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Global Distribution of Thermosteric Contribution to Sea Level Rising Trend

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Abstract The sea level derived from TOPEX/Poseidon (T/P) altimetry data shows prominent long term trend and inter-annual variability. The global mean sea level rising rate during 1993–2003 was 2.9 mm a^{-1}. The T/P sea level trend maps the geographical variability. In the Northern Hemisphere (15˚–64˚N), the sea level rise is very fast at the mid-latitude (20˚–40˚N) but much slower at the high-latitude, for example, only 0.5 mm a^{-1} in the latitude band 40˚–50˚N. In the Southern Hemisphere, the sea level shows high rising rate both in mid-latitude and high-latitude areas, for example, 5.1 mm a^{-1} in the band 40˚–50˚S. The global thermosteric sea level (TSL) derived from Ishii temperature data was rising during 1993–2003 at a rate of 1.2 mm a^{-1} and accounted for more than 40% of the global T/P sea level rise. The contributions of the TSL distribution are not spatially uniform; for instance, the percentage is 67% for the Northern Hemisphere and only 29% for the Southern Hemisphere (15˚–64˚S) and the maximum thermosteric contribution appears in the Pacific Ocean, which contributes more than 60% of the global TSL. The sea level change trend in tropical ocean is mainly caused by the thermosteric effect, which is different from the case of seasonal variability in this area. The TSL variability dominates the T/P sea level rise in the North Atlantic, but it is small in other areas, and shows negative trend at the high-latitude area (40˚–60˚N, and 50˚–60˚S). The global TSL during 1945–2003 showed obvious rising trend with the rate of about 0.3 mm a^{-1} and striking inter-annual and decadal variability with period of 20 years. In the past 60 years, the Atlantic TSL was rising continuously and remarkably, contributing 38% to the global TSL rising. The TSL in the Pacific and Indian Ocean rose with significant inter-annual and decadal variability. The first EOF mode of the global TSL from Ishii temperature data was the ENSO mode in which the time series of the first mode showed steady rising trend. Among the three oceans, the first mode of the Pacific TSL presented the ENSO mode; there was relatively steady rising trend in the Atlantic Ocean, and no dominant mode in the Indian Ocean.

Key words thermosteric effect; sea level trend; T/P altimeter; spatial distribution

1 Introduction

The global sea level rose with the rate of 1–2 mm a^{-1} during the past 50–100 years (Church *et al.*, 2001). Leuliette *et al.* (2004) analysed the T/P and Jason altimeter data during 1993–2003 and obtained the global mean sea level rising rate (2.8±0.4) mm a^{-1}. Cabanes *et al.* (2001a) studied the inter-annual variability of the sea level on both the global and the basin scales with T/P data, which indicated that the tropical Pacific Ocean (30˚S–30˚N) was the main contributor to the quick rise of the global sea level in the spring of 1997 and the sea level rise was in good correlation with an increase of SST, especially for the period 1997–1999.

As pointed out in the IPCC third assessment report, according to the results of Atmosphere-Ocean General Circulation models (AOGCMs), the most important contributor to the sea level rise was thermal expansion, about 0.3–0.7 mm a^{-1} when averaged over the 20th century; melting of mountain glaciers and ice caps contributed 0.2–0.4 mm a^{-1}; the ice melting of the Greenland and the Antarctic ice sheet contributed −0.2–0.6 mm a^{-1} (Church *et al.*, 2001).

For the period 1955–2003, the thermal expansion of the 0–700 m layer of the world ocean contributed approximately 0.3 mm a^{-1} to the global sea level rise (Antonov *et al.*, 2005). About half of this rise was due to the Atlantic Ocean warming and one third came from the warming of the Pacific Ocean. For the period of available T/P altimetry data (1993–2003), the linear rise of the thermosteric sea level was 1.2 mm a^{-1} in upper ocean (0–700 m), 60% of which was due to the rise in the Pacific Ocean. Chen *et al.* (2000) pointed out the observed seasonal sea level was mainly affected by the steric sea level at mid-latitude. The thermal effect accounted for 86% and 73% of the seasonal variability in the Northern and Southern Hemisphere, respectively (Zuo *et al.*, 2009). Lombard *et al.* (2005a) found that the inter-annual variability was

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dominated by ENSO, PDO, and NAO. The regional steric sea-level change trends were not stationary on a century time scale, showing a typical lifetime on the order of a decade (Ishii *et al.*, 2006; Antonov *et al.*, 2005).

In this paper, the global sea level trend and inter-annual sea level variability are studied and we focus on the spatial patterns of the sea level change in different basins and the geographical distribution of thermosteric effect contribution to the sea level change. Finally, the TSL principal modes in different basins are presented for the past 60 years.

2 Data

The monthly mean sea level anomaly data (1993–2003) of T/P and Jason-1 satellite altimeter provided by the Austin Center for Space Research (UT/SCR) of the University of Texas, with the spatial resolution of 1˚×1˚, are used in this study. The data have been corrected with media and instrument corrections (ionosphere, dry and wet troposphere, and electromagnetic bias) and geophysical correction (tidal and inverted barometer) before analysis.

The Ishii data set consists of monthly 1˚×1˚ gridded temperature data at 16 levels in the upper 700 m of the ocean during 1945–2003, and its version 6.1 is the historical objective analysis of subsurface temperature and salinity field provided by Japan Meteorological Agency. The analysis is based on the World Ocean Database (WOD05), the global temperature and salinity in the tropical Pacific from IRD (L'institut de recherche pour le développement, France) and the sea surface temperature from Centennial *in situ* Observation Based Estimates (COBE). ARGO profiling buoy data have also been used in the last several years. The XBT depth bias correction is applied in the current version (Ishii *et al.*, 2006). The Ishii data spatial coverage is nearly global within 89.5˚S–89.5˚N, 0.5˚–359.5˚E. Lombard *et al.* (2005b) computed the thermosteric sea level change using two global temperature data sets of Levitus and Ishii respectively, and found that the Ishii sea level was lower than the Levitus sea level after 1990. However, the two data sets showed good coincidence over 1950–1990, both in terms of thermosteric sea level trends and global mean. The IPCC fourth assessment report (Bindoff *et al.*, 2007) cited the result from the Ishii data.

In this paper, the thermosteric effect represents the sea level variation caused by the thermal expansion. The thermosteric sea level is calculated from vertically integrating the temperature anomalies in Ishii data at each time step and each grid spacing as explained in detail in Yan *et al.* (2007).

3 Sea Level Rise and Thermosteric Effect During 1993–2003

Previous studies with tide gauge record and T/P altimetry data showed global or regional sea level rise in the 20th century (Cabanse *et al.*, 2001b; Church *et al.*, 2001; Ishii *et al.*, 2006; Zuo *et al.*, 2009). This paper will focus on the T/P sea level and TSL variation in different regions and over different time scales. Two aspects of the problem are discussed: secular change in different regions (global, ocean basins and latitude bands) and spatial distribution of T/P sea level and TSL variations from 1993 to 2003 together with the thermosteric effect contributions in the variation.

