Sea level rise and the warming of the oceans in the Simple Ocean Data Assimilation (SODA) ocean reanalysis

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[1] A new reanalysis of the global ocean circulation is used to distinguish between the steric and eustatic components of sea level rise. Recent altimeter observations indicate an increase in the rate of sea level rise during the past decade to 3.2 mm/yr, well above the centennial estimate of 1.5–2 mm/yr. This apparent increase could have resulted from enhanced melting of continental ice or from decadal changes in thermosteric and halosteric effects. The contribution from steric effects is explored using the new eddy-permitting Simple Ocean Data Assimilation version 1.2 (SODA1.2) reanalysis of global temperature, salinity, and sea level spanning the period 1958–2001. The applicability of this ocean reanalysis for sea level studies is evaluated by comparing subseasonal variability with a collection of 20 tide gauge station sea level records, comprising a total of 740 years of data. A positive relationship is found at all gauge stations, with an average correlation of \( r = 0.7 \) after correction for the inverted barometer effect. Dynamic height calculated relative to 1000 m from the SODA1.2 reanalysis, used as a proxy for the steric component of sea level, is compared with satellite-derived sea level for the years 1993–2001. During this 9-year period dynamic height increases at a global rate of 2.3 ± 0.8 mm yr\(^{-1}\), a substantial acceleration beyond the multidecadal steric rate of 0.5 mm yr\(^{-1}\). The similarity of the rate of increase in the thermosteric contribution to sea level rise as well as the similarity of its spatial structure in comparison with satellite-derived sea level rise suggests that the recent acceleration in sea level rise is explainable to within the error estimates by fluctuations in warming and thermal expansion of the oceans.


1. Introduction

[2] Sea level rise represents one of the potentially catastrophic consequences of climate change. Estimates of sea level based on examination of tide gauge records suggest a global average rise ranging from a minimum of 1 mm yr\(^{-1}\) [Nakiboglu and Lambeck, 1991; Shennan and Woodworth, 1992; Lambeck et al., 1998; Cabanes et al., 2001] to a maximum of about 2 mm yr\(^{-1}\) [Douglas, 1991, 1997; Trupin and Wahr, 1990; Peltier, 2001; Miller and Douglas, 2004; Church et al., 2004] during the 20th century.

[3] Global sea level rise represents a combination of changes including changes of the mass of the oceans due to melting of continental ice and filling of continental reservoirs (eustatic changes), changes in the thermal and haline structure of the oceans (steric changes), and geologic changes that cause vertical crustal movements of tide gauges (mainly postglacial rebound) [Church et al., 2001]. The thermosteric term is known to be a significant contributor to global average rise at a rate which Antonov et al. [2002] estimate to be 0.5 ± 0.2 mm yr\(^{-1}\).

[4] Recent satellite-based estimates of global sea level, available since 1993, suggest that sea level rise has increased to a faster rate of 3.2 mm yr\(^{-1}\) as shown in Figure 1 (compare with Cazenave and Nerem [2004] and Holgate and Woodworth [2004]). These results suggest that the recent increase may reflect an increase in the rate of melting of continental ice, a result consistent with recent measurements at both poles, particularly if we accept a centennial rate of sea level rise near to 1 mm yr\(^{-1}\) [e.g., Mitrovica et al., 2001; Thomas et al., 2003, 2004].
Another possible explanation discussed in the extensive review by Cazenave and Nerem [2004] is that the recent increase in sea level rise may be due to an increase in heat storage within the ocean. Such an increase only requires a net global increase in surface flux of 1–2 W m$^{-2}$ [Willis et al., 2004], well below the uncertainty in flux estimates. Examination of the spatial distribution of the sea level rise during the 6-year period 1993–1998 considered by Cabanes et al. [2001] and Cazenave and Nerem [2004] and the 11-year period 1993–2003 considered by Willis et al. [2004] shows climate effects associated with the El Niño of 1997–1998 together with effects related to decadal climate variability. Sea level rise in these studies is inhomogeneous and this spatial inhomogeneity may have consequences for the interpretation of centennial rate estimates based on the limited tide gauge archive. Miller and Douglas [2004], however, argue effectively that the spatial scales broaden as one considers longer and longer time-scales and thus the centennial trend may in fact be estimated from a limited set of representative gauges.

