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Seasonal Global Mean Sea Level Change From Satellite Altimeter, GRACE, and Geophysical Models

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Abstract: We estimate seasonal global mean sea level changes using different data resources, including sea level anomalies from satellite radar altimetry, ocean temperature and salinity from the World Ocean Atlas 2001, time-variable gravity observations from the Gravity Recovery and Climate Experiment (GRACE) mission, and terrestrial water storage and atmospheric water vapor changes from the NASA global land data assimilation system (GLDAS) and National Centers for Environmental Prediction (NCEP) reanalysis atmospheric model. The results from all estimates are consistent in amplitude and phase at the annual period, in some cases with remarkably good agreement. The results provide a good measure of average annual variation of water stored within atmospheric, land, and ocean reservoirs. We examine how varied treatments of degree-2 and 1 spherical harmonics from GRACE, laser ranging, and Earth rotation variations affect GRACE mean sea level change estimates. We also show that correcting the standard equilibrium ocean pole tide correction for mass conservation is needed when using satellite altimeter data in global mean sea level studies. These encouraging results indicate that is reasonable to consider estimating longer-term time series of water storage in these reservoirs, as a way of tracking climate change.

Keywords. Sea level change, Global, Seasonal, GRACE, Altimeter, Hydrology

1. Introduction

Global mean sea level changes arise from a number of geophysical processes within the Earth system. Temperature and salinity variations cause seawater density variations resulting in steric sea level change. For example, the strong seasonal mean sea level change in mid and high latitudes in the northern hemisphere is mainly driven by seasonal temperature variation in the mixing layers of the northern oceans (e.g., Chen et al. 2000). Water mass transport among oceans, land and atmosphere introduce non-steric sea level change as total water mass is conserved within the Earth system. Contributing processes include changes in glacial and polar ice sheet mass, terrestrial water storage changes (in soil moisture, snow, and ground water), and atmospheric water vapor variations (Douglas et al. 1990, Schmitt 1995, Chen et al. 1998, Minster et al. 1999). Direct processes resulting in non-steric sea level change include river discharge (runoff) from land, snow and ice melting from glacial and snow/ice sheet, and precipitation and evaporation over the oceans. Post glacial rebound (PGR) or glacial isostatic adjustment (GIA), tectonics, and other processes change ocean basin volume on longer time scales, leading to global mean sea level change, as well as local changes in sea level (Lambeck 1988, Peltier and Tushingham 1989).

Global mean sea level changes occur over a broad band of temporal scales, from sub-daily to seasonal to longer term. Global warming of the oceans, glacial and polar ice melting, and GIA are major contributors to long-term sea level rise (Douglas 1995). Sea level changes at periods less than a few days are mainly driven by tides, evaporation and precipitation as the oceans exchange water with the atmosphere, and storm surges. At seasonal time scales, temperature and salinity change of sea water, and water mass exchange between land and oceans are probably dominant (Chen et al. 1998, 2000, Minster et al. 1999, Cazenave et al. 2000, Milly et al. 2003), although storage in the atmosphere (water vapor variation) plays an important role as well (Chen et al. 1998). This study will focus on non-tidal seasonal sea level change with respect to the mean sea surface over a given time period.

The TOPEX/Poseidon (T/P) and its successor Jason-1 (launched in December, 2001) satellite radar altimeters have been measuring sea level change on a global basis at approximately 10-day intervals for over 12 years, and provide an essential data resource for the study of global sea level change. A 2-3 mm/year global sea level rise has been observed in the T/P and Jason-1 records (e.g., Cabanes et al. 2001, Nerem and Mitchum 2001). Superimposed on this steady rise is a clear seasonal signal of several mm in amplitude. Maximum and minimum global mean sea levels occur around September and March, respectively. Previous studies (e.g., Chen et al. 1998, 2002a,b; Minster et al. 1999, Cazenave et al. 2000) suggested that T/P seasonal changes can largely be accounted for by adding together separate effects of steric (temperature and salinity) and non-steric water mass exchange between the oceans and land. These earlier studies were limited by the immaturity of hydrological models used to estimate changes in terrestrial storage, and uncertainty in steric effects estimated from available seasonal climatology of ocean temperature and salinity.