3.1 Secular Change in Different Regions

3.1.1 Global

The global mean T/P sea level (64˚S–64˚N) shows prominent rising trend with the rising rate of 2.9 mm a^{-1} (Fig.1), showing good agreement with Leuliette *et al.* (2004). The trends of the mean T/P sea level in the three selected regions at latitude bands of 15˚–64˚S, 15˚–64˚N and 15˚S–15˚N, are shown in Fig.2. The T/P sea level rises rapidly in the Southern Hemisphere (15˚–64˚S), at a rate of 3.9 mm a^{-1}, which contributes 58% to the mean sea level rise for the three selected areas (Fig.2c), while the rising is relatively slow in the North Hemisphere (15˚–64˚N) and low latitude area (15˚S–15˚N), at a rate of about 2.0 mm a^{-1}. The T/P mean sea level at the low latitude area (15˚S–15˚N) shows a strong inter-annual variation, especially during the 1997/1998 El Niño event.

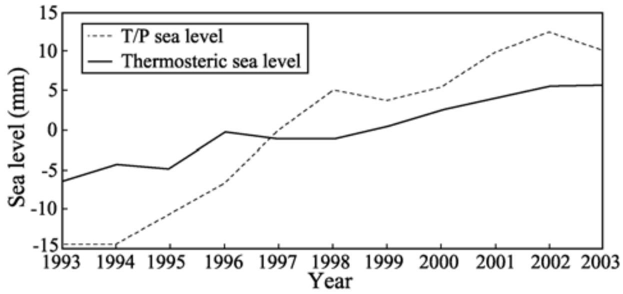

Fig.1 Annual variation of the global mean T/P sea level (dashed) and the thermosteric sea level (solid).

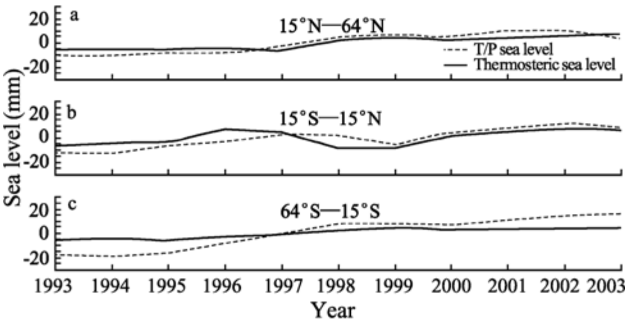

Fig.2 Annual variation of the T/P sea level (dashed), the TSL (solid) in the Northern Hemisphere (upper), the low-latitude area (middle) and the Southern Hemisphere (bottom).

The global TSL shows obvious rising trend (Fig.1), at a rate of 1.2 mm a^{-1}, which accounts for the 42% rise of the T/P sea level. The TSL rise by 1.5 mm a^{-1}, at the latitude band of 15˚–64˚N is the fastest, while the rising rates in the low-latitude area and the Southern Hemisphere are almost the same, about 1.1 mm a^{-1}. The contribution of regional TSL to T/P sea level rise maps extinctively the geographical variability. The contribution of the TSL trend to the T/P sea level rise is 67% at the northern mid-latitude, showing good correlation between these two kinds of the sea level, while it is only 29% at the southern mid-latitude. In the tropical ocean (30˚S–30˚N), the rate of TSL rise is 1.1 mm a^{-1}, accounting for 53% of the T/P sea level rise (Fig.2). The thermosteric effect is the main contributor to the sea level rise, which represents a quite different case for the seasonal variability.

3.1.2 Three oceans

The T/P sea level shows an obvious rising trend for all ocean basins (Fig.3), especially in the South Hemispheres, *e.g.* 4.7 mm a^{-1} in the South Pacific, and also larger than 4.0 mm a^{-1} in the South Atlantic and the South Indian Ocean. But the rising rate is relatively small, about 2.0 mm a^{-1} in the North Hemispheres with significant seasonal variability. Among the three oceans, the biggest contributor to global sea level rise appears in the Pacific, about 52%, which is related with its vast area.

The nonuniform distribution of the TSL rise exists in the different basins (Fig.3). The Pacific TSL rise is the largest, about 1.5 mm a^{-1}, and accounts more than 60% for the global TSL rise. The TSL rising rate is approximately 1.0 mm a^{-1} for the Atlantic and the Indian Ocean. On basin scale, the rise of mean TSL of the Northern Atlantic is most remarkable, while it is less so in the tropical Atlantic. The Pacific presents a different case, where the TSL rise in the tropical Pacific is larger than that in the Northern Pacific (Table 1, Fig.3).

The contribution of the TSL rise to the T/P sea level rise in the Pacific Ocean is the largest among the three oceans (50%); the percentage is over 30% for both the Atlantic Ocean and the Indian Ocean. For the Pacific Ocean, the TSL contribution to the T/P sea level rise derived from Ishii data is 71% in the tropical area, while it is negative in the North Pacific. For the Atlantic Ocean, the contribution is very small in the tropical area, while thermosteric effect is the major contributor in the Northern Atlantic, about 113%. For the three southern basins, especially the Southern Atlantic, the thermosteric effect contributes little to the T/P sea level rise. The intense inter-annual sea level variation around 1997/1998 for the tropical Indian ocean is mainly the result from the thermosteric effect (Nerem *et al.*, 1999).

Table 1 Sea level trend and the contribution of TSL in different ocean regions

Regions	T/P Sea level		TSL derived from Ishii data			Area percentage (%)
	Trend (mm a^{-1})	Variance	Trend (mm a^{-1})	Variance	Ishii/(T/P) (%)	
0˚–10˚N	1.8	6.4	1.0	8.4	55	10
10˚–20˚N	2.3	7.6	2.2	17.1	97	9
20˚–30˚N	2.6	6.9	1.4	8.8	54	8
30˚–40˚N	4.2	8.9	2.1	10.4	50	6
40˚–50˚N	0.5	0.8	−0.7	−2.6	146	4
50˚–60˚N	−0.7	−0.7	1.4	3.5	205	3
0˚–10˚S	1.9	6.8	0.9	7.5	47	10
10˚–20˚S	2.8	9.9	1.1	9.0	39	10
20˚–30˚S	3.2	10.5	1.4	10.9	44	9
30˚–40˚S	4.3	14.6	2.3	18.6	54	10
40˚–50˚S	5.1	16.6	1.0	7.4	19	9
50˚–60˚S	3.5	9.3	−0.1	−0.8	−4	8
Atlantic	2.9	24.8	1.0	21.0	35	25
North Atlantic	2.3	4.6	2.6	12.5	113	6
Tropical Atlantic	2.4	9.7	0.4	4.0	17	12
South Atlantic	4.1	10.5	0.7	4.6	17	8
Indian	3.0	21.3	1.1	19.2	38	20
Tropical Indian	2.4	10.3	1.3	13.2	54	13
South Indian	4.1	10.8	0.9	5.7	22	8
Pacific	3.0	51.9	1.5	61.0	50	50
North Pacific	1.7	4.7	−0.0	−0.1	1	8
Tropical Pacific	2.6	27.0	1.9	45.5	71	29
South Pacific	4.7	20.2	1.5	15.7	33	12
15˚–64˚N	2.2	20.1	1.5	32.0	67	26
15˚S–15˚N	2.1	22.1	1.1	27.9	53	30
15˚–64˚S	3.9	57.8	1.1	40.1	29	44
30˚–64˚N	2.0	9.7	1.1	13.4	57	14
30˚S–30˚N	2.4	48.1	1.3	61.7	54	57
30˚–64˚S	4.2	42.2	1.0	24.9	24	29
45˚S–45˚N	2.9	82.0	1.5	96.0	50	80
Global Ocean (64˚S–64˚N)	2.9	100	1.2	100	42	100