In this study we introduce the application of data assimilation-derived ocean reanalyses to the problem of determining the steric component of sea level rise using the recently available Simple Ocean Data Assimilation Version 1.2 (SODA1.2) global reanalysis. The SODA1.2 reanalysis has improved eddy-permitting resolution, potentially side-stepping some of the resolution issues raised by the coarse resolution and data coverage handicaps of previous studies (discussed by Cabanes et al. [2001] and Miller and Douglas [2004]). We examine the accuracy of the SODA1.2 reanalysis in reproducing the tide gauge results by comparison to gauge records at a distributed set of locations. These comparisons then allow us to explore the causes of low-frequency variability evident in the gauge-based sea level rise estimates.

### 2. SODA1.2 Reanalysis

In this section we describe the SODA1.2 reanalysis of ocean climate. More details are provided by J. A. Carton and B. S. Giese (SODA: A reanalysis of ocean climate, submitted to Journal of Geophysical Research, 2005, hereinafter referred to as Carton and Giese, submitted manuscript, 2005). The ocean model component is based on Parallel Ocean Program 1.3 numerical representation of the Boussinesq primitive equations [Dukowicz and Smith, 1994]. This ocean model has 900 grid points with a total of 40 vertical levels. Vertical diffusion is based on the KPP parameterization of Large et al. [1994], while horizontal diffusion is biharmonic. Topography is based on the ETOPO30 data set of Smith and Sandwell [1997] with a few modifications to ensure reasonable basin exchange rates.

Figure 1. Global sea level 1968–2001. Time series of 3-year average SODA1.2 global dynamic height 0/1000 m (bold black); SODA1.2 dynamic height with climatological monthly salinity (thin black); 0/700 m heat content from Levitus et al. [2005] (red); and Cazenave and Nerem [2004] altimeter sea level low-pass filtered with a 12-month running boxcar filter. The linear trends from extended Miller and Douglas [2004] global sea level gauge estimates based on 5-year smoothed data for two periods, 1968–1998 and 1993–1998 (blue thin and bold). The SODA1.2 dynamic height has been demeaned. The means of the other curves have been adjusted to be the same as that for SODA1.2 dynamic height for the period of overlap. Standard errors are shown for SODA1.2 dynamic height (with appropriate scaling in the case of integrated temperature).
lated diagnostically using a linearized continuity equation, valid for small ratios of sea level to fluid depth [Dukowicz and Smith, 1994]. Steric sea level is estimated using 0/1000 m dynamic height following Miller and Douglas [2004].

SODA utilizes a multivariate sequential data assimilation scheme in which observations of ocean temperature and salinity are used to update the ocean model. This assimilation scheme, which is an outgrowth of that of Carton et al. [2000], uses empirically determined observation error covariances to estimate the forecast errors every 10 days. These error covariances include relationships between temperature and salinity errors (which become decorrelated within the mixed layer). They vary with depth between temperature and salinity. These checks are in addition to the substantial quality control already included in the WOD2001 [see Conkright et al., 2002]. Our additional checks eliminate an additional 5% of the profiles. Finally, the analysis files are averaged monthly and mapped onto a uniform 0.5° × 0.5° latitude-longitude horizontal grid using simple bilinear interpolation.

