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Abstract. Analysis of TOPEX/Poseidon satellite altimeter data indicates that the global mean sea level variation has a clear seasonal signal with an amplitude of about 2 to 3 mm, along with a long term drift. This seasonal variation is associated with mass redistribution within the global hydrological cycle plus steric thermal contributions. We investigate seasonal variations of water vapor in the atmosphere and water storage on land using both assimilated atmospheric models and climatological data, and to estimate the corresponding global mean sea level changes. The predicted seasonal global mean sea level changes are then compared with the seasonal variabilities observed by TOPEX/Poseidon altimetry data, after the latter are corrected for the steric effect using a simplified thermal model derived from the NOAA World Ocean Atlas 1994. The good agreement in both amplitude and phase indicates that the T/P altimeter may provide key information for the global water mass budget by placing observational constraints on the mass budget variations predicted by global atmospheric and hydrological models.

Introduction

The global mean sea level (GMSL) change observed by the TOPEX/Poseidon (T/P) altimeter shows a clear seasonal variation plus a long term change. The amplitude of this seasonal mean sea level variation is about 2-3 mm [Nerem, et al., 1997]; the maximum and minimum mean sea surface heights are in September and March respectively (Figure 1). It is generally believed that this seasonal variation reflects: (1) steric or thermal effects associated with temperature changes within the oceans, and (2) water mass exchange of the atmosphere and continental water storage with the oceans.

If the steric effects are known, this seasonal signal provides vital information about seasonal water mass budget in the global hydrological cycle or vice versa. A good understanding of mass induced GMSL change will help evaluate model performances in satellite altimetry (e.g. ocean tides and inverted barometer), and provide insights into the dynamical interactions between the atmosphere, hydrosphere, and solid Earth.

The main objective of this paper is to investigate the seasonal mass variations in atmospheric water vapor contents (ΔM_{vapor}), continental water storage (ΔM_{land}), and oceans (ΔM_{ocean}) using NASA assimilated atmospheric model (GEOS-1) [Schubert et al., 1993], the NCEP-NCAR Data Assimilation System I (CDAS-1) [Kalnay et al., 1996], the climatological water budget data archive produced by *Willmott et al.* [1985], and the global surface runoff data compiled by Oki et al. [1997], and to estimate the mass induced GMSL change (ΔH_{mass}) based on water mass conservation on the Earth's surface, i.e.

$$\Delta M_{vapor} + \Delta M_{land} + \Delta M_{ocean} = 0 \qquad (1)$$

For seasonal time scales, this approximation is reasonably accurate. The corresponding GMSL change (ΔH_{mass}) is then ΔM_{ocean} = -($\Delta M_{vapor} + \Delta M_{land}$) divided by the ocean area (S_{ocean}, about 71% of the Earth's surface) and fresh water density (ρ_o), i.e.,

$$\Delta H_{mass} = \frac{1}{\rho_o} \frac{\Delta M_{ocean}}{S_{ocean}} \qquad (2)$$

The observed GMSL change associated with mass redistribution is calculated by removing the steric GMSL change from the T/P altimeter measurement using a thermal expansion model based on the the objectively analyzed temperature fields of the NOAA World Ocean Atlas 1994 (WOA94) [Levitus and Boyer, 1994]. We will also discuss possible error sources in T/P altimeter observation, the steric model, and the global hydrological models that may affect the results.

Data

The T/P altimeter data set used in this research covers the time period from October 1992 to April 1997 (repeat cycles 2 to 168), after the application of all media, instrument, and geophysical corrections, except for the inverted barometer 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, which are deviations from a 4 year mean surface, are computed by interpolating the data to a fixed grid and then removing the mean sea surface height. The sea surface anomalies are then averaged into a uniform 1° grid for each 10-day cycle.

