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Closure of the budget of global sea level rise over the GRACE era: the importance and magnitudes of the required corrections for global glacial isostatic adjustment

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ABSTRACT

The budget of global sea level rise includes contributions from several distinct factors, including thermosteric effects, the wasting of small ice sheets and glaciers, and the loss of mass by the great polar ice sheets and by the continents due to desiccation. Since the former contribution may be estimated on the basis of both hydrographic survey data and more recently using Argo float data, the second may be estimated on the basis of mass balance measurements on existing ice-fields, and the latter on the basis of modern GRACE-based time dependent gravity field measurements, the inputs to the globally averaged rate of sea level rise may be directly constrained. Since GRACE also provides a measurement of the rate at which mass is being added to the oceans, we are now in a position to ask whether this rate of mass addition to the oceans matches the rate at which mass is being removed from the continents. As demonstrated herein, the mass component of the budget of global sea level is closed within the observational errors. When the mass-derived contribution is added to the thermosteric contribution it is furthermore shown that the inference of the net rate of global sea level rise by the altimetric satellites Topex/Poseidon and Jason 1 is also reconcilable over the GRACE era. It is noted those individual terms in the budget, especially the contribution from small ice sheets and glaciers, remains insufficiently accurate. It is demonstrated that the lingering influence of the Late Quaternary ice-age upon sea level is profound and that closure of the budget requires an accurate model of its impact.

1. Introduction

Although it has been well understood for some time that modern measurements of the rate of sea level rise are significantly contaminated by the influence of the ongoing process of glacial isostatic adjustment (GIA) due to the most recent deglaciation event of the Late Quaternary ice-age, a systematic assessment of this influence upon modern space-based measurements has been lacking. Insofar as surface tide gauge data are concerned, it has been clear since the analyses of Peltier (1986), Peltier and Tushingham (1989) and Peltier (2002) that such contamination was highly significant, at least regionally, not only in the specific regions that were once ice covered, but also in locations both immediately peripheral to and well removed from these regions. When GIA contamination was eliminated from annually averaged long tide gauge records from the permanent service for mean sea level (PSMSL), an average rate of global sea level rise of approximately 1.84 mm/year was inferred to have been operating over the post war period (Peltier, 2002).

Insofar as the contamination of modern space-based measurements of the rate of global sea level rise is concerned, the first demonstration that a correction must be applied to Topex/Poseidon derived altimetric measurements was demonstrated in Peltier (2002). Using the ICE-4G (VM2) model of the GIA process described in Peltier (1994, 1996), analysis demonstrated that such measurements would be biased down by approximately 0.3 mm/year, meaning that the global rate of sea level rise measured by such altimetric satellites would be an underestimate of the rate due to modern greenhouse gas induced global warming by this amount. In the 4th Assessment Report of the IPCC (2007) the altimetric satellite-based inference is reported to be approximately 3.1 mm/year when account is taken of this downward bias (e.g. see Cazenave and Nerem, 2004). This is a significant increase over the earlier tide gauge derived estimate, implying that, insofar as the impact of global warming upon global sea level rise is concerned, this impact appeared to be accelerating.

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Although significant progress in achieving closure of the sea level budget is suggested to have been achieved in the IPCC AR4, there remained large, though weakly overlapping, error bars on the net rate of sea level rise observed altimetrically and the sum over the individual contributions mentioned in the abstract of this paper. Since launch of the GRACE satellites in March 2002 and the beginning of the subsequent period from which useful data is available, however, there has existed a promise that the time dependent global gravity field data that GRACE is delivering would be able to provide much increased leverage on this problem that would enable us to significantly reduce the error bars on each of the contributions involving the loss of mass from the continents and enable us to compare the sum of these contributions to the net increase of mass over the ocean basins. The purpose of this paper is to provide an assessment of the extent to which closure of the budget has been enabled by GRACE observations. The analyses to be presented build upon the similar analysis recently published by Cazenave et al. (2008). As will be shown, however, the new results to be reported here differ in certain respects from those provided in this recent paper.

The success of this analysis will depend strongly upon the accuracy with which we are able to estimate both the rate of mass loss from the continents and the rate of mass gain by the oceans. Since both the rates of mass loss by the great polar ice sheets and the rate of mass gain by the oceans may be strongly contaminated by the GIA process, the success of such analysis will also depend upon the availability of a demonstrably accurate model of this process. In the work to be presented herein, the ICE-5G (VM2) model of this process (Peltier, 2004) will be primarily employed for the purpose of "decontaminating" the contributions to the modern budget due to ice-age influence. This model has the advantage that it has been verified as accurate by the GRACE satellite observations of the ongoing glacial rebound of the North American continent caused by the deglaciation of the Laurentide, Innuitian and Cordilleran ice sheets that began following Last Glacial Maximum approximately 21,000 years ago (Paulson et al., 2007; Peltier, 2007b; Peltier and Drummond, 2008). Although further refinements of this model are possible and are being pursued in the process of producing further improvements for possible use in the context of the continuing Paleoclimate Model Intercomparison Project (PMIP, see http://www-lsce.cea.fr/pmip2), it is expected that the existing model will provide a useful preliminary basis for the analyses to be presented herein.

In the next section of this paper the theory to be employed to provide the required GIA corrections for GRACE data as well as altimetric satellite data will be discussed in detail. Section 3 will document the analysis procedures to be applied to the GRACE observations. In Section 4 the use of these observations to provide best estimates of the rates of loss of land ice is discussed. Section 5 discusses the implications for understanding the mass component of the budget of global sea level rise and conclusions are offered in Section 6.

2. Satellite data decontamination of Late Quaternary ice-age influence

The detailed theory of the glacial isostatic adjustment process has been fully reviewed recently in Peltier (2007b) and no purpose will be served by providing a re-capitulation here. The primary construct of the theory is the so-called sea level equation (SLE), solutions of which consist of predictions of the history of relative sea level produced by an assumed known history of continental glaciation and deglaciation. In this theory, sea level is taken to be instantaneously defined by the surface of constant gravitational potential which would best fit the actual surface of the sea in the absence of ocean currents and tides. If we denote by $S(\theta, \lambda, t)$ the height of this surface of constant gravitational potential with respect to the time dependent surface of the solid Earth, the prediction of its evolution takes the form:

$$S(\theta, \lambda, t) = C(\theta, \lambda, t) \times \left[\int_{-\infty}^{t} \mathrm{d}t' \iint_{\Omega} d\Omega' \left\{ L(\theta', \lambda', t') G_{\varphi}^{L}(\varphi, t-t') + \Psi^{R}(\theta', \lambda', t') G_{\varphi}^{T}(\varphi, t-t') \right\} + \frac{\Delta\Phi(t)}{g} \right]. \tag{1}$$

In this integral equation θ, λ, and t are latitude, longitude and time respectively, $\mathrm{d}\Omega'$ is an element of surface area, C is the space and time dependent "ocean function" which is unity over the surface of the oceans and zero elsewhere, L is the surface mass load per unit area which contains both ice and water contributions as:

$$L(\theta, \lambda, t) = \rho_I \, I(\theta, \lambda, t) + p_w \, S(\theta, \lambda, t). \tag{2}$$

In Eq. (2) ρ_I and ρ_w are the densities of ice and water respectively and I is the space and time dependent thickness of grounded ice on the continents. Because L also involves S as in Eq. (2), Eq. (1) is an integral equation (of Fredholm type). Also in Eq. (1) Ψ^R is the variation of the centrifugal potential of the planet due to the change in its rotational state caused by the glaciation–deglaciation process. The functions G_ϕ^L and G_ϕ^G are visco-elastic Green functions for surface mass and tidal potential loading respectively. The final time dependent and space independent term in Eq. (1), $\Delta\Phi(t)/g$, is a correction that must be added to the right-hand-side of Eq. (1) in order to ensure that there is precise balance between the time dependent mass lost (or gained) from (by) the continents and the time dependent gain (or loss) of mass by the oceans. The methodology employed for the solution of Eq. (1) has been reviewed in Peltier (1998, 2005) and is an iterative method in which the fields are expressed as truncated spherical harmonic expansions. I first neglect the influence of rotational feedback by dropping the convolution of Ψ^R with G_ϕ^T from the integrand in Eq. (1). Given the initial result for "S" obtained by solving Eq. (1) subject to this first approximation, a first approximation for Ψ^R may be computed following Dahlen (1976) as:

$$\Psi^R(\theta, \lambda, t) = \Psi_{00} Y_{00}(\theta, \lambda, t) + \sum_{m=-1}^{+1} \Psi_{2m} Y_{2m}(\theta, \lambda, t) \tag{3}$$

with

$$\Psi_{00} = \frac{2}{3}\omega_3(t)\Omega_o a^2 \tag{4a}$$

$$\Psi_{20} = -\frac{1}{3}\omega_3(t)\Omega_o a^2 \sqrt{4/15} \tag{4b}$$

$$\Psi_{2,-1} = \left(\omega_1^{(t)} - i\omega_2^{(t)}\right)\left(\Omega_o a^2/2\right)\sqrt{2/15} \tag{4c}$$

$$\Psi_{2,+1} = -\left(\omega_1^{(t)} + i\omega_2(t)\right)\left(\Omega_o a^2/2\right)\sqrt{2/15} \tag{4d}$$

Eq. (1) is then solved again using this first approximation to the feedback term and the iterative process so defined is continued until convergence is achieved to within a specified tolerance. Typically only a few iterations are necessary and the calculation is highly efficient. For the purpose of the analyses to be presented in this paper, it will turn out that the influence of rotational feedback on the solutions to Eq. (1) is important. Insofar as the understanding of ^{14}C dated relative sea level histories from the Holocene interval of Earth history are concerned, it has already been shown (Peltier, 2002, 2004, 2005, 2007a) that, in the absence of this influence, a large volume of such data would be inexplicable. With it, however, the records are well explained.

In order to compute the contribution of the GIA process to the time dependence of the gravitational field as this is measured by the GRACE satellites, we simply add to the predicted global field $S(\theta, \lambda, t)$ the theoretical prediction of the variation of the local radius of the planet with respect to the center of mass. This field is computed using the expression (e.g. Peltier, 2004):

$$U(\theta,\ \lambda,\ t)\ =\ \sum_{\ell=o}^{\infty}\ \sum_{m=-\ell}^{+l}\left[\frac{4\pi a^3}{(2\ell+1)_{m_e}}\left(L_{\ell m}h_\ell^{E,L}+\sum_{k=1}^{k(\ell)}q_k^\ell\beta_{\ell m}^k\right)\right. \\ \left.+\frac{4\pi}{(2\ell+1)g}\left(T_{\ell m}h_\ell^{E,T}+\sum_{k=1}^{k(\ell)}q_k^{1\ell}\beta_{\ell m}^{1k}\right)\right]Y_{\ell m} \tag{5}$$

In Eq. (5) "a" and m_e are the mean radius and mass of the Earth, $L_{\ell m}$ and $T_{\ell m}$ are the spherical harmonic coefficients in the expansions of the surface mass and centrifugal potential loads, the $h_\ell^{E,L}$ and $k_\ell^{E,T}$ are the elastic asymptotes of the radial displacement Love numbers for surface mass and tidal potential loading (Peltier, 1974) and the β parameters are as defined in Wu and Peltier (1982) as:

$$\beta_{\ell m}^k\ =\ \int_{-\infty}^{t}\ L_{\ell m}(t)\ \mathrm{e}^{-s_k^l(t-t')}\ \mathrm{d}t' \tag{6a}$$

$$\beta_{\ell m}'k\ =\ \int_{-\infty}^{t}\ L_{\ell m}(t)\ \mathrm{e}^{-s_k^l(t-t')}\ \mathrm{d}t' \tag{6b}$$

Given $S(\theta, \lambda, t)$ from Eq. (1) and $U(\theta, \lambda, t)$ from Eq. (5) we may then compute the time rate of change of geoid height caused by the glaciation–deglaciation process as (Peltier, 2005):

$$\frac{\mathrm{d}G}{\mathrm{d}t}=\frac{\mathrm{d}S(\theta,\ \lambda,\ t)}{\mathrm{d}t}+\frac{\mathrm{d}U(\theta,\ \lambda,\ t)}{\mathrm{d}t} \tag{7}$$

The Stokes coefficients that represent this time rate of change of geoid height are simply determined from the expression:

$$\dot{G}(\theta,\ \lambda,\ t)\ =\ \sum_{\ell=o}^{\infty}\ \sum_{m=-\ell}^{+\ell}\ \dot{G}_{lm}Y_{\ell m}(\theta,\ \lambda) \tag{8}$$

or equivalently, with $\dot{C}_{\ell m}$ and $\dot{S}_{\ell m}$ the rates of change of the conventional Stokes coefficients, by:

$$\dot{G}(\theta,\ \lambda,\ t)\ =\ \sum_{\ell=o}^{\infty}\ \sum_{m=o}^{\ell}\ (\dot{C}_{\ell m}\cos(m\lambda)+\dot{S}_{\ell m}\sin(m\lambda))P_{\ell m}, \tag{9}$$

where it is important to notice in Eq. (9) that the normalization condition employed to define the spherical harmonics must be adjusted to correspond to the fully normalized forms employed in the reduction of the GRACE observations themselves.

