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Contributions of hydrological processes to sea level change

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Abstract

We estimate the global mean sea level (GMSL) change using TOPEX/Poseidon satellite radar altimeter measurements and investigate possible contributions from water mass redistribution within the global hydrological cycle using a few numerical models. We examine the global mean sea level change at seasonal, interannual, and long-term time scales. The atmospheric and hydrological models include the ECMWF operational atmospheric model and the NCEP/NCAR reanalysis system. The World Ocean Atlas 1998 and over 19 years' satellite sea surface temperature observations are used to evaluate steric mean sea level change at different time scales. Both hydrological cycle and steric change provide important contribution to seasonal GMSL change. At interannual time scales, atmospheric water vapor variation shows good correlation to the altimeter observation and can introduce observable changes in the mean sea level. The snow water over Greenland and Antarctica estimated from the ECMWF model also shows encouraging interannual variability during the 1997/1998 El Niño period. Preliminary results show that thermal effect is a major but not a dominant contributor to long-term sea level rise, indicating that snow and ice melting associated with global warming may play an important role in driving GMSL rise.

Keywords: Mean sea level; TOPEX/Poseidon; Water; Snow; Thermal

1. Introduction

Monitoring and understanding global mean sea level (GMSL) change is one of the top issues in global change and environmental studies. The US/France joint TOPEX/Poseidon (T/P) satellite radar altimeter has been providing global measurements of sea level change every 10 days for over 9 years with unprecedented accuracy of 3–4 cm (Fu et al., 1994). The T/P altimeter and its extended mission Jason-1 (launched late last year) will provide over 14-years' continuous measurements of sea level change on a global basis and will significantly improve our knowledge of global sea level change at different time scales, especially at interannual and long-term periods.

The global sea level change is the consequence of two major effects in the oceans. One is the total water mass change caused by redistribution within the Earth system, including snow/ice sheet melting or accumulation and water mass exchange with the atmosphere and continents through precipitation, evaporation, and surface runoff. The other major cause of sea level change is density variation of seawater, mainly owing to temperature and salinity, commonly called steric effects. Determination and/or separation of steric and non-steric GMSL change (owing to water mass change) will provide key information in understanding the global hydrological and energy cycle, and relationships to changes in global climate.

A number of recent studies (e.g. Chen et al., 1998; Minster et al., 1999; Chen et al., 2001) demonstrated a clear relationship between seasonal continental water storage change, atmospheric water vapor variation, and seasonal GMSL change observed by the T/P satellite altimeter. It appears that seasonal continental water storage change can cause a corresponding seasonal change in global mean sea level of several mm. Geophysical model estimates agree reasonably well with altimeter observation after steric effects are removed based on climatological data (Chen et al., 1998; Minster et al., 1999).

In this paper, we intend to revisit this problem and look at a broader frequency band, including seasonal, interannual, and long-term time scales. The main focus

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is to better understand seasonal, interannual, and long-term GMSL change and estimate contributions from water mass exchange between the ocean, atmosphere, and land. We present here some preliminary results based on limited data resources.

2. Data and processing

2.1. Satellite altimeter measurements

The T/P altimeter sea surface anomaly data used in this study cover the time period from January 1993 to September 2000 (repeat cycles 10–296), after the application of all media, instrument, and geophysical corrections, except for the inverted barometer (IB) correction. These corrections include ionospheric delay, wet and dry tropospheric delay, electromagnetic bias, and tides. The original GDR orbits have been replaced with those computed using the JGM-3 gravity field model (Tapley et al., 1996), the ocean tide model has been replaced with the UT/CSR 3.0 model (Eanes and Bettadapur, 1995), and an error in the pole tide correction has been removed. Sea level anomalies, deviations from a 4-year mean surface, are computed by interpolating the data to a fixed grid and then removing mean sea surface height. The sea surface anomalies are then averaged into a uniform $1° \times 1°$ grid for each 10-day cycle. The GMSL change is then estimated using the $1° \times 1°$ sea level anomaly grid and a weighting function of cosine of latitude. The seasonal (including annual and semiannual), interannual, and long-term sea level variations are computed using least squares fit to the time series.

