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1. ABSTRACT

GPS, absolute gravity and GRACE satellite data have been combined to map postglacial rebound (glacial isostatic adjustment) and to identify large spatial-scale water storage variations in the Nelson River drainage basin. GPS data from 27 continuous sites over the period 1996-2010 with an average time-series length of 10.6 years were combined with data from over 50 regularly-surveyed monuments over the period 1995-2011 to produce an updated vertical velocity map for the basin. Annual absolute gravity measurements at eight sites (six co-located with continuous GPS receivers) with an average time-series length of 15.6 years over the period 1987-2011 were used to quantify the linear relationship between vertical velocity and the rate of change of gravity characteristic of postglacial rebound. The relationship yielded two important results: 1) confirmation that the ITRF2005/2008 is well-aligned to the Earth center of mass, and 2) computation of a 'virtual' gravity rate map of postglacial rebound based on the superior spatial coverage provided by GPS. Monthly GRACE data for the period 2002-2011 complete to spherical harmonic degree and order 60 were used to produce a gravity rate map of the study area. The availability of an independent, 'virtual' gravity rate map provided a means of removing the postglacial rebound signal from the GRACE map to reveal the annual rate of change in water storage over a 90-month period (2002-2009). A major, long-term, water storage rate anomaly stretching from Lake Winnipeg to Saskatoon was identified and confirmed by absolute gravity and geological weighing lysimeter measurements. Short-term inter-annual variations (2 - 4 yrs.) detected by GRACE and observed at individual absolute gravity sites are generally well correlated suggesting that the source of the variations is spatially coherent over a wide area. Surface and satellite gravity data from particular sites in the Winnipeg River and Saskatchewan River sub-basins correlate well with river flow rate and deep well (lysimeter) observations in the two basins, respectively, demonstrating the water-storage origin of the gravity variations. Constraints on the spatial scale of these variations (600 -1000 km) are provided by 1) theoretical calculations, 2) an observed gravity displacement ratio for the Winnipeg River sub-basin, and 3) differences in water-mass sub-basin averages from GRACE. Two practical applications of this study are: 1) an updated estimate of the rate of reduction in hydraulic head at the Jenpeg generating station of 0.21 m/century as a result of postglacial rebound and lake level regulations, 2) development of a method of tracking long-term changes in water storage for use in flood prediction.

2. INTRODUCTION

Geophysical processes in the solid Earth, the hydrosphere, the atmosphere and the cryosphere can significantly affect human activities on many different time-scales. Such processes generally involve re-distribution of mass and are often accompanied by movement of the Earth's surface. Combining high-precision gravity data with surface displacement data provides a powerful means of understanding the interactions and predicting the effects in both the short-term and the long-term.

Since its inception in 1995, this project has expanded from a study of postglacial rebound (glacial isostatic adjustment), which affects the flow of water on time-scales of hundreds of years, to include variations in water flow on seasonal and inter-annual time-scales. The new capability was facilitated by the discovery of inter-annual gravity variations of unknown origin in our annual absolute gravity data (*Lambert et al.,* 2005) and the availability of monthly gravity data from the GRACE mission (*Tapley et al.,* 2004). Our results illustrate that the pre-launch, hydrological objectives of the GRACE mission (*Dickey et al.*, 1997; *Wahr et al.,* 1998 and *Rodell and Famiglietti,* 1999) have been met.

In this report we combine surface absolute gravity (AG), satellite gravity (GRACE) and surface GPS data to map and quantify postglacial rebound and to study the interaction between the solid Earth and the hydrosphere in mid-continent North America and in the Nelson River drainage

basin, in particular. Combining the three techniques takes advantage of their complementary strengths and weaknesses. AG is independent of reference systems and networks but its spatial and temporal resolution is limited somewhat by the small number of instruments available and the labor intensiveness of the measurements. However, the availability of long (> 10 yrs) series of co-located AG and GPS data has provided a unique opportunity to evaluate the precision with which the International Terrestrial Reference System 2005 (ITRF2005) in mid-continent North America tracks the center of mass of the Earth (*Mazzotti, et al.*, 2011). Both the Canadian GPS networks and the GRACE system provide good temporal resolution for detection of seasonal and long-term effects but the GRACE system lacks spatial resolution at present. Another important difference between the three techniques is that GPS measures surface bedrock movement, GRACE measures mass re-distribution and AG measures a combination of the two.

This report is based on data collected under Manitoba Hydro R&D Project G117 since October 1995 as well as relevant pre-existing data in the study area. The report extends to March 31, 2011 a previous study of postglacial rebound in the Nelson River Basin (Lambert et al., 2005). Our interpretations take into account two new surface gravity monitoring sites in the western part of the basin, longer geodetic time-series at six pre-existing sites, a new adjustment of all available GPS data in the mid-continent of North America, and newly available satellite gravity data. Whereas the earlier study was based on the adjustment of a Laurentide ice-sheet history model to fit a combination of relative sea-level, geo-morphological, geodetic and lake-gauge data at a number of sites, the present study is based entirely on geodetic data collected at a greater number of sites over the last two decades (continuous GPS, campaign-style GPS, annual absolute gravity (AG), and monthly satellite gravity (GRACE) data).

We compare available geodetic data with hydrological data from two specific sub-basins of the Nelson River system to illustrate the potential for geodetic monitoring of total water variations. It is not a comprehensive study of water variations in the entire basin.

3. VERTICAL CRUSTAL MOVEMENT

3.1 *Continuously Operated GPS Network Adjustment*

We define the vertical velocity field in the North America mid-continent region using 27 continuous GPS stations from Hudson Bay to central U.S.A and from the Rocky Mountains to the Great Lakes (Fig. 1). This subset comprises all existing continuous GPS stations in Canada pertinent to our region of interest and a selection of north-central U.S.A. stations based on time span, monument, and data quality. The time period considered for analysis is January 1996 to December 2010, with an average time series length of 10.6 yr (longest 15.0 yr, shortest 6.1 yr).