3. GRACE data analysis: testing the validity of the ICE-5G (VM2) model

For the purpose of the majority of the analyses to be discussed, I will primarily employ the RL04 release of data from the Centre for Space Research (CSR) at the University of Texas in Austin, but these will be compared, where it is helpful to do so, with those from the Geoforshung Zentrum (GFZ) in Potsdam, Germany. The data processing procedure applied to this Level 2 data set involves the following sequence of steps:

(i) The data are downloaded from http://podaac.jpl.nasa.gov/grace/data_access.html.
(ii) The geoid height Stokes coefficients are converted to mass-rate coefficients through the operation (e.g. see Swenson and Wahr, 2006):

$$(C_{\ell m},\ S_{\ell m})_{\text{mass}}=(C_{\ell m},\ S_{\ell m})_{\text{geoid}}\left(\rho_{\text{avg,earth}}/\rho_{\text{water}}\right) \\ \left[\frac{(2\ell+1)}{3\left(1+k_\ell^E\right)}\right] \tag{10}$$

(iii) The correlated-error filter of Swenson and Wahr (2006) is applied to smooth the coefficients of order m with a quadratic polynomial in degree ℓ with a moving window of width 6. The filter is applied only for order $m>8$ as suggested. After smoothing, the coefficients are converted back from mass-rate coefficients to geoid rate coefficients.
(iv) Each discrete time series of monthly Stokes coefficients is fit by least squares to a function consisting of a constant bias plus a linear trend plus three periodic components consisting of a unique amplitude and phase for each having periods of 365.25, 182.625, and 161 days. This is therefore an eight term fit.
(v) The coefficient of the linear term is employed to define the secular rate of change of each Stokes coefficient.
(vi) Normally the coefficients must be corrected before comparison with the results of the GIA theory by removing the influence of surface hydrology. This is done using the equivalent secular rate of change of the mass-rate Stokes coefficients for the period April 2002–December 2006 produced by the Global Land Data Assimilation Scheme (GLDAS) as described in Rodell et al. (2004) (personal communication from John McCarthy).
(vii) Once this influence is eliminated, the resulting field is normally smoothed by application of a Gaussian filter of half width 300–500 km as described in Wahr et al. (1998). It is important for most applications that the theoretical prediction of both the GIA and hydrology models be similarly filtered.

In order to begin to fix ideas, Fig. 1a shows the global surface mass-rate reconstruction based upon the new analysis of GRACE data based upon the RL04 data set from the Centre for Space Research which has been analysed using a two term fit only of the data for the period April 2002 to December 2006. A Gaussian filter of half width 400 km has been employed to smooth this data set.

In Fig. 1b is shown the secular variation in surface mass-rate due to hydrology according to the GLDAS model of Rodell et al. (2004). Inspection of this plate of the figure will show that the signal over the continents is predominantly negative, indicating that, over the GRACE period at least, the continents have been losing water to the oceans and thus contributing to the rate of global sea level rise. The third frame of Fig. 1c, shows the global difference between GRACE and GLDAS, demonstrating that the dominant high latitude signals may be significantly influenced by the hydrology correction. This is certainly not a negligible effect over Alaska for example. Far more important, however, is the impact of the GLDAS correction over the Canadian land mass. In this region, application of the correction modifies the raw GRACE signal in such a way as to convert a single north west–south east trending elliptical anomaly into an anomaly having two independent centers, one to the west of Hudson Bay and one over the James Bay region. This is extremely important as the prediction of the ICE-5G (VM2) model of the GIA process is

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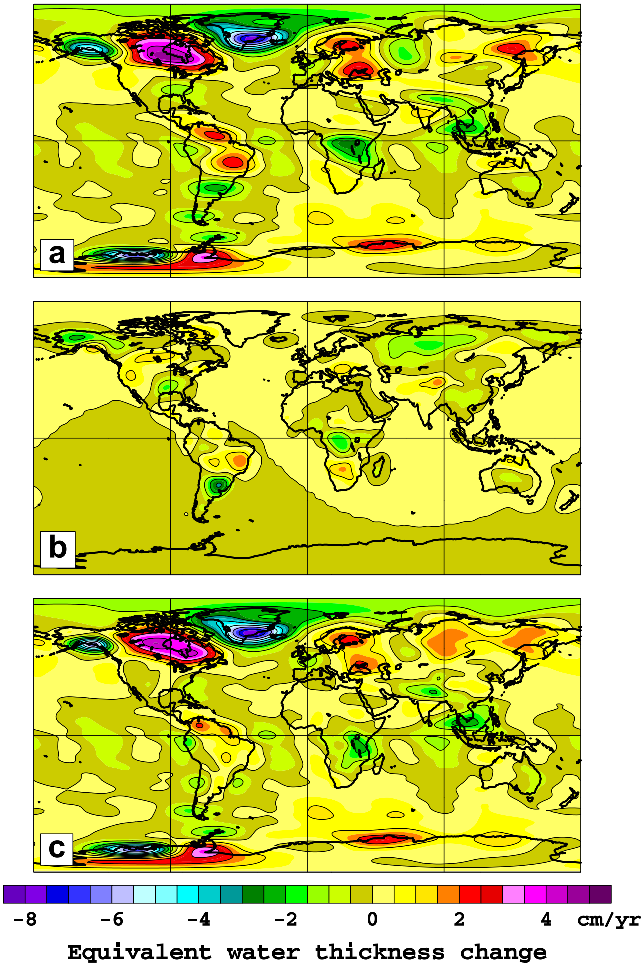

Fig. 1. (a) The CSR based reconstruction of the GRACE surface mass-rate field based upon the new analyses reported herein A Gaussian filter of half width 400 km has been employed in reducing the data; (b) the GLDAS reconstruction of the surface mass-rate field due to the secular variations in surface hydrology; and (c) the difference between the fields in (a) and (b). Note the important impact that the hydrology correction has upon the GIA related anomaly over the Canadian land mass.

characterized by precisely this same double "bulls-eye" structure (Peltier, 2004).

In Figs. 2a–c are shown the analogous results to those in Fig. 1, also based upon the original computations under discussion herein, for selected half widths of the Gaussian filter of 200, 300, and 400 km. Fig. 2d shows the equivalent result obtained by Jianli Chen using 46 months of CSR RL01 data for April 2002–May 2006. Inspection will show that the Toronto analyses quite closely reproduce those of the CSR (kindly provided by Jianli Chen), although there are apparently differences in several regions, due to the fact that the Toronto analyses are based upon the RL04 data set whereas the results provided to us by Jianli Chen are based upon the RL01 data set. Also notable by inspection of Figs. 2a–c is the fact that there is very little influence of filter width upon the final result that is visible at this global scale. As will be demonstrated explicitly below, however, the amplitude of the signal over Alaska will be sensitive to this assumption in the analysis procedure.

Focusing attention now on the North American continent and Greenland, Fig. 3 illustrates the dependence of the inferred GRACE signal upon the number of terms kept in the fit to the monthly Stokes coefficient time series, where the number of terms is varied from two to eight. For the purpose of these analyses a half width of the Gaussian filter has been fixed to 500 km. Noticeable is the fact that even the two term fit to the individual Stokes coefficient time series delivers a very accurate approximation to the more accurate eight term fit, the only difference being a weakening of the second extremum in the positive mass-rate signal over James Bay. The negative signals over Greenland and Alaska are of particular interest for the discussion to follow as these are associated with the ongoing loss of northern hemisphere polar ice that is an expected effect due to greenhouse gas induced global warming of the lower atmosphere.

Fig. 4 shows the influence of the half width of the Gaussian filter employed to smooth the field over North America for half widths of 200, 300, 400, and 500 km. It is worth noting that the double bulls-eye structure of the signal over the North American continent is an extremely important diagnostic of the validity of any model of the GIA process suggested to be accurate for this region. Its structure is rendered stable only by the larger of the choices for filter half width. It is important to note that the negative anomalies over Greenland and Alaska are also somewhat influenced by the choice of filter half width and this will prove to be important to recognize, especially for the Alaska region.

The eight term fit to the hydrology corrected GRACE observations are compared with the predictions of the ICE-5G (VM2) model on Fig. 5. This comparison omits all coefficients prior to (2,2) and uses a Gaussian half width of 500 km. The reason for the omission of the lowest degree and order coefficients for the purpose of this initial comparison has to do with the fact that the (2,0) coefficient is not accurately measured by GRACE and the (2,1) coefficients are strongly influenced by mass loss from continental icesheets and glaciers due to the modern process of global warming associated with the increasing atmospheric concentrations of the greenhouse gases. The model of continuing Late Quaternary ice-age influence does not include such "Anthropocene" impacts upon the time dependence of the gravitational field. Notable by inspection of Fig. 5 is the fact that the double bulls-eye in the hydrology corrected GRACE data is such that one of these positive extrema lies somewhat to the west of Hudson Bay and the second on or somewhat to the east of James Bay. The corresponding field predicted by the ICE-5G (VM2) model is shown on Fig. 5b. Comparison with GRACE demonstrates that the GIA model has predicted the positive signal over Canada in the observed field quite accurately, the only flaw being a slight under-prediction of the second maximum in the observed mass-rate field on or to the east of James Bay. The difference between the predicted and observed mass-rate fields is shown on Fig. 5c, inspection of which demonstrates that the prediction very nearly perfectly annihilates the observed signal over Canada. However, over Greenland and the high mountains of Alaska, significant negative anomalies remain, anomalies that are only slightly affected by the removal of the signal associated with ice-age GIA related influence. The fact that the ICE-5G (VM2) model provides a highly satisfactory fit to the dominant North American signal in time dependent gravity has been previously noted in Peltier (2007b), Paulson et al. (2007) and Peltier and Drummond (2008). It is towards the understanding of the residual signals over Greenland and Alaska and the related signals observed over the Antarctic continent that this paper is directed.

