sea level. For all layers, the Ishii sea level is lower than the Levitus sea level beyond 1990 (see Section 2). However before 1990, there is generally good agreement between the two curves whatever the layer.

3.4. Global thermosteric sea-level trends 1950–1990

Fig. 3 compares thermosteric sea-level trends based on the two data sets for the period 1950–1990. The two maps show similar patterns and compare quite well. Over this 40-year period, thermosteric sea-level change is highly non-uniform, as reported previously by Cabanes et al. (2001). The main patterns appear related to (1) the west–east dipole in the tropical Pacific associated with the El Niño Southern Oscillation (ENSO), (2) the north–south dipole in the north Atlantic corresponding to North Atlantic Oscillation (NAO), (3) the signature of the Pacific Decadal Oscillation (PDO) in the North Pacific. Besides, the Ishii map shows strong signals related to the western boundary currents (Gulf Stream and Kuroshio current) as well as significant signal associated with the Antarctic Circumpolar Current. These patterns are less visible in the Levitus map which appears noisier, with high-energy meso-scale structures for which it is hard to say whether these are artefacts or not (see Section 2).

3.5. EOF analysis of gridded thermosteric sea-level time series for 1950–1998

Empirical Orthogonal Function (EOF) decomposition was applied to the gridded thermosteric sea-level time series (based on temperature data down to 500 m) for 1950–1998. Fig. 4 compares the first mode of the EOF decomposition for each data set.
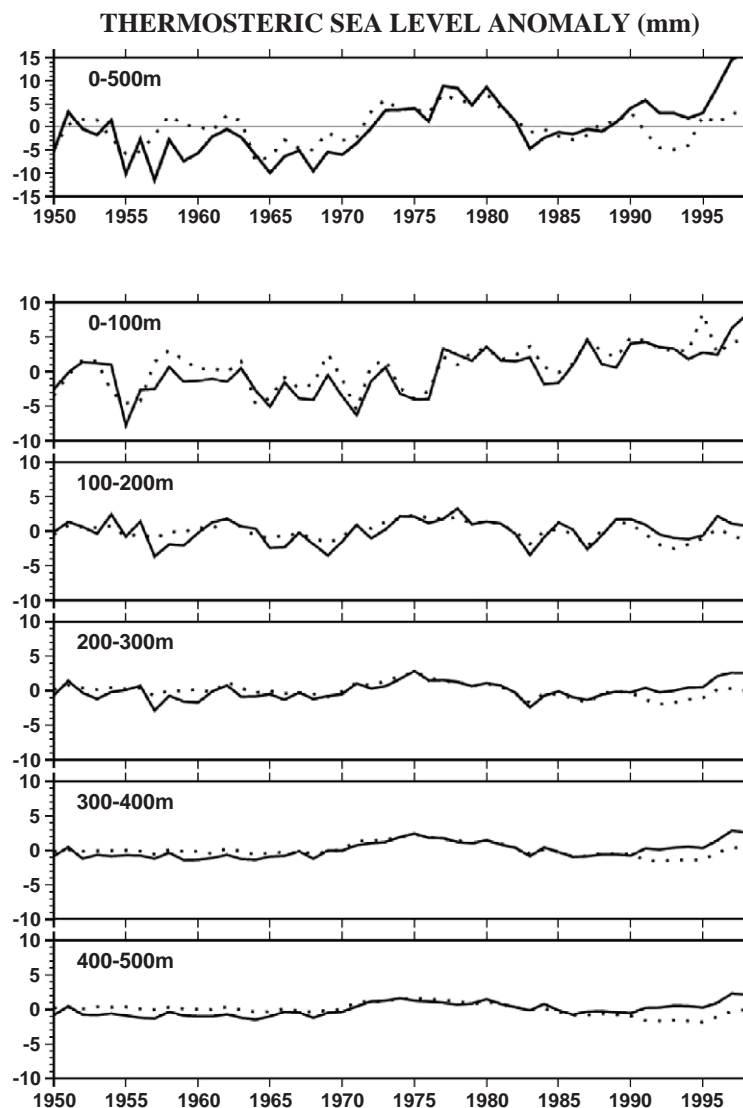
THERMOSTERIC SEA LEVEL ANOMALY (mm)

Fig. 2. Thermosteric sea level for different depth layers (top curve: 0–500 m, then for 100-m-thick layers from surface to 500 m). Solid curves are based on Levitus data. Dotted curves are based on Ishii data.

