J Oceanogr (2015) 71:297–310
DOI 10.1007/s10872-015-0289-1

ORIGINAL ARTICLE

Basin-scale features of global sea level trends revealed by altimeter data from 1993 to 2013

Mingqiang Fang[1] · Jing Zhang[1]

Received: 14 October 2014 / Revised: 27 March 2015 / Accepted: 1 April 2015 / Published online: 12 April 2015

Abstract In this study, altimeter sea level data (from http://www.aviso.oceanobs.com) are used to study large scale, non-uniform patterns of sea level trends of the world's major oceans from 1993 to 2013. The three major oceans: the Pacific Ocean, the Indian Ocean and the Atlantic Ocean, are all rising, with different large-scale patterns. The Indian Ocean has the greatest mean sea level rise trend at 4.06 mm/year. Standard deviations of the spatial distribution of Pacific Ocean and Indian Ocean sea levels have been increasing during the last two decades while those of the Atlantic Ocean have been decreasing. By defining a new index, the volume centroid of the upper ocean layers, we find that, during the past two decades, the meridional volume centroids of the three major oceans have been moving southward. The zonal volume centroids of the Pacific Ocean and the Indian Ocean are closely related, exhibiting almost opposite phases during the last two decades. The long-term trends of the zonal volume centroids of the Pacific and Indian Oceans reveal that the areas around the western Pacific warm pool are at great risk of extreme sea level rise.

Keywords Global change · Sea level rise · Sea level trends · Basin scale · Non-uniformity · Volume centroid

1 Introduction

Global sea level trends have been calculated by many studies, with various conclusions reached when different time coverage, data processing, geophysical correction and other factors are taken into account (Peltier 2004; Church and White 2006; Beckley et al. 2007; Ablain et al. 2009; Masters et al. 2012). Ablain et al. (2009) showed a 3.11 ± 0.6 mm/year rising trend of global mean sea level during 1993–2008 with a 0.9 confidence interval. Recently, the global mean sea level seems to be rising at a rate of ~3.2 mm/year (Nicholls and Cazenave 2010; Meyssignac and Cazenave 2012) with great non-uniformities. Church and White (2006) pointed out that sea level trends for different time periods vary significantly and there seems to be positive acceleration in the mean sea level rising since the 1990s, which hints that the global mean sea level is not only rising, but also with positive acceleration.

Currently, parts of the related studies are focused on how to acquire a mean global sea level trend of high confidence. Although measurement of global mean sea level trend is very important for climate change studies, the global mean sea level trend alone cannot reveal all the potential risks for all local ocean areas. In fact, the global sea level trends vary greatly from one place to another. Nicholls and Cazenave (2010) presented some detailed images showing how the vulnerable coasts and islands are distributed on a world map mainly in regards to the spatial distribution of global sea level trends. In their results, one of the important features of the sea level trend distribution is the non-uniformity: in some areas, the sea levels are rising at more than 10 mm/year and in some areas, the sea levels are decreasing. Their results show that studying the non-uniformity of global sea level trends is very important for society. For example, wide ocean areas around the western Pacific warm pool may have had the highest rising trends during the past 20 years or so (Nicholls and Cazenave, 2010; Meyssignac and Cazenave 2012; Merrifield 2011). From a long-term point of view, the sea level

✉ Mingqiang Fang
orsl@ouc.edu.cn

[1] Department of Marine Technologies, Ocean University of China, Qingdao 266100, China

rise trend in this region is more than three times the global mean sea level rise trend and certainly puts the surrounding areas at a very high risk. Meyssignac and Cazenave (2012) showed that the non-uniformities of sea level trends might come mainly from differences in thermal expansion. Other oceanic processes may also contribute to the non-uniformity in global/regional sea level trends (Wijffels and Meyers 2004; Alory et al. 2007; Merrifield 2011; Schwarzkopf and Böning 2011; Nidheesh et al. 2013; Han et al. 2014). Most of the previous studies seemed to show that the sea level trends are a comprehensive result of multi-physical processes, and to show that the non-uniformity is a natural characteristic of global sea level trends.

Measurement of global mean sea level trends is very important for the long-term climate change studies, but mean sea level trends alone might not be able to tell the full story of global sea level rise, as mentioned above. Some new indices might be needed to describe the spatial non-uniformities of the global sea level trends, which may help give more detailed images of the global sea level changes.

In the following sections, we firstly calculate the mean sea level trends of the global and the major oceans that

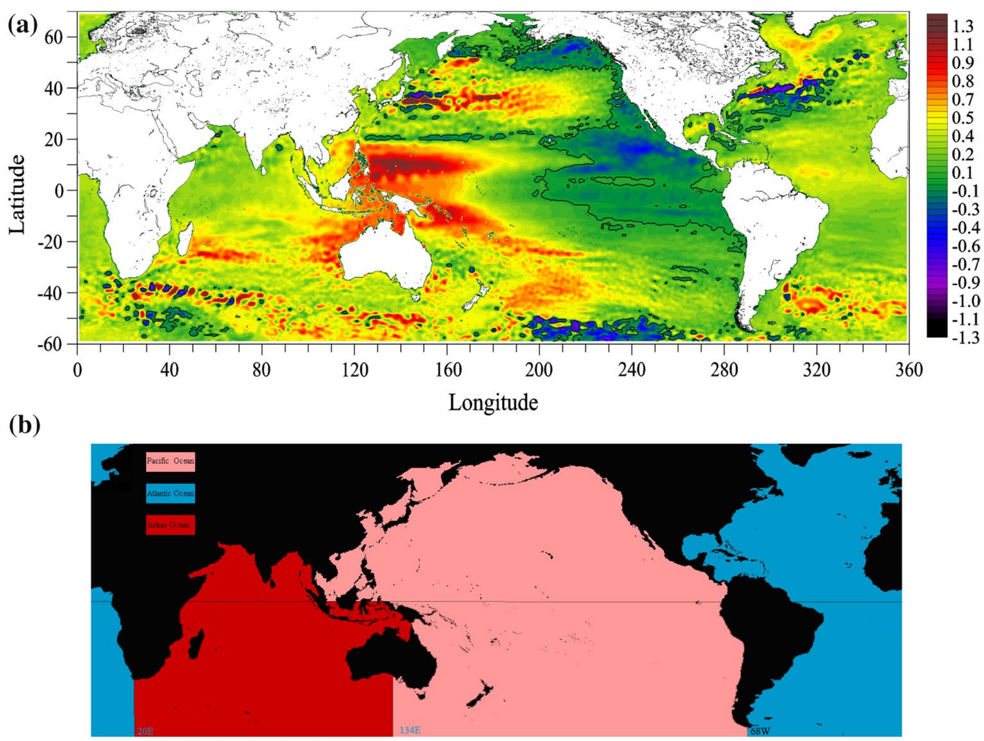


Fig. 1 Sea level trend (unit: cm/year) distribution for the global ocean from 1993 to 2013 using 20 years of monthly absolute dynamic topography anomaly data derived from AVISO altimeter products is shown by (**a**). *Dark contour lines* show the zero trends. The geographic classifications of the world's oceans in this study are shown by (**b**). It should be noted that, here, we are not presenting the ocean ranges' definition. The *colored blocks* are only used for a convenient and reasonable mask processing

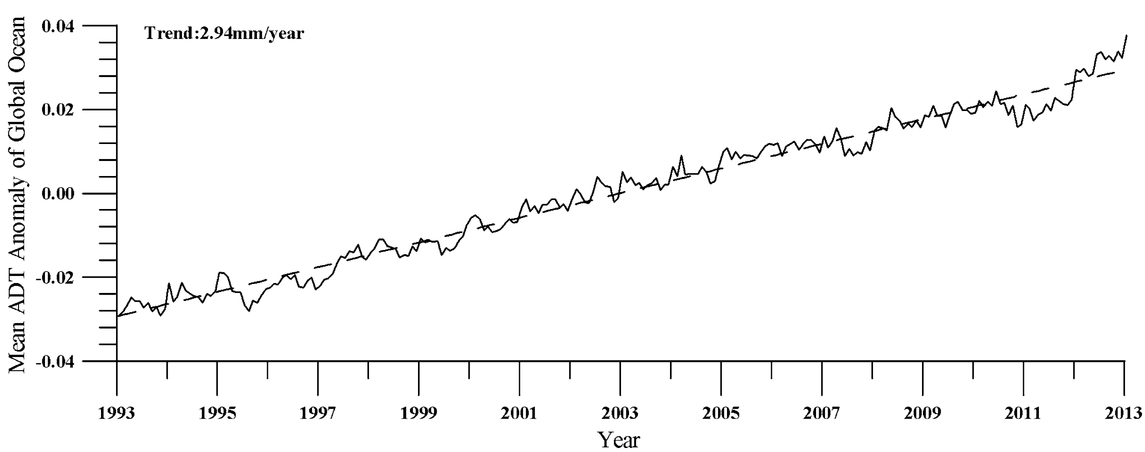


Fig. 2 Linear mean ADT anomaly (in m) trends for the global ocean from 1993 to 2013 using 20 years of weekly ADT data from AVISO altimeter products. The trend interval for the 0.95 confidence level is 2.94 ± 0.05 mm/year

