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Hydrological impacts on seasonal sea level change

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Abstract

In this paper, we present some extended results of hydrological impacts on seasonal sea level change using a few different hydrological models and an updated steric model, and compare with the results of Chen et al. [Geophys. Res. Lett., 25 (19) (1998) 3555] and Minster et al. [Global Planet. Change, 20 (1999) 157]. Even though different hydrological models show significant discrepancies in seasonal water storage change at local scales, most of the model-derived seasonal global mean sea level (GMSL) changes agree well with TOPEX/Poseidon (T/P) data. This further increases our confidence in using TOPEX/Poseidon satellite altimeter data, especially when combined with the TOPEX/Poseidon extended mission, Jason-1's data to provide observational constraints on water mass budget of global atmospheric and hydrological models. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The TOPEX/Poseidon (T/P) satellite altimeter has been monitoring sea level change on a global basis for over 7 years. The T/P-observed global mean sea level (GMSL) change shows a clear seasonal signal of a few millimeters in amplitude (Nerem, 1999; Nerem et al., 1997; Chen et al., 1998; Minster et al., 1999). The maximum and minimum mean sea surface heights are in September and March, the late winter and late summer in the Northern Hemisphere, respectively. This seasonal sea level change mainly reflects two kinds of effects: the change due to density variation of sea water and the change due to water mass redistribution within the Earth system. Density variation of sea water is primarily introduced by temperature and salinity change, and the temperature appears to be the dominant factor (Chen et al., 1998; Minster et al., 1999). The sea level change associated with density variation involves no mass variation and is commonly called steric change. The non-steric change represents water mass variation of the oceans and provides observational constraint on water mass budget in global atmospheric and hydrological models, provided that we are able to effectively quantify the steric signals in the oceans.

Preliminary results from Chen et al. (1998) and Minster et al. (1999) show good correlation between the T/P-derived non-steric seasonal GMSL change and the GMSL change inferred from seasonal con-

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tinental water storage and atmospheric water vapor variations, under the assumption that the global surface water mass is conserved. The amplitude agreement is within a few millimeters, and phase agreement is within a month (Chen et al., 1998; Minster et al., 1999). However, due to the immaturity of available hydrological models and limitations of the steric models in those studies, based on the World Ocean Atlas 1994 (WOA94) (Levitus and Boyer, 1994), it is hard to give a definite conclusion yet.

In this study, we revisit this problem using different hydrological models and an improved steric model by Chen et al. (2000), which combined satellite sea surface temperature observations and WOA94 ocean temperature data, and compare the results with those from Chen et al. (1998) and Minster et al. (1999). The main focus is to show a clearer relationship between observed seasonal GMSL and water mass redistribution between the oceans and atmosphere and continents. Also, the comparison between this study and the previous results (Chen et al., 1998; Minster et al., 1999) will increase our confidence about the potential application of satellite altimeter data to place observational constraint on water mass budget in numerical models.

We estimate seasonal mass variations in atmospheric water vapor $\Delta M_{\mathrm{vapor}}$ using surface pressure data from the National Center for Environment Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) jointly developed Data Assimilation System I (CDAS-1) (Kalnay et al., 1996). Continental water storage change (ΔM_{land}) is computed using soil moisture and snow data from the above model. The basic equation is similar to that in Chen et al. (1998), i.e. under the assumption that the total water mass on the Earth surface is conserved, the summation of water mass change in the atmosphere ($\Delta M_{\mathrm{vapor}}$), continent ($\Delta M_{\mathrm{land}}$), and ocean ($\Delta M_{\mathrm{ocean}}$) should be zero, so:

$$\Delta M_{\mathrm{ocean}} = -(\Delta M_{\mathrm{vapor}} + \Delta M_{\mathrm{land}}) \tag{1}$$