Before proceeding with the analysis of these signals, however, it is important to understand the implications of the good fit to the data over North America that the model has provided. The ICE-5G (VM2) model consists not only of a global (G) surface loading history (ICE-5G) but also a model of the depth variation of mantle viscosity (VM2). The radial viscosity element of this model is as important as is the loading history as it determines modern rates of rebound once the loading history is specified. Very recently, Paulson et al. (2007) have performed an independent test of the ICE-5G (VM2) model. Their test involved fixing the loading history to

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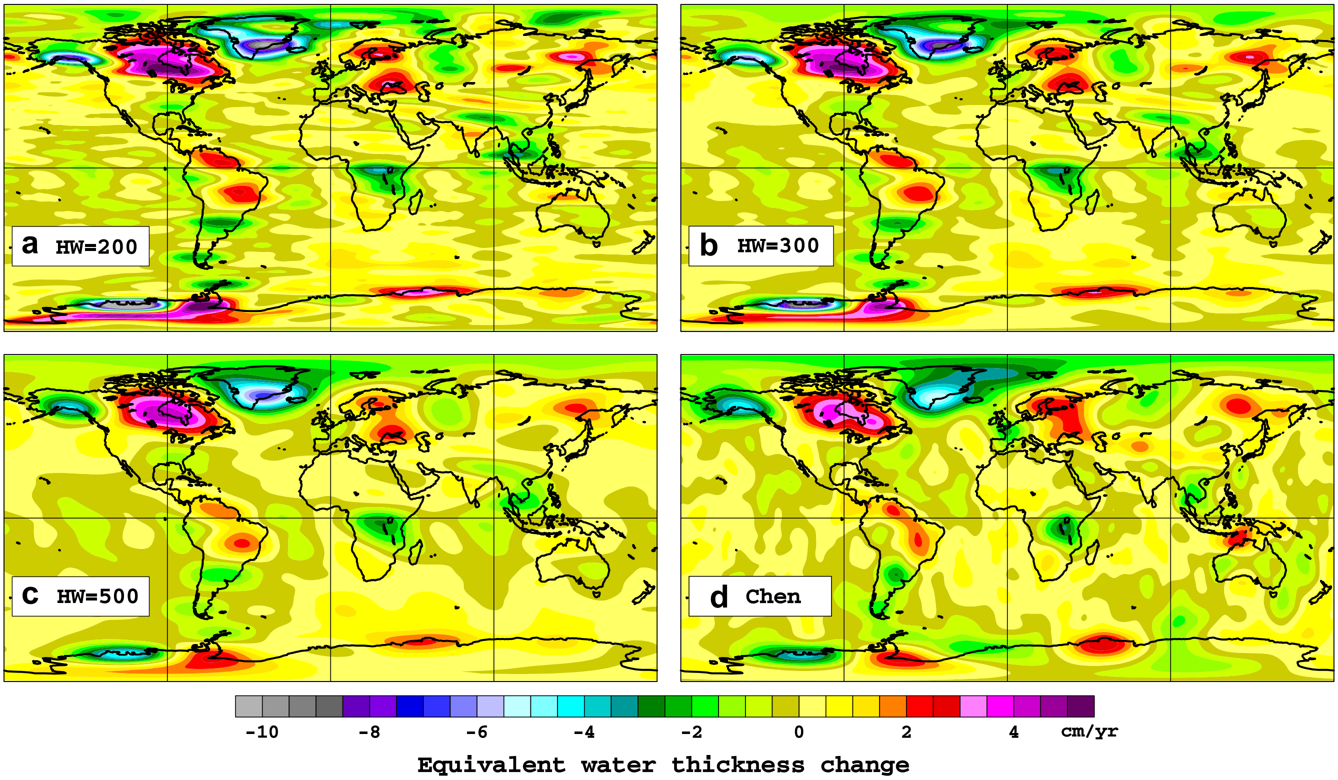

Fig. 2. GRACE global surface mass-rate reconstructions based upon the RL04 data sets from CSR, corrected for surface hydrology using the GLDAS data set, compared to the reconstruction provided by Jianli Chen (plate d). The University of Toronto reconstructions in plates a, b, and c correspond respectively to analyses performed using Gaussian filters of half width 200, 300, and 400 km. Noticeable is the fact that the dependence upon the filter width is weak at this global scale and based simply upon visual inspection.

ICE-5G and attempting to infer the depth variation of mantle viscosity. As constraints upon the latter, they employed only the GRACE observations themselves together with a small number of ^{14}C dated RSL histories from sites around Hudson Bay. The same relative sea level histories were also employed in constraining the ICE-5G (VM2) model itself although GRACE data could not be employed for this purpose as they were not yet available. By comparing the dependence of the misfit of their model to these data as a function of the depth dependence of mantle viscosity, they were able to constrain both the mean viscosity above 660 km depth and that below this depth. The minimum misfit model was found to provide a highly accurate two layer fit to VM2. The ICE-5G (VM2) model provides an excellent fit to a wide range of globally distributed observations. These include the total mass loss from the continents based upon the quality of its fit to the coral based sea level record from Barbados (Peltier and Fairbanks, 2006) which provides a good approximation to eustatic sea level history itself. The model also fits the rebound data from both Fennoscandia (Peltier, 2004) and the British Isles (Peltier et al., 2002), as well as an extremely large number of relative sea level histories from sites well removed from the regions where active deglaciation of the continents occurred. It is therefore expected to provide the best presently available means of predicting the magnitude of the contamination of both GRACE and altimetric satellite measurements of surface mass variations involved in the modern rate of global sea level rise due to the global warming process.

4. Estimating the rates of mass loss from the land: Greenland, Alaska and Antarctica

The results of the preceding analyses suggest that we are now in a position to attempt to estimate these contributions, appropriately corrected for the influence of the GIA process. Beginning with Greenland, Figs. 6c,d compares two results for GRACE-GLDAS-ICE-5G, both based upon the use of CSR geoids and the application of a Gaussian filter of half width 400 km. The first of the Greenland frames (Fig. 6c labeled “no stop at 2 ka”) employs the ICE-5G loading history as published in Peltier (2004) for the purpose of computing the GIA correction. The second, unlabelled, employs a slightly modified local Greenland loading history in which the original deglaciation history for Greenland in the ICE-5G model is modified by eliminating any change in ice-loading subsequent to 2000 years before present, in particular the continuing Neoglacial re-advance of Greenland ice contained in the Greenland model of Tarasov and Peltier (2002). Since the Neoglacial re-advance of Greenland ice did not continue to present day, the result in Fig. 6d will clearly be the most accurate. Evident is the fact that this correction reduces the observed rate of surface mass change somewhat.

In order to estimate the Greenland contribution to the present day rate of relative sea level rise, this field is simply integrated over the anomaly in the box whose latitudinal boundaries are 56.15 degrees north and 89.61 degrees north and whose longitudinal boundaries are 274.59 degrees east and 9.49 degrees east, respectively. Evident is the fact that this residual anomaly is everywhere negative over the Greenland continent. Regions of positive anomaly within this “bounding box” are excluded from the integral as these could not be connected to spectral leakage of the negative signal due to mass loss from the continent onto the surface of the surrounding ocean. All coefficients are included from degree 2 and order zero and this leading coefficient is replaced with the value determined on the basis of satellite laser ranging observations, the data period used is August 2002–January 2007 and the Gaussian half width of the filter is 400 km. To estimate the error in the

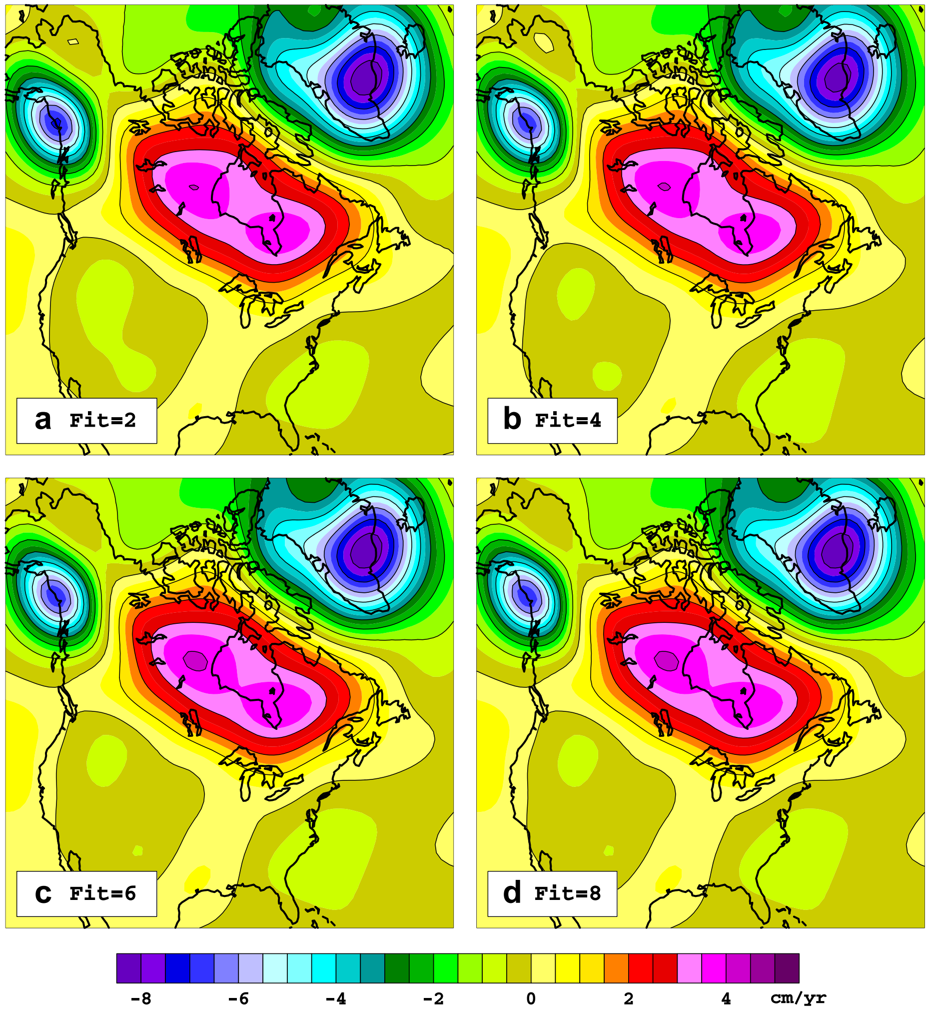

Fig. 3. Inferences of the surface mass-rate field over the North American continent corrected for the influence of hydrology using the GLDAS data set as a function of the number of terms kept in the fit to the monthly time series of Stokes coefficients in order to extract the strength of the secular variation which is to be attributed to the influence of the GIA effect. The two term fit includes only the mean and a best linear fit to the time rate of change. The four term fit includes a fit to the amplitude and phase of the annual cycle. The six term fit includes the amplitude and phase of the semi-annual cycle and the eight term fit also includes the amplitude and phase of the contribution of period 161 days.

mapping of this integral into a rate of global sea level rise, we will determine the result by also computing it using GFZ geoids. The result based upon the use of CSR geoids for the rate of global sea level rise is thereby found to be 0.63 mm/year. This may be compared with that previously obtained by Velicogna and Wahr (2005, 2006a) of 0.62 mm/year with an error bar of ±0.09 mm/year for the period April 2002–April 2006. In comparison Chen et al (2006a), through analysis of the data for the period 2002–2005, obtained the value 0.60 mm/year The modest difference between these previous results and that reported here is due in part to the elimination of the Neoglacial re-advance of Greenland ice from the local glaciation history. Since these differences are small, this suggests that our results are not significantly compromised by the use of a Gaussian filter of half width 400 km, nor by the different methodology to estimate the equivalent rate of global sea level rise due to mass loss from the continent (more on this below). When the analysis is repeated using the GFZ geoids, again employing the slightly revised version of the local deglaciation history, the result obtained for the implied contribution from Greenland for the rate of global sea level rise is somewhat reduced to the value 0.54 mm/year. I will assume that a best estimate of the rate of mass loss from Greenland is that provided by the average of the results delivered by use of the CSR and GFZ geoids, namely 0.59 mm/year in eustatic sea level rise equivalent. I will also assume that a reasonable estimate of the error in this estimate is provided by the error in the mean, i.e. ±0.05 mm/year. This estimate of the error is somewhat smaller than the value of ±0.09 mm/year suggested by Velicogna and Wahr (2006a). I will accept their larger estimate of the error as the more accurate because of the methodology employed to produce it (see below). Insofar as the error in the estimate of the rate of mass loss from Greenland is concerned it is also important to note the result reported by Luthcke et al. (2006) obtained through application of a methodology based upon the "mascon" technique rather than global spherical harmonics. These authors infer a rate of mass loss over the period 2003–2005 of 0.28 mm/year in eustatic sea level rise equivalent with an error of ±0.04 mm/year. This is considerably smaller than either my new estimate based upon spherical harmonics or the previous estimate by Velicogna and Wahr (2006a) but pertains to an earlier period following which the rate of mass loss appears to have accelerated.