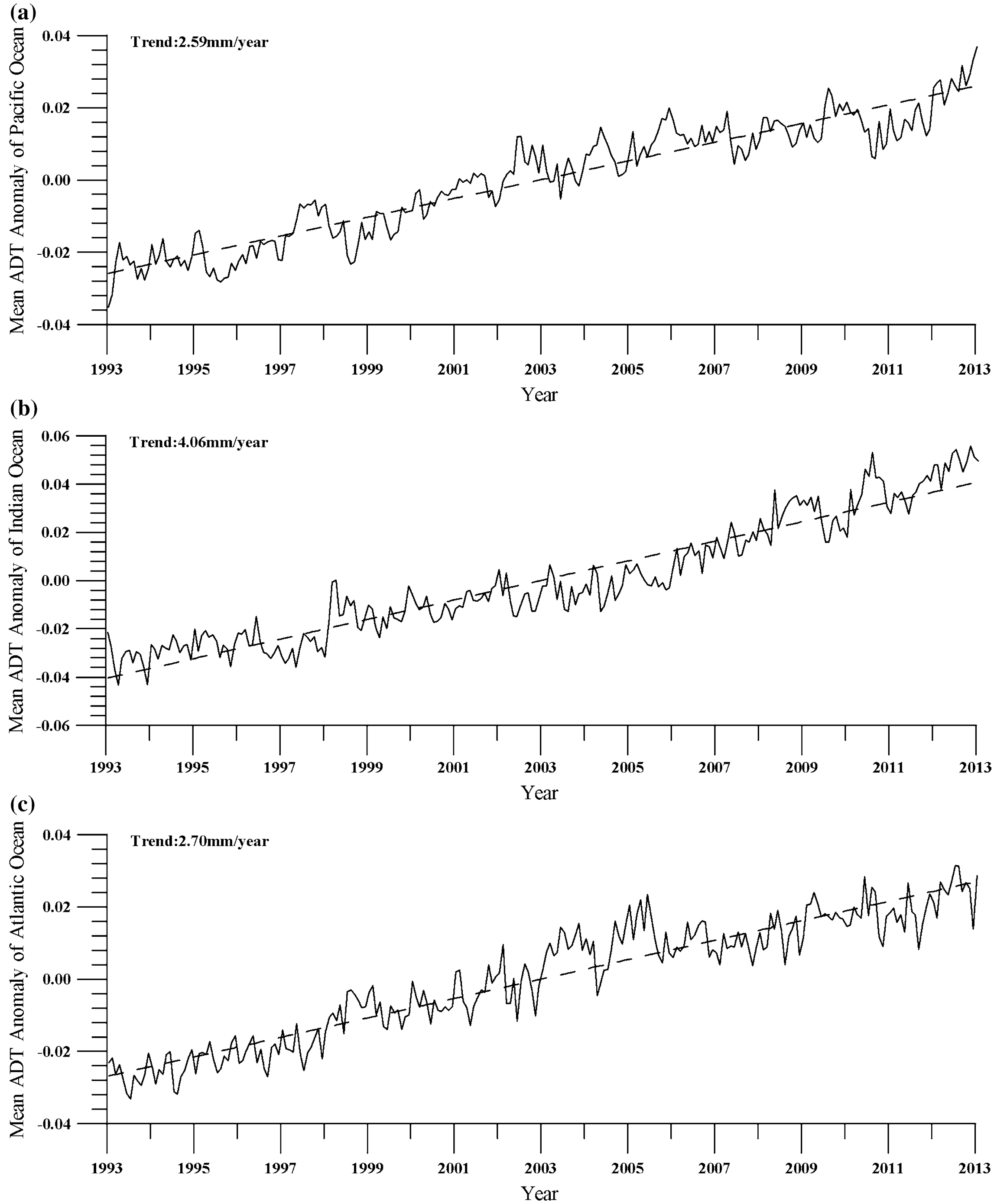


Fig. 3 Linear mean ADT anomaly (in m) trends for the Pacific Ocean (**a**), the Indian Ocean (**b**) and the Atlantic Ocean (**c**) from 1993 to 2013 using 20 years of weekly ADT data from AVISO altimeter products. The trend interval for the 0.95 confidence level for the Pacific Ocean, the Indian Ocean and the Atlantic Ocean are 2.59 ± 0.05, 4.06 ± 0.17, 2.70 ± 0.12 mm/year, respectively

demonstrate the trend differences among them. The spatial standard deviation (SD) trend of the sea level distribution for each major ocean in a longitude-latitude plane is also calculated, which is able to show how the spatial uniformity of the sea levels for each major ocean has been changing for the last two decades. A new index, namely, the volume centroid of the upper ocean layers, is then proposed and calculated to describe the basin-scale seawater volume variation for each major ocean. Some new features of the global sea level trends are found and preliminarily discussed through analysis of an anomaly time series of the above parameters.

Table 1 Mean ADT anomaly trends of the global oceans (mm/year, 0.95 confidence interval)

Sea level trends	The Pacific Ocean	The Indian Ocean	The Atlantic Ocean
Northern part	2.39 ± 0.13	2.88 ± 0.34	2.32 ± 0.14
Southern part	2.78 ± 0.16	4.23 ± 0.16	3.09 ± 0.16

2 Data

The weekly absolute dynamic topography (ADT, January 1993–January 2013) datasets of the global ocean surface can be downloaded from http://www.aviso.oceanobs.com. The Ssalto/Duacs gridded ADT data is mapped onto a 1/3° × 1/3° Mercator grid. This study uses up-to-date ADT datasets that have up to four satellites at a given time (go to http://www.aviso.oceanobs.com for details, CNES 2013) to calculate sea level trends for the global and major oceans. The physical significance of ocean ADT measurements can be found in the work by Rio and Hernandez (2004), but in this study only data within the latitude ranges of 60°S–70°N is used. It should be noted that the trends from ADT data are the same as those from the sea level anomaly (SLA) data from AVISO products because they only have a fixed difference at each longitude-latitude grid, which has no effect on the long-term trend calculation. Before measuring the long trends of the parameters in this study, the anomaly time series are calculated based on the 1993–2012 climatology and then the linear trends are estimated within a 0.95 confidence interval by using these anomaly time series. It should be noted that glacial isostatic adjustment is not applied in this study.

3 Methodologies and analysis

Global sea level trends are calculated by a simple linear fitting method using the altimeter ADT data products from AVISO (see Fig. 1a). The monthly anomaly time series is calculated from the original ADT products based on the 1993–2012 climatology and then the linear fittings are applied to these anomaly time series for each grid location. The result shown by Fig. 1a is quite similar to previous results, such as those of Ablain et al. (2009) and Nicholls and Cazenave (2010). Figure 1a shows clearly that sea levels of most parts of the global ocean are rising and that the trends are not uniformly distributed. Figure 1b shows geographic classifications of the world's oceans in this study (note that only 60°S–70°N is included and that the area classification is only for mask convenience).

The mean sea level trend of the global ocean is 2.94 ± 0.05 mm/year (0.95 confidence level; see Fig. 2), which is within the range defined by previous calculations, such as that of Ablain et al. (2009, 3.11 ± 0.6 mm/year). If glacial isostatic adjustment correction for the altimeter records is applied following Masters et al. (2012), then the global mean sea level trend would be about 3.24 mm/year, which is quite close to the operational result of AVISO (3.27 mm/year, see http://www.aviso.altimetry.fr). The difference may come from the differences in time and spatial coverage. Hereby it is believed that the data set used here is reliable for long-term trend studies of the global ocean.

