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

James A. Carton
Department of Atmospheric and Oceanic Science, University of Maryland, College Park, Maryland, USA

Benjamin S. Giese
Department of Oceanography, Texas A&M University, College Station, Texas, USA

Semyon A. Grodsky
Department of Atmospheric and Oceanic Science, University of Maryland, College Park, Maryland, USA

Received 23 November 2004; revised 10 March 2005; accepted 25 May 2005; published 9 September 2005.

[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 1000m 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.

Citation: Carton, J. A., B. S. Giese, and S. A. Grodsky (2005), Sea level rise and the warming of the oceans in the Simple Ocean Data Assimilation (SODA) ocean reanalysis, *J. Geophys. Res.*, *110*, C09006, doi:10.1029/2004JC002817.

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].

0148-0227/05/2004JC002817$09.00

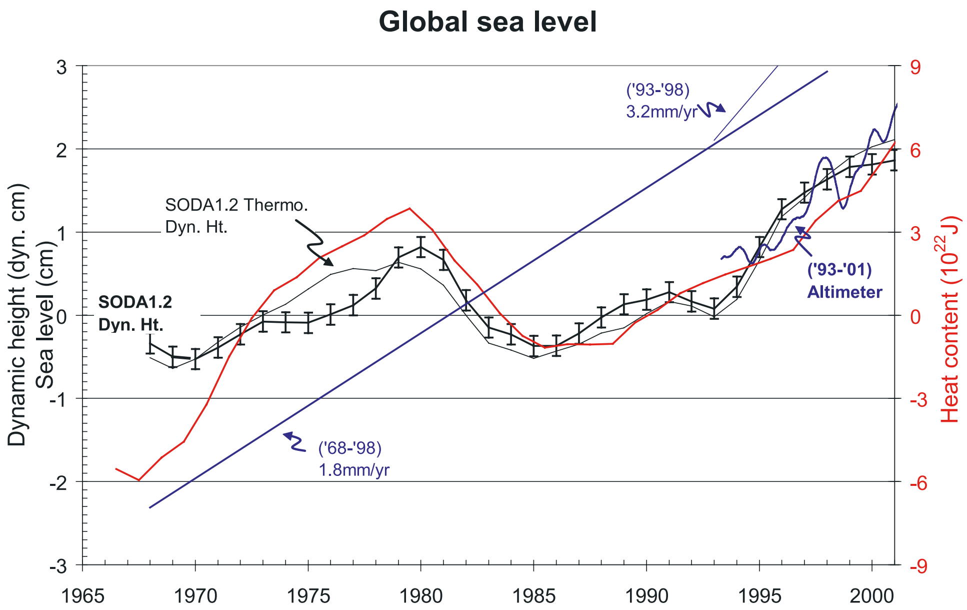

Figure 1. Global sea level 1968–2001. Time series of 3-year average SODA1.2 global dynamic height 0/1000 m (bold black); SODA1.2 dynamic height with climatological monthly salinity (thin black); 0/700 m heat content from *Levitus et al.* [2005] (red); and *Cazenave and Nerem* [2004] altimeter sea level 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).

[5] 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 timescales and thus the centennial trend may in fact be estimated from a limited set of representative gauges.

[6] 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 sidestepping 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

[7] 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 × 601 grid points with an average 0.25° × 0.4° resolution and a north pole displaced onto Canada in order to resolve the Arctic Ocean. The vertical resolution is 10 m near surface 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.

[8] There is no attempt to include mass contributions due to continental or atmospheric water storage. Surface wind-forcing for SODA1.2 is provided by the recent European Center for Medium Range Weather Forecasts ERA-40 reanalysis spanning the period from January 1958 through 2001. Surface freshwater flux for the period 1979–2001 is provided by a combination of Global Precipitation Climatology Project monthly merged product. Sea level is calcu-

