# Thermosteric sea level rise, 1955–2003

J. I. Antonov, S. Levitus, and T. P. Boyer

National Oceanographic Data Center, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, USA

Received 30 March 2005; revised 5 May 2005; accepted 16 May 2005; published 16 June 2005.

[1] For the 1955–2003 period, the thermal expansion of the 0–700 m layer of the World Ocean contributed approximately 0.33 mm/year to global sea level rise. About half of this thermosteric trend is due to warming of the Atlantic Ocean. Approximately one third of the total thermosteric rise is due to the warming of the Pacific Ocean. For the period of available TOPEX/Poseidon (T/P) satellite altimetry data (1993–2003), the linear trend of thermosteric sea level (0–700 m) is 1.23 mm/year, 60% of which is due to the trends in the Pacific Ocean. For the 0–3000 m layer of the entire World Ocean, the linear trend of thermosteric sea level is 0.40 mm/year for 1955–1959 through 1994–1998. For the 50°S–65°N region that we previously reported (Antonov et al., 2002) which was characterized by a 0.50 mm/year trend for 1955–1959 through 1992–1996, our new estimate is 0.47 mm/year for this same period. **Citation:** Antonov, J. I., S. Levitus, and T. P. Boyer (2005), Thermosteric sea level rise, 1955–2003, *Geophys. Res. Lett.*, *32*, L12602, doi:10.1029/2005GL023112.

## 1. Introduction

[2] Thermosteric sea level is defined as the variation in sea surface height caused by expansion/contraction of ocean volume due to temperature changes [*Pattullo et al.*, 1955; *Tabata et al.*, 1986; *Antonov et al.*, 2002]. *Levitus et al.* [2000] analyzed 5.3 million temperature profiles and found that mean ocean temperature increased during the second half of the twentieth century. Analysis of salinity observations suggested that this warming was accompanied by ocean freshening [*Antonov et al.*, 2002]. Studies of recent (since 1993) changes in sea level based on satellite altimetry data stated that the rate of global sea level rise is much larger during the past decade compared to a century-long trend [e.g., see *Nerem and Mitchum*, 2001; *Leuliette et al.*, 2004]. These results renewed discussion of the major causes of the 1–2 mm/year sea level rise in the 20th century determined from tide gauge records [*Munk*, 2002, 2003; *Miller and Douglas*, 2004; *Wadhams and Munk*, 2004].

[3] Here we present revised estimate of thermosteric sea level changes based on recently updated 1° gridded global temperature anomaly fields [*Levitus et al.*, 2005] based on approximately 7 million temperature profiles.

## 2. Global and Zonal Variability of Thermosteric Sea Level

[4] Based on in-situ temperature observations, yearly (1955–2003) and pentadal (1955–1959 through 1994–1998) objectively analyzed temperature anomaly fields (global 1° latitude-longitude grid) from the sea surface to depths of 700 m and 3000 m respectively, can be used for climate change studies. *Levitus et al.* [2005] pointed out that a significant part of the change in global ocean heat content is accounted for by the 0–700 m layer. To quantify the variability of thermosteric sea level, we present time series and linear trends of globally averaged thermosteric sea level for the 0–700 m and 0–3000 m layers in Figure 1 (see *Antonov et al.* [2002] for details of thermosteric sea level computation). Based on the ratio of trends of pentadal thermosteric sea level for the 1955–1959 through 1994–1998 period, the upper 700-m layer accounts for about 75% of sea level rise due to thermal expansion of the 0–3000 m layer. Overall, the three global curves are very similar each other and well correlated with heat content [*Levitus et al.*, 2005] time series.

[5] For the 0–3000 m layer, the linear trend is 0.40 ± 0.05 mm/year for the entire World Ocean for the 1955–1959 through 1994–1998 period. In our previous work we presented the linear trend (0.50 mm/year) for the 50°S–65°N region based on pentadal data through 1992–1996. For this same region our new estimate is 0.45 ± 0.05 mm/year for the entire period and 0.47 ± 0.06 mm/year for the 1955–1959 through 1992–1996 period. These values illustrate that the estimates of "global" linear trend vary up to 10% with relatively small variations of the time domain and how one defines "global".