The GPS data are processed with the NRCan Precise Point Positioning PPP 1.05 software (*Heroux and Kouba,* 2001). For each site, daily solutions are computed using ionosphere-free combinations of un-differenced pseudorange and phase observations, with satellite clocks fixed to the International GNSS Service (IGS) precise products, absolute phase-center calibrations for the GPS and satellite antennas (*Schmid et al.*, 2007), gridded Vienna Mapping Functions (VMF1, *Boehm et al.*, 2006) for the troposphere model, and solid earth and ocean tide corrections.

We estimate the linear trends in North, East, and Up components at each station using a weighted least-square inversion of the daily coordinates and a model that comprises a linear trend, annual and semi-annual sine functions, and step functions at the times of antenna or monument modifications. Standard errors on the model parameters are calculated using the general formula for uncertainties for a colored noise source of *Williams* (2003). For each individual time series, we estimate the spectral index K of the residual power spectrum. The average spectral index is 0.64, i.e. a noise process between white and flicker, which yields standard errors about 1.6

times larger than formal white noise uncertainties (See *Mazzotti et al.,* 2011; Supplementary Text S1 for details)

Initially, site positions and velocities derived from PPP processing are loosely aligned to the IGS05 reference frame through the IGS orbits and satellite clocks. We align the network velocities to the ITRF2005 realization of the International Terrestrial Reference Frame (*Altamimi et al.,* 2007) by finding the seven-parameter Helmert transformation that best fits the velocities at the ten sites common between our network and ITRF2005. The very small average residuals (less than 0.01 mm/yr) indicated a robust alignment to the reference frame.

3.2 ***Vertical Velocity Map of Postglacial Rebound from Continuous and Epoch GPS***

The velocities of the continuous GPS stations were combined with velocities from the more densely-spaced Canadian Base Network (**CBN**) monuments (Fig 1b). The **CBN** is a network of pillars capped with a plate having a threaded bolt on which a GPS antenna or a theodolite can be mounted (*Henton et. al.,* 2006). Over fifty CBN monuments in the Prairie Provinces and Western Ontario have been re-surveyed by GPS a number of times. A combined CBN velocity solution using data collected over the period 1995-2011 was oriented and scaled to fit the continuous GPS network solution. Vertical velocities at the individual sites have been interpolated to a grid with 2˚ x 2˚ spacing using a "single nearest neighbor" technique and smooth contours were estimated using a "minimum curvature" technique to produce a vertical velocity map for the Nelson River drainage basin (Fig. 2).

Given that acceleration is negligible over the time span the vertical velocity map can be used to estimate the relative crustal movement between any two points by multiplying the difference in vertical velocity by the time period of interest. If the change in crustal elevation relative to a continuous body of water is required, the accompanying change in geoidal height controlling the water surface must also be taken into account. Generally speaking, the deformation of geoidal heights associated with postglacial rebound occurs at a rate approximately one tenth of the crustal deformation rate. For example, if the crustal uplift rate at Churchill is 1 cm/yr the geoidal height there will increase by 1 mm/yr.

With reference to Fig. 2 the change in hydraulic head between Jenpeg in the north and the south-west corner of Lake Winnipeg in 100 years can be estimated by multiplying the difference in vertical velocities, v1-v2 (4.6 mm/yr), between the two points by 0.9, to take into account the geoidal deformation, and by 100 to convert to hydraulic head in millimeters per century. Thus, there will be a change in hydraulic head between Jenpeg and the south end of the lake of 0.414 m/century. If the mean level of the lake is maintained constant by regulation, the reduction in hydraulic head at Jenpeg will be one half of the difference along the length of the lake or 0.207 m/century, while that at the south end of the lake will increase by the same amount.

4. SURFACE GRAVITY VARIATIONS

4.1 ***Method of Gravity Observation and Analysis***

Absolute gravity (AG) measurements, consisting of measurements of the acceleration of a test mass falling in a vacuum, have been carried out repeatedly at eight calibration sites in mid-North America from Churchill, Manitoba in the north to Iowa City, Iowa in the south (Fig. 1a, Table 1). Observations began in 1987/88 at Churchill, MB (CHUR) and International Falls, MN (INTF), and in 1995 at Flin Flon, MB (FLIN), Pinawa, MB (PINA), Wausau, WI (WAUS) and Iowa City, IA (IOWA) (*Lambert et al.,* 2001). Measurements were made annually from late September to early October, supplemented occasionally by additional measurements in Spring or early Summer (May to July). Annual Fall measurements were added at Saskatoon, SK (SASK) and Priddis (Calgary), AB in 2001 and 2002, respectively. Each gravity measurement typically involved around 2400

drops of the test mass over a period of at least 24-hours. From 1987 to 1992 observations were made at CHUR and INTF by Natural Resources Canada (NRCan) and by National Oceanic and Atmospheric Administration (NOAA) using instruments JILA-2 and JILA-4, respectively (*Faller et al.,* 1983). From 1993 to the present, observations have been made with FG5-series instruments (*Niebauer et al.,* 1995): most frequently FG5-106 (NRCan – 104 observations) and, from time to time over the period 1993 to 2002, FG5-102 and FG5-111 (NOAA- 23 observations and two observations, respectively). Two measurements made by NRCan using FG5-236 were added in 2010 (NRCan – two additional observations).