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

Station	Location		Time	Number of Years	Dynamic Height Correlation	Sea Level Correlation	$\sigma_{SODA}/\sigma_{Gauge}$
Auckland	36.9°S	174.8°E	1959–1998	40	0.12[b]	0.49	1.2
Lyttleton[c]	44.4°S	171.3°E	1958–1987	30	0.21[b]	0.44	1.0
Pago Pago	14.4°S	189.4°E	1958–1999	39	0.74	0.83	0.7
Rabaul	4.3°S	152.3°E	1975–1997	34	0.97	0.96	1.1
Christmas[d]	2.1°N	203.0°E	1974–1999	23	0.95	0.95	0.8
Kwajalein	8.8°N	167.8°E	1958–1999	43	0.79	0.78	1.4
Balboa[d]	9.1°N	280.5°E	1958–1986	29	0.79	0.78	1.2
Quepos	9.5°N	275.9°E	1958–1994	36	0.68	0.70	0.7
Johnston	16.8°N	191.0°E	1958–1998	40	0.65	0.67	1.3
Hilo	19.8°N	205.0°E	1958–1998	43	0.56	0.62	1.0
Honolulu	21.4°N	202.2°E	1958–1998	43	0.71	0.77	0.9
Naha	26.2°N	127.7°E	1967–1999	33	0.87	0.88	1.4
San Francisco	37.8°N	122.5°W	1958–2001	44	0.66	0.81	0.6
Sitka	57.1°N	135.3°W	1958–1999	42	0.55	0.75	1.3
Fremantle	32.1°S	115.7°E	1958–2000	41	0.62	0.84	0.8
Tenerife[e]	28.5°N	16.3°W	1958–1989	33	0.25	0.27	1.1
St. Georges	32.4°N	64.7°W	1958–1998	37	0.48	0.66	0.9
Brest	48.4°N	4.5°W	1958–1999	42	0.26	0.70	0.6
Newlyn	50.1°N	5.55°W	1958–2001	44	0.21	0.65	0.5
Reykjavik[e]	64.2°N	21.9°W	1958–1983	24	0.24	0.50	0.8

[a]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.
[b]Correlations of annual averaged data that do not pass a *t* test of significance at the 95% level.
[c]Record variance below (3 cm)^2.
[d]Record shorter than 30 years.
[e]Wide shelf.

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].

[9] 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 and location, being more zonal in the tropics. They are additionally modified by the local flow conditions in order to reduce the influence of errors across strong density fronts. Updating follows the incremental analysis update procedure of *Bloom et al.* [1996] in which the forecast error estimates are used to correct a second model forecast.

[10] The basic subsurface temperature and salinity data sets consist of approximately 7×10^6 profiles, of which two thirds have been obtained from the World Ocean Database 2001 (WOD2001) [*Conkright et al.*, 2002]. This data set represents an increase of some 1.7 million profiles relative to the WOD 1998 data used in many of the recent sea level studies. The WOD2001 has been further extended by including the National Oceanographic Data Center NOAA monthly updates, as well as operational profile observations from the Global Temperature-Salinity Profile Program archive (including observations from the tropical mooring thermistor arrays, generally extending to 500 m, and Argo floats). Additional mixed layer temperature observations are obtained from the COADS surface marine observation set [*Diaz et al.*, 2002]. This extended data set is particularly important in improving the data coverage during the past decade, during which entries in the WOD2001 decline.

[11] Data checking for the SODA1.2 reanalysis includes checks for duplicate reports and errors in the recorded position and time of observations, for static stability, for deviation from climatology, and checks on the relationship 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.

3. Gauge Sea Level

[12] To evaluate the usefulness of the SODA1.2 reanalysis sea level, we compare it with sea level gauge records from the archive maintained by the Permanent Service for Mean Sea Level [*Woodworth and Player*, 2003] (see http://www.pol.ac.uk/psmsl for access to data). Of the total 1800 gauge records in the archive, most are not attractive for our purposes. Here we apply four criteria to select the records we consider. We look for well-maintained gauges with long (>30 years, sufficient at least to resolve interannual variability) continuous or nearly continuous records without obvious jumps in the record. We look for gauges in different basins and latitudes which are exposed to the open ocean either by being located on an island or on an eastern continental boundary with a narrow shelf isolated from major river deltas. Finally, we look for gauges whose records show significant subseasonal variability. Unfortunately, few gauges satisfy all these criteria and so some compromises have been made (Table 1).