Figure 3 shows the mean sea level trends of the Pacific Ocean, the Indian Ocean and the Atlantic Ocean. The trends of the Pacific Ocean and the Atlantic Ocean are lower than that of the global ocean but the sea level trend of the Indian Ocean (~4.06 ± 0.17 mm/year,) is much higher (about 38 %) than the global average from 1993 to 2013. Table 1

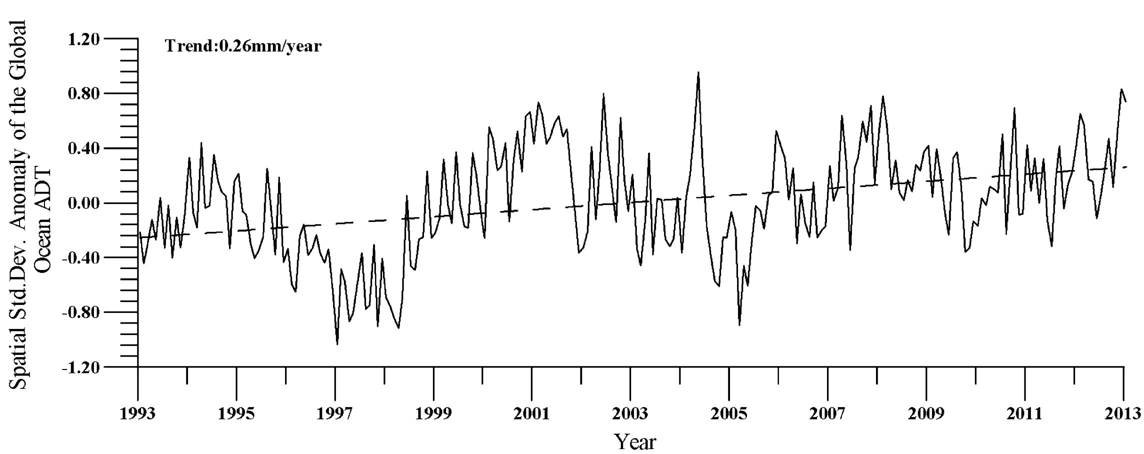


Fig. 4 Trend of spatial standard deviation anomaly (in cm) of the global ocean ADT from 1993 to 2013. The trend interval for the 0.95 confidence level is 0.26 ± 0.08 mm/year

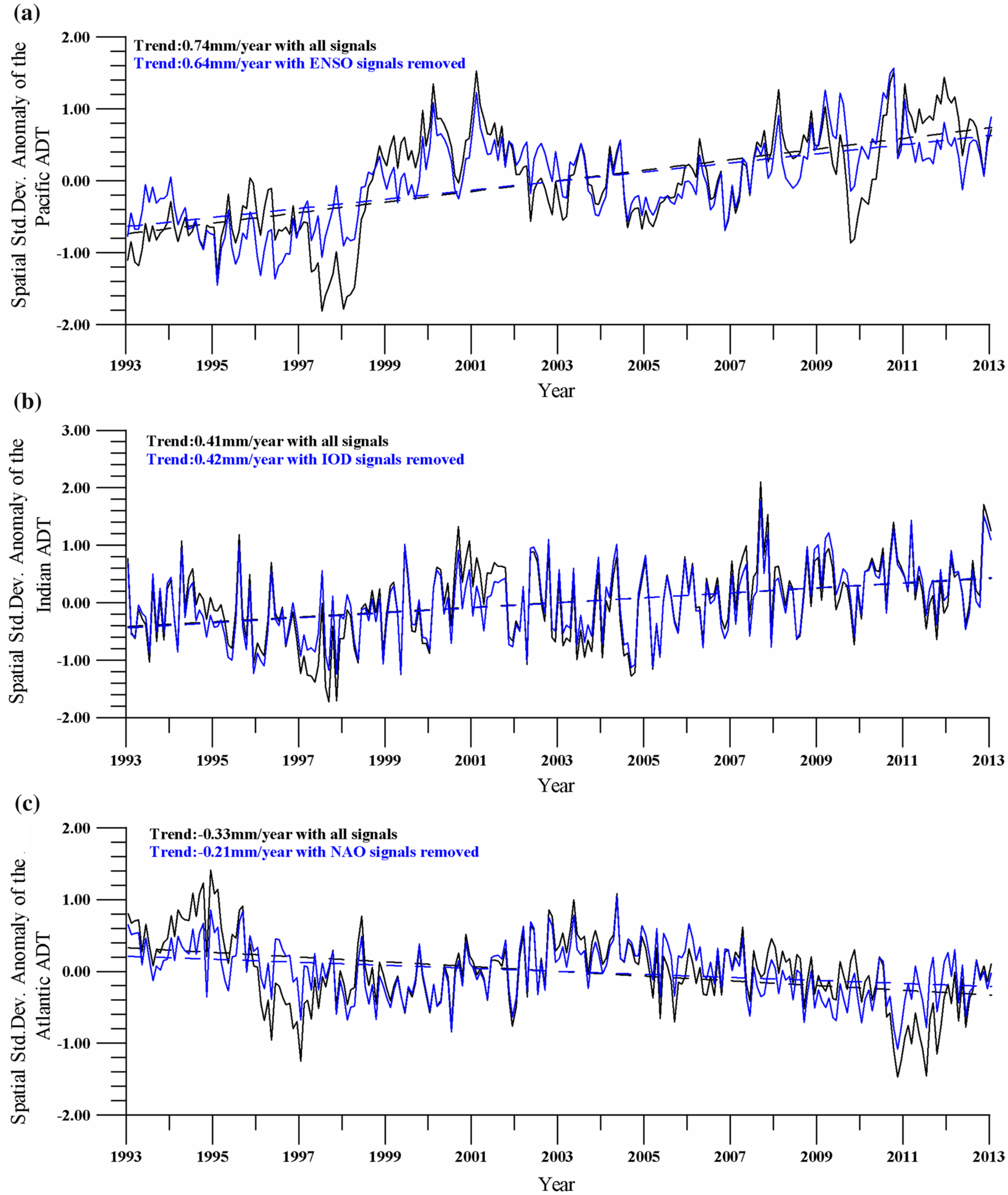


Fig. 5 Trends of spatial standard deviation anomaly (in cm) of the Pacific Ocean ADT (**a**), the Indian Ocean ADT (**b**) and the Atlantic Ocean ADT (**c**) from 1993 to 2013. The standard deviation anomaly trend (in *black*) interval for the 0.95 confidence level for the Pacific Ocean, the Indian Ocean and the Atlantic Ocean are 0.74 ± 0.12, 0.41 ± 0.13, −0.33 ± 0.10 mm/year, respectively. For reference, *blue lines* show the standard deviation anomaly after the El Nino and southern oscillation (ENSO)-, Indian Ocean dipole (IOD)- and Northern Atlantic oscillation (NAO)-like signals are removed for the Pacific Ocean, the Indian Ocean and the Atlantic Ocean, respectively. *Dashed blue lines* show the linear trends of the *blue lines*

further shows the mean sea level trends for the northern part and southern part of each major ocean, which tells that there are significant trend differences between the northern and southern parts of each major ocean. Figures 3, 1a and Table 1 together clearly show significant non-uniformity in the sea level trend distribution for the global ocean; several previous studies have shown the same (Milne et al. 2009; Unnikrishnan and Shankar 2007; Woodworth et al. 2009).

Since the sea level trends are different for different regions and the global mean sea level trend alone might not be enough for studying features of the global sea level trends, some parameters describing the non-uniformity of the sea level trends for the global oceans might be established. In this study, the global oceans, the Pacific Ocean, the Indian Ocean and the Atlantic Ocean are selected below as four major regions of interests to study their sea level trend features at a global or basin scale. In these large scales, seawater mass redistribution may have important effects on the long-term rotation variability of our planet, which have already drawn close attention. For example, the western Pacific warm pool water mass redistribution was studied by Yan et al. 2003 and Zhou et al. 2004 and they found that large scale water mass redistribution impacts the length of the day and the polar motion, respectively. To study large-scale phenomena related to global sea level changes, a set of non-uniformity indices may be necessary.