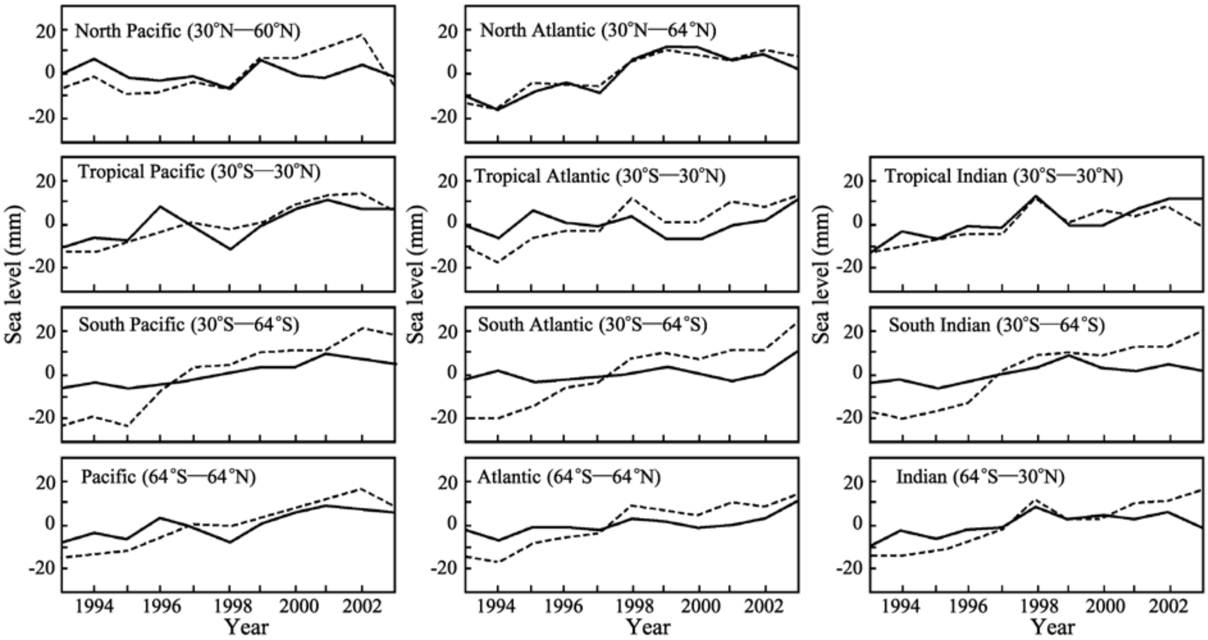

Fig.3 Annual variation of the mean T/P sea level (dashed) and the TSL (solid) in the South/North Pacific, the South/North Atlantic, the South Indian Ocean, the tropical Pacific, the tropical Atlantic, the tropical Indian Ocean, the Pacific, the Atlantic and the Indian Ocean.

3.1.3 Different latitude bands

The T/P sea level change in each 10˚ latitude band is shown in Fig.4. The T/P sea level rises at the high- and mid-latitude in the Southern Hemisphere, about 5.1 mm a^{-1} in the band of 40˚–50˚S (Fig.4a). For the Northern Hemisphere, it is larger at the mid-latitude band of 30˚–40˚N, while smaller at the high latitude (0.5 mm a^{-1} in 40˚–50˚N) and negative in 50˚–60˚N. An evident rising trend exists at low latitude (20˚S–20˚N), with a large inter-annual range of about 40 mm a^{-1} in 0˚–10˚S and 10˚–20˚N.

There exist large differences among the TSL variation at different latitude bands (Fig.4). The TSL rises faster at mid-latitude of the two hemispheres, while it rises slower, even descends, in the tropical and the high-latitude areas; for example, it shows negative trend at the latitude bands of 50˚–60˚S and 40˚–50˚N.

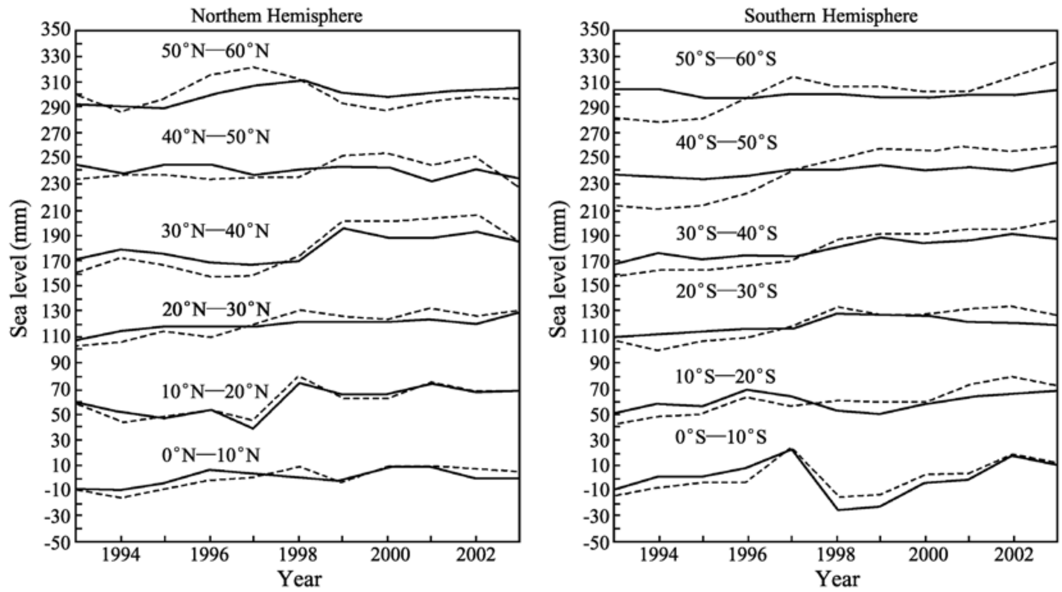

Fig.4 Variation of the T/P sea level (dashed) and the TSL (solid) obtained from Ishii data for every 10˚ latitude band.

