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Corresponding Author: Professor William Richard Peltier, PhD

Corresponding Author's Institution: University of Toronto

First Author: William Richard Peltier, PhD

Order of Authors: William Richard Peltier, PhD

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 dessication. Since the former contribution may be estimated on the basis of both hydrographic survey data and more recently using Argus 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 are well constrained. The net rate of global sea-level rise is also measured directly by the TOPEX/POSEIDON and Jason-1 altimetric satellites. 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. The answer to this question depends critically upon the accuracy with which we are able to eliminate the contamination of both the measured rates of mass loss from the land and mass gain by the oceans due to the influence of the ongoing process of glacial isostatic adjustment. This issue is addressed in detail.

Cover Letter

DEPARTMENT OF PHYSICS - UNIVERSITY OF TORONTO, TORONTO, ONTARIO, CANADA, M5S 1A7
From:W.R. Peltier, Tel: (416)-978-2938, Fax: (416)-978-8905, e-mail:peltier@atmosp.physics.utoronto.ca

October 13, 2008

The Editor
Quaternary Science Reviews

Dear Sir:

Please consider the enclosed article entitled “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” for publication in Quaternary Science Reviews. It describes a new series of analyses that are focused upon the importance of ongoing ice-age influence upon the understanding of modern sea level history measurements being made by the GRACE gravimetric and Topex/Poseidon-Jason 1 altimetric satellites that are now in space.

Yours sincerely

W.R. Peltier DSc, FRSC
University Professor and
Professor of Physics

"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"

W.R. Peltier

Department of Physics

University of Toronto

Toronto, Ontario

Canada M5S 1A7

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 dessication. Since the former contribution may be estimated on the basis of both hydrographic survey data and more recently using Argus 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 are well constrained. The net rate of global sea-level rise is also measured directly by the TOPEX/POSEIDON and Jason-1 altimetric satellites. 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. The answer to this question depends critically upon the accuracy with which we are able to eliminate the contamination of both the measured rates of mass loss from the land and mass gain by the oceans due to the influence of the ongoing process of glacial isostatic adjustment. This issue is addressed in detail.

There are several aspects of the analysis presented here that warrant comment. First, there is the importance of the estimate for the input of mass into the oceans due to the continuing meltback of small ice sheets and glaciers over the GRACE era. The value of 1.1 mm/yr +/- 0.24 mm/yr recently provided by Meier et al (2007) is especially important to the success of the closure analysis. It is important to note that this number is more than double that thought accurate **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 assessments 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 too and well removed from these regions. When GIA contamination was eliminated from annually averaged long records from the Permanent Service for Mean Sea Level, an average rate of global sea level rise of 1.84 mm/yr 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 0.3 mm/yr, 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 3.1 mm/yr 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, the impact is accelerating.

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 mention in the abstract of this paper. Since launch of the GRACE satellite in 2002 and the beginning of the subsequent period from which useful data is available in 2003, 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 success of this analysis will depend strongly upon the accuracy with which we are able to estimate both the rates 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 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 employed for this purpose of “decontaminating” the contributions to the 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 (Peltier, 2007; Paulson et al., 2007; Peltier and Drummond, 2008). Although further refinements of this model are possible and are being pursued in the process of producing a model for use in the context of the continuing Paleoclimate Modelling Intercomparison Project (PMIP, see http://www-lsce.cea.fr/pmip2), it is expected that the existing model will provide an excellent 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 2 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 GIA influence

The detailed theory of the glacial isostatic adjustment process has been fully reviewed recently in Peltier (2007) 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 above the time dependent surface of the solid Earth, the prediction of its evolution takes the form:

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

In which θ, λ, t are latitude, longitude and time respectively, dΩ' 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:

$$L(\theta,\lambda,t) = \rho_{I}\, I(\theta,\lambda,t) + \rho_{w}\, S(\theta,\lambda,t) \quad (2)$$

In which 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 the L also involves S as in (2), equation (1) is an integral equation (of Fredholm type). Also in (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 function 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 (1), ΔΦ(t)/g is a correction that must be added to the right-hand-side of (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 (1) has been reviewed in Peltier (1998) 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 (1). Given I, (1) is then solid for S(θ, λ, t). Given this first approximation to S, Ψ^R is computed following Dahlen (1976) as:

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

with

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

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

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

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

For the purpose of the analyses to be presented in this paper it will turn out that the influence of rotation feedback on the solutions to (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, 2007) 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(θ, λ, 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:

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

$$\left. + \frac{4\pi}{(2\ell+1) g} \left(T_{\ell m}\, h_\ell^{E,T} + \sum_{k=1}^{k(\ell} q_k^{1E}\, \beta_{\ell m}^{1K} \right) \right] Y_{\ell m} \qquad (5)$$

In equation (5) "a" is the mean radius of the Earth, m_e is it's mass, $L_{\ell m}$ 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):

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

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

Given S(θ, λ, t) from (1) and U(θ, λ, t) from (5) we may then compute the time rate of charge of geoide height caused by the glaciation-deglaciation process as:

$$\frac{dG}{dt} = \frac{dS(\theta, \lambda, t)}{dt} + \frac{dU(\theta, \lambda, t)}{dt} \tag{7}$$

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

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

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 (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 (CRS) at the University of Texas in Austin, but these will be compared, where it is helpful to do so, with those from the Geoforshung centrum (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 RL04 data from CSR is cut-off at a maximum spherical harmonic degree of 60. The Stokes coefficients required to express the rate of change of the gravitational field in terms of the time rate of change of the thickness of an equivalent layer of water at the Earth's surface are computed. This involves conversion of the geoid height Stokes coefficients to mass rate coefficients through the operation (e.g. see Swenson and Wahr, 2006):

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

(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 widow 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 days, 182.625 days, and 161 days. This is therefore an 8 term fit.

(v) The coefficient of the linear term is employed to define the secular rate of change in 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 by subtracting from the mass-rate versions of the Stokes coefficients the values of the mass-rate coefficients produced by the Global Land Data Assimilation Scheme (GLDAS) as described in Rodell et al. (2004). 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).

In order to begin to fix ideas, Figure 1a shows the global surface mass-rate reconstruction based upon the analysis GRACE data by Jianli Chen of the Center for Space Research using the RL04 data set. In Figure 1b is shown the secular variation in surface mass-rate due to hydrology according to the GLDAS model of Rodell et al (2005). Inspection of the latter 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 this Figure, Figure 1d, shows the global difference between GRACE and GLDAS, demonstrating that the dominant high latitude signals are only very weakly influenced by the hydrology correction although the influence is still not negligible for Alaska as we shall see.

In Figure 2a-Figure 2c are shown the analogous results to those in Figure 1 based upon original computations performed at the University of Toronto, based respectively upon choices for the half width of the Gaussian filter of 200 km, 300 km and 400 km. Inspection will show that the Toronto analyses quite closely reproduce those of the CSR although there are slight differences in several regions. Also notable is the fact that there is very little influence of filter width upon the final result.

Focussing attention now on the North American continent and Greenland, Figure 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 numbers varied from 2 to 8. Noticeable is the fact that even the 2 term fit to the individual Stokes coefficient time series delivers a very accurate approximation to the more accurate 8 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 north polar ice due to greenhouse gas induced global warming. Figure 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, the latter being the width suggested by the earlier work of Wahr et al. (1998). 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.

The 8 term fit to the hydrology corrected GRACE observations are compared with the predictions of the ICE-5G (VM2) model on Figure 5. Notable 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 Figure 5(b). 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 Figure 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. It is towards the understanding of these signals and the related signals observed over the Antarctic continent that this paper is directed.