The geographical maps are very similar to the trends maps shown in Fig. 3. The temporal curves super-impose quite well. We first notice a shift around 1980, with negative values before 1980 and positive values later on. We also observe strong interannual/decadal oscillations which correspond to the ENSO signature. As shown in Fig. 4, this is indeed confirmed by the high correlation (0.80) noticed between the temporal curves and the Southern Oscillation Index (SOI) which is superimposed. Thus, ENSO-related variability accounts for the largest fraction of variance in spatial patterns of thermosteric sea-level variability. Note that the variances of the leading modes are higher in the Ishii EOF (Mode 1: 27.8%, Mode 2: 15.0%, Mode 3: 8.4%) than in the Levitus EOF (Mode 1: 14.9%, Mode 2: 8.1%, Mode 3: 5.4%), suggesting that the former data set contains more significant signal.
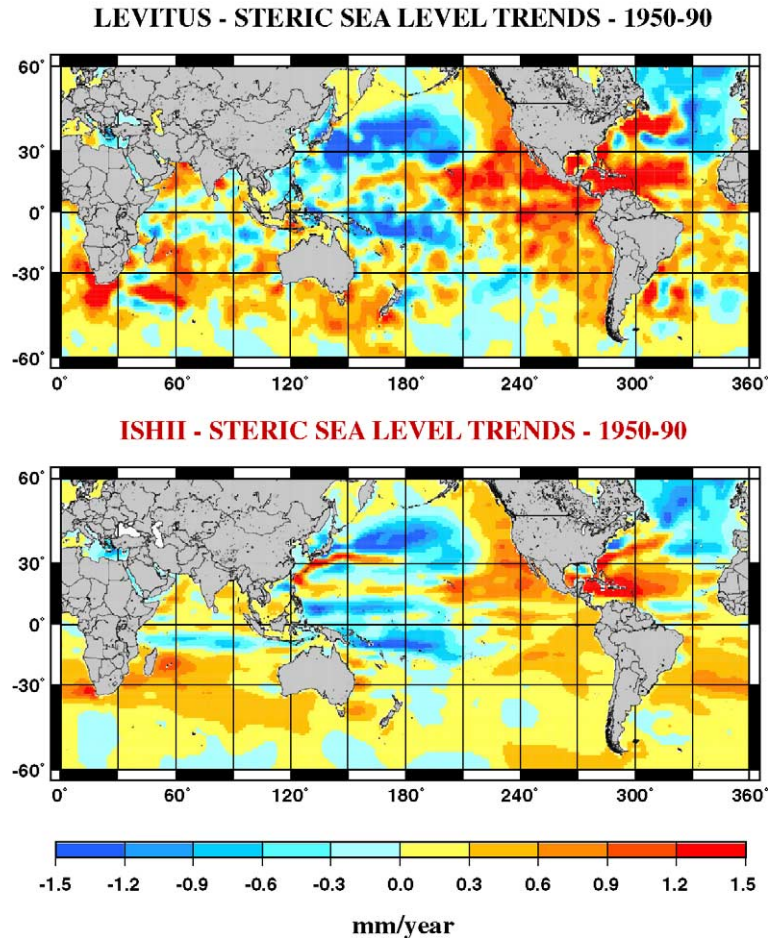
Fig. 3. Geographical distribution of thermosteric sea-level trends for 1950–1990 and the upper 500 m. Upper panel—Levitus data; lower panel—Ishii data.

If thermosteric sea-level data over the tropical Pacific are removed – in order to cancel the effects of ENSO –, then the temporal curves of the first EOF mode (Fig. 5) show a dominant long-term behaviour, with a quasi-monotonic increase since 1965 for the Levitus curve while the Ishii curve shows an abrupt increase in the mid-1970s. Such behaviour seems to originate in the Atlantic Ocean, as confirmed by the first EOF mode calculated with Atlantic sea-level data only (not shown). The latter result agrees with Levitus et al. (2000b) conclusions who reported almost continuous warming in the Atlantic Ocean during the past 50 years. Although warming in the Pacific and Indian oceans was also pronounced, the heat content in the latter two oceans is dominated by

