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Thermosteric Effects on Interannual and Long-Term Global Mean Sea Level Changes

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Abstract. We investigate global mean sea level (MSL) changes and different geophysical contributions at interannual and long-term (decadal) time scales. Thermosteric effects of global MSL changes are estimated from ocean temperature anomaly data for the period 1955 to 2003 from the World Ocean Database 2001 (WOD01), plus additional data processed through to June 2004. Estimates based on WOD01 show significant differences to previously published results based on similar temperature anomaly data from the World Ocean Database 1998 (WOD98), especially during the period overlapping with the TOPEX/Poseidon (T/P) satellite altimeter mission. During this period (1993 – 2004), the WOD01-estimated thermosteric contribution of global mean sea level change is less than half of the estimate from WOD98 (1.3 ±0.1 vs. 3.0 ±0.6 mm/year), as compared to the rate of 2.6 ±0.06 mm/year observed by satellite altimeters. The larger uncertainty in ocean temperature profiles and incomplete data collection in WOD98, especially in the later years (1997 and 1998) appear to be the major error sources to the overestimated steric effects by WOD98. During the entire 50-year period, the steric effect on global MSL change amounts to about 0.34 – 0.39 (±0.05) mm/year. Strong interannual and decadal variability exists in estimated thermosteric contributions to the global MSL change, and (surprisingly) the thermosteric effect does not show any pronounced contribution to the strong interannual variability during the 1997/1998 El Niño/La Niña event. Our analysis based on the National Centers for Environmental Prediction (NCEP) reanalysis atmospheric model and the National Oceanic and Atmospheric Administration Climate Prediction Center (CPC) global land data assimilation system (LDAS) indicates that atmospheric water vapor and terrestrial water storage changes show strong interannual variability well correlated with observed global MSL change, and could have significant effects on interannual global MSL changes.

Keywords: Thermosteric, Global Sea Level Change, WOD01, Terrestrial Water, Interannual

1. Introduction

Understanding global MSL change has long been a top issue in global and climate change studies. In addition to having tremendous environmental and ecological impacts on coastal regions (e.g., Douglas 1995), global sea level rise is a measure of the global warming and planetary climate change (Church et al. 2001, Sea Level Chapter in the 2001 Third assessment report of the Intergovernmental Panel on Climate Change (IPCC), available at http://www.ipcc.ch/). Observed global MSL change results from three major types of contributions (Church et al. 2001). First, the glacial and polar ice sheet melting thought to be associated with global warming and long-term water mass exchange between the ocean and land (and atmosphere) carry additional fresh water into the oceans and cause global MSL to rise, although these fresh water fluxes will cause spatially non-uniform sea level change as well (Farrell and Clark 1976). Secondly, temperature and salinity variations in the oceans result in density change of seawater and therefore change the volume of the ocean, which is commonly referred as steric sea level change. Thirdly, the glacial isostatic adjustment (GIA) and/or other factors causing uplift or subsidence of the Earth's crust will also cause observable changes of sea level at both local and global scales (e.g., Peltier 1986, Lambeck 1988, Peltier and Tushingham 1989, Peltier 2001). A better understanding of global MSL change provides key information of the global climate change and the water and energy cycle of the Earth system.

Determination of the steric contribution of global sea level change has been a challenging issue owing to the sparse nature (time and space) of *in situ* temperature and salinity measurements on a global basis. Most of previous studies focused on regional or basin-scale steric effects on sea level change, limited by temporal and spatial data distribution (Church et al. 2001). A few studies (Antonov et al. 2000, Cabanes et al. 2001) used temperature fields from the World Ocean Database 1998 (WOD98) (Levitus et al. 2000) to estimate steric contributions of global MSL change for the period 1955 to 1998, and concluded that the steric effect on global MSL rise is about 0.50 to 0.55 mm/year. However, during the more recent period overlapping with the TOPEX/Poseidon (T/P) satellite radar altimeter, Cabanes et al. (2001) suggested that the steric effect could be as large as 3.1 ±0.4 mm/year and could fully explain T/P observed sea level rise (3.2 ±0.2 mm/yr) during the period 1993 to 1998. Willis et al. (2004) applied approximately 1,000,000 in situ temperature profiles combined with merged satellite altimeter data (Ducet et al. 2000) to produce global estimates of upper ocean heat content and thermosteric (i.e., thermal expansion-induced steric) sea level variability on interannual and long-term timescales, and concluded that during the period from mid-1993 to mid-2003, thermosteric sea level rose at a rate of 1.6 mm/yr, significantly smaller than the WOD98-based estimate from Cabanes et al. (2001). Lombard et al. (2005) revisited thermosteric effects on long-term sea level change using WOD98 and historical ocean subsurface temperature analysis by Ishii et al. (2003), and also noticed considerably different estimates from these two datasets during the period since the early 1990s.