Before proceeding with their analysis, 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 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 ^{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. 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 correspond very closely to VM2. Given that ICE-5G provides an excellent fit to 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), and that the VM2 viscosity structure also fits the rebound data from both Fennoscandia (Peltier, 2004) and the British Isles (Peltier et al., 2002), the model is expected to provide the best presently available means of assessing the magnitude of the contamination of the GRACE and altimetric satellite measurements of surface mass variations involved in the modern rate of global sea level rise.

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, Figure 6 inter-compares two results for GRACE-GLDAS-ICE-5G. The first of these employs the ICE-5G loading history as published whereas the second, labelled "Stop at 2 KBP" shows the result obtained when the original deglaciation history for Greenland in the ICE-5G model is modified by eliminating the Neoglacial re-advance of Greenland ice contained in the Greenland model of Tarasov and Peltier (2002) after 2000 years before present. Evident is the fact that this modifies the observed rate of surface mass change only slightly. In order to estimate the Greenland contribution to the present day rate of relative sea level rise, this field is integrated over the box whose latitudinal boundaries are 55.1 degrees north and 89.9 degrees north and whose longitudinal boundaries are 269.9 degrees east and 359.9 degrees east, respectively. To estimate the error in the mapping of this integral into a rate of global sea level rise, we first include in this integral only the area with the box in which the field is negative. This gives a result for the rate of global sea level rise based upon the use of CSR geoids of 0.55 mm/yr or 0.48 mm/yr based upon the use of GFZ geoids. When both negative and positive values of the field are included the result drops to 0.50 mm/yr(CSR) or 0.44mm/yr(GFZ). Given that there is clearly "leakage" of this signal from the continent itself onto the surface of the surrounding ocean (e.g. see Luthcke et al., 2006) and given that when effort is made to connect for this influence (op.cit.) the inferred rate of global sea level rise caused by the loss of land ice from Greenland is somewhat reduced, I will take a value of 0.5mm/yr +/-0.05 mm/yr to represent a best estimate of the modern rate of sea level rise due to land ice melting from this source, recognizing that a small effect due to double counting may be involved when GLDAS data is employed to correct the Greenland GRACE field. My best estimate of the maximum contribution to globl sea level rise over the GRACE era is 0.55 mm/yr.

Figure 7 presents equivalent results to those in Figure 6 but for the region of Alaska where the second of the major northern hemisphere negative anomalies is located. This compares the GRACE observation based upon CSR geoids with the signal corrected for the influence of surface hydrology. The hydrology correction in this region is clearly non-negligible and its application by subtraction from the raw GRACE observation makes the signal somewhat more negative. When this signal is integrated over the latitude range from 47. degrees north latitude to 89.9 degrees north latitude, and 180.2 degrees longitude to 240.1 degrees longitude, 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 0.18 mm/yr (CSR geoids) or 0.15mm/yr (GFZ geoids) where only the negative signal within the box is allowed to contribute to the integral, a value that is reduced to 0.08 mm/yr (CSR geoids) or 0.02mm/yr (GFZ geoids) when both the negative and positive regions within the box are allowed to contribute to the integral, I will assume a value of 0.1 mm/yr to represent a best estimate of the contribution from Alaska to the modern rate of global sea level rise over the GRACE era, recognizing that the error on this estimate may be as large as 0.5 mm/yr. The maximum contribution I will take to be 0.15 mm/yr.

The final region of interest for the purpose of these analyses is the continent of Antarctica. Figure 8a shows the results of detailed analyses of the GRACE fields over this region based upon the use of CSR geoids. The Figure shows both the GRACE result corrected for surface hydrology, the prediction of the surface mass rate field from the ICE-5G (VM2) model, and the difference between these results which represents the Antarctic field corrected for the influence of the continuing action of the GIA process since the end of the last deglaciation event of the Late Pleistocene ice-age. Figure 8b shows the results of the equivalent analyses from the GFZ geoids are used in place of those generated by the CSR Analysis Centre. Comparison of the results in Figure 8a with those in Figure 8b, demonstrates that although the fields are strikingly similar, differences do exist. In the case of Antarctica, we are much better able to isolate the net mass balance of the continent from the GIA corrected GRACE data set simply by integrating the full field over the latitudinal range from the coastline of the continent to -90 degrees south latitude and over all longitudes. 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 (2006). For example if, using the CSR geoids, we simply integrate the GLDAS corrected GRACE mass rate field directly over land, that is neglecting the GIA correction, we obtain an implied rate of global sea level rise of -0.055 mm/yr, a number that decreases to -0.062 mm/yr if the GLDAS correction is not made. The GFZ geoids, on the other hand, give a rate of -.018 mm/yr decreasing to -0.025 mm/yr if the GLDAS correction is not made. 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 0.15 mm/yr when the integral is restricted to apply only over land. In comparison, the GFZ geoids imply a contribution of the global sea level rise of 0.19 mm/yr when the integration of the mass-rate field is performed over land only (of course allowing both positive and negative values of the field to contribute to the integral). These values are to be compared with that proposed by Ivins and James (2005) who obtain a value of approximately 0.5 mm/yr for the present day contribution of Antarctica to the rate of global sea level rise. Their result appears to be primarily due to the assumption of a radial variation of mantle viscosity that differs significantly from the VM2 model in that the viscosity beneath a depth of 660 km is approximately 5x that of the VM2 model that has now been verified as accurate by the GRACE observations over the Canadian land mass (Peltier 2007; Paulson et al., 2007; Peltier and Drummond, 2008). Since there do not exist data from the south polar region itself that would allow one to infer a new model on the basis of such local data, the Ivins and James result must be considered to be entirely speculative. Furthermore, the loading model employed by these authors is not in accord with the new 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). Based upon these analyses I will assume a value of 0.2 mm.yr of global sea level rise to represent an upper bound on the contribution of Antarctic land ice melting to global sea level rise over the GRACE era.

The final input of water mass into the oceans over the GRACE era is that potentially derived from the surface of all continents. 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 mass over the continents but the GRACE signal over these regions includes a strong contribution from GIA, not only in ice covered regions but also from elsewhere due to the influence of hydro-isostasy. It is probably more useful for present purposes to estimate the impact of continental warming by directly integrating the GLDAS global surface hydrology field over the extra-polar continents. This integral delivers a result that accords with a-priori expectations that continental drying should result in a net transfer of water from the land to the oceans and therefore to an additional contribution to the rise of global sea level. When the global GLDAS field shown in Figure 2b is integrated in this way, it implies a rate of global sea level rise due to continental dessication of 0.14 mm/yr. This estimate is very close to that recently obtained by Ramillien et al. (2008) based upon the analysis of GRACE data itself which led them to prefer a value of 0.17 mm/yr on these different grounds.

If we simply add the previously enumerated contributions to the increase of the mass of water being added to the ocean basins, taken together these imply a maximum net rate of global sea level rise of $\dot{M}'_L = 0.55$ mm/yr (Greenland-maximum) + 0.15 mm/yr (Alaska-maximum) + 0.20 mm/yr (Antarctica-maximum) + 0.14 mm/yr (GLDAS-continents) = 1.04 mm/yr (maximum).