The World's oceans are under control of different regional climate systems, which might have caused the non-uniformity of the global sea level trends (Nicholls and Cazenave 2010; Merrifield 2011; Schwarzkopf and Böning 2011; Meyssignac and Cazenave 2012). Here firstly, the SD trend of the global ocean on a longitude-latitude grid is calculated (Fig. 4). Figure 4 shows that, as a whole, the spatial variability of global ocean ADT has been increasing from 1993 to 2013. The SD trends of the ADT of the Pacific Ocean, the Indian Ocean and Atlantic Ocean on a latitude-longitude plane are shown in Fig. 5, which suggests that the spatial sea level variabilities of the Pacific Ocean and the Indian Ocean have been increasing while those of the Atlantic Ocean have been decreasing during the past two decades. The big difference in SD trends shows that, in the long term, from 1993 to 2013, the spatial sea level distribution of the Pacific Ocean and the Indian Ocean has become increasingly non-uniform while that of the Atlantic Ocean has increased in uniformity.

In statistics theory, the SD shows how much variation exists from the mean value. An increasing (decreasing) SD trend of the sea level data indicates, largely, that the sea level data value range is getting wider (narrower). Figure 5a shows that the Pacific Ocean has the strongest SD trend among these three major oceans, up to 0.74 mm/year, though the Pacific Ocean has the most uniform sea level distribution among these three major oceans, with a mean SD of about 42.4 cm for the Pacific Ocean, 68.0 cm for the Indian Ocean and 50.8 cm for the Atlantic Ocean (not shown in the plot). All the SD trends shown in Fig. 5 are within the 0.95 confidence level. The SD percentage changes the trends represent are about 17.0, 6.0, and −6.5 % per century for the Pacific Ocean, the Indian Ocean and the Atlantic Ocean, respectively. Figure 1a shows that, from a basin scale point of view, sea levels of large areas of the western Pacific ocean are on a rise while those of areas west of the US western coasts and areas around the eastern Pacific equator are decreasing. Hence, the difference between the maximum and the minimum sea level might have been increasing during the past two decades, which may have contributed significantly to the SD trend for the Pacific Ocean. On the contrary, the sea level distributions of the Atlantic Ocean seem to have been getting more and more uniform during the last two decades, showing that the Atlantic Ocean may be under some different controls, which may require further study. The SD trends in Fig. 5 and the sea level trends in Fig. 3 show that, although all the mean sea levels of the three major oceans have been rising for the last two decades, their sea level trends show significant differences in spatial distribution. The SD of the sea level distribution and its trend for a specific ocean can help provide more details of the sea level rise. Many factors, such as different warming rates (Wigley and Raper 1987; Church et al. 1991; Levitus et al. 2005; Rahmstorf 2007; Domingues et al. 2008; Cazenave and Llovel 2010), different water/ice/glacial discharges into the ocean (Cazenave and Llovel 2010; Shepherd et al. 2012; Gardner et al. 2013) and other factors may have contributed to the different SD trends for different oceans. For example, after we remove the El Nino and southern oscillation (ENSO)-like signals from the Pacific Ocean, Indian Ocean dipole (IOD)-like signals from the Indian Ocean and the Northern Atlantic oscillation (NAO)-like signals from the Atlantic Ocean using the empirical mode decomposition (EMD) method following Huang et al. (1998) and Yan et al. (2002), the SD trends of the three major oceans change a bit, but the long term trend features still remain, as can be found in Fig. 5 in the blue lines, which suggests that, the interannual signals also have some effects on the SD trends and that there might be some decadal or interdecadal background causes.

The spatial SD of the sea level is able to reflect the uniformity of the sea level distribution but it cannot show how the seawater volume distribution of the upper ocean changes along the longitude-latitude plane during the past two decades on a large scale, such as in which areas the sea levels are holding the tendency to rise more. Here, we try to define a "volume" centroid to depict how seawater volumes in a specific region vary on a large scale. A physical law stating that density changes within the body of an object may cause changes in its mass centroid suggests that, if the grid volume is compared to the grid mass, volume "centroid" changes may reflect changes of sea level distribution. Similar to the definition of a mass centroid given by Desloge (1982), the form of the volume centroid could be described as:

$$\begin{cases} x = \sum_i V_i \cdot x_i \Big/ \sum_i V_i \\ y = \sum_i V_i \cdot y_i \Big/ \sum_i V_i \end{cases}, \tag{1}$$

where V_i stands for the seawater volume of each surface grid. To avoid the seawater volume of each surface

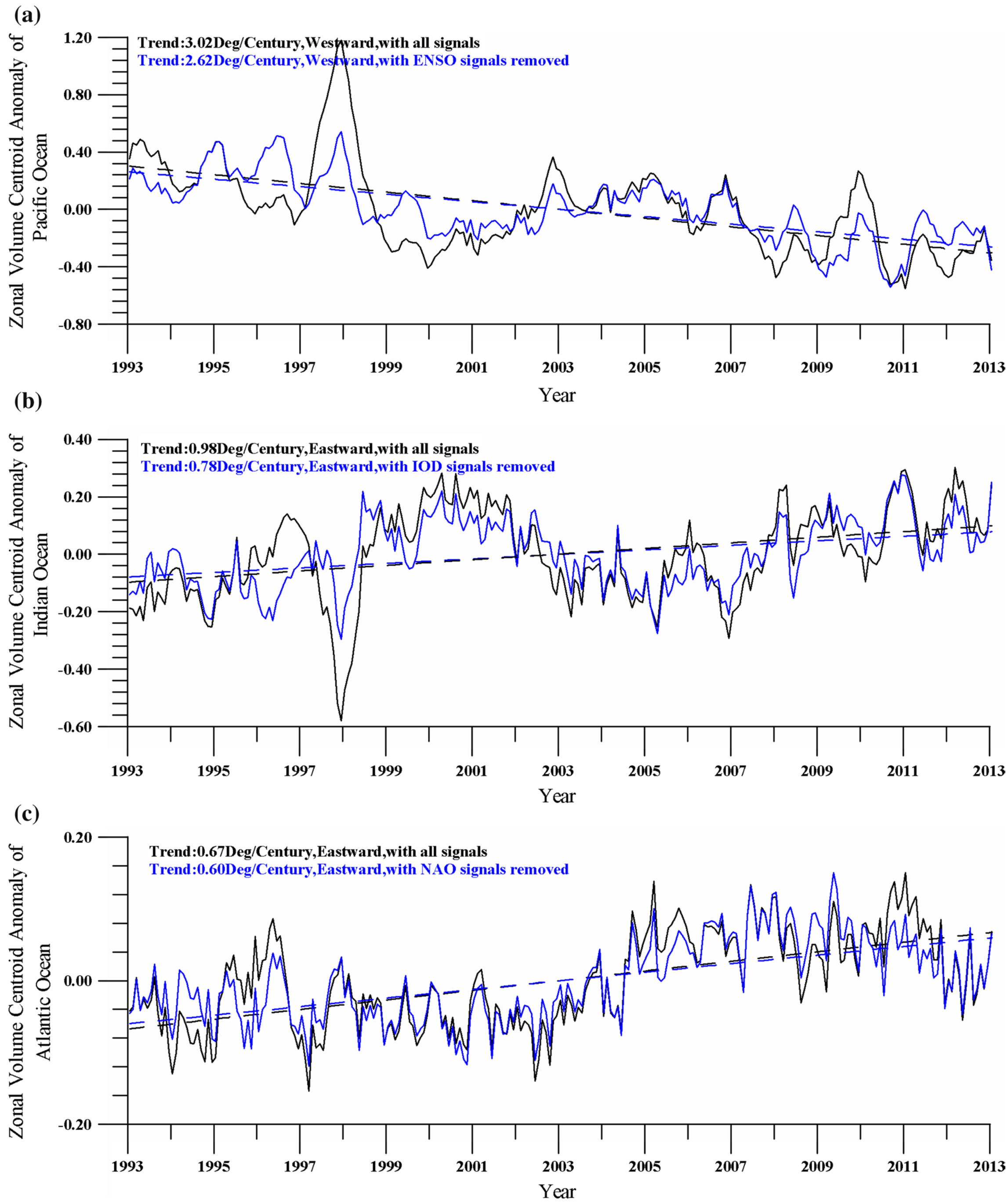


Fig. 6 Zonal volume centroid anomaly (in longitude degree) for the Pacific Ocean (**a**), the Indian Ocean (**b**) and the Atlantic Oceans (**c**) from 1993 to 2013. *Black dashed lines* show the linear trends of the zonal volume centroid anomaly (in *black line*). The zonal centroid anomaly trend intervals for the 0.95 confidence level for the Pacific Ocean, the Indian Ocean and the Atlantic Ocean are -3.02 ± 0.59, 0.98 ± 0.32, 0.67 ± 0.11 degree/century, respectively. For reference, the *blue lines* show the zonal volume centroid anomaly with ENSO-, IOD- and NAO-like signals removed for the Pacific Ocean, the Indian Ocean and the Atlantic Ocean, respectively. *Blue dashed lines* are the linear trends of the *blue lines*