A new data type relevant to the sea level problem became available after the launch of the Gravity Recovery and Climate Experiment (GRACE) satellite mission in March 2002 (Tapley et al. 2004a). GRACE provides time changes in Earth's gravity field about every 30 days, allowing an independent estimate of changes in water mass stored in the oceans through the inversion of time-variable gravity change (Tapley et al. 2004b, Wahr et al. 2004). Chambers et al. (2004) examined GRACE data from the first year and a half of the mission (August 2002 to December 2003) to estimate non-steric global mean sea level change. The results agreed well with average seasonal variations from T/P altimeter measurements for the 11-year T/P and Jason-1 period (1992 to 2003), verifying the utility and precision of GRACE in sea level studies.

The purpose of this study is to develop a more complete picture of the annual global water cycle as manifested in global sea level change and related storage changes in the oceans, on land, and in the atmosphere. We examine T/P and Jason-1 time series during the GRACE observation period (April 2002 through July 2004), instead of mean seasonal sea level changes used in earlier studies. More advanced data assimilating climate models are now available, providing new estimates of seasonal water storage changes on land and in the atmosphere. Finally, we examine the influence of low-degree spherical harmonics on GRACE estimates. Degree-2 coefficients in GRACE products are currently not well determined (e.g., in the 0001 release as we use in this study) limited probably by orbit geometry and other unknown reasons (Tapley et al. 2004b), and we experiment by replacing them with independent estimates from Earth rotation changes (Chen and Wilson 2003, Chen et al. 2004) and satellite laser ranging (SLR) observations (Cheng and Tapley 2002). GRACE does not measure degree-1 spherical harmonics, related to geocenter motion, but these are available from SLR observations (Chen et al. 1999), and have a measurable effect on GRACE-derived sea level estimates.

Previous studies (e.g., Chen et al. 1998, 2002a,b; Minster et al. 1999, Cazenave et al. 2000) show reasonable agreement between T/P non-steric seasonal sea level change and climate model estimates from changes in terrestrial water storage. However, there is considerable variability in the amplitude of the annual signal among the climate models, with estimates in the range of 5.6 mm to 18 mm. The phase of the annual signal is more consistent among climate model estimates, with a range of about 1 month (Chen et al. 2002). Recent studies suggest that the global land data assimilation system (GLDAS) (Rodell et al. 2004) improves simulations of large-scale terrestrial water storage changes relative to earlier models (Chen et al. 2005). Therefore, in this study we will use terrestrial water storage estimates from GLDAS to reassess land water contribution to seasonal global mean sea level change.

2. Data and Processing

2.1 Mean Sea Level Anomalies From Satellite Altimetry

Merged mean sea level anomalies derived from T/P and Jason-1 (plus available ERS-1/2 and Envisat altimeters) are provided by the French Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) (available at http://www.aviso.oceanobs.com/). Mean sea level anomalies are given on 1° x 1° grids, every 7-days for the period Oct. 1992 to Aug. 2004. Global mean sea level change is the sum of sea level anomalies over the global ocean grid (from 65°S to 65°N) weighted by cosine of latitude. Tidal effects, including ocean tide, solid earth tide, and pole tide have been removed in altimeter data processing (for details, see the AVISO User Handbook available at http://www.aviso.oceanobs.com/). An inverted barometer (IB) correction (ΔH) is applied to remove atmospheric pressure effects on observed sea level change, which is given as (Gill 1982),

$$\Delta H = -0.9948 * (P - \overline{P}_{ocn}) \tag{1}$$

in which, ΔH is in units of cm, P (in mb) sea surface pressure at given grid point, and $\overline{P}_{ocn}$ (in mb) the global mean sea surface pressure over the oceans. P and $\overline{P}_{ocn}$ are from the European Centre for Medium-Range Weather Forecasts atmospheric model (M. Gasc 2004, personal communication). Eq. (1) is a modified version of the Eq. Given by Gill (1982).