### Table 1. Comparison of Annually Averaged Tide Gauge Data With Sea Level and 0/1000 m Dynamic Height From SODA1.2 Through Year 2001*

<table>
<thead>
<tr>
<th>Station</th>
<th>Location</th>
<th>Time</th>
<th>Number of Years</th>
<th>Dynamic Height Correlation</th>
<th>Sea Level Correlation</th>
<th>$\sigma_{\text{SODA}}/\sigma_{\text{Gauge}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auckland</td>
<td>36.9°S</td>
<td>174.8°E</td>
<td>1959–1998</td>
<td>0.12b</td>
<td>0.49</td>
<td>1.2</td>
</tr>
<tr>
<td>Lyttleton</td>
<td>44.4°S</td>
<td>171.3°E</td>
<td>1958–1987</td>
<td>0.21b</td>
<td>0.44</td>
<td>1.0</td>
</tr>
<tr>
<td>Pago Pago</td>
<td>14.4°S</td>
<td>189.4°E</td>
<td>1958–1999</td>
<td>0.74</td>
<td>0.83</td>
<td>0.7</td>
</tr>
<tr>
<td>Rabaul</td>
<td>4.3°S</td>
<td>152.3°E</td>
<td>1975–1997</td>
<td>0.97</td>
<td>0.96</td>
<td>1.1</td>
</tr>
<tr>
<td>Christmas</td>
<td>2.1°N</td>
<td>203.0°E</td>
<td>1974–1999</td>
<td>0.95</td>
<td>0.95</td>
<td>0.8</td>
</tr>
<tr>
<td>Kwajalein</td>
<td>8.8°N</td>
<td>167.8°E</td>
<td>1958–1999</td>
<td>0.79</td>
<td>0.78</td>
<td>1.4</td>
</tr>
<tr>
<td>Balboa</td>
<td>9.1°N</td>
<td>280.5°E</td>
<td>1958–1986</td>
<td>0.79</td>
<td>0.78</td>
<td>1.2</td>
</tr>
<tr>
<td>Quepos</td>
<td>9.5°N</td>
<td>275.9°E</td>
<td>1958–1994</td>
<td>0.68</td>
<td>0.70</td>
<td>0.7</td>
</tr>
<tr>
<td>Johnston</td>
<td>16.8°N</td>
<td>191.0°E</td>
<td>1958–1998</td>
<td>0.65</td>
<td>0.67</td>
<td>1.3</td>
</tr>
<tr>
<td>Hilo</td>
<td>19.8°N</td>
<td>205.0°E</td>
<td>1958–1998</td>
<td>0.56</td>
<td>0.62</td>
<td>1.0</td>
</tr>
<tr>
<td>Honolulu</td>
<td>21.4°N</td>
<td>202.2°E</td>
<td>1958–1998</td>
<td>0.71</td>
<td>0.77</td>
<td>0.9</td>
</tr>
<tr>
<td>Naha</td>
<td>26.2°N</td>
<td>127.7°E</td>
<td>1967–1999</td>
<td>0.87</td>
<td>0.88</td>
<td>1.4</td>
</tr>
<tr>
<td>San Francisco</td>
<td>37.8°N</td>
<td>122.5°W</td>
<td>1958–2001</td>
<td>0.66</td>
<td>0.81</td>
<td>0.6</td>
</tr>
<tr>
<td>Sitka</td>
<td>57.1°N</td>
<td>135.3°W</td>
<td>1958–1999</td>
<td>0.55</td>
<td>0.75</td>
<td>1.3</td>
</tr>
<tr>
<td>Fremantle</td>
<td>32.1°S</td>
<td>115.7°E</td>
<td>1958–2000</td>
<td>0.62</td>
<td>0.84</td>
<td>0.8</td>
</tr>
<tr>
<td>Tenerife</td>
<td>28.5°N</td>
<td>16.3°W</td>
<td>1958–1989</td>
<td>0.25</td>
<td>0.27</td>
<td>1.1</td>
</tr>
<tr>
<td>St. Georges</td>
<td>32.4°N</td>
<td>64.7°W</td>
<td>1958–1998</td>
<td>0.48</td>
<td>0.66</td>
<td>0.9</td>
</tr>
<tr>
<td>Brest</td>
<td>48.4°N</td>
<td>4.5°W</td>
<td>1958–1999</td>
<td>0.26</td>
<td>0.70</td>
<td>0.6</td>
</tr>
<tr>
<td>Newlyn</td>
<td>50.1°N</td>
<td>5.5°S</td>
<td>1958–2001</td>
<td>0.21</td>
<td>0.65</td>
<td>0.5</td>
</tr>
<tr>
<td>Reykjavik</td>
<td>64.2°N</td>
<td>21.9°W</td>
<td>1958–1983</td>
<td>0.24</td>
<td>0.50</td>
<td>0.8</td>
</tr>
</tbody>
</table>