To this total we must add the input to the oceans that derives from the melt-back of the small ice-sheets and glaciers of the world, for which the most recent estimate over the GRACE era (Meier, et al., 2007) is 1.1 mm/yr with an error bar of ± 0.24 mm/yr. I will take the latter error bar to approximate that for the maximum rate at which mass is being added to the ocean basins from the land:

$$M_L = \dot{M}'_L + 1.1 \text{ mm/yr} = 2.14 \text{ mm/yr.} \pm 0.24 \text{ mm/yr (maximum)}$$

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 will be considered to be compatible with closure of 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 oceans (the global field is that shown on Figure 1), I infer an average rate of global sea level <u>rise</u> to be -0.1 mm/yr when either the CSR or GFZ geoids are employed to make the estimate. It is important to note, as is made explicit in Table1, 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. The variants upon the analysis procedure for which results are provided in Table 1 include: (1) the range of latitudes over which the ICE-5G(VM2) mass-rate field is integrated over the oceans, (2) the degree and order in the spherical harmonic expansions employed in constructing solutions to the Sea Level equation, and (3) the terms omitted in the representation of the mass-rate field It is nevertheless true that 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 occurring but the amount of mass contained within these basins is actually 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 themselves.

Of special note in Table 2, which provides the results of a sequence of variants on the computation of the 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 due to the Stokes coefficients of degree 2 and order one. Based upon equations (4c-4d) 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. When the full influence of this contribution to the rate of mass increase over the oceans is taken into account in inferring the rate to be attributed to the global warming of the lower atmosphere, the following result is obtained:

$$\dot{M}_{O,rot} = -0.1mm/yr - (-2.0mm/yr) = +1.9mm/yr$$

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, then the result is:

$$\dot{M}_{O,norot} = -0.1mm/yr - (-1.4mm/yr) = +1.3mm/yr$$

There is therefore a very substantial difference between the rate at which mass is inferred to being added to the oceans depending upon the assumptions made in computing the correction due to the influence of the GIA process.

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 $\dot{M}_L = +2.14mm/yr +/- .24mm/yr$. 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.

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 has been recently determined by Cazenave et al (2008) to have been equal to 2.5mm/yr when the raw altimetric data is adjusted so as to remove the influence due to GIA contamination which is -0.3mm/yr (Peltier,2002). 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, identical and equal to $\dot{S}_{steric} = 0.37mm/yr$. The net rate of sea level rise is therefore predicted to be:

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

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

$$\dot{S}_{net} = 0.37mm/yr + 2.14mm/yr = 2.51mm/yr + /-.24mm/yr$$

or

$$\dot{S}_{net} = 0.37mm/yr + 1.9mm/yr = 2.27mm/yr + /-.24mm/yr$$

Clearly these estimates are both consistent with the net rate of global sea level rise of 2.5mm/yr that has been measured by the altimetric satellites over the GRACE era (Cazenave et al., 2008). We may therefore assume that the sea level budget over this 5 year interval of time is closed.

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 2003-2008 for which these data are available. at the time of the Third Assessment Report of the IPCC (2001). The accuracy of this revised estimate is therefore extremely important and further work will be required to more tightly constrain it through both detailed local mass balance analyses that may be employed to test the efficacy of the extrapolation methods on which the global estimates must be made. Second, there is the importance of the estimate of the rate of mass loss from the Antarctic ice sheet which so strongly depends upon the correction for the influence of the glacial isostatic adjustment process. I have previously noted the marked difference between the estimate published by Ivins and James (2006) and that obtained in the present work in which all of the estimates of the GIA correction have been based upon the ICE-5G(VM2) model of Peltier (2004). If the Ivins and James inference of 0.5 mm/yr in global sea level rise equivalent were correct, this would add an additional 0.3 mm/yr to the ICE-5G(VM2) estimate of 2.14 mm/yr to imply a rate of mass addition from the land to the ocean of 2.44 mm/yr. When we add to this the 0.37 mm/yr of global sea level rise due to the steric effect of ocean warming we obtain a predicted net rate of global sea level rise of 2.81 mm/yr, significantly in excess of the net rate of 2.5 mm/yr required to fit the satellite altimetric measurements being provided by Topex/Poseidon and Jason 1. My conclusion is that Ivins and James estimate of the current rate of mass loss from Antarctica is excessive, a flaw due to their use of a model of the GIA process that is characterized by an invalid model of the depth dependence of mantle viscosity. Since the VM2 model of the deep structure of mantle viscosity has been confirmed by the analysis of GRACE data over the once ice covered region of the North American continent (Peltier, 2007; Paulson et al., 2007; Peltier and Drummond, 2008) it remains the best such model currently available.

An equally important aspect of the analyses presented here, however, concerns the value of the correction required to the GRACE data over the ocean basins themselves. I have shown that this correction is strongly dependent upon the magnitude of the contribution due to the influence of rotational feedback onto post glacial sea level history. This is controlled by the polar wander contribution to this influence, one that is carried by the secular rates of change of the degree 2 and order 1 Stokes coefficients. If these terms, as predicted by the ICE-5G (VM2) model, are simply set to zero then the magnitude of the GIA correction to the GRACE mass-rate field over the oceans is so significantly reduced (see Table 2) that the inferred rate of mass increase over the oceans ceases to correspond, within the observational error, to the rate of mass loss from the land. This may be construed to constitute a demonstration that the rates of change of these coefficients being predicted by the ICE-5G (VM2) model are accurate. This remains a significant issue in GRACE data analysis, one that will require further attention.

Table 1. Presents estimates of the integral of the GRACE mass-rate field over the oceans subject to a number of different assumptions concerning the detailed assumptions 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, (3) the period over which the GRACE data have been assimilated for the purpose of the analysis. The values shown are all based upon CSR geoids excepting those in brackets which are based upon GFZ geoids.

Gaussian half-width	Coefficients excluded	Avg. over the oceans 62 months Start--August 2002 End -- July 2008	57 months August--2002 February--2008	49 months August--2002 June--2007
No filter	none	-0.14 mm/yr (-0.19)	+0.01 mm/yr	-0.20 mm/yr
400 km	none	-0.21 mm/yr (-0.26)	-0.06 mm/yr	-0.26 mm/yr
No filter	(2,1)	-0.26 mm/yr (-0.31)	-0.10 mm/yr	-0.30 mm/yr
400 km	(2,1)	-0.33 mm/yr (-0.38)	-0.18 mm/yr	-0.35 mm/yr
No filter	(0,0)--(2,0)	-0.41 mm/yr (-0.24)	-0.36 mm/yr	-0.46 mm/yr
400 km	(0,0)--(2,0)	-0.48 mm/yr (-0.31)	-0.42 mm/yr	-0.51 mm/yr
No filter	(0,0)—(2,1)	-0.53 mm/yr (-0.36)	-0.47 mm/yr	-0.56 mm/yr
400 km	(0,0)—(2,1)	-0.60 mm/yr (-0.43)	-0.54 mm/yr	-0.61 mm/yr

Table 2. 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, and (3) the maximum degree and order of the spherical harmonic expansions employed to characterize the ICE-5G(VM2) model predictions.

Gaussian half-widths	Coefficients excluded	Max degree and order	Avg. mass-rate over the oceans	Avg. dGeoid over the oceans
No filter	none	120	-1.98 mm/yr	-0.32 mm/yr
400 km	none	120	-1.90 mm/yr	-0.32 mm/yr
No filter	(2,1)	120	-1.43 mm/yr	-0.28 mm/yr
400 km	(2,1)	120	-1.35 mm/yr	-0.28 mm/yr
No filter	none	57	-1.97 mm/yr	-0.32 mm/yr
400 km	none	57	-1.90 mm/yr	-0.32 mm/yr
No filter	(2,1)	57	-1.42 mm/yr	-0.28 mm/yr
400 km	(2,1)	57	-1.35 mm/yr	-0.28 mm/yr

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Figure Captions

Figure 1. (a) The CSR reconstruction of the GRACE surface mass–rate field, (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).