Since Willis et al. (2004) and Lombard et al. (2005) all compared WOD98-based results with other independently derived ocean subsurface temperature analysis, the discrepancies could be introduced by the different data processing techniques in deriving these analytical temperature fields. It is not clear yet to say whom to 'blame' for the significant discrepancies, although a later discovered depth correction error in the XBT recording software may have played a role in causing the significant discrepancies (Lombard et al. 2005) (see also the online announcement at http://www.nodc.noaa.gov/OC5/anomaly.html).

In order to have a clearer picture of interannual and long-term sea level changes, in this study, we reassess the thermosteric effect on long-term global MSL change using temperature anomaly fields for the period 1955 to 2003 from the World Ocean Database 2001 (WOD01), plus additional data processed through June 2004 (Levitus et al. 2005). WOD01 is an updated version of WOD98 and based on the same data processing technique. With more recent temperature measurements included in WOD01, we anticipate that this updated dataset can provide more reliable estimates of steric contributions to global MSL change and lead to a better understanding of satellite altimeter observed 'long-term' global MSL change. WOD01-derived results will be compared with altimeter observations, as well as those from WOD98, to identify any major improvements (or differences) in the assessment of any thermosteric effect of global MSL change. We also examine non-steric effects, such as water vapor variation in the atmosphere and terrestrial water storage change, on interannual sea level change using estimates from the NCEP reanalysis atmospheric and CPC LDAS hydrological models, based on consideration of the conservation of water mass of the Earth system (Chen et al. 1998, Minster et al. 1999). This is a related study to a recent publication (Chen et al. 2005), which focuses on seasonal global MSL change using satellite altimetry, satellite gravimetry, and climatology of ocean temperature data.

2. Data and Computation

2.1 Steric Sea Level Changes

The WOD01 yearly temperature anomaly fields are defined as the mean differences for the given year from the mean annual climatology of ocean temperature fields (in the upcoming release of World Ocean Database 2004) (Levitus et al. 2005). The fields are given on 1°x 1°grids, and include 16 layers from the surface to 700 m depth. The yearly fields cover the period 1955 to 2003. Another dataset, the 5-year running average, pentadal (5yearly) temperature anomaly fields are available for the period 1957 to 1996 (with data from 1955 to 1998 used in computing the 5-year running average). The pentadal temperature anomaly fields include 28 layers from the surface to 3000 m depth. Yearly and pentadal temperature fields are reconstructed by adding the temperature anomaly fields to the mean climatology from WOD01. Similar yearly temperature anomaly data from WOD98 are analyzed for comparison. The WOD98 data only cover 14 layers from the surface to 500 m depth.

Steric sea surface height (SSH) change at any given grid can be computed from density change of seawater as (Gill 1982)

$$SSH_{steric} = -\frac{}{\rho_0} \cdot \int_{-h} \Delta\rho \cdot dz \qquad (1)$$

in which ρ_0 is the mean density of sea water (1028 kg/m^3), and $\Delta\rho$ is the density change as a function of temperature (*T*), salinity (*S*), and pressure (*P*). The integral in Eq. (1) is from the ocean bottom to the sea surface (*h=0*). *T* is from either yearly or pentadal temperature fields, *S* from the mean salinity of the WOD01 climatology, and *P* is computed from the mean depth of each layer. $\Delta\rho$ is computed using the UNESCO (United Nations Educational, Scientific and Cultural Organization) standard equations (Fofonoff and Millard 1983). Since the mean salinity is used in Eq. (1), any salinity effect on steric sea level change is not considered here and we only focus on the thermosteric contribution. Salinity effects on global steric sea level change are regarded as relatively insignificant as compared with the thermal contribution (Maes 1998, Sato et al. 2000) as they mainly impact on local density variations and hence local MSL changes, e.g., in the western Pacific, salinity effects can lead to sea level changes of up to 10 cm.

