Long-term monitoring by absolute gravimetry: Tides to postglacial rebound

A. Lambert*, N. Courtier, T.S. James

Geological Survey of Canada, 9860 West Saanich Road, Sidney, BC, Canada V8L 4B2

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Abstract

Absolute gravity measurements over nearly a decade at 10 field sites in North America have provided insights on a range of phenomena from tides to postglacial rebound. In this overview we demonstrate the potential of long-term, terrestrial gravity measurements at selected sites to assist in the interpretation of temporal variations in the global gravity field from the Gravity Recovery and Climate Experiment (GRACE) mission. Absolute gravity measurements can be used to calibrate annual soil moisture effects observed by GRACE and to complement GRACE results over periods longer than the expected mission lifetime. Although the preferred terrestrial gravity monitoring system is a global network of superconducting gravimeters (Global Geodynamics Project) in combination with regular absolute gravity measurements, major advances can be made using absolute gravimetry alone. Operating the FG5 gravimeter in continuous mode at a near-shore site shows that special attention must be paid to possible sea-level related biases on gravity values as a result of near-shore hydrological effects. Where soil becomes saturated annually, simple soil moisture models can be used to remove the annual soil moisture effect from gravity, or to invert gravity observations for the soil moisture effect on space missions. Our measurements show that the phenomenon of “episodic tremor and slip” (ETS) in the Cascadia Subduction Zone is accompanied by gravity change that is most likely caused by mass redistribution and not height change. An inter-annual variation of unknown origin with a “period” of around 7 years is present at 10 North American field sites, as well as in data from Table Mountain Gravity Observatory, Boulder, Colorado. Correcting the long-term gravity trends for the inter-annual variation brings the trends into line with GPS vertical rates from four, co-located, continuous, GPS sites in the mid-continent and allows conclusions to be drawn on the thickness of the Laurentide ice-sheet.

Keywords: Temporal gravity variations; FG5 gravimeter; Ocean tide loading and attraction; Soil moisture modelling; Episodic tremor and slip; Postglacial rebound; GRACE

1. Introduction

Gravity variations on the Earth’s surface arise from a variety of processes spanning a wide spectrum of frequencies and spatial scales. As a result of space-based measurement capabilities developed over the last decade, there is a new appreciation of processes associated with mass redistribution in the Earth and its fluid envelope. Major advances are being made in characterizing processes in the oceans in the period range between tides and long-term, global sea-level change (e.g., Stammer et al., 2002), in quantifying inter-annual groundwater variations over continental scales (e.g.,
Wahr et al., 2004; Andersen and Hinderer, 2005), and in the understanding of relatively, short-period, episodic motions at plate boundaries (e.g., Dragert et al., 2001) (Fig. 1). The GRACE mission is expected to lead to major advances in gravity field monitoring (Tapley et al., 2004). GRACE is expected to map temporal changes in the gravity field at the 1 μGal (10^{-8} m/s^2) level at scales of 300 km and up and at periods from 2 months to a maximum of 8 years. As precise as it is, GRACE will monitor variations in a relatively restricted area of our spectral diagram (Fig. 1). Processes to the left of this box will show up as indistinguishable long-term trends. Processes to the right could affect the measurements through aliasing. Thus, Global Geodynamics Project (Crossley et al., 1999, 2003) measurements and other decade-long, surface-based, gravity measurement campaigns are important contributors to the overall gravity monitoring effort.

Here we report on progress in understanding a variety of processes in the spectral range from tides to postglacial rebound based on North American absolute gravity observations. For over 8 years Natural Resources Canada (NRCan) and the U. S. National Oceanic and Atmospheric Administration (NOAA) have been measuring gravity at a number of sites in western Canada and the U.S.A using FG5 absolute gravimeters (Niehauer et al., 1995), the normal mode of operation being a 24 h set of measurements at each site. FG5 measurements at two of these sites were predated by measurements with JILA (Faller et al., 1983) absolute gravimeters beginning in the late 1980s. Since 1995, four sites have been observed four times per year by NRCan on Vancouver Island, and six sites have been observed once or twice annually in the mid-continent (Fig. 2). In addition, annual or semi-annual inter-comparisons have been made with other FG5 instruments at Table Mountain Gravity Observatory (TMGO) near Boulder, Colorado (Fig. 2). Recently, we have also been operating the FG5 gravimeter as a recording instrument for periods of a week or more at a sample rate of 15 min for studies of short-term, subduction-zone dynamics. Moving from right to left in Fig. 1, we present examples of observed gravity variations relating to a variety of geodynamic processes from ocean tide loading at around 1 cycle per day, to seasonal groundwater variations at around 1 cycle per year, to aseismic slip in the Cascadia Subduction