Drop data from the primary instrument, FG5-106 and from FG5-236, were analyzed by NRCan using the Micro-g LaCoste "g8" software, where gravity values are corrected for solid Earth tides, ocean tide loading, atmospheric effects, and polar motion. NOAA drop data from 1993 to 2002 was analyzed using an earlier version of the Micro-g Solutions "g" software with corrections compatible with those used by NRCan. Gravity rates were calculated for each of the eight mid-continent sites by fitting a linear trend by weighted least squares to the gravity values. As in earlier studies an offset was specified between absolute gravimeter FG5-106 (NRCan) and other instruments used in this study (FG5-102 (NOAA), JILA-2 (NRCan) and FG5-236 (NRCan). FG5-102 was found to give values 0.9 ± 1.5 μGal higher than FG5-106 by comparing six simultaneous measurements at Table Mountain Gravity Observatory (TMGO), Boulder, CO and three nearly simultaneous measurements in the field (1 μGal = 10 nm/s^2). This offset is lower than an earlier estimated offset of 4.1 μGal, which was based on a few comparisons before 2000. JILA-2 was found to give values that were 4.1 ± 0.3 μGal higher than FG5-106 in a simultaneous comparison controlled by superconducting gravimeter data at the Canadian Absolute Gravity Site, near Ottawa, ON (*Liard et al.,* 2003). FG5-236 was found to have an offset of 0.6 ± 2.5 μGal in a North American comparison exercise at TMGO (*Schmerge et al.,* 2012). FG5-102, FG5-111 and JILA-4 were assumed to produce compatible values (within ± 2 μGal) throughout the experimental period as they were regularly compared at TMGO.

The linear trend errors quoted in the next section and shown in Fig. 3 are based on a white noise model of gravity and, as such, might be under-estimated. An analysis was carried out to evaluate the fractal nature of the gravity noise spectrum in order to accurately estimate the gravity rate errors. A colored ($1/f^K$) plus white noise model was fitted to the frequency spectra of the de-trended gravity data from each of the eight sites (See *Mazzotti et al.,* 2011; Supplementary Text S1 for details). The results showed that the colored component of the noise can be fitted by a relatively low index, K, of 0.5. This is consistent with noise in absolute-g calibrated superconducting gravity (SG) data, which tends toward white noise below a frequency of 1 cycle per year (*Van Camp et al.,* 2005; 2010). The parameters of these fits were used to estimate more reliable errors on the gravity change rates at each site (Table 1). The numerical results from the frequency-domain computations at certain sites were checked by time-domain computations using the maximum likelihood estimator (*Langbein and Johnson,* 1997).

4.2 ***Surface Gravity Observational Results***

The observed gravity values at each of the eight absolute gravity sites in the North American mid-continent are shown in Figs. 3a to 3h. Note that gravity values having larger errors were made with instruments other than the primary absolute gravimeter FG5-106. The errors include the uncertainties involved in the instrument inter-comparisons. In general, the mostly annual gravity values exhibit a linear trend plus inter-annual variations of variable amplitude. The most striking features are the strong linear decrease in gravity of 1.75 ± 0.08 μGal/yr at Churchill, Manitoba and the significant linear increases of 0.51 ± 0.15 μGal/yr at Iowa, City and 1.25 ± 0.29 μGal/yr at Saskatoon. As we shall see later the Saskatoon rate, derived from a relatively short record, is heavily influenced by water. The inter-

annual gravity variations tend to correlate from site to site. For example, the eastern sites, which have the longest history, exhibit low gravity values around 1998. All sites with the exception of Saskatoon exhibit low gravity values in 2007-2008. With the exception of Churchill, all sites in the Nelson River drainage system, Flin Flon, Pinawa, International Falls, Saskatoon and Priddis, indicate a minor low in 2003. We shall see later that there is strong evidence that these inter-annual variations correlate with total water content, particularly at Saskatoon.

4.3 ***GPS Vertical Rate / Surface Gravity Rate Comparison***

Since uplift and gravity change are both a direct result of glacial isostatic adjustment, which is the dominant process in our study region, we can expect a linear relationship between surface gravity rates and height rates (vertical velocities) that passes through the origin of the gravity-rate, height-rate axes. To demonstrate this, theoretical values of vertical velocity and gravity rate were calculated for the seven observation sites based on a preferred Laurentide ice sheet model and Earth viscosity structure known as MultiDome1/VM2 (*Lambert et al., 2005*) (Fig. 4). This model is a modification of ICE-3G (*Tushingham and Peltier, 1991*) with a thinner ice-sheet in southern Manitoba and immediately west of Hudson Bay relative to ICE-5G (*Peltier, 2004*), as required by a combination of recent geodetic data (*Argus and Peltier, 2010*). The results show that a linear fit to the theoretical rates gives a slope of -0.155 ± 0.023 μGal/mm and passes through the intersection of the gravity-rate, height-rate axes within computational errors. A similar result is expected for observed data, provided that the reference system is aligned to the Earth centre of mass and there is no water-related bias.

The observed gravity rates and vertical velocities at our co-located sites provide an empirical evaluation of the ratio of gravity rate to height rate, and a test of the alignment of the GPS reference system. Absolute gravity rates and vertical velocities at our eight collocated or nearby sites are given in Table 1. The International Falls, MN, and Wausau, WI, gravity sites are not collocated with a continuous GPS station. We estimate the vertical velocity at these sites by interpolating the velocities of nearby GPS stations (Fig. 1), using a 2-D adaptive Gaussian interpolation function, with a half-width defined as the distance to the nearest GPS station (107 km and 226 km, respectively). Fig. 5 shows the observed absolute gravity rates versus vertical velocities in ITRF2005, as well as the best-fit linear regression between the two variables taking into account the uncertainties on both axes (so-called geometric-mean regression, cf. *York*, 1966). Because of significant hydrological effects during the relatively short time span of measurements (see Section 6.2), the data point for Saskatoon does not fit the same trend as the other sites and is excluded from the regression analysis. The best-fit model yields a gravity/uplift ratio of -0.165 ± 0.012 μGal/mm and an intercept of -0.04 ± 0.08 μGal/yr (or -0.24 ± 0.50 mm/yr).