It is important to note that the methodology that I am employing to estimate the rate of mass loss from a given region

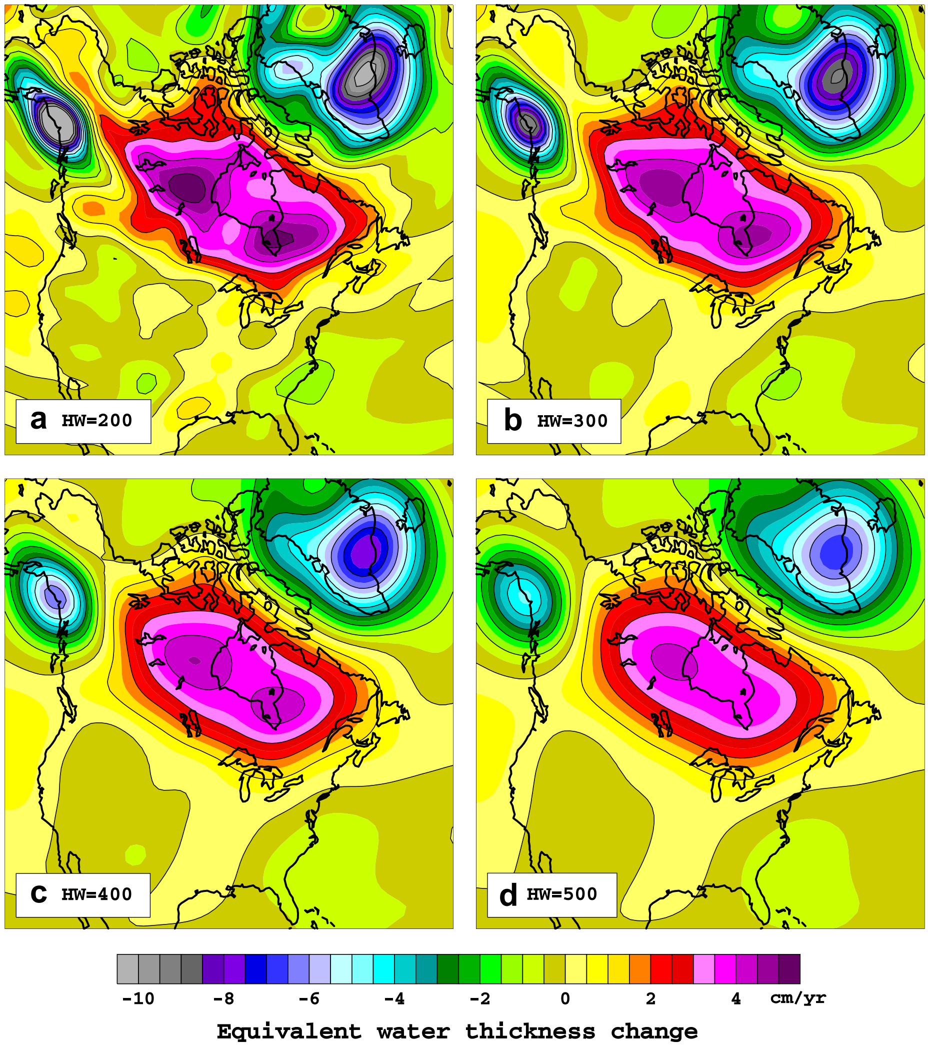

Fig. 4. Inferences of the surface mass-rate field over North America corrected for hydrology of eight term fits to the individual Stokes coefficients when the Gaussian filter applied to the spherical harmonic representations of the field have half widths of 200, 300, 400, and 500 km.

differs from that which has become conventional in this field. In the conventional method which is based upon that advocated by Jekeli (1981) as discussed in Wahr et al. (1998), one first defines a mask in terms of a spherical harmonic decomposition which is unity over the area of interest and zero outside but with the amplitude of the mask field amplified near the edge so as to compensate for the influence of spectral leakage. One then windows the Stokes coefficient based expansion of the gravitational field for each month by applying this mask to isolate the field over the target region. One then produces a time series for the target region from the individual monthly estimates and fits the mass-rate version of the time series by linear least squares to infer a rate of mass loss for the region as a whole. Rather than applying this conventional methodology in the present paper, my methodology involves simply integrating over the target region the mass-rate map determined by employing spherical harmonic coefficients provided by the secular term in the eight term fit to each of the individual Stokes coefficients provided by the individual analysis centers. In principle this method should deliver equivalent results to those delivered by the conventional method when care is taken to properly include in the integral over the target region any portion of the mass loss signal that is associated with spill-over onto the ocean from the land due to spectral leakage. That my method successfully reproduces the results obtained previously by applying the conventional method should be seen as providing confidence in the accuracy of the results obtained by both. The slight drawback of the method *I* employ is that it provides no simple method of estimating the error in the inference. I have compensated for this by estimating the error by comparing the results inferred by using the Level 2 data sets provided by the two primary analysis centers, CSR and GFZ. In the following section of this paper where it is necessary to compute the rate at which mass is being added to the oceans, I will explicitly compare the results produced by the two methods in a region, the global ocean, to which the conventional method has not previously been applied. This will demonstrate that they do in fact produce effectively identical results.

Figs. 6a,b presents equivalent results to those in Figs. 6c,d but for the region of Alaska where the second of the major northern hemisphere negative residual anomalies is located. This compares the GRACE observations based upon CSR geoids either corrected for the influence of surface hydrology or not and using GIA corrections for ICE-5G (VM2). The period analysed is again from August 2002 to January 2007 and a filter with Gaussian half width of 400 km has once more been employed. The hydrology correction in this region is non-negligible and its application by subtraction from the raw GRACE observation makes the signal somewhat more negative, i.e.

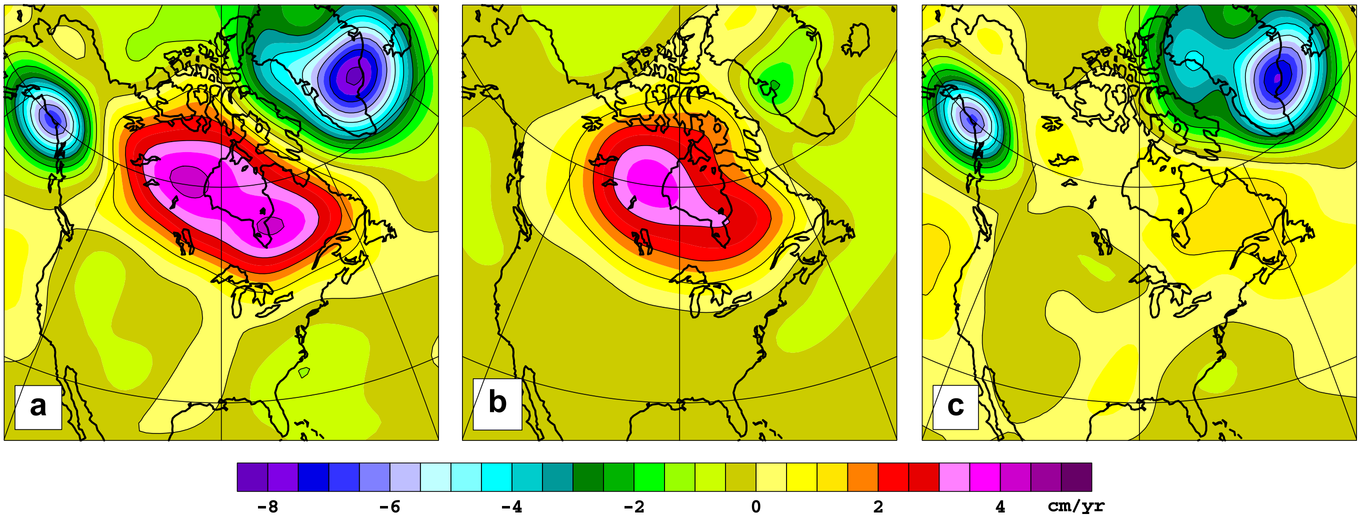

Fig. 5. A comparison between the GRACE mass-rate field over the North American continent in (a) and the prediction of the ICE-5G(VM2) model of the GIA process in (b). The difference between these two fields is shown on (c) and demonstrates the high quality of the fit to the observed signal over Canada due to the continuing impact of the rebound of the crust forced by the elimination of land ice from this region at the end of the last ice-age. The fields in both parts (a) and (b) of the figure are reconstructions that include spherical harmonic coefficients from degree 2 and order 2 and higher. This is to eliminate from the comparison the large misfit between the degree two and order one coefficients between GRACE and ICE-5G(VM2). The reason for the discrepancy between these coefficients for the two models is discussed at length in Peltier and Luthcke (2009).

increases the inferred rate of mass loss from that which would be inferred in the absence of its application. When this signal is integrated over the latitude range from 49.13 degrees north latitude to 70.18 degrees north latitude, and 192.30 degrees longitude to 238.01 degrees longitude (i.e. within the "bounding box" drawn around the Alaska anomaly on Fig. 6), the rate of global sea level rise inferred to be due to the diminution of ice cover over the high mountains of Alaska is predicted to be 0.13 mm/year (CSR geoids) or 0.11 mm/year (GFZ geoids), where only the negative signal within the box is allowed to contribute to the integral. If no GIA correction is applied then the results obtained from these two different data sets are somewhat increased as expected since Alaska lies in the peripheral bulge region of the Laurentide/ Cordilleran ice sheet complex. As in the case of Greenland, I will assume the best estimate of the rate of mass loss from Alaska as an average for the period August 2002–January 2007 to be provided by the average of the GIA corrected results, or 0.12 mm/year, with an error estimated by the deviation of these results from the mean or $\pm$0.01 mm/year. This result may be compared with that of Rignot and Thomas (2002) who, analysing the data over the shorter interval 2002–2004 obtained the result 0.27 mm/year. I attribute the lower result delivered by the present analysis partly to the short interval of time over which this previous analysis was performed but primarily due to the different methodology employed by these authors (mass balance estimates for the individual watersheds rather than analysis of GRACE data). The analysis of Tamisiea et al. (2005) was performed using GRACE data from an even shorter interval of time (2002–2003), and they obtained an even larger rate of mass loss of 0.3 mm/year. This suggests that the length of the time series on the basis of which such mass loss estimates are performed is especially important for a region of small area. Also important, as inspection of Fig. 5 demonstrates, is the application of an appropriate GIA correction and this influence is such as to significantly reduce the magnitude of the hydrology corrected negative anomaly.

There are additional caveats to the results reported for Alaska that may also be significantly implicated in explaining the differences between these new results and those previously referred to that have been reported by others. These include the issue as to which low degree and order coefficients are excluded or replaced by satellite laser ranging results and also the width of the Gaussian filter employed to eliminate the influence of spectral leakage. Table 1 provides a detailed listing of results that allow a quantification of these two influences. It will be noted first, that replacing the (2,0) coefficient with the satellite laser ranging estimate diminishes the CSR result but increases the GFZ result. Eliminating this coefficient entirely, however, further modifies these results. It should clearly be kept and the (2,0) coefficient should be replaced by the SLR value as has been done consistently for the purpose of the analyses reported herein. In each case dropping it reduces the result on average by 0.02 mm/year. If we also omit the (2,1) coefficients this leads to a slight further increase, on average, of 0.013 mm/ year. Any analysis that employs a reduced value of the (2,1) coefficients from those predicted by the ICE-5G(VM2) model will therefore somewhat exaggerate the contribution of Alaska to the modern rate of global sea level rise. None of these variations upon the analysis procedure provides an explanation for the higher values inferred by either Rignot and Thomas (2002) or Tamisiea et al. (2005).

Further inspection of the last six rows of Table 1, however, does provide evidence of what could be a partial source of the difference between these interpretations. It is clear on the basis of these data that as the half width of the Gaussian filter employed to reduce the data is diminished, the inferred rate of sea level rise due to the melting of land ice from Alaska increases monotonically. The final result varies from a lowest value of 0.09 mm/year, for GFZ geoids and a filter half width of 500 km, to a highest vale of 0.23 mm/year, for CSR geoids and a filter half width of 0 km. It will be observed that only the result obtained when no filter is applied in the data reduction is marginally close to those reported by Rignot and Thomas (2002) and Tamisiea et al. (2005).

In summarizing the totality of our results for Alaska I will therefore employ an estimate of the contribution of Alaska to global sea level rise of 0.12 ± 0.04 mm/year recognizing, in the quoted value of the standard error, that by employing a Gaussian filter of smaller half width the value obtained using a filter half width of 400 km would be increased appreciably.

