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

W.R. Peltier*

Department of Physics, University of Toronto, 60 St. George Street, Toronto, Ontario M5S 1A7, Canada

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ABSTRACT

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

1. Introduction

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

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

* Tel.: +1 416 978 2938; fax: +1 416 978 8905.
E-mail address: peltier@atmosp.physics.utoronto.ca

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

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

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

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

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

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

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

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

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

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

with

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

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

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

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

Eq. (1) is then solved again using this first approximation to the feedback term and the iterative process so defined is continued until convergence is achieved to within a specified tolerance. Typically only a few iterations are necessary and the calculation is highly efficient. For the purpose of the analyses to be presented in this paper, it will turn out that the influence of rotational feedback on the solutions to Eq. (1) is important. Insofar as the