The TSL rise contributes differently to the T/P sea level rise at the different latitude bands. The thermosteric effect is an important contributor to the T/P sea level rise, and both are in good correlation at the mid-latitude of the Northern Hemisphere. In the band of 20˚–30˚N, the thermosteric effect contribution derived from Ishii data is 54% while it is negative at high latitudes, such as 40˚–50˚N and 50˚–60˚N. At the southern mid-latitude, the T/P sea level rises faster than the thermosteric sea level. Their correlation becomes poor at the southern high latitudes. In consideration of the inter-annual variability at low latitude oceans, the correlation between the T/P sea level and the TSL is good. Their inter-annual amplitudes during the 1997/1998 ENSO event were close, especially in the bands of 0˚–10˚S and 10˚–20˚N, which suggested that the TSL change influences significantly the sea level change at low latitudes.

3.2 Spatial Distribution

3.2.1 T/P sea level trend

The T/P sea level trend mapped the obvious geographical variability during 1993–2003 (Fig.5a). Important regional difference is visible over this time span.

Some regions, the rate of the T/P sea level rise amounts to almost ten times the global mean. The larger rising rate occurs somewhere in the west Pacific, for example, the western tropical Pacific with the central rate of 12.0 mm a^{-1}, being up to five times the global mean. And the sea level rising is remarkable in a narrow band of Kuroshio extension area which stretches from the east of Japan to the central North Pacific, with the central rate of 16.0 mm a^{-1}. Another sea level rising center lies around Australia and New Zealand in the southwestern Pacific, with the central rate of 14.0 mm a^{-1}. Meanwhile, the sea level is descending in the eastern Pacific, with the central rate of −10.0 mm a^{-1}. The Indian and the Atlantic Ocean are alike, for the sea level rises in the whole basins except the northwestern Indian Ocean and some regions in the western and the central North Atlantic.

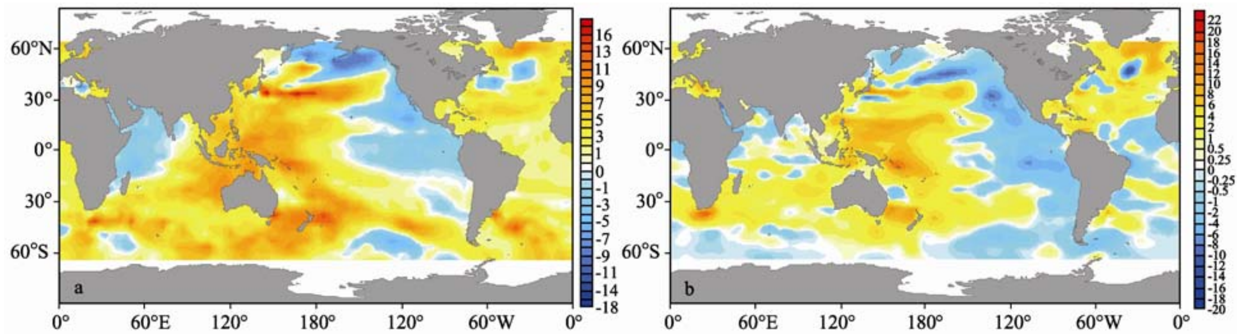

Fig.5 a. Geographical distribution of T/P sea level trend during 1993–2003. b. Geographical distribution of TSL trend derived from Ishii data during 1993–2003.

3.2.2 Thermosteric sea level trend and its contribution

The spatial distribution of the TSL trend during 1993–2003 derived from Ishii data is shown in Fig.5b. It is found that the spatial distribution of the TSL trend is in good agreement with that of the T/P sea level in the Pacific, Indian and North Atlantic with the same geographical distribution and magnitude of the maximum rates, except in the Southern Atlantic and the high latitude area. It indicates that the thermosteric effect plays an important role with the contemporaneous T/P sea level change.

In the tropical and southern Atlantic, the T/P sea level rises while the TSL drops, but they both have a rising maximum in the southwestern Atlantic. At the southern high latitudes, especially south to 50˚S, there are distinct differences between the T/P trend and the TSL rise. The southern oceans warming was also found in observed SST (Cabanse *et al.*, 2001a), which was higher than elsewhere in the world oceans. Gille (2002) analyzed the temperature data recorded by Autonomous Lagrangian Circulation Explorer float between depths 700 and 1100 m and suggested that mid-depth temperature in the Southern Ocean had been rising strikingly between the 1950 s and the 1980 s. Thus the sea level rise in the Southern Ocean during the T/P satellite observation period could be due to thermal expansion of seawater. The T/P sea level rise, the TSL trend and its contribution in different regions are shown in Table 1.

In the global oceans (64˚S–64˚N), the correlation coefficient between the T/P sea level rise and the TSL rise is 0.62; however, it is 0.71 in the oceans north of 30˚S.

4. Thermosteric Sea Level Variation in the Past 60 Years

4.1 Secular Change

Secular change of the thermosteric sea level is calculated with 0–700 m Ishii data in the past 60 years (1945–2003).

4.1.1 Global

The global TSL rose remarkably from 1945 to 2003 (Fig.6), when significant fluctuations on decadal time scales were superimposed on it. The global TSL rose by the rate of 0.3 mm a^{-1}, which was almost the same as the results from ocean general circulation models (Church *et al.*, 2001). But the trend was not monotonic: the TSL rose slowly before 1967 but rapidly during 1967–1975 with the rate of about 2.0 mm a^{-1}, and began to descend from 1980 to a minimum value in 1986. Since 1986, the TSL had been rising with a rate close to that of the period 1967–1975.

The TSL in the Northern Hemisphere showed noteworthy rising trend with a rate of 0.5 mm a^{-1}, associated with significant decadal variability (Fig.7). The rising rate of the northern TSL was almost 1.6 times of that in the Southern Hemisphere. The contribution of the northern TSL to the global mean TSL was less than that of the Southern Hemisphere because of the larger area of the southern oceans.

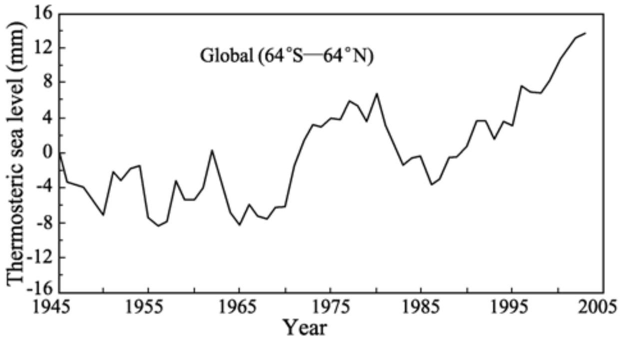

Fig.6 Annual variation of the global mean TSL derived from Ishii data during 1945–2003.

