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GRACE estimates of sea surface height anomalies in the Gulf of Carpentaria, Australia

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ABSTRACT

The Gulf of Carpentaria in northern Australia has a weather-driven annual periodic amplitude in sea surface height of ~0.4 m. Such a signal generates a mass variation that is readily detected by the GRACE mission. We used this naturally occurring phenomenon over a region of ~2.6×10^5 km^2 to evaluate the accuracy of the GRACE estimates of temporal mass variation. Comparison of the Groupe de Recherche de Géodesie Spatiale 10-day GRACE solutions and observations from a nearby tide gauge show a correlation of 0.93, indicating that the GRGS GRACE solutions capture well the regional signal. On the other hand, the MOG2D-G barotropic model accounts for only ~50% of the non-gravitational annual signal, suggesting either deficiencies in the model or that some other non-barotropic process is occurring.

1. Introduction

The Gravity Recovery and Climate Experiment (GRACE) satellite gravity mission has produced spectacular results in terms of improving global gravity models and detecting temporal changes in the Earth's gravity field. Launched in 2002 (Tapley et al., 2004), data from the mission has been used for studying hydrologic signals (e.g. Ramillien et al., 2004), glacial isostatic adjustment (e.g. Tamisiea et al., 2007), ice mass balance studies (e.g. Chen et al., 2006a; Velicogna and Wahr, 2006; Ramillien et al., 2006) and, in conjunction with satellite altimetry, for studying steric sea level variations (Garcia et al., 2007).

In many cases, there is no independent estimate of the geophysical process of interest against which to compare the GRACE estimate. Rietbroek et al. (2006) compared ocean mass estimates in the Crozet–Kerguelen region with ocean bottom pressure records and found correlations of 0.7–0.8. Ponte et al. (2007) compared GRACE estimates with bottom pressure values from the ECCO project (Wunsch and Heimbach, 2007) and found 'good agreement' over the Southern Ocean at annual and semi-annual periods. Vaz et al. (2007) compared basin-scale estimates of mass variations – in terms of equivalent water height – with river gauges and found that scaling factors were necessary to equate the two estimates; however, this is almost certainly related to the small spatial scale of the river drainage basins being undetectable by GRACE.

In this study, we have made use of a naturally occurring, large-amplitude variation in ocean mass in the Gulf of Carpentaria to assess the accuracy of estimates of mass variations (Fig. 1). Forbes and Church (1983) demonstrated the annual variations in sea surface heights in the Gulf based on observations of currents and sea surface heights from sea bed drifters and buoys. The largest annual range of monthly mean sea level estimates in the Gulf is 75 cm in the southeast corner (Forbes and Church, 1983). 70% of the observed variations could be accounted for by the cumulative effects of atmospheric pressure, winds and steric variations.

Given that the analysis of GRACE data is expected to have an accuracy of ~20–30 mm equivalent water height when a Gaussian filter of radius 750 km is used (Wahr et al., 2006; Chen et al., 2006b), the annual signals should be readily detectable. The presence of a tide gauge on Groote Eylandt on the western side of the Gulf provides an independent measure of the magnitude of the non-tidal ocean variations against which the GRACE estimates can be validated.

The majority of studies to date using GRACE data have used the solutions from the Center of Space Research (CSR) (e.g. Velicogna and Wahr, 2006; Chen et al., 2006a) or from GeoForschungsZentrum (GFZ) (e.g. Reigber et al., 2005). These solutions are known to have high levels of noise in the higher-degree coefficients of the spherical harmonic representations of the gravity field and statistical techniques for reducing the contribution of the noise have been invoked (e.g. Wahr et al., 2006). Additionally, off-diagonal correlations between coefficients generate a north–south striping effect that