grid being negative, we searched for the minimum ADT (in this study, the minimum ADT, −164.63 cm, was found at 1.75ºE, 53.75ºS, 28th week, 1994. We then set $ADT_{min} = 164.63$ cm) for the global oceans from 1993 through 2013 and transformed all the absolute dynamic height data to a new form by adding the minimum absolute dynamic height to them. So, here in this study, the grid water height is actually set to $ADT_i + 164.63$ cm. Then, after we set $V_i = Area_i \cdot (ADT_i + ADT_{min})$ for a grid volume, we have:

$$\begin{cases} x = \sum_i \text{Area}_i \cdot (\text{ADT}_i + \text{ADT}_{\text{min}}) \cdot x_i \Big/ \sum_i \text{Area}_i \cdot (\text{ADT}_i + \text{ADT}_{\text{min}}) \\ y = \sum_i \text{Area}_i \cdot (\text{ADT}_i + \text{ADT}_{\text{min}}) \cdot y_i \Big/ \sum_i \text{Area}_i \cdot (\text{ADT}_i + \text{ADT}_{\text{min}}) \end{cases}, \tag{2}$$

where $(\text{ADT}_i + \text{ADT}_{\text{min}})$ stands for grid seawater height and Area_i stands for grid area. It would be convenient if we put the volume centroid on a longitude-latitude plane. We then change Eq. (2) to get the volume centroid of a specific ocean area:

$$\begin{cases} \text{longitude} = \sum_i \text{Area}_i \cdot (\text{ADT}_i + \text{ADT}_{\text{min}}) \cdot \text{Lon}_i \Big/ \sum_i \text{Area}_i \cdot (\text{ADT}_i + \text{ADT}_{\text{min}}) \\ \text{latitude} = \sum_i \text{Area}_i \cdot (\text{ADT}_i + \text{ADT}_{\text{min}}) \cdot \text{Lat}_i \Big/ \sum_i \text{Area}_i \cdot (\text{ADT}_i + \text{ADT}_{\text{min}}) \end{cases}, \tag{3}$$

where Lon_i represents the grid's longitude and Lat_i indicates its latitude. The integration region could be any specific areas, such as the Pacific Ocean or the global ocean in this study.

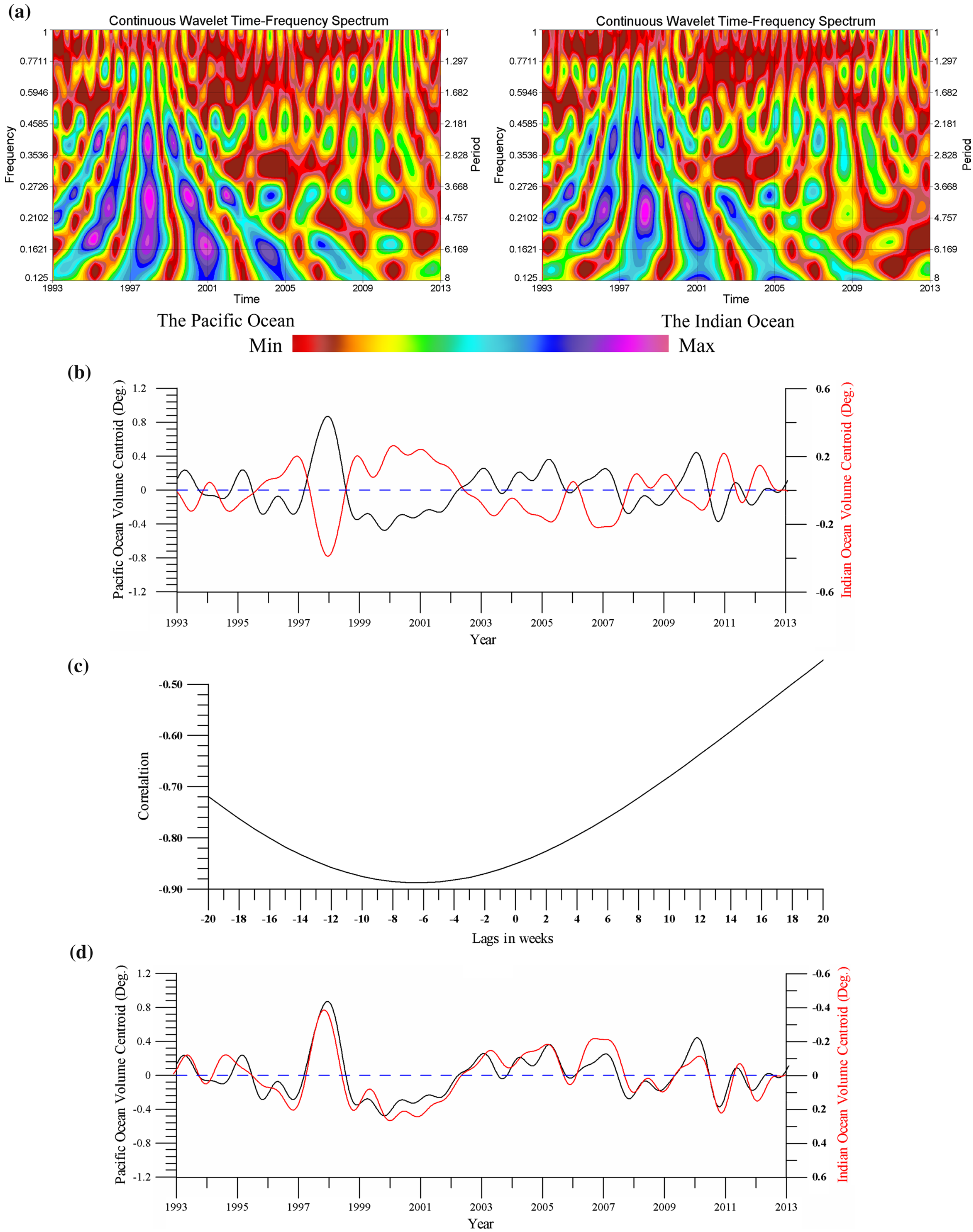
Figure 6 shows the zonal trends of the volume centroid anomaly of the Pacific Ocean, the Indian Ocean and the Atlantic Ocean. Figure 6a suggests that the zonal centroid of the Pacific Ocean has been moving westward during the past two decades at a rate of 3.02º ± 0.59/century while Fig. 6b shows the zonal centroid of the Indian Ocean has been moving eastward at a rate of 0.98 ± 0.32º/century. As a reference, after the ENSO-, IOD- and NAO-like signals are removed (by EMD method as Yan et al. 2002), the long tern trends of all the zonal volume centroid anomalies of the major oceans still remain in Fig. 6 (in blue lines), suggesting that there also might be some decadal or interdecadal trends as the cause. Table 2 further shows the zonal volume centroid trends for the northern part and southern part of each major ocean, which tells that, except for the north Indian Ocean and the south Atlantic Ocean, the zonal volume centroid trend for the other parts of the global oceans are quite significant. The zonal volume centroid movements of the Pacific Ocean and the Indian Ocean are in opposite directions and have different speeds. These results agree quite well with those suggested by Fig. 1a and the results of other studies, such as Ablain et al. (2009) and Merrifield (2011), which showed that the water volumes were piling up around the Indo-Pacific warm pool and its surrounding areas. The zonal volume centroids in Fig. 6a, b and the sea level trends in Fig. 1a together show that the ocean areas around 100–170ºE, 20ºS–20ºN, especially areas around the western Pacific warm pool (Yan et al. 2002), are at great risk of extreme sea level rise. The trends revealed by Figs. 1a and 6 may continue in the coming years and should be given more attention by local and global administrations.