*Stations are grouped according to their basin (Pacific, Indian, Atlantic, Southern), and latitude. Processing of the gauge data includes linear detrending to account for global sea level rise and local geophysical effects. SODA1.2 time series have also been detrended. Ratios of sea level variance are also provided.

**Correlations of annual averaged data that do not pass a t test of significance at the 95% level.

**Record variance below (3 cm).**

**Record shorter than 30 years.**

**Wide shelf.**
The 20 gauge locations we have chosen are weighted toward the Pacific (14) with 9 in the tropics. This weighting occurs partly because of the prevalence of acceptable records. The North Atlantic is sampled with 5 stations, but none were deemed acceptable in the South Atlantic, and in the Indian Ocean we have only one station. Our criteria are somewhat different than those applied in studies to determine centennial sea level trends, which have selected locations primarily based on lack of vertical tectonic effects, and an attempt to divide the world ocean into regions by the character of their sea level variation [Douglas, 1991; Cabanes et al., 2001; Miller and Douglas, 2004]. (The nine stations chosen by Miller and Douglas [2004] and used to calculate the gauge-based trends in Figure 1 are New York City, New York; Key West, Florida; San Diego, California; Balboa, Panama; Honolulu, Hawaii; Cascais, Portugal; Newlyn, England; Trieste, Italy; and Auckland, New Zealand).

The monthly average sea level at each of the 20 stations is corrected for the inverted barometer effect by using surface air pressure analyses from the National Centers for Environmental Prediction National Center for Atmospheric Research (NCEP/NCAR) reanalysis and for postglacial isostatic rebound by using the ICE-4G (VM2) model of Peltier [2001]. The inverted barometer correction is most significant for stations poleward of the subtropics where the amplitude of the correction may exceed 40% of this sea level amplitude.

At the Honolulu, Hawaii, gauge, a station that is included in most gauge-based sea level rise estimates, sea level has strong intraseasonal and seasonal variability (Figure 2a).

Figure 2. Sea level at Honolulu (19.8°N, 205.0°E) 1960–2001. (a) Monthly and (b) annual gauge sea level (after correction for inverted barometer effects and postglacial isostatic rebound) is shown in black. SODA1.2 is shown in blue. c) Difference between gauge sea level and SODA1.2 reanalysis sea level. Linear trend for the difference (red) has a slope of 1.4 mm yr\(^{-1}\).
This variability is captured by the SODA1.2 reanalysis (the correlation between the two when linear trends are removed is \( r = 0.67 \), increasing to \( r = 0.77 \) when annually averaged with a running boxcar filter). Annual time averaging reveals a 28 cm² RMS variance superimposed on a linear trend (Figure 2b). This variability, which includes locally and remotely generated Rossby waves [Firing et al., 2004], is a source of noise when using gauges to estimate sea level rise. This noise is reduced to 14 cm² when SODA1.2 reanalysis sea level is subtracted from the gauge sea level time series (and further reduced to 2.1 cm² when smoothed with a 5-year moving average time filter).