Fig. 1. A diagram depicting geodynamic processes of different spatial scales (vertical scale) and periods (horizontal scale) that are expected to produce measurable gravity variations. Over the last decade space-based methods have extended our monitoring capability into new areas of the space-time spectrum pertaining to sea-level change, groundwater variations on land and plate boundary deformation (dashed boxes). Boxes with dark shading relate to the hydrosphere. Boxes with lighter shading and dark edges relate to the solid Earth. GRACE is expected to provide data in an important but relatively restricted portion of the spectrum (solid box).
Zone at 1.2 cycles per year, to processes of uncertain origin associated with inter-annual gravity variations of around 1 cycle per 7 years, and finally to postglacial rebound and its associated long-term trends.

2. Ocean tide effects on gravity

In an effort to improve ocean tide loading corrections on gravity observations near the coast in Canada and northern U.S.A. a more precise representation of the ocean tides that complements the available global models was introduced (Lambert et al., 1998). This led to a demonstrable reduction in tidal gravity residuals at various Canadian sites near the coast but a tidal component remained in the data. The remaining signal was believed to be the result of direct attraction by local tidal waters, which is not included in the model. Recent measurements indicate that direct attraction may be larger than anticipated at some sites. Three weeks of continuous FG5 observations at a site on Vancouver Island, located in an underground seismic vault 38 m from the shore, revealed some unexpected effects. First, the peak to peak tidal residuals are larger than expected (averaging around 7 μGal) and second, comparison with predicted and observed tides indicates an apparent distortion of the tidal signal (Fig. 3). Spectral analysis shows that the diurnal component of the gravity residual is enhanced over the semi-diurnal component relative to the local ocean tide. This would be consistent with 1D landward pressure diffusion. However, the phase of the tidal gravity signal is found to lead the local ocean tide in both the diurnal and semi-diurnal components. Such phase behavior suggests the need for a more complex model, such as has been used to explain tidal-induced pressure measurements in ocean bottom boreholes where phase leads were observed (Wang and Davis, 1996). We envisage a water-saturated, high-porosity formation below the gravity

Fig. 2. Map showing the location of absolute g monitoring sites in western Canada and the U.S.A. and the inter-comparison site TMGO, near Boulder, Colorado used in the present study. The mid-continent sites from Churchill down to Iowa City form a profile along which comparisons can be made with theoretical postglacial rebound rates.
Fig. 3. Gravity variations observed over an 18-day period at the underground vault site at the Pacific Geoscience Centre, Sidney, British Columbia, Canada (top panel). Points are 15 min gravity values. The solid line represents a 3 h moving average. Predicted (dark curve) and actual, observed ocean tides (light curve) at the same site are shown for comparison (lower panel).

site under the influence of tidally-induced pressure variations from the direction of the sea shore. A phase lead would result if pore pressure diffusion out of the formation in a direction away from the shore were delayed with respect to the pressure input from the ocean. An exact hydrological model is under development and may require verification by direct measurement of the expected pore pressure variations close to the gravity site. Tidal gravity residuals at other near-shore gravity sites are being examined similarly.

Gravity measurement sites close to the sea shore have the advantage that they are relatively free of long-term variations in groundwater caused by changes in precipitation. On the other hand, as we have seen, changes in relative sea level may affect gravity measurements through hydrology. The 24 h averaging procedure, used to calculate $g$-values, is not effective in dealing with long-period tides and secular variations of sea level. It is important, therefore, to measure the effect of local sea level change at various periods in order to estimate the response at the long period limit. Continuous gravity observations several months in length are required to study the change in hydrological response in the long-period tidal band. The response to the fortnightly tides, in particular, should provide a good indication of the possible effect of mean sea level change on gravity trends at near-shore sites.