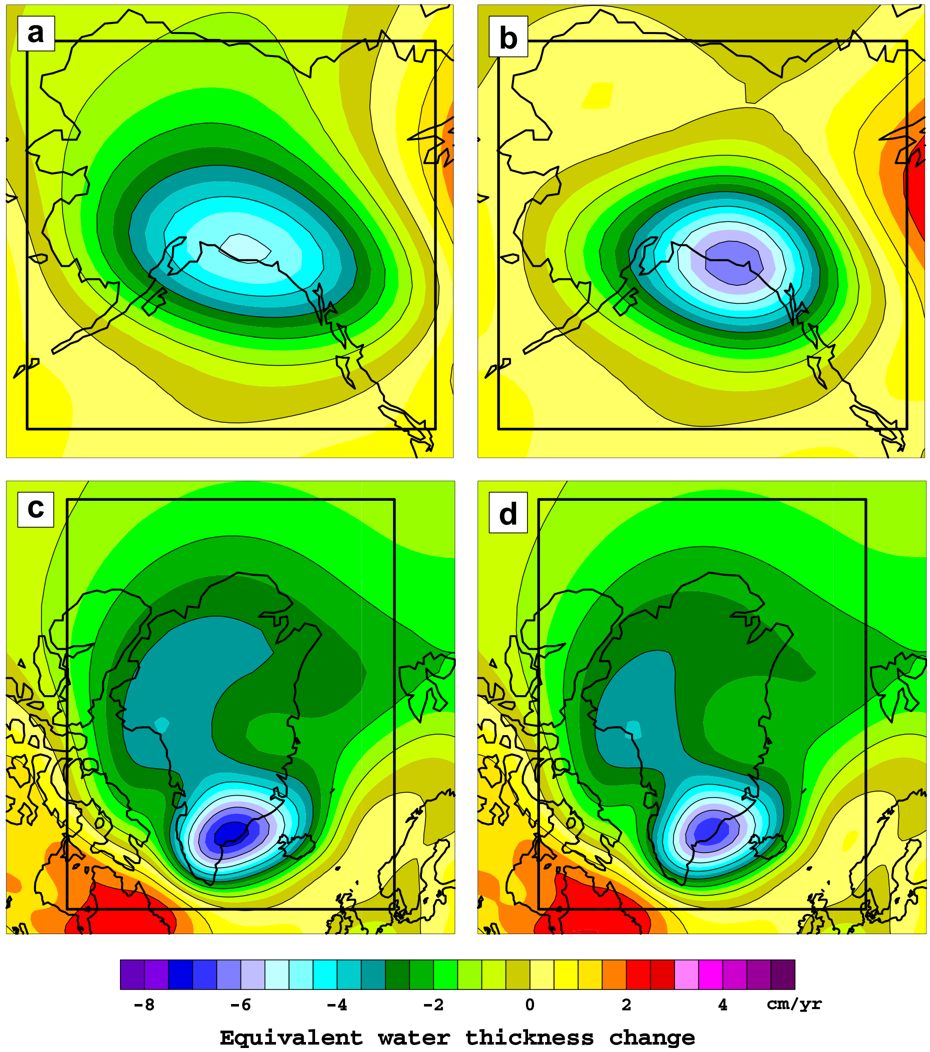

Fig. 6. (a) Surface mass-rate field over Alaska from GIA corrected GRACE data. (b) Alaska mass-rate field corrected for the influence of surface hydrology using GLDAS and glacial isostasy using the predictions of the ICE-5G (VM2). The box drawn around the anomaly defines the region within which the negative anomaly is considered to be due to land ice melting. (c) Surface mass-rate field for Greenland based upon the glacial history for this region in the original ICE-5G model that contained a neoglacial re-advance of ice that continued until the present day (denoted "no stop at 2 ka"). (d) The mass-rate field for Greenland assuming that the neoglacial re-advance in the original ICE-5G model is eliminated from 2 ka onwards.

The final region of interest for the purpose of these analyses is the continent of Antarctica. Fig. 7 shows the results of detailed analyses of the GRACE field over this region based upon the use of both CSR and GFZ geoids. The mass-rate maps based upon the geoids produced by these two analysis centers are shown in parts (a) and (b) of the figure respectively.

The mass-rate map for the GIA correction based upon the ICE-5G(VM2) model is shown on part (c) of the figure. Once more the period of analysis is from August 2002 to January 2007 and the half width of the filter employed is 400 km. The figure shows both the raw GRACE results for surface mass-rate and the difference between this and the prediction of the surface mass-rate field from the ICE-5G (VM2) model in parts (d) and (e). There is no significant correction for surface hydrology provided by the GLDAS model for Antarctica (see Fig. 1) and so this influence is not relevant to understanding the inference of net mass balance for the continent as a whole. Comparison of the GIA filtered results based upon CSR geoids with those based upon GFZ geoids, demonstrates that, although the fields are strikingly similar, differences in magnitude do exist. In attempting to isolate the *net* mass balance of the continent from the GIA corrected GRACE data set care is clearly required to fully capture the contributions from the main regions from which mass loss is currently occurring, namely the Antarctic Peninsula and the sector of West Antarctica adjacent to the Amundsen Sea in Marie Byrd Land. For Antarctica, as for the strong positive signal over Canada associated with the ongoing rebound of Earth's crust, the GIA correction is clearly of overwhelming importance, as previously noted by Velicogna and Wahr (2006b). For example if, using the CSR geoids, we simply integrate the GRACE mass-rate field directly over land, we obtain an implied rate of global sea level rise of −0.062 mm/year implying that the continent is in a state of almost perfect mass balance. The GFZ geoids, on the other hand, give a rate of −0.025 mm/year with the same implication. After correction for GIA contamination using the ICE-5G (VM2) model, however, the CSR geoids imply a positive contribution to the global rate of sea level rise of 0.31 mm/year. In comparison, the GFZ geoids imply a contribution to global sea level rise of 0.36 mm/year. In both cases the integral over land is augmented by the integral of the negative signal from the two dominant regions of mass loss that extend into the oceans as

Table 1
Results are provided from sensitivity tests to determine the accuracy of estimates of the rate of mass loss from Alaskan glaciers.

Spherical harmonic coefficients				Filter half width (km)	CSR (mm/year)	GFZ (mm/year)
(2,0)	(2,1)	(3,0)	(4,0)			
Included	Included	Included	Included	400	0.16	0.10
Replaced	Included	Included	Included	400	0.13	0.11
Omitted	Included	Included	Included	400	0.13	0.11
Omitted	Omitted	Included	Included	400	0.18	0.16
Replaced	Included	Included	Included	500	0.11	0.09
"	"	"	"	400	0.13	0.11
"	"	"	"	300	0.15	0.13
"	"	"	"	200	0.18	0.16
"	"	"	"	100	0.21	0.19
"	"	"	"	0	0.23	0.23

In the first four lines of the table results are shown for both CSR and GFZ geoids with the half width of the Gaussian filter fixed to 400 km and a range of assumptions concerning the treatment of the low degree and order Stokes coefficients. In the remaining lines of the table results are shown as a function of the half width of the Gaussian filter employed to minimize the influence of spectral leakage.

a consequence of spectral leakage (see the boxed regions in the figure). In these analyses the contribution from East Antarctica is such as to suggest that it slightly compensates the mass loss occurring from West Antarctica by amounts, in global sea level rise equivalents of -0.08 and -0.04 mm/year respectively for the CSR and GFZ geoids. Again I will take the best estimate of the Antarctic contribution to the present day rate of global sea level rise to be that determined by the average of the CSR and GFZ based results, namely 0.34 mm/year with an estimate of the error provided by the deviation of these results from the mean, namely $\pm$0.03 mm/year.

Since there may be some concern that the methodology that I am employing is not capable of delivering accurate estimates of the rates of change of surface mass on the basis of the GRACE data, it will be instructive to compare the results quoted above for the implications of the rate of mass loss over the land by applying the conventional method as well to both the CSR and GFZ geoid data sets. To this end Fig. 8a shows time series for the change of mass over Antarctica expressed in terms of mm/year of implied global sea level rise. The result for the CSR data set of -0.128 mm/year for the period from August 2002 to January 2007 with an error bar of 0.038 mm/year is to be compared with the result of Velicogna and Wahr (2006) for the period April 2002–August 2005 who quote at rate of volume increase of 39 ± 14 km^3/year which is equivalent to -0.098 ± 0.035 mm/year of global sea level rise. Their result for the earlier period therefore differs only slightly in magnitude, the difference being explicable solely in terms of the different period being analysed, that of the present analysis being 16 months longer than in the earlier paper. Furthermore the error estimate we obtained by applying the non-standard method is also the same as that obtained by Velicogna and Wahr. These results may be compared with the results obtained using the non-standard method which, when applied to the CSR geoids give a result of -0.062 mm/year which is within 2 sigma of the new result we have obtained by applying the standard method. It would therefore appear that the two methods are essentially equivalent. Fig. 8a also shows the result obtained by applying the standard method using the GFZ geoids. This delivers the estimate of Antarctic mass loss of -0.084 mm/year in global sea level equivalent with a 1 sigma error estimate of 0.028 mm/year. For comparison our non-standard method based upon the GFZ geoids gave the result -0.025 mm/year. The results obtained by applying the standard method to this problem therefore does not deliver results that differ significantly from those obtained using the non-standard method.

It is also important to test the stability of these results against a modest increase in the duration of the period analysed using this more conventional method. Furthermore it is important to realize that the result obtained also depends somewhat upon the number of terms kept in the fit to the mass loss data. To this end Fig. 8b shows equivalent results to those in Fig. 8a for the period August 2002–December 2008. Inspection of these results will show that the CSR data give an estimate of the mass loss from Antarctica of -0.089 ± 0.02 mm/year whereas the estimate based upon the GFZ data is -0.083 ± 0.018 mm/year, these estimates being based upon a four term fit to the observations for the entire continental region of Antarctica. It will be noted that these estimates from the two data centers are now very close to one another in both the estimate of the rate of loss and the error involved in the estimate.

It is extremely important to notice that the geographical regions of West Antarctica that are inferred to be losing mass consist not only of the peninsula but also of a vast region of Marie Byrd Land. It has been clear for some time on the basis of *in situ* observations that the former region was warming. It is therefore not a surprise that mass loss should be occurring from the same region. However it has been suggested that this may be entirely a consequence of a projection onto the southern annular mode of the impact of stratospheric ozone loss within the polar vortex (Thompson and Solomon, 2002). If our results are to have a straightforward explanation in terms of climate dynamics this explanation is most probably incomplete. How then might we explain the much more significant rates of mass loss occurring over Marie Byrd Land. A much more likely explanation has been recently provided by Steig et al. (2009) in their analysis of Antarctic warming during the 50 years that have passed since the International Geophysical Year in 1957. This suggests that all of West Antarctica has been warming over this period and that the warming has been most intense over Marie Byrd Land. Our geographically disaggregated picture of the mass loss occurring over Antarctica is entirely consistent with their analysis of Antarctic surface temperature trends. It is also worthwhile to recognize that this picture relies heavily upon the accuracy for Antarctica of the ICE-5G (VM2) model of the GIA process.

In order to test the stability of these results to slight changes in both the melting history and mantle viscosity profile, two further variants upon the calculation have been performed. First the sharp onset melting pulse that occurs in ICE-5G v.2b at 11 ka is reduced by 3 m in eustatic sea level amplitude. With this modification, the CSR and GFZ based net results are reduced to 0.271 and 0.316 mm/year respectively leading to a best (average) estimate of 0.29 mm/year, a reduction of 0.05 mm/year from the previous value of 0.34 mm/year. Second, the VM2 viscosity model is changed to the VM5a model of Peltier and Drummond (2008) and the strength of the pulse at 11 ka is reduced by 3 m eustatic sea level equivalent. This leads to new CSR and GFZ estimates of 0.289 and 0.316 mm/year respectively and thus a new best estimate of 0.31 mm/year for the rate of globally averaged sea level rise due to Antarctic melting.

