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► **To cite this version:**

Laurent Métivier, Marianne Greff-Lefftz, Zuheir Altamimi. On secular geocenter motion: The impact of climate changes. *Earth and Planetary Science Letters*, 2010, 296, pp.360-366. 10.1016/j.epsl.2010.05.021 . insu-03605306

HAL Id: insu-03605306

<https://insu.hal.science/insu-03605306>

Submitted on 21 Apr 2024

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On secular geocenter motion: The impact of climate changes

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We investigate the impact of recent climate changes on the long-term displacement of the Center of Figure (CF) of the Earth (also defined as the geocenter in our convention) with respect to the Center of Mass of the whole Earth (CM). The two realizations of the International Terrestrial Reference System (ITRS), entitled ITRF2000 and ITRF2005, present a difference of 1.8 mm/yr between the velocities of their respective frame origins, suggesting an acceleration of the geocenter towards the North Pole. We investigate if such a displacement could be explained by geophysical phenomena, such as the present ice melting and the sea level rise. Using published observations on ice caps and glaciers, we calculated the range of geocenter motion that may occur today. We found that the global ice melting induces long-term displacements of the geocenter mainly along the Z-axis, toward the North Pole. The geocenter velocity is today between 0.3 and 0.7–0.8 mm/yr and has doubled during last decade with the recent acceleration of ice melting. Combining with Greff-Lefftz (2000) results on post-glacial rebound, we conclude that a present secular geocenter velocity of 1 mm/yr is possible. However, the recent increase of the geocenter velocity cannot explain the difference observed between the two last realizations of the ITRS. Our results comfort the previous conclusions about ITRF2000 and ITRF2005 and the pre-analysis of ITRF2008 data, suggesting that the large Z-translation rate between the ITRS realizations is probably due to an imprecise ITRF2000 origin. Finally, we show that determining precisely the geocenter velocity would give a new type of information that may be useful to more precisely constrain mass exchanges associated with climate changes.

1. Introduction

Mass redistributions within the Earth induce displacements of the center of mass of the whole Earth (CM) with respect to its purely geometrical center of figure (CF), and inversely. In the present study we define as geocenter the CF of the Earth. Note that in other studies the geocenter is sometimes defined as the CM.

Reference systems, which are used to express positions on the Earth, aimed at being centered with respect to the CM of the whole Earth system, including the oceans and the atmosphere, as for the International Terrestrial Reference System (ITRS). Current realizations of the ITRS (called International Terrestrial Reference Frame—ITRF) are constructed by combination of individual frames determined from observations of four space geodesy techniques: Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Positioning System (GPS) and Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS). The ITRF origin is defined in such a way that there is nulls translation and translation rate between

the ITRF and the SLR individual frame used in each ITRF solution. Assuming the SLR frame origin is the center of mass (point around which the satellite orbits), the ITRF origin is consequently the mean Earth center of mass, averaged over the time span of the SLR observations used and modeled as a secular (linear) function of time. However the position of the CM within the Earth is not easily determined and its observation may present artificial and/or geophysical motions that will impact the accuracy of the reference system realization, and therefore the precision of the positions determination on the Earth, using GPS for example.

Unlike the ITRF2000 where global long-term solutions of the individual techniques were used, the ITRF2005 uses as input data time series (weekly from satellite techniques and 24-hour session-wise from VLBI) of station positions and daily Earth Orientation Parameters (EOPs). Time series have the advantage that we can monitor not only the station behavior (non-linear motion and discontinuities), but also the reference frame parameters, especially the physical ones: the origin and the scale. The SLR solutions submitted to the ITRF elaboration use the entire history of observations, up to 2000.0 in case of ITRF2000, and up to 2005.0 for the ITRF2005.

The ITRF2005 presents a particularly large translation rate of 1.8 mm per year along the Z-component (the south–north axis of the frame) with respect to the ITRF2000 (Altamimi et al., 2002, 2007). Such a rate is particularly large considering that a stability of the frame

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origin at the 0.1 mm/yr level is required for Earth science applications. If it has a geophysical origin, it would imply an acceleration of the geocenter quite exceptional. Actually at the time of writing, a pre-analysis of the input data of the ITRF2008 (being under preparation) shows negligible rate of the later with respect to ITRF2005 (Altamimi et al., 2010). Consequently the rate between ITRF2005 and ITRF2000 is most likely an indication of an imprecise origin of the ITRF2000 solution. This large rate could be induced by the heterogeneous shape of the station measurement network or technique systematic errors (Collilieux et al., 2009). On the another hand, we do not know exactly what kind of long-term and secular geocenter motions one could expect to observe today and that may perturb (directly or indirectly) ITRF determination. Only a very few studies investigated partly this aspect of geophysical processes. Yet, a precise and stable determination of the ITRF is fundamental today to interpret precise position measurements. It will impact, for example, the determination of sea-level rise (Morel and Willis, 2005; Beckley et al., 2007; Wöppelmann et al., 2009), in which precise estimation is today crucial for scientific and human reasons.