2.2 Satellite Altimeter Observations

Altimeter observations, from the merged MSL anomalies derived from T/P and Jason1 (plus available ERS-1/2 and Envisat altimeters), are provided by the French Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) (available at http://www.aviso.oceanobs.com/) (Ducet et al. 2000). MSL anomalies are given on 1°x 1°grids, every 7-days for the period Oct. 1992 to Aug. 2004. Tidal effects, including ocean tide, solid Earth tide, and pole tide, have been removed in the altimeter data processing, and the inverted barometer (IB) correction is also applied to remove atmospheric pressure loading effects on sea level measurements (for details, see the AVISO User Handbook available at http://www.aviso.oceanobs.com/). Global MSL change is computed by summing sea level anomalies over the global ocean grid (from 65°S to 65°N) weighted by cosine of latitude.

2.3 Terrestrial Water Storage Change

Monthly average soil water storage estimates are from the LDAS land surface model (Fan and van den Dool 2004), which is forced by observed precipitation derived from CPC daily and hourly precipitation analyses, downward solar and long-wave radiation, surface pressure, humidity, 2-m temperature and horizontal wind speed from NCEP reanalysis. The output consists of soil moisture in the top 1.6 m of soil below the ground, with an effective holding capacity of 76 cm of water at a porosity of 0.47. At the surface, it includes all components affecting energy and water mass balance, including snow cover, depth, and albedo. Monthly average soil water storage changes are provided on a 0.5°x 0.5°grid for the period January 1948 to present. No estimate is provided over Antarctica. The total terrestrial water storage change is computed by summing soil water change with cosine of latitude as weighting.

2.4 Atmospheric Water Vapor Change

The change of the total mass of the atmosphere represents the total water vapor variation in the atmosphere, under the assumption that the total mass of the dry atmosphere is nearly a constant (Trenberth and Smith 2005). Therefore, atmospheric water vapor variation can be estimated by global integration of atmospheric surface pressure change. The global mean water vapor change is estimated from daily surface pressure data from the National Centers for Environmental Prediction (NCEP) reanalysis atmospheric model (Kalnay et al. 1996), available on a Gaussian grid, about 1.904° latitude by 1.875° longitude, for the period from 1948 to present. Water vapor estimates from surface pressure may differ slightly from specific humidity and precipitable water integrals (Trenberth and Smith 2005). The reason we use surface pressure is based on the consideration that surface pressure is likely to be a more accurately determined quantity (than specific humidity) because of the greater number of surface pressure observations available.

When assuming the total water mass of the atmosphere, hydrosphere, and ocean is conserved, terrestrial water storage and atmospheric water vapor changes can be converted into contributions of equivalent non-steric global MSL change (Chen et al. 1998, Minster et al. 1999). At interannual and long-term time scales, snow/ice melting and accumulation in polar regions and of glaciers and other period geophysical processes, such as GIA are expected to have major effects on the global mean sea level change (Douglas 1995, Peltier and Tushingham 1989, Peltier 2001). Terrestrial water storage change also shows strong long-term variability and could significantly affect the global MSL changes (Milly et al. 2003, Ngo-Duc et al. 2005). In this study, we only focus on terrestrial water and atmospheric effects on the global mean sea level change during the period overlapping with T/P and Jason-1 altimeter mission, (i.e., 1993 – 2004), and directly compare model estimates with altimeter observation. Our main purpose here is not to try to close global MSL change budget at interannual and long-term time scales, but to demonstrate potential contributions from atmospheric water vapor and terrestrial water storage changes.