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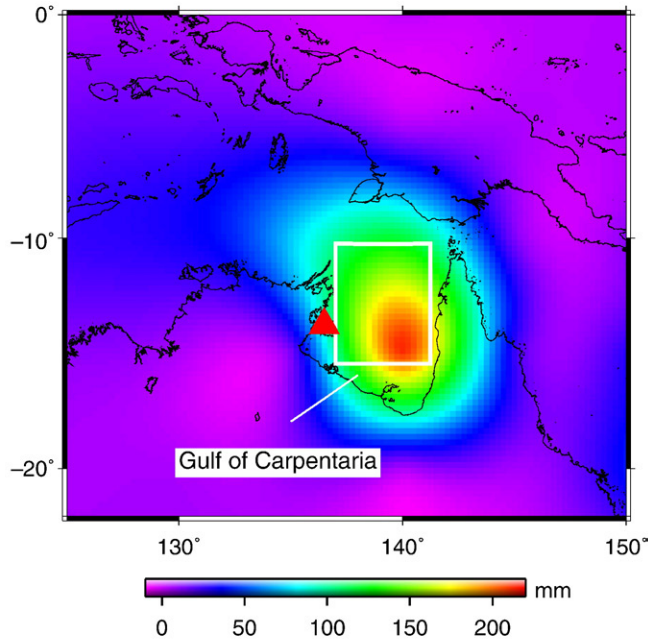

Fig. 1. Amplitude of the annual variation of the MOG2D-G model (2002.0 to 2007.5) in the Gulf of Carpentaria as a degree 100 spherical harmonic representation. The kernel region for the GRACE study is shown in white and the location of the Groote Eyrlandt tide gauge is indicated (triangle).

must be removed before the remaining signals can be interpreted geophysically (Swenson and Wahr, 2006).

The Groupe de Recherche en Géodesie Spatiale (GRGS) produce GRACE solutions using a strategy that imposes constraints on the permitted deviation of higher-degree coefficients from a mean gravity field (Lemoine et al., 2007) and choose to limit the degree of their solutions to degree 50 (CSR and GFZ RL04 solutions are provided to degree 100). The GRGS solutions do not suffer from the striping effect seen in the CSR/GFZ solutions, nor is there any need to invoke a Gaussian smoothing filter to reduce the noise of higher-degree coefficients (Lemoine et al., 2007). Sasgen et al. (2006) compared the four available GRACE solutions and concluded that the GRGS solutions matched more closely the predicted glacial isostatic adjustment signal for Antarctica.

In this study we used the GRGS solutions from 2002 to mid-2007. A full description of the analysis strategy is given in Lemoine et al. (2007); we mention here only that the non-tidal oceanic variations are removed from the GRACE solutions in the reduction of the K-band range rate observations using the barotropic model, MOG2D-G, of Carrère and Lyard (2003). This model is driven by the wind stress and atmospheric pressure variations from the global weather model of the European Center for Medium-range Weather Forecasts (ECMWF).

The Gulf of Carpentaria region has the largest amplitude non-tidal annual variations in the MOG2D-G model (we used data from 2002–2007 to compute annual amplitudes on a global 5° grid) but is thought to be poorly modelled due to the poor spatial resolution of the bathymetry used for the region (F. Lyard, pers. comm., 2007). Fig. 1 shows the amplitude of the annual variation of sea surface height from the MOG2D-G model. The maximum modelled amplitude in the Gulf of Carpentaria is ~0.2 m.

2. GRACE data

The GRGS analyse K-band range rate observations using the CNES/GRGS dynamo software to generate 10-day normal matrices. They then construct temporal gravity solutions by accumulating three consecutive 10-day matrices, applying double the weight to the central matrix (Lemoine et al., 2007). We computed the mean gravity field of the 10-day sliding window solutions of GRGS for the period 2002.6 to 2007.5 to generate coefficients that represented gravity anomalies about the mean value. We defined a kernel for a rectangular region in the Gulf – containing no land – with a spherical harmonic representation, then calculated the integrated mass variations within this region in terms of equivalent water height according to (e.g. Ramillien et al., 2006):