The objectively analyzed ocean temperature fields compiled in WOA94 provide three dimensional descriptions of the mean temperature for each month of the year based on all available historical *in situ* ocean temperature profiles from various instrument groups, including XBT, MBT, CTD, and traditional bottle data. These fields have a horizontal spatial resolution of 1° × 1° and cover 19 layers extending from the ocean surface to a 1000 meter depth. The

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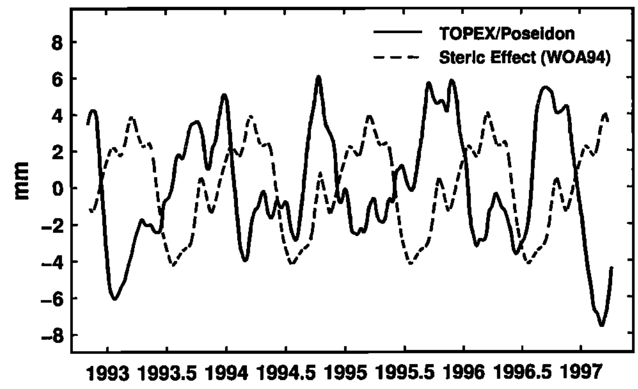

Figure 1. Seasonal GMSL changes determined from T/P altimeter (cycles 5 - 168), and the steric GMSL variations from WOA94.

top 14 layers (0 - 500 meter depth) are used to derive the thermal expansion model.

Atmospheric total precipitable water data are from the monthly intrinsic fields of CDAS-1 climate assimilation system [Kalnay et al., 1996], running from Jan. 1958 to present. The spatial resolution is $2.5^o \times 2.5^o$ (latitude x longitude). The total precipitation and evaporation data are adopted from surface diagnostic fields of GEOS-1 [Schubert, et al., 1993] with a 3-hourly sampling rate, spatial resolution of $2.5^o \times 2^o$, and a coverage from March 1980 to May 1995. The global gridded ($1^o \times 1^o$, monthly) seasonal precipitation and evapotranspiration fields produced by *Willmott et al.* [1985] based on climatological data are also applied to benchmark the results from assimilation systems. The global monthly surface runoff grids ($1^o \times 1^o$, 1987-1988) are compiled by Oki et al. [1997] from gauge discharge measurements. The seasonal variations in total precipitation, evaporation, and surface runoff are estimated from the above datasets, and applied to predict the mass induced seasonal GMSL change.

Global Mean Sea Level Variation

T/P Altimetry

Figure 1 shows the GMSL changes measured by T/P, after a linear trend is removed by least squares' method. An area weighting function (i.e. $cos(\theta)$; θ is latitude) is applied when calculating the mean sea level variation, and the time series is low-pass filtered through a 59-day moving average. The average annual variability is about 2.6 mm with the maximum sea surface height occurring in September and the minimum in March, the late summer and late winter of northern hemisphere, respectively. This seasonal variability varies slightly when using different averaging scheme (compared to 2.0 mm and roughly the same phase from *Nerem et al.*, [1997 and personal communication]). Other major error sources will be discussed later.

Steric sea surface height changes ($\Delta H(\theta, \lambda, t)$) caused by seasonal temperature variations are estimated from the WOA94 objectively analyzed temperature fields described as

$$\Delta H(\theta, \lambda, t) = \sum_{i=1}^{14} K(T, P) \cdot \Delta T(\theta, \lambda, t) \cdot h_i \qquad (3)$$

where θ is latitude, and λ is east longitude; $\Delta T(\theta, \lambda, t)$ is the temperature deviation from the annual mean at month t, and $K(T, P)$ describes the thermal expansion coefficient as a function of temperature (T) and pressure (P). h_i is the thickness of layer i ($i = 1, 2, ..., 14$). The $K(T, P)$ we used is from Knauss [1978], interpolated to the mean pressures and temperatures corresponding to each layer.

The monthly series of global mean steric sea surface height variations estimated from the above model are shown in Figure 1. The steric correction actually implies a larger variability of the GMSL change associated with mass redistribution than that observed by T/P, since it is approximately 6 months out of phase with the T/P observations.

The WOA94 analyzed temperature fields well represent the large scale seasonal temperature variations in the northern hemisphere and equatorial regions [Chambers et al., 1997; Levitus and Boyer, 1994]. Due to the sparse data samples, the accuracy in the southern hemisphere (SH) is relative poorer. However, because (i) this seasonal cycle is derived from all available historical temperature profiles of over 4.4 million (of which about 1/2 million in SH with 1/10 million in regions above 40 degree of latitude); (ii) we are looking at the seasonal variations of the longest wavelength (global mean), these fields should provide relatively accurate representation of the seasonal global mean temperature variation of the southern oceans.