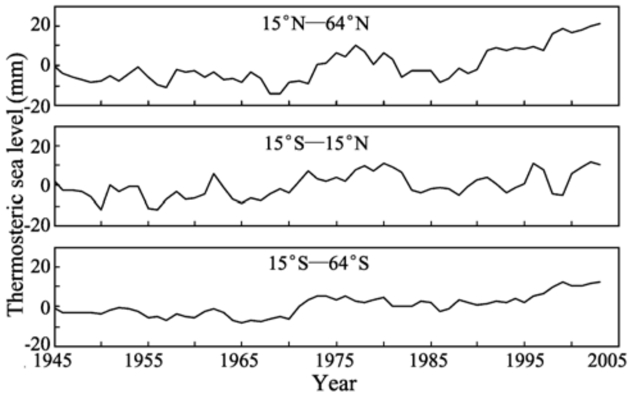

Fig.7 TSL variation in the Northern Hemisphere (upper), tropical area (middle) and Southern Hemisphere (bottom) during 1945–2003.

The TSL in the tropical area showed weaker rising trend but significant inter-annual variability that might be associated with ENSO events (Lombard *et al.*, 2005a). There was a peak around 1977–1979 associated with the 1977/78 ENSO event.

4.1.2 Three oceans

The TSL variations in the past 60 years were calculated for the South /North Pacific, the South/North Atlantic, the South Indian, the tropical Pacific, the tropical Atlantic, and the tropical Indian; the variations in the latitude band 64˚S–64˚N in the Pacific, Atlantic and Indian ocean were also calculated (Fig.8).

The Atlantic TSL kept rising over the past 60 years with little inter-annual and decadal fluctuation, but it was rising in the Pacific and the Indian Ocean associated with striking inter-annual and decadal variabilities. In the Pacific Ocean, the TSL trend was similar to that of the global mean TSL, both of which rose rapidly in the beginning of the 1970s and mid-1980s. In the Indian Ocean, it had been rising rapidly since 1960s. While the case was a little different in the Atlantic Ocean, where the TSL kept rising from the 1950s to the beginning of the 1990s with a constant rate, but thereafter it began to rise rapidly.

The Atlantic TSL rose the fastest among the three oceans during the past 60 years. The rising rate was 0.5 mma^{-1} in the Atlantic Ocean, which accounts for 38% of the global mean TSL rise (Table 2). According to Levitus *et al.* (2005), the heat content was changing mainly in the upper 1000m layer in the Atlantic Ocean, but occurred only above 300m in the Pacific and Indian Ocean. Therefore, the contribution of the Atlantic Ocean to the global TSL variation should be larger. The TSL rising in the Pacific and Indian Ocean was smaller, with a rate of about 0.2mma^{-1}, but with significant inter-annual variability.

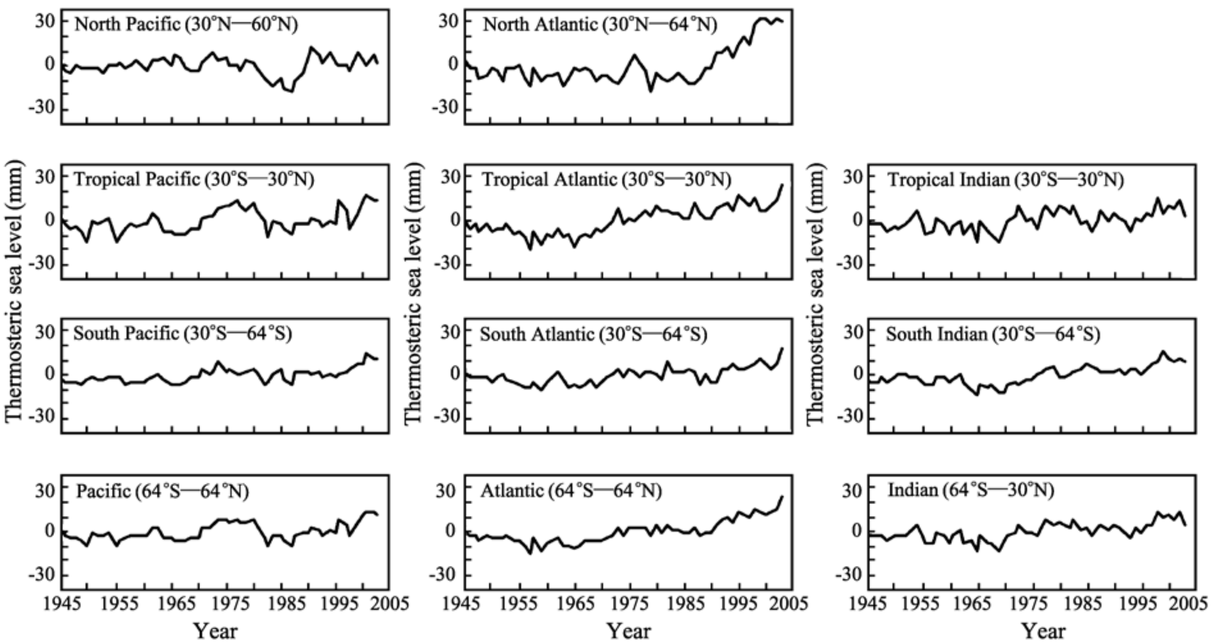

Fig.8 TSL variation in the different regions.

For the northern regions, there's significant decadal variability of the TSL in the North Pacific and North Atlantic. From the beginning of the 1970 s to the end of the 1980 s, the TSL in the North Pacific descended prominently, but began to rise since 1987, and rose by nearly 30 mm in the next 5 years. The TSL in the North Atlantic descended from 1955 to the later 1980 s, and turned to be rising again from 1987 to 2003 with a rate of 2.0 mm a^{-1}. During 1955–2003, the TSL in the North Pacific descended while it rose at the rate of 0.7 mm a^{-1} in the North Atlantic.

The TSL variation in the tropical regions was similar to that of the whole ocean basins, which suggested the TSL variation in the tropical regions was the main contributor to that of the whole ocean. In the tropical Pacific and Indian oceans, the TSL showed a noteworthy decadal variability, and was associated with a relatively small rising rate. However, a fast rising was found in the tropical Atlantic, with a slower rate after the 1980 s and an insignificant decadal variability. The area of the tropical Atlantic Ocean is 12% of the global ocean area (Table 2), but its TSL variation contributed 21% to the global TSL variation.