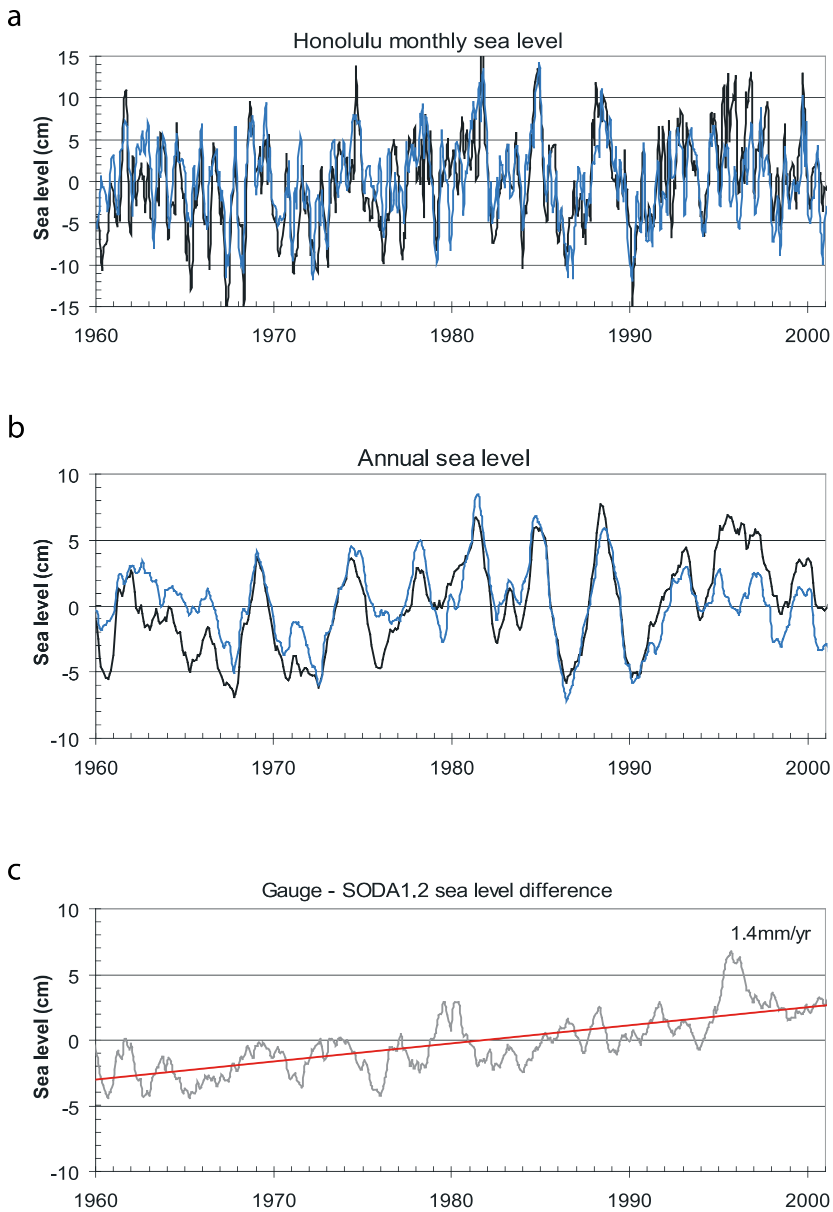

Figure 2. Sea level at Honolulu (19.8°N, 205.0°E) 1960–2001. (a) Monthly and (b) annual gauge sea level (after correction for inverted barometer effects and postglacial isostatic rebound) is shown in black, SODA1.2 is shown in blue. c) Difference between gauge sea level and SODA1.2 reanalysis sea level. Linear trend for the difference (red) has a slope of 1.4 mm yr^{-1}.

[13] 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).

[14] 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.

[15] 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).

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 cm^2 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 cm^2 when SODA1.2 reanalysis sea level is subtracted from the gauge sea level time series (and further reduced to 2.1 cm^2 when smoothed with a 5-year moving average time filter).

[16] 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.

[17] 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.

[18] 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 cm^2). In contrast, many of the most highly correlated stations are in the tropical or subtropical Pacific with strong El Niño–Southern Oscillation-related variability.

[19] 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

[20] 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 ± 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.

[21] 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.

[22] During the past decade, 1993–2001, the trend in dynamic height increases to 2.3 ± 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).

[23] 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].