[6] Figure 1 shows that the yearly thermosteric sea level for the 0–700 m layer and the pentadal time series for the same layer are quite similar. Trends for this layer based on pentadal (0.30 ± 0.04 mm/year) and yearly (0.33 ± 0.04 mm/year) data are very close each other. Thus, the longer (through year 2003) and less smoothed yearly (compared to pentadal) thermosteric sea level data for the 0–700 m layer is reasonable for analysis of regional variability in thermosteric sea level.

[7] Because changes in thermosteric sea level are not geographically uniform [*Antonov et al.*, 2002], it is interesting to compare averages for different ocean subdomains. Figure 2 shows the time series of thermosteric sea level averaged for the entire World Ocean and five subdomains defined by increments of 30° of latitude. The most prominent features of the global time series are a linear trend with substantial interdecadal variability. In contrast, the average for the equatorial 15°S–15°N region (28% of the World Ocean area) exhibits significant interannual variability (associated in part with El-Nino/Southern-Oscillation (ENSO) events and possibly the Pacific Decadal Oscillation (PDO) [*Stephens et al.*, 2001]) which is comparable to the magnitude of the decadal oscillation (10–20 mm) seen in the time series for larger ocean regions.

[8] To emphasize similarities and differences in thermosteric sea level changes between oceans, we averaged the thermosteric sea level by 1° latitude belts for each individual


0094-8276/05/2005GL023112$05.00

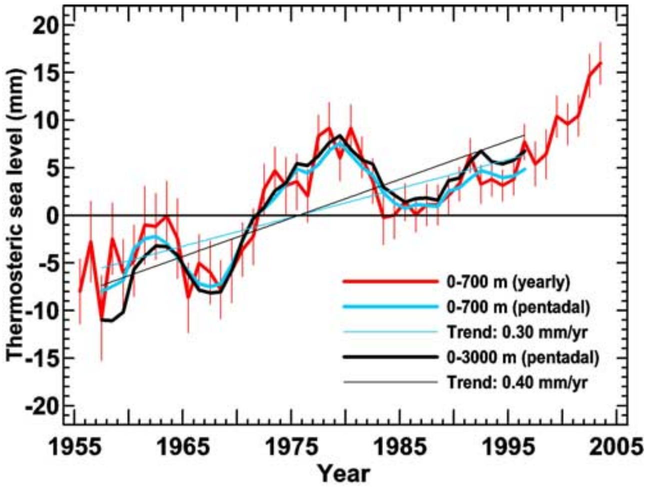


**Figure 1.** Time series of yearly thermosteric sea level (mm) for the 0–700 m layer (red curve) and pentadal (5-year running composites for 1955–1959 through 1994–1998) thermosteric sea level (mm) for the 0–700 m (blue curve) and 0–3000 m (black curve) layers. Vertical lines through each yearly estimate represent ± 1 standard error. The linear trend for each pentadal series is plotted as a thin blue (black) line.

ocean. The time series of zonally averaged yearly thermosteric sea level for the Atlantic (including Arctic Ocean), Indian, Pacific, and the World Ocean are shown in Figure 3. We multiplied each yearly zonal average by the percentage of corresponding area of 1°-zonal belt to area of the World Ocean. This scaling has two useful properties: (1) the sum of the time series of Figures 3a–3c is equal to the time series for the World Ocean (Figure 3d) for each 1°-degree zonal band, and (2) the sum of all zonal time series in Figure 3d equals the time series of the thermosteric sea level for the World Ocean in Figure 2. For instance from Figure 3, we see that a relatively high thermosteric sea level during 1977–1981 seen in Figure 2 is attributable to the peaks in each ocean, mainly, between the equator and 25°N.