The geocenter motion at secular timescale is due to the combined impact of different geodynamical phenomena, including the post-glacial rebound, the mantle dynamics, continent mass redistributions induced by plate tectonics, large period climatic variations, etc. Greff-Lefftz (2000) investigated theoretically the impact of the post-glacial rebound on secular geocenter motions. Depending strongly on the Earth's internal viscosity, Greff-Lefftz (2000) showed that the present post-glacial rebound may induce geocenter motion up to the 0.5 mm/yr. Recently, Greff-Lefftz et al. (2010) investigated the impacts of mantle convection and continent lateral motions. They concluded that these phenomena lead today to a geocenter displacement rate close to 1 mm/century, which is negligible considering the present precision of positioning measurements (see also Barkin, 1999). Geocenter motions may also be induced by the climate dynamics. Water and ice mass redistributions within the surface fluid layers of the Earth induce a surface loading on the solid Earth that will deflect the surface and change the gravity. Mass redistributions and surface deformations both affect the geocenter position. The questions we want to address in the present paper are: what impact has the last decade climate changes on the apparent secular geocenter motion and its determination? Does this geocenter long-term motion help to evaluate the accuracy of ITRF origin? Finally, can we infer information on the climate evolution from geocenter motion observations?

In the first section of this paper, we review the different studies that quantified the ice mass changes on Earth. In the second section we present the surface loading theory. In the third section, the geocenter motion is calculated. We then discuss and conclude in the last section.

2. Today and past ice melting

Geocenter motions are essentially induced by mass redistributions in and between the surface fluid layers, such as oceans, the atmosphere, ice sheets, or the continental hydrology. In recent climate changes, the most important mass exchange that has been observed between fluid layers seems to be a global ice melting, creating water that mainly goes to the oceans and participates to the sea level rise. Such dynamics may impact the long-term geocenter velocity. In the present study, we investigate this geocenter long-term motion, using observations on glaciers and polar ice sheets.

Satellite altimetry measurements have detected a sea-level rise of 3.1 mm/yr during the last decade (Cazenave and Nerem, 2004), which is approximately two times larger than the mean sea level rise observed during the last century using tide gauge observations (Church and White, 2006; Wöppelmann et al., 2007; Milne et al., 2009). Such discrepancy may be interpreted as a recent acceleration in sea level rise due to a recent global climate change. However, it may

also be due to the short time window of observation of satellite altimetry, or to the uneven distribution of tide gauges around the world (e.g., Conrad and Hager, 1997). A recent study shows that satellite altimetry observations seem coherent with tide gauges recent observations (Prandi et al., 2009), tending to confirm an acceleration in the sea-level rise. It has been largely shown that such acceleration in sea-level rise is most probably due to the thermal expansion of oceans (e.g., Antonov et al., 2005; Nerem et al., 2006), which do not theoretically involve any mass redistributions, neither geocenter motions. However, a component is also coming from ice melting, particularly from Greenland and Antarctica ice sheets, and non-polar glaciers (e.g., Nerem et al., 2006). Such component may lead to geocenter displacements over time, displacements that have never been clearly quantified (a partial estimation has been made by Argus (2007), for a melting of Antarctica ice sheet equivalent to 1 mm/yr of eustatic sea level rise).

The melting of Greenland and Antarctica ice caps is today observed and debated. If melting of glacier is clearly observed on many coastal regions (e.g., Hock et al., 2009), the global mass balance of the ice sheets is still discussed.

In Greenland, Rignot and Kanagaratnam (2006), using satellite radar interferometry observations, concluded that the ice mass deficit has doubled during the last decade, from 90 to 220 km³/yr, i.e. approximately from 80 to 200 Gt/yr (assuming an ice density of 917 kg/m³). This estimation had been globally confirmed, using GRACE data, by Chen et al. (2006) who found a mass ice trend of -219 ± 21 Gt/yr (from 2002 to 2005). Luthcke et al. (2006) however found a mass ice trend smaller, about -114 ± 17 Gt/yr. More recently, Baur et al. (2009) analyzed 3 GRACE solutions, showing ice mass trends from -88 Gt/yr to -222 Gt/yr in Greenland (from 2002 to 2008). They concluded that the most probable value is -162 ± 11 Gt/yr. Other estimations (Velicogna and Wahr, 2005, 2006; Ramillien et al., 2006), using GRACE data, show a similar range of possible ice mass trends. Finally, combining ICESat and GRACE observations, Slobbe et al. (2009) estimated that the mass change rate for the whole Greenland ranges between -128 and -218 Gt/yr (see also Baur et al., 2009), with a global diminution of ice volume and a global increase of snow volume.