The TSL of the South Atlantic was also rising, but the rate was much smaller than elsewhere in the Atlantic Ocean. The TSL in the South Pacific showed a smaller rising rate and a weaker decadal variability than those in the tropical Pacific. However, in the South Indian, the TSL rose much faster than that in the tropical Indian.

Table 2 Linear trend of TSL and the ratios in different regions

Basin	TSL (1945–2003)		Area percentage (%)
	Trend (mm a^{-1})	Percentage (%)	
Pacific	0.2	34	49.5
North Pacific	0.0	1	7.8
Tropical Pacific	0.2	24	29.4
South Pacific	0.2	9	12.3
Indian	0.2	18	20.4
Tropical Indian	0.2	10	12.5
South Indian	0.3	8	7.7
Atlantic	0.4	38	25.2
North Atlantic	0.5	11	5.8
Tropical Atlantic	0.4	21	11.5
South Atlantic	0.2	7	7.9
15˚N–64˚N	0.4	39	26.1
15˚S–15˚N	0.2	22	30.3
15˚S–64˚S	0.2	40	43.6
30˚S–64˚S	0.2	12	14.2
30˚S–30˚N	0.3	63	56.5
30˚N–64˚N	0.2	25	29.4
45˚S–45˚N	0.3	92	79.6
Global ocean (64˚S–64˚N)	0.3	100	100.0

4.1.3 Spatial distribution

The spatial distribution of the TSL trend during 1945–2003 was dramatically inhomogeneous with intense regional characteristics (Fig.9), which was obviously different from that during 1993–2003 (Fig.5). The thermosteric sea level indicated a zonal dipole in the tropical Pacific Ocean associated with ENSO event, descending in the west with a minimum in the warm pool and rising fast in the east. In the northern Pacific, the TSL trend showed the spatial pattern associated with the Pacific Decadal Oscillation (PDO). In the North Atlantic, thermosteric sea level exhibited a meridional dipole associated with the North Atlantic Oscillation (NAO), ascending fast in the Gulf Stream and its extension area but descending in the subpolar region. A zonal descending located near the tropical Indian.

In some regions (*e.g.* the mid-latitude of the North Atlantic), the TSL rising rate could reach 5.0 mm a^{-1}, about 10 times the global mean. The thermosteric sea level was strikingly correlated with the ocean current circulation such as the western boundary current (the Gulf Stream and Kuroshio) and the Antarctic Circumpolar Current.

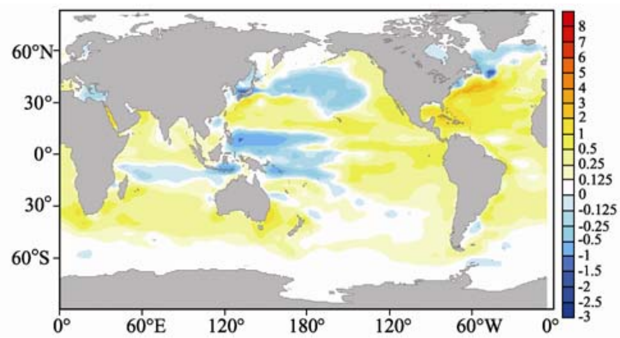

Fig.9 Distribution of the TSL trend derived from Ishii data during 1945–2003.

As in the above analysis on the similar spatial distribution of the T/P sea level trend and the TSL trend during 1993–2003, the secular change of the two kinds of sea level trend presented a similar spatial pattern. The mechanism of the regional characteristics is still not clear, but it might be associated with the dynamic processes in the ocean, especially the horizontal and vertical redistribution of heat through ocean-atmosphere interaction and thermohaline circulation.

4.1.4 Different time period

The thermosteric sea level exhibited strikingly secular trend and varied significantly with time; it might be superimposed to decadal variability in the past 60 years. The oscillation of the dipoles in the tropical Pacific, North Pacific and North Atlantic also changed with time (Fig.10).

The global mean TSL trend for different time span was

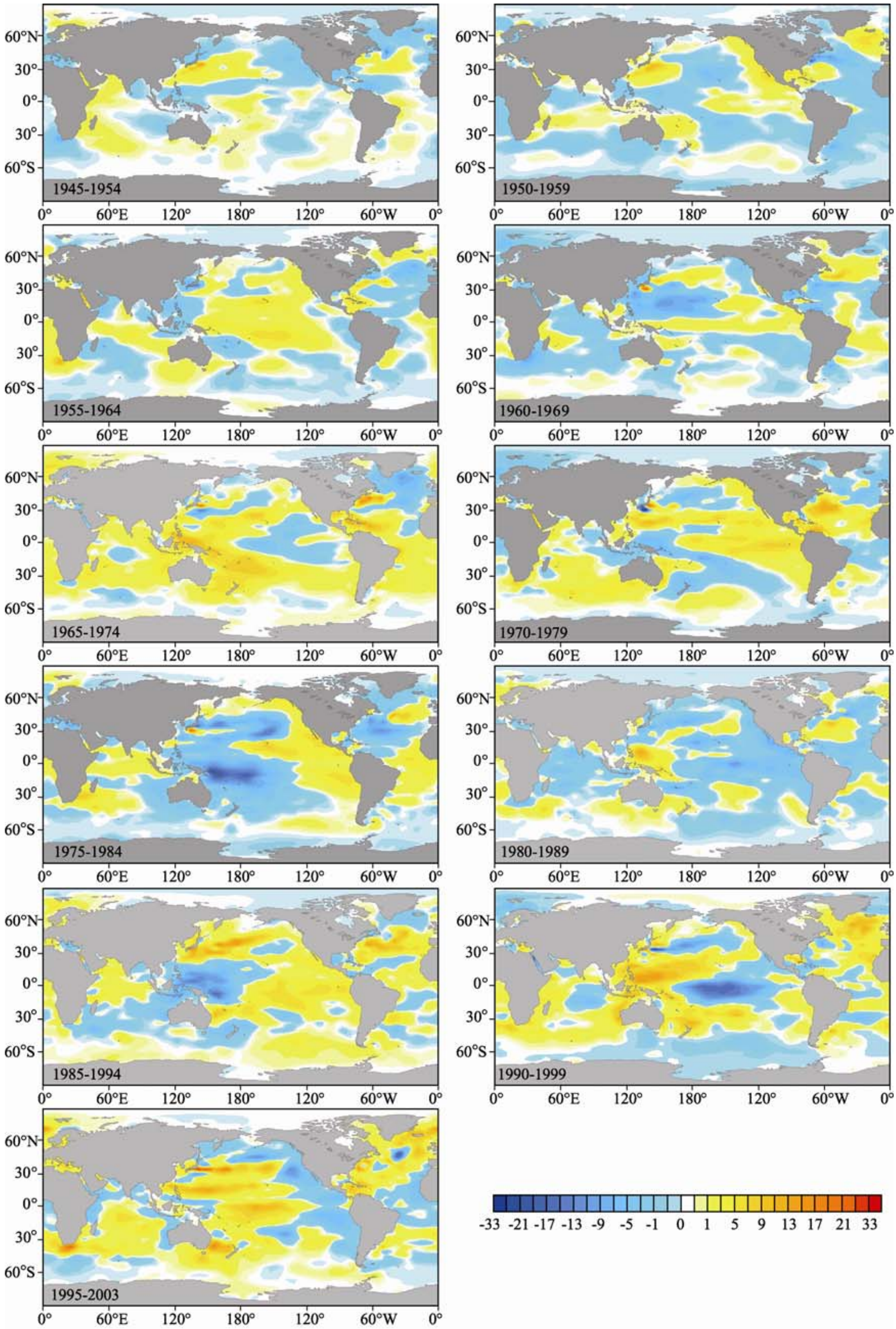

Fig.10 Distribution of the ten-year smoothed linear trend of global TSL.