[24] 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

[25] 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

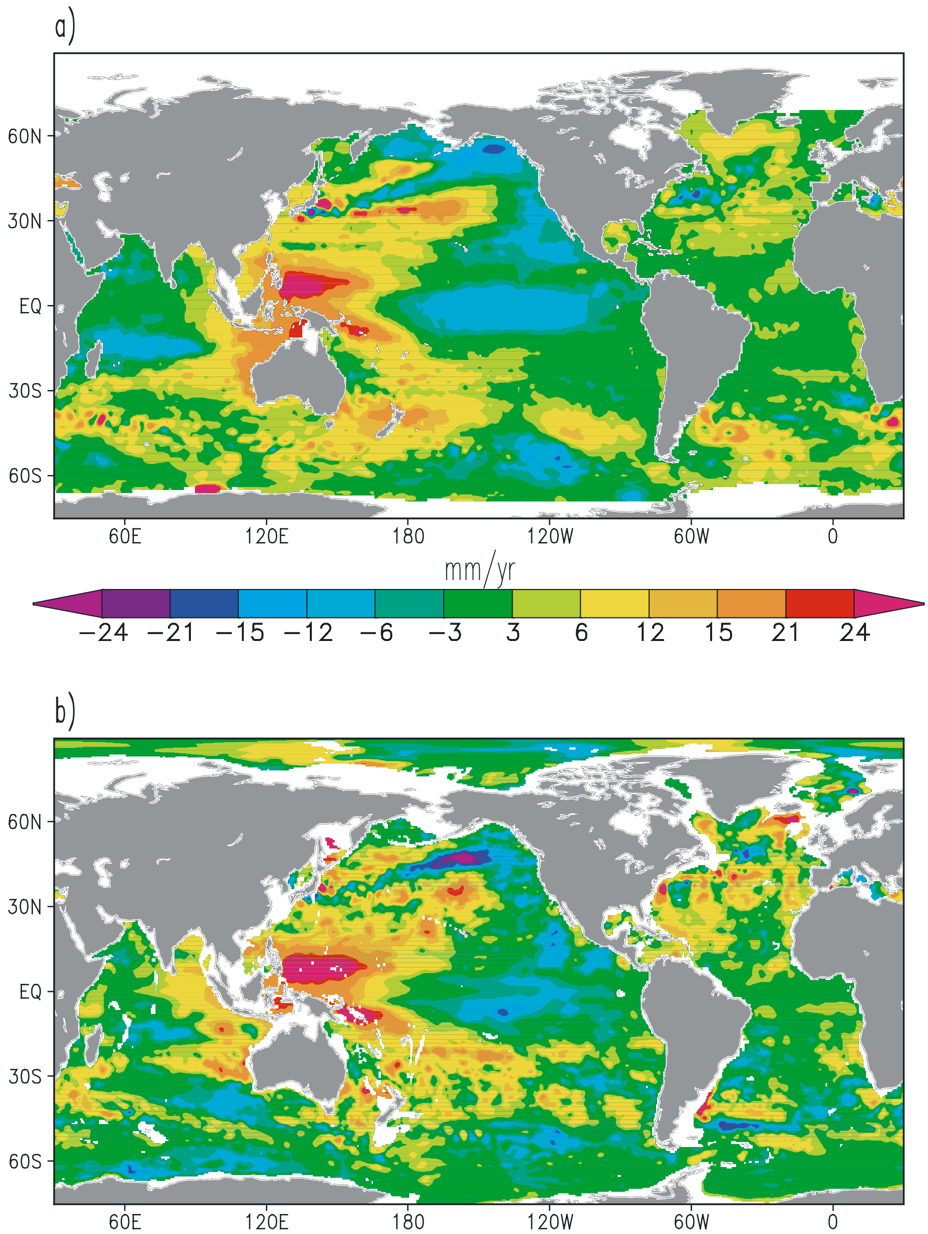

Figure 3. Linear trends in altimeter and steric sea level 1993–2001. (a) Altimeter sea level based on the Pathfinder 2.1 analysis of combined TOPEX/Poseidon altimetry (C. Koblinsky, personal communication, 2001). (b) SODA1.2 dynamic height 0/1000 m. Units are mm yr^{-1} and dyn mm yr^{-1}. Areas shallower than 1000 m are masked out in Figure 3b.

SODA1.2 reanalysis, which shows a substantial improvement relative to a previous generation of the SODA reanalysis [*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.