To understand the difference between gauge sea level and the SODA1.2 reanalysis time series (Figure 2c), we need to understand the processes contributing to SODA1.2 sea level. Because of the diagnostic algorithm used to produce it, global average SODA1.2 sea level remains nearly constant in time and thus does not include eustatic effects. This global constraint also means that the global average steric signal is eliminated from SODA1.2 sea level but is present in SODA1.2 dynamic height. In contrast to these global signals, the SODA1.2 sea level does contain the influences of mass redistribution between hemispheres and within the subtropical gyre. It also contains local steric effects such as those resulting from changes in the depth of the pycnocline around Hawaii. Thus the gauge-SODA1.2 reanalysis sea level difference of 1.4 mm yr⁻¹ provides one noisy estimate of the sum of eustatic plus global average steric effects. We can estimate the global steric effect separately using global average dynamic height in section 4.

The similarity of the Honolulu gauge and SODA1.2 reanalysis sea level has provided us with some confidence in the accuracy of steric estimates at this one location. We next evaluate the usefulness of the SODA1.2 reanalysis elsewhere by examining the similarity of gauge and reanalysis sea level at the additional representative set of 19 gauge locations.

The correlations between annually averaged and decimated tide gauge and SODA1.2 reanalysis sea level at all 20 stations is shown in Table 1. The average correlation for the 20 stations is \( r = 0.70 \). For one station, Tenerife, the correlation falls below the 95% confidence level for significance. This poor correlation may be due to the low sea level variability at this location (variance below 9 cm²). In contrast, many of the most highly correlated stations are in the tropical or subtropical Pacific with strong El Niño–Southern Oscillation-related variability.

The frequency dependence of the agreement between gauge and SODA1.2 reanalysis sea level was explored by low-pass filtering both data sets with a 5-year running smoother prior to computing the correlations. The correlations are generally reduced by 10%, although interestingly for some stations the agreement improves.

4. Global Sea Level

Following Miller and Douglas [2004], we approximate the steric component of sea level by the 0/1000 m dynamic height, shown in Figure 1. We focus on the 34-year period 1968–2001 which follows the widespread introduction of the expendable bathythermograph (XBT) observation set in the late 1960s (Carton and Giese, submitted manuscript, 2005) because this change in technology affects global average quantities. During this period the global average change in dynamic height shows a rise of \( 0.5 \pm 0.15 \) dyn mm yr⁻¹, similar to the Intergovernmental Panel on Climate Change (IPCC) estimate [Church et al., 2001; Antonov et al., 2002]. A rise of this magnitude implies a net downward heat flux into the ocean of approximately 0.2 W m⁻² [Levitus et al., 2005]. However, examination of the time series in Figure 1 makes clear that there is considerable decadal variability in global sea level, with rapid increases during the late 1970s and again beginning in the 1990s.

The thermosteric component of global sea level, obtained when salinity is replaced with its climatological monthly value, is rather similar to that calculated using observed salinity (Figure 1, compare bold and thin black curves). The globally averaged difference when salinity variations are included is around 1–2 dyn mm, although it is larger in the subpolar gyres, as reported by Antonov et al. [2002]. The effect of salinity on the multidecadal sea level trend is small.

During the past decade, 1993–2001, the trend in dynamic height increases to \( 2.3 \pm 0.8 \) dyn mm yr⁻¹ (Figure 1). Here the uncertainty estimate, calculated following Higbie [1991], is relatively large due to the limited record length (9 years), the decorrelation timescale of global sea level anomalies of 4 months and the resulting modest 11 degrees of freedom for the linear trend estimate. The trend in dynamic height during the past decade is not uniformly distributed in space. Instead, it is concentrated in the western tropical Pacific, eastern Indian, Southern Ocean, and to a lesser extent throughout the north Atlantic Ocean, and is very similar to the spatial distribution of altimeter sea level (Figures 3a and 3b).

In the western tropical Pacific and eastern Indian oceans the rate of increase exceeds 15 mm yr⁻¹ in the past decade, and has been accompanied by a modest rise in sea surface temperature [McPhaden and Zhang, 2002; Folland et al., 2003], while the eastern tropical Pacific shows a decrease in sea level during the same time interval. Examination of the vertical structure of temperature in this region (Figure 4) shows that much of this recent rise in steric sea level is the result of decadal fluctuations in the depth of the tropical thermocline by 20 m that are part of basin-scale changes [Giese and Carton, 1999].