The use of atmospheric surface pressure to compute the total atmospheric water vapor variation is only valid when the mass of dry atmosphere is considered to be a constant. At seasonal scales, this approximation is reasonably accurate. Continental water storage change represents the change of water stored in soil layer, snow, lakes, and underground reservoirs. If the water changes in lakes and underground reservoirs are neglected (limited by observations), the sum of soil and snow water variations is a good approximation of continental water storage change, in addition to the traditional approach of using precipitation, evaporation, and surface runoff (e.g. as used in Chen et al., 1998). The above equation indicates that any mass variation in atmospheric water vapor and continental water (as a total) will cause a corresponding mass change in the oceans, which can be measured by non-steric GMSL change. The model-derived non-steric GMSL change is directly computed from estimated oceanic mass change ($\Delta M_{\mathrm{ocean}}$), divided by the ocean area (A_{ocean}) and fresh water density (ρ) (Chen et al., 1998):

$$\Delta GMSL_{\mathrm{model}} = \frac{1}{\rho}\frac{\Delta M_{\mathrm{ocean}}}{A_{\mathrm{ocean}}} \tag{2}$$

On the other hand, the non-steric GMSL change is derived from T/P altimeter measurement, after the steric effects are removed based on the results of Chen et al. (2000):

$$\Delta GMSL_{\mathrm{non-steric}} = \mathrm{GMSL}_{\mathrm{T/P}} - \mathrm{GMSL}_{\mathrm{steric}} \tag{3}$$

We compare the results with those from Chen et al. (1998) and Minster et al. (1999), and discuss some possible error sources in T/P altimeter observation, steric models, and the global hydrological models that may affect the results.

2. Data

2.1. Sea level measurements

The T/P altimeter sea surface anomaly data used in this study cover the time period from December 1992 to September 1998 (repeat cycles 10 to 221), after the application of all media, instrument, and geophysical corrections. These corrections include ionospheric delay, wet and dry tropospheric delay, electromagnetic bias, tides, and the inverted barometer (IB). 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, 1994), 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 $1^\circ \times 1^\circ$ grid for each 10-day cycle.

The steric effects are removed using the results from Chen et al. (2000), based on satellite sea surface temperature (SST) observations and the World Ocean Atlas 1994 (WOA94) objectively analyzed ocean temperature fields (Levitus and Boyer, 1994). The improvement is mainly from the use of satellite SST observations to compute the steric sea surface height change of the top 50 m of sea water, combined with the steric height change of the deeper layers (50–500 m) from the WOA94 climatology (Levitus and Boyer, 1994).

2.2. Atmospheric and hydrological models

The NCEP–NCAR CDAS-1 surface pressure, soil moisture, and snow accumulation data are given monthly on a Gaussian grid, spanning the period January 1958 to 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 data are given in volumetric fraction, i.e. percentage by volume, and the snow water is given as water equivalent in centimeters. The CDAS-1 soil moisture and snow data are purely from model estimates with no observational constraints [L.H. Pan, 1997, personal communication]. Snow depth over Antarctic and Greenland is set to be constant in the model. However, along the west coast of Antarctic, the model shows a very large snow water change over sea ice, according to the land mask definition. Due to the large uncertainties of the bathymetry in that region (west Antarctic), we treat this part of snow water change in two different ways. In the first case (called Model 1 hereafter), this snow change is considered as over floating sea ice and the Antarctic is excluded completely, and in the second case (called Model 2 hereafter), this snow change is considered as over an ice sheet but the ice sheet is rooted on continental shelf and, therefore, this change is treated as part of continental water variation.

3. Results and comparison

3.1. Global mean sea level change

Fig. 1a shows the T/P observed GMSL change (the linear trend is removed), superimposed on the steric GMSL change from Chen et al. (2000). The non-steric GMSL change residuals, i.e. T/P observations minus steric effect, are shown in Fig. 1b. The time series are low-pass filtered through a 59-day moving average.

The average annual amplitude of T/P measured GMSL change is about 4.6 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 time spans of T/P observations and different averaging schemes. Different geophysical model corrections (e.g. different IB treatments) will introduce different results too. Table 1 lists the annual and semiannual amplitude and phase of GMSL change from this study and those from Chen et al. (1998) and Minster et al. (1999), including both T/P observations and steric estimates.