[26] 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 ± 0.15 dyn mm yr^{-1}. This trend is consistent with previous estimates summarized in the IPCC report even though our methodology, and to a lesser extent the data set, differs from those used in the IPCC report [*Levitus et al.*, 2000]. An examination of the relative contribution of salinity shows that the effect on global sea level rise of changing salinity is small except in subpolar regions, as noted by *Antonov et al.* [2002].

[27] We next consider the extent to which steric effects are responsible for recent changes (1993–2001) in sea level during which the observed altimeter sea level trend increases by 1.4 mm yr^{-1} over the 1968–2001 average. The SODA1.2 dynamic height trend increases from 0.5 ± 0.15 over the same period to 2.3 ± 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

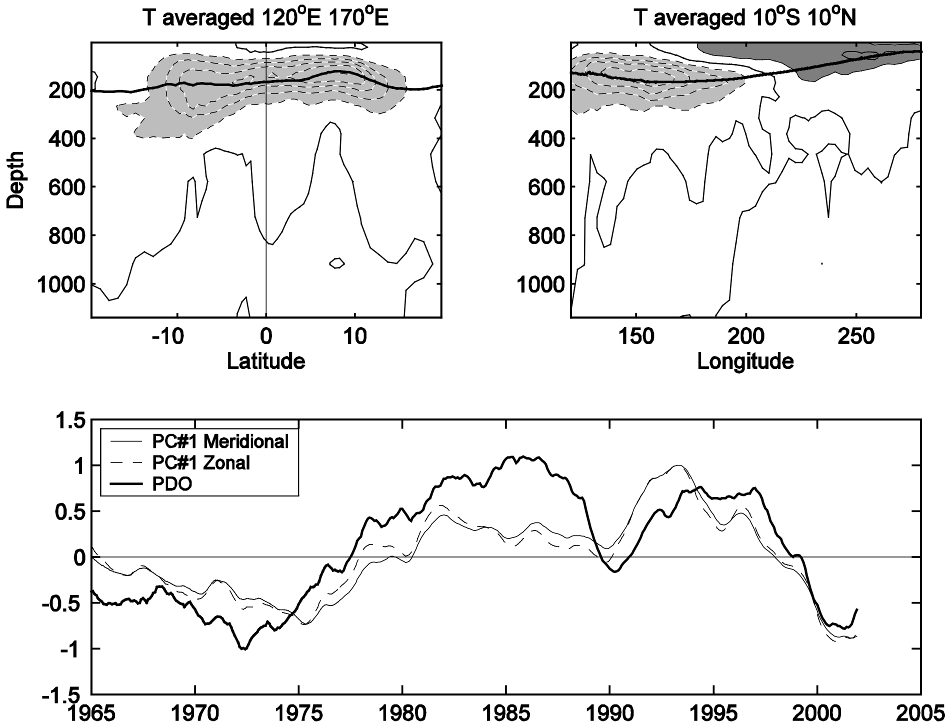

Figure 4. Empirical orthogonal eigenfunction analysis of the meridional-vertical and zonal-vertical structures of 4-year average temperature in the tropical Pacific. (top) Spatial structure of the first principal components of the two vertical sections. For each section the first principal components 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.

