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ICE MASS BALANCE AND ICE DYNAMICS FROM SATELLITE GRAVITY MISSIONS

J. FLURY
Institut für Astronomische und Physikalische Geodäsie, Technische Universität München
(E-mail: flury@bv.tum.de)

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Abstract. An overview of advances in ice research which can be expected from future satellite gravity missions is given. We compare present and expected future accuracies of the ice mass balance of Antarctica which might be constrained to 0.1–0.3 mm/year of sea level equivalent by satellite gravity data. A key issue for the understanding of ice mass balance is the separation of secular and interannual variations. For this aim, one would strongly benefit from longer uninterrupted time series of gravity field variations (10 years or more). An accuracy of 0.01 mm/year for geoid time variability with a spatial resolution of 100 km would improve the separability of ice mass balance from mass change due to glacial isostatic adjustment and enable the determination of regional variations in ice mass balance within the ice sheets. Thereby the determination of ice compaction is critical for the exploitation of such high accuracy data. A further benefit of improved gravity field models from future satellite missions would be the improvement of the height reference in the polar areas, which is important for the study of coastal ice processes. Sea ice thickness determination and modelling of ice bottom topography could be improved as well.

Keywords: Geoid time variation, ice mass balance, ice thickness, satellite gravity missions, sea level change

1. Introduction

Understanding the mechanisms controlling ice sheet mass balance is essential to studies of long term changes in sea level and ocean circulation and of climate change. The masses of the Antarctica and Greenland ice sheets, of glaciers and ice caps vary in time through the exchange of water with the atmosphere and with the oceans, see Committee (1997). Ice mass balance is the comparison of mass gain due to accumulation and mass loss due to sublimation, evaporation, melting and discharge, as functions of time, respectively. In the near future detailed mass balance will be feasible from the combination of models (atmospheric models, flow models, surface energy balance), *in-situ* measurements (ice cores, surface GPS, absolute gravimetry, automatic weather stations), airborne measurements (shallow layer radar, ice penetrating radar, and airborne gravimetry) and spaceborne measurements (satellite microwave, INSAR, satellite radar and laser altimetry, and satellite gravity), see Figure 1 (from Thomas, 2001). Temporal variations of gravity are of particular importance as they are directly proportional to mass changes. The challenge will be to separate postglacial isostatic mass adjustment, the effect of ice compaction and the mass changes of ice, see Wahr and Velicogna (2003).

2. Ice Mass Balance (Ice Sheets and Glaciers)

The history of past glaciation and the present-day ice mass balance are parts of a complex process: past ice load changes, in particular the deglaciation after the last ice age, continue to act through Glacial Isostatic Adjustment (GIA), i.e. vertical land movements due to removed ice loads and related lateral mass shifts in the Earths's interior. The GIA geometric and mass signals are superimposed by the recent ice thickness and mass changes, caused by the meteorological and climatological variability, with seasonal and annual to interannual and secular components. Measurements of geometry and mass changes in time always represent the total of these effects, and – in addition – of other phenomena such as variations in the atmosphere, in adjacent oceans and – for areas free of ice today – also in continental hydrology (cf. Vermeersen, 2004). Ice mass and sea level are closely connected by the hydrological cycle including ice, ocean and atmosphere.

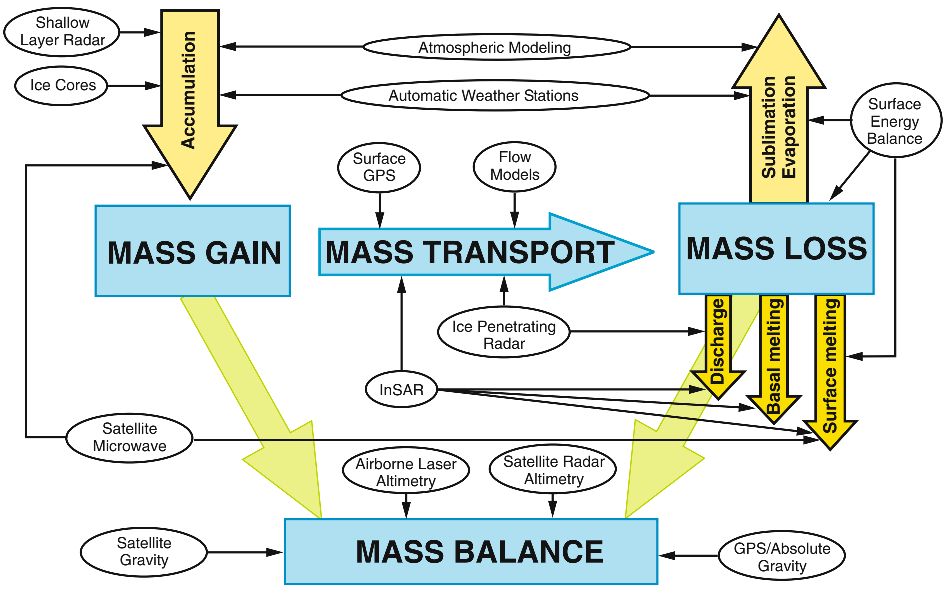

Figure 1. Processes contributing to ice mass balance and applied measurement methods, after Thomas, 2001).

