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On secular geocenter motion: The impact of climate changes

Laurent Métivier [a,b,*], Marianne Greff-Lefftz [b], Zuheir Altamimi [a]

[a] Institut Géographique National, LAREG/GRGS, Champs-sur-Marne, France
[b] Institut de Physique du Globe de Paris, 4 place Jussieu, 75005 Paris, France

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ABSTRACT

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 Radiopositionning 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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* Corresponding author. Institut Géographique National, LAREG/GRGS, Champs-sur-Marne, France. Tel.: +33 157278487.
E-mail address: laurent.metivier@ign.fr (L. Métivier).

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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 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 km^3/yr, i.e. approximately from 80 to 200 Gt/yr (assuming an ice density of 917 kg/m^3). 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