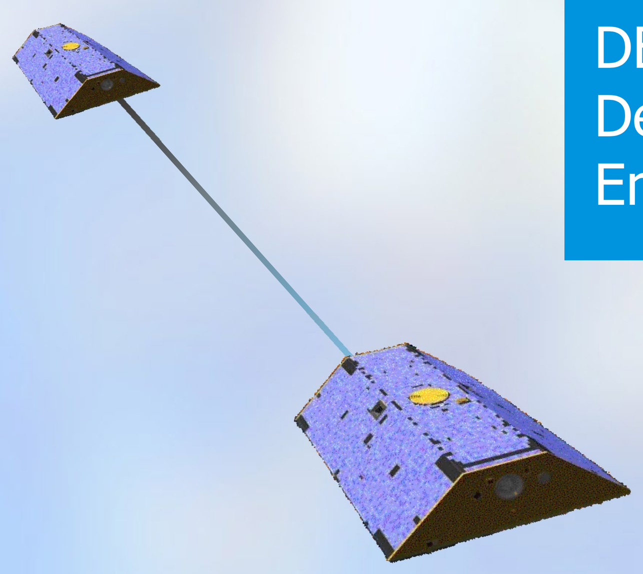
Ocean Mass and Heat Changes Recovery from GRACE and Altimetry Data



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Abstract

Sea level variability consists of two components, i.e. changes due to mass redistribution (eustatic) and due to variations in ocean heat content (steric). Altimetry observes the total variation in sea level height and cannot distinguish between the two components. The GRACE monthly solutions of the time-variable gravity field allow direct estimates of changes in the ocean water mass budget. Combined with satellite altimetry observations, this can be used to estimate changes in the ocean heat content as well. Since the amplitudes of these signals are relatively small (compared to the hydrological signal over land), it is important that both the GRACE and altimetry data are corrected and combined in a consistent manner. By definition, GRACE is insensitive to variations in the degree 1 terms of the potential. Chambers et al. (2004) first noted that the inclusion of these geocenter variations in the GRACE monthly solutions leads to an improved estimations of global ocean mass variations when compared with altimetry corrected for steric effects. The influence of this effect on both the altimetry and GRACE observations is further explored in this presentation. Additionally, we discuss the other corrections that should be applied to correctly reconcile the two data sets.

Data

The main goal of this study is to separate variations due eustatic and steric changes in the ocean. To accomplish this, three different data sets have been used:

1) GRACE data: 21 monthly solutions of the gravity field are provided by the GRACE team, which can be converted to equivalent water height changes (i.e. mass) over the oceans. A gaussian smoothing filter with a radius of 1000 km has been applied. The data spans the period April 2002-July 2004 (CSR release 01).
2) Altimetry: observes the total sum of eustatic and steric changes. We use the JASON-1 data for the same period as the GRACE data. All standard corrections are applied, including an inverted barometer (IB) correction.
3) World Ocean Atlas 2001 (WOA01): consists of analyzed monthly temperature and salinity grids based on in-situ observations. Using an equation of state, this data can be converted to changes in steric height. The WOA01 climatology is used as a reference set.

Method

Because we are dealing with three different data set, each having their own temporal resolution and sample interval, we make use of empirical orthogonal function (EOF) analysis to isolate the dominant signal. This statistical tool decomposes any time series of data Z(, ,t) in number of modes consisting of spatial maps B(,) and associated amplitudes a(t):

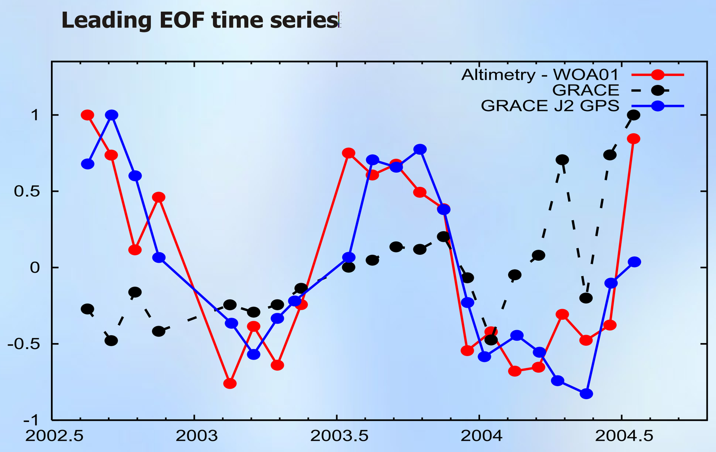
$$Z(\ ,\ ,t)= \quad a_i(t).B_i(\ ,\ )$$

Each mode represents part of the total variance present in the data time series, where the first mode explains most of the variance. In this study we use only the first EOF mode, representing the seasonal cycle, which explains 50 to 70% of the total variance.