3. Seasonal gravity variations from soil moisture

Soil moisture and water table variations are major sources of time variations in gravity at a period of around 1 cycle per year (e.g., Makinen and Tattari, 1991). The relative importance of these sources depends on the depth of soil and the topographic environment near the site. The sites on Vancouver Island are on sloping terrain where most of the variation in water content is in the soil. Mean annual precipitation levels vary quite drastically across western North America, ranging from 40 cm/year at Churchill (desert) to 350 cm/year at Ucluelet on the west coast of Vancouver Island (rain forest) (Fig. 2). Soil moisture levels on Vancouver Island typically range from 40% water by volume during the winter rainy season to anywhere between 0% and 20% in the summer, depending on the soil depth. In contrast to the Vancouver Island sites, the mid-continent sites are generally located on bedrock where rock porosities are usually around 3% by volume, leading to smaller gravity variations. Thus, the large annual variations of soil moisture on Vancouver Island produce a large scatter in $g$ values and must be modelled to enable the extraction of information from other parts of the gravity spectrum.
The variations in gravity due to seasonal changes in the water content of soil are modelled using a “single-tank” soil moisture balance model. The soil water content per unit area ($W$) can be expressed as: $W = P - R - E - S$, where $P$ is the precipitation, $R$ the surface runoff, $E$ the evapotranspiration and $S$ the seepage or drainage out of the system. $R$ depends on a specified surface infiltration rate limit and can be equal to $P$ when the total moisture capacity is exceeded. $E$ is the product of evapotranspiration efficiency and potential evapotranspiration which depends largely on temperature (Thornthwaite, 1944). $S$ is proportional to the actual soil moisture content at the site. Certain parameters of the model are determined through measurements of typical variations of soil moisture with depth and through empirical tests and are fixed at each site; these are the maximum moisture capacity, a limit on the daily surface infiltration and the evapotranspiration efficiency, which depends on the type of ground cover (e.g., lawn, wild grass, forest). Two additional parameters, an empirical geometric factor relating gravity to time-varying soil moisture content per unit area, and a seepage time constant, are calculated at each site by fitting the model to the observed absolute gravity values by least squares.

An example of a large seasonal variation can be seen in the gravity values at Albert Head, Vancouver Island (Fig. 4). The large seasonal effect at this site is thought to be the result of its location on a small hill. Except in rare cases (e.g., the dry winter of 2000/2001), the soil becomes completely saturated during the winter rainy season which produces a constant and repeatable gravity effect. The soil moisture model provides corrections at Vancouver Island sites for the reduction of gravity in the summer months as a result of the departure from the repeatable, fully-saturated state (Fig. 5).

Ironically, the site at Ucluelet in the area of highest annual precipitation exhibits the smallest seasonal variations as a result of the rocky environment and the proximity to the ocean.
4. Episodic tremor and slip

Careful analysis of data from continuously recording Global Positioning System (GPS) receivers in the northern part of the Cascadia Subduction Zone (Dragert et al., 2001; Miller et al., 2002) has revealed transient deformations in the period range 1–2 cycles per year, accompanied by tremor-like seismic signals (Rogers and Dragert, 2003). This phenomenon is thought to be associated with slip events on the deeper (25–45 km) part of the Cascadia Subduction Zone interface and has been dubbed “episodic tremor and slip” (ETS). The discovery of this phenomenon introduces the possibility of detecting accompanying short-term gravity variations, particularly if the phenomenon is associated with relatively rapid fluid flow or fluid pressure change at depth (Obara, 2002). Such short-term gravity variations might be superimposed on longer term gravity trends associated with the predicted, inter-seismic, vertical crustal deformations of plate convergence (Fluck et al., 1997; Wang et al., 2003).

To-date seven ETS events have been confirmed by both GPS and seismic observations in the area of southern Vancouver Island beginning in 1997 (Rogers and Dragert, 2003). These events generally start south of Vancouver Island and propagate, over a period of 1–3 weeks, north-westward, along the axis of the Island. Some events begin in the north-west and propagate south-east along the axis of the Island (G. Rogers, pers. commun.). As described earlier, the Ucluelet absolute gravity site exhibits very small seasonal effects (see Fig. 5) and, for that reason, it is well suited for detection of the possible gravity effects of ETS. A preliminary analysis was carried out comparing the times of strong mid-Island tremor activity with gravity values observed at Ucluelet (Fig. 6). A drop in gravity at Ucluelet of about 3–4 μGal seems to occur each time there is a strong tremor sequence within about 50 km of the site. The fitted model allows a different step in gravity at the times of each strong tremor and a common inter-slip recovery rate. An F-test suggests a significant reduction in residual variance (21 versus 15 degrees of freedom) for the slip model compared to the simple linear trend at the 98% confidence level over the period 1997–2003. Changes in GPS vertical position at Ucluelet appear to be too small to explain the change in terms of vertical movement (H. Dragert, pers. commun.).