The ratio of -0.165 ± 0.012 μGal/mm, including all sites (except Saskatoon), is consistent with the predicted gravity/uplift ratio of -0.155 ± 0.023 μGal/mm derived for the theoretical model described above and with other postglacial rebound models (-0.15 μGal/mm; *Wahr et al.*, 1995, *James and Ivins*, 1998).

The observed intercept of -0.24 mm/yr (-0.04 μGal/yr) is not significantly different from zero given the uncertainty of ±0.50 mm/yr (±0.08 μGal/yr) (Fig. 5). In a previous study of gravity and GPS rates in North America mid-continent, *Larson and van Dam* (2000) found a similar zero gravity/uplift offset, albeit with a precision of about ± 2.0 mm/yr due to the limited absolute gravity data used in their analysis. In contrast, non-zero gravity/uplift offsets (0.5 – 2.0 mm/yr) have been reported for studies in western Canada (*Mazzotti et al.*, 2007) and Britain (*Teferle et al.*, 2006). Because of uncertainties in the ITRF2000 reference frame definition (e.g., *Altamimi et al.* 2007; *Argus*, 2007) and potential biases in antenna phase-center calibrations (*Ge et al.*, 2005), these non-zero offsets may be attributed to GPS velocity biases or regional mass

redistribution processes (*Teferle et al.*, 2006; *Mazzotti et al.*, 2007).

Mazzotti et al. (2011) using antenna absolute phase-center calibrations and gravity data up to 2009 showed that, at least in the North American mid-continent region, vertical velocities aligned to the ITRF2005 are also properly aligned to the Earth Center of Mass, within 0.96 mm/yr at the 95% confidence level. Our results (Fig. 5), based on slightly longer gravity data, confirm these conclusions.

5. SATELLITE GRAVITY VARIATIONS

5.1 *GRACE Mission*

The GRACE (Gravity Recovery and Climate Experiment) satellite system, launched in March 2002, consists of two co-orbiting satellites which maintain a distance of about 220 km between each other along a nearly polar orbit at an altitude of about 450 km above the Earth's surface (*Tapley et al.*, 2004). GRACE can detect a change of 1 billionth of the Earth's gravity field over time and space, that approximately corresponds to a change of 2.5 cm in equivalent water thickness at a spatial resolution of 350 - 450 km. The gravity changes over time are caused by mass movement within the whole Earth system, comprising the atmosphere, the hydrosphere and the "solid" Earth. In standard GRACE data processing (*Bettadpur* 2007; *Flechtner* 2007), gravity effects of secular variations of the low-degree harmonics, solid Earth, ocean and pole tides, and atmospheric and non-tidal oceanic variations are combined into the so-called background models. These models are removed before release of the gravity field information. Thus, the resulting GRACE gravity models, expressed in terms of spherical harmonics, mainly contain water mass changes on and below the Earth's surface, as well as solid mass changes associated with non-tidal geodynamic processes beneath the Earth's surface. Due to errors in the background models and measurement errors, the GRACE gravity models are subject to errors dominated by a stripe-like correlation error. Furthermore, GRACE has only a limited spatial resolution because a local-scale mass change causes a gravity change that is too weak to be detected at the satellite altitude.

5.2 *Method of GRACE Data Analysis*

A two-step method has been used to extract the gravity change signal from the GRACE models (*Huang et al*, 2012). It combines and improves the de-striping method (*Swenson and Wahr*, 2006), the statistical filtering method (*Davis et al.*, 2008) and non-isotropic Gaussian filtering (*Wahr et al.*, 1998; *Han et al.*, 2005) (see Fig. 6). This combined method minimizes the resulting signal loss from the three methods while retaining their efficiency and effectiveness in extracting the signal.

The monthly GRACE models of Release 4 by the Center for Space Research (CSR) for the period of 2002 - 2011 have been used in this study. There are a total of 110 global, monthly, spherical harmonic models for this period. All the monthly models are complete to spherical harmonic degree and order 60, which is approximately equivalent to a spatial resolution of 350 km in the region of study. Due to model error, their actual resolution is between 350 and 450 km depending on the quality of a model for a specific month.

5.3 *Gravity Signature of Long-term Mass Redistribution Rate*

A gravity change rate map has been derived from the first 90 GRACE monthly gravity models and is shown in Fig. 7. A least-squares fitting method has been used to derive this map. It is based on a time-varying parametric model for each spherical harmonic coefficient. The parametric model consists of "velocity", "acceleration", and annual and semi-annual terms. The resulting "velocity" and "acceleration" estimates are used to compute the mean rate of each coefficient over the GRACE observation period. Finally, all mean rate coefficients are used to synthesize the gravity change rate map.

The map shows a gravity change pattern with the peak rate around Hudson Bay reflecting

the effect of postglacial rebound. The high gravity rates extend over a large area of northern Ontario, Manitoba and Saskatchewan. Comparing this map with the vertical velocity map for the same region (Fig. 2), shows that the area of high gravity rate and the zero rate line are significantly further south-west compared to similar features of the velocity rate map. This is partly the result of the smoothing effect of the (truncated) spherical harmonic representation used in the satellite data processing but it also suggests a source other than postglacial rebound. This is discussed further in section 6.1

5.4 *Gravity Signature of Temporal Variation in Total Water Storage*

The monthly satellite gravity values for each grid point have also been analyzed for their root mean square (RMS) variation about the best fitting linear trend. The RMS gravity variations are typically dominated by seasonal variations in total water storage, modulated by inter-annual variations. A contour map of the water-mass equivalent RMS variations in the study area (Fig. 8) shows that the area of greatest variation in seasonal water content east of the Rocky Mountains is centered on the Winnipeg River system in northern Minnesota, south-eastern Manitoba and western Ontario (55 mm). The seasonal variation high extends north through eastern Manitoba and western Ontario to the northern part of the Saskatchewan River system (50 mm). This RMS variation is equivalent to an average peak-to-peak seasonal variation in total water content of around 150mm in these areas.