2.2 Steric Sea Level Change

Steric sea surface height (SSH) change at any given grid point is computed from density change of seawater as,

$$SSH_{steric} = -\frac{1}{\rho_0} \cdot \int_{-h}^{0} \Delta\rho \cdot dz \tag{2}$$

in which ρ_0 is the mean density of sea water (1028 kg/m^3), and $\Delta\rho$ the density change as a function of temperature (T), salinity (S), and pressure (P). The integral in Eq. (2) is from the ocean bottom to the surface ($h=0$). T and S are from the World Ocean Atlas 2001 (WOA01) climatologies (Stephens et al. 2002), and P is computed from the depth of each layer. $\Delta\rho$ is computed using the UNESCO (United Nations Educational, Scientific and Cultural Organization) standard equations (Fofonoff and Millard 1983). Same as Chambers et al. (2004), we compute contributions from the surface to 1500 m depth (24 layers). To be consistent with the altimeter records, data between 65°S to 65°N are used to form the global average with cosine (latitude) weighting.

2.3 Terrestrial Water Storage Change from a Climate Model

GLDAS was developed as a joint effort of the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) (Rodell et al. 2004). GLDAS parameterizes, forces, and constrains sophisticated land surface models with ground and satellite products with the goal of estimating land surface states (e.g., soil moisture and temperature) and fluxes (e.g., evapotranspiration). In the particular simulation used in this study, GLDAS drove the Noah land surface model version 2.7.1 (Ek et al. 2003), with observed precipitation and solar radiation as inputs. GLDAS terrestrial water storage estimates are the sum of soil moisture (2 m column depth) and snow water equivalent. Greenland and Antarctica are excluded because the Noah model lacks ice sheet physics, and GLDAS also omits storage changes in deeper ground water. Soil moisture and snow data are provided on 1° x 1° grids at 3-hour intervals, covering the period Jan. 1, 2002 to Dec. 31, 2004. A cosine (latitude) weighting is applied when we compute terrestrial water mass change.

2.4 Atmospheric Water Vapor Change

The total mass of the dry atmosphere is nearly a constant (Trenberth and Smith 2005). Therefore, atmospheric water vapor variation can be estimated by global integration of atmospheric surface pressure change. Daily surface pressure data from the NCEP reanalysis atmospheric model (Kalnay et al. 1996) are available on a Gaussian grid, about 1.904° latitude by 1.875° longitude, for the period from 1948 to present. Water vapor estimates from surface pressure may differ slightly from specific humidity and precipitable water integrals (Trenberth and Smith 2005). However, surface pressure is likely to be a more accurately determined quantity because of the greater number of surface pressure observations available.

2.5 GRACE Observations

We use 22 approximately monthly time-variable gravity fields from the 0001 release of GRACE for the period April 2002 to July 2004 (Tapley et al. 2004a). These gravity fields are fully normalized spherical harmonics up to degree and order 120, except that the Sept. 2002 solution is a 90x90 field because of limited data quality and quantity. The mean gravity field is the GRACE GGM01 gravity model, derived from the first 111 days of GRACE data (Tapley et al. 2004a). Tidal effects, including ocean, solid Earth, and solid Earth pole tides have been removed in GRACE data processing, but the ocean pole tide (OPT) was not removed, though the next GRACE reprocessing will correct for the OPT. However, the OPT does not change the total mass of the oceans, so it can be neglected in this study. Non-tidal atmospheric and oceanic contributions are removed in GRACE processing (Bettadpur 2003). However, the oceanic contribution removed is determined from a mass-conserving barotropic model (developed at the Jet Propulsion Laboratory), which would not affect the computation of global mean sea level change from GRACE data (Chambers et al. 2004), although the de-aliasing procedure does affect regional oceanic mass change estimated from GRACE since part of the oceanic mass signal (if not all) has been removed. Because high degree spherical harmonics in GRACE products are dominated by noise (Tapley et al. 2004b, Wahr et al. 2004), we truncate solutions at degree and order 60, and apply 400 km radius Gaussian smoothing (Jekeli 1981, Wahr et al. 1998), prior to computing equivalent mean non-steric change by averaging between 65 degrees north and south latitudes, to be consistent with satellite altimeter data.

