



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 $\sim 2.6 \times 10^5$ km² 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.

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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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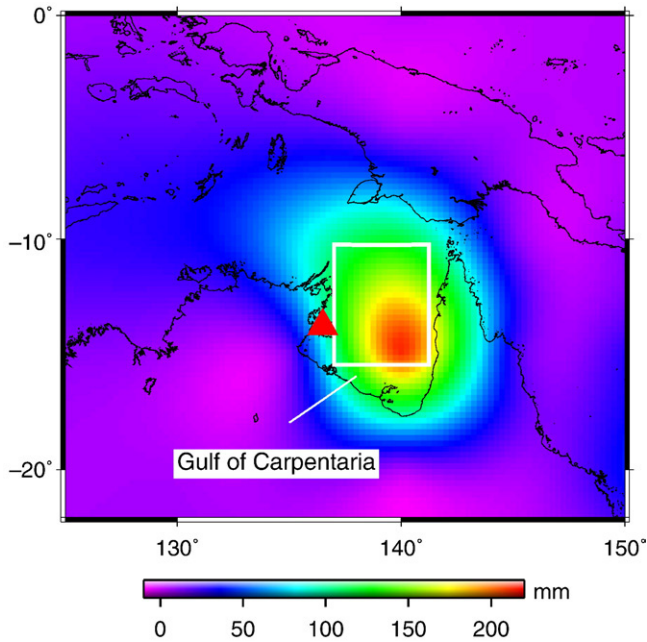


Fig. 1. Amplitude of the annual variation of the MOG2D-G model (2002.0 to 2007.5) in the Gulf of Carpentaria as a degree 100 spherical harmonic representation. The kernel region for the GRACE study is shown in white and the location of the Groote Eylandt tide gauge is indicated (triangle).

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

The Groupe de Recherche en Géodésie 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 ($6.673 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$) and ρ_w is the mean density of sea water (1030 kg/m^3).

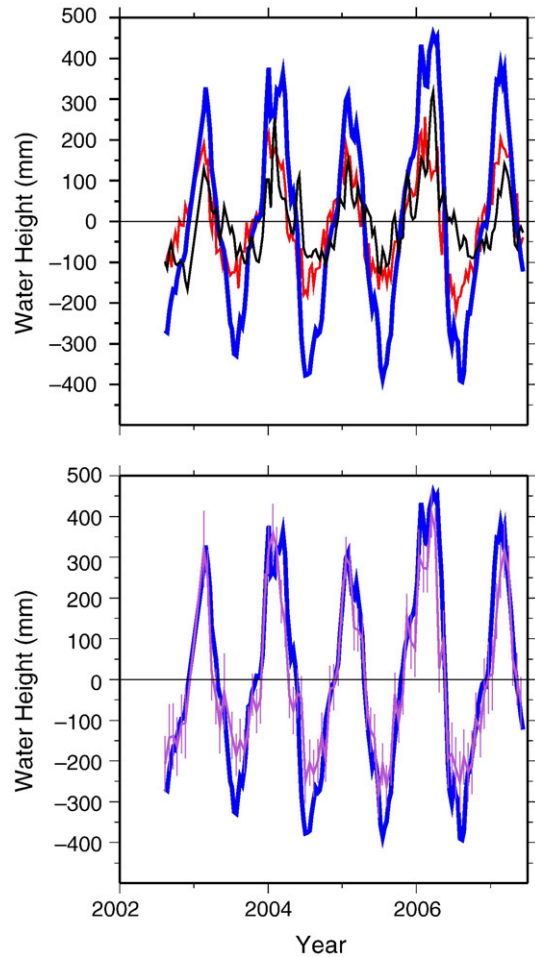


Fig. 2. a) Time series of tide gauge observations of sea surface height anomalies (blue), barotropic anomalies (red) and GRACE estimates (with barotropic model removed) (black). b) Comparison of the tide gauge observations and GRACE estimates (barotropic model restored) with 1σ error bars (purple). (For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

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