5.5 *Total Water Storage Variations Averaged over Basins*

From the monthly GRACE gravity values at each grid point we have also calculated monthly equivalent water-mass values relative to a best fitting linear trend for specific sub-basins of the Nelson drainage system. The total water storage (TWS) change in water thickness equivalent (WTE) within a water drainage basin can be estimated from the GRACE TWS result as

$$\overline{\Delta h}_{TWS}(t_i) = \frac{1}{A}\iint_D w(\phi,\lambda)\Delta h(\phi,\lambda,t_i)dA \quad (1)$$

where

$$A = \iint_D w(\phi,\lambda)dA \quad (2)$$

w is the exact basin averaging weight function which equals 1 inside and 0 outside the water basin D. Δh is the WTE change at a point within the basin.

The WTE change Δh from GRACE does not represent a point value because of the limited spatial resolution of GRACE models. It is mathematically equivalent to the low-pass filtered value which can be considered as the averaged Δh over a large area. Therefore, the TWS change from Eq. (1) is affected by both leakage and omission errors. In general, the larger the basin, the smaller is the error.

Computations were carried out for the Winnipeg River drainage basin and the Saskatchewan River drainage basins (locations, Fig. 9). The monthly residual water-mass values for these two basins for the period of 2002 – 2009 are shown in Fig. 10. A three-point running average has been used to smooth these time series and the values are plotted relative to the mean of the values from 2005 to 2009. The GRACE data have been de-trended by estimates of the gravity effect of glacial isostatic adjustment based on the vertical crustal velocity map of Fig. 2 (Section 6.1, Fig. 13). From these plots we see that the seasonal variations, while showing a fairly consistent high in the Spring and a low in the Fall, are highly variable in amplitude from year to year. This amplitude variability during the period of study is quite different in the two sub-basins. Fig. 10 shows clearly the serious drought ending in 2005 in the Saskatchewan River basin (*Hanesiak et al.*, 2011; *Yirdaw et al.*, 2008) and a somewhat smaller deficit in the same period in the Winnipeg River basin. Also shown is a water storage deficit occurring in the Winnipeg River Basin starting in early 2006 and lasting until late 2008 with a decline of ~100 mm in water thickness equivalent. A corresponding drop of around 4 μGal in surface gravity is seen from late 2005 to late 2008 at Pinawa and International Falls (Figs. 3c and 3d). In the Saskatchewan River Basin there are signs

of a multi-year deficit beginning at a later date (late 2007) and continuing until late 2009. This is also reflected in the surface gravity values at Saskatoon (Fig. 3g). During this period the seasonal changes in the Saskatchewan River Basin are relatively pronounced compared to the Winnipeg River Basin.

6. SURFACE & SATELLITE GRAVITY VARIATIONS COMPARED

6.1 *Comparison of Multi-year Rates*

Assuming that postglacial rebound is the dominant process in the study area, a gravimeter on the Earth's surface is sensitive to the change in gravity associated with the movement of the instrument relative to the Earth's centre of mass, as well as to the re-distribution of sub-surface mass, whereas a satellite is not sensitive to the former effect. Therefore, in order to compare surface and satellite observations we must correct the observed surface gravity variations for changes in vertical position using the co-located GPS vertical data. The time variation in surface gravity due to sub-surface mass redistribution only is given by

$$g_m(t) = g(t) - (dg/du)v(t-t_0) - g_0 \qquad (3)$$

where g(t) is observed surface gravity at time t, dg/du is the free-air gravity gradient (-0.3086 μGal/mm), v is the ITRF2005 GPS vertical velocity (Table 1) and g_0 is a reference gravity value at reference time t_0. Monthly GRACE and surface absolute gravity observations at each of our eight calibration sites are compared in Figs. 11a-h where, in some cases, the GRACE and surface gravity plots are shifted vertically with respect to each other for better visibility. We fit linear trends to the GRACE and surface gravity observations and compare the results in Table 2. Note that correcting for the vertical movement of the sites changes the sign of the gravity trends, since the areas of uplift are areas of sub-surface mass accumulation.

Referring to Figs. 11a to 11h and Table 2, we see that, with the exception of Churchill and Saskatoon, the GRACE trends are all positive and significantly higher than the surface gravity trends. This difference is most likely the result of the GRACE observations being an average over a much larger area than the surface gravity observations, since the GRACE spherical harmonics are truncated at degree and order 60. GRACE is sampling uplifting areas of sub-surface mass accumulation as well as the accumulation of near-surface water in areas distant from the surface gravity sites. The discrepancy in rates is small at Churchill, Manitoba because the Churchill surface site is more representative of the postglacial rebound around it and groundwater recharge is minimal. The good agreement at Saskatoon is the result of the dominance of local water redistribution (Section 7.2).

The shift toward higher positive gravity rates for GRACE compared to surface measurements is investigated further by deriving a 'virtual' mass redistribution gravity rate map from the vertical crustal velocity map of Fig. 2. We transform the vertical crustal velocities into equivalent surface gravity rates using the observed ratio of gravity to vertical velocity, -0.165 μGal/mm (section 4.3) characteristic of postglacial rebound (glacial isostatic adjustment), and then correct those rates for the free-air effect of vertical velocity, +0.3086 μGal/mm. Combining these two ratios, a virtual gravity rate in μGal/yr reflecting mass redistribution only is given by

$$dg_{vm}/dt = +0.1436\ du/dt \qquad (4)$$

where du/dt is the ITRF2005 GPS vertical velocity in mm/yr. The resulting map (Fig. 12) is a 'virtual' gravity rate map reflecting mass-redistribution as it would be seen at a fixed height at the surface. In order to compare this map to the GRACE gravity rate map of Fig. 7, the 'virtual' gravity rate map must be subjected to equivalent spatial filtering. This is achieved by expressing the gravity rate map in a spherical harmonic geopotential model that is comparable with monthly GRACE models and truncating at degree and order 60 (Fig. 13). To avoid possible edge effects the computations are carried out over a

significantly larger area (35° N, 125° W; 68° N, 70° W) than the study area shown in the figures. A predicted gravity rate grid from the ICE3G model is used to fill the data gap over the rest of the Earth. This filling further reduces the edge effect and has negligible effect on the gravity rate over the area of study.