decadal fluctuations. In our EOF decomposition, in agreement with the Levitus et al. (2000b) heat content estimates, thermosteric sea level appears dominated by interannual and decadal variability in the Pacific and Indian Oceans, while it shows a long-term, perhaps step-like pronounced increase in the Atlantic. In addition, the Atlantic thermosteric sea-level mode seems to be influenced by the NAO. This is illustrated in Fig. 6 which shows the first EOF mode for the North Atlantic (20°N–80°N, Ishii data only) with the temporal curve on which is super-imposed the Winter NAO index (the NAO index data were provided by the Climate Analysis Section, NCAR, Boulder, USA, Hurrell (1995)). Although the correlation (0.55) is smaller than with SOI in the
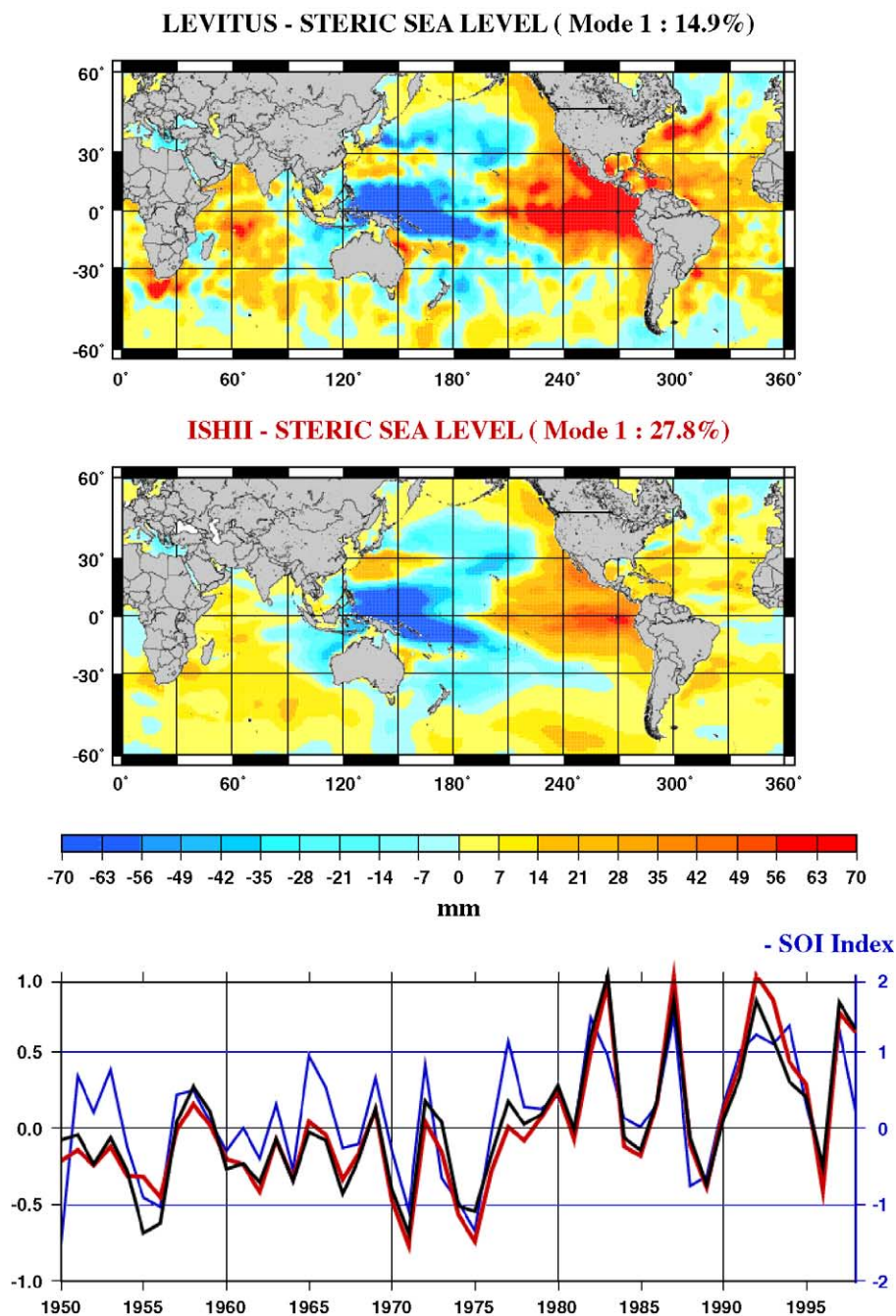
Fig. 4. The first EOF mode of thermosteric sea level computed with Levitus data (black) and Ishii data (red) down to 500 m. The SOI index is shown in blue.

tropical Pacific, decadal thermosteric sea-level fluc-tuations in the north Atlantic are well correlated with the NAO index. We note a long-term decrease from 1950 to 1970 followed by a long-term increase from 1970 to 1995, both observed in NAO index and thermosteric sea-level EOF first mode time series.

LEVITUS - STERIC SEA LEVEL (Mode 1: 10.2%)

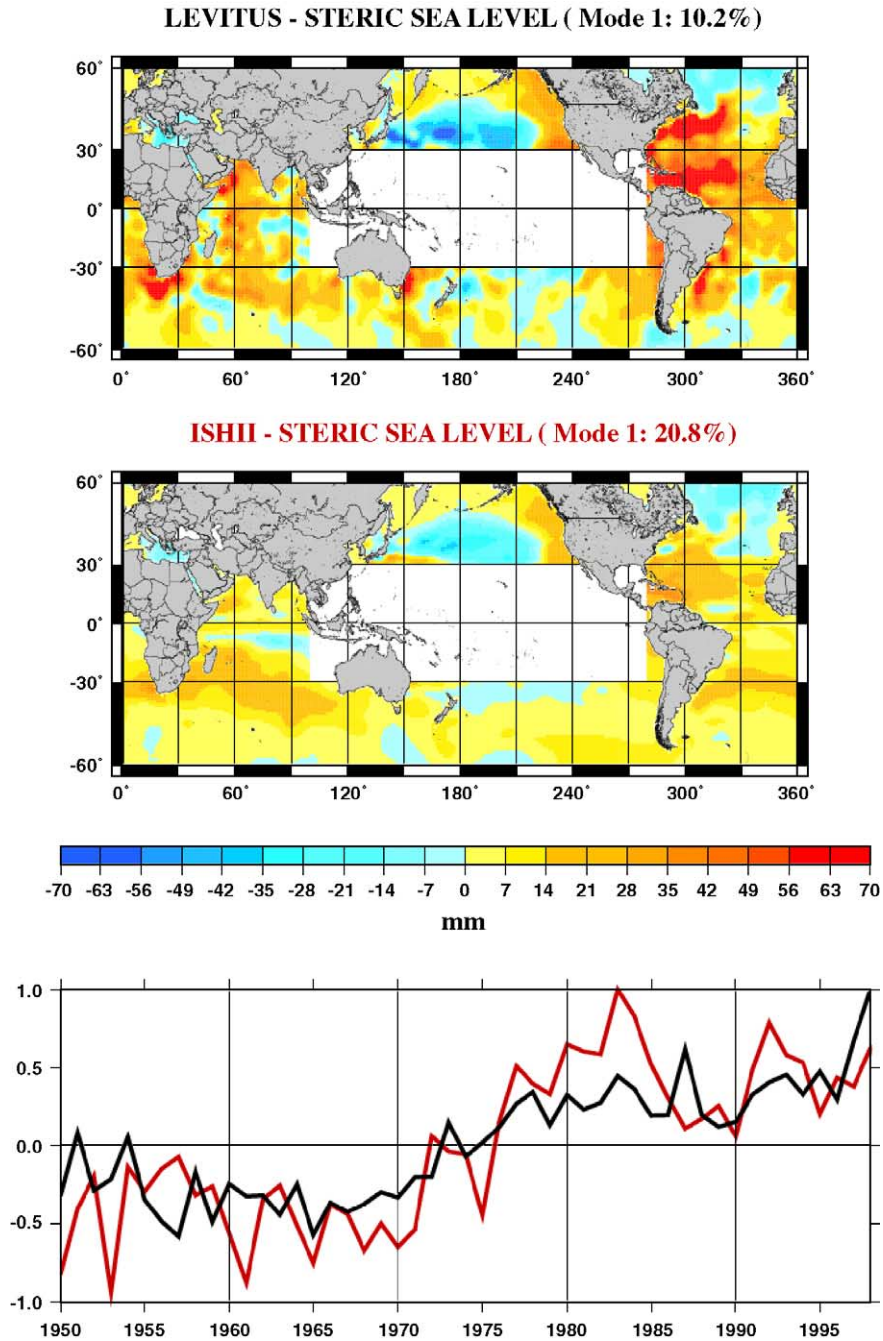## ISHII - STERIC SEA LEVEL (Mode 1: 20.8%)