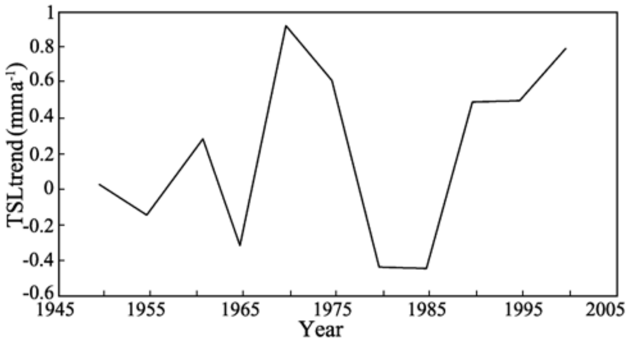

Fig.11 Ten-year smoothed linear trend of global TSL.

calculated with an area-weighting function (Fig.10). The time series of the global TSL trend in different time span presented a fluctuation with the period of about 20 years (Fig.11) and the peak appeared during the span of 1993–2003. The most prominent trend of the global mean TSL occurred around 1970, followed by a rapid descent in the next 10 years.

4.2 Spatial-Temporal Variation of the Thermosteric Sea Level

4.2.1 Global

The Empirical Orthogonal Function (EOF) method was applied to the 1°×1° gridded TSL. The spatial distribution of the first mode of the global TSL was similar to the spatial distribution of the trend (Fig.12a). The seasonal and decadal variations associated with ENSO were dominant in the first mode, which correlated well with ENSO index, the absolute coefficient being larger than 0.8 (Fig. 12b).

In order to eliminate the influence from the tropical ENSO events, the TSL variation over the tropical Pacific was removed from the EOF decomposition. The secular change of first EOF temporal mode showed an abrupt increase in the mid-1980s (Fig.13).

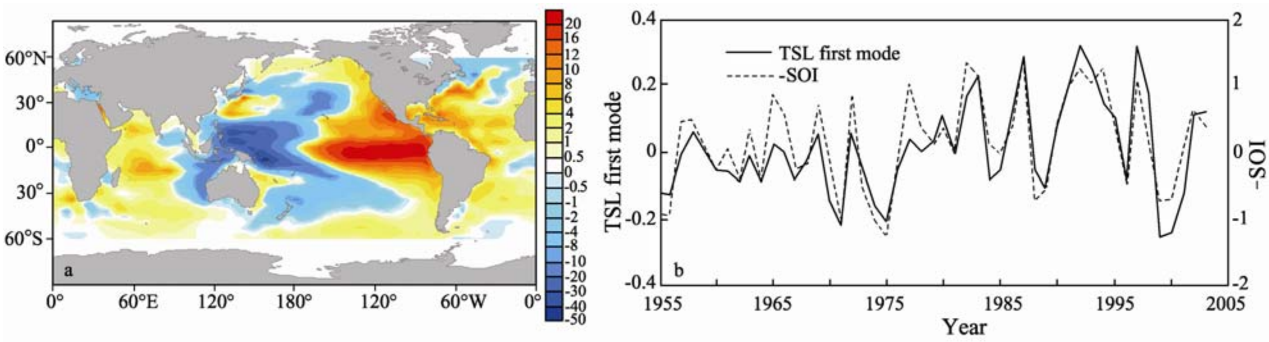

Fig.12 a. The first mode of the TSL derived from Ishii data (24%). b. The time series of first mode of the TSL (solid) and the SOI index (dashed).

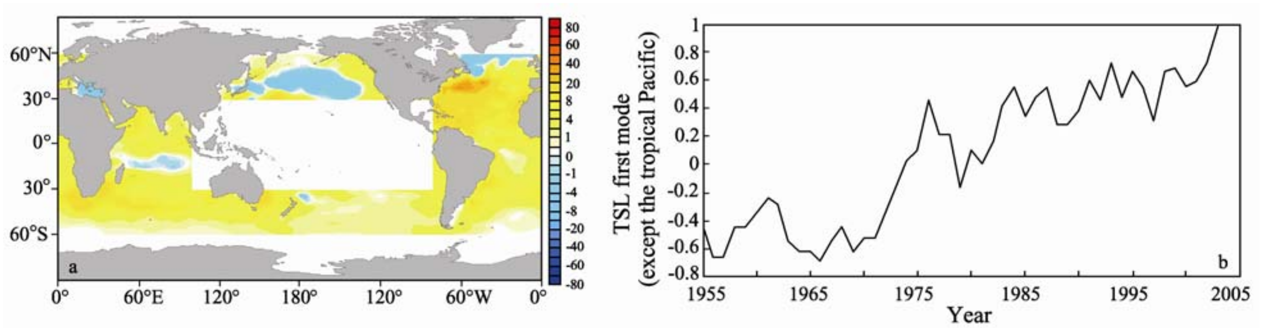

Fig.13 a. The first EOF mode of global TSL (except for the tropical Pacific Ocean). b. Annual variation of the first EOF temporal mode of global TSL (excluding the tropical Pacific).

4.2.2 Different oceans

Separated EOF analyses for the Pacific, Atlantic and Indian Ocean were made in order to examine the detailed variation in the three basins. Their spatial-temporal variations were not illustrated in the following for the compactness of this paper. The variance contribution of the first 5 modes in the eight regions and the correlation coefficients between the first EOF temporal modes and interannual or decadal oscillation indices (*e.g.* ENSO, PDO and NAO) are listed in Table 3 and Table 4 respectively.

For the three oceans, the first EOF temporal mode of the Pacific TSL presents the ENSO mode. The Atlantic first mode shows a long-term rise, which is similar to the case of the global first EOF temporal mode (excluding the tropical Pacific). It indicates that the present rise of the global TSL is related with the Atlantic warming. There's no leading mode in the Indian TSL variation as compared with the results of contemporaneous 49-year Levitus data (1955–2003). The variance contributions of first two modes of the Indian TSL variation were 22.2% and 19.1%. The correlation coefficient between the temporal EOF2 and SOI (Southern Oscillation Index) was −0.72, which would indicate that ENSO events might affect the TSL variation in the Indian Ocean.