Figure 1

3. Results and Comparisons

3.1. Long-Term Sea Level Rise

Figure 1 shows two separate estimates of steric contributions to global MSL change using the WOD01 yearly (blue curve) and pentadal (red curve) temperature anomaly data referenced to 700m and 3000m respectively. The two straight lines represent the unweighted least squares fit of the linear trend of each estimate. To be consistent with satellite altimeter data, all global steric MSL change estimates discussed in this study are computed from data in regions between 65°S to 65°N. The steric contributions to global MSL rise, computed from the two datasets, are about 0.34 ± 0.04 and 0.39 ± 0.05 mm/year, respectively. The slight difference is mainly from the inclusion of deeper ocean data in the pentadal data (0-3000 m depth as compared to 0-700 m depth in the yearly fields). We also compute the trend of the yearly time series only using the data covering the same time span as the pentadal data (i.e., 1957 – 1996), and the long-term rate is about 0.28 ± 0.05 mm/year, considerably smaller than the 0.39 ± 0.05 mm/year from pentadal data. This means the deep ocean (from 700m to 3000m) is also showing significant warming during the past several decades.

Aside from the evident long-term sea level rise, interannual and decadal steric sea level changes are also significant, especially during the late 1970's and early 1980's, consistent with the findings of recent studies (e.g., Church et al. 2004, White et al. 2005). It is interesting to notice that, based on the result from the yearly temperature anomalies, there appears an 'acceleration' of steric sea level rise since the early 1990's. This could be associated with another strong decadal variation or indicate effects from global warming. This period coincides with the T/P and Jason-1 satellite altimeter missions, which were launched in August 1992 and December 2001, respectively. Therefore, these results can be particularly useful in interpreting T/P and Jason-1 altimeter(s) observed global mean sea level change during the same period (although the same results are seen in altimetry as well as ocean data). For example, the significantly larger global MSL rise rate observed by T/P altimeter (at ~ 2 – 3 mm/year) would not represent the long-term sea level rise rate (see Church et al. 2001, IPCC, and others to conclude this) and is likely to be associated with a strong decadal variation.

Figure 2

Altimeter observed global MSL change estimated from AVISO merged mean sea level anomaly (MSLA) data is shown in the top panel of Fig. 2a. The straight line is the linear trend estimated from unweighted least squares fit. The altimeter data show a clear long-term sea level rise at the rate about 2.6 ± 0.06 mm/year during the 12 years period from 1993 to 2004, which is slightly smaller than the estimate (2.8 mm/year) by Cazenave and Nerem (2004) based on only T/P and Jason-1 data during the period from 1993 to 2003 (or 3.1 mm/year after correcting for the effects of post glacial rebound) . We remove seasonal and shorter period variations from the altimeter time series by first removing the seasonal (i.e., annual and semiannual) variation using unweighted least squares fit, and then removing residual signals with periods shorter than 1 year using a 1-year sliding window, and show the long-term (interannual or longer periods) signals in Fig. 2b (blue solid curve). The WOD01 steric contribution (from yearly temperature anomaly) is shown by a solid red curve. During the period 1993 to 2003, the WOD01 steric contribution shows a significantly larger trend than the 50-year average (1.2 ± 0.1 vs. 0.34 ± 0.04 mm/year). However, it still can only account for about half of the altimeter-observed sea level change rate (i.e., 2.6 ± 0.06 mm/year).

During this period, the steric contribution estimated from WOD01 is significantly different from any previously published results based on WOD98 (e.g., Cabanes et al. 2001), and is less than half of the magnitude of the WOD98 based estimate (1.2 ± 0.1 vs. 3.0 ± 0.6 mm/year). This large difference is unlikely caused by the fact that WOD01 includes data down to 700 m depth, while WOD98 stops at 500 m depth. Detailed analysis of the differences and possible error sources will be given in Section 3.2.