Fig. 5. Same as Fig. 4, but without the tropical Pacific data.

Moreover, the clear 5 to 10 years of oscillation seen in the NAO time series is also found in the thermosteric sea-level curve, although presenting often less relative amplitude and a shift in time. Moreover,

the NAO index exhibits a large change around 1970. A similar behaviour is observed in the EOF first mode which clearly displays the positive sea-level anomaly associated with the subtropical gyre south of 30°N–

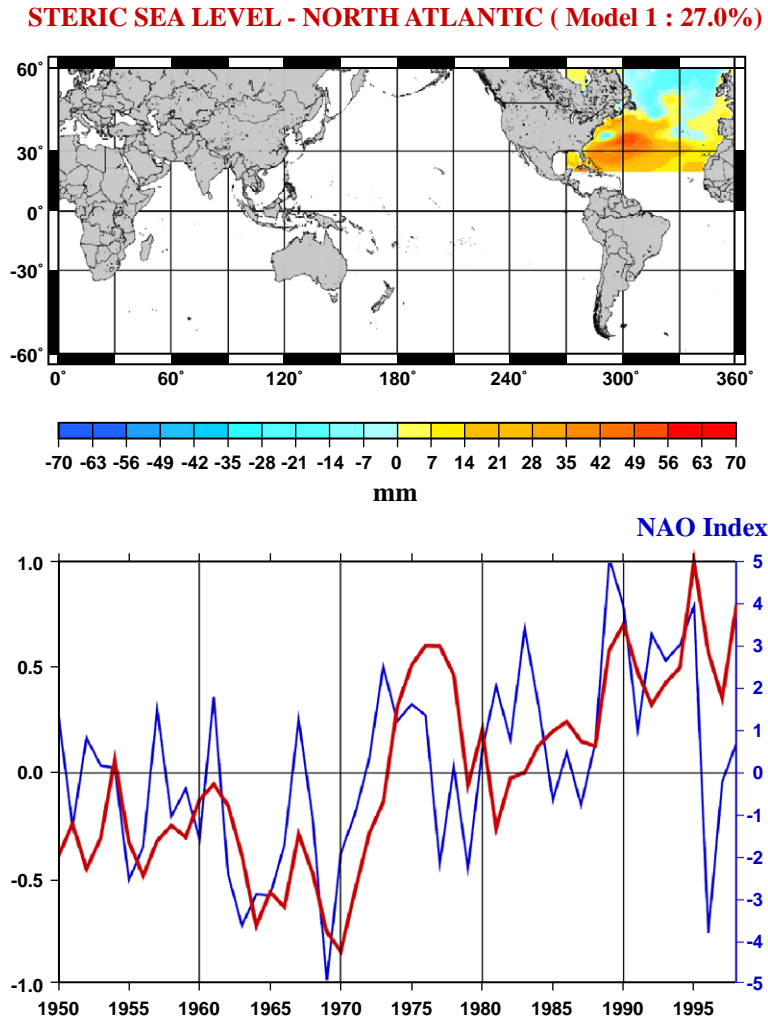**STERIC SEA LEVEL - NORTH ATLANTIC (Model 1 : 27.0%)**

Fig. 6. First EOF mode of the Ishii thermosteric sea level over the North Atlantic for 1950–1998. The blue curve is the NAO index.

40°N, as well as the negative anomaly due to the subpolar gyre, although less well marked.