Rémy and Frezzotti (2006) observed that the West Antarctica ice sheet seems to reduce over time, when the East Antarctica ice sheet may be more or less in balance. These observations seem to be comforted by satellite radar interferometry observations of Antarctica. Rignot et al. (2008) estimated a total rate of ice mass variations in Antarctica of -196 ± 92 Gt/yr in 2006, compared to -112 ± 91 Gt/yr in 1996. Using GRACE data, Chen et al. (2008) found negative regional ice rates on the continent. More recently, Horwath and Dietrich (2009) estimated a mass ice trend of -109 ± 48 Gt/yr for the period 2002 to 2008. However, other solutions, like Ramillien et al. (2006), are more contrasted. They quantified a rate of -36 ± 47 Gt/yr in Antarctica, which is quite smaller than Rignot et al. (2008), and which means that the ice mass rate could even be positive.

Actually, Barletta et al. (2007) showed that, depending on the solid Earth parameters and post-glacial rebound uncertainties, the trend in ice mass variations in Greenland and Antarctica can be very variable, ranging between -209 to $+88$ Gt/yr in Antarctica and -122 to -50 Gt/yr in Greenland. Nevertheless, they also concluded that the most probable earth parameters lead to a mass loss in both regions, about -171 ± 39 and -101 ± 22 Gt/yr for Antarctica and Greenland, respectively.

These observations have been compiled in Fig. 1 including ranges of uncertainty estimated by the authors. Conclusions of the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report (Bindoff et al., 2007; Lemke et al., 2007) have been also added. We denote by "recently", an estimation based on a set of measurements made during a period smaller than 10 years, and including observations that has been made after the year 2000. We denote by "a decade ago", an observation that has been made during the nineties, or an

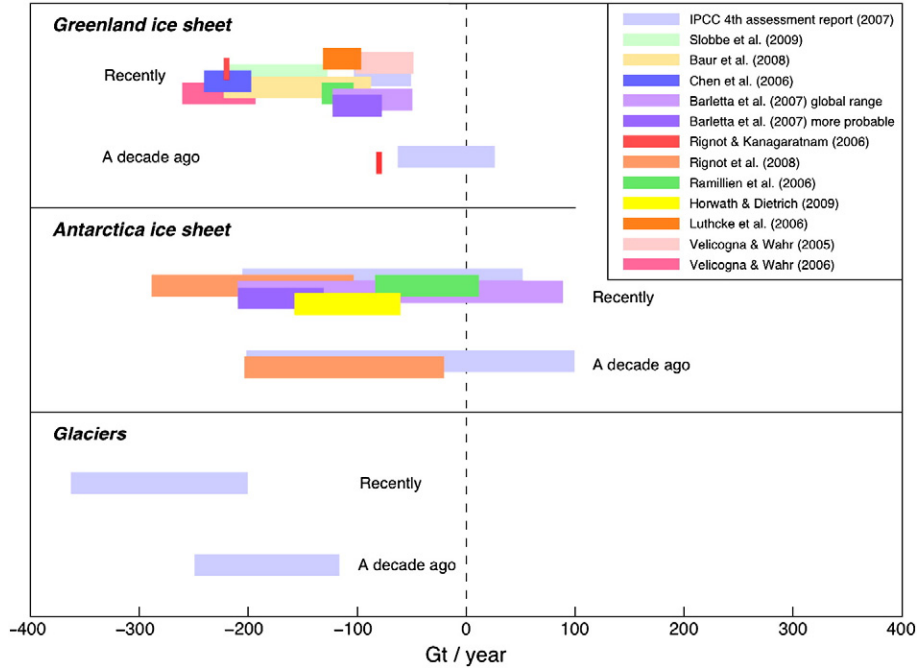


Fig. 1. Global mass variations of Greenland ice sheet, Antarctica ice sheet, and non-polar glaciers, in gigatons/yr. Different estimations are superimposed with different colors and different length, showing the precision of each estimation. We denote by “recently”, an estimation based on a set of measurements made during a period smaller than 10 years, and including observations that has been made after the year 2000. We denote by “a decade ago”, an observation that has been made during the nineties, or an estimation based on a set of measurements made during a period larger than 20 years, including eventually recent data.