Global Water Mass Balance

The water vapor content varies as a consequence of seasonality, mainly because the saturation pressure is a function of temperature (increasing with temperature). Total precipitable water is the vertical integral of specific humidity in a given area. Using the monthly surface intrinsic precipitable water fields of CDAS-1, we estimate the global mean water vapor mass fluctuations ($M_{vapor}(t)$) in a given month t by,

$$M_{vapor}(t) = \sum_{\theta=-\frac{\pi}{2}}^{\frac{\pi}{2}} \sum_{\lambda=0}^{2\pi} \Delta V(\theta, \lambda, t) \cdot \Delta S \qquad (4)$$

in which, $\Delta S = R^2 \Delta\theta \Delta\lambda \cos\theta$ is surface area element (in units of cm^2); $\Delta V(\theta, \lambda, t)$ is the departure of the gridded

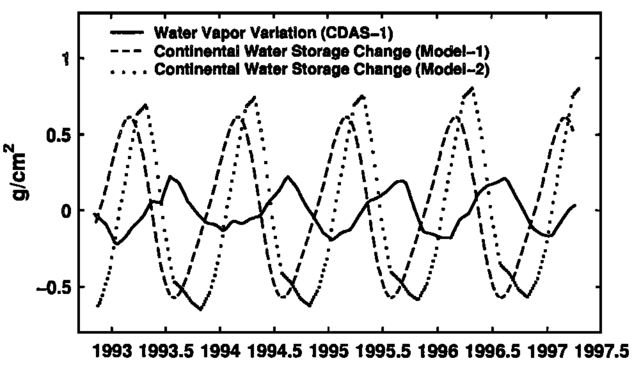

Figure 2. Water vapor fluctuation in the atmosphere and continental water storage changes from Model-1 and Model-2. Both are converted into global mean, i.e. averaged over the entire Earth's surface in unit of g/cm^2.

Table 1. Annual and semiannual global mean sea level variations observed from TOPEX/Poseidon altimeter with steric effect removed, and predicted from two continental hydrological models.

Sources	Annual		Semiannual	
	amp (mm)	phase (deg)	amp (mm)	phase (deg)
T/P - Steric	7.1	199	0.6	119
Model-1	5.9	214	1.6	111
Model-2	8.9	171	1.7	102

The phase is refered to Jan 1 0.0h.

total precipitable water ($V(\theta, \lambda, t)$, in unit of g/cm^2) relative to the mean over the time span; R is the mean radius of the Earth; $\Delta\theta$ and $\Delta\lambda$ are grid intervals determined by the spatial resolution of the gridded field. The total water vapor variation is normalized by the Earth's surface area and shown in Figure 2. There is a clear seasonal variation of water vapor content in the atmosphere with a mean annual variability of about 0.2 g/cm^2 water equivalent. The atmosphere holds the maximum water vapor in August and minimum in February.

Continental water storage changes ($\Delta M_{land}(t)$) at given month t are computed using the hydrological conservation equations,

$$\frac{dS(t)}{dt} = \sum_{\theta=-\frac{\pi}{2}}^{\frac{\pi}{2}} \sum_{\lambda=0}^{2\pi} (P - E - R)cos(\theta) \tag{5}$$

$$\Delta M_{land}(t) = \sum_{t'=0}^{t} \frac{dS(t')}{dt'} \Delta t' \tag{6}$$

in which $dS(t)/dt$ is water mass storage change rate; P, E, and R are precipitation, evapotranspiration, and surface runoff, respectively (all fields are averaged into monthly mean, and in unit of g/month); $\Delta t' = 1$ month, is the sampling interval.

$\Delta M_{land}(t)$ are computed using two different hydrological models. In Model-1, P and E are adopted from GEOS-1 assimilation system, while in Model-2, P and E are adopted from *Willmott et al.*'s [1985] climatological model. The surface runoff fields given by *Oki et al.* [1997] are used in both models. The estimated $\Delta M_{land}(t)$ are also normalized by the total area of the Earth's surface and shown in Figure 2.

Conclusion

The GMSL changes due to water mass exchange with the Earth system are derived from ΔM_{vapor} and ΔM_{land} according to equation (2), for both Model-1 and Model-2. The results are shown in Figure 3, compared with the non-steric T/P (T/P - Steric) observations. It is seen that seasonal water mass exchange of the atmosphere and land with the oceans causes GMSL to change by ± 6 to ± 9 mm, which agrees well with the non-steric T/P observation (7 mm) in both amplitude and phase (See Table 1). The model predicted semiannual GMSL changes (1.6 mm) seem too large than T/P observation, while the phases agree quite well (See Table 1). Figure 4 shows the vector representations of annual GMSL changes from T/P observation and two model predictions.