Figure 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 km, 300 km, and 400 km. Noticeable is the fact that the dependence upon the filter width is weak.

Figure 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.

Figure 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 km, 300 km, 400 km and 500 km.

Figure 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.

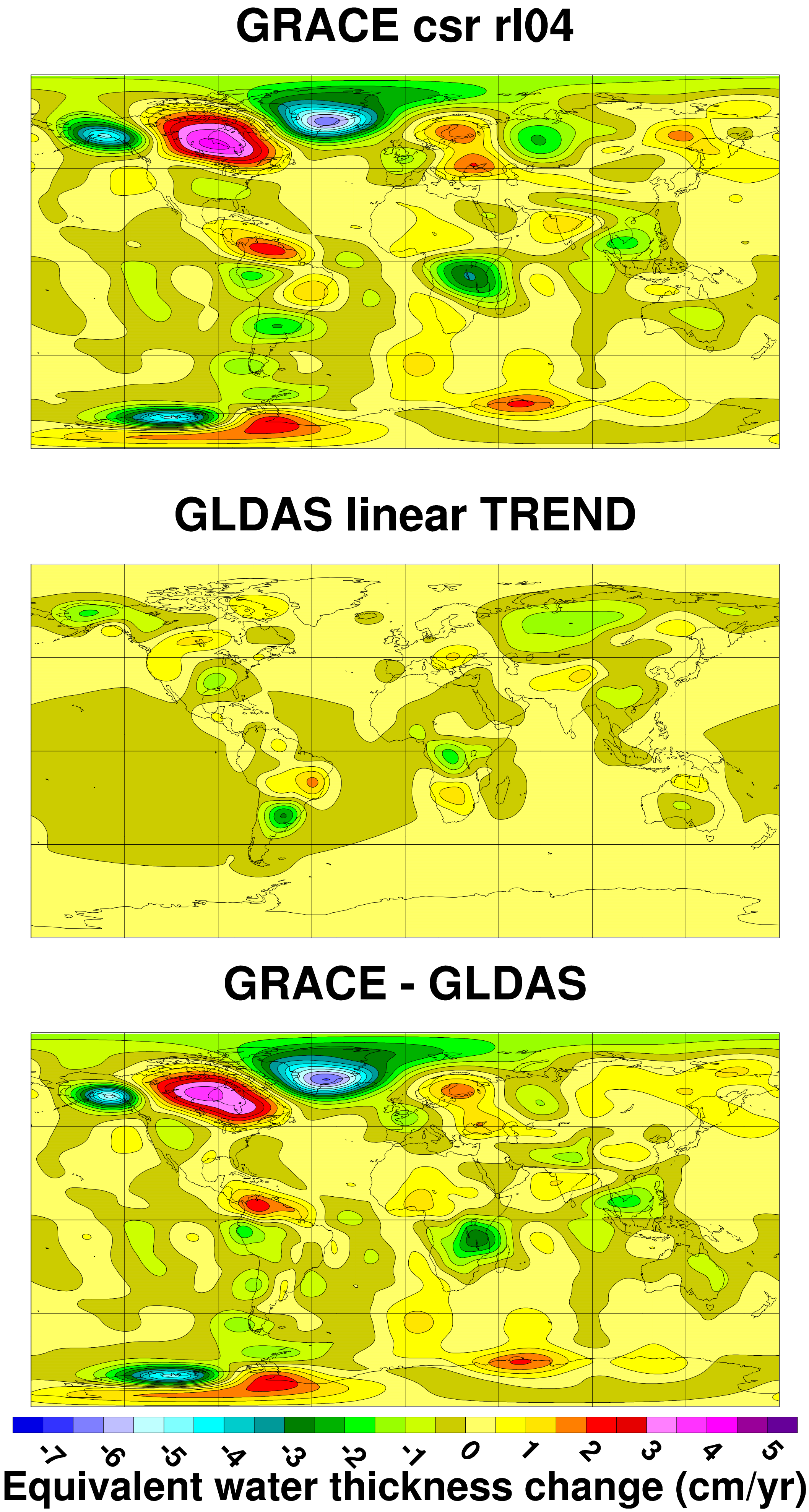
Figure 6. Surface mass-rate field over Greenland corrected for the influence of surface hydrology using the predictions of the ICE-5G (VM2) model in which it was hypothesized that the Neoglacial re-advance of land ice continued up to the present. Also shown is the result for this region in which it is assumed, more reasonably, that this Neoglacial re-advance ended 2000 years ago.

Figure 7. Surface mass-rate field over Alaska, both uncorrected and corrected for the influence of surface hydrology.

Figure 8a. Inferred surface mass-rate field over Antarctica based upon the use of CSR geoids together with the predicted mass-rate field for this region based upon the ICE-5G)VM2) model of the glacial isostatic adjustment process. Also shown is the difference between these two fields which is the basis for the computation of the contribution to the rate of global sea level rise derivative of this geographical region over the GRACE era.

Figure 8b. Same as Figure 8a but based upon the use of GFZ geoids.