We compute GRACE estimates of non-steric global mean sea level change for four cases involving various treatments of low-degree harmonics. The four test cases are: 1) the GRACE ΔC_{20} coefficient is omitted; 2) the GRACE ΔC_{20} coefficient is retained; 3) SLR values for ΔC_{20} and seasonal ΔC_{11}, ΔS_{11}, and ΔC_{10} are used (Chen et al. 1999); and 4) SLR seasonal ΔC_{11}, ΔS_{11}, and ΔC_{10} are used, GRACE values of ΔC_{21} and ΔS_{21} are replaced with estimates from Earth Orientation Parameters (EOP) (Chen et al. 2004), and SLR annual and semi-annual ΔC_{20} are substituted for GRACE values (Cheng and Tapley 2002).

Figure 1

3. Results

3.1 Observed Global Mean Sea Level Change

Satellite altimeter global mean sea level changes from 1993 to 2004 are shown in Fig. 1 (thin light curve). The linear trend estimated by least squares is also shown, with a slope of about 2.6 mm/year during this period. Strong seasonal variations of several mm are superimposed upon this trend. Interannual variation is also evident, especially during the 1997/1998 El Niño period. During the GRACE observation period of the past few years, seasonal amplitudes appear smaller than in earlier years. Fig. 2 shows global mean sea level change (blue curve) after the linear trend is removed. The seasonal steric contribution estimated from WOA01 (red curve) is similar in magnitude to the altimeter measurement, but of opposite phase, consistent with previous studies (Chen et al. 1998, 2002, Minster et al. 1999). The green curve shows non-steric global mean sea level change (AVISO altimetry minus WOA01 steric estimate).

The opposite phases of altimeter observed global mean seasonal sea level change and estimated steric contribution can be explained as that the observed sea seasonal signal is basically the sum of two seasonal signals with opposite phases. One is from non-steric effects (i.e., mass redistributions) and the other is from steric effects (i.e., temperature and salinity changes). As non-steric contribution is larger than the steric counterpart, the sum of the two, i.e., altimeter observed signal is, therefore, in similar phase as the non-steric contributor and out-of-phase if compared with estimated steric effects.

Figure 2

The OPT (i.e., rotational deformation of sea level) effect has been removed from satellite altimeter sea level measurements using an equilibrium OPT model (Wahr 1985).

However, this correction lacks mass conservation, which could introduce a spurious volume change not related to any geophysical processes, as the oceans do not cover the entire Earth's surface. To estimate possible effects from the lack of mass conservation of the OPT model, we compute OPT introduced global sea level change during the GRACE period April 2002 to July 2004 using the same OPT model used in Jason-1 altimeter data, and then compute the global average (between 65S to 65N). We regard this global average, supposedly to be a constant, as the effect from OPT mass conservation (OPT MC). The OPT MC correction, shown in Fig. 3, is measurable, about 1 mm in magnitude, similar in phase to the altimeter record.

Figure 3

3.2 Sea Level Change from Mass Balance

Assuming water mass is conserved, total terrestrial water storage and atmospheric water vapor changes can be used to predict equivalent non-steric mean sea level changes (Chen et al. 1998, Minster et al. 1999). The GLDAS estimate is shown in Fig. 4 in a cyan curve, with the NCEP atmospheric water vapor prediction show by the green curve, and their sum in the red curve. The non-steric altimeter estimate (AVISO – OPT MC – WOA01 Steric) is also shown (blue curve). The results show that terrestrial water storage is dominant, but atmospheric storage (water vapor) is also significant. Their sum agrees remarkably well with the altimeter estimate. Though water vapor storage is a minor effect, including it in the water storage calculation improves phase agreement with the altimeter results, especially in the second half of 2003.

We estimate the amplitude and phase of annual and semiannual global mean sea level changes from various estimates and contributions to global mean sea level change using least squares fit, and list the results in Table 1. To be consistent with GRACE observations examined later, only data during the period April 2002 to July 2004 are used. Results from Chambers et al. (2004) are also included for comparison. The combined contribution from land and atmosphere water storage variations agrees very well with altimeter measurements, especially when the OPT MC is applied. Annual phases of the two estimates (AVISO/OPT-WOA01 and TWS+Vapor) are nearly identical (179° vs. 180°). The altimeter annual amplitude is slightly larger than the storage estimate (8.81 vs. 7.17 mm), but consistent with the estimate from Chambers et al. (2004), who did not apply the OPT MC correction.