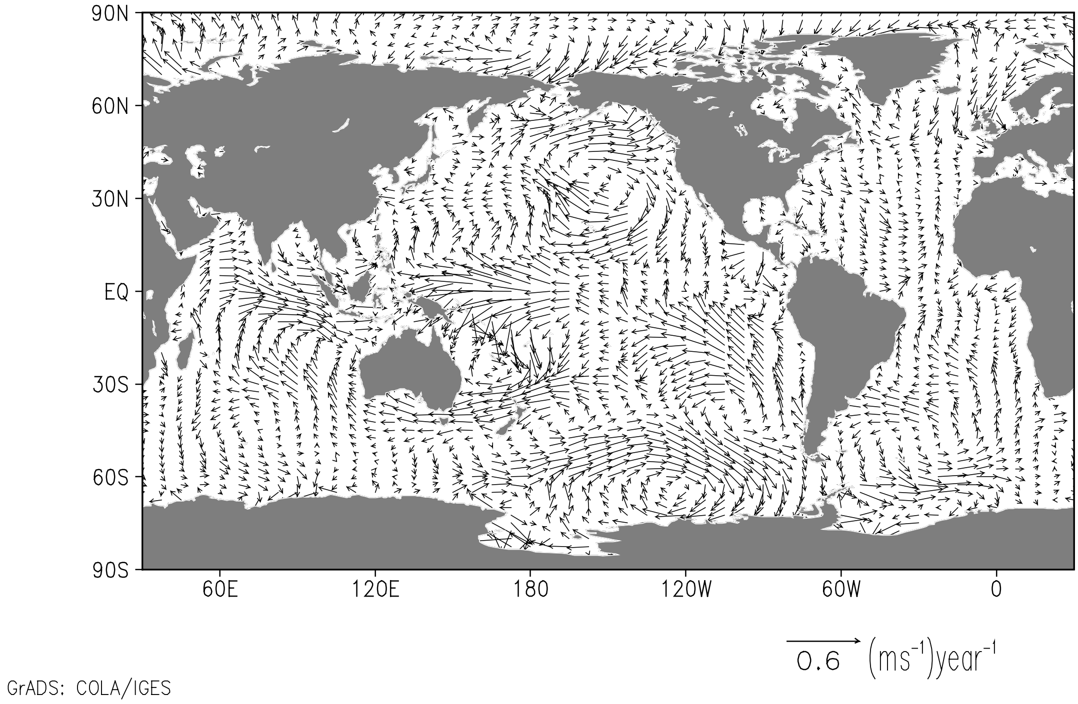

Figure 5. Linear trend in ERA40 surface wind velocity 1993–2001.

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 dyn mm yr^{-1} 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.

[29] **Acknowledgments.** We gratefully acknowledge the following people and organizations for providing access to data sets as well as advice: Sydney Levitus and the National Oceanographic Data Center NOAA for providing our hydrographic data set; the European Centre for Medium Range Weather forecasts for the ERA-40 reanalysis; the National Centers for Environmental Prediction for the NCEP/NCAR reanalysis; the Permanent Service for Mean Sea Level for the tide gauge records; Chet Koblinsky of the Office of Global Programs NOAA, who provided the altimeter data, and Bruce Douglas of Florida International University, who provided gauge data. Bruce Douglas and Laury Miller of NOAA provided helpful advice on an earlier version of this manuscript. S.A.G. and J.A.C. gratefully acknowledge support from the Oceans Program of NASA. This material is also based upon work supported by the National Science Foundation under grant 0351319. B.S.G. gratefully acknowledges support from the National Oceanic and Atmospheric Administration.

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.

Bengtsson, L., S. Hagemann, and K. I. Hodges (2004), Can climate trends be calculated from reanalysis data?, *J. Geophys. Res.*, *109*, D11111, doi:10.1029/2004JD004536.

Bloom, S., L. L. Takacs, A. M. da Silva, and D. Ledvina (1996), Data assimilation using incremental analysis updates, *Mon. Weather Rev.*, *124*, 1256–1271.

Cabanes, C., A. Cazenave, and C. Le Provost (2001), Sea level rise during past 40 years determined from satellite and in situ observations, *Science*, *294*, 840–842.

Carton, J. A., G. Chepurin, X. H. Cao, and B. S. Giese (2000), A Simple Ocean Data Assimilation analysis of the global upper ocean 1950–95. Part I: Methodology, *J. Phys. Oceanogr.*, *30*, 294–309.

Cazenave, A., and R. S. Nerem (2004), Present-day sea level change: Observations and causes, *Rev. Geophys.*, *42*, RG3001, doi:10.1029/2003RG000139.

Church, J., J. M. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, M. T. Nhuan, D. Qin, and P. L. Woodworth (2001), Changes in sea level, in *Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton et al., pp. 639–693, Cambridge Univ. Press, New York.

Church, J. A., N. J. White, R. Coleman, K. Lambeck, and J. X. Mitrovica (2004), Estimates of the regional distribution of sea level rise over the 1950–2000 period, *J. Clim.*, *17*, 2609–2625.

Conkright, M. E., et al. (2002), *World Ocean Database 2001*, vol. 1, *Introduction*, *NOAA Atlas NESDIS 42*, edited by S. Levitus, 167 pp., U.S. Gov. Print. Off., Washington, D. C.

Diaz, H., C. Folland, T. Manabe, D. Parker, R. Reynolds, and S. Woodruff (2002), Workshop on the advances in the use of historical marine climate data, *WMO Bull. 51*, pp. 377–380, World Meteorol. Org., Geneva.