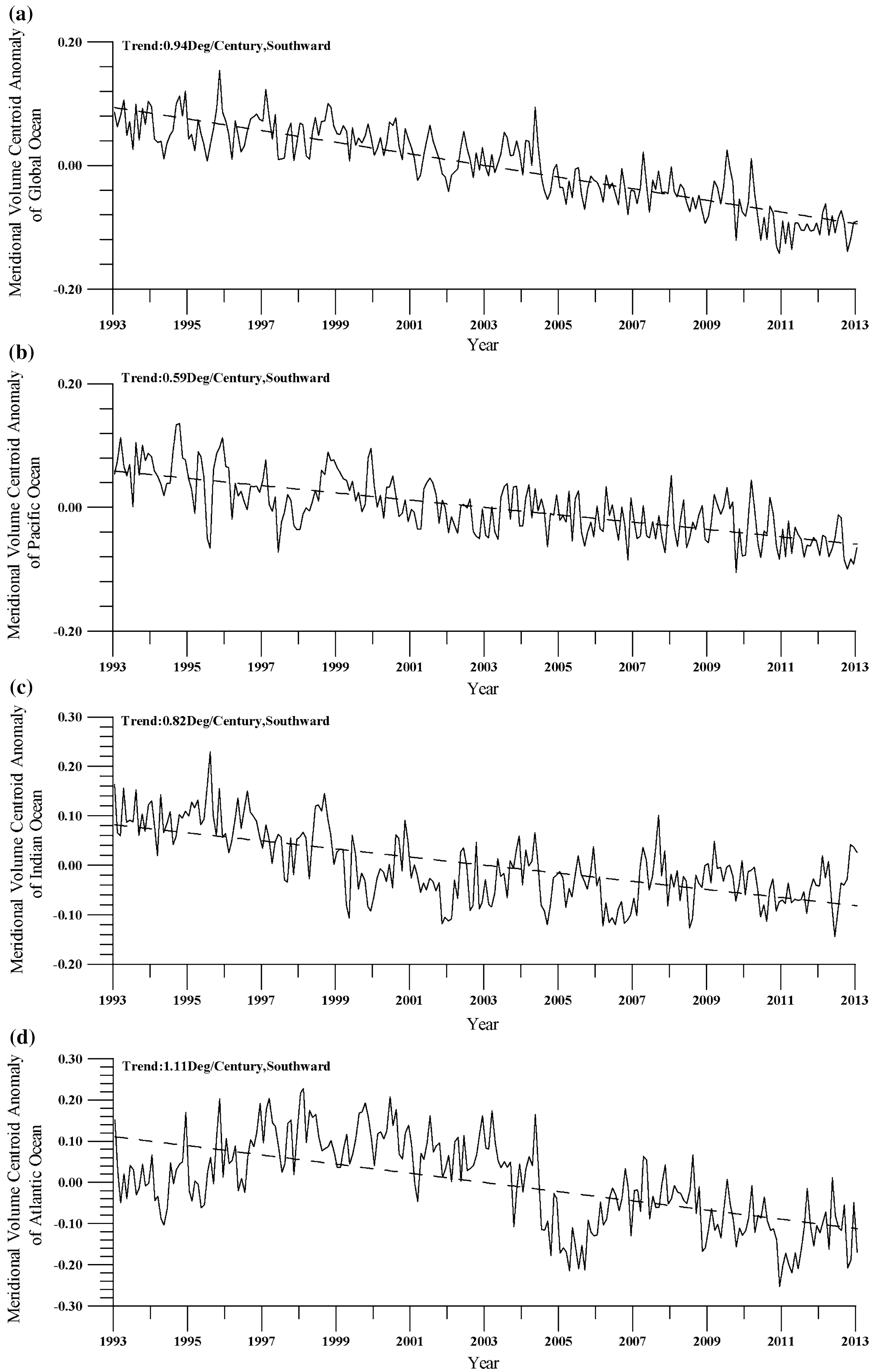
Figure 7 shows the relation between the zonal volume centroid of the Pacific Ocean and that of the Indian Ocean after these two time series are linearly detrended. Figure 7a shows that, in the wavelet spectrum panels, the wavelet patterns of these two oceans are very similar to each other in the frequency domain lower than 1 cycle per year. The highest correlation between these two time series is −0.89 when the Pacific Ocean is leading about 6 weeks ahead of the Indian Ocean (see Fig. 7b, c, d in which the two time series are smoothed by a Morlet wavelet filter to remove the signals with periods less than one year). The significant correlation at the 95 % confidence level is only about 0.60 with numbers of degrees of freedom estimated as in Trenberth (1984) and Davis (1976). Figure 7 suggests that, on a large basin scale, the sea level distribution changes in the Pacific Ocean and those in the Indian Ocean are strongly correlated to each other with almost opposite phases. It should be

Fig. 7 **a** Shows the wavelet (Morlet) spectrum of the detrended ▶ zonal volume centroid of the Pacific Ocean (*left*) and the detrended zonal volume centroid of the Indian Ocean (*right*). Frequencies are in cycles/year and periods are in years. Only the signals with periods longer than one year are shown. **b** Shows the detrended zonal volume centroid of the Pacific Ocean (*dark*) and the detrended zonal volume centroid of the Indian Ocean (*red*). Both of the signals are smoothed using a Morlet wavelet filter to remove the signals with perioda less than one year. **c** Shows the lead-lag correlation between the two plots in (**b**). The highest correlation is −0.89 when the Pacific Ocean is leading 6 weeks ahead. **d** Shows the plots in (**b**) but the *red curve* is moved 6 weeks earlier and the *Y*-axis for it is descending

Table 2 Zonal volume centroid anomaly trends of the global oceans (degree/century, 0.95 confidence interval, a negative value means westward)

Zonal trends	The Pacific Ocean	The Indian Ocean	The Atlantic Ocean
Northern part	−3.50 ± 0.69	0.17 ± 0.27	0.66 ± 0.14
Southern part	−2.86 ± 0.41	1.05 ± 0.35	0.096 ± 0.12


(a)
Continuous Wavelet Time-Frequency Spectrum
Frequency
Period
Time
The Pacific Ocean
The Indian Ocean
Min
Max
(b)
Pacific Ocean Volume Centroid (Deg.)
Indian Ocean Volume Centroid (Deg.)
Year
(c)
Correlaltion
Lags in weeks
(d)
Pacific Ocean Volume Centroid (Deg.)
Indian Ocean Volume Centroid (Deg.)
Year


(a)
Trend:0.94Deg/Century,Southward
Meridional Volume Centroid Anomaly of Global Ocean
0.20
0.00
-0.20
1993 1995 1997 1999 2001 2003 2005 2007 2009 2011 2013
Year
(b)
Trend:0.59Deg/Century,Southward
Meridional Volume Centroid Anomaly of Pacific Ocean
0.20
0.00
-0.20
1993 1995 1997 1999 2001 2003 2005 2007 2009 2011 2013
Year
(c)
Trend:0.82Deg/Century,Southward
Meridional Volume Centroid Anomaly of Indian Ocean
0.30
0.20
0.10
0.00
-0.10
-0.20
1993 1995 1997 1999 2001 2003 2005 2007 2009 2011 2013
Year
(d)
Trend:1.11Deg/Century,Southward
Meridional Volume Centroid Anomaly of Atlantic Ocean
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
1993 1995 1997 1999 2001 2003 2005 2007 2009 2011 2013
Year

◀ **Fig. 8** Meridional volume centroid anomaly (in latitude degree) for the global oceans (**a**), the Pacific Ocean (**b**), the Indian Ocean (**c**) and the Atlantic Ocean (**d**) from 1993 to 2013. *Dashed lines* show the linear trends. The meridional centroid trend interval for the 0.95 confidence level for the global ocean, the Pacific Ocean, the Indian Ocean and the Atlantic Ocean are 0.94 ± 0.07, 0.59 ± 0.08, 0.82 ± 0.12, 1.11 ± 0.19 degree/century, respectively

noted that the Pacific Ocean and the Indian Ocean share the same coverage limits (around the warm pool areas), which may help increase the correlation in Fig. 7. However, the zonal centroid is calculated for the whole Pacific Ocean or the Indian Ocean, so the boundary sharing is not the only contributor for the high correlation in Fig. 7.