Figure


GRACE csr rl04
GLDAS linear TREND
GRACE - GLDAS
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-6
-5
-4
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-2
-1
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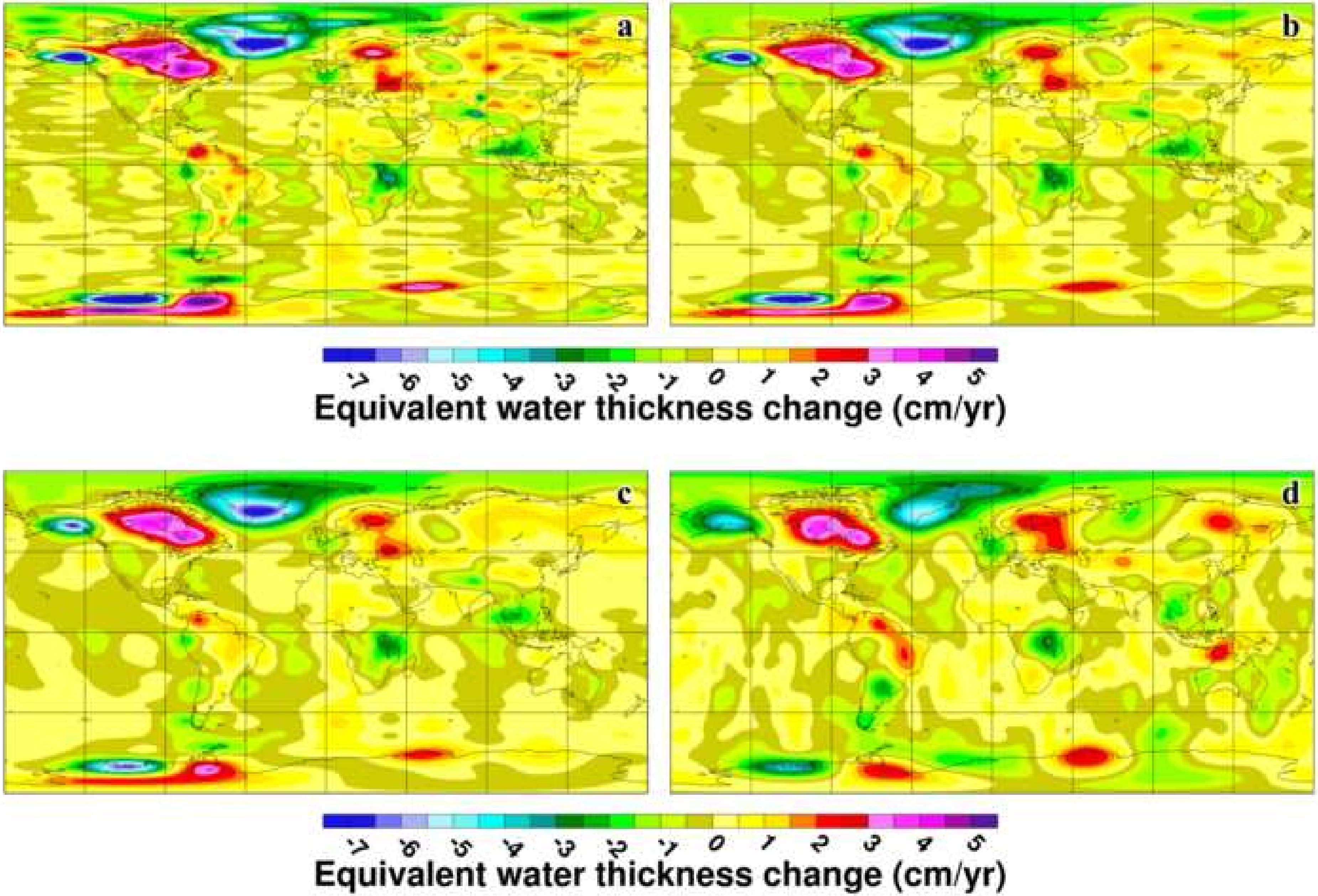
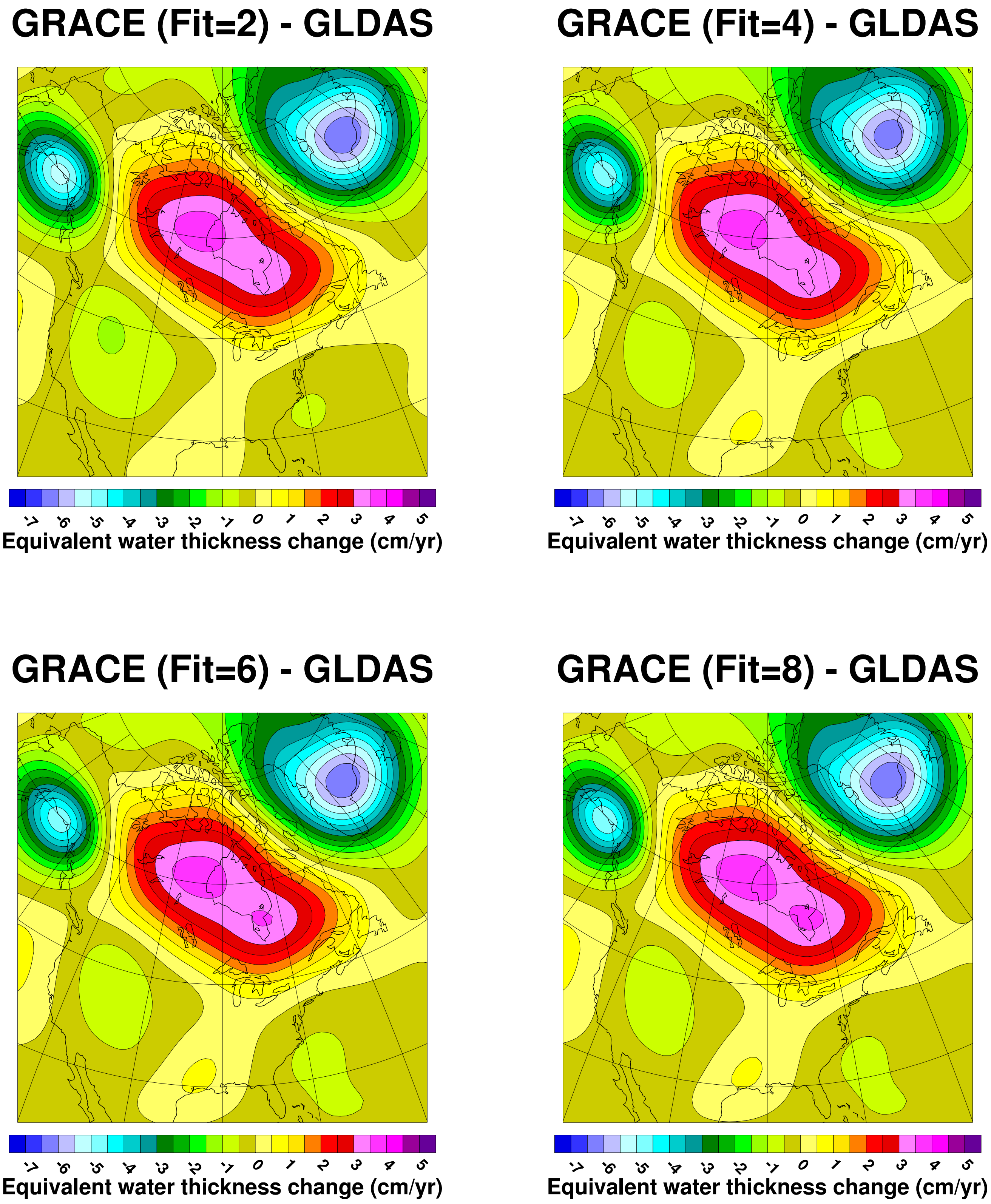
1
2
3
4
5
Equivalent water thickness change (cm/yr)

Figure


a
b
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
Equivalent water thickness change (cm/yr)
c
d
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
Equivalent water thickness change (cm/yr)