2.2. Steric sea level change model

Due to the lack of in situ observation of temperature and salinity change in the ocean, accurately estimating steric sea level change has been a challenging problem (or simply impossible). However, at seasonal scales we can get a fairly good estimate using climatological data. Similar to Chen et al. (2000), we compute seasonal steric change using satellite sea surface temperature (SST) observations and objectively analyzed ocean temperature fields in the World Ocean Atlas 1998 (WOA98) (Levitus and Boyer, 1994) (see Chen et al., 2000 for details).

As for interannual and long-term time scales, we will test a new approach to use SST data and the WOA98 average temperature field and also the historical temperature profiles (from XBT, MBT, and etc.) collected in WOA98. The basic thought is that for longer time scales, the dynamical (or mixing) effects on temperature variation with depth will become less important, and the diffusion of heat will become more dominant. In this case, temperature change near the surface will decline exponentially with depth (Knauss, 1996, p. 179). We use least squares fit to estimate this vertical temperature change with an empirical function for the purpose of estimating the temperature profile using only SST.

2.3. Atmospheric and hydrological models

Atmospheric water vapor variation is computed from the NCEP-NCAR reanalysis surface pressure data. The continental water storage change is estimated using soil moisture and snow accumulation data from the NCEP-NCAR reanalysis. The NCEP data are given daily on a Gaussian grid, spanning the period January 1948 to the present (Kalnay et al., 1996). The soil moisture fields include two layers, from the surface to 10 cm depth and 10–200 cm depth. The soil moisture and snow data are purely from model estimates with no observational constraints. Snow water over Antarctic is set to constant in the NCEP model. The continental water storage change is estimated by adding snow water and soil water in the top 2 m. The atmospheric water vapor is computed from direct integral of surface pressure over the globe based on the assumption that the total mass of the dry atmosphere is conserved (see Chen et al., 2001 for details about the computation). The soil moisture and snow data from a different model, the ECMWF operational model are also used to examine snow water variation over Greenland and Antarctica. The data are given every 6 hours, covering a five years' period from 1994 to1998. The ECMWF soil moisture fields cover the top 289 cm of soil.

3. Results and comparisons

3.1. Global mean sea level change

Fig. 1a shows T/P observed GMSL change during 1993–2001, superimposed the long-term draft rate. The seasonal (annual and semiannual) and interannual variations during the same period are shown in Fig. 1b and c, respectively. In addition to the seasonal and some high frequency variability, we see a clear trend of sea level rise at about 1.4 mm/yr. The seasonal signal is featured by approximately 1 cm peak-to-peak amplitude with maximum and minimum in the spring and fall, respectively. After the seasonal variation and long-term drift are removed, some interannual variability clearly exist, especially during the strong 1997/1998 El Niño period.

After the seasonal steric effects are removed from the T/P observations, the non-steric seasonal GMSL change agree reasonably with geophysical model estimates (see Fig. 2a and b; for details see Chen et al., 2001). Most hydrological model results show evident seasonal effects

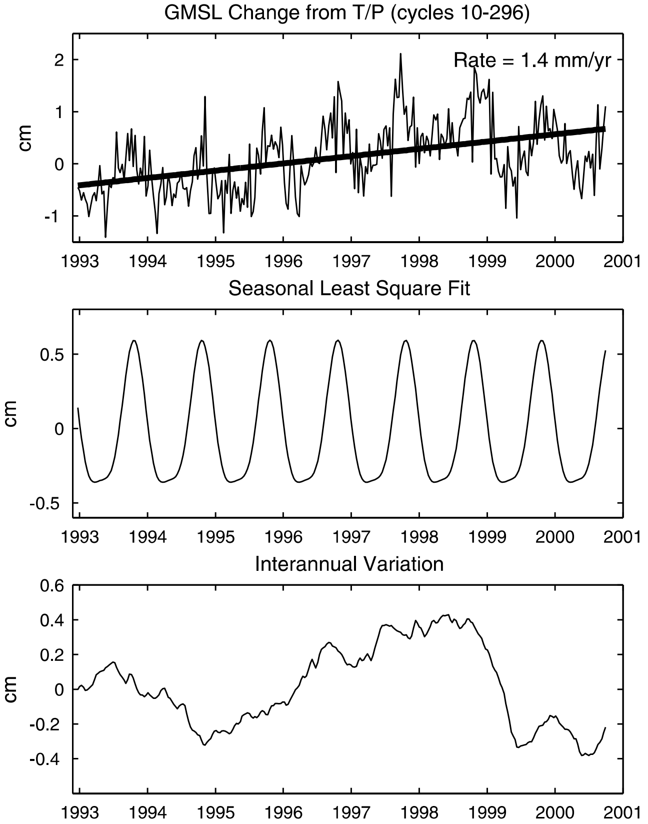

Fig. 1. The GMSL change from T/P observation (top), annual and semiannual least squared fit (mid), and interannual variation (bottom).