Finally, if we focus on the North Pacific Ocean, thermal expansion patterns appear dominated by dipole-like oscillations again: in Fig. 7 are plotted the spatial and temporal representations of the thermosteric sea-level EOF first mode with Ishii data set. Clearly the thermosteric sea-level fluctuations are highly correlated (0.90) with the Pacific Decadal Oscillation index (the PDO Index was provided by N.J. Mantua et al. (1997), through the following website: http://www.jisao.washington.edu/pdo/PDO.latest).

4. Lifetime of thermosteric trends variability

As indicated by the EOF analyses, thermosteric sea-level variations seem to be influenced by decadal climate-related fluctuations. This suggests that thermosteric spatial trends are not stationary with time. In order to investigate this hypothesis further, we have computed series of thermosteric trends maps over successive 10-year periods (with a 5-year overlap) over 1955–1998. Fig. 8 highlights the non-stationary behaviour of steric trends patterns, which exhibit clear oscillations with dipole-like patterns. These patterns seem to be associated with the main coupled ocean–
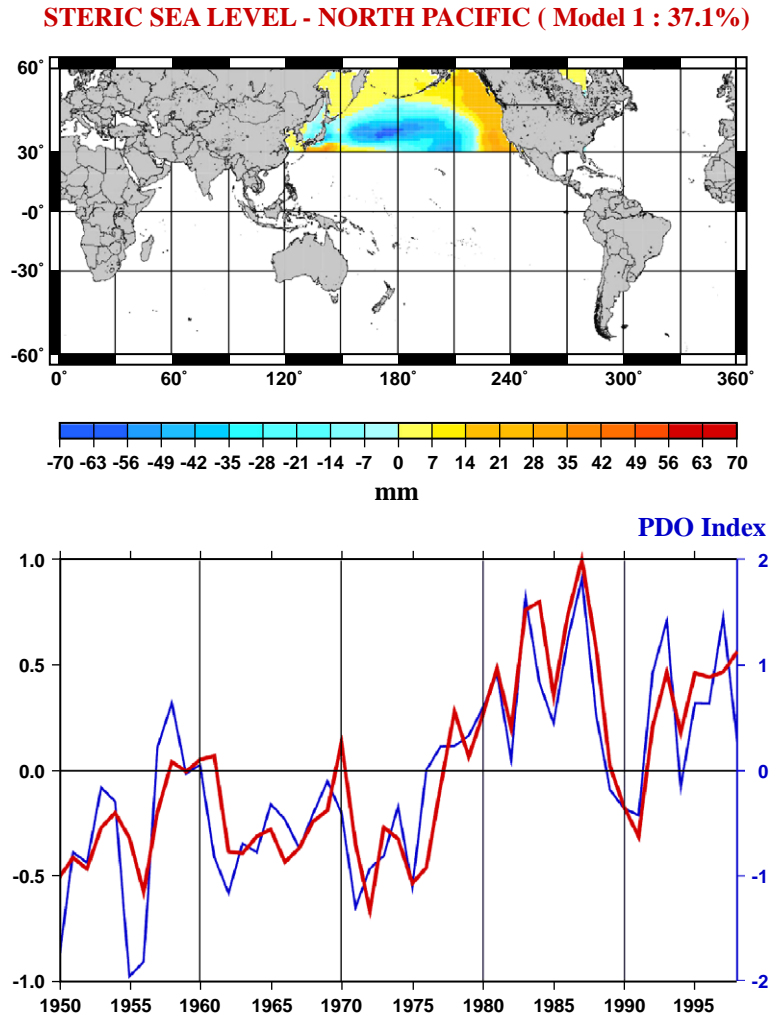
Fig. 7. First EOF mode of the Ishii thermosteric sea level over the North Pacific for 1950–1998. The blue curve is the PDO index.

atmosphere climatic perturbations (ENSO, PDO and NAO). The decadal pattern in Fig. 8 is in good agreement with the pattern found by Groger and Plag (1993) from tide gauge data analysis.

Global mean thermosteric sea-level trends within 10-year windows are plotted in Fig. 9: These trends computed over 10-year windows show large fluctuations in time, with positive values (in the range 1 to 1.5 mm/year for the decade centered on 1970) and negative values (−1 to −1.5 mm/year for the decade centered on 1980).

This analysis confirms that thermal expansion patterns are far from being stationary in time: from Fig. 8, there is a typical time scale of 5–15 years in

the thermal contribution to sea-level variations. Besides, Fig. 9 shows that in terms of global mean, thermosteric trends computed over 10-year windows exhibit a time oscillation of ~20-year period. Thus deriving trends from intervals shorter than the longest oscillatory time scale cannot be used for extrapolating backward or forward in time.