Figure 3

To examine the spatial or regional variability of sea level rise rates, we compute global steric sea level change rates at each geographical location (i.e., each grid point) using WOD01 yearly temperature data from 1993 through 2003, and show the results in Fig. 3a. Satellite altimeter observed global sea level change rates are shown in Fig. 3b. The AVISO merged altimeter MSL anomalies (at 1° x 1° grids) contain significant spatial noise, especially at high latitudes. To reduce errors in altimeter data, a 2-D 5-degree moving average is applied to the altimeter results. There are some strong geographical patterns of the global sea level change rate. In many regions, altimeter-observed and WOD01-estimated 'long-term' sea level change rates can be as large as over 1 cm/year, consistent with previous studies (e.g., Cabanes et al. 2001, Kuhn et al. 2005). During this 11-year period, both WOD01 and satellite altimeter data show significant warming in the western Pacific, likely in part the ocean's response to an increase in greenhouse gases in the atmosphere and resultant global warming. This geographically non-uniform ocean warming can be attributed to a number of reasons: 1) natural and anthropogenic aerosols are not well mixed geographically and can have a substantial effect on regional warming rates (Levitus et al. 2005), 2) any change in the Earth's radiative balance may induce global and regional changes in the circulation of the atmosphere and ocean which could in turn affect the net flux of heat across the air-sea interface on a regional basis (Levitus et al. 2005), and 3) the regional ocean warming appears to be related to ocean freshening (Boyer et al. 2005) and regional fresh water flux between the atmosphere and ocean will also affect regional ocean warming.

Reasonable correlation exists between WOD01 and altimeter results (see Figs. 3a and b). For example, during the period 1993 to 2004, the warming in the western Pacific can be largely explained by the warming of the ocean during the same period. The altimeter results show a relatively larger mean, consistent with the time series shown in Fig. 2. This is mainly because altimeter observations include both steric and non-steric global MSL changes.

WOD01 estimated steric effects only account for about half of altimeter-observed long-term global MSL rise (1.2 vs. 2.6 mm/year).

3.2 Comparisons between WOD01 and WOD98

To help us understand what may cause the significant difference between WOD01 and WOD98 estimates during the period after the early 1990's, we independently computed the steric contribution to global MSL change using similar temperature and salinity data from WOD98. To eliminate possible contributions from temperature change from 500 to 700 m depth in WOD01, we compute a separate estimate of the WOD01-based contribution using exactly the same number of layers as in WOD98 (i.e., layers 1 – 14, covering the top 500 m). Fig. 4a shows the comparison of these two estimates (from WOD01 and WOD98, thin curves). The two thick lines represent the unweighted least squares fit of the long-term trend. For the entire time span, the two time series agree well, especially from 1955 to the early 1990's. The two estimates show similar long-term steric sea level rise rates (WOD01's 0.30 vs. WOD98's 0.34 mm/year). However, during the period after the early 1990's, or the period overlapping with T/P and Jason-1 missions, these two time-series show significant differences (see the zoomed-in comparison in Fig. 4b), and show two distinct 'long-term' rates, 1.3 ± 0.1 mm/year from WOD01 vs. 3.0 ± 0.6 mm/year from WOD98.

Figure 4

Our WOD98 estimates are consistent with those from Cabanes et al. (2001). The contribution from layers between 500 m and 700 m depth in WOD01 is relatively minor, but does increase the estimated steric effect from 0.30 to 0.34 mm/year (see Figs. 1 and 4). The large discrepancy between WOD01- and WOD98-estimated results is mainly introduced by the difference between the two in the later years in WOD98, especially in 1997 and 1998. The significant discrepancy suggests that the differences between WOD01 and WOD98 temperature fields are not simply the incomplete collection of data in WOA98. Data corruption and/or processing error (such as the XBT depth correction error) appear to have played a major role in the discrepancies (Lombard et al. 2005).

3.3 Interannual Sea Level Change

Another finding of this study is that the WOD01-estimated steric global MSL change fails to resemble the strong interannual variability observed by satellite altimeter during the 1997/1998 El Niño event (see Fig. 2b). Similar finds can be identified from Willis et al. (2004, Fig. 11), Levitus et al. (2005, Fig. 1), and Antonov et al. (2005, Fig. 1). This can be attributed to either errors in the WOD01 temperature anomalies (e.g., underestimated temperature change during this period) or non-steric effects, such as water redistribution between the oceans and atmosphere and land (including polar ice sheet). To quantify some of these non-steric effects on global MSL change at interannual time scales, we compute equivalent global MSL changes from the total water vapor variation in the atmosphere based on NCEP reanalysis atmospheric model, and terrestrial water storage variations from the CPC land surface model using the same water mass conservation equations as used by Chen et al. (1998, Eq. 1 and 2).