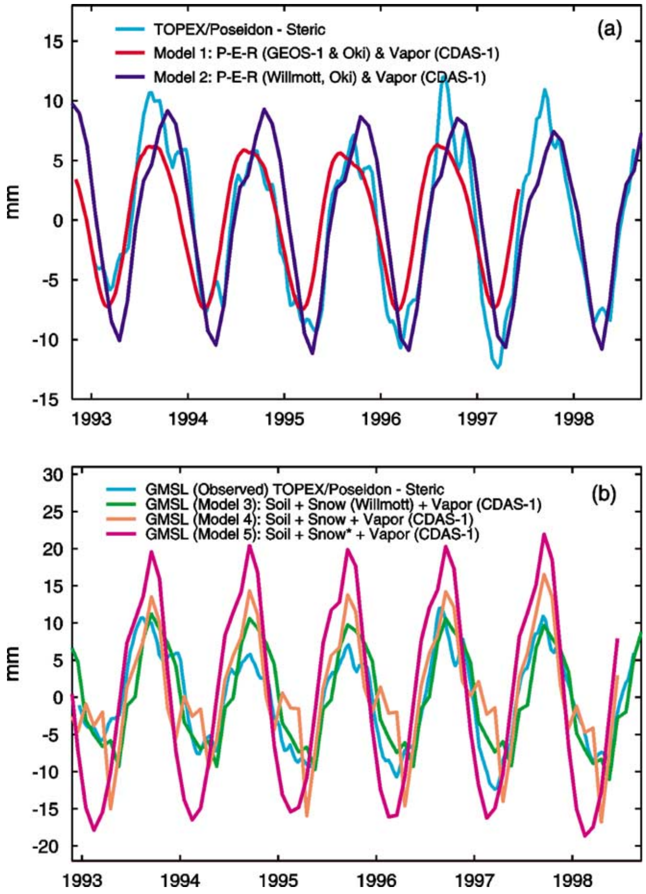

Fig. 2. (a) Non-steric GMSL change from T/P observation compared with two hydrological model estimates; (b) the same result compared with three other models (Chen et al., 2001).

on GMSL changes with seasonal amplitudes ranging from several mm to over 10 mm. The maximum and minimum hydrological contributions appear in the fall and spring in the northern hemisphere respectively, which agree well with the non-steric GMSL changes observed by T/P. However, we do see quite large discrepancies in the magnitudes of hydrological effects on GMSL changes between different hydrological models, indicating the immaturity of these models (Chen et al., 2001).

3.2. Interannual change and water vapor variation

Fig. 3a shows the interannual atmospheric water vapor variation (the dashed curve), superimposed on the interannual GMSL change observed by the T/P altimeter (the solid curve). These two curves are shown with different scales and units represented by the right and left vertical axes, respectively. We see a surprisingly good agreement between these two variations, which indicates a strong coupling between the atmosphere and ocean at interannual time scales. However, if we convert the atmospheric water vapor change into equivalent global mean sea level change, these two variations (i.e., interannual water vapor and mean sea level variations) are actually anti-correlated (as shown in Fig. 3b). Interannual atmospheric water vapor variation can cause observable changes in GMSL, e.g., it caused about a 2-mm decrease in mean sea level during the 1997/1998 El Niño period. This anti-correlation, on the other hand, indicates that steric effects combined with land water (including snow/ice sheet) should be expected to produce even stronger interannual GMSL changes than the T/P observations, and also demonstrates possible major hydrological contributions to interannual GMSL changes (Chambers et al., 2000) in addition to the commonly assumed steric effects.