5. Thermosteric and Topex/Poseidon-based sea-level trends for 1993–1998

Fig. 10 compares sea-level trends maps for 1993–1998 from Topex/Poseidon with thermosteric sea-

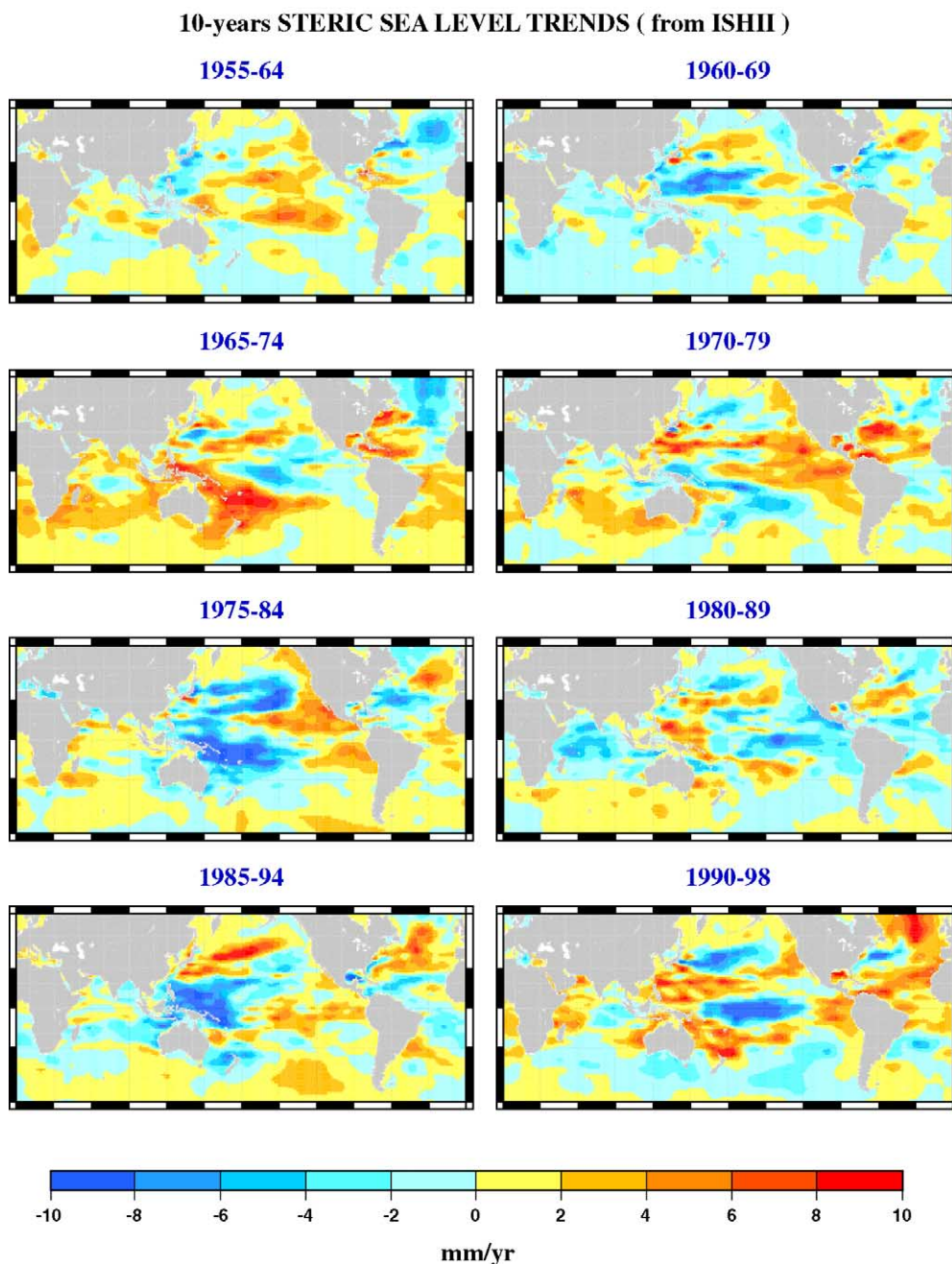**10-years STERIC SEA LEVEL TRENDS (from ISHII)**

Fig. 8. Geographical distribution of thermosteric sea-level trends for successive and overlapping 10-year periods from 1955 until 1998, from Ishii data set.

level trends based on Ishii data (we do not reproduce here the trends map based on Levitus data since it is shown in Cabanes et al., 2001). As previously noticed by Cabanes et al. (2001), the agreement between thermosteric trends and Topex/Poseidon sea-level trends is excellent. The correlation is even better with

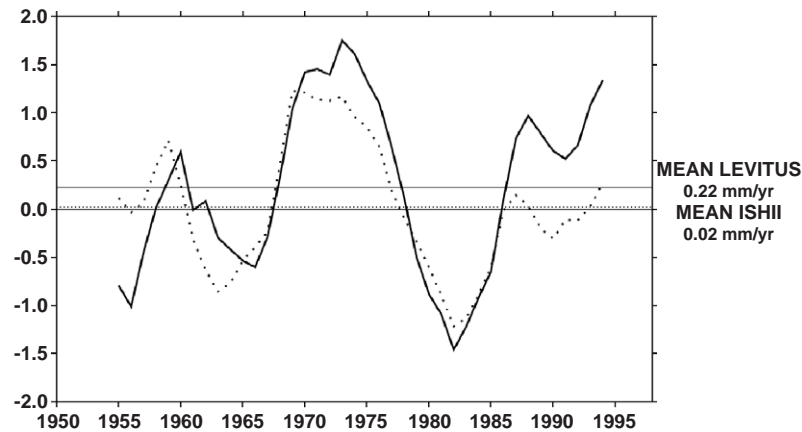**10-YEAR PERIOD GLOBAL MEAN STERIC SEA LEVEL TRENDS (mm/yr)**