Figure 4

3.3 Mean Sea Level Change from GRACE

Oceanic mass change is estimated from GRACE time-variable gravity data (Wahr et al. 1998, Chen et al. 2005). Non-steric global mean sea level change is therefore computed from averaging GRACE estimated oceanic mass change. The four estimates of equivalent global mean sea level change from GRACE, corresponding to the varied treatments of low-degree harmonics, are shown in the top panel of Fig. 5, with the altimeter series. No linear trend is removed. There is reasonable agreement in Fig. 5 with any of the four GRACE estimates, but those which include GRACE ΔC20 (green stars and yellow triangles) show a trend similar to the altimeter result, though GRACE results suggest a higher rate of sea level rise during this period. Probable errors in GRACE ΔC20 translate into a significant effect on sea level change estimates. When GRACE ΔC20 is excluded (red circles in Fig. 5), the seasonal amplitude is notably smaller. Among the four GRACE estimates, EOP/SLR/GEOC using both EOP (degree 2, order 1) and SLR (degree 2, order 0 and degree 1) shows the best agreement with altimetry.

The bottom panel of Fig. 5 shows the same time series as in the top panel with linear trends removed. The agreement between GRACE and altimeter estimates at seasonal time scales is excellent. The amplitude and phase of annual and semiannual variations in the four GRACE estimates are computed using least squares, and given in Table 1, together with estimates from Chambers et al. (2004). An OPT correction is not applied to GRACE data used in this study (see Section 2.5 for details). An equilibrium OPT correction (not mass conserving) was applied by Chambers et al. (2004) as in the standard altimetry product, and their estimates show a larger amplitude. The difference may be related to a number of causes, including the fact that additional GRACE data is used in this study, differences in smoothing, treatment of low degree harmonics, or differences in the OPT correction.

Figure 5

Fig. 6 compares non-steric global mean sea level estimates from satellite altimetry (AVISO–OPTMC–WOA Steric), GRACE (the EOP/SLR/GEOC case), and water storage (GLDAS TWS+NCEP Vapor). Agreement is excellent in both amplitude and phase, especially between GRACE and water storage estimates. Annual amplitudes and phases are 7.22 vs. 7.17 mm, and 174° vs. 180°, respectively. The altimetry estimate has a slightly larger annual amplitude (8.81 mm) than the others. Agreement with semi-annual terms is not as good.

Figure 6

4. Conclusions

We estimated seasonal global mean sea level changes using several independent data sources, leading to separate estimates from radar altimetry, GRACE (satellite gravimetry), and water storage changes in the atmosphere and on land. A new estimate of steric effects is derived from the recent WOA01 climatology. The three estimates agree remarkably well, with difference in phase of only 6 days, significantly better than in previous studies (e.g., Chen et al. 1998, 2002a,b; Minster et al. 1999, Cazenave et al. 2000).

Non-conservation of mass in the standard equilibrium OPT correction for satellite altimetry has a small but measurable effect on estimates. With mass conservation enforced, agreement among altimetry and GRACE and water storage estimates is improved.

Hydrological contributions to global mean sea level change estimated from GLDAS storage changes and NCEP atmospheric (water vapor) storage variation show better agreement with altimetry relative to previous studies (Chen et al. 1998, 2002, Minster et al. 1999, Cazenave et al. 2000, Milly et al. 2003). This is consistent with continuing improvement in GLDAS. This assessment is consistent with other recent findings (Tapley et al. 2004b, Chen et al. 2005, Famiglietti et al. 2005) showing good agreement between GLDAS and GRACE estimates of water storage changes in large river basins.

Treatment of low-degree harmonics of gravitational field significantly influences GRACE estimates. Sensitivity to ΔC_{20} is particularly large, as shown by replacing GRACE ΔC_{20} with other estimates. Including SLR degree-1 (geocenter) changes improves agreement between GRACE sea level and other estimates from altimetry and water storage. Replacing degree-2 coefficients with EOP and SLR estimates also improves the agreement.