We also look at the interannual continental water storage change. The continental water estimated from NCEP reanalysis shows very little interannual variability, which is owing to the lack of observational constraints. However the snow water data over Greenland and Antarctica from the ECMWF (not NCEP) model indicates an encouraging interannual variability (though we are not clear what cause this change at the moment), which when converted into equivalent mean sea level change corresponds to ~3 mm sea level rise during the 1997/1998 El Niño period (see Fig. 3c). The T/P

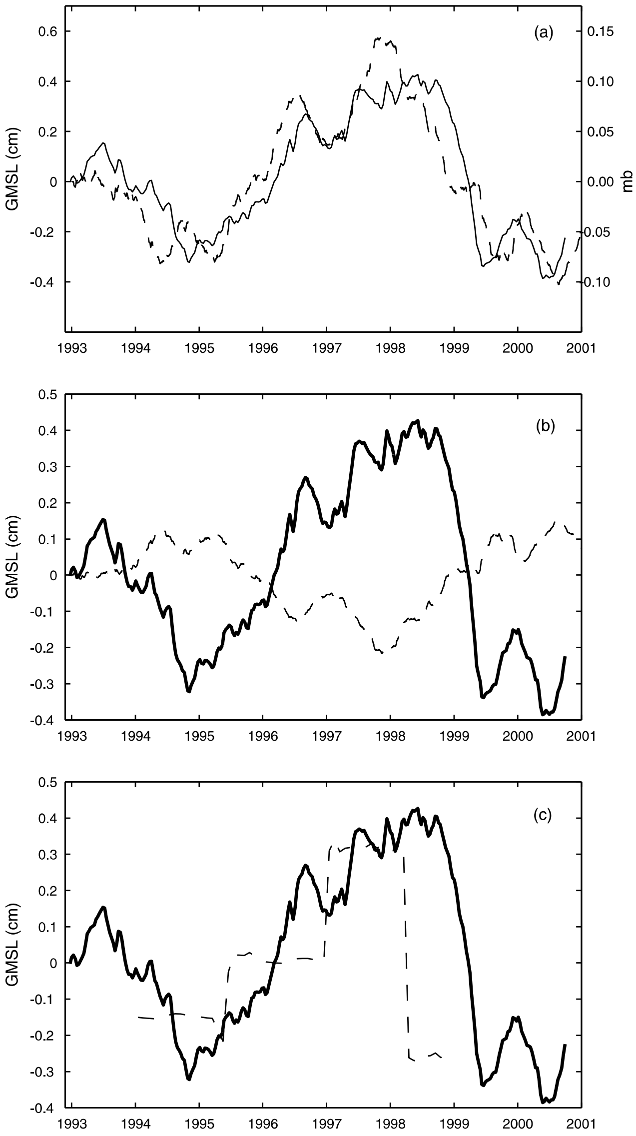

Fig. 3. (a) Interannual GMSL change from T/P observation (solid curve) compared with interannual water vapor variation (dashed curve). (b) The same comparison when water vapor is converted into equivalent mean sea level change (dashed curve). (c) Interannual GMSL change from T/P observation (solid curve) compared with the equivalent mean sea level change from snow/ice variation over Antarctica and Greenland (from ECMWF dashed curve).

measured rise is ∼4 mm during that time period. This interannual snow variation, if confirmed, is a good indication that continental water is also a major contributor (in addition to steric effects) to GMSL changes at interannual time scales. The comparison between interannual GMSL change and SST variation (see Fig. 4) shows a reasonable correlation during the 1997/1998 El Niño period. In other time periods (e.g., 1993–1996), the agreement is poor, indicating the complexity and difficulty of assessment of interannual steric sea level change using SST data.

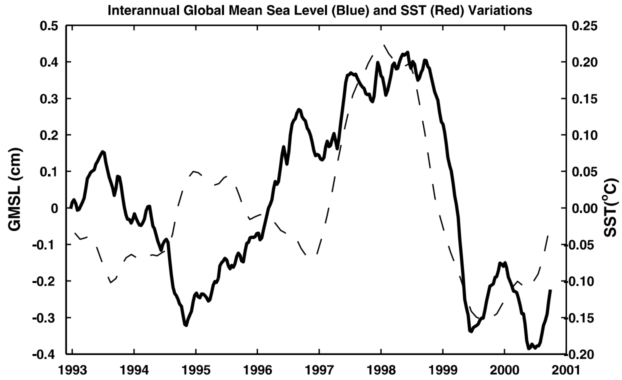

Fig. 4. Interannual GMSL change from T/P observation (solid curve) compared with interannual SST variation (dashed curve).