Therefore, ice mass balance is often expressed in units of equivalent sea level change.

Figure 1 shows the wide variety of data connected to ice mass changes: ice cores and geological records revealing past climate changes (Thomas, 2001), relative sea level changes from tide gauges (Woodworth, 2004), meteorological data and models, surface ice velocities from INSAR, surface structure and temperature from satellite microwave data, vertical motion from GPS, changes in the low harmonic coefficients of the gravity field and in the earth orientation parameters (James and Ivins, 1997), gravity changes as measured by terrestrial absolute gravimetry, and others.

All these data have characteristic limitations in their role for the determination of the ice mass balance. Often the sampling is sparse and uneven, resulting in a limited spatial and temporal resolution. For others the conversion of the measured quantity into mass variations contains many error sources.

From the currently available data it has been deduced, that the Antarctica ice sheet is today approximately in equilibrium. However, the uncertainties of this conclusion are large. Table I (first row) shows the current accuracy estimates as given by various authors, ranging from ±0.2 mm/year up to ±1.4 mm/year for the resulting secular change in sea level equivalent. In the mass budget, the mass output is constrained only to about ±20% of the mass input (Huybrechts et al., 2004). The seasonal and interannual components are probably even more uncertain. Also for Greenland, the mass balance is poorly known. Here, melting and discharge prevail, resulting in a sea level rise of at least 0.1 mm/year, maybe considerably more (Rignot and Thomas, 2002).

TABLE I

Ice mass balance of the Antarctica ice sheet: current and future accuracies for secular ice mass change and corresponding sea level equivalent, as estimated for the spatially averaged change of the whole ice sheet

	Accuracy estimates (mm/year)		References
	Secular ice mass change	Secular sea level change	
today	20–40	0.2–1.4	James and Ivins (1997); Wahr et al. (2000); Rignot and Thomas (2002); Wu et al. (2002)
GRACE only	20	0.6	Wahr et al. (2000)
ICESat + GRACE	4–9	0.1–0.3	Wahr et al. (2000); Wu et al. (2002)
20year missions altimetry + gravity	3–4	0.1	Wahr et al. (2000)

At present, the data situation is changing significantly with the availability of precise temporal gravity variations from GRACE and altimetric ice surface data from ICESat and – in the next future – CryoSat. These missions allow to determine directly the ice volume and mass changes with a very high precision, with a nearly complete coverage of ice sheets and glaciers, with high spatial resolution and with sufficient temporal resolution (monthly sampling of mass changes by GRACE, whereas the time resolution of ice altimetry depends on the type of cross-over analysis). The lower rows of Table I show the improvements in accuracy expected from the use of these new data.

To derive the ice mass balance from these new data, one will have to deal with the following main problems:

- The most important task is the separation of signals from GIA, from recent ice mass changes and from the mass changes in the neighboring oceans, in atmosphere and hydrology.
- When volume changes from altimetry are converted to mass changes, ice compaction has to be modelled, which introduces considerable conversion errors. In particular, time variations of compaction caused by variable accumulation rates are a critical issue (Wahr et al., 2000; Wu et al., 2002).
- In the polar areas, sequences of years with higher-than-normal or lower-than-normal snowfall rates cause strong interannual variations in the ice mass balance, which are not yet well understood. Figure 2 (from Wahr et al., 2000) shows snow-ice variations from a climate model for a time span of 200 years, demonstrating that strong, fast changes alternate with much more stable periods. Since the current missions have a lifetime between 3 and 6 years, it becomes clear that they will capture rather a snapshot of current change, while for a reliable determination of interannual to secular variations longer mission durations have to be considered (Wahr et al., 2000). Wu et al. (2002) show that also for attempts to model the past ice load history by inversions, these interannual variations are the major error source.
- The capability of GRACE to detect variations in the ice mass balance is limited to a spatial resolution of about 500 km (spherical harmonic degree 40, see Figure 3). Variations over shorter scales will not be resolved.