Fig. 9. Global mean thermosteric sea-level trends for successive and overlapping 10-year periods from 1950 until 1998, from Levitus data set (solid curve) and from Ishii data set (dotted curve). Horizontal lines indicate the global average rates for the decade of respectively 0.22 mm/year for Levitus data, and 0.02 mm/year for Ishii data.

the Ishii map (0.57 for 60S–60N and 0.71 for 30S–60N) than with the Levitus map (0.48 for 60S–60N and 0.62 for 30S–60N). However, as in Cabanes et al. (2001)'s study based on Levitus data, the Ishii-based thermosteric trends map also appears unable to reproduce the large positive trends observed by Topex/Poseidon in the southern oceans. This raises the problem of the lack of hydrographic observational data south to 30°S. The spatial distribution of hydrographic measurements for the 1993–1998 period shows large zones in the Indian and Pacific oceans totally under sampled, and temperature coverage in remote southern oceans is really sparse. On the other hand, the small thermosteric sea-level trends obtained with Ishii data set in the southern oceans may also result from their uncorrected XBT temperature data in this region.

Fig. 11 is a map of sea-level differences (Topex/Poseidon sea-level trends minus Ishii-based thermal expansion). The residual sea-level map may contain variability from four different sources: (1) errors on the thermosteric contribution estimation (due to scarce temperature data, especially south of 30°S and lack of XBT depth correction), (2) deep (500–3000 m) thermal contribution, (3) water mass addition (from continents and ice caps) and (4) local salinity variations. The root-mean-square of the residual is 1.3 mm/year.

An attempt to quantify the deep thermal contribution for the last decade was made by Cabanes (2003) who computed the global mean thermal expansion for

the ocean layers 500–3000 m, for successive 10-year periods between 1955 and 1990. For that purpose, she used the 0–3000-m and the 0–500-m Levitus data sets to compute the global mean thermosteric sea-level difference between both contributions. She found that the mean contribution of the 500–3000-m layers is about 0.2 ± 0.2 mm/year, and adopted this value for the period 1993–1998. On a longer time scale, for the historical time span 1955–1994, she found that the first 500-m thermal expansion explains about 55% of the total 0–3000-m thermal expansion. This result seems not to be applied to shorter time scales, however it would leave a large place for deep thermal contribution to explain the residual sea-level trends.

In terms of global mean over the period 1993–1998, the observed (i.e., from Topex/Poseidon) rate of sea-level rise amounts to 3.2 ± 0.2 mm/year while the Ishii-based thermosteric trend is only 1.7 ± 0.4 mm/year. Thus thermal expansion based on the Ishii data set accounts for only about half of the rate of observed sea-level rise during 1993–1998, whereas the Levitus data suggested that enough warming occurred during this period to account for all the T/P observed sea-level rise. However, keeping in mind that the estimate of the Ishii-based thermosteric contribution is likely to be underestimated to the omission of XBT depth correction and the Levitus-based contribution may be overestimated, we conclude that the real thermosteric sea-level rate lies between these two values. It is

TOPEX/POSEIDON - SEA LEVEL TRENDS - 1993-98

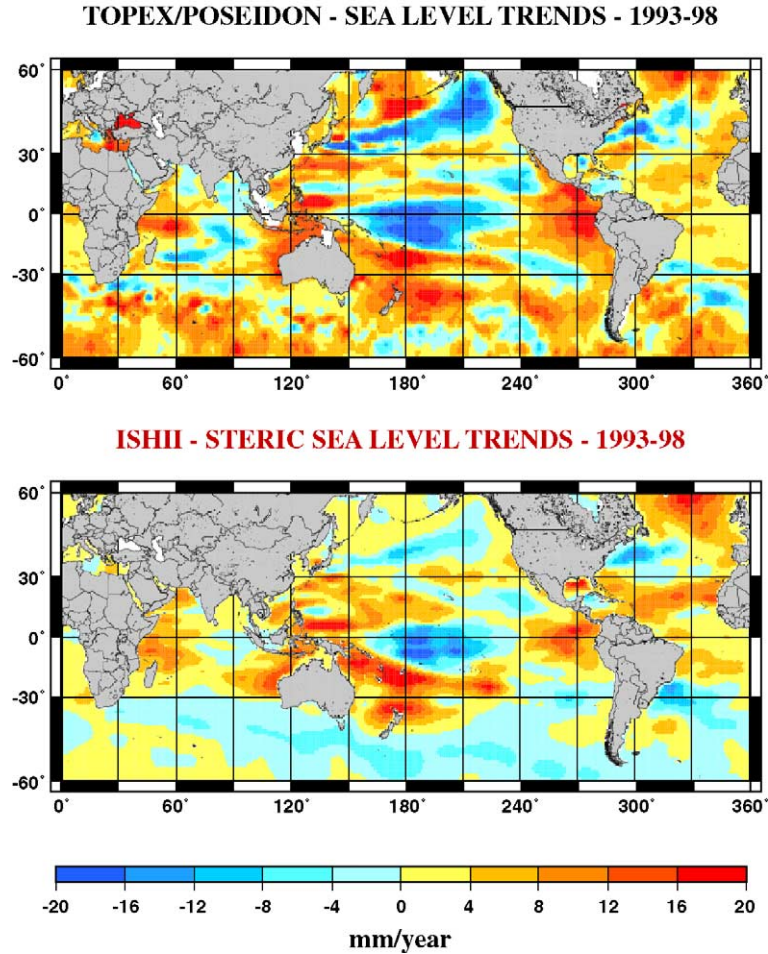## ISHII - STERIC SEA LEVEL TRENDS - 1993-98