estimation based on a set of measurements made during a period larger than 20 years, including eventually recent data. For example, the “a decade ago” IPCC estimation of mass balances has been compiled from observations made during the period 1961–2003. We note a large scatter in the recent estimations of Greenland ice mass balance. The IPCC estimation of the mass deficit is notably smaller compared to most of other studies. It may be explained by the fact that some of the studies (the ones that observed a very large mass deficit) include data more recent than 2005. Velicogna and Wahr (2006) proposed that the Greenland ice mass deficit has even more increased since then. In the present paper, we do not separate these estimations, because we want to determine an order of magnitude of the geocenter motions and accelerations. We will anyway highlight the impact of very recent mass balance estimations on geocenter motion (see Section 3).

Glaciers melting in other regions than Antarctica and Greenland area also produce important mass redistributions and consequently affects the geocenter position. Their global contributions have been taken into account (see Fig. 1), based on the IPCC fourth assessment report (Bindoff et al., 2007; Lemke et al., 2007).

3. Surface loading deformations

Mass redistributions induced by the ice melting and the sea level rise induce a loading on the solid Earth surface, leading to ground deformations and gravity variations (e.g., Longman, 1962; Farrell, 1972; Conrad and Hager, 1997; Métivier et al., 2006). We recall in this section the basic formalism of surface loading deformations and we precise our notations.

Mass redistributions between ice caps and oceans are located on the surface. Compared to the Earth radius a , the layer in where masses are moving is extremely thin, and can be approximated as an infinitely thin layer on a spherical Earth (Longman, 1962; Farrell, 1972; Wahr et al., 1998). Let us denote by σ the surfacic density change in the surface load layer induced by mass redistributions. One

can express this density redistribution using a spherical harmonic expansion:

$$\sigma(\theta, \varphi, t) = \sum_{n=0}^{+\infty} \sum_{m=-n}^{+n} \sigma_{nm}(t) Y_{nm}(\theta, \varphi)$$

where Y_{nm} is a normalized spherical harmonic function of degree n and order m (we use here Schmidt norm), σ_{nm} is a spherical harmonic coefficient, θ the colatitude, φ the longitude and t the time.

The density distribution $\sigma(\theta, \varphi, t)$ creates a gravitational load potential $V(r, \theta, \varphi, t)$ leading to elastogravitational deformations of the Earth (r is the radius position in spherical coordinates). One can show that the spherical harmonic coefficients of the load potential are linearly linked to the surface density distribution (e.g., Farrell, 1972; Blewitt, 2003), following the relation:

$$V_{nm}(t) = \frac{4\pi}{2n+1} \frac{a^3 g_o}{M_T} \sigma_{nm}(t),$$

where M_T is the total mass of the Earth and g_o the mean surface gravity.

It is well known since the work of Love (1911) on the elastogravity, that, assuming a radially symmetric Earth, the surface displacements and the surface gravity variations can be expressed in terms of non-dimensional numbers, the so-called Love numbers. Let us define \mathbf{u} the surface displacement vector and ϕ the surface gravity potential variation created by the surface load:

$$\mathbf{u}(\theta, \varphi, t) = \sum_{n=0}^{+\infty} \sum_{m=-n}^{+n} \frac{V_{nm}(t)}{g_o} (h'_n Y_{nm}(\theta, \varphi) \mathbf{e}_r + l'_n \nabla Y_{nm}(\theta, \varphi))$$

where h'_n , l'_n and k'_n are the load Love numbers of degree n , \mathbf{e}_r is the radial unit vector, and ∇ the gradient vector operator that can be expressed in spherical coordinates as $\nabla = \mathbf{e}_\theta \partial_\theta + (\mathbf{e}_\varphi / \sin \theta) \partial_\varphi$ (∂_i being the partial derivative along the coordinate i).