The linear trend in the GRACE ΔC_{20} coefficient introduces a trend in estimated global mean sea level of the same sign, but much larger than the altimetry value (7.1 vs. 2.8 mm/year). Thus, some part of the ΔC_{20} linear trend seen by GRACE, could be associated with sea level rise. At the moment though, ΔC_{20} from SLR is probably better determined, and more useful for long-term global mean sea level change estimates.

5. Discussions

Despite of the remarkably good agreements among altimeter, GRACE, and geophysical model estimated non-steric global mean sea level changes during this two plus year period, many error sources could still affect these estimates. As demonstrated in this study, the global mean sea level change estimate is sensitive to many factors. A good example is the mass conservation adjustment to the standard equilibrium OPT correction in altimetry. This would not be a concern for regional- or basin-scale studies, but becomes important in the global average. Another example is the IB correction. A variable reference pressure has not been standard in the T/P MGDR (merged geophysical data record), but its use in AVISO data avoids a spurious effect associated with constant reference pressure.

Steric effects on global mean sea level change are computed from long-term seasonal temperature and salinity climatologies. Different versions of WOA climatologies (released in 1994, 1998, and 2001) give consistent estimates of seasonal steric changes. However, significant interannual variability exists and limits the validity of the steric correction from average seasonal climatology. Still, the WOA climatologies remain the most useful data resource (Stephens et al. 2002). Temperature and salinity estimates from data assimilating ocean general circulation models may provide another useful way to estimate steric changes in the future. However, the Boussinesq approximation (i.e., volume conservation) used in most current such models limits their utility for estimating global mean steric changes, although at regional or basin scales, effects from this approximation are minor.

GLDAS estimates are quite consistent with independent results from space geodesy (altimetry and gravity), indicating that GLDAS is providing improved estimates of global terrestrial water storage. However, lack of Antarctic and Greenland ice contributions and deep ground water storage are deficiencies (Rodell et al. 2004). Atmospheric water vapor is computed from surface pressure integration, rather than from more fundamental specific humidity and precipitable water vapor. Differences between the two methods could be significant (Trenberth and Smith 2005).

GRACE results are encouraging at present. However, many factors can affect the GRACE estimates as well. Better determined ΔC_{20} coefficients from GRACE itself in a reprocessed data release, or from a SLR time series (replacing the seasonal model in this study), and the use of an improved geocenter (degree 1) time series should all improve the estimates of oceanic mass change from GRACE time-variable gravity.

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Figures:

Figure 1. The global mean sea level change estimated from the AVISO merged mean sea level anomaly data. The thick solid line represents the long term sea level rise rate (2.6 mm/year) estimated from least squares fit.

Figure 2. The global mean sea level change estimated from the AVISO merged mean sea level anomaly data, when long term rate (2.6 mm/year) is removed (blue curve), steric effects on the global mean sea level change from WOA01 (red curve), and non-steric global mean sea level change, i.e. AVISO – WOA01.

Figure 3. Global mean sea level change from altimeter (AVISO GMSL) and contribution from ocean pole tide mass conservation (OPT MC, thick solid curve) during the period April 2002 to July 2004. Long-term signals are removed from altimeter time series.

Figure 4. Non-steric global mean sea level change during 2002 to 2004 estimated from AVISO merged altimeter measurements (AVISO – OPT MC –WOA) and contributions from GLDAS terrestrial water storage (TWS) change and NCEP atmospheric water vapor variation.

Figure 5. a) Non-steric global mean sea level changes estimated from GRACE time-variable gravity data with 4 different treatments of the low-degree spherical harmonics. Altimeter result (AVISO – OPT MC –WOA) is shown in blue curve. b) same as a), but the altimeter result is detrended and the apparent trend in the case when C20 is included is also removed.

Figure 6. Non-steric global mean sea level changes from altimeter observation (AVISO – OPT MC - WOA), global water mass balance (GLDAS TWS + NCEP Vapor), and GRACE observation (when EOP/SLR derived degree-2 harmonics and SLR estimated geocenter motion are included).