3.3. Long-term change and thermal effects

This investigation is continuing. It involves extensive study of temperature profiles from huge amount of historical in situ (e.g., XBT and MBT) data. Fig. 5a shows the geographical “long-term” sea level change rate (in mm/yr) estimated from 6 years (1993–1998) T/P altimeter data and Fig. 5b shows the steric sea level change rate estimated from OISST (also 1993–1998) and WOA98 under an over simplified assumption—the long-term vertical temperature departure profile is uniform

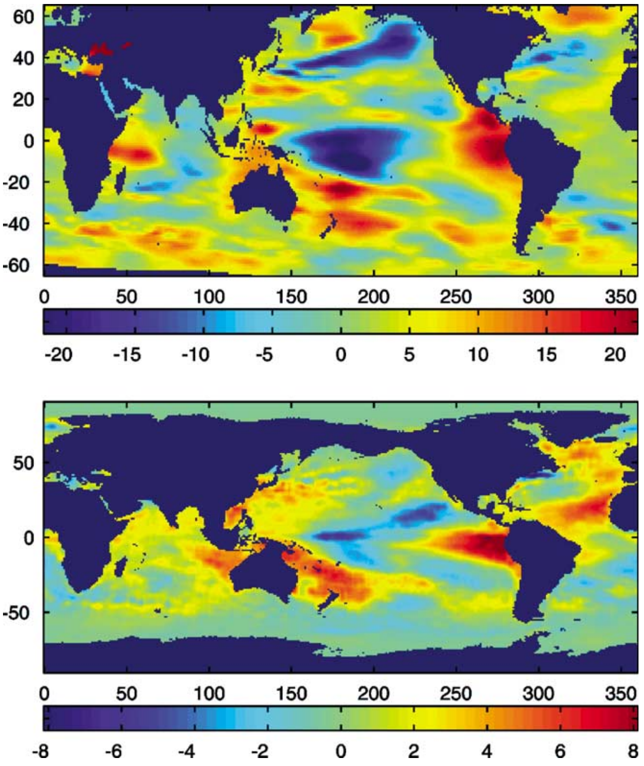

Fig. 5. Long term sea level rate (in mm/yr) during 1993–1998 estimated from T/P observation (top) and thermal effects from OISST and WOA98 (bottom).

over the ocean (simply not the case in the real world) and the averaged temperature departure profile is estimated from least squares fit of the temperature data in northern Pacific from WOA98. The results are very preliminary, not to say the strong interannual variability associated with the period (1993–1998). We expect to be able to see a more clearer picture with more observational data and also outputs from ocean general circulation models (OGCMs).

4. Conclusions

Consistent with previous studies, seasonal water mass exchange among the atmosphere, land, and oceans may cause 7–9 mm's changes in GMSL, which agree reasonably well with T/P observations. This seasonal signal is in the same order of magnitude as thermal and pressure loading effects, which indicates that hydrological effects on seasonal global mean sea level change should be taken into account when we want to study heat storage change or the IB response using satellite altimeter data.

Interanual atmospheric water vapor variation provides notable contribution to mean sea level change, though seems anti-correlated to T/P observation. Interannual snow melting and accumulation over Greenland and Antarctic derived from ECMWF model outputs, if confirmed, has the potential to account for a major part of the observed interannual GMSL variability.

The simplified estimates shown in Fig. 5b based on OISST and WOA98 data show some similar patterns of long-term sea level change rate compared to the T/P observation (Fig. 5a). Preliminary results suggest that thermal expansion is a major but not the dominant contributor to long term sea level rise, indicating the potential more important role of snow/ice sheet melting due to global warming. Limited by the poor model performance at long-term time scales and the lack of observational data, we are not able to see a clear contribution from snow/ice melting and accumulation to long-term sea level change from this study. The upcoming GRACE and GLAS missions are expected to be able to provide important measurements of snow water change over the polar regions and enhance our capability to understand long-term GMSL change.

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