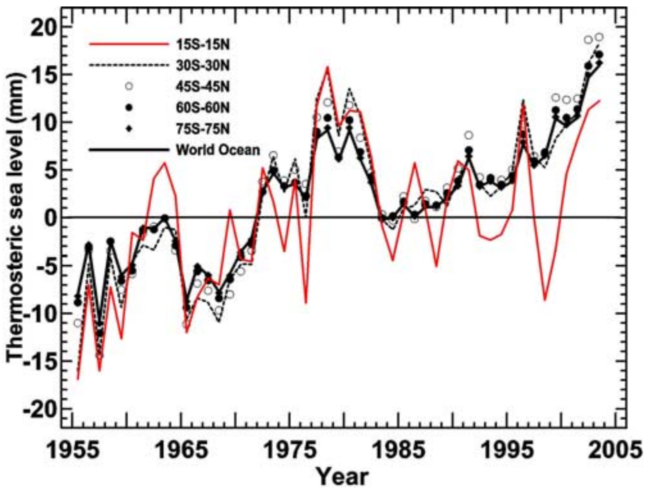


**Figure 2.** Time series of yearly thermosteric sea level (mm) for the 0–700 m layer for 1955–2003 period averaged for different latitudinal subdomains of the World Ocean: 15°S–15°N (red curve), 30°S–30°N (black dashed curve), 45°S–45°N (open circles), 60°S–60°N (filled circles), 75°S–75°N (filled diamonds), 86°S–90°N (thick black curve). Each yearly value is plotted at the midpoint of the year. Reference period: 1957–1990.

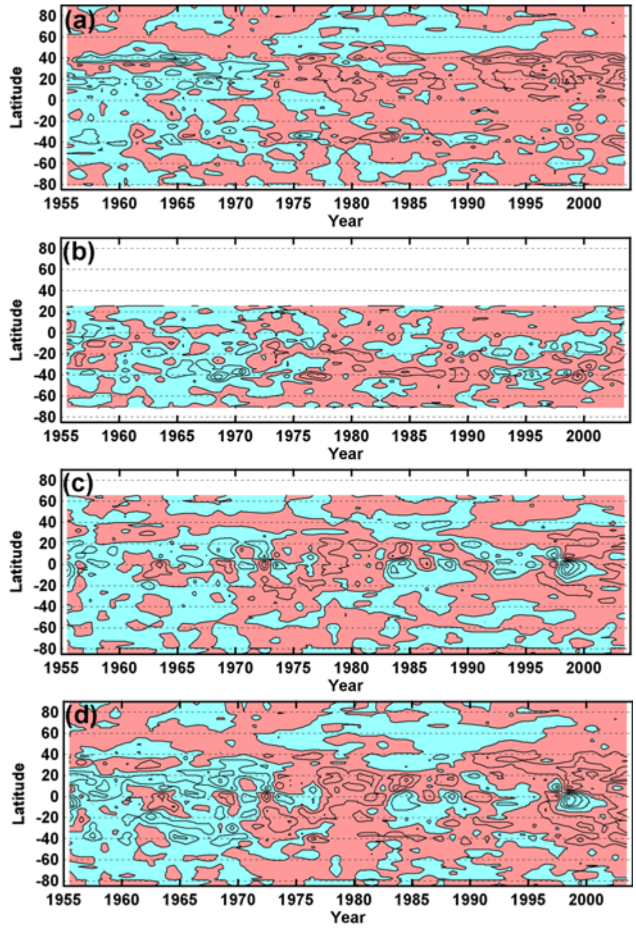


**Figure 3.** Time series of zonally averaged (by 1° latitude belts) thermosteric sea level for the 0–700 m layer for the 1955–2003 period for the (a) Atlantic, (b) Indian, (c) Pacific, and (d) World Ocean. Reference period: 1957–1990. Zonally averaged data were multiplied by percentage of area of World Ocean represented by corresponding one-degree zonal belt. Contour interval is 5.0 (a, b), and 10.0 (c, d); negative (positive) values shown in blue (red).

[9] In each ocean, the variability (or magnitude) of the thermosteric component poleward of 50° latitude is relatively small. Between ~50°S and ~50°N, contributions from each ocean to the World Ocean thermosteric sea level variability are different. The Pacific Ocean variability is dominant in the tropics while the Atlantic and Indian oceans play visible roles in the subtropics. Analysis of the variance of the time series of zonally averaged (by 1° latitude belts) yearly thermosteric sea level (not shown) for each ocean shows that the maximum values of the variance are located at ~4°S–3°N and ~6°N–10°N in the Pacific Ocean, ~32°S–42°S and ~12°N–43°N in the Atlantic Ocean, and ~35°S–45°S in the Indian Ocean.