We compute a gravity rate difference map (Fig. 14) (GRACE minus 'virtual' gravity) by applying the 'virtual' gravity rate map as a postglacial rebound 'correction' to the raw GRACE data before spherical harmonic truncation and processing. The corrected GRACE gravity map shows a significant gravity rate anomaly centered on the Manitoba-Saskatchewan border just west of Lake Winnipegosis. Based on hydrological data from Saskatchewan described in the next section (Fig. 19), we infer that the gravity rate anomaly revealed in the 'corrected' GRACE map results from an excess rate of surface water accumulation over the 90-month GRACE observation period. The rate and spatial extent of the accumulating water can be estimated by comparison with the gravity anomaly associated with an hypothetical, uniform, spherical cap centered on the GRACE rate anomaly. This hypothetical spherical cap is not a unique solution but a highly simplified, symmetrical, mass load that produces a gravity rate anomaly similar in amplitude and scale to the observed anomaly of Fig. 14. The actual mass anomaly is undoubtedly much more complex. We estimate that the gravity rate anomaly represents an average water accumulation of about 3 cm/yr over a region extending about 800 km north-south and 1200 km east-west (Appendix A). The water thickness equivalent of the gravity anomaly will be reduced slightly when we take into account the elastic loading effect of the water on GPS vertical velocities in the region (Appendix B). However, the elastic loading effect on our estimate is minimized for two reasons: 1) the 90-day GRACE observation period was at the time of most rapid water accumulation, whereas the GPS velocity map incorporates several years of data prior to the drought of 2002 (Appendix B), and 2) expressing the 'virtual' gravity rate map in spherical harmonics up to degree and order 60 tends to smooth out any deflection of the gravity contours in the vicinity of the water load. We estimate a total water accumulation of about 24 cm over the region described above from 2002 to the end of 2009. As we shall see in section 7.2, a further accumulation occurred in the region through 2010 to the spring of 2011.

6.2 ***Comparison of Inter-annual Variations***

Given the inability of our annual, surface, absolute gravity observations to track seasonal variations and given the demonstrated disparity between GRACE and surface absolute gravity observations in long-term (multi-year) rates, we direct our attention to short-term (2 to 4 year) inter-annual variations. By removing a linear trend and overlaying the two observation series we see good agreement at sites where the short-term, inter-annual variations are significant (Figs. 15a to 15h), namely, Flin Flon, Pinawa, International Falls and Saskatoon. A mean reduced χ^2 goodness of fit test between the absolute gravity and GRACE estimates for all eight absolute gravity observation sites yields a value of 1.19, where the reduced-Chi square is defined as

$$\chi^2_{red} = (1/\upsilon)\, \Sigma\, (g_{si} - g_{GRACEi})^2 / (\sigma_{si}^2 + \sigma_{GRACEi}^2) \quad (5)$$

where υ is the number of degrees of freedom, g_s and σ_s denotes surface gravity and its errors, g_{GRACE} and σ_{GRACE} denotes GRACE gravity and its errors, and Σ denotes summation over all measurements i. Based on theoretical considerations explained in the next paragraph, we interpret this good agreement to mean that the source of the variations is a mass redistribution that is coherent over many hundreds of kilometers. Variations in total water content are once again the primary suspect as the source of these short-term inter-annual gravity variations.

The theoretical difference in spatial resolution between a surface gravity measurement and a GRACE satellite measurement is illustrated by considering the measurement response for spherical caps of different radii, simulating a

change in water content in a uniform 10 m thick layer. Calculations have been made at the center of thin spherical caps of different radii assuming a change in water content of 0.2 m. We neglect loading effects in the case of the surface gravity measurement (loading would increase the surface gravity response by about 1 μGal at a radius of 100 km). The results show a similar response for the two methods only when the water mass has a 250-300 km radius or greater (Fig. 16) and is centered near the surface measurement site. Thus, water content variations over a wide area are implied.

7. COMPARISON WITH HYDROLOGICAL DATA

7.1 *Water Storage Variations: Winnipeg River Basin*

Two of the absolute gravity sites which show significant inter-annual variations are Pinawa and International Falls in the Winnipeg River drainage basin (locations, Figs.1a & 9). Annual surface gravity and GRACE monthly gravity data at these two sites show a rise in gravity from 2004 to early 2006 followed by a drop in gravity in mid-2006 and a recovery beginning in 2007, a feature that is seen clearly in the flow rate of the Winnipeg River as measured at Pine Falls, Manitoba (Figs. 17a and 17b). A similar variation is seen in the GRACE results integrated over the Winnipeg River Basin (Fig. 10). The base flow rate is related to the total water storage in the basin in some complex manner. A similar rough correlation is seen between stream flow at the Grand Rapids outlet of the Saskatchewan River basin and GRACE total water storage estimates for the basin (*Yirdaw et al.*, 2008). The drop in water mass detected by GRACE and averaged over the basin is 100-150 mm or approximately 4-6 μGal, similar to the 6-8 μGal change seen at the two surface gravity sites in the basin from 2005 to 2007 (Fig. 17a).

An additional indication of a drop in total water storage in 2006 is provided by an average of GPS vertical observations at four sites surrounding the Winnipeg River basin (locations, Fig. 9). The averaged and smoothed GPS heights indicate an uplift of approximately 5 mm corresponding to the approximately 7 μGal drop at the surface gravity sites (Fig. 18). A g/u ratio of approximately 1.4 μGal/mm suggests that an elastic response to loading (unloading) is taking place over an area much larger than the Winnipeg River Basin (*de Linage et al.*, 2007; Fig. 6).