Douglas, B. C. (1991), Global sea level rise, *J. Geophys. Res.*, *96*, 6981–6992.

Douglas, B. C. (1997), Global sea rise: A redetermination, *Surv. Geophys.*, *18*, 279–292.

Dukowicz, J., and R. D. Smith (1994), Implicit free-surface method for the Bryan-Cox-Semtner ocean model, *J. Geophys. Res.*, *99*, 7991–8014.

Firing, Y. L., M. A. Merrifield, T. A. Schroeder, and B. Qiu (2004), Interdecadal sea level fluctuations at Hawaii, *J. Phys. Oceanogr.*, *34*(11), 2514–2524.

Folland, C. K., et al. (2003), Trends and variations in South Pacific island and ocean surface temperatures, *J. Clim.*, *16*, 2859–2874.

Giese, B. S., and J. A. Carton (1999), Interannual and decadal variability in the tropical and midlatitude Pacific Ocean, *J. Clim.*, *12*, 3402–3418.

Higbie, J. (1991), Uncertainty in the linear regression slope, *Am. J. Phys.*, *59*, 184–185.

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

Lambeck, K., C. Smither, and M. Ekman (1998), Tests of glacial rebound models for Fennoscandinavia based on instrumented sea- and lake-level records, *Geophys. J. Int.*, *133*, 375–387.

Large, W. G., J. C. McWilliams, and S. C. Doney (1994), Oceanic vertical mixing: Review and a model with a nonlocal boundary layer parametrization, *Rev. Geophys.*, *32*, 363–403.

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

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

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis (1997), A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteorol. Soc.*, *78*, 1069–1079.

McPhaden, M. J., and D. X. Zhang (2002), Slowdown of the meridional overturning circulation in the upper Pacific Ocean, *Nature*, *415*, 603–608.

Miller, L., and B. C. Douglas (2004), Mass and volume contributions to twentieth-century global sea level rise, *Nature*, *428*, 406–409.

Mitrovica, J. X., M. E. Tamisiea, J. L. Davis, and G. A. Milne (2001), Recent mass balance of polar ice sheets inferred from patterns of global sea level change, *Nature*, *409*, 1026–1029.

Nakiboglu, S. M., and K. Lambeck (1991), Secular sea level change, in *Glacial Isostasy, Sea Level and Mantle Rheology*, edited by R. Sabadini, K. Lambeck, and E. Boschi, pp. 237–258, Springer, New York.

Peltier, W. R. (2001), Global glacial isostatic adjustment and modern instrumental records of relative sea level history, in *Sea Level Rise: History and Consequences*, edited by B. C. Douglas, M. S. Kearney, and S. P. Leatherman, chap. 4, pp. 65–93, Elsevier, New York.

Shennan, I., and P. L. Woodworth (1992), A comparison of late Holocene and twentieth-century sea level trends from the UK and North Sea region, *Geophys. J. Int.*, *109*, 96–105.

Smith, W. H. F., and D. T. Sandwell (1997), Global seafloor topography from satellite altimetry and ship depth soundings, *Science*, *277*, 195–196.

Thomas, R. H., et al. (2003), Investigation of surface melting and dynamic thinning on Jakobshavn Isbrae, Greenland, *J. Glaciol.*, *49*, 231–239.

Thomas, R. H., et al. (2004), Accelerated sea level rise from west Antarctica, *Science*, *306*, 255–258.

Trenberth, K. E., et al. (2002), Changes in tropical clouds and radiation, *Science*, *296*, 2095.

Trupin, A., and J. Wahr (1990), Spectroscopic analysis of global tide gauge sea level data, *Geophys. J. Int.*, *100*, 441–453.

Wielicki, B. A., et al. (2002), Evidence for large decadal variability in the tropical mean radiative energy budget, *Science*, *295*, 841–844.

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.

Woodworth, P. L., and R. Player (2003), The permanent service for mean sea level: An update to the 21st century, *J. Coastal Res.*, *19*, 287–295.

J. A. Carton and S. A. Grodsky, Department of Atmospheric and Oceanic Science, University of Maryland, 2417 Computer and Space Sciences Bldg., College Park, MD 20742, USA. (carton@atmos.umd.edu)

B. S. Giese, Department of Oceanography, Texas A&M University, College Station, TX 77843, USA.