4. Geocenter motions

Let us define $\mathbf{x}_{CF/CM}$ the motion vector of Earth's center of figure (CF or geocenter) relative to its center of mass (CM). We have:

$$\begin{aligned} \mathbf{x}_{CF/CM}(t) &= \frac{1}{S_T} \iint_{S_T} \mathbf{u}(\theta, \varphi, t) dS \\ &= \frac{1}{4\pi a^2} \sum_{n=0}^{+\infty} \sum_{m=-n}^{+n} \iint_{S_T} \frac{V_{nm}(t)}{g_o} (h'_n Y_{nm}(\theta, \varphi) \mathbf{e}_r + l'_n \nabla Y_{nm}(\theta, \varphi)) a^2 \sin \theta d\theta d\varphi. \end{aligned} \quad (2)$$

As it has been shown by various authors (Greff-Lefftz and Legros, 1997; Blewitt, 2003), using orthogonality properties of spherical harmonic functions (Dahlen and Tromp, 1998), one can simply reduce Eq. (2) to:

$$\mathbf{x}_{CF/CM} = \frac{4\pi a^3}{3M_T} \frac{h'_1 + 2l'_1}{3} (\sigma_{1-1} \mathbf{e}_x + \sigma_{11} \mathbf{e}_y + \sigma_{10} \mathbf{e}_z).$$

As we can see the geocenter motion depends only on the degree 1 coefficients of surface loads. h'_1 and l'_1 are the vertical and the tangential degree 1 load Love numbers. The Love numbers depend primarily on the frame in which are expressed the positions (e.g., Blewitt, 2003). We are looking at CF motion relative to the CM, consequently the origin of our frame is chosen on the CM and the Love numbers to be used are classically $h'_1 = -1.286$ and $l'_1 = -0.896$ (Greff-Lefftz and Legros, 1997). Note that one cannot infer the load coefficients directly from space gravity mission (GRACE) because space gravity measurements are not sensitive to degree 1 mass redistributions. For this reason, we estimated global ice mass variations from a combination of regional ice mass balance estimations that have been inferred using different types of data (including space gravity, altimetry, ground measurements etc.) and that have been published (see below).

In the present work, we assumed homogeneous variations of ice elevation over the three distinct "regions": Greenland, Antarctica and the non-polar glaciers geographical mask (see Fig. 2). Considering the very large spatial wavelength of degree 1 spherical harmonics, only regional mass variations are necessary to infer the geocenter motion. We constrained the global mass balance on each regions with the observations reported in Fig. 1. The glaciers geographical mask has been constructed from a global compilation of glacier observations from the National Snow and Ice Data Center (Dyurgerov and Meier, 2000, 2005) (see Fig. 2). Finally, a fourth "region" is taken into account: the oceans. In order to ensure a global mass conservation, we calculated a theoretical sea level rise from the total ice melting, summing contributions from the three other regions. It is well known today (e.g., Conrad and Hager, 1997; Mitrovica et al., 2001) that the melting of ice sheets is accompanied by a sea level rise highly non-uniform (i.e. non-eustatic) over the whole oceanic surface as a consequence of the direct gravitational effects of the unloading of ice and the loading of water. Following previous works on sea level rise, we calculated the sea level rise associated with ice mass loss on the first three distinct regions. Let us denote $h_{SL}(\theta, \phi, t)$ as the sea level rise. $h_{SL}(\theta, \phi, t)$ is theoretically a function of the gravitational impact of the space-time evolution of ice cover $h_I(\theta, \phi, t)$ and a function of its own gravitational impact. Following for example Mitrovica and Milne (2003):

$$h_{SL}(\theta, \varphi, t) = \frac{\rho_I}{g_o} \Phi(\theta, \varphi) * h_I(\theta, \varphi, t) + \frac{\rho_{oc}}{g_o} \Phi(\theta, \varphi) * h_{SL}(\theta, \varphi, t)^{SL} + C(t) \quad (3)$$

where ρ_I and ρ_{oc} are respectively the ice and ocean densities, $\Phi(\theta, \varphi)$ is a Green's function for the gravitational potential perturbation that is constructed by suitably combining load Love numbers, and the symbol * represents the convolution product over space. $\Phi(\theta, \varphi)$, here, is independent of time because the Earth response to surface loads is essentially elastic. Indeed, the time scale of recent ice melting is too short for Earth deformation to significantly present a visco-elastic