7.2 *Water Storage Variations: Saskatchewan River Basin*

As mentioned in section 5.5 gravity values and total water content from integrated GRACE data over the Saskatchewan River Basin began to decrease from a relative high in 2007 to a low in 2009, a delay of about one year behind the Winnipeg River Basin (Fig. 10). The increase in water content from 2003 to 2007 and the subsequent decrease until 2010 can also be seen in the annual surface gravity data and the monthly GRACE data from Saskatoon (Fig. 15g). This inter-annual variation is clearly seen in data from deep observations wells in southern Saskatchewan (Fig. 19). Deep observation wells used as geological weighing lysimeters provide records of pressure variations in confined aquifers on the order of 100 m below the ground surface, which can be interpreted in terms of variations in the total water content above the pressure sensor (*Marin et al.*, 2010). Fig. 19 shows good agreement in both phase and magnitude between the surface absolute gravity and GRACE data observed at Saskatoon and the average of four lysimeters located within about 200 km of the surface site (locations, Fig. 9). Note that the extreme high values of gravity and lysimeter readings in late 2010 preceded serious flooding in Saskatchewan, Manitoba and the northern U.S.A. in 2011.

8. SUMMARY AND DISCUSSION

In this report we have derived a new map of vertical crustal velocity associated with postglacial rebound in central North America and have identified a long-term, inter-annual variation in total water content in the Nelson River drainage basin. This was accomplished by combining

annual surface absolute gravity, continuous and campaign-style GPS observations and monthly GRACE gravity observations. In addition, we have mapped the amplitude of seasonal variations in total water content from place to place in the basin based on GRACE gravity observations alone.

A new map of vertical crustal velocities (Fig. 2) combines data from 27 continuous GPS stations (Fig. 1a) having an average time-series length of over 10 years and over 50 regularly-occupied GPS pillars (Fig. 1b). The map shows a range of vertical velocities from +10 mm/yr at Churchill to -3.1 mm/yr at Iowa City and has sufficient detail to provide tilt estimates across important physical features, such as Lake Winnipeg. The map predicts a reduction in hydraulic head at the Jenpeg generating station of 0.207 m/century as a combined result of the naturally occurring postglacial rebound and regulations requiring the Lake Winnipeg mean water levels to be maintained at a constant level.

GPS vertical rates and rates of change of gravity at co-located sites have been compared (Fig. 5), showing a high degree of consistency between the two data sets with the exception of Saskatoon where we have demonstrated a clear correlation with total water variations (Fig. 19). The observed ratio of gravity rate to vertical velocity of -0.165 ± 0.01 μGal/mm is identical, within the estimated errors, to the postglacial rebound model estimate of -0.155 ± 0.023 μGal/mm, confirming that postglacial rebound is indeed the dominant process affecting long-term variations at all comparison sites except Saskatoon. The small intercept of -0.24 ± 0.50 mm/yr confirms that the vertical velocities aligned to the ITRF2005 are also properly aligned to the Earth center of mass as reported earlier (*Mazzotti et al.*, 2011).

The linear correlation between gravity rates and GPS vertical rates provides a means of converting the map of vertical crustal velocity (Fig. 2) into a surface gravity rate map, which can be corrected for vertical ("free-air") movement effects to produce a 'virtual' gravity rate map (Fig. 12) reflecting the sub-surface mass re-distribution associated with postglacial rebound.

The map of long-term gravity rates from the analysis of GRACE data (Fig. 7) shows a markedly different spatial distribution from the map of 'virtual' gravity rates (Fig. 12) derived from GPS. This difference is also revealed when surface gravity rates corrected for vertical velocity at individual surface sites are compared with corresponding gravity rates from GRACE (Figs. 11a–h; Table 2). Clearly, GRACE is responding to mass accumulation over a time-scale of several years that does not affect the majority of our surface gravity sites.

The location and amplitude of this mass accumulation is illustrated in Fig. 14, which shows the difference between the GRACE gravity rates and 'virtual' gravity rates that have been spatially filtered identically to GRACE. This ensures that the gravity rate anomaly is not affected by differences in spatial resolution. Since the 'virtual' gravity rates reflect the sub-surface mass re-distribution associated with postglacial rebound, the excess mass accumulation centered west of Lake Winnipeg must have a different origin. The excellent agreement at Saskatoon between GRACE variations, surface gravity variations and the mean of four geological weighing lysimeters (Fig. 19) strongly suggests that the anomaly is caused by the accumulation of near-surface water over the period 2002-2009. The equivalent gravity change estimated from the GLDAS NOAH025 soil moisture and snow model (*Rodell et al.*, 2004) (Fig. 20) indicates that about one third of the anomaly comes from an accumulation of soil moisture and the rest is associated mainly with groundwater and surface water. The deep well level variations over the last 15 years shown in Fig. 19 suggest that the anomaly is a long-term inter-annual phenomenon. The data suggest that the hydrological conditions leading to the devastating floods of the spring of 2011 were developing for a decade.

By comparison with the gravity effect of a uniform spherical cap with a radius of 300 km centered on the observed anomaly, we estimate a water accumulation rate of about 3 cm/yr over an elliptical shaped area 800 km across (N-S) and 1200 km across (E-W), leading to a total water accumulation of 24 cm over eight years. A

reduction in this rate, as a result of the effect of elastic loading of the water on GPS vertical velocities, is estimated to be small (~2-3%) because GPS vertical velocities are estimated over a longer time span, not restricted to the period of rapid water accumulation observed by GRACE.