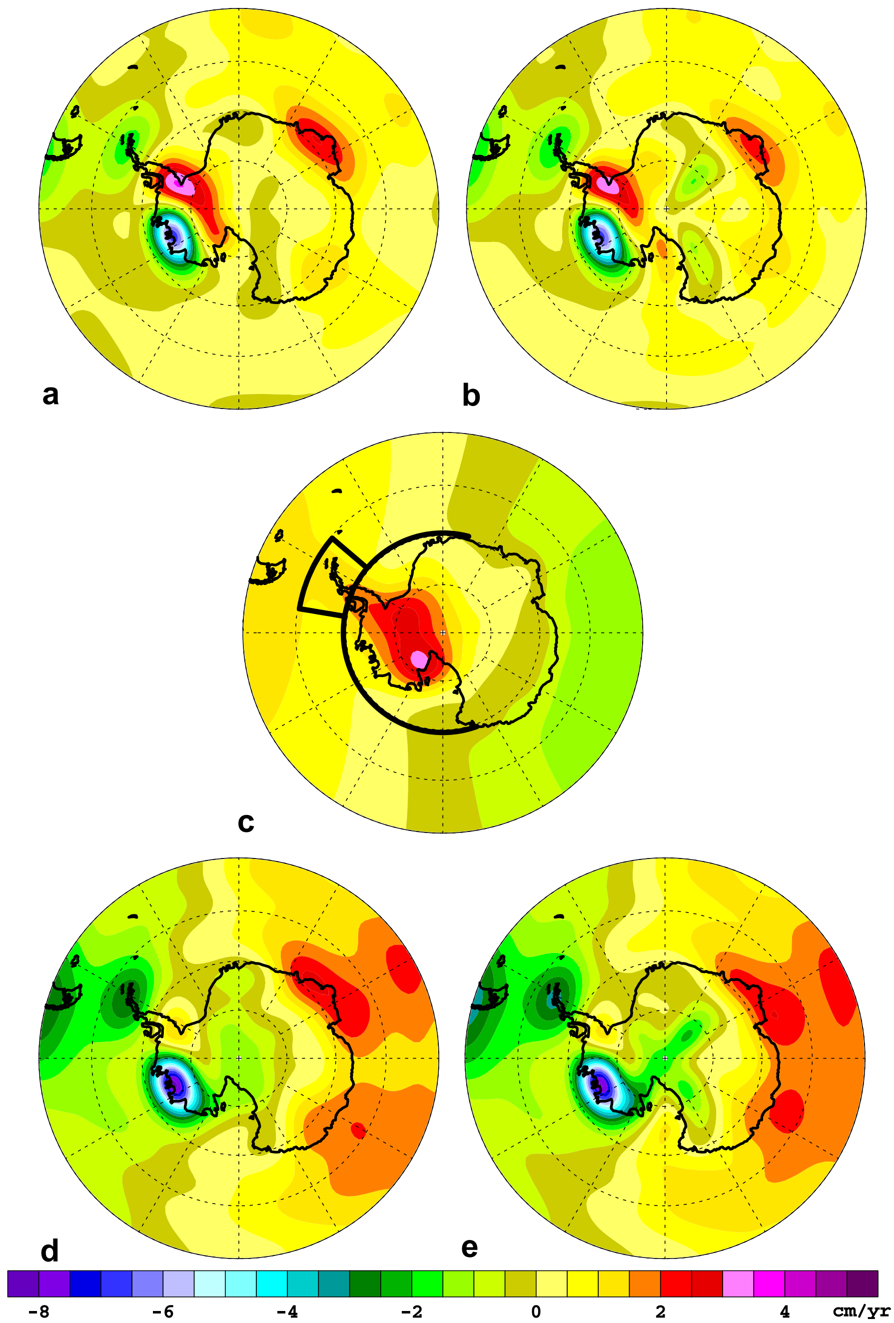

Fig. 7. (a) Inferred surface mass-rate field over Antarctica based upon the use of CSR geoids together with (d) the corrected mass-rate field for this region based upon the application of the ICE-5G (VM2) model of the glacial isostatic adjustment process to eliminate the contamination due to ice-age influence. (b) Same as (a) but analyses based upon the use of GFZ geoids with (e) being the result corrected for GIA. Plate (c) shows the GIA correction applied to both the CSR and GFZ results. As in Fig. 6 the boxes employed to isolate different regions denote the areas within which the negative signals are analysed that are attributed to mass loss from the land.

Accepting these variants upon the inference of the rate at which the Antarctic ice sheet is disintegrating as equally likely, we would be obliged to increase our estimate of the error bar on it from ±0.03 mm/year noted above to ±0.05 mm/year. We will therefore take our best estimate of Antarctic melting to be 0.34 ± 0.05 mm/year.

These results may be compared with the earlier result of Velicogna and Wahr (2006b) who have inferred a global sea level rise contribution of 0.37 mm/year by employing an average of the GIA corrections provided by the Ivins and James (2005) model of the local glaciation history and that provided by ICE-5G (VM2). My result is clearly very close to this earlier estimate. Additional results have been published by Ramillien et al. (2008) who obtained a value of ~0.30 mm/year for West Antarctica alone that was offset by an inferred increase of mass on East Antarctica such that the net contribution to global sea level rise for Antarctica as a whole was inferred to be 0.11 mm/year. Chen et al (2006b), on the other hand, inferred Antarctica to be in a state of almost perfect mass balance, making no significant contribution to the present day global rate of sea level rise at all. The more recent result of Chen et al. (2008), in which the glaciation history model of Ivins and James (2005) was also employed to make the correction for glacial isostatic adjustment has suggested an contribution to global sea level rise of 0.36 ± 0.06 mm/year, a result that is very close to that originally

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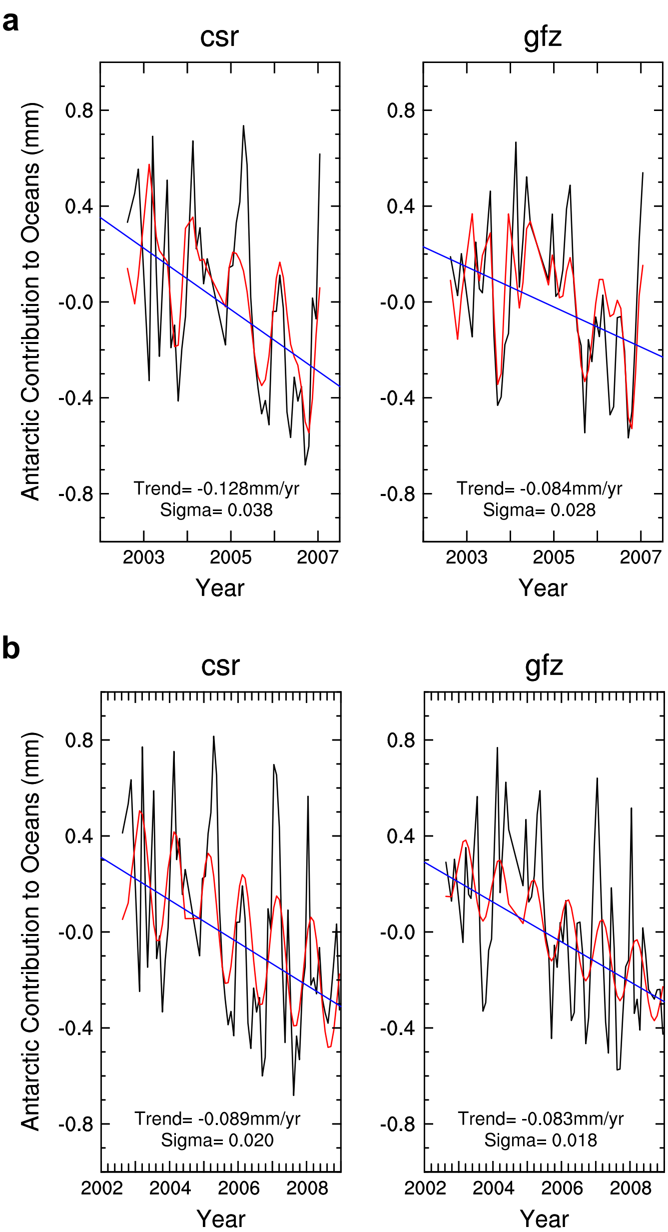

Fig. 8. (a) Estimates of the rate of mass loss from the Antarctic continent neglecting the correction for the influence of the glacial isostatic adjustment process based upon both the CSR data and the GFZ data. On the inset to the figure are shown the estimate of the secular trend in the data as well as the 1 sigma error in the estimation of this quantity. The red curves are the eight term fits to the data and the straight lines are the secular trends. The period analysed extends from August 2002 to January 2007. (b) This is the same as a, but for the period August 2002 to December 2008. In this case, however, the fit to the data includes only a mean value, a linear trend and an annual cycle, the fit therefore involves only four terms rather than the usual eight.

reported by Velicogna and Wahr (2006b) and to that reported herein. Both of these estimates are very close to my new estimate of the ongoing contribution of Antarctica to global sea level rise of 0.34 ± 0.05 mm/year. Since this new estimate based upon the use of the ICE-5G (VM2) model does not differ significantly from some estimates that have been based upon the use of the IJ05 model of Antarctic deglaciation it would appear that either model is appropriate for the purpose of this analysis. This conclusion would follow only if the analysis procedures employed in each case were the same and this is unclear. There are reasons to believe that the IJ05 model should be considered suspect.

Firstly it is important to understand that the GIA correction depends as strongly upon the model of mantle viscosity as it does upon local deglaciation history. Since there do not exist data from the south polar region that would allow one to infer a viscosity model for this region that one could argue to be more appropriate than VM2, results obtained using the IJ05 loading history that simply explore a range of unconstrained viscosity models must be considered highly speculative. Furthermore, the IJ05 loading model is itself incompatible with newly available constraints on the timing of the deglaciation of Antarctica that have been provided by the work of Eugene Domack and colleagues (e.g. see Leventer et al., 2006), whose ^{14}C dating of the onset of marine sedimentation on the Antarctic shelf has fixed the timing of the pull-back of grounded ice from the shelf-break to ~11.5 ka, a time that is coincident with the timing of meltwater pulse 1b in the Barbados sea level record (e.g. see Peltier and Fairbanks, 2006). A rapid onset of deglaciation at this time has always been a characteristic of the ICE-NG set of models. There are also a number of erroneous comments in the paper by Ivins and James (2005) concerning the differences between their IJ05 model and ICE-5G (VM2) that are worth pointing out herein. In their Summary on page 547 for example, it is asserted that "the ICE-5G model constructed by Peltier (2004)—has a collapse phase concentrated between 9 and 4 kyr BP". This is simply incorrect. The meltback of Antarctic ice in the ICE-5G v2.b model being employed herein, and which has been distributed internationally, has a sharp onset of deglaciation coincident with meltwater pulse 1b, a feature that is now well resolved in the extended Barbados sea level record of Peltier and Fairbanks (2006) and which is required to fit the shelf sedimentation data of Domack and colleagues mentioned previously.

It is also worth pointing out that the total ice melted in ICE-5G from Antarctica is approximately 16 m in eustatic sea level equivalent, the southern hemisphere total being 17.6 m (see Fig. 7 in Peltier, 2007a). The remaining ~1.6 m eustatic sea level equivalent of southern hemisphere ice is actually assumed in ICE-5G to have loaded the mountainous regions of Patagonia. As noted in Ivins and James (2005) the ice melted from Antarctica in the ICE-5G model is "about 65% larger by volume" than in the Ivins and James model. This increased amount of Antarctic ice is entirely consistent, however, with the most recent glaciological reconstruction by Philippon et al. (2006). The difference of ~6 m eustatic between IJ05 and ICE-5G is approximately equal to the total land ice on Greenland or West Antarctica at present. The test of the stability of the result reported here in which the magnitude of the meltwater pulse that emanates from Antarctica at 11 ka was reduced by 3 m is intended to test the stability of the inference of the rate of current sea level rise originating from Antarctica against a reduction in the rate of mass loss of this kind. As demonstrated, the effect is rather modest.

The final input of water mass from the land into the oceans over the GRACE era is that potentially derived from the surface of all continents that is associated with the lowering of the water table. It is well known on the basis of both the observational record of the increase in surface temperature over the past many decades as well as on the basis of the global warming predictions of coupled atmosphere-ocean general circulation models (e.g. IPCC AR4, 2007) that the continents warm more than do the oceans as a consequence of their reduced surface heat capacity. Of course the GRACE satellites are also able to provide an estimate of the rate of increase or decrease of surface water mass over the continents, but the GRACE signal over these regions also includes a strong contribution from GIA in several regions as previously demonstrated. This is not only the case in regions that were previously ice covered but also from elsewhere due to the influence of hydro-isostasy. It is probably more useful therefore, for present purposes, to estimate the impact of continental warming by directly integrating the GLDAS global surface hydrology field over the continents. This integral delivers a result that accords with *a priori* expectations that continental drying should be resulting in a net transfer of water from the land to the oceans and therefore an additional contribution to the rise of global sea level. The sign of this effect is evident on the basis of Fig. 1 on which it is clear that negative signal dominates positive in the GLDAS model of continental hydrology. When the global GLDAS field shown in Fig. 1b is integrated over all continents, it implies a net rate of global sea level rise due to continental desiccation of 0.14 mm/year. This estimate is very close to that recently obtained by Ramillien et al. (2008) whose preferred value is 0.17 mm/year on different grounds.