Simulations by Wahr et al. (2000) and Velicogna and Wahr (2002a, 2002b) show, that a joint modelling and a separation of GIA signal and ice mass trend is possible. When using simulated GRACE data alone the separation does not succeed very well (Table I, second row), the achieved accuracies for ice mass and sea level change being not much better than from current data. When using GRACE and ice altimetry together, the accuracy improves considerably (Table I, third row), and some further improvements can be achieved adding a set of GPS vertical movement data. Also regional

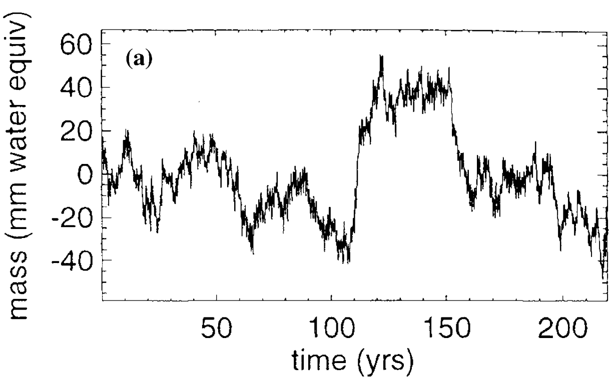

Figure 2. 219 years of monthly values of the snow-ice mass averaged over the Antarctic ice sheet, as predicted by the CSM-1 climate model, from Wahr et al. (2002). Units are equivalent water thickness.

variations could be recovered by these simulations, with accuracies varying between 5 and 20 mm/year of equivalent water thickness (Velicogna and Wahr, 2002a). In the approach of Wahr et al. (2000) and Velicogna and Wahr (2002a, 2002b), volume changes from ice altimetry are converted to mass changes, introducing a significant error due to the unknown ice compaction, which dominates the measurement errors. Therefore the results of

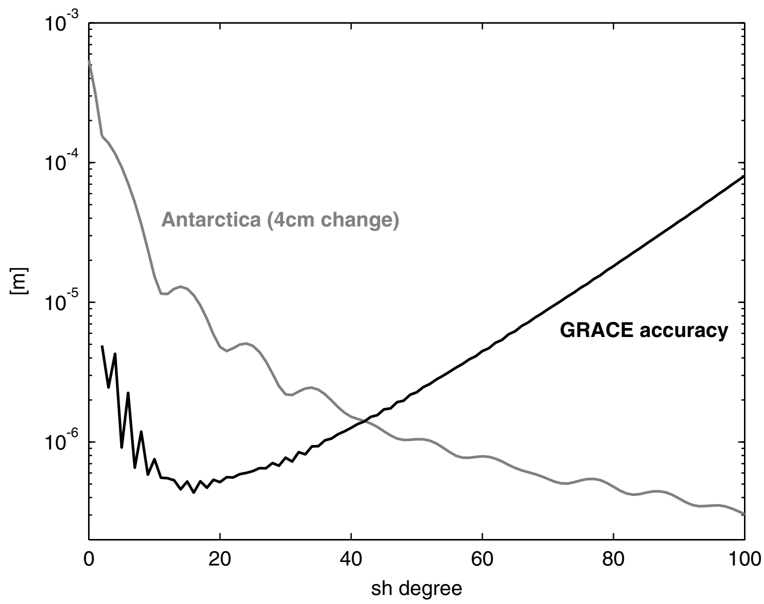

Figure 3. Degree amplitudes of the geoid effect of a 4 cm ice thickness change for the entire antarctic continent, compared to the GRACE baseline error.

this approach would not benefit by a higher precision gravity mission. For the future, either ice compaction must be modelled more precisely (e.g. based on extensive shallow coring of the ice sheets, see Huybrechts et al., 2004), or other approaches for the separation of mass changes and compaction changes have to be developed.

Future satellite gravity missions could bring benefits for the following areas:

– Determination of the important interannual ice mass changes (Figure 2) and identification of long-term trends. This requires longer and consistent time series of geoid, gravity and surface height variations. Future missions – possibly with longer duration – would continue the time series started at present by GRACE and ice altimetry. Ideally, this continuation should be without interruption.
– Understanding of the Glacial Isostatic Adjustment mechanism and the viscoelastic properties of the Earth from gravity missions with better spatial resolution, higher accuracy and longer lifetime (Vermeersen, 2004). This will facilitate the separation of ice mass changes and mass shifts in the Earth's interior (Velicogna and Wahr, 2003a). Therefore, the mission precision requirements imposed by GIA research are supported by the needs of ice mass balance determination. GIA mass changes and ice mass changes have distinct spatial signatures. The GIA mass signal has most of its power at scales (wavelengths) greater than 500 km. The ice mass change signal, at the other hand, will contain considerable contributions at scales between 50 and 500 km. For example, West Antarctica is experiencing fast melting and discharge by glaciers, with pronounced regional variations in the size of the changes (Rignot and Thomas, 2002). Also for Greenland, high variability on such spatial scales is observed. If future gravity missions will allow to resolve also the small scale structures of ice mass changes, a much better separation from the GIA signal should be possible. Further improvement will be possible if simultaneous ice surface observations by follow-on satellite altimetry missions will be available. However, new approaches for the separation have to be studied, in particular for the identification of the amount of compaction for the conversion of volume to mass.
– At the same time, improved models of GIA vertical movements all over the globe would be important to correct records of the relative sea level at the coast and enhance their value for ice load history determination (Huybrechts et al., 2004).
– A higher resolution would improve the separation between ice mass changes and mass variations in the adjacent ocean.
– If a very high spatial resolution of about 20–30 km could be reached, this could even allow a monitoring of narrow fast flowing ice streams in Antarctica, which suddenly and unexpectedly stop or resume their movement (Joughin and Tulaczyk, 2002).

Therefore, a future mission should meet the following requirements:

- the time span covered by a single mission or series of missions should be as long as possible, at least 10 years;
- the mission accuracy should meet the needs of GIA research, i.e. in the order of 0.01 to 0.001 mm/year; (Vermeersen, 2004);
- the spatial resolution should reach 100 km or better.

Besides gravity time variations, also an improved static gravity field could contribute to study ice mass balance. The uncertainty of ice compaction mentioned above could possibly be reduced by combining gravity field and ice thickness data, see next section. Furtheron, a high resolution static geoid with a 10 cm accuracy or better could play a role for the determination of ice thickness along the grounding lines of ice shelves and glaciers that cover large parts of the coast of Antarctica. The geoid could be used as an approximation of sea level and allow the height determination of the ice bottom at the grounding line. From ice thickness, together with ice velocity determined by INSAR, the ice mass discharge can be assessed, which is an important contribution to ice mass balance and represents a major part to the present uncertainty in the mass budget of Antarctica (Huybrechts et al., 2004).

3. Ice Bottom Topography

The bottom topography beneath the ice sheets is an important boundary condition for ice flow models. Today it is obtained mainly from ice penetrating radar measurements. Current ice flow models use grids with 20 to 40 km resolution (Huybrechts et al., 2003). If the static gravity field from a future mission would reach such a resolution, it could allow an independent check of radar derived ice thickness. For such small spatial scales, airborne gravimetry is an important complementary data source. The better the spatial gravity field resolution achieved by a satellite mission, the broader will be the range of scales where both satellite and airborne data have good quality. This will enable a mutual validation of both sensor systems and a combination of results. Furthermore, when combining the geometry from radar with the ice mass derived from the gravity signal, ice density and compaction could be determined, which is today known only at few borehole sites. With simple rules of thumb one can derive that for an accuracy of 1 m in bottom topography at least a 0.1 mGal gravity accuracy is required. To detect a relative density anomaly of 0.001 for a 2 km thick ice sheet a 0.04 mGal gravity signal is required.

4. Sea Ice

The extent of the areas covered by sea ice and the transport of ice to lower latitudes by ocean currents play an important role for Earth climate and are an indicator of secular and interannual climate changes. Sea ice carries a big amount of freshwater and supplies cold water to the circulation system. These are important boundary conditions for ocean circulation. Another climate related issue is the increased reflection of solar radiation by sea ice. The distribution and thickness of sea ice is characterized by strong interannual variations, with important consequences for the high latitude ocean circulation and climate, which is shown by Venegas et al. (2001) for the Southern Ocean and by Laxon et al. (2003) for the Arctic.

While the extent of sea ice is being measured already today by various remote sensing techniques, the actual height of the ice surface and the freeboard height (the height of the sea ice at its edges) will be measured by the ICESat and CryoSat missions during the next years. To determine sea ice thickness and mass all over the sea ice cover, in addition to the ice surface also the geometry of the sea surface (as if there were no ice) has to be introduced. Therefore, the static geoid and the dynamic sea surface topography due to currents must be known. As the variations of the geoid variations are much larger than those of the sea surface topography, a static geoid in very high resolution down to wavelengths of about 10 km with an accuracy of 10 cm would lead to an improvement of an order of magnitude for sea ice thickness and mass transport determination (see Hvidegaard and Forsberg, 2002).

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