Figure



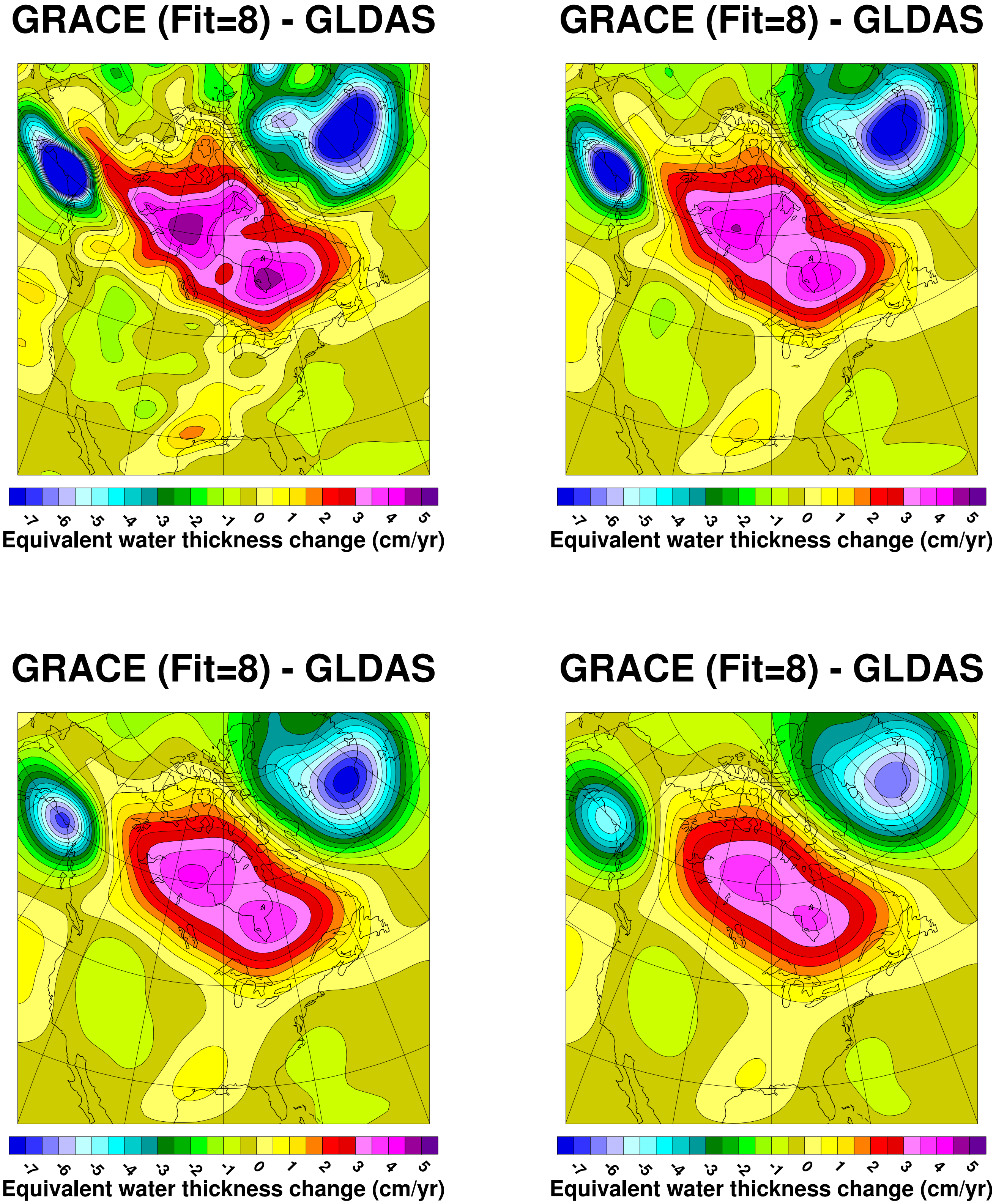
GRACE (Fit=2) - GLDAS

GRACE (Fit=4) - GLDAS

GRACE (Fit=6) - GLDAS

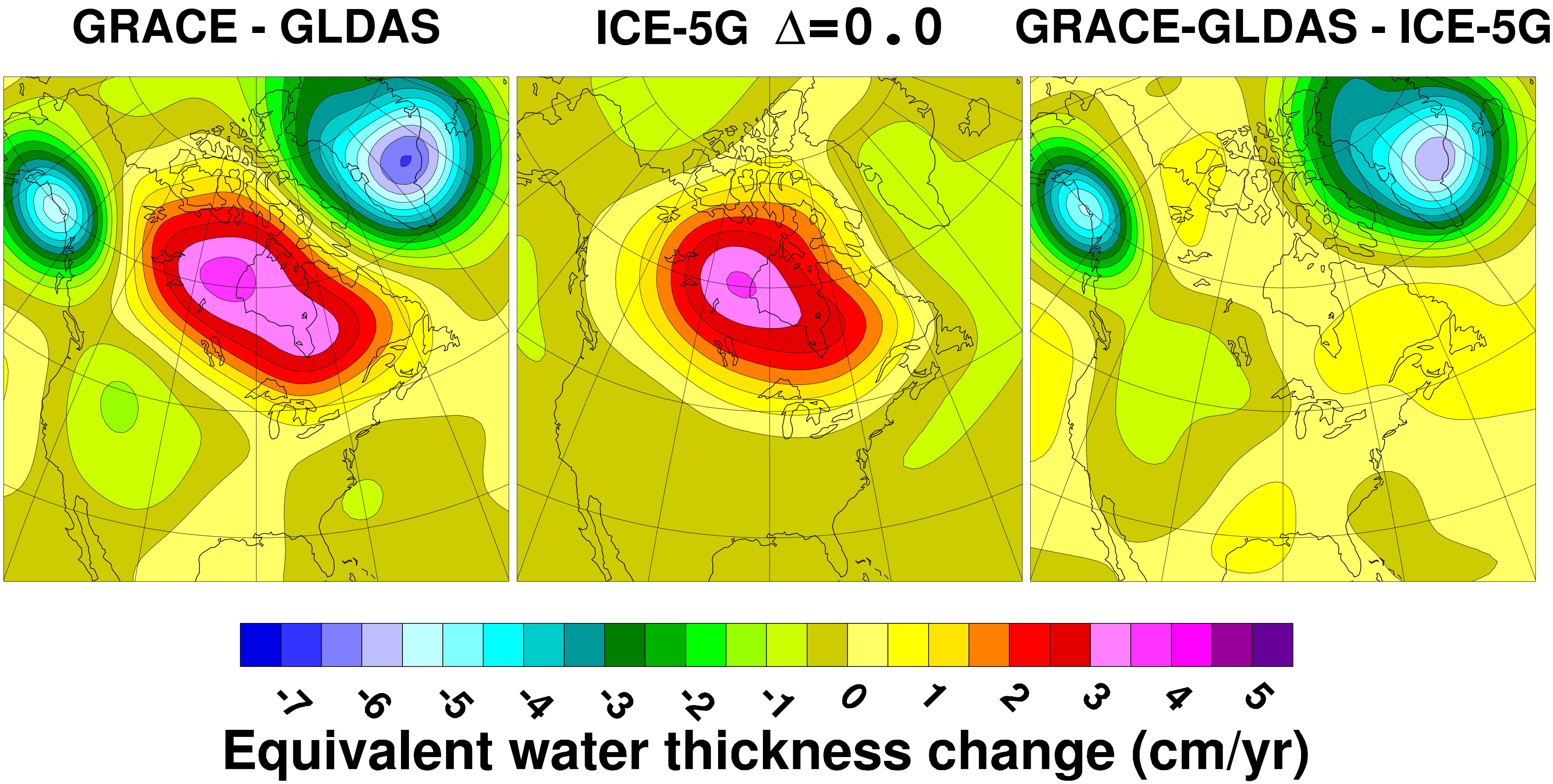
GRACE (Fit=8) - GLDAS

Figure



Gaussian halfwidths 200,300,400,500Km

Figure


GRACE - GLDAS
ICE-5G Δ=0.0
GRACE-GLDAS - ICE-5G
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-6
-5