Table 1. Amplitude and phase of annual and semiannual global mean sea level changes during April 2002 and July 2004 estimated from altimeter (AVISO merged), steric effects (WOA98), ocean pole tide (OPT) mass conservation effects, global water mass balance, and GRACE (GRC) time-variable gravity. The phase is defined as ϕ in $\sin(2\pi(t-t_0)+\phi)$, where t_0 refers to UTC 0h on January 1.

GMSL Change	Annual Amplitude (mm)	Annual Phase (deg)	Semiannual Amplitude (mm)	Semiannual Phase (deg)
GMSL (AVISO)	4.89	152	1.34	212
OPT Mass Conservation (OPT MC)	0.82	133	0.08	297
GMSL (AVISO/OPT MC)	4.18	154	1.36	210
Steric GMSL (WOA01)	5.30	18	1.70	206
Non-steric GMSL (AVISO-WOA01)	9.38	176	0.39	4
Non-steric GMSL (AVISO/OPT-WOA01)	8.81	179	0.36	12
Non-steric GMSL (Chambers)	8.50	188	N/A	N/A
GLDAS TWS	8.33	192	0.61	54
NCEP Vapor	2.09	63	0.66	185
TWS + Vapor	7.17	180	0.53	125
GRACE (no C20)	5.85	154	0.64	276
GRACE (with C20)	6.77	179	1.51	286
GRACE (with C20 & GEOC)	8.47	188	2.07	293
GRACE (EOP/SLR/GEOC)	7.22	174	1.44	303
GRACE (+GEOC, Chambers)	8.60	175	N/A	N/A
GRACE (+GEOC, Chambers) (OPT MC)	8.00	179	N/A	N/A

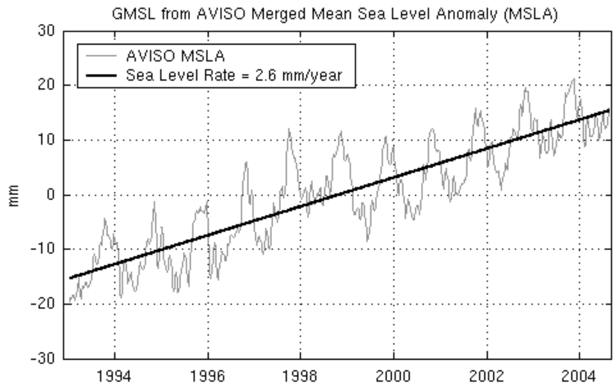
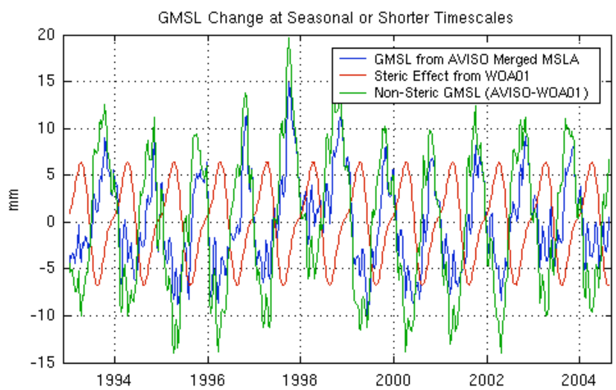


Figure 1



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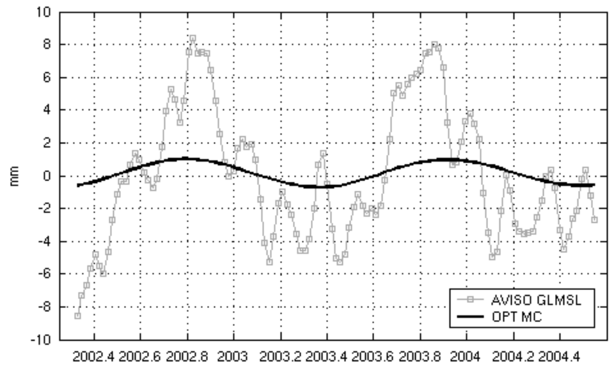