3.2. GMSL change from water mass exchange

The water vapor content varies as a consequence of seasonality, mainly because the saturation pressure is a function of temperature (increasing with temperature). Assuming that the total mass of the dry atmosphere is conserved, the total water vapor change in the atmosphere is virtually the same as the total mass change of the atmosphere. We compute the total wet atmospheric mass change using the CDAS-1 assimilated surface pressure (P_s) as:

$$M_{\mathrm{vapor}}(t) = \frac{1}{g} \sum_{\phi=-\frac{\pi}{2}}^{\frac{\pi}{2}} \sum_{\lambda=0}^{2\pi} P_s(\phi, \lambda, t)\Delta S \tag{4}$$

where, $\Delta S = R^2 \Delta\phi \Delta\lambda \cos\phi$ is the surface area element, R is the mean radius of the earth (6.371×10^8

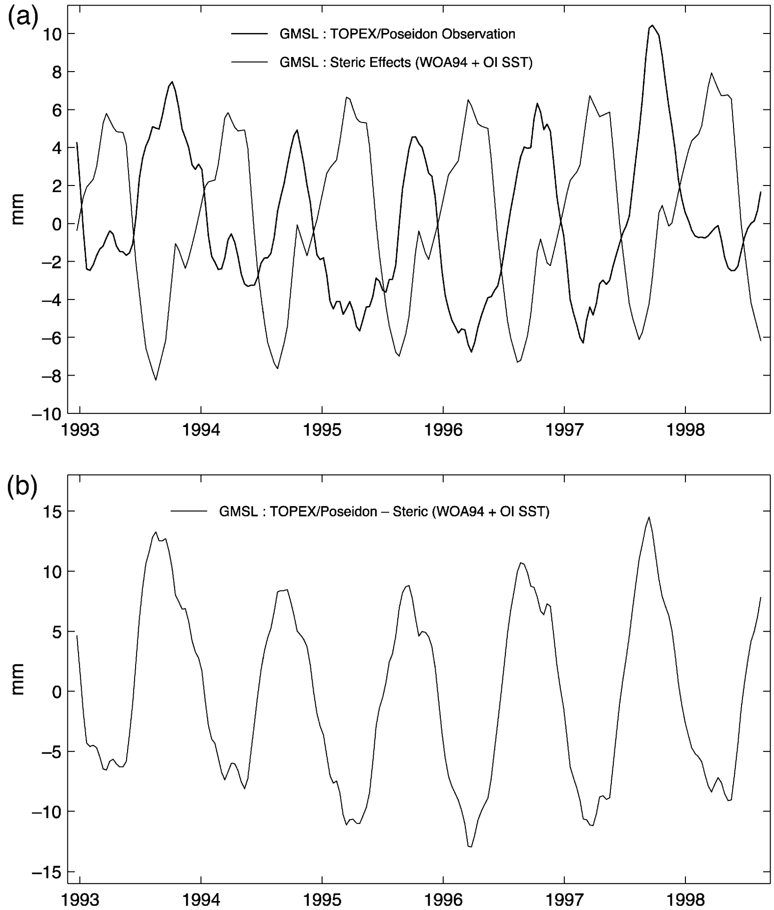

Fig. 1. (a) The GMSL changes determined from T/P altimeter (cycles 10–221) and the steric GMSL variations from Chen et al. (2000). (b) The non-steric GMSL changes after the steric effects are removed from T/P observation.

cm), $\Delta\phi$ and $\Delta\lambda$ are grid intervals of latitude ϕ and longitude λ determined by the models, and g is the gravity acceleration rate.

We estimate the continental water storage changes using soil moisture and water equivalent snow accumulation data from the NCEP–NCAR CDAS-1

Table 1
Amplitude and phase of annual and semiannual GMSL change from T/P observations and steric effects, compared with the results from Chen et al. (1998) and Minster et al. (1999)

Global mean sea level	Annual		Semiannual	
	Amplitude (mm)	Phase (deg)	Amplitude (mm)	Phase (deg)
T/P (IB) (This study)	4.6	176	1.3	249
T/P (NB) (Chen et al., 1998)	3.6	176	1.6	214
T/P (IB) (Minster et al., 1999)	4.6	179	N/A	N/A
Steric effects (WOA94 + OI SST, this study)	5.5	23	2.1	219
Steric effects (WOA94, Chen et al., 1998)	5.0	33	1.8	230
Steric effects (WOA94, Minster et al., 1999)	5.0	15	N/A	N/A

The phase is defined as ϕ in $\sin(2\pi(t-t_0)+\phi)$, where t_0 refers to h^0 on January 1.