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-3
-2
-1
0
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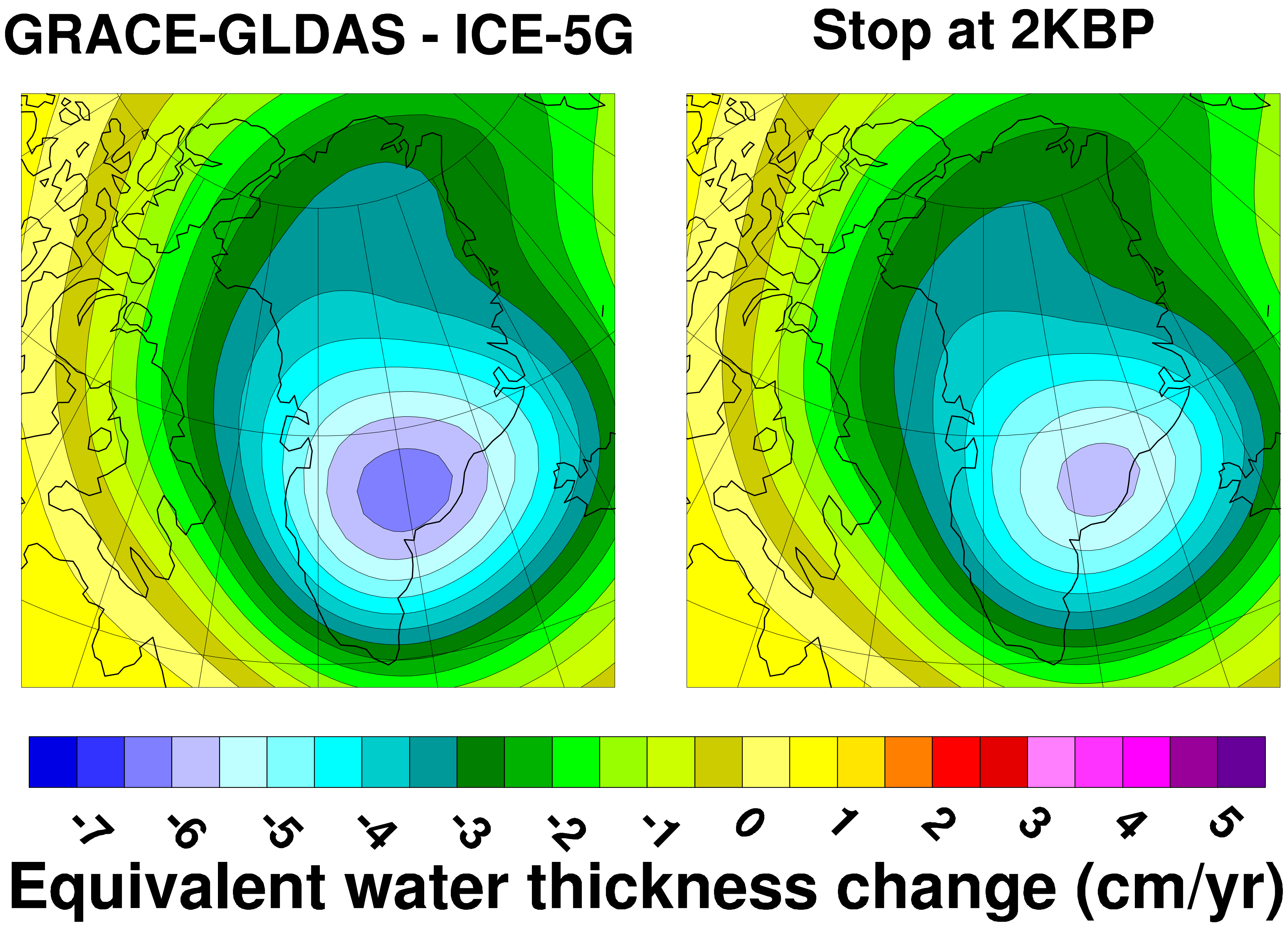
2
3
4
5
Equivalent water thickness change (cm/yr)

Figure


GRACE-GLDAS - ICE-5G
Stop at 2KBP
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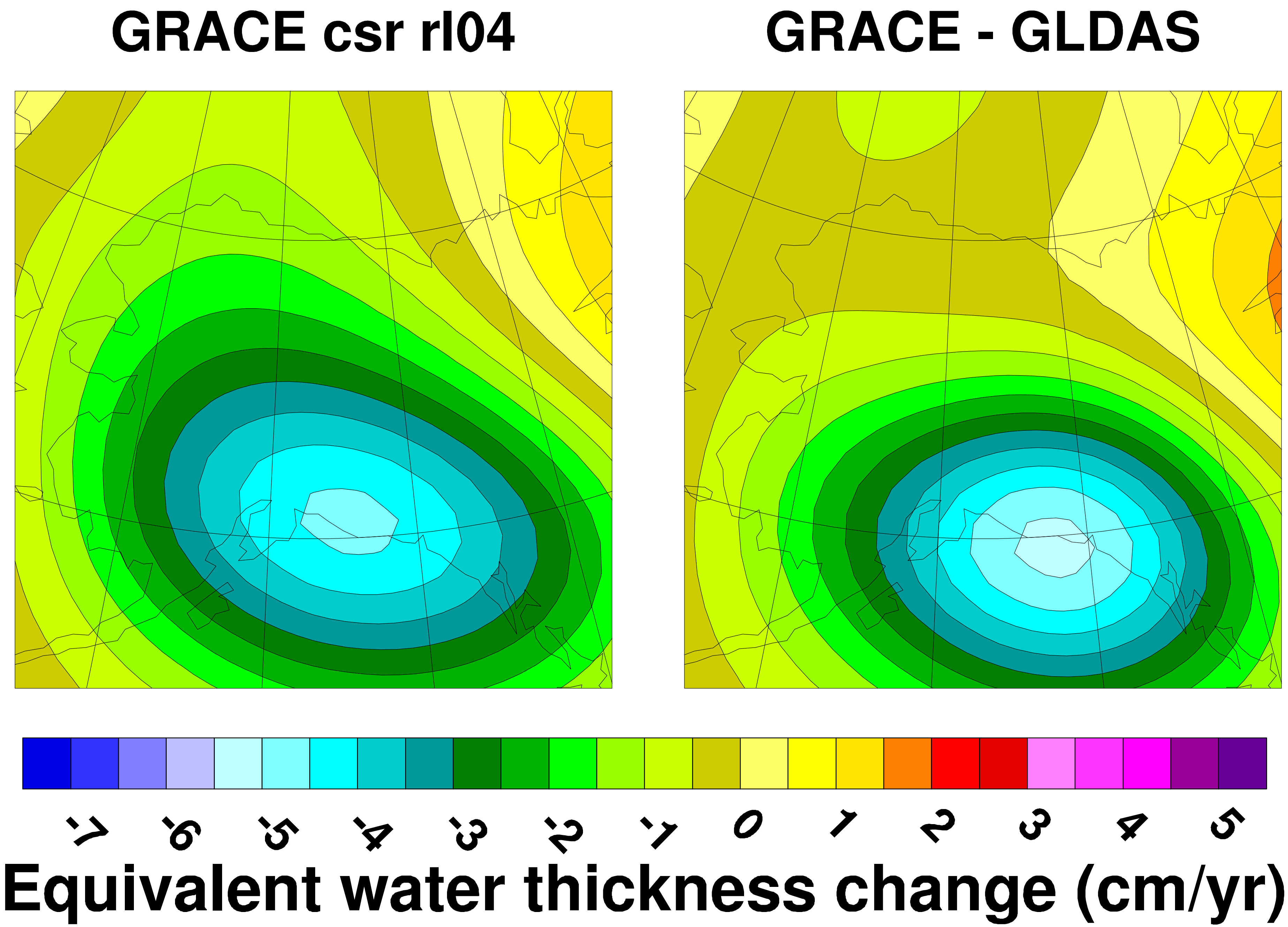
5
Equivalent water thickness change (cm/yr)