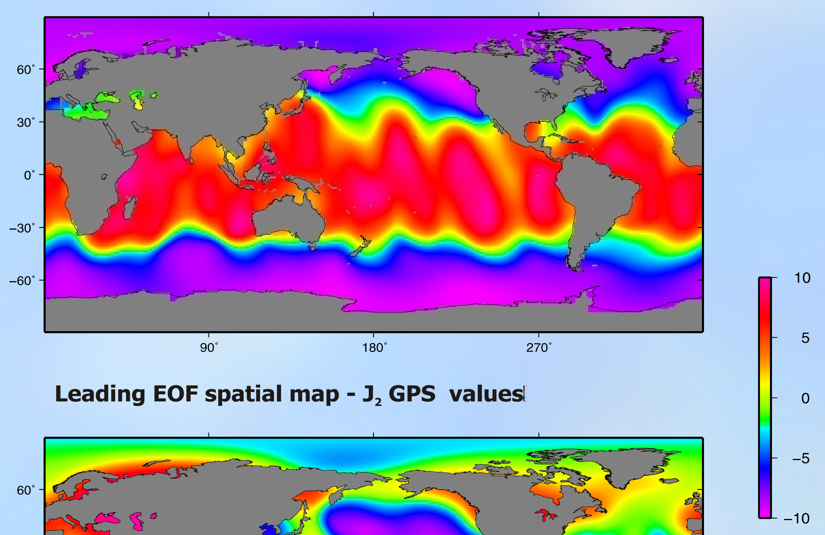
Correction for J_2 term:

The GRACE solutions for the degree 2, order 0 term, or J_2 are generally regarded as being less reliable. In comparison with estimates from other geodetic observation techniques, this term exhibits large fluctuations and shows no real seasonal signal, as would be expected from the annual mass redistribution on the Earth's surface. Using the original GRACE J_2 values results in a mainly zonal signal, with no distinct geographical patterns. This can be seen in the right panel, showing the leading EOF of the GRACE water mass signal. In the time series, only a very weak annual signal can be distinguished (dotted line). To overcome this problem, we have replaced the J_2 terms with values based on a joint inversion of GPS observations and GRACE solutions (see Kusche and Schrama, 2005). This results in more pronounced geographical features and a clear seasonal signal in the time series of the EOF leading mode (blue line). As a reference, the time series of the steric corrected altimetry (red line) is plotted as well.

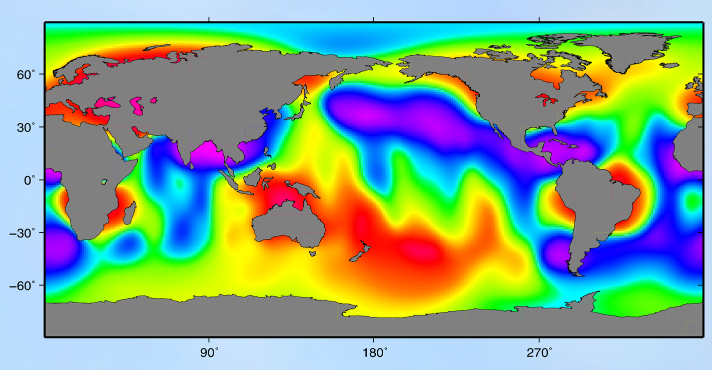
Leading EOF time series



Leading EOF spatial map - J_2 GRACE values



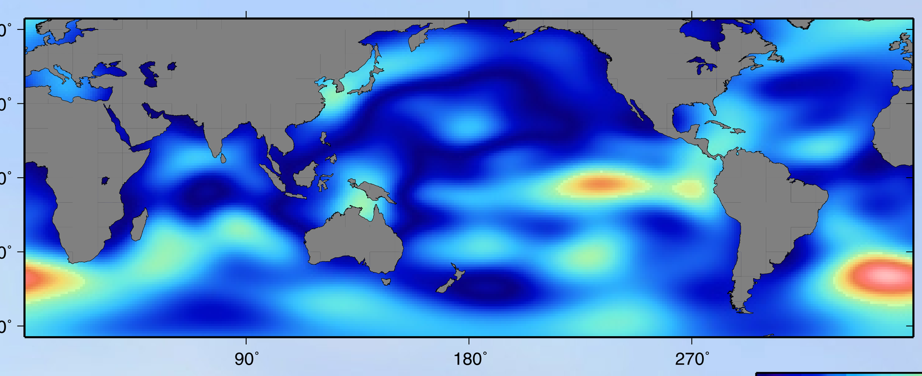
Leading EOF spatial map - J_2 GPS values