[10] To identify the most important patterns of the thermosteric sea level variability in each ocean, we have decomposed the zonally averaged thermosteric sea level time series into empirical orthogonal functions (EOFs) (not

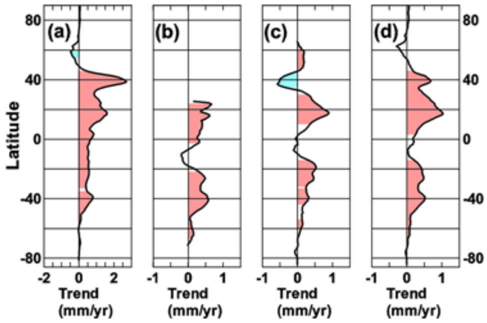


**Figure 4.** Linear trends (mm/year) of zonally averaged (by 1° latitude belts) thermosteric sea level for 0–700 m layer for the 1955–2003 period for the (a) Atlantic, (b) Indian, (c) Pacific, and (d) World Ocean. Statistically significant at 95% confidence level trends are shaded. Note that the scale for the Atlantic is twice of that for other oceans. No area weighting has been applied.

shown). We found that the time series of the dominant mode for the Pacific Ocean (39% of the total variance) and 2nd mode for the World Ocean (21%) reveal a distinct signature of ENSO events. The time series of the 1st EOFs for each ocean, except the Pacific, are highly correlated with the time series of thermosteric sea level averaged for the corresponding ocean basin. The zonal distribution of 1st EOF for the Atlantic (52%), Indian (35%), and the World Ocean (40%) as well as the 2nd EOF (outside the 15°S–10°N zonal band) for the Pacific (21%) resembles the distribution of linear trends of zonally averaged thermosteric sea level.

## 3. Linear Trends of Thermosteric Sea Level for 1955–2003 and 1993–2003 Periods

[11] Figure 4 shows the estimates of the linear trend of zonally averaged thermosteric sea level (not scaled) for each ocean and the World Ocean for the 1955–2003 period. For each curve, the shaded areas emphasize the trends which are statistically significant at the 95% confidence level.

[12] For most latitudes in all oceans, the thermosteric sea level increased significantly during the 1955–2003 period. Statistically significant negative trends occur in the North Atlantic subpolar gyre and in the subtropical/subpolar transition zone in North Pacific. Strong warming around 40°N in the Atlantic was partly compensated by cooling in the Pacific resulting in less net warming of the World Ocean at these latitudes. Trends in all three oceans make a significant contribution to World Ocean trends around 40°S. No trends are found near the equator in the Indian (∼5°S–20°S) and Pacific (∼10°S–10°N) Oceans.

[13] Table 1 gives a summary of the estimates of the linear trend of thermosteric sea level (0–700 m) for each ocean, the World Ocean and subdomains (see Figure 2). In addition to the linear trends for the 1955–2003 period, Table 1 presents the linear trends for the period when we have both TOPEX/Poseidon (T/P) satellite altimetry data and in-situ estimates available (1993–2003).

[14] For both periods, all trends are positive. The trends for the 1993–2003 period are more than three times larger than for the entire period. The contribution from each individual ocean to the global trend is different for these periods. For the entire period, warming in the Atlantic contributed about 52% to the global thermosteric sea level trend. For the 1993–2003 period, the Pacific contribution to global thermosteric rise is the largest compared to other oceans (see Figure A1 for the time series of thermosteric sea level for each individual ocean[1]). Geographically, most positive trends in the Pacific for the 1993–2003 period are located in the western tropical Pacific and between Australia and New Zealand (see Figures A2–A3 for 1° gridded, global fields of the thermosteric sea level trend and interannual standard deviation for both periods).