If we simply add the previously enumerated contributions to the increasing mass of water being added to the ocean basins, taken together these imply a preliminary estimate of the net rate of global sea level rise from land sources of $\dot{M}_{L'} = 0.59 \pm 0.05$ mm/year (Greenland) $+0.12 \pm 0.04$ mm/year (Alaska) $+0.34 \pm 0.05$ mm/year (Antarctica) $+0.14$ mm/year (GLDAS-continents) $= 1.19 \pm 0.14$ mm/year.

To this total we must further add the input to the oceans that derives from the meltback of the small ice sheets and glaciers of the world, for which the most recent estimate over the GRACE era by Meier et al. (2007) is 1.1 mm/year with an error bar of ± 0.24 mm/year in eustatic sea level rise equivalent. Since this estimate also includes the result from Alaska, we must subtract from it the previously presented new estimate for the rate of mass loss from this region of 0.12 mm/year. This reduced value for the small ice sheets and glaciers contribution during the GRACE era is therefore 0.98 ± 0.24 mm/year. This could be a significant overestimate if Meier has employed either the Rignot et al. or the Tamasiea et al. previous, and apparently excessive, estimates of the rate of mass loss from Alaska. Adding the small ice sheets and glaciers contribution to the four previously discussed contributions we obtain the following estimate for the rate at which mass is being added to the global oceans from the continents in sea level rise equivalent as:

$$M_L = M'_L + 0.98 \text{ mm/year} = 2.17 \text{ mm/year} \pm 0.37 \text{ mm/year}$$

5. Closing the budget of global sea level rise: the GRACE measurement of the rate of increase of mass over the global oceans

The water mass contributions to the global rate of sea level rise inferred above that is implied by the rate of loss of water mass from the land will be considered compatible with closure of the global sea level budget if and only if, within the errors on the determination of the sum over the individual terms, the same rate of mass addition is inferred to be occurring to the global ocean.

A critical question is therefore whether GRACE is observing a rate of mass increase in the ocean basins that is consistent with this range of inferences. When the GRACE mass-rate is integrated over the entire surface area of the oceans (the global field is that shown on Fig. 1), I infer an average rate of global sea level *rise* to be -0.49 mm/year when the CSR geoids are employed to make the estimate and -0.07 mm/year when GFZ geoids are employed and when these estimates are based upon the same period August 2002–January 2007 employed for the other analyses discussed previously (Table 2). These results are obtained when no filter is employed to reduce the data and when the (2,0) coefficient is replaced by the value delivered by satellite laser ranging. The average of these values is -0.28 mm/year which is somewhat more negative than the value recently reported by Cazenave et al. (2008) of -0.17 mm/year. It is important to note, as is made explicit in Table 2, that there is a significant degree of instability involved in this estimate as it varies considerably depending upon the range of time over which the computation is performed (see the results in columns 3–6 in the table). The additional variants upon the analysis procedure for which results are provided in Table 2 include: (1) the Gaussian half width of the filter employed in the analysis; and (2) the terms omitted in the representation of the mass-rate field. I will accept as a best estimate of this quantity the average of the results obtained using the CSR and GFZ geoids respectively, namely -0.28 mm/year with an error estimate provided by the deviation of the individual estimates from this mean, namely ± 0.21 mm/year. Insofar as the raw data is concerned, when the integral is performed over the entire area of the global ocean, not only is there no increase of mass inferred to be occurring but the amount of mass contained within these basins is actually inferred to be decreasing! However, just as the altimetric satellite measurements of global sea level rise must be corrected for the influence of glacial isostatic adjustment, so must the GRACE data over the ocean domain.

In order to ensure the accuracy of this estimate, especially given how critical it will prove to be to our final result and given the unconventional method that has been employed to produce it, it will be useful to test its stability by comparing this result to that which would have been obtained had the conventional method been employed in which error estimates are simple to produce using the monthly geoids produced by the individual analysis centers. To this end Fig. 9 presents reconstructions of the time series for the variations of mass over the global oceans, in mm of average sea level change, based upon the distinct CSR and GFZ data sets for the time periods August 2002–January 2007. In order to extract the secular variation of mass we apply the same eight term fit to the time series as previously employed in the extraction of the secular rates of change from the time series of the individual Stokes coefficients. Based upon this method the CSR data deliver an estimate of the secular rate of change of mass of -0.49 mm/year with a 1 sigma error estimate of ± 0.12 mm/year. The GFZ data, on the other hand deliver an estimate of the secular rate of change of mass of -0.07 mm/year with a 1 sigma error estimate of ± 0.13 mm/year. It will be noted that the new estimates based upon both the CSR data and the GFZ data are the same as those obtained previously by applying the unconventional method. If we average these new results to obtain a new best estimate of the rate of gain of mass by the oceans over the target period we again obtain the value -0.28 mm/year with an estimate of error of ± 0.13 mm/year. It is important to note that the two methodologies have delivered essentially identical best estimates as well as similar estimates of the error. For present purposes I will therefore employ the results delivered by the unconventional method of analysis in what follows as this has the larger attached error bar. It may also be of some interest to readers that I have found the GFZ estimates to be less stable to variations in the length of the analysis period (results not shown) than are those provided by the CSR.

Prior to discussion of the GIA correction to which this estimate of the rate at which the oceans are gaining mass must be subjected, there is a further important issue to be addressed. This involves the fact that when the raw GRACE field is integrated over the entire surface area of the oceans, as it has been to produce either of the above estimates, the integral will include negative contributions from the spill-over effect due to spectral leakage from the signal we have already ascribed to the disappearance of ice mass from the land. There will therefore be a correction that must be applied in order to eliminate the "double counting" that would otherwise occur. In order to compute the error thereby incurred we must compute from the results shown on Figs. 6 and 7 for the Greenland, Alaska and Antarctica signals, the parts of the negative signal within the boundaries of the target boxes that overlap onto the

Table 2
Estimates of the integral of the GRACE mass-rate field over the oceans subject to a number of different assumptions concerning subject to which the calculation has been performed, including: (1) whether or not a Gaussian filter has been applied to the raw data; (2) whether, and if so which, spherical harmonic constituents have been eliminated from the calculation; and (3) the period over which the GRACE data have been assimilated for the purpose of the analysis.

Gaussian half width	Coefficients excluded	Avg. over the oceans 62 months start-Aug 2002–end-July 2008	57 months Aug 2002–Feb 2008	49 months Aug 2002–June 2007	CSR 45 months Aug 2002–Jan 2007	GFZ 45 months Aug 2002–Jan 2007	Av of CSR and GFZ 45 m Aug 2002–Jan 2007
No filter	None	−0.14 mm/year	+0.01 mm/year	−0.20 mm/year	−0.26	−0.20	−0.23
400 km	None	−0.21 mm/year	−0.06 mm/year	−0.26 mm/year	−0.31	−0.31	−0.31
No filter	(2,0) replaced	−0.48	−0.43	−0.53	−0.49	−0.07	−0.28
400 km	(2,0) replaced	−0.55	−0.50	−0.59	−0.54	−0.18	−0.36
No filter	(2,1)	−0.26 mm/year	−0.10 mm/year	−0.30 mm/year	−0.39	−0.35	−0.37
400 km	(2,1)	−0.33 mm/year	−0.18 mm/year	−0.35 mm/year	−0.44	−0.45	−0.44
No filter	(0,0)–(2,0)	−0.41 mm/year	−0.36 mm/year	−0.46 mm/year	−0.42	−0.00	−0.21
400 km	(0,0)–(2,0)	−0.48 mm/year	−0.42 mm/year	−0.51 mm/year	−0.47	−0.10	−0.28
No filter	(0,0)–(2,1)	−0.53 mm/year	−0.47 mm/year	−0.56 mm/year	−0.55	−0.14	−0.35
400 km	(0,0)–(2,1)	−0.60 mm/year	−0.54 mm/year	−0.61 mm/year	−0.59	−0.25	−0.42

The values shown are based upon both CSR and GFZ geoids (those in brackets are GFZ based).

ocean surface. For Greenland, Alaska and Antarctica these signals are determined to be −0.25, −0.06 and −0.12 mm/year respectively in global eustatic sea level rise equivalent. The sum of these terms, namely −0.43 mm/year, must be subtracted from the integral of the raw GRACE field over the oceans in order to eliminate the influence that would otherwise arise due to double counting. The value that must be employed for the number that the raw GRACE data suggest to be indicative of the rate at which water mass is being added to the global ocean is then (-0.28 ± 0.16) mm/year – $(-0.43$ mm/year$) = +0.15 \pm 0.16$ mm/year. The proper accounting for the influence of this spill-over effect is therefore extremely important in the analysis of the closure of the sea level budget. This issue that arises when the GRACE signal is integrated over the oceans to estimate the rate at which mass is being delivered from the land appears not to have been recognized previously.

We turn next to a discussion of the GIA correction to which this estimate based upon the raw GRACE data must also be subjected. Of special note in Table 3, which provides the results of a sequence of

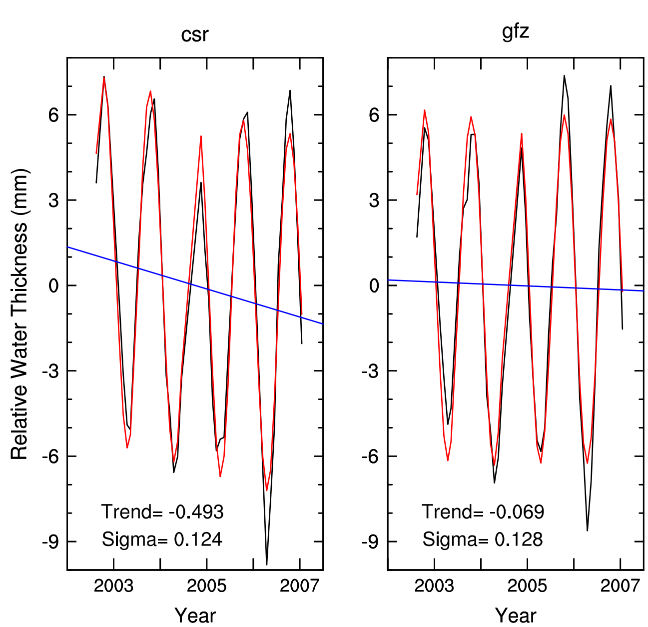

Fig. 9. Time series for the variation of mass over the global oceans derived from the CSR and GFZ reductions of the raw range rate data measured by the GRACE satellite system. The eight term model fit to the data is shown as the red curve on each plate. The secular rate of change is shown as a straight line drawn through the center of the frame. Both this secular rate of change and the 1 sigma error associated with the secular term are noted in the two parts of the figure.

variants on the computation of the required ICE-5G (VM2) mass-rate prediction over the oceans, is the impact upon the GIA correction to the GRACE data over the oceanic domain of eliminating the contribution from the Stokes coefficients of degree two and order one. Based upon Eqs. (4c, d) it will be clear that these coefficients determine the impact upon the global GIA process due to the influence of the wander of the pole induced by the ice-age glaciation and deglaciaton process. The full influence of this correction is of course assumed to be that obtained when the average is taken over the entire surface area of the oceans (the entries denoted as extending over a latitudinal range from −90 degrees to +90 degrees latitude), no filter is applied in the analysis procedure and the degree 2 and order 1 coefficients are included. The reasons why the impact of variations in the range of latitude over which the integral is performed are included in the table are twofold. First, since we also require estimates of the correction to be applied to the altimetric satellite measurements and since these systems provide data only over the latitude range from −66 degrees to +66 degrees, limited area integrations are needed for this purpose. Second, the comparison between the mass-rate correction that would be obtained from the same reduced range of integration and the full range allows us to conclude (see below) that there is a substantial impact due to the spill-over effect of GIA related positive anomaly onto the oceans The GIA corrected result obtained for the rate of increase of mass over the ocean basins is therefore:

$$\begin{aligned}\dot{M}_{\mathrm{O,rot}} &= +0.15 \pm 0.16\ \mathrm{mm/year} - (-1.80\ \mathrm{mm/year}) \\ &= +1.95 \pm 0.16\ \mathrm{mm/year}\end{aligned}$$

On the other hand, if the contribution to the inferred global warming induced rise of sea level due to the polar wander component of the rotational response is neglected, i.e. the contribution from the degree 2 and order 1 Stokes coefficients is eliminated, then the result is:

$$\begin{aligned}\dot{M}_{\mathrm{O},norot} &= +0.15 \pm 0.16\ \mathrm{mm/year} - (-1.32\ \mathrm{mm/year}) \\ &= +1.47 \pm 0.16\ \mathrm{mm/year}\end{aligned}$$

There is therefore a very substantial difference between the estimates of the rate at which mass is being added to the oceans depending upon the assumptions made regarding the influence of rotational feedback in computing the correction due to the influence of the GIA process. It is useful to note here that the result for the GIA correction obtained by eliminating the degree two and order one coefficients from the calculation is very close to the result obtained when the model of the GIA process is re-run by excluding

Table 3
Values for the glacial isostatic adjustment correction to be applied both to GRACE surface mass-rate data over the oceans (Avg. mass-rate) and Topex/Poseidon and Jason 1 data over the oceans (dGeoid) are provided for the ICE-5G(VM2) model for several variants of the analysis procedure including: (1) whether or not a Gaussian filter is applied to smooth the data; (2) whether any of the Stokes coefficients predicted by the model are eliminated from the analysis; (3) the maximum degree and order of the spherical harmonic expansions employed to characterize the ICE-5G(VM2) model predictions; and (4) the range of latitudes over which the computation is performed.

