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Validating gravimetry measurements in Canada with a continental-scale hydrological database

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Abstract Water balance simulation is a basic but essential part of large-scale hydrological modelling. Gravity data provided by GRACE (Gravity Recovery and Climate Experiment) may present an alternative, or supplement, to *in situ* data for verifying and supporting hydrological and glacier mass balance studies on a continental scale. This work attempts to determine the utility of GRACE data for use in large-scale mass balance calculations through an *in situ* hydrological database that supports hydrological mass balance calculations for major drainage basins within Canada. The development of the database is determined by the spatial and temporal scale of the GRACE data. A variety of monthly observed hydro-climatological data essential to hydrological mass balance modelling were collected for 2003, 2004 and 2005 for all of Canada (where available). GRACE estimates of average equivalent water height were computed for the Nelson River catchment in Canada. Preliminary results demonstrate that GRACE data show a seasonal cycle characteristic of snow accumulation and melt in western Canada. This cycle is strong in the foothills in the western side of the basin, but it may also leak into the gravity data from the mountainous regions outside the basin area. This signal likely dominates the summer precipitation maxima in the centre and east side of the basin.

Keywords geodesy; GRACE gravity data; hydrological continental mass-balance

INTRODUCTION

Managing the water resources of Canada's five major drainage areas is an essential task for inter-provincial water rights, industrial and agricultural water use, and environmental protection. Management often entails hydrological mass balance modelling, generally conducted using hydrological data measured *in situ*. A great deal of *in situ* observations is available for the five major drainage basins. This data can also be used to validate GRACE gravimetry measurements, and this validation can lead to future uses of GRACE data for hydrological mass balance modelling.

GRACE can detect mass variations on a month to month basis, which, on a global and regional/basin scale, result from variations in water storage. Due to the nature of the measurements, the space-resolution is limited to just a few hundred kilometres, which in principle is enough to detect variations in the major drainage areas.

Some of the first results with time-variable gravity of the GRACE mission were presented in Wahr *et al*. (2004), where it was shown that GRACE water storage estimates in major river basins such as the Mississippi Basin and the Amazon Basin agree well with predictions based on global hydrology models. Since then, GRACE data have been used to study other signals in or around North America such as snow at high latitude (Frappart *et al*., 2006), melting of Alaskan glaciers (Tamisiea *et al*., 2005) and ice loss in Greenland (Velicogna *et al*., 2005; Luthcke *et al*., 2006).

Water mass variations at the continental scale can be computed by numerical models of land surface processes. The annual cycle from GRACE generally agrees well with that of the numerical models (e.g. Andersen & Hinderer, 2005). However, the differences between those models show the shortcomings in predicting soil moisture (Schmidt *et al*., 2006). In an evaluation of five global hydrology models, GRACE estimates revealed errors in the model predictions of maximum annual flow and a bias in the seasonal amplitude (Swenson & Milly, 2006). Moreover, GRACE has shown the potential to improve knowledge of evapotranspiration (Rodell *et al*., 2004a, Ramillien *et al*., 2005). Where most studies consider large basins, Swenson *et al*. (2006) show that water heights from GRACE compare well with *in situ* measurements of soil moisture in Illinois, an area of only 288 000 km^2.

In situ measurements of soil moisture content such as that in Illinois are generally not available. Therefore, indirect methods must be used to estimate the accuracy of GRACE derived water storage changes. Wahr *et al* (2006) derive an error up to 2.2 cm in water equivalent height for most of North America, after smoothing with a 750 km half-width filter.

The objective of this research is to study the utility of GRACE data for mass balance calculations of moderately-sized drainage systems. The methodology employed here involves GRACE data analysis similar to Swenson *et al*. (2006), but the mass balance analysis will be conducted using *in situ* data observed within meso-scale Canadian catchments. The focus of the analysis in this paper is the Nelson Catchment.

GRACE DATA

The GRACE satellite data used in this research are CSR release 1 data for the years 2003–2006 (data for June 2003 is missing due to accelerometer failure). These so-called level 2 data comprise of spherical harmonic coefficients representing the gravity field in a particular month. The fields have been corrected by processing agencies for short-term processes that would affect the monthly gravity fields, such as ocean and solid Earth tides, atmospheric and ocean variability. Assuming the change in gravity results from a mass change in a thin layer at the Earth's surface, we convert the Stokes coefficients to changes in equivalent water height (Wahr *et al*., 1998). We remove a mean of 4-years of monthly gravity fields in addition to correcting for the ocean pole tide (IERS Conventions, 2003) and we replace the C_{20} coefficient with values derived from Satellite Laser Ranging (Grace Technical Note 5, 2005). Since GRACE does not observe variations in the Earth's geocentre, we choose to add degree-1 variations from a global hydrology model (as in Swenson *et al*., 2006) for which we take the GLDAS model of Rodell *et al*. (2004b). The Nelson River is subject to postglacial rebound, which shows up as a trend in the water height time series. Since this is a solid Earth process which is not our primary interest; we remove the trend using the postglacial rebound model of Peltier (2004). A small residual trend may be present due to inadequate modelling in this model, or it may reflect interannual variations in water storage.