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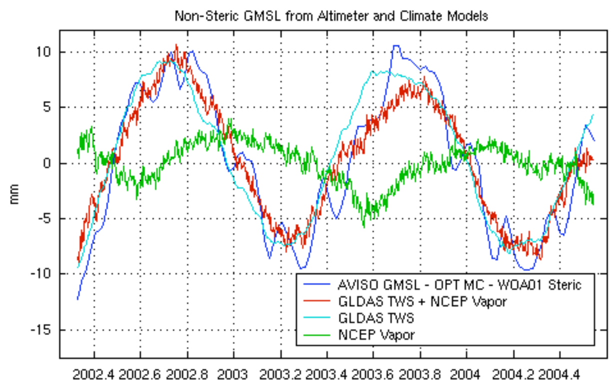

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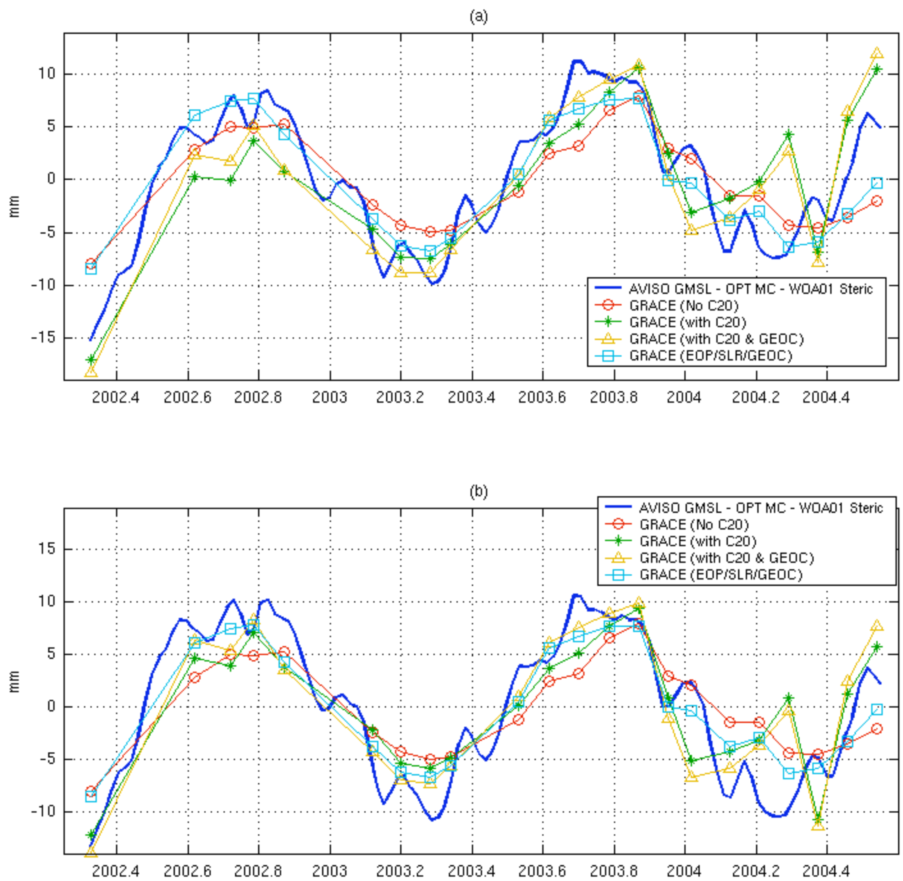

Figure 5

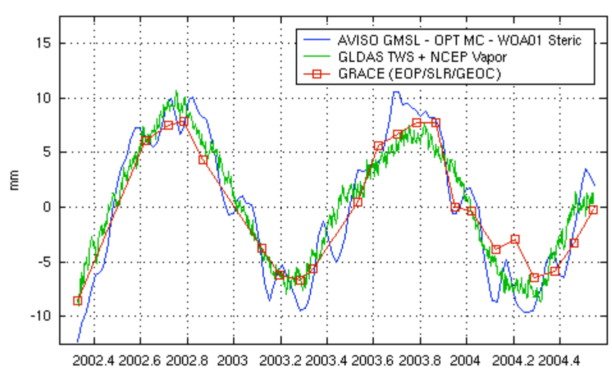

Figure 6