monthly diagnostic fields. The soil water is represented by volumetric fraction ($\Delta\eta_i$). Snow water variations are directly measured by water equivalent snow accumulations (in unit g/cm^2). Continental water storage changes are then computed by adding soil water $\Delta M_{\rm soil}$ (including all layers) and snow water variations $\Delta M_{\rm snow}$, as:

$$\Delta M_{\rm soil}(\phi,\lambda,t) = \rho_{\rm o} \sum_{i=1,N} \Delta\eta_i(\phi,\lambda,t) h_i \Delta S \tag{5}$$

$$\Delta M_{\rm snow}(\phi,\lambda,t) = \Delta N(\phi,\lambda,t)\Delta S \tag{6}$$

and

$$\Delta M_{\rm land} = \Delta M_{\rm soil} + \Delta M_{\rm snow} \tag{7}$$

where, N is the number of soil layers of the model (N=2 for CDAS-1), h_i is the depth of layer i, $\rho_{\rm o}$ is the density of water (1 g/cm^3), and $\Delta\eta_i(\phi,\lambda,t)$ and $\Delta N(\phi,\lambda,t)$ are soil and snow water changes at grid

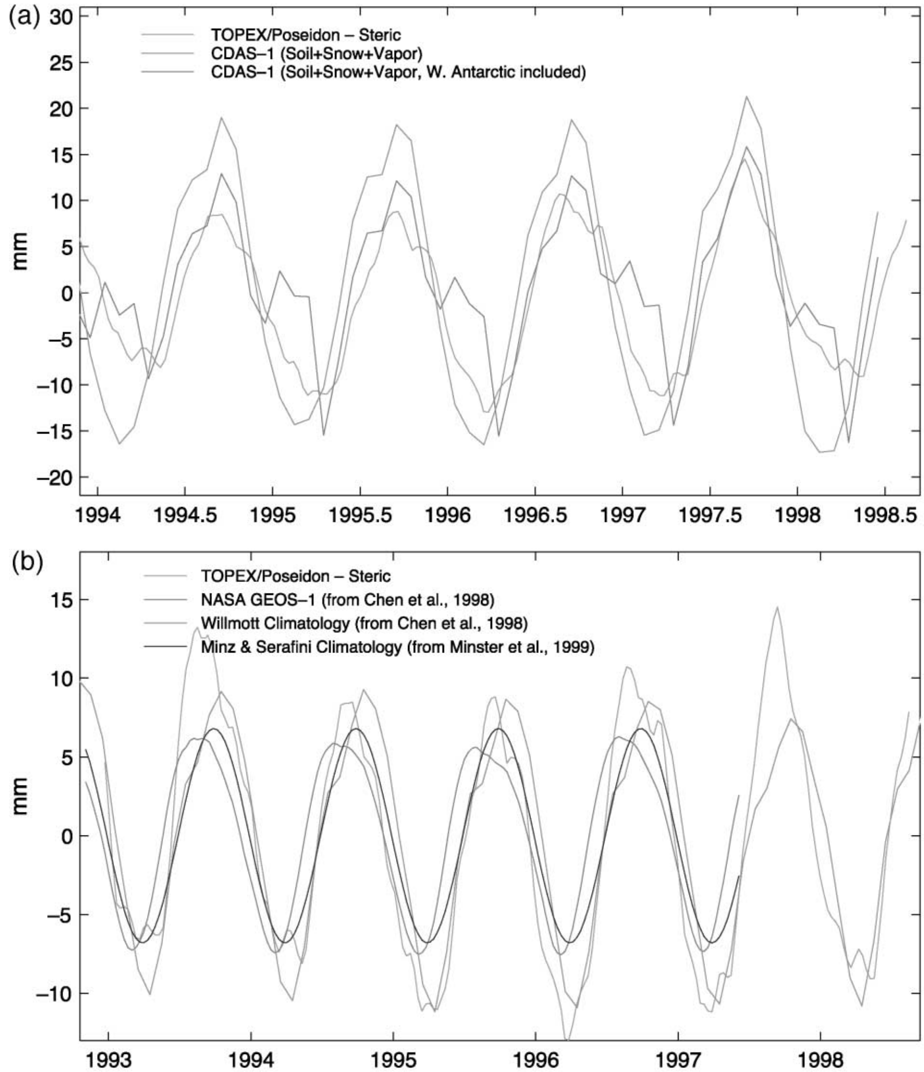

Fig. 2. (a) The comparison between two hydrological model predicted GMSL changes (from this study) with the non-steric GMSL time series from T/P observations. (b) The comparison between three hydrological models predicted GMSL changes from Chen et al. (1998) and Minster et al. (1999) with the non-steric GMSL time series from T/P observations.