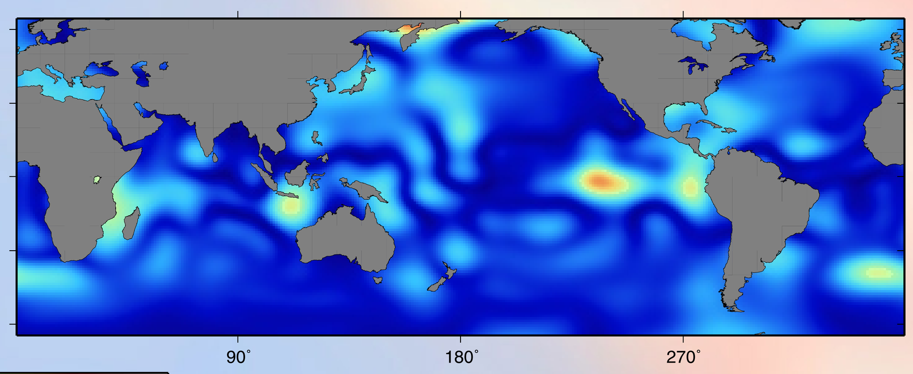
Steric changes from GRACE and altimetry - Local results

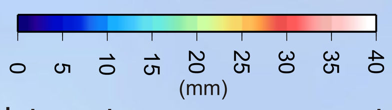
To study the accuracy of GRACE on a local scale, a comparison has been made between the traditional method of estimating variations in the steric sea level from altimetry alone (thus neglecting mass variations) and the newer method of correcting the altimetry data with mass variations from space born gravimetry. To isolate the seasonal signal, the time series have been decomposed using the EOF method and then reconstructed by multiplying the leading mode with the associated EOF spatial maps. Leakage of hydrological signals over land has been reduced by subtracting a climatology based on the LaD hydrology model (smoothed with a 1000 km radius). To assess the accuracy of the two methods, the resulting two series of monthly maps were subtracted from the monthly WOA01 steric sea level reference maps and the variances of the residuals were calculated. As can be seen below, including the water mass variations inferred from the GRACE data results in a significant decrease of the variance in most regions. The global mean variance reduces from 10.1 cm² to 7.6 cm² when GRACE data is included. The changes are most significant in the Indian Ocean, the southern-eastern part of the Pacific and in the South Atlantic. On the other hand, including the GRACE data increases the RMS slightly in some (isolated) regions. Signals close to land should be interpreted with care, as leakage of land hydrology is still visible in some regions.

WOA01 - Altimetry: mean variance 9.9 cm²



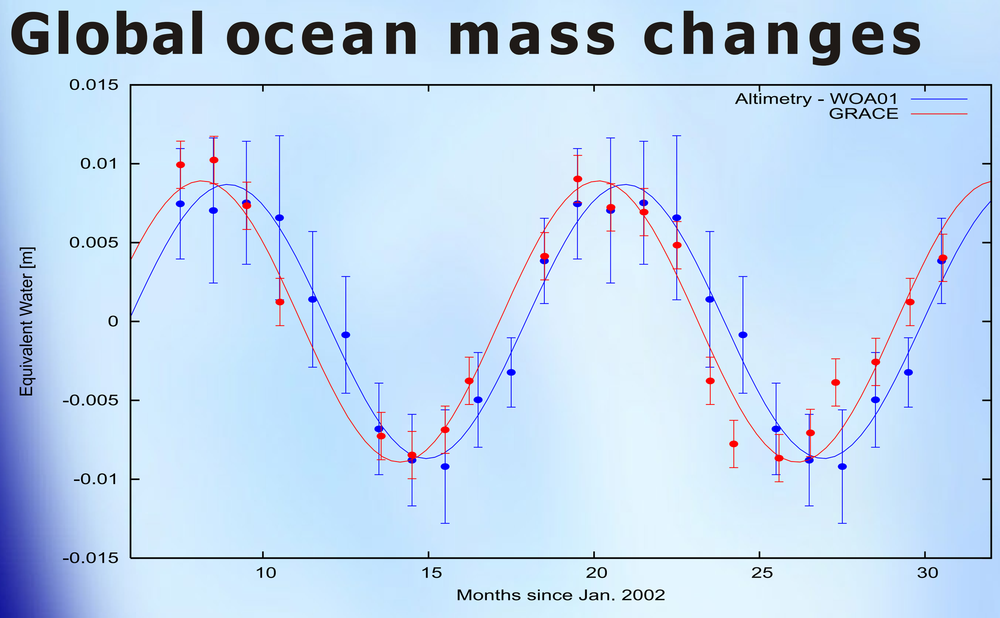
WOA01 - (Altimetry - GRACE): mean variance 7.6 cm²





Applied Corrections:
In order to reconcile the altimetry and GRACE data sets, various corrections have been applied to the GRACE data before converting to equivalent water level; an ocean pole tide correction, based on the self-consistent, mass conserving model of Desai (2002) was subtracted; the background ocean-atmosphere model - removed during the processing of the raw GRACE data to prevent aliasing - was added back, and, as mentioned before, the J2 values were replaced by estimates from GPS/GRACE. Furthermore a geocenter correction was applied to the GRACE solutions (see below).