The GRACE mission has provided the capability of measuring gravity variations in the Nelson River basin on a monthly basis allowing seasonal and inter-annual variations to be investigated, as well as long-term gravity rates. The RMS variation in total water storage, usually dominated by seasonal variations, is shown to peak at 55 mm in the Winnipeg River basin and to remain high over Lake Winnipeg and the North Saskatchewan River valley (Fig. 8). An average peak-to-peak seasonal variation of about 150 mm is implied for these areas. The spatial distribution of the seasonal range in water storage is not particularly well correlated with the long-term water accumulation anomaly, suggesting that the latter has more to do with natural flow dynamics and hydrological properties than with available meteorological input.

Inter-annual variations in both surface gravity and GRACE gravity are well correlated with hydrological data, as shown in examples from the Winnipeg River basin (17 a & b) and the Saskatchewan River basin (Fig. 19) near Saskatoon. In fact, the short-term (2 - 4 yrs.), inter-annual signals from surface gravity and GRACE (Fig. 15 a-h) are shown quantitatively (section 6.2) to track each other extremely well. Thus, short-term inter-annual variations in total water content are shown to be spatially correlated over a wide area whereas the longer-term accumulation west of Lake Winnipeg appears to be more spatially limited. With reference to Fig. 16, the marked similarity between short-term, inter-annual variations in GRACE data and surface gravity data suggests that the spatial scale of the variations is greater than 600 km. The ratio of gravity change to vertical displacement for a particular inter-annual change in the Winnipeg River basin, although a relatively crude measurement, leads to a similar conclusion regarding the spatial scale of the water storage change.

Integrating the GRACE results over specific river sub-basins, namely, the Winnipeg River basin and the larger Saskatchewan River basin (Fig. 10), shows that, whereas the times of seasonal highs and lows in total water storage tend to correlate between the two basins, the amplitudes of seasonal variations can vary significantly from basin to basin, giving rise to considerably different inter-annual signatures. Given that the distance between the sub-basins is of the order of 1200 km, this puts an upper limit on the spatial scale of short-term (2-4 yrs.) inter-annual water storage variations.

Changes in water storage (dS) provided by gravimetry are complementary to the traditional methods of estimating water budgets through measurements of precipitation (P), evapotranspiration (E) and runoff (Q) and are related to them by $dS = P - E - Q$. Particularly at large scales, the availability of dS provided by gravimetry has the potential, through budget closure requirements, to assist in evaluating the accuracy of the traditional variables and to promote the study of phase delays in the hydrological system. Such improvements are the key to understanding water resource availability, the potential for floods and droughts and the interactions between land and atmosphere.

The results on water storage variations were largely unexpected when this study began in 1995. We did not expect that our surface gravity measurements would be sensitive to inter-annual variations in water storage and that these variations would be coherent over such a wide area. The unexpected availability of GRACE satellite data, the increasing density of GPS coverage in the Nelson River basin and the long series of surface absolute gravity observations also provided the means to isolate the gravity effects of long-term water storage change from the dominant gravity effects of postglacial rebound. The method described here can be used to track the future evolution of the water storage anomaly. Longer observations and more hydrological analysis are necessary to relate the water storage anomaly to climatic variations, changes in surface conditions and spatial variations in storage capacity.

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APPENDIX A

Estimated GRACE response to a uniform surface load centered on the observed gravity rate anomaly

We calculate the surface gravity anomaly at the un-deformed surface of the Earth arising from a spherical cap water load 300 km in radius and 3 cm thick (Fig. A1), taking into account the redistribution of mass in the Earth due to elastic loading (*Simon et. al.*, 2010). The resulting gravity anomaly expressed in terms of spherical harmonics of degree and order 2 to 256 is shown in Fig. A1. The anomaly peaks at a value of 1.4 μGal and falls off rapidly to about 40% of its value at the edge. The GRACE equivalent result is calculated by considering only spherical harmonics of degree and order 2 to 60 (Fig. A2). Comparison of Figures A1 and A2 shows that the GRACE anomaly is more symmetrical and falls off more gradually to zero well beyond the limits of the mass load. Some effects of ringing can be seen outside the loaded area. Therefore, comparing the results of Figure A2 with the

observed anomaly (Fig. 14) suggests that water has accumulated at a rate of about 3 cm/yr over an approximately elliptical area 800 km wide (N-S) and 1200 km wide (E-W).

APPENDIX B

Effect of water accumulation on GPS vertical rates

It has been shown that continental water storage loading can affect GPS vertical heights by several millimeters (*van Dam et. al.*, 2001). We calculate the elastic vertical displacement resulting from an assumed spherical cap water load 300 km in radius and 3 cm thick on a Maxwell viscoelastic compressible Earth model with a 90 km elastic lithosphere (*Simon et al.*, 2010). The expected rate of subsidence corresponding to a 3 cm/yr accumulation of water expressed in terms of spherical harmonics of degree and order 2 to 256 is shown in Fig. B1. The corresponding pattern of subsidence expressed in terms of spherical harmonics of degree and order 2 to 60, as would be mapped by GRACE, is shown in Fig. B2. Hence, the GPS vertical uplift rates associated with postglacial rebound would be reduced in the vicinity of the water load. As a consequence, the corresponding gravity rates in the 'virtual' gravity rate map are also reduced. Reduced rates in the postglacial rebound correction lead to increased rates in the gravity anomaly associated with the accumulating water load. However, the map of GPS vertical velocity (Fig. 2) is based on GPS data from 1996 to 2011, not just the (GRACE analysis) period of rapid water accumulation (2002 to 2009). A linear fit to the deep well level data from Saskatchewan for these two time periods (Fig. B3) suggests that the effect of water loading on the vertical velocity map is reduced to about one quarter of the subsidence rates shown in Figs. B1 and B2 (i.e., a maximum of 0.15 mm/yr). Thus, according to equation 4, the gravity anomaly rate would be affected only at the 1-2% level.