Fig. 5 shows the comparison between interannual global MSL change observed by satellite altimeter and possible contributions from water vapor variations in the atmosphere and terrestrial water storage changes over land. In terms of water content, water vapor is a very minor component in the Earth system, and only amounts to 0.04% of the total fresh water (see USGS online publication at http://ga.water.usgs.gov/edu/earthhowmuch.html). However, it does show significant interannual variability and its contribution to interannual sea level change appears negatively correlated with altimeter observations. Terrestrial water storage change plays a major role in interannual sea level change, as well. There is a very good correlation between altimeter observation and model estimated land water contribution at interannual time scale, especially during the 1997/1998 El Niño event and other two major peaks in 2000 and 2003. The long-term tends in NCEP atmospheric water vapor and CPC terrestrial water storage are not evident and therefore not evaluated here.

Figure 5

The above analysis is to demonstrate that at interannual time scales, many factors could have major contributions to the global MSL change. In addition to steric effects, water storage changes in the two largest fresh water bodies on the Earth, polar ice caps (plus glaciers and permanent snow) and ground water, accounting for ~ 99% of the total fresh water in combination, will likely have even more significant contributions than water vapor and soil moisture to the global MSL changes.

Although on global average, the WOD01-estimated steric contribution fails to resemble the strong 1997/1998 interannual MSL change observed by satellite altimeters (see Fig. 2b), however, at regional or basin scales, ocean temperature anomalies associated with the strong El Niño /Southern Oscillation (ENSO) events are wide recognized as the main driving force to interannual sea level change during the ENSO periods (Chambers et al. 1999, Merrifield et al. 1999, Kuhn et al. 2005). There is also evidence indicating that global mean SST is well correlated with global MSL change during the ENSO periods (e.g., Nerem et al. 1999).

4. Conclusions

Based on our reassessment of steric effects on long-term global MSL change using the WOD01 temperature anomaly fields, the ocean warming causes the global mean sea level rise at about 0.34 to 0.39 ± 0.05 mm/year over the near-50-year period from 1955 to 2003. However, during the period overlapping with T/P and Jason-1 altimeter observations (since 1993), the steric effects are significantly larger (~ 1.2 ± 0.1 mm/year referenced to 700 m) than the 50 years average, and amount up to about 50% of the satellite-altimeter-observed sea level rise (~ 2.6 ± 0.06 mm/year). Temperature variations in the deep ocean (i.e., from 700 m to 3000 m depth in this study) have significant effects on the long-term steric sea level change. This is demonstrated by the significantly different estimates of the steric global MSL rise rates (0.28 ± 0.05 mm/year from the yearly 0-700m data vs. 0.39 ± 0.05 mm/year from the pentadal 0-3000m data). Our WOD01-based estimates are consistent with those by Antonov et al. (2005), a recent study based on the very same dataset.

During the period since the early 1990's, steric effects estimated from WOD01 (plus additional data processed through June 2004) are significantly different from previously published results based on WOD98 (Cabanes et al. 2001). The WOD01-estimated steric contribution is less than half of that from WOD98, with this difference mainly caused by errors in the WOD98 temperature anomaly data and incomplete collection of in situ measurements in WOD98, especially in the later years (e.g., 1997 and 1998) (Lombard et al. 2005).

On global average, the estimate from WOD01 fails to show obvious correlation with the strong interannual variation from altimeter observation during the 1997/1998 El Niño event, for reasons yet to be determined. The analysis of the NCEP reanalysis atmospheric model and the CPC LDAS indicate that terrestrial water storage change and atmospheric water vapor variation have significant contributions to global mean sea level change at interannual time.

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Figures:

Figure 1. The global mean steric sea level changes estimated from the WOD01 yearly and pentadal temperature anomaly fields (thin curves). The thick straight lines represent the long-term trends estimated from unweighted least squares fit. The units are mm of sea level change.