$$\delta\Psi(t) = 4\pi R^2 \sum_{n=1}^{N} \sum_{m=0}^{n} \{A_{nm}\delta C_{nm}(t) + B_{nm}\delta S_{nm}(t)\} \quad (1)$$

where A_{nm} and B_{nm} are the fully-normalised harmonic coefficients of the geographical region mask, and $\delta C_{nm}(t)$ and $\delta S_{nm}(t)$ are the time-varying GRACE harmonic coefficients in units of surface mass density:

$$\begin{pmatrix} \delta C_{nm}(t) \\ \delta S_{nm}(t) \end{pmatrix} = \left[\frac{4\pi G \rho_w R^2}{(2n+1)\gamma}(1+k'_n)\right]^{-1} \times \begin{pmatrix} \delta U_{nm}(t) \\ \delta V_{nm}(t) \end{pmatrix} \quad (2)$$

where n and m are the harmonic degree and order, δU_{nm} and δV_{nm} are the residual Stokes coefficients after removing a mean over the period 2002.6 to 2007.5, k'_n is the elastic Love number of degree n, R is the mean radius of the Earth (6371 km), γ is the mean gravity acceleration (9.81 m/s^2), G is the gravitational constant (6.673 × 10^{-11} m^3 kg^{-1} s^{-2}) and ρ_w is the mean density of sea water (1030 kg/m^3).

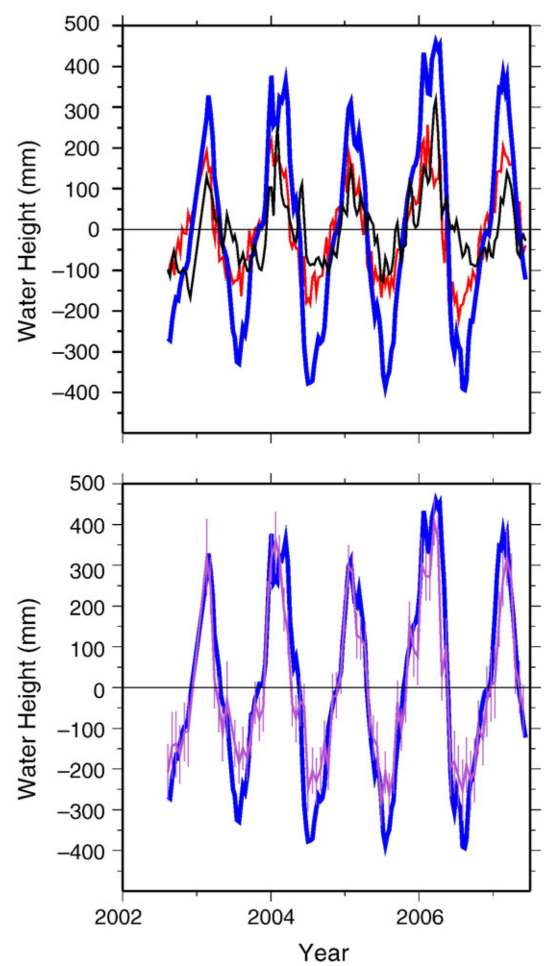

Fig. 2. a) Time series of tide gauge observations of sea surface height anomalies (blue), barotropic anomalies (red) and GRACE estimates (with barotropic model removed) (black). b) Comparison of the tide gauge observations and GRACE estimates (barotropic model restored) with 1σ error bars (purple). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The GRACE satellites orbit around the centre of mass of the solid Earth plus the fluid envelope; therefore, GRACE estimates of gravity anomalies are insensitive to the degree-1 deformations and origin translations between the centre of mass of the solid Earth and the total Earth. However, a tide gauge connected to the solid Earth measures changes in ocean height that include degree-1 effects. We used the periodic estimations of Munekane (2007) – derived from a combination of GPS deformations and GRACE estimates of higher-degree loading effects – to insert the degree-1 spherical harmonic coefficients into the GRACE solutions, placing them in the same reference frame as tide gauge estimates of sea surface height and thus making them directly comparable.