Our preliminary interpretation is that the ETS process results in a temporary withdrawal of fluid from beneath the site. Continuous series of absolute gravity measurements are planned for the purpose of determining more precisely the changes associated with ETS.

5. Inter-annual gravity variations

The oceans, the hydrosphere and the solid Earth provide a variety of possible sources of mass redistribution at inter-annual periods that could result in measurable variations in gravity (Fig. 1). At annual periods, variations in continental hydrology are expected to dominate over mass redistributions in the oceans (Wahr et al., 1998). Inter-annual trends as high as 1.5 μGal/year from modelled water induced loading are estimated for some superconducting gravimeter sites.
Fig. 7. Observed gravity values from 10 North American field sites and TMGO, Boulder shown in Fig. 2. A linear, temporal trend has been removed from the gravity values at each site. The fitted curve is a sinusoid with a period of 6.85 years.

(van Dam et al., 2001). Trends as high as 3 μGal/year over 2 years have been found on the continents in a preliminary analysis of GRACE data (Andersen and Hinderer, 2005). The influence of the oceans at inter-annual periods cannot be ruled out; estimated ocean bottom pressure variations in the Adriatic have been found to correlate well with both GPS and superconducting gravimeter data (Zerbini et al., 2004) leading to the possibility of inter-annual ocean influences on near-shore gravity measurements.

A significant, common, inter-annual variation is seen at all absolute gravity sites in this study. Gravity is high in 1995, low in 1999 and high again in 2002 with a range of about 4.5 μGal (Fig. 7). As a first approximation, a simple sinusoid with a period of 6.85 years is found to be very effective in removing the non-linear behavior at all 11 sites. Several possible causes of the inter-annual gravity variations have been investigated, including elastic loading and direct attraction by groundwater and sea level, as well as motions of the axis of the inner core. None of the physical causes investigated, so far, provide a satisfactory explanation (Lambert et al., 2005a,b). Clearly, an understanding of the origin of the inter-annual variation is important, since it could bias estimates of long-term gravity trends (g-dots). The possibility that the common variation can be characterized by two offsetting rapid changes is also being investigated.

6. Postglacial rebound

Long-term monitoring of gravity using JILA absolute gravimeters was initiated in 1987/1988 at Churchill, Canada and International Falls, U.S.A. by NRCan and NOAA. In 1993 JILA instruments were replaced by FG5-model instruments for measurements at these sites, and in 1995 regular annual measurements at four additional sites began in the mid-continent of North America (Fig. 2). This joint experiment was designed to measure the long-term rate of change of gravity associated with postglacial rebound (Lambert et al., 2001). Churchill, where more than 20 measurements have been made, exhibits a gravity rate of −1.9 μGal/year, the highest rate of all the sites (Fig. 8).
Fig. 9. Observed gravity change rates compared to predicted rates for three different ice-sheet models, ICE-3G (dark solid line), ICE-5GP (dashed line) and MULTID-1 (light solid line) along a profile from the centre of Hudson Bay to Iowa. The profile observation sites are at Churchill (CHUR), Flin Flon (FLIN), Pinawa/Lac Dubonnet (PINA/DUBO), International Falls (INTF), Wausau (WAUS) and Iowa City/North Liberty (IOWA/NLIB). Vertical bars denote standard errors on observed rates.

The six sites in the mid-continent lie on a curved profile that can be drawn from the centre of Hudson Bay through Churchill, Canada to Iowa City, U.S.A., a profile that passes from an area of rapid uplift around Hudson Bay southward to an area of negligible uplift or subsidence south-west of the Great Lakes. The observed gravity rates along this profile are compared with theoretical rates for three different ice-sheet histories that load the surface of a spherically-symmetric Earth having a fluid outer core, compressible Maxwell viscoelastic mantle and elastic lithosphere (Fig. 9). In the comparison shown here we assume the mantle viscosity profile VM2 (Peltier, 1998, 2002). Details of the computational model are given by James and Ivins (1998). Three ice-sheet histories considered in this comparison are ICE-3G (Tushingham and Peltier, 1991), an approximation to a preliminary model, ICE-5GP (Peltier, 2002) and MultiDome-1, a model with the same chronology of ICE-3G but with the ice thickness west of Hudson Bay and north of Lake Superior increased by 50%. Details of MultiDome-1 and comparison between geodetic and geomorphological data are given by Lambert et al. (2005a,b). Comparing observed and predicted rates (g-dots) for three models along our profile (Fig. 9) shows that the ICE-3G model tends to under-predict the observed rates, preliminary model ICE-5GP over-predicts at Flin Flon and our model MultiDome-1 provides a good fit to the totality of the data.