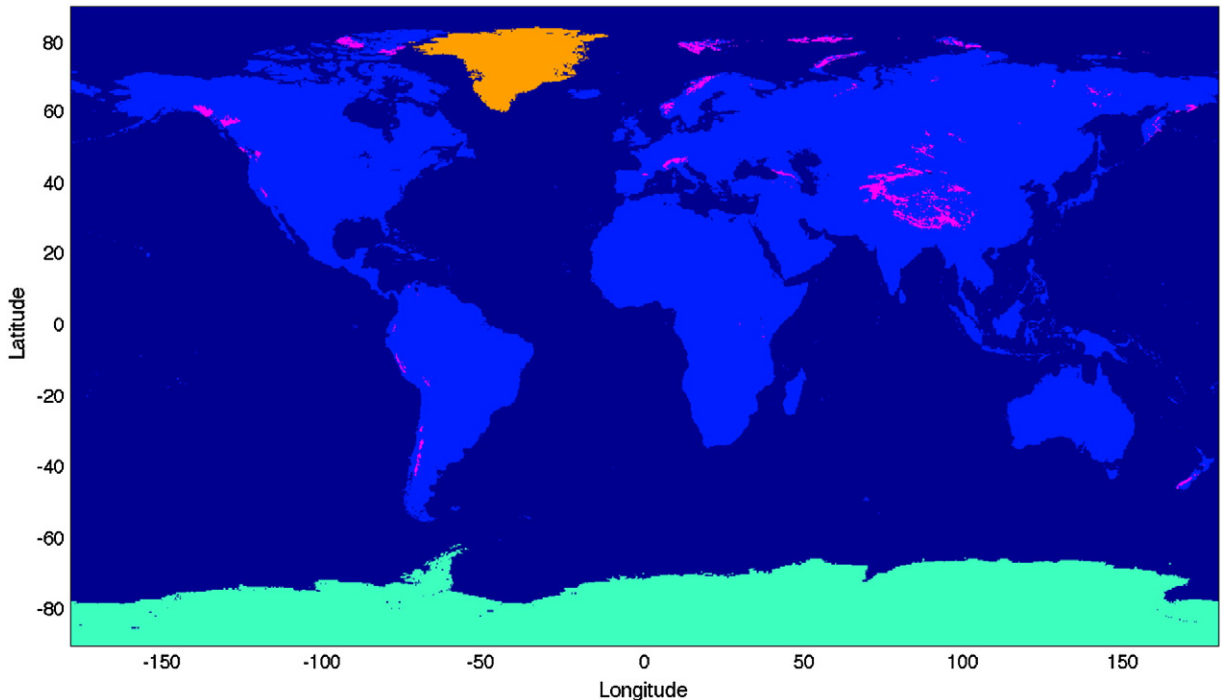


Fig. 2. Map showing the 4 distinct regions considered here: Greenland (orange), Antarctica (green), non-polar glaciers (purple), and the oceans (dark blue). Ice and water mass variations are assumed to be homogeneous over the different regions.

behavior. Finally $C(t)$ is a function of the eustatic sea level rise, i.e. the mean sea level rise (for more details see, e.g., Peltier, 1998; Mitrovica and Milne, 2003). Using Eq. (3) and the classical Green's function for elastogravitational deformations (Farrell, 1972; Greff-Lefftz and Legros, 1997), the sea level rise can be calculated iteratively, converging towards a constant geographical pattern, for a given ice mass loss. Fig. 3 shows the sea level rise associated with an ice mass rate of -100 Gt/yr on the different regions.

We calculated the degree 1 spherical harmonic coefficients ($\sigma_{10}, \sigma_{1-1}, \sigma_{11}$) of the different loading contributions. After summing these contributions, we inferred the geocenter global motion induced

by different configurations of mass redistributions. Using observations reported in Fig. 1, we estimated the global range of geocenter possible velocities. These results are presented in Fig. 3. We see that x- and y-components of the geocenter velocity are relatively small, less than 0.2 mm/yr, with a light increase during the last decade. On contrary, the z-component can be quite larger than the other components, up to $0.7-0.8$ mm/yr. However it shows a wide range of possible solutions, even negative velocities (light blue in Fig. 4). This range of possible values is mostly due to the uncertainty on ice mass balance in Antarctica. Indeed, some studies concluded that a positive ice mass balance, though less probable, may be possible in this region (see