Table 2
Amplitude and phase of annual and semiannual non-steric GMSL change from model estimation and T/P observation, compared with the results from Chen et al. (1998) and Minster et al. (1999)

Non-steric global mean sea level	Annual		Semiannual	
	Amplitude (mm)	Phase (deg)	Amplitude (mm)	Phase (deg)
T/P (IB)−steric (this study)	8.3	193	0.7	73
T/P (NB)−steric (Chen et al., 1998)	7.1	199	0.6	119
T/P (IB)−steric (Minster et al., 1999)	9.5	187	N/A	N/A
Model 1 (CDAS-1) (this study)	17.9	212	2.2	225
Model 2 (CDAS-1) (this study)	9.2	175	1.0	277
GEOS-1 (Chen et al., 1998)	5.9	214	1.6	111
Willmott climatology (Chen et al., 1998)	8.9	171	1.7	102
Mintz and Serafini climatology (Minster et al., 1999)	6.8	184	N/A	N/A

The phase is defined as ϕ in $\sin(2\pi(t-t_0)+\phi)$, where t_0 refers to h^0 on January 1. Atmospheric water vapor contribution from CDAS-1 has been included in model predictions in this study.

(ϕ,λ) and time t with respect to the mean ($\Delta\eta$ is dimensionless and ΔN is in units of g/cm^2).

The corresponding GMSL change due to model-inferred water mass exchange between the oceans and land and atmosphere is then computed using Eqs. (1) and (2). The two time series based on NCEP−NCAR CDAS-1 Models 1 and 2 are shown in Fig. 2a, superimposed by the non-steric GMSL change

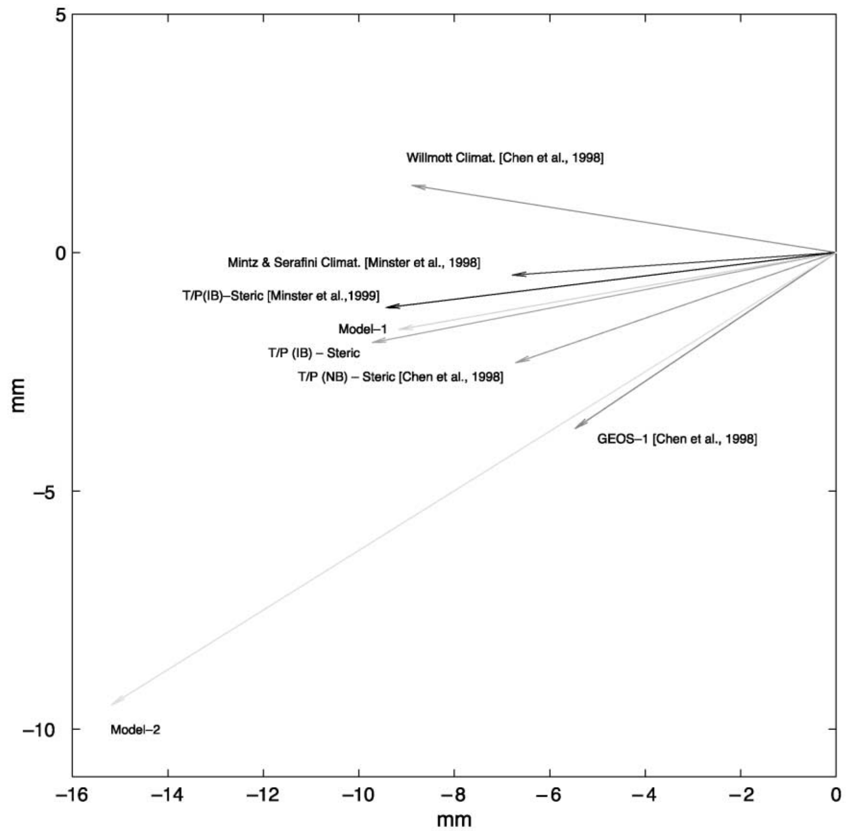

Fig. 3. Vector plots of annual variations in non-steric T/P GMSL changes and hydrological model predictions.

observed by T/P altimeter. The annual and semiannual amplitude and phase of model-inferred and T/P-measured non-steric GMSL change are estimated using least-squares and listed in Table 2. The estimates from Chen et al. (1998) and Minster et al. (1999) are also listed in Table 2 for comparison.