3. Results

The resulting time series of sea surface height anomalies is shown in Fig. 2a, along with the corresponding estimates from the tide gauge observations (we removed a mean value from the tide gauge data, calculated over the period 2002.6 to 2007.5). Since there is no land within the kernel region, the only geophysical phenomenon that can conceivably cause a mass variation is the non-tidal movement of the ocean. The GRACE estimates already have the barotropic signal removed, using the MOG2D-G model; therefore, if the barotropic model was complete and accurate the sea surface height variations estimated from GRACE would be zero. The GRACE estimates (with the barotropic model removed) do vary significantly and are in phase with the tide gauge estimates, although the amplitude is considerably smaller (about 50%). The fact that there is a residual annual variation indicates either a deficiency in the MOG2D-G model or that some non-barotropic process is occurring that is causing a change in mass in the Gulf.

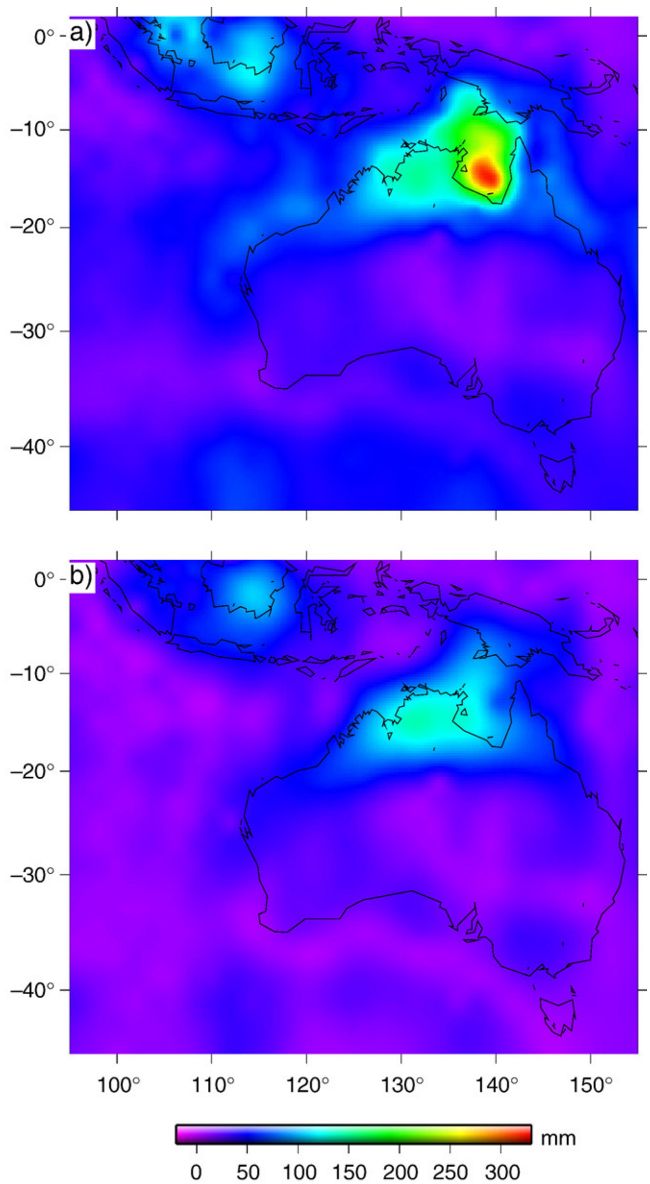

Fig. 3. a) Amplitude of annual variations (equivalent water height) in the Australian region for the sum of GRACE and MOG2D-G. This represents the total long-period oceanic signal that is seen by the GRACE satellites. b) GRACE estimates (GRGS) after the removal of the barotropic model.