Global ocean mass changes



To assess the global performance of GRACE over the ocean, we first look at annual mass changes. The monthly GRACE gravity solutions are converted to equivalent water level and compared with values from JASON-1 corrected for steric expansion using the WOA01 climatology, giving the global mean eustatic sea level signal. A cosine function with an annual frequency has been fit tot both time series. This yields an amplitude of 8.4 ± 1.1 mm and a phase of 244°±9° for the GRACE data (red line) and an amplitude of 8.6± 0.6 and phase of 274°± 5° for the steric corrected altimetry data (blue line). The two signals agree very well, considering the fact that the GRACE and altimetry data are influenced by interannual variations whereas the WOA01 data is not. Despite this, the amplitudes and phases are consistent, indicating that both observations techniques are measuring the same mass variations and that the GRACE satellites are capable of observing real ocean mass variations, at least on a global scale.

Geocenter correction

The GRACE mission is based on measurements of changing distances between two satellites, which can be related to the Earth's geopotential. Since a change of the geocenter position - defined as the position of the center of mass of the Earth with respect to it's figure - will affect the orbit of both satellites in an identical way (i.e. without changing the intersatellite distance), GRACE is insensitive to these variations, whereas altimetry is not. To reconcile the two data sets, one of the two has to be corrected for this phenomena. Since changes in the geocenter can be easily related to changes in the degree 1 coefficients of the geopotential, we choose to apply the correction to GRACE. Several available geocenter models have been tested, based on either satellite laser ranging (SLR), GPS or geophysical models. Some of the results are shown in the table below. Generally speaking, inclusion of the geocenter correction decreases the mean variance of the difference with the WOA01 reference data. Models based on SLR tend to perform best, with a minimum variance of 7.6 cm² for the Lageos model of Cretaux (2002). GPS based models perform less well, which can be attributed to the larger estimated amplitudes.

Model	Source	x-ampl	y-ampl	z-ampl	x-phase	y-phase	z-phase	variance
SLR Lageos	Cretaux et al ., 2002	1.1	2.5	3.3	16	292	57	7.6
SLR/DORIS	Eanes, 2000	1.9	2.9	2.8	44	320	41	7.5
SLR Lageos	Bouille et al., 2000	2.1	2	3.5	48	327	43	8.2
GPS	Dong et al, 2003	2.1	3.3	7.1	46	333	38	12.2
Geophys. Mod	Chen et al, 1999	2.4	2	4.1	26	0	43	8.8
Geophys. Mod	Cretaux et al., 2002	1.2	1.2	1.9	350	313	57	7.1
No geocenter correction	-	-	-	-	-	-	-	9.1

Furthermore, we constructed a geocenter model that reduces the variance in a least square sense, using the Levenberg-Marquardt method. This results in values close to those from SLR observations, as can be seen below. The mean variance reduces to 5.9 cm²

	x-ampl	y-ampl	z-ampl	x-phase	y-phase	z-phase	variance
Least-squares minimization	1.2 +/- 0.2	3.0+/- 0.3	3.2+/- 0.2	16+/- 5	341+/- 4	42+/- 8	5.9

Conclusion

This study indicates that GRACE is capable of measuring seasonal mass variations in the ocean on a global scale. Global amplitude and phase of mass changes compare well with values obtained from altimetry corrected for steric expansion. Combining the GRACE data with Jason-1 observations leads to better estimates of steric sea level changes, also on local scales: including GRACE data reduces the variance of the difference with a reference climatology (WOA01). However, care has to be taken that the altimetry and GRACE data are reconciled properly. Using the original GRACE J_2 values leads to a mainly zonal signal in the mass changes, a feature which disappears when using values based on a joint inversion of GRACE and GPS data. Furthermore, a geocenter correction should be aplied to make the two data sets consistent. Several geocenter models are available, of which models based on SLR measurements perform best. A least square method minimizing the variance as function of the geocenter parameters results in values close to those based on SLR.

References:
- Chambers D. P., J. Wahr, R. S. Nerem, Preliminary observations of global ocean mass variations with GRACE, Geophys. Res. Lett., 31, L13310, 2004.
- Chambers D. P., Observing seasonal steric sea level variations with GRACE and satellite altimetry, J. Geophys. Res., 111, C03010, 2006.
- Desai S. D., Observing the pole tide with satellite altimetry, J. Geophys. Res., 107 (C11), 3186, 2002.
- Kusche J., E. J. O. Schrama, Surface mass redistribution inversion from global GPS deformation and Gravity Recovery and Climate Experiment (GRACE) gravity data, J. Geophys. Res., 110, B09409, 2005.

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