Figure 2. a) The global mean sea level change (thin blue curve) estimated from the AVISO merged mean sea level anomaly (MSLA) data during the period 1993 to 2004. The red thick line is the long-term trend estimated from least squares fit. b) Comparison among long-term sea level change observed by satellite altimeter (blue curve), and steric effects estimated from WOA01 (green curve) and WOD98 (green curve) yearly temperature anomaly data. The dashed lines represent the long-term trends estimated from unweighted least squares fit. The units are mm of sea level change.

Figure 3. a) Global steric mean sea level change rate (in units of cm/year) estimated from WOD01 yearly temperature fields between 1993 and 2003; b) Global observed mean sea level change rate (in units of cm/year) estimated from AVISO merged satellite altimeter sea level anomalies between 1993 and 2003.

Figure 4. a) Steric global mean sea level changes from WOA01 (red curve) and WOD98 (blue curve). The thick straight lines represent the long-term trends estimated from unweighted least squares fit. b) Same as a) but zoomed into the period 1993 to 2004. The units are mm of sea level change.

Figure 5. Interannual global mean sea level changes (in units of mm) from altimeter observations, atmospheric water vapor variations, and terrestrial water storage change.

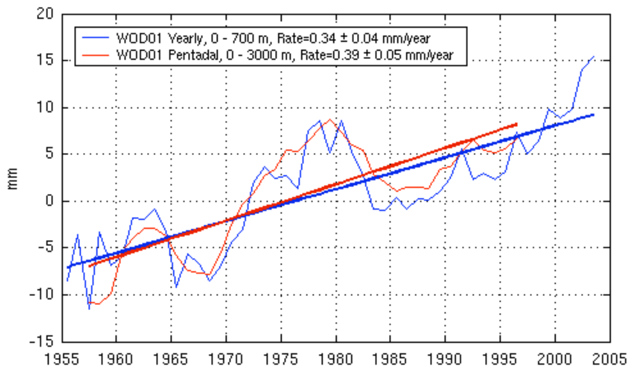

Figure 1

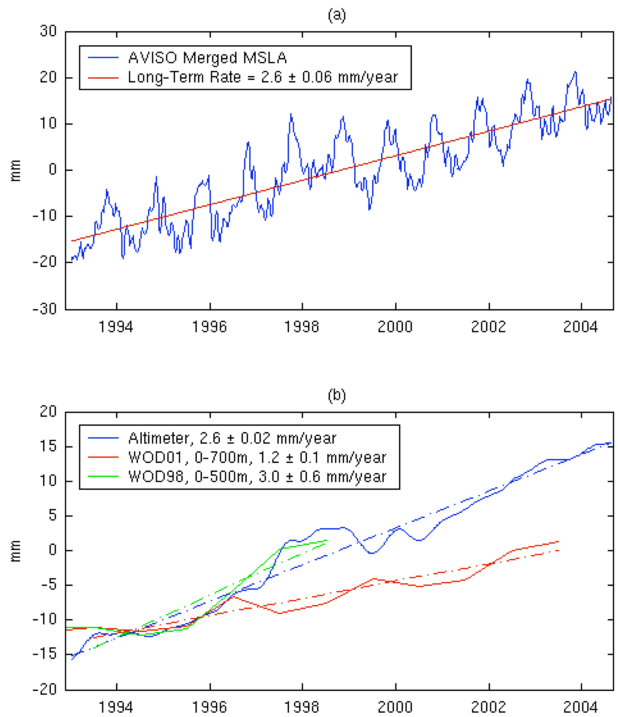
(a)
AVISO Merged MSLA
Long-Term Rate = 2.6 ± 0.06 mm/year
mm
30
20
10
0
-10
-20
-30
1994
1996
1998
2000
2002
2004
(b)
Altimeter, 2.6 ± 0.02 mm/year
WOD01, 0-700m, 1.2 ± 0.1 mm/year
WOD98, 0-500m, 3.0 ± 0.6 mm/year
mm
20
15
10
5
0
-5
-10
-15
-20
1994
1996
1998
2000
2002
2004