Figure


GRACE csr rl04
GRACE - GLDAS
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-6
-5
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-3
-2
-1
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2
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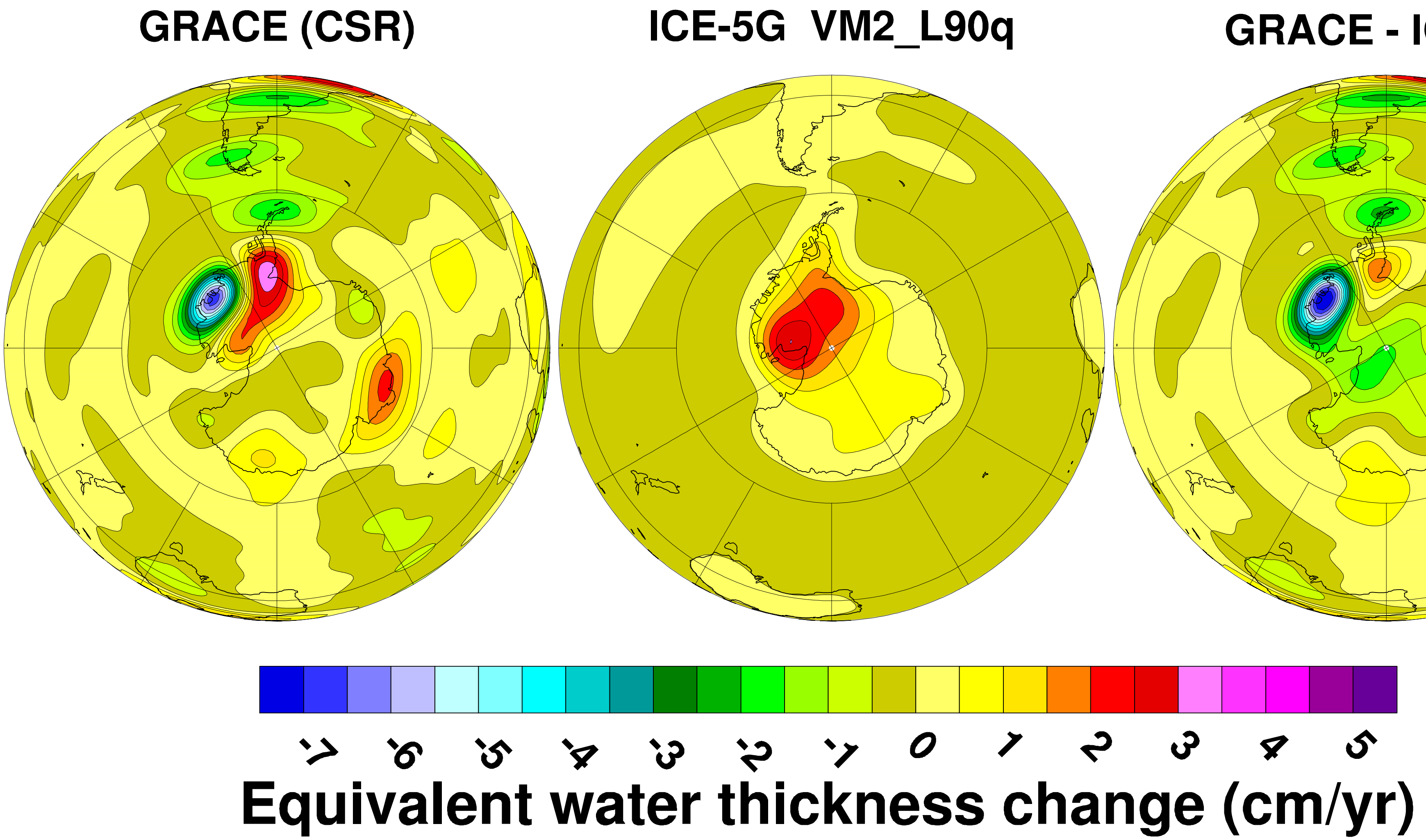
4
5
Equivalent water thickness change (cm/yr)

Figure


GRACE (CSR)
ICE-5G VM2_L90q
GRACE - ICE-5G
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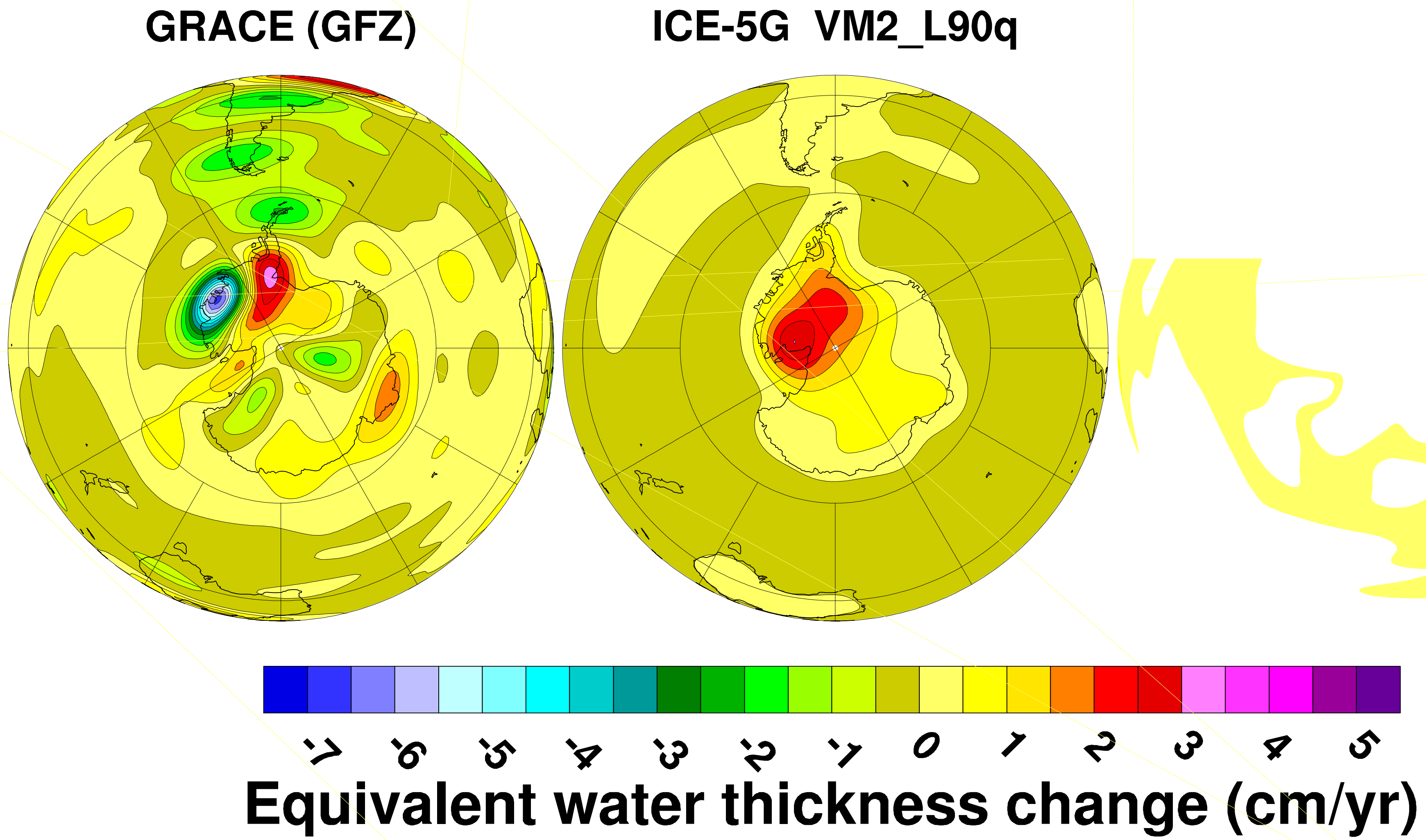
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
Equivalent water thickness change (cm/yr)

Figure


GRACE (GFZ)
ICE-5G VM2_L90q
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
Equivalent water thickness change (cm/yr)