Gaussian half widths	Coefficients excluded	Maximum degree and order	Range of latitude (degrees)	Avg. mass-rate over the oceans (mm/year)	Avg. dGeoid over the oceans (mm/year)
No filter	None	120	±60	−1.98	−0.32
400 km	None	120	±60	−1.90	−0.32
No filter	(2,1)	120	±60	−1.43	−0.28
400 km	(2,1)	120	±60	−1.35	−0.28
No filter	None	120	±66	−1.99	−0.32
400 km	None	120	±66	−1.88	−0.32
No filter	(2,1)	120	±66	−1.41	−0.27
400 km	(2,1)	120	±66	−1.30	−0.27
No filter	None	120	±90	−1.80	−0.30
400 km	None	120	±90	−1.65	−0.29
No filter	(2,1)	120	±90	−1.32	−0.26
400 km	(2,1)	120	±90	−1.17	−0.26

the influence of rotational feedback on *a priori* grounds (results not shown).

The reason why results are presented which both include and exclude the contribution from the Stokes coefficients of degree 2 and order 1 is connected with a misunderstanding that has arisen in the community over the issue as to why the time rates of change of these coefficients observed by the GRACE satellite observations are not well fit by the predictions of the ICE-5G (VM2) model (in fact the C(2,1) coefficient is quite well fit whereas the S(2,1) coefficient is not; see discussion in Peltier and Luthcke, 2009). It needs to be understood that the ICE-5G (VM2) model does not include the influence of modern continental ice mass loss due to global warming. It is rather intended to represent only the influence of the Late Quaternary ice-age cycle which is assumed, in the model, to have ended approximately 4000 years ago. The predictions of this model are therefore expected to agree with GRACE observations only for those aspects of the observations that are not strongly influenced by the impact upon the time-dependence of the gravitational field of modern continental deglaciation processes. If the degree 2 and order 1 coefficients had been included for the purpose of the comparison between GRACE and ICE-5G (VM2) on Fig. 5, for example, a misfit of the model to the observations would have been revealed. This misfit should not be interpreted as indicative of a flaw in the GIA model. It is more likely to be a consequence of the fact that the collective effects of modern ice sheet melting that are under investigation herein are such as to project strongly upon the polar wander process. Although the theory that I have developed is capable of including the influence of such additional forcing, this will require a very detailed, accurate and spatially disaggregated model of the contribution of both small ice sheets and glaciers and continental dessication to employ together with forcings from the three regions of mass loss that have been under discussion herein.

It is worth comparing the above results for the GIA correction that must be applied to GRACE data over the oceans with that recently employed in Leuliette and Miller (2009) who quote Paulson et al. (2007) in support of their use of a value of −1.0 mm/year. This is almost a factor of 2 lower than the value obtained in the present analysis. Paulson and Wahr apparently believe, following some earlier discussion, that the misfit between the GRACE observations and the predictions of the ICE-5G (VM2) model is indicative of a flaw in the model. If their preferred value of the GIA correction for the rate of mass addition to the oceans were correct it would not be possible to close the sea level budget, a conclusion that is in agreement with that recently reported in Cazenave et al. (2008) who have employed the present ICE-5G (VM2) value with the full influence of rotational feedback in their analysis. If this value were employed in place of that employed by Leuliette and Miller (2009), their own result concerning the closure of the sea level rise budget would also be dramatically improved. It is also worth noting that their analysis of the budget closure problem is entirely distinct from that provided herein. It was based upon an analysis restricted to the oceanic domain in which it was the rate of global sea level rise obtained on the basis of altimetric satellite observations that was compared to the sum of the steric contribution inferred from Argo data and the mass contribution obtained from GRACE.

It is also important to note from Table 3 that the result obtained for the GIA correction is strongly dependent upon the latitudinal range over which the integral over the oceans is performed. When the highest latitudes are included the correction is rendered less strongly negative by approximately 10%. This shows that the contribution from the relatively small area of the high latitude Antarctic Ocean that overlaps the Ross Sea and the ocean immediately surrounding the Antarctic Peninsula cannot be neglected.

It is the above result for the rate that mass is being added to the oceans $\dot{M}_O$ that is to be compared to the previously obtained result for the contribution from the land $\dot{M}_L$. It will be clear that it is only the result for $\dot{M}_o$ that includes the full influence of the polar wander effect that is compatible with the result $\dot{M}_L = +2.17 \pm 0.37$ mm/year given the error bars on these quantities. The sea level budget is therefore closed insofar as the mass component is concerned if we accept the previously assumed error estimates on the individual components, the residual misfit being 1.95mm/yr–2.17mm/yr = − 0.22 mm/year. This of course assumes that the best estimate of the GIA correction is −1.8 mm/year, a result that obtains only if no filter is applied to the analysis of the field for this purpose. This is justifiable based upon the fact that the theoretically produced field if already smoothed across coastlines by the visco-elastic physics embodied in the model. If the degree two and order one coefficient is dropped in the computation of the GIA correction over the oceans, then the budget would not be closed. This further reinforces my preferred interpretation of the reason for the misfit between the GIA predicted and GRACE observed values of the Stokes coefficients of degree 2 and order 1. A dominant contribution to the misfit is due to the importance of the rotational response to modern polar ice melting.

It remains to be determined, however, whether the total rate of global sea level rise that has been measured by the altimetric satellites Topex/Poseidon and Jason-1 over the GRACE era is similarly reconciled. This total rate so measured has recently been redetermined by Cazenave et al. (2008) to have been equal to 2.5 mm/year over the GRACE era when the raw altimetric data is adjusted so as to remove the influence due to GIA contamination which is −0.3 mm/year (Peltier, 2002; a result reconfirmed by the new sequence of results tabulated in Table 3). In their paper, Cazenave et al. present two different estimates of the contribution to the global rate of sea level rise due to thermosteric influence, one based upon the difference between altimetry and GRACE and the other based upon the recently available Argo float data (Roemmich and Owens, 2000). Both estimates are, within error, consistent and equal to $\dot{S}_{\rm steric} = 0.37 \pm 0.15$ mm/year

The net rate of sea level rise is therefore predicted to be:

$$\dot{S}_{\rm net} = \dot{S}_{\rm steric} + \dot{S}_{\rm mass}$$

In which $\dot{S}_{\rm mass}$ is either $\dot{M}_L$ or $\dot{M}_O$. These two possibilities deliver the estimates:

$$\begin{aligned}\dot{S}_{\rm net} &= 0.37\ \text{mm/year} \pm 0.15\ \text{mm/year} + 2.17 \pm 0.37\text{mm/year}\\ &= 2.54\ \text{mm/year} \pm 0.52\ \text{mm/year}\end{aligned}$$

or

$$\begin{aligned}\dot{S}_{\rm net} &= 0.37\ \text{mm/year} \pm 0.15\ \text{mm/year} + 1.95 \pm 0.16\text{mm/year}\\ &= 2.32\ \text{mm/year} \pm 0.31\ \text{mm/year}\end{aligned}$$

Clearly both of these estimates are consistent with the net rate of global sea level rise of 2.5 mm/year that has been measured by the altimetric satellites over the GRACE era (Cazenave et al., 2008).

6. Summary

The availability of the time dependent gravity field observations being made by the Gravity Recovery and Climate Experiment (GRACE) satellites that are now in space has made possible a detailed check on the extent to which we are in a position to argue that the budget of global sea level rise is closed over the interval of time from 2003 to 2008 for which these data are available. At the time of the Third Assessment Report of the IPCC (2001) and the more recent Fourth Assessment Report (2007), the extent to which it was possible to argue that closure had been achieved was somewhat less compelling as the analyses were for the most part based upon the application of tide gauge recordings that extended much further back in time. The improved accuracy of these new estimates, as discussed in both Cazenave et al. (2008) and in the present paper, is therefore important but further work will be required to more tightly constrain them. Of particular importance is the most recent estimate of the small ice sheets and glaciers contribution provided by Meier et al. (2007), as the suggested error bounds on this estimate are large and the inferred contribution over the most recent 5 years is very much larger than has been suggested to be the case in previous decades, implying an accelerating contribution from this source.

Of particular importance from the perspective of this paper has been the demonstration of the important impacts upon both the GRACE and altimetric satellite measurements of global sea level rise of the global process of glacial isostatic adjustment (GIA). For Antarctica the correction of the raw GRACE observations converts a signal suggestive of mass balance into a signal suggestive of a significant contribution. For the ocean basins as a whole, the GIA correction also converts an inference based upon the raw GRACE fields that the oceans are gaining mass only very slowly into an inference that they are gaining mass at a rate that is consistent with the GRACE inferred rate at which mass is being lost from the continents.

Of special importance is the fact that the new analyses described herein demonstrate the critical contribution to the GIA correction for the integral of the mass-rate signal over the oceans associated with the process of rotational feedback. When this contribution to the GIA process is eliminated, the result is a prediction of a mass-rate correction due to GIA that is so small as to significantly exacerbate the problem of sea level budget closure. Further discussion of this issue will be found in Peltier and Luthcke (2009).

Of equal importance has been the demonstration of the importance in the sea level budget analysis of ensuring that the influence of spectral leakage of the mass loss from the land signals onto the oceanic domain in GRACE data are excluded when the integral of the raw GRACE signal over the oceans is computed.

The VM2 model of the radial variation of viscosity employed together with the ICE-5G model of global glaciation history has been constructed so as to reconcile the glacial isostatic adjustment data from both North America and Fennoscandia. The rebound data sets from these regions together constrain the viscosity to a depth of approximately 1200 km (see Peltier, 1998 for a review of the results from the application of formal inverse theory demonstrating this fact). At greater depth the viscosity is constrained by observations of GIA related anomalies in the Earth's current rotational state, respectively the ongoing true polar wander along the 76–79 degree west meridian at a rate of approximately 1 degree per million years, and the so-called non-tidal acceleration of the Earth's rate of rotation. Taken together these data sets suffice to fix the properties of the VM2 spherically symmetric visco-elastic Earth model. Since there do not yet exist the local data from Antarctica that would be necessary to demonstrate that VM2 is also appropriate for this region, the only logical assumption to make is that this model will turn out to be as appropriate there as it has proven to be elsewhere. Since the mantle of the Earth is efficiently mixed by the thermal convection process and since this high Rayleigh number process renders the radial temperature profile adiabatic in regions removed from subduction zones and upwelling thermal plumes, it would be surprising indeed if VM2 should prove an inappropriate choice for the sub-continental viscosity structure below Antarctica. The adiabat in the mixed region beneath the surface lithosphere is effectively unique.

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