For the north basins, the spatial pattern of first TSL mode in the North Pacific showed a dipole-like pattern as the PDO pattern. Although the correlation coefficient between the first temporal mode in the North Atlantic Ocean (20˚–80˚N) and the NAO index was relatively small (Table 4), the thermosteric sea level showed the correlated variations on a decadal time scale. The first TSL mode descended from 1950 to 1970 and rose from 1970 to 2003, which was similar to the variation of NAO index. In addition, both the temporal EOF1 and NAO index exhibited a 5–10 year oscillation with the peak appearing around 1970. In the tropical Pacific, the correlation coefficient between the temporal EOF1 and SOI was −0.88.

Table 3 The variance contributions of the first 5 modes in different ocean regions

Area	EOF1	EOF2	EOF3	EOF4	EOF5
Atlantic	33.4	12.9	6.9	6.2	4.6
Indian	22.2	19.1	8.2	6.5	5.9
Pacific	32.9	17.1	8.2	5.4	4.9
Tropical Pacific	38.8	18.4	8.4	5.7	3.8
North Pacific	25.4	15.2	12.5	9.1	5.7
North Atlantic	36.8	15.6	7.4	5.8	4.6
Global Ocean (excluding Tropical Pacific)	23.1	9.5	7.4	6.3	5.6
Global Ocean	24.3	14.0	11.3	5.3	4.4

Table 4 The correlation coefficients between the TSL temporal modes and corresponding indices

Temporal mode and corresponding index	Correlation coefficient
Global Ocean EOF1 and SOI	−0.88
North Pacific EOF1 and PDO index	0.70
North Atlantic EOF1 and NAO index	0.47
Pacific EOF1 and SOI	−0.88
Tropical Pacific EOF1 and SOI	−0.88
Atlantic EOF1 and NAO index	0.48
Indian EOF2 and SOI	−0.72

5 Conclusion and Discussion

5.1 Sea Level Trend and Thermosteric Contribution During 1993–2003

5.1.1 T/P Sea level trend

The T/P sea level shows prominent trends besides the seasonal variability. The rising rate of the global mean sea level was 2.9 mm a^{-1} during 1993–2003. The T/P sea level trend maps the geographical variability and presents intense regional difference, the rising rate being 3.9, 2.2 and 2.1 mm a^{-1} at the latitude bands of 15˚–64˚S, 15˚–64˚N and 15˚S–15˚N, respectively. The mean sea level presents prominent rising trends for the three ocean basins.

In the Southern Pacific, the rising rate of the T/P sea level is 4.7 mm a^{-1}; it is over 4.0 mm a^{-1} in the Southern Atlantic and the Southern Indian Ocean. The rising rates in the basins of the Northern Hemisphere and the tropical ocean are 2.0 mm a^{-1}, which is a little smaller than that in the Southern Hemisphere where the latter was superimposed on the prominent annual cycle. The rising rate of the North Pacific is the smallest among the eight regions (1.7 mm a^{-1}). In the Southern Hemisphere, the rising trend is larger at the mid- and high-latitude area, about 5.1 mm a^{-1} at the latitude band 40˚–50˚S. In the Northern Hemisphere, it rises faster at the mid-latitude area (30˚–40˚N), while is rises slowly at the high-latitude area, about 0.5 mm a^{-1} at 40˚–50˚N, and even descends at 50˚–60˚N.

5.1.2 Thermosteric sea level trend and its contribution to T/P sea level

The rising rate of the global TSL was 1.2 mm a^{-1} during 1993–2003. The thermosteric sea level in the North Atlantic is rising very fast, while there is a nearly nonlinear trend in the tropical Atlantic. The Pacific TSL rises fast, but it does not rise in the same manner as that in the Atlantic. In the Southern Hemisphere, the thermosteric sea levels present an intense and homogenous rising trend in the three ocean basins. The TSL at the mid-latitude area in the two hemispheres shows a striking rising trend, but it is small at the low- and high-latitude area, even descending in some regions (50˚–60˚S and 40˚–50˚N).

The global mean TSL trend contributes more than 40% to the global mean T/P sea level rise, but there is a significant difference between the trends for the Northern and the Southern Hemispheres. Since the large rising trend in the southern basins can not be explained only by the thermal expansion, for relevant observations in the south oceans are sparse. Among the three oceans, the thermosteric effect contribution to the sea level rise is the largest in the Pacific Ocean, 50%, derived from Ishii data. In tropical areas, especially in the tropical Pacific, the T/P sea level rise is mainly caused by the TSL rise, which is quite different from the case of the seasonal sea level variability in this area. In the North Pacific, the thermosteric effect contributes a small portion to the T/P sea level rise, while it is an important contributor in the North Atlantic. In the south regions, the thermosteric effect contributes the smallest in the Atlantic Ocean.

At mid-latitude of the Northern Hemisphere, the sea level rise is mainly caused by the thermosteric effect, while this effect is small at the southern mid-latitude. For high-latitude areas (40˚–60˚N and 50˚–60˚S), the thermosteric contribution to sea level rise is negative.

5.2 Thermosteric Sea Level Variation in the Past 60 Years

5.2.1 Secular trend

The global mean TSL in the past 60 years (1955–2003) showed an obvious positive trend, the TSL rising rate for the upper 0–700 m derived from Ishii data was about 0.3 mm a^{-1}. Moreover, the thermosteric sea level presented striking inter-annual and decadal variability.

In the past 60 years, the thermosteric sea level in the Atlantic Ocean was continuously rising and its contribution to the rising of the global TSL was the largest among the three world oceans, *i.e.* more than 38%. The thermosteric sea level in the Pacific and Indian Ocean was rising, but the variation was dominated by inter-annual and decadal variability. The thermosteric effect at the low-latitude area (30˚S–30˚N) was the most important contributor to the global mean TSL rise.

5.2.2 Decadal and inter-decadal variability

The variability of the global mean TSL in the past 60 years showed an obvious fluctuation of 20 years (Section 4.1.4) and the spatial distribution of its linear trend showed a nonuniform pattern. This prominent regional difference changed with time, which presented a decadal variability.

The EOF decomposition is applied to the thermosteric sea level derived from the Ishii temperature data in the past 60 years. It is suggested that the first mode of the global TSL is ENSO mode. The first temporal mode shows the relatively steady rising trend in the global oceans except in the tropical Pacific. Among the three oceans, the first mode of the Pacific TSL is the ENSO mode. The first temporal mode in the Atlantic Ocean shows relatively steady rising trend. There is no dominant mode in the Indian TSL variation and the ENSO event may play a role in its thermosteric sea level variation.

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