Fig. 10. Sea-level trends maps for Topex/Poseidon-derived (upper panel) and thermosteric sea level from Ishii data (lower panel) for 1993–1998.

worth mentioning that if we exclude the 30°S–60°S region, the mean thermosteric trend based on Ishii data amounts to 2.6 ± 0.4 mm/year over 1993–1998, value in good agreement to the Topex/Poseidon trend, of 2.4 ± 0.2 mm/year over the same period and same region. This probably results from the large number of good quality TOGA data in the tropical Pacific.

In a recent study based on combined satellite and in situ hydrographic data, Willis et al. (2004) estimated the thermosteric sea-level rise for the last decade (1993 to 2003) at 1.6 ± 0.3 mm/year, explaining about two-thirds of the total observed sea-level rise (2.5 ± 0.4 mm/year for 1993–2003). Thus different estimates of last decade contribution of thermal expansion to global mean sea-level rise are in the

range one half to hundred percent of the total observed sea-level increase. Please remember that these results may not be representative of 20th century sea-level rise, because of the important decadal variability of thermal expansion (see Section 4).

6. Discussion

The main results of this study are the following:

– Thermosteric sea-level variations are dominated by the decadal oscillations of the main coupled ocean–atmosphere climatic perturbations (ENSO, PDO and at a less extent NAO). Global mean thermo-

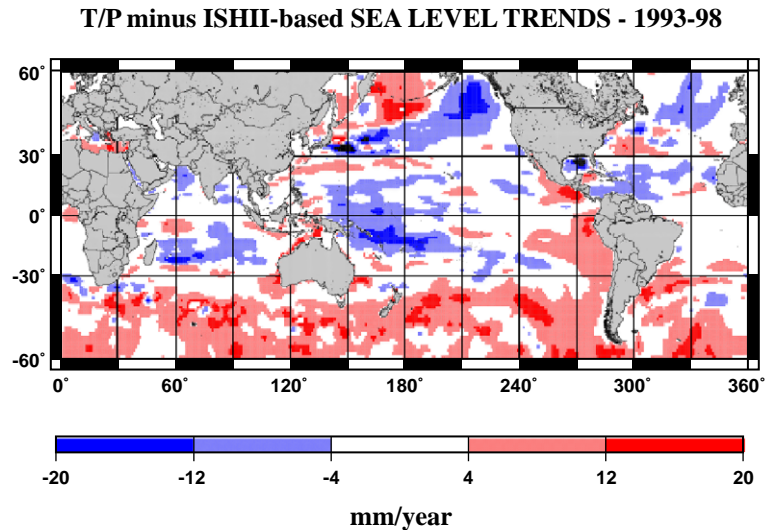**T/P minus ISHII-based SEA LEVEL TRENDS - 1993-98**

Fig. 11. Differences (T/P minus Ishii thermosteric) sea-level trends map for 1993–1998.

steric sea-level trends have an oscillatory behaviour on multi-decadal time scale. This multi-decadal variability has a great influence on the estimation of long-term rate of thermal expansion.

– Observed regional trends patterns in sea-level trends over 1993–1998 from T/P are mainly explained by thermal expansion (at least in regions where there is a reasonable coverage of hydrographic observations, i.e., 30S–60N). As thermal expansion fluctuates geographically in response to ENSO, PDO and NAO, so do the T/P sea-level trends. Thus presently, we simply cannot extrapolate sea level into the past or the future using satellite altimetry alone.

– However non-negligible differences are observed between T/P sea-level variations and thermal expansion (based on Ishii et al. data), both in terms of trend patterns and of global mean sea-level variations. Regional residuals may arise from unknown deep thermal contribution, local salinity variations or water mass addition. But the major source of discrepancies between T/P observed sea-level trends and thermosteric sea-level patterns may be due to the dramatic lack of observational hydrographic data south of 30°S. This may lead to wrong estimates of thermal expansion in these remote regions. Another cause of discrepancy between Ishii-based, Levitus-based and T/P sea-level varia-

tions may be due to the XBT depth correction which was not applied in Ishii data while applied twice in the Levitus one. Finally, elastico-gravity effects on observed sea level (i.e., T/P) may partly contribute to the observed difference.

– In the future, we should be able, however, to much better estimate the steric sea-level variations thanks to the global array of profiling floats that is deployed as part of the Argo project (Roemmich et al., 1999). Furthermore, combined analysis of altimetry-derived sea level and GRACE observations (launched in 2002 and providing an observation of the water mass exchange with continents) will offer indirect information on steric effects.

Acknowledgements

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