Figure 2

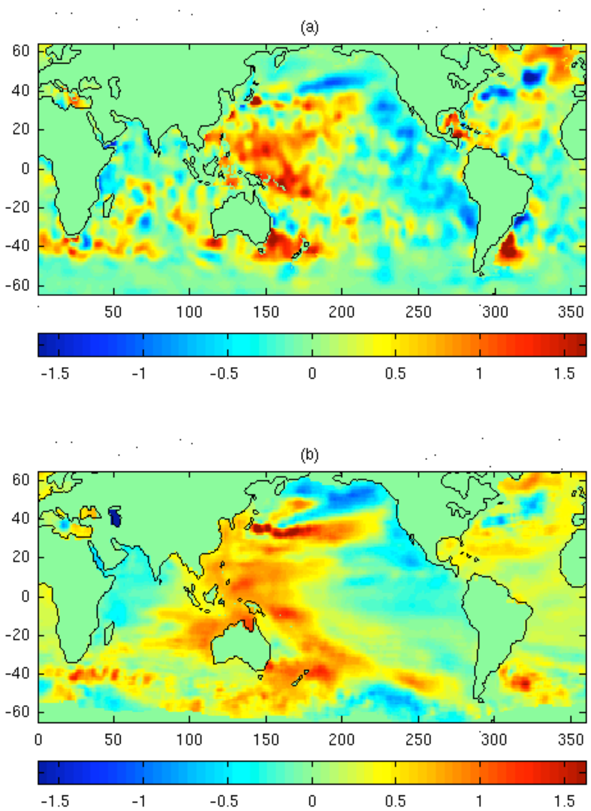
(a)
60
40
20
0
-20
-40
-60
50
100
150
200
250
300
350
-1.5
-1
-0.5
0
0.5
1
1.5
(b)
60
40
20
0
-20
-40
-60
0
50
100
150
200
250
300
350
-1.5
-1
-0.5
0
0.5
1
1.5

Figure 3

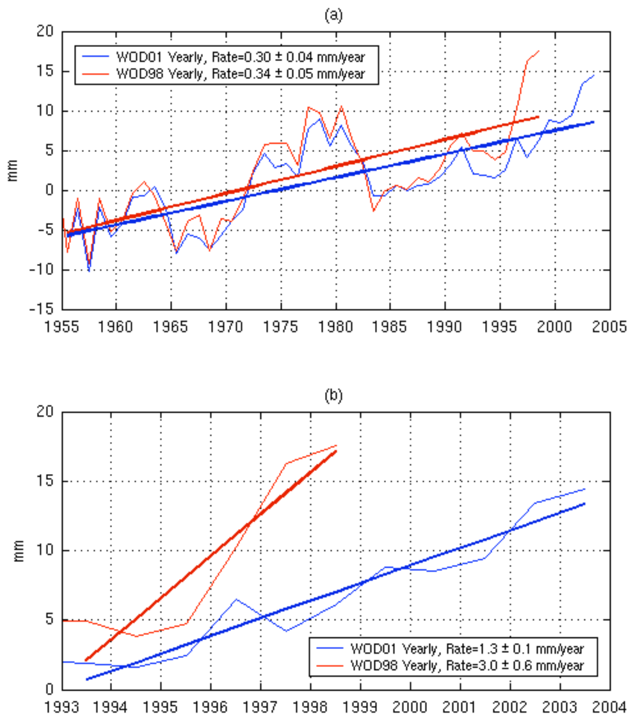

Figure 4

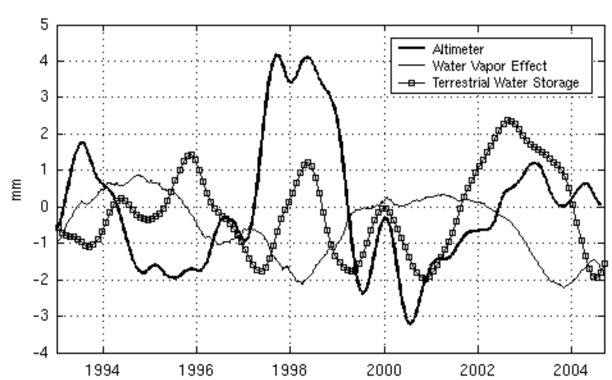

Figure 5