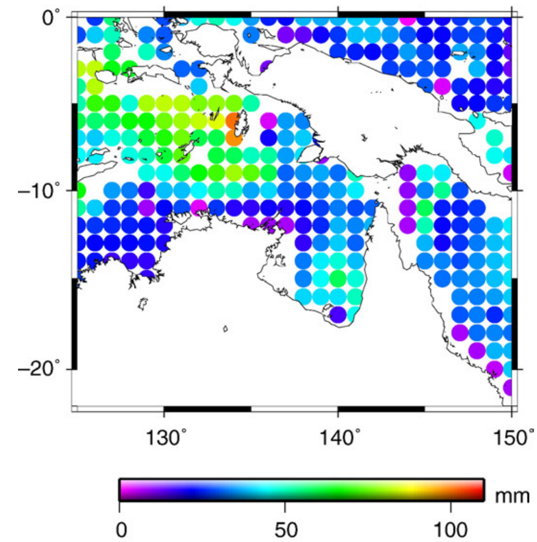

Fig. 4. Amplitude of annual steric variations.

We reinserted the MOG2D-G modelled signal for non-tidal ocean movement and compared the GRACE+barotropic estimate with the tide gauge values (Fig. 2b). There is good agreement, both in terms of amplitude and phase, with a correlation of 0.93. A least-squares estimate of a scaling factor to best super-impose the two curves yields a value of 1.18. Applying this scaling factor to the GRACE estimates reduces the RMS by only ~7% and we do not consider this to be a significant improvement. The GRGS GRACE solutions do not require the upscaling that has been suggested necessary for the CSR solutions (e.g. factor of 1/0.62 by Velicogna and Wahr, 2006).

We also calculated the amplitude of annual variations of the reconstituted GRACE estimates (i.e. including the MOG2D-G component) for the Australian region (Fig. 3a). The notable hydrologic signals in the region are in the Northern Territory south to ~S18° (amplitude ~150 mm) and an annual variation in southern Borneo (amplitude ~120 mm). The non-gravitational oceanic mass variations in the Gulf of Carpentaria are more than double the magnitude of the hydrologic variations and are the dominant signals in the entire region (Fig. 3).

4. Discussion

The GRACE+MOG2D-G estimates of sea surface height variations are of the same magnitude as derived from tide gauge observations at Groote Eylandt. This demonstrates that the estimation and stabilisation process by the GRGS GRACE team does not need any additional scaling and/or filtering prior to interpreting the observed geophysical signals in the Australian region.

Significant ocean mass variations remain in the GRACE estimates after the barotropic effects modelled by the MOG2D-G model are removed. Assuming that all the observed mass variations are barotropic in origin, the MOG2D-G model underpredicts the amplitude of the variations in the Gulf of Carpentaria by ~50%. The modelled barotropic variations between Java and the northwest coast of Australia have an amplitude of ~30–50 mm but the GRACE-alone estimates of annual signals between Java and the northwest coast of Australia suggest that there may be an additional 20–40 mm annual amplitude (Fig. 3b) that is not modelled in MOG2D-G. Similar annual variations are seen in the GRACE-alone results to the east of Cape York in the Gulf of New Guinea.

Landerer et al. (2007) demonstrated that net mass transfers could occur between shallow and deep zones as a result of steric changes in the oceans. Essentially, the increase in sea surface height in deep regions can be larger than nearby shallow regions, with the difference being the expansion in the layer below the maximum depth of the shallow region. The additional deep-water expansion then flows into shallow regions, resulting in a mass gain there and a mass loss in the deep regions. Such a mechanism might explain the annual mass variation that remains in the GRACE solutions once the MOD2D-G model has been removed. Fig. 4 shows the annual amplitude of steric variations from the model of Ishii et al. (2006). There are typically <5 observations/month in the Gulf and in the region immediately beyond in the Arafura Sea and the Torres Strait. It is beyond the scope of this study to assess whether possible net mass transfer from steric effects might explain the mass variations observed by GRACE.

The observation of non-gravimetric periodic signals from GRACE presents the possibility of improving the accuracy of barotropic/baroclinic models of ocean variability. In the Australian region, the magnitude of the unmodelled component of the annual variation is typically 100–150% of the modelled values.

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