[15] Our global estimate of thermosteric sea level rise may be biased due to sparse data coverage in the southern hemisphere and the Arctic. A recent attempt to blend oceanographic observations with satellite altimetry data by *Willis et al.* [2004] (henceforth abbreviated as WRC) suggests that our analysis may underestimate the global thermosteric sea level rise for 1993–2003 by approximately twenty five percent. However, the WRC estimate is, in turn, biased toward satellite altimetry (in regions where in situ temperature measurements do not exist) which includes non-thermosteric effects. Nevertheless, the difference between the WRC estimate (1.6 ± 0.3 mm/year) and our global trend of 1.2 ± 0.2 mm/year (Table 1) is three to four times smaller compared to the total sea level rise detected from the space (2.8 ± 0.4 mm/year) [*Leuliette et al.*, 2004] for this period. (Note that a value of 0.3 mm/year must be added to the 2.8 mm/year estimate to account for global isostatic adjustment (GIA) [*Douglas and Peltier*, 2002].) The difference between thermosteric trends and the total trend in sea level based on altimetry suggests to us that sea level rise during the past decade has a substantial component from the addition of water mass to the World Ocean, the eustatic component.

[16] It is worth to note that the rate of global thermosteric sea level increase from 1993 to 2003 is not extraordinary. An increase of similar intensity occurred from the late-1960s to mid-1970s (Figure 2).

**Table 1.** Linear Trends of Yearly Thermosteric Sea Level (mm/year) for the 0–700 m Layer of the World Ocean, Latitudinal Subdomains, and Individual Ocean Basins for the 1955–2003 and 1993–2003 Periods[a]

| | 1955–2003 | | 1993–2003 | | |
|---|---|---|---|---|---|
| Basin | Trend, mm/yr | Percent Variance | Trend, mm/yr | Percent Variance | Area of WO, % |
| World Ocean | 0.33 | 63.0 | 1.23 | 88.4 | 100.0 |
| 75°S–75°N | 0.34 | 63.1 | 1.25 | 88.3 | 97.7 |
| 60°S–60°N | 0.37 | 63.7 | 1.31 | 87.7 | 90.0 |
| 45°S–45°N | 0.42 | 61.8 | 1.52 | 86.5 | 74.0 |
| 30°S–30°N | 0.42 | 56.0 | 1.34 | 72.8 | 53.0 |
| 15°S–15°N | 0.26 | 23.1 | (1.18) | 30.4 | 28.5 |
| Atlantic Ocean | 0.60 | 82.8 | 1.06 | 40.8 | 28.2 |
| Indian Ocean | 0.25 | 33.1 | 0.97 | 41.3 | 21.0 |
| Pacific Ocean | 0.22 | 27.2 | 1.45 | 73.8 | 50.7 |

[a]All trends are statistically significant at the 95% confidence level except the trend in parentheses for the 15°S–15°N zonal belt for the 1993–2003 period.

## 4. Discussion

[17] The global linear trend (0–700 m) of thermosteric sea level account for more than 60 percent of the variance

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL023112.

for 1955–2003. Distinct interannual variability in the equatorial region, part of which is ENSO and possibly PDO related, is significantly masked out for thermosteric sea level averaged for the 30°S–30°N and larger regions of the World Ocean.

[18] Despite strong inter-decadal variability and a substantial increase of available oceanographic observations our 0–3000 m trend is in good agreement with our previous estimate of thermosteric sea level rise based on pentadal data for the 50°S–65°N region. This suggests that near-global thermosteric trends for entire period are robust estimates. Analysis of tide gauge measurements for the past 100 years results in a linear trend of sea level of approximately 1.8 mm/year [*Douglas*, 2001; *Peltier*, 2001] and an analysis of the past 55 years of such data yields an estimate of 1.7 mm/year [*Holgate and Woodworth*, 2004]. If we subtract our estimate of the thermosteric trend (0–3000 m) 0.4 mm/year for the world ocean from the 1.7 mm/year estimate, then approximately 1.3 mm/year is left to be explained due to other causes. A similar computation can be done for the 1993–2003 period. Using a value of 3.1 mm/year for linear trend of sea level based on altimetry including the effect of GIA, and our value of 1.2 mm/year (0–700 m layer) as the thermosteric linear trend we are left with a residual of 1.9 mm/year. Assuming that the 0–700 m layer during this period accounts for 75% of the 0–3000 m layer trend in the thermosteric component (as we found for the 1955–1998 period), we would have a residual of 1.5 mm/year to be accounted for by non-thermosteric effects.