The 1990s in particular are marked by a transition from relatively cool conditions in the western tropical Pacific during the early part of the decade to warmer conditions by 2001 (Figure 4). This transition occurs in response to a strengthening of the equatorial trade winds west of the date line in the Pacific by 0.5 m s⁻¹ yr⁻¹ and a weakening of trade winds in the Indian Ocean (Figure 5). In the Southern Ocean, development of a cyclonic circulation between longitudes 120°W–60°W causes a drop in sea level (Figure 3).

5. Summary and Conclusions

In this study we use the SODA1.2 reanalysis of the ocean to examine sea level rise during the 34-year period 1968–2001 and to diagnose the causes of an apparent acceleration of sea level rise observed by altimeters and tide gauges since 1993. We begin with an evaluation of the
SODA1.2 reanalysis, which shows a substantial improvement relative to a previous generation of the SODA reanalysis \cite{Carton et al., 2000} in the comparison with 20 tide gauge sea level records. For the eight tide gauge stations considered in both studies the average correlation has increased from 0.44 to 0.70. The average correlation of annual average sea level with SODA1.2 at the 20 gauge locations is 0.70.

We next examine global average steric sea level rise for the 34-year period 1968–2001 using 0/1000 m dynamic height as a proxy for steric sea level. During this period we find an average trend of $0.5 \pm 0.15$ dyn mm yr$^{-1}$ over the 1968–2001 average. The SODA1.2 dynamic height trend increases from $0.5 \pm 0.15$ dyn mm yr$^{-1}$ over the same period to $2.3 \pm 0.8$ dyn mm yr$^{-1}$ 1993–2001. We also compare the spatial structure of altimeter sea level rise to that of its steric component and find striking similarities with the most notable increases occurring in the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Linear trends in altimeter and steric sea level 1993–2001. (a) Altimeter sea level based on the Pathfinder 2.1 analysis of combined TOPEX/Poseidon altimetry (C. Koblinsky, personal communication, 2001). (b) SODA1.2 dynamic height 0/1000 m. Units are mm yr$^{-1}$ and dyn mm yr$^{-1}$. Areas shallower than 1000 m are masked out in Figure 3b.}
\end{figure}
Figure 4. Empirical orthogonal eigenfunction analysis of the meridional-vertical and zonal-vertical structures of 4-year average temperature in the tropical Pacific. (top) Spatial structure of the first principal components of the two vertical sections. For each section the first principal components explain more than half of the variance. The time-mean depth of the thermocline as indicated by 20°C isotherm is indicated by a bold line. Contour interval is 0.5°C, while values above and below ±0.5°C are shaded dark and light grey, respectively. (bottom) Very similar principal component time series. The time series of the Pacific Decadal Oscillation Index [Mantua et al., 1997] is included for comparison.

Figure 5. Linear trend in ERA40 surface wind velocity 1993–2001.
western tropical Pacific. Thus steric effects are enough to explain much of the observed rate of increase in the rate of sea level rise in the last decade of the 20th century without need to invoke acceleration of melting of continental ice. However, the error bounds on the linear trend estimates remain uncomfortably large.

[28] If 2.3 mm yr$^{-1} \times 10^5$ of sea level rise 1993–2001 is primarily thermosteric, this will require an imbalance of net heat flux of a couple of watts per square meter averaged over the ocean surface. The Earth’s radiation budget at the top of the atmosphere has been examined during these years by Wielicki et al. [2002]. Their results suggest a decrease in tropical albedo due to a reduction in low-level clouds in the 1990s. However, the presence of systematic errors affecting global fluxes [Trenberth et al., 2002; Bengtsson et al., 2004] suggests that estimates of heat storage in the global ocean is likely more accurate than surface flux estimates and thus may be most useful as a means to test the flux estimates.

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