Previous studies have discussed the interactions between the Pacific Ocean and the Indian Ocean through the relation between the IOD index and ENSO index (Yu and Rienecker 1999; Ashok et al. 2001; Behera and Yamagata 2003; Annamalai et al. 2005; Behera et al. 2006; Yuan et al. 2011, 2013). Yuan et al. (2011, 2013) have clearly demonstrated that the Indonesian throughflow variability plays an important role in forcing the interannual variations of the tropical Pacific Ocean by the IOD. Wijffels and Meyers (2004) also showed that these two basins are closely related to each other by studying the sea water advection variabilities in the Indonesian throughflow region. They found that the signature of the Pacific energy radiating westward across the Banda Sea and into the subtropical south Indian Ocean within 1500 km of the coast is prevalent. Schwarzkopf and Böning (2011) also related the two basins by studying the contribution of Pacific wind stress to multi-decadal variations in upper ocean heat content and sea level in the tropical South Indian Ocean. They found that "whereas interannual variability in the southwestern tropical Indian Oceans appears mainly governed by Indian Ocean atmospheric forcing, but the longer term changes in the south tropical Indian Oceans involve a strong contribution from the western Pacific via wave transmission of thermocline anomalies through the Indonesian Archipelago, and their subsequent westward propagation by baroclinic Rossby waves." Most of the previous studies have suggested that the strong connection between these two basins is a comprehensive result of different dynamical processes. Results shown by Fig. 7 agree quite well with previous conclusions with even higher correlation, and probably for the first time suggest that the basin-scale sea level variation is also an important connector between the Pacific Ocean and the Indian Ocean. It seems that we should study the strong connections between the Pacific Ocean and the Indian Ocean not only around the equatorial tropical areas but also on the two whole ocean basins. The mechanisms for this strong correlation between these two major oceans should be given more attention by future studies. The zonal volume centroid of the basin scale could be a good index relating these two whole basins.

Figure 8 shows the meridional trends of the volume centroid of the global oceans, the Pacific Ocean, the Indian Ocean and the Atlantic Ocean. The meridional volume centroids of the major three oceans all have the long-term trends of moving southward for the last two decades. This agrees well with the recent results (Alory et al. 2007; Chen and Tung 2014; Thompson and Merrifield 2014). Because the potential energies (gravity related) of seawater relative to a certain depth is linear to the sea level, Fig. 8 tells that the total potential energies of the global upper ocean layers, on a large scale, have been shifting southward during the last two decades under the background of global climate changes. Figure 8 also may tell that, on a large scale, the sea levels in the oceans of the Southern Hemisphere have been receiving and will receive more impacts from the global climate changes than those of the Northern Hemisphere.

Interestingly, the recent study by Friedman et al. (2013) suggests that the temperature contrast between the Northern and Southern Hemispheres—the inter-hemispheric temperature asymmetry (ITA, north minus south)—has ranged within 0.8 °C and features a significant positive trend since 1980, which means that the Northern Hemisphere may have higher warming rates than the Southern Hemisphere. Meyssignac and Cazenave (2012) concluded that the non-uniformities of the sea level trends might come mainly from the different thermal expansion rates. It might be natural to believe that the mean sea level of the Northern Hemisphere is rising faster than that of the Southern Hemisphere but this study suggests that this is far from the real case. This study hints that further explanations other than surface warming for the inter-hemispheric sea level asymmetry revealed by Fig. 8 are needed.

As can be seen in Table 1, all the southern oceans have higher sea level trends than those of the northern oceans. It partly explains the southward shift of all the meridional volume centroids of the three major oceans since 1993 shown in Fig. 8. Table 3 further shows that, except for the north Indian Ocean and the north Atlantic Ocean, the meridional volume centroid trend for the other parts of the global oceans have been significantly moving southward. Alory et al. (2007) show a widespread SST increase across the Indian Ocean during 1960–1999, mainly near 40–50ºS and the warming could extend to as deep as 800 m depth, which can partly explain the southward shift of the volume centroid of the Indian Ocean during that period. Results of Chen and Tung (2014) hint that the southward shift may also be related to the deep ocean warming of the southern oceans. They found that the recent global warming slowdown is mainly caused by heat transported to deeper layers in the Atlantic and the southern oceans. In a study of the unique asymmetry in the pattern of recent sea level change for the global ocean, Thompson and Merrifield

Table 3 Meridional volume centroid anomaly trends of the global oceans (degree/century, 0.95 confidence interval, a negative sign means southward)

Meridional trends	The Pacific Ocean	The Indian Ocean	The Atlantic Ocean
Northern part	-0.13 ± 0.05	-0.055 ± 0.042	0.013 ± 0.12
Southern part	-0.50 ± 0.11	-0.47 ± 0.10	-1.00 ± 0.10

(2014) hypothesized that the asymmetry between northern and southern region sea level trends may be related to wind-driven ocean volume redistribution. Conclusions of Mitrovica et al. (2001) also might help partly explain Fig. 8. Their results suggested that if Greenland (the Antarctic) ice cap melts, then the gravitational pull on the seas will decrease and will result in lower sea levels around Greenland (the Antarctic). The sea level will rise on average while the ice cap melts. However, when the melt water leaves Greenland (the Antarctic) it will raise the sea levels in the Southern Hemisphere (Northern Hemisphere). Shepherd et al. (2012) showed that "between 1992 and 2011, the ice sheets of Greenland, East Antarctica, West Antarctica, and the Antarctic Peninsula changed in mass by -142 ± 49, $+14 \pm 43$, -65 ± 26, and -20 ± 14 gigatonnes/year, respectively," which suggests that Greenland has been melting away more ice than the Antarctic since 1992. This difference, according to the findings by Mitrovica et al. (2001), seems to have partly contributed to the trends revealed by Fig. 8. The ice-related mechanism alone is, of course, only one of the possible explanations for Fig. 8, though the influence of the Greenland ice melt on the meridional asymmetry is quite small (Thompson and Merrifield 2014). All this work together shows that the southward shift of the volume centroid was a comprehensive result of multiple processes under the background of global changes. However, further work is needed to determine the dominant physical processes, as stated by Thompson and Merrifield (2014).

4 Conclusions

In this study, altimeter sea level data sets were used to study the basin-scale, non-uniform patterns of the sea level trends of the global major oceans from 1993 to 2013. The three major oceans: the Pacific Ocean, the Indian Ocean and the Atlantic Ocean, are all rising with patterns of great difference:

(A) Among these three major oceans, the Indian Ocean has the top sea level trend, up to 4.06 mm/year, which is far beyond those of the other two major oceans and the global ocean. The differences in the mean sea level trends of the major oceans obviously show the great non-uniformity of the global sea level trends. Another important feature is that all the southern oceans have higher sea level trends than the northern oceans.

(B) The SD trends of the spatial distribution of the sea levels of the major oceans are also calculated, showing that the spatial sea level distributions of the Pacific Ocean and the Indian Ocean have been getting more and more non-uniform, while those of the Atlantic Ocean have been getting more and more uniform for the last two decades. The long term SD trends still remain even if the inter-annual signals are removed. These differences also indicate great non-uniformity in the sea level trends of the global oceans.

(C) By defining a new index, the volume centroid of the upper ocean layers, we find that during the past two decades, the meridional volume centroids of all the three major oceans have been moving southward but at different speeds, which might be a comprehensive result of several different dynamical processes. A quantitative analysis might be needed in future studies to give the contribution of each dynamical factor to explain the southward shift of the meridional volume centroid for each major ocean.

(D) The zonal volume centroids of the Pacific Ocean and the Indian Ocean are closely related with almost opposite phases during the last two decades. The long-term trends of the zonal volume centroids of the Pacific Ocean and the Indian Ocean reveal that the seawaters in the areas around the western Pacific warm pool have been "piling up" and may bring great risks of extreme sea level rise to the neighboring areas in coming years. The zonal volume centroid appears to be a new and strong connector between the whole Pacific Ocean and the whole Indian Ocean.

This study suggests that under the global climate change circumstances, the three major oceans all show different characteristics in sea level changes. The non-uniformity in the sea level distributions and in the sea level trend distributions contribute greatly to the complexity of the global sea level rise and global climate change. Further studies should be carried out and some new indices similar to or different from those suggested by this study should be established to describe conveniently the non-uniformity features in sea level and its trend distribution.

Acknowledgments This study was jointly supported by the National Basic Research Program of China (No. 2012CB957704), the National Basic Research Program of China (No. 2009CB723903) and the National Natural Science Foundation of China (No.40506035). Sincere thanks go to anonymous reviewers who have given their very constructive suggestions. We also thank the Aviso and Cnes Teams for providing the altimeter data (products before Jan 2014).