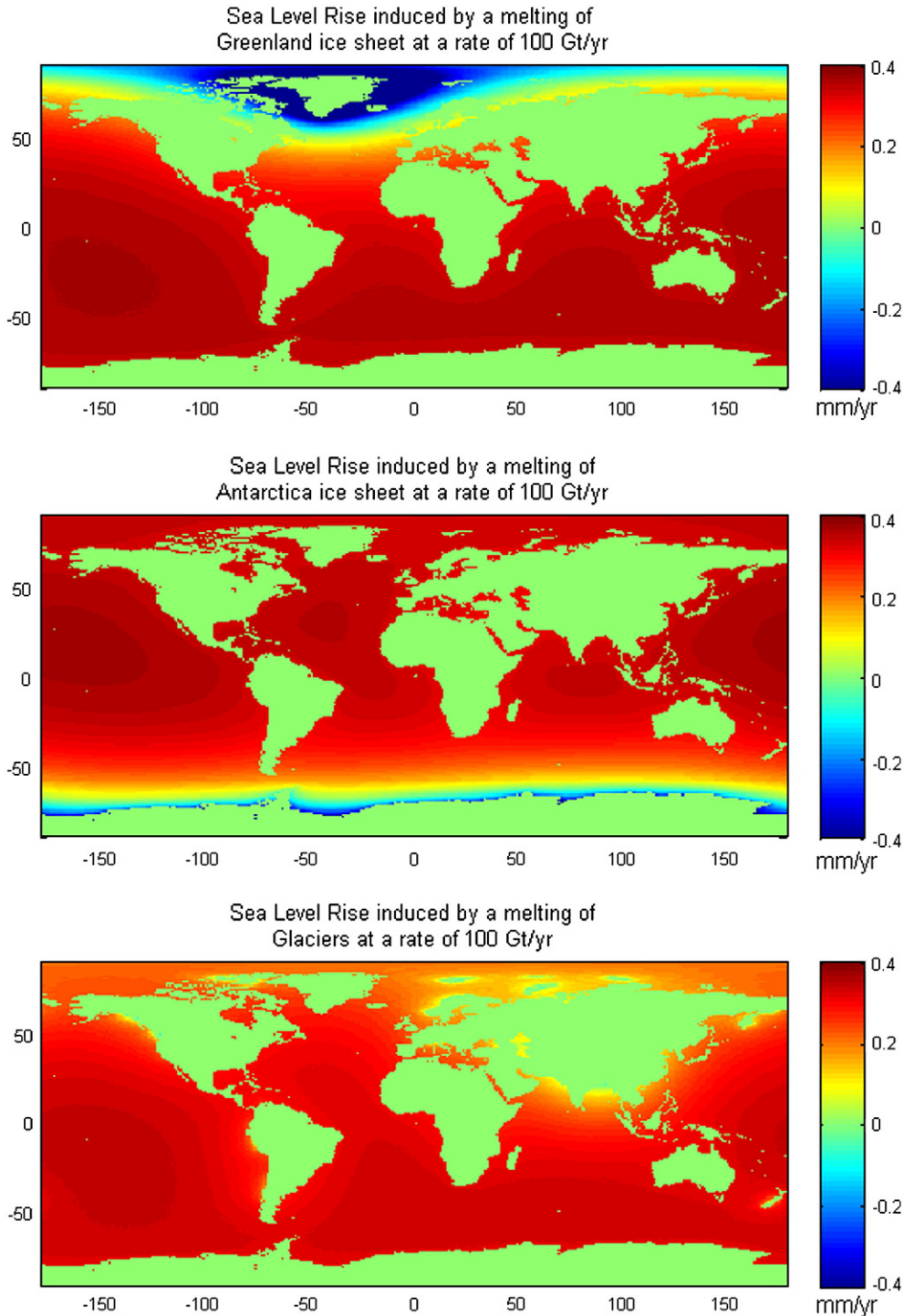


Fig. 3. Non-eustatic sea level rise induced by the melting of Greenland ice sheet (top map), Antarctica ice sheet (middle map) and glaciers (bottom map), at a rate of 100 Gt/yr.