[19] **Acknowledgments.** This work was supported by the NASA Physical Oceanography Program. We acknowledge the scientists and technicians who have collected and submitted data to national and regional data centers, as well as managers and staff at oceanographic data centers and funding agencies. Particularly, we thank our colleagues at the Ocean Climate Laboratory for their effort in constructing the *World Ocean Database*. The views, opinions, and findings contained in this report are those of the authors, and should not be construed as an official NOAA or U.S. Government position, policy, or decision.

## References

Antonov, J. I., S. Levitus, and T. P. Boyer (2002), Steric sea level variations during 1957–1994: Importance of salinity, *J. Geophys. Res.*, *107*(C12), 8013, doi:10.1029/2001JC000964.

Douglas, B. (2001), Sea level change in the era of the recording tide gauge, in *Sea Level Rise: History and Consequences*, *Int. Geophys. Ser.*, vol. 75, edited by B. Douglas, M. Kearney, and S. Leatherman, pp. 37–64, Elsevier, New York.

Douglas, B. C., and W. R. Peltier (2002), The puzzle of global sea level rise, *Phys. Today*, *55*, 35–40.

Holgate, S. J., and P. L. Woodworth (2004), Evidence for enhanced coastal sea level rise during 1990s, *Geophys. Res. Lett.*, *31*, L07305, doi:10.1029/2004GL019626.

Leuliette, E. W., R. S. Nerem, and G. T. Mitchum (2004), Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change, *Mar. Geod.*, *27*, 79–94, doi:10.1080/01490410490465193.

Levitus, S., J. I. Antonov, T. P. Boyer, and C. Stephens (2000), Warming of the world ocean, *Science*, *287*, 2225–2229.

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

Miller, L., and B. C. Douglas (2004), Mass and volume contributions to twentieth-century global sea level rise, *Nature*, *300*, 406–409.

Munk, W. (2002), Twentieth century sea level: An enigma, *Proc. Nat. Acad. Sci.*, *99*, 6550–6555.

Munk, W. (2003), Ocean freshening, sea level rising, *Science*, *300*, 2041–2043.

Nerem, R. S., and G. T. Mitchum (2001), Sea Level Change, in *Satellite Altimetry and Earth Sciences: A Handbook of Techniques and Applications*, *Int. Geophys. Ser.*, vol. 69, edited by L.-L. Fu and A. Cazenave, pp. 329–349, Elsevier, New York.

Pattullo, J., W. Munk, R. Revelle, and E. Strong (1955), The seasonal oscillation in sea level, *J. Mar. Res.*, *14*, 88–156.

Peltier, W. (2001), Global glacial isostatic adjustment and modern instrumental records of relative sea level history, in *Sea Level Rise: History and Consequences*, *Int. Geophys. Ser.*, vol. 75, edited by B. Douglas, M. Kearney, and S. Leatherman, pp. 65–95, Elsevier, New York.

Stephens, C., S. Levitus, J. Antonov, and T. Boyer (2001), On the Pacific regime shift, *Geophys. Res. Lett.*, *28*, 3721–3724.

Tabata, S., B. Thomas, and D. Ramsden (1986), Annual and interannual variability of steric sea level along line P in the northeast Pacific Ocean, *J. Phys. Oceanogr.*, *16*, 1378–1398.

Wadhams, P., and W. Munk (2004), Ocean freshening, sea level rising, sea ice melting, *Geophys. Res. Lett.*, *31*, L11311, doi:10.1029/2004GL020039.

Willis, J. K., D. Roemmich, and B. Cornuelle (2004), Interannual variability in upper ocean heat content, temperature, and thermosteric expansion on global scales, *J. Geophys. Res.*, *109*, C12036, doi:10.1029/2003JC002260.

J. I. Antonov, UCAR Project Scientist, NESDIS/NOAA, NODC, E/OC5, 1315 East-West Highway, Silver Spring, MD 20910, USA. (john.antonov@noaa.gov)

T. P. Boyer and S. Levitus, NESDIS/NOAA, NODC, E/OC5, 1315 East-West Highway, Silver Spring, MD 20910, USA. (tim.boyer@noaa.gov; sydney.levitus@noaa.gov)