References

Ablain M, Cazenave A, Valladeau G, Guinehut S (2009) A new assessment of the error budget of global mean sea level rate estimated by satellite altimetry over 1993–2008. Ocean Sci 5:193–201

Alory G, Wijffels S, Meyers G (2007) Observed temperature trends in the Indian Ocean over 1960-1999 and associated mechanisms. Geophys Res Lett 34:L02606. doi:10.1029/2006GL028044

Annamalai H, Xie SP, McCreary JP (2005) Impact of Indian Ocean sea surface temperature on developing El Nino. J. Clim 18:302–319

Ashok K, Guan Z, Yamagata T (2001) Impact of the Indian Ocean dipole on the relationship between the Indian Monsoon rainfall and ENSO. Geophys Res Lett 26:4499–4502

Beckley BD, Lemoine FG, Luthcke SB, Ray RD, Zelensky NP (2007) A reassessment of global rise and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits. Geophys Res Lett 34(L14608) doi:10.1029/2007GL030002

Behera SK, Luo JJ, Masson S, Rao SA, Sakuma H, Yamagata T (2006) A CGCM study on the interaction between IOD and ENSO. J Clim 19:1608–1705. doi:10.1175/JCLI3797.1

Behera SK, Yamagata T (2003) Influence of the Indian Ocean Dipole on the Southern Oscillation. J Meteorol Soc Jpn 81(1):169–177. doi:10.2151/jmsj.81.169

Cazenave A, Llovel W (2010) Contemporary sea level rise. Annu Rev Mar Sci 2:145–173

Chen X, Tung KK (2014) Varying planetary heat sink led to global-warming slowdown and acceleration. Science 345(6199):897–903. doi:10.1126/science.1254937

Church JA, White NJ (2006) A 20th century acceleration in global sea-level rise. Geophys Res Lett 33(L01602)

Church JA, Godfrey JS, Jackett DR, McDougall TJ (1991) A model of sea level rise caused by ocean thermal expansion. J Clim 4:438–456

CNES (2013) SSALTO/DUACS user handbook: (M) SLA and (M) ADT near-real time and delayed time products. Issue 3(Rev.4). http://www.aviso.oceanobs.com/fileadmin/documents/data/tools/hdbk_duacs.pdf

Davis RE (1976) Predictability of sea surface temperature and sea level pressure anomalies over the North Pacific Ocean. J Phys Oceanogr 6(3):249–266

Desloge EA (1982) Classical Mechanics, vol I. Wiley, New York, p 507

Domingues CM, Church JA, White NJ, Gleckler PJ, Wijffels SE, Barker PM, Dunn JR (2008) Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature 453:1090–1093. doi:10.1038/nature07080

Friedman AR, Hwang Y-T, Chiang JCH, Frierson DMW (2013) Interhemispheric temperature asymmetry over the twentieth century and in future projections. J Clim 26:5419–5433

Gardner AS, Moholdt G, Cogley JG, Wouters B et al (2013) A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. Science 340(6134):852–857. doi:10.1126/science.1234532

Han W, Vialard J, McPhaden MJ, Lee T, Masumoto Y, Feng M, de Ruijter WPM (2014) Indian Ocean decadal variability: a review. Bull Am Meteorol Soc 95:1679–1703. doi:10.1175/BAMS-D-13-00028.1

Huang NE, Shen Z, Long S, Wu M, Shin H, Zheng Q, Yen N, Tung C, Liu H (1998) The empirical mode decomposition and Hilbert spectrum for nonlinear and nonstationary time series analysis. Proc R Soc Lond A 454:903–995. doi:10.1098/rspa.1998.0193

Levitus S, Antonov J, Boyer TT (2005) Warming of the world ocean, 1955–2003. Geophys Res Lett 32(L02604). doi:10.1029/2004GL021592

Merrifield MA (2011) A shift in western tropical pacific sea level trends during the 1990s. J Clim 24:4126–4138. doi:10.1175/2011JCLI3932.1

Masters D, Nerem RS, Choe C, Leuliette E, Beckley B, White N, Ablain M (2012) Comparison of global mean Sea level time series from TOPEX/Poseidon, Jason-1, and Jason-2. Mar Geod 35(sup1):20–41

Meyssignac B, Cazenave A (2012) Sea level: a review of present-day and recent-past changes and variability. J Geodyn 58:96–109

Milne GA, Gehrels WR, Hughes CW, Tamisiea ME (2009) Identifying the causes of sea-level change. Nat Geosci 2:471–478. doi:10.1038/ngeo544

Mitrovica JX, Tamisiea ME, Davis JL, Milne GA (2001) Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. Nature 409:1026–1029. doi:10.1038/35059054

Nicholls RJ, Cazenave A (2010) Sea-level rise and its impact on coastal zones. Science 328:1517–1520. doi:10.1126/science.1185782

Nidheesh AG, Lengaigne M, Vialard J, Unnikrishnan AS, Dayan H (2013) Decadal and long-term sea level variability in the tropical Indo-Pacific Ocean. Clim Dyn 41:381–402. doi:10.1007/s00382-012-1463-4

Peltier R (2004) Global glacial isostasy and the surface of the ice-age earth: the ICE-5G (VM2) model and GRACE. Annu Rev Earth Planet Sci 32:111–149. doi:10.1146/annurev.earth.32.082503.144359

Rahmstorf S (2007) A Semi-Empirical Approach to projecting future sea-level rise. Science 315:368–370. doi:10.1126/science.1135456

Rio MH, Hernandez F (2004) A mean dynamic topography computed over the world ocean from altimetry, in situ measurements and a geoid model. J Geophys Res 109(C12032). doi:10.1029/2003JC002226

Schwarzkopf FU, Böning CW (2011) Contribution of Pacific wind stress to multi-decadal variations in upper ocean heat content and sea level in the tropical south Indian Ocean. Geophys Res Lett 38:L12602. doi:10.1029/2011GL047651

Shepherd A, Ivins ER, Barletta GAVR et al (2012) A reconciled estimate of ice-sheet mass balance. Science 338(6111):1183–1189. doi:10.1126/science.1228102

Thompson PR, Merrifield MA (2014) A unique asymmetry in the pattern of recent sea level change. Geophys Res Lett 41(21):7675–7683. doi:10.1002/2014GL061263

Trenberth KE (1984) Signal versus noise in the Southern Oscillation. Mon Weather Rev 112:326–332

Unnikrishnan AS, Shankar D (2007) Are sea-level-rise trends along the coasts of the north Indian Ocean consistent with global estimates? Glob Planet Chang 57:301–307

Wigley TML, Raper SCB (1987) Thermal expansion of sea water associated with global warming. Nature 330:127–131. doi:10.1038/330127a0

Wijffels S, Meyers G (2004) An intersection of oceanic waveguides: variability in the Indonesian Throughflow region. J Phys Oceanogr 34:1232–1253

Woodworth PL, White NJ, Jevrejeva S, Holgate SJ, Church JA, Gehrels WR (2009) Evidence for the accelerations of sea level on multi-decade and century timescales. Int J Climatol 29:777–789

Yan XH, Zhou YH, Pan JY, Zheng DW, Fang MQ, Liao XH, He MX, Liu WT, Ding XL (2002) Pacific warm pool excitation, earth rotation and El Niño southern oscillations. Geophys Res Lett 29(21):271–274. doi:10.1029/2002GL015685

Yu L, Rienecker MM (1999) Mechanisms for the Indian Ocean warming during the 1997–1998 El Nino. Geophys Res Lett 26:735–738

Yuan D, Zhou H, Zhao X (2013) Interannual climate variability over the tropical Pacific Ocean induced by the Indian Ocean dipole through the Indonesian Throughflow. J Clim 26:2845–2861

Yuan DL, Wang J, Xu TF, Xu P, Hui Z, Zhao X, Luan YH, Zheng WP, Yu YQ (2011) Forcing of the Indian Ocean dipole on the interannual variations of the tropical Pacific Ocean: roles of the Indonesian Throughflow. J Clim 15:3597–3608

Zhou YHXH, Yan XL, Ding XH, Liao DW, Zheng WT, Liu JY, Pan MQ Fang, He MX (2004) Excitation of non-atmospheric polar motion by the migration of the Pacific warm pool. J Geod 78:P109–P111