It is quite evident from the results in this investigation and previous studies (Chen et al., 1998; Minster et al., 1999) that water mass exchange between the oceans and atmosphere and continental water has significant impacts on seasonal GMSL change. Most hydrological models show reasonable agreement with T/P observations. The annual amplitude discrepancies are within 2–3 mm and phase differences are within 1 month. Fig. 3 shows the annual vectors of GMSL changes from T/P observation and model predictions, including some of the results from Chen et al. (1998) and Minster et al. (1999). This investigation leads 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 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.

4. Discussion

This paper intends to show a clear picture about potential hydrological influences on seasonal GMSL change. Hydrological model prediction based on CDAS-1 soil moisture and snow data, especially from Model 2, is in reasonable agreement with non-steric T/P observation and also agrees well with the results from Chen et al. (1998) and Minster et al. (1999). This investigation reinforces the general conclusion from previous studies that seasonal continental water storage change is one major contributor to GMSL change.

This study demonstrates the capability of using satellite altimeter measurements to place observational constraint to the global water mass budget of hydrological models. For the two models we consider in this study, Model 2 apparently agrees better with T/P observation and results of Chen et al. (1998) and Minster et al. (1999) than Model 1. If the large snow water variability along west Antarctic is true and the change is over floating sea ice, the NCEP–NCAR CDAS-1 assimilation system appears to overestimate the seasonal continental water storage change by a factor of 2. On global average (to combine soil water and snow water), Model 1 agrees well with other models used in Chen et al. (1998) and Minster et al. (1999). However, when we look into individual components, i.e. soil moisture and snow water contribution, CDAS-1 shows a much stronger global mean seasonal soil moisture change, compared to other models (Chen et al., 1999), which can be easily verified by GRACE measurements. When combined with Jason-1 altimeter data, the T/P and Jason-1 altimeters will provide accurate determination of GMSL change for a considerably longer time span, and therefore are able to determine better seasonal and long-term GMSL variations and provide observational constraints to natural and anthropogenic changes in continental water over broader time scales.

The steric correction of GMSL change is based on the model of Chen et al. (2000), derived from the combination of satellite SST data and WOA94 climatology. On global average, the result agrees quite well with those from Chen et al. (1998) and Minster et al. (1999), but shows a slightly larger amplitude (see Table 1). Steric effect is one of the major error sources in estimating non-steric GMSL change (or water mass change in the oceans). The use of satellite SST data can only improve the result at the very top layer of the mixing layer. The main part is still based on WOA94 climatology in this study, which shows some large uncertainties in the Southern Hemisphere (Chen et al., 2000). Using ocean circulation models could be an alternative approach, but we need to solve the limitations due to the volume (or mass) conservation of the models, especially when we are looking at global average.

Other error sources could have affected the results, including the sampling errors of T/P sea level observation, geophysical corrections to T/P measurement, and 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 variability is 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 altimetry measurement. Even though there is a potential water vapor drift [T. Urban, personal communication, 1998], no result on seasonal water vapor error is available yet. Different treatments of the IB effect will also affect the determination of GMSL change. In this study, we apply the IB results by Raofi (1998) and Dorandeu and Le Traon (1999). Theoretically, the IB effect will not change the total volume of the ocean, but owing to the non-global coverage (only from 65S to 65N), the IB correction can cause about 1 mm difference in GMSL change (compared to the non-IB case; see Table 1).

Continental water is a least-known process in the Earth's system. The general 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. However, discrepancies between different hydrological models are also obvious. A better understanding of continental water storage change relies on the improvement of hydrological models and independent observational constraints from future space-borne gravity measurements (e.g. the Gravity Recovery And Climate Experiment-GRACE mission) and satellite altimeter missions (e.g. the Jason-1 mission).

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