This investigation has led to a better understanding of the GMSL changes observed from the T/P altimeter. The good agreement between hydrological model predictions and T/P observations indicates that the seasonal GMSL is indeed greatly influenced by water mass exchanges with atmosphere and continents. The results suggest that data from T/P and future satellite altimeter missions (e.g. Jason-1) can provide important observational constraints on water mass budget of global atmospheric and hydrological models.

Discussion

This paper intends to show some encouraging results about the potential hydrological influences on seasonal GMSL change. Two hydrological model predictions are in reasonable agreement with the non-steric T/P measurements. Many error sources could have affected the results, including the errors in T/P sea level measurement, its steric corrections, and especially the hydrological model predictions. The T/P measurement only covers the region between 65° N and 65° S latitude, however, since T/P covers over 93% of the global ocean area and sea level variabilities are not particularly large in very high latitude, this sampling error should be relatively small. Another potential error source is the wet troposphere delay effect on the altimetry measurement. Even though there is a potential water vapor drift (-1 to -2 mm/year by Urban, personal communication, 1998), no result on seasonal water vapor error is available yet.

The steric corrections we applied are based on WOA94 analyzed seasonal ocean temperature fields. The historical *in situ* temperature data used in WOA94 are currently the only practical data resource in studying the global steric sea level change. The general ocean circulation models are presently limited in this application by the assumptions of conservation of volume. A steric ocean model by assimilating *in situ* observations and satellite radiometer sea surface temperature measurements should lead to better estimates of the steric GMSL change in the future.

The budget of continental water cycle is a least known process in the Earth's system, especially so for the evapo-

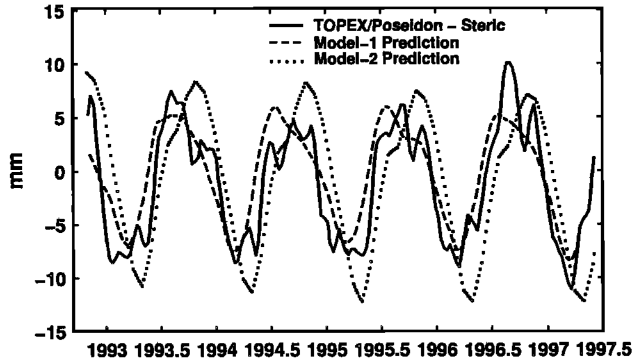

Figure 3. The comparison between model predicted GMSL variations with T/P observations with thermal steric effects removed.

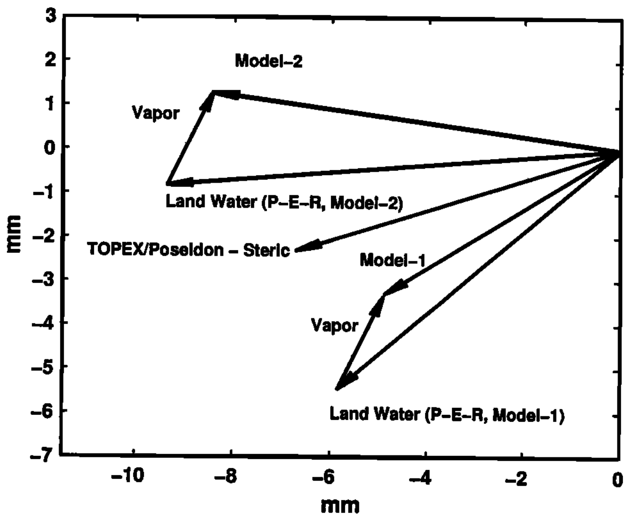

Figure 4. Vector plots of annual variations in T/P GMSL changes and hydrological model predictions. The phase is referred to 0h Jan. 1.

transpiration and surface runoff. The generally good agreement between different hydrological model predictions is a good indication that both assimilation systems and climatological data can reasonably represent the broad features of the global hydrological cycle. Improvement of global hydrological models are needed and will rely on increased *in situ* observations as well as measurements from future remote sensing and satellite gravity measurement (e.g. the GRACE mission).

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