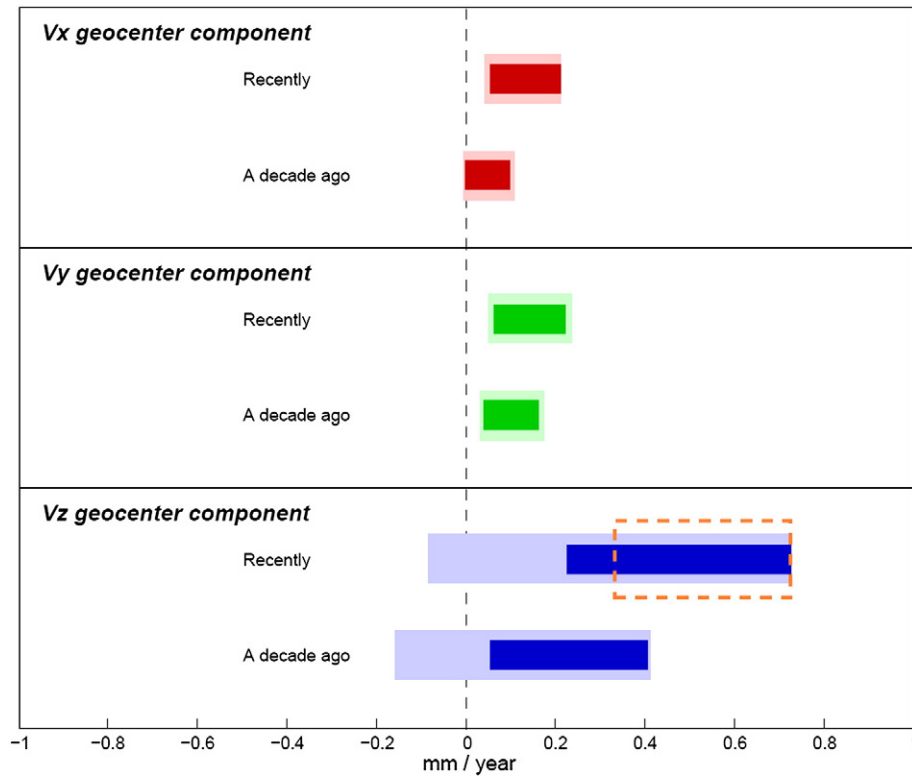


Fig. 4. Geocenter velocity components induced by the global ice melting in mm/year. Light colors present the total range of possible solutions, depending on the different ice melting estimations (Fig. 1). In dark colors are presented the range of “more probable” solutions, assuming a negative ice mass balance in Antarctica. Finally, the orange dashed box presents the “more probable” solutions that include observations in Greenland after 2005.

Fig. 1; Ramillien et al., 2006; Barletta et al., 2007; Bindoff et al., 2007; Lemke et al., 2007). If we only take into account configurations where the Antarctica mass balance is negative, then we got a smaller range of solutions (dark blue on Fig. 4). We see also that the z-component of the geocenter velocity may probably have increase during the last decade. It is even more clear, if we consider in Greenland only studies that take into account data after 2005 (orange dashed box).

5. Discussion and conclusion

Global ice melting on the Earth induces long-term displacements of the geocenter particularly along the Z-axis, toward the North Pole. The geocenter velocity can be up to 0.7–0.8 mm/yr, and is today most probably between 0.3 and 0.8 mm/yr. Compared to the last decade, the geocenter velocity seems to have increased with recent climate changes and the acceleration of ice melting particularly in Greenland. The increase is typically at the order of 0.2–0.3 mm/yr, however this is a rough estimation considering that the “last decade” solution has been inferred from a wide range of data, including recent data (see Section 1). For this reason the increase in geocenter velocity can be theoretically larger. But considering the order of magnitude that we obtained here, it is difficult to envisage an increase superior to 0.5 mm/yr.

The international terrestrial reference system is defined as centered on the center of mass of the whole Earth. Its two latest realizations, the ITRF2000 and ITRF2005, present a difference of 1.8 mm/yr between the velocities of their respective frame origins. This would suggest an acceleration of the CM motion towards the South Pole, or inversely an acceleration of the geocenter motion towards the North Pole, which is coherent with the results that we obtained. However the order of magnitude is clearly larger than our estimation of geocenter velocities. Combining our results with Greff-Lefftz (2000) results on post-glacial rebound, we can conclude that a present secular geocenter velocity of

1 mm/yr towards North Pole is clearly possible. However the recent acceleration cannot be due to a phenomenon such as the post-glacial rebound. The true recent increase of the geocenter velocity is probably at least two times smaller than the difference observed between the two last realizations of the ITRS. Our results comfort the previous conclusions about ITRF2000 and ITRF2005 and the pre-analysis of ITRF2008 data, suggesting that the large Z-translation rate between the origins of the two last ITRS realizations is probably due to an imprecise ITRF2000 origin.

One of the main objectives in the present development of reference frames is stability at the 0.1 mm/yr level. We see here that if we get to such a stability and accuracy we may be able to detect the impact of climate changes on geocenter motion. Considering the large variability in the global ice mass balance estimations, geocenter acceleration observations would give a different and complementary viewpoint on mass exchanges that would permit to constrain climate evolutions with better precision. The Z-component, for example, is highly dependent on the relative mass rates in Greenland and in Antarctica (though a large melting of glaciers tends to slightly increase the value too). A geocenter velocity around 0.3 mm/yr would be due to a melting globally similar in Greenland and in Antarctica, whereas the largest value would be due to a very low melting in Antarctica.

Acknowledgements

We thank Yannick Ricard, Giorgio Spada and an anonymous reviewer for their fruitful comments on the initial manuscript. We used data from the National Snow and Ice Data Center, 1999, updated 2009, *World glacier inventory*, World Glacier Monitoring Service and National Snow and Ice Data Center/World Data Center for Glaciology (Boulder, CO. Digital media). This publication is IGP contribution number 3024.

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