Both the preliminary ice-sheet model ICE-5GP and our MultiDome-1 model propose substantially thicker ice in the western part of the Laurentide ice-sheet. ICE-5GP, however, was based, in part, on the higher gravity rates reported (Lambert et al., 2001) prior to the recognition of a widespread inter-annual variation that has now been taken into account in the analysis performed here. Thus, less additional ice is required to satisfy available geodetic data, assuming the ICE-3G chronology.

Four gravity sites along the mid-continent profile, Churchill, Flin Flon, Pinawa/Lac Dubonnet, and Iowa City/North Liberty, are co-located with or near continuously-operating GPS receivers. At the first three sites the absolute gravity measurement point is located a few metres from the GPS antenna on the same bedrock formation. The absolute gravity site at Iowa City is 12 km from the VLBI/GPS site at North Liberty. Vertical rates for the four GPS sites derived by Bock et al. (2004), HeFlin (2004) and Sella et al. (2004) are averaged to obtain mean estimates of vertical velocities in the global FTRF2000 reference frame. A comparison between the gravity rates and the averaged GPS vertical rates at the four sites (Fig. 10) gives a linear relationship with a slope of $-0.18 \pm 0.03 \mu \text{Gal/mm}$, very close to the theoretical value of $-0.16$ (Wahr et al., 1995; James and Ivins, 1998) and confirming preliminary results by Larson and van Dam (2000). Moreover, the line passes through the origin within experimental error, which suggests that there is no serious bias between gravity rates and GPS rates. However, four comparison points provides only two degrees of freedom in the determination of the intercept. More comparison sites are needed to provide a definitive comparison. Significantly, the present level of agreement was achieved only after correcting the gravity values for a common inter-annual variation.
Fig. 10. Comparison between observed gravity rates and averaged GPS vertical rates at four sites in the North American mid-continent. Site acronyms are explained in Fig. 9. Error bars are standard errors on observed rates.

7. Discussion and conclusions

Measurements at a near-shore site show that the gravity effect of ocean tides can be amplified and distorted by hydrological coupling. Although near-shore sites tend to be less affected by long-term, precipitation-related, groundwater variations, the gravity effect of hydrologically-coupled, long-term, sea-level change may bias tectonically-related gravity trends. Further work is required to confirm hydrological coupling at a number of near-shore sites by examining the gravity response to local sea-level at a range of tidal periods. Seasonal variations of soil moisture may produce large gravity effects, particularly at hilltop sites or sites above sloping terrain but these effects can be modelled adequately in high precipitation areas where the soil regularly becomes saturated. Even in areas of extremely high annual precipitation, the magnitude of the annual soil moisture effect can be negligible depending on the local geology (e.g., Ucluelet). Soil moisture modelling at Vancouver Island sites has been very effective in correcting for the change in gravity during the summer months when soil moisture reduction occurs. The same models could be used to invert the gravity changes for soil moisture variation, which, together with soil cover data, could be used to estimate the soil moisture influence on GRACE results.

Analysis of the gravity time series at Ucluelet, a site having minimal seasonal variation, indicates that Cascadia Subduction Zone “episodic tremor and slip” is accompanied by gravity change, which is most likely caused by mass redistribution, possibly fluid flow, not height change. Further work is being done to determine the detailed gravity signature of a specific ETS event and to determine whether the signal is seen at other sites.

An inter-annual variation of unknown origin with a “period” of around 7 years is present at all 11 North-American absolute-g sites considered in this study. Correcting for this variation brings the long-term gravity trends at mid-continent sites into agreement with long-term vertical rates from GPS. In addition, the modified gravity rates are also in agreement with other geomorphological constraints on Laurentide ice-sheet unloading scenarios (Lambert et al., 2005a,b). The origin of the inter-annual variation is being investigated.

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