Filtering of the GRACE signal is necessary, as the sampling characteristics of the GRACE orbit lead to an artificial stripe-pattern in plots of global water height variations (e.g. Chen *et al*., 2006). After Wahr *et al*. (1998), an isotropic Gaussian filter is generally applied, which convolves a Gaussian curve with the point estimates. Filtering methods to directly mitigate the striping problem are discussed in Swenson & Wahr (2006) and Chen *et al*. (2006). For larger areas, the spatial pattern of an annual or semi-annual cycle can be obtained by least-squares estimation of a trend and sine and cosine cycle. As an alternative, principal component analysis can be used to analyze the spatial patterns in the continental water signal (Rangelova *et al*., 2007).

We apply a de-striping filter (Swenson & Wahr, 2006; see also Chambers, 2006) and smooth the data with a Gaussian filter. We vary the smoothing radius in order to investigate the effect of the size of area on the shape of the time series. A so-called optimal averaging kernel can be designed (Swenson & Wahr, 2002), which requires knowledge of the variance of the observed signal to minimize both leakage error and truncation error, but this approach was not pursued here. We simply integrated the filtered and smoothed GRACE data with a mask grid file representing the Nelson Basin, to obtain a monthly average water height for the basin.

Because of resonance effects in the GRACE orbit in the months of September, October, and November 2004, the gravity field cannot be resolved accurately for small wavelength features and those months are left out of the time series. The final time series is plotted in Fig. 4 and is discussed below.

HYDROLOGICAL MASS BALANCE MODELLING

Following the development of the database, a mass balance (ΔS) analysis is performed for each time step as shown below in equation (1):

$$P - ET - Q = \frac{\Delta S}{\Delta t} \tag{1}$$

where P is the total precipitation, ET is the evapotranspiration, Q is the outflow exiting the basin and estimated from discharge, ΔS is the change in water storage over the time step Δt (equal to one month), reflecting water that is stored as seasonal snow or in the surface, soil, or groundwater systems. Groundwater flow is considered negligible over the time step. Changes in storage in the area will have a gravitational signal that can be compared to GRACE water height estimates. In a glaciated catchment, an additional term is introduced on the left-hand-side to reflect the gain or loss of glacial ice over time interval Δt:

$$P - ET - Q + \frac{\rho_i}{\rho_w} B = \frac{\Delta S}{\Delta t} \tag{2}$$

where B is the change in ice volume and ρ_i and ρ_w are the densities of ice and water, respectively. ET is the most difficult quantity to estimate and thus a variety of methods for computing actual ET will be tested in future work. Soil moisture quantities provided by the *in situ* database will be used to determine evaluate and constrain the parameterization of ET rates.

Developing the hydrological *in situ* database

In situ data was collected for the whole of Canada to order to derive the components of equation (2). The data types and sources are listed in Table 1.

Table 1 *In situ* database sources. Data collected are monthly totals or averages (where applicable) for 2003–2005. Resolution of spatial data is 1° or better.

Data Type	Source	Data Collected if Available*
Meteorological Time Series	*Environment Canada* www.ec.gc.ca	Monthly Precipitation, Rainfall and Snowfall Totals 1826 stations in 2003 1885 stations in 2004 1337 stations in 2005 Monthly Minimum, Maximum, Average Temperature 1724 stations in 2003 1766 stations in 2004 1279 stations in 2005 Averaged from daily data if available: wind speed, sunshine hours, humidity, pressure
Hydrometric Time Series	*Water Survey of Canada* www.wsc.ec.gc.ca	HYDAT monthly average flow rates from 27 stations (of 1646 available) draining 13 minor Canadian subcatchments
GIS	*GeoGratis:* www.geogratis.cgdi.gc.ca/clf/en	National Frameworks Administrative Boundaries National Scale Frameworks Hydrology – Catchments
GIS	*Prairie Farm Rehabilitation Administration*: www.agr.gc.ca/pfra/main_e.htm	Major Drainage Systems and Major Basins PFRA and Environment Canada sub-basins Lines of Gross and Effective Drainage Gross watersheds for hydrometric stations Hydrometric gauging station network Areas of non-contributing drainage Effective drainage areas of PFRA watershed project ASCII file of Gross and Effective Drainage areas
Additional Snow Data	*MODIS:* www.modis-snow-ice.gsfc.nasa.gov	MOD10CM MODIS monthly snow-cover product
	NSIDC: www.nsidc.org/data/ae_mosno.html	AMSR-E/Aqua Monthly L3 Global Snow Water Equivalent EASE-Grids
	SOCC: www.socc.ca	Snow data, snow water equivalent (SWE) and snow on ground by station Gridded snow depth and SWE climatology SWE maps of prairies NOAA monthly snow and ice cover Northern hemisphere snow cover
Soil moisture	*NSIDC:* www.nsidc.org/data/docs/daac/ae_land_l2b_soil_moisture.gd.html	AMSR-E L3 Soil Moisture

The number of stations providing precipitation and temperature shown in Table 1 clearly demonstrate that the meteorological network in Canada has suffered cuts in recent years and may continue to suffer reductions in the future. Figure 1 shows that the distribution of stations is heavily concentrated around urban centres, which are in turn concentrated at the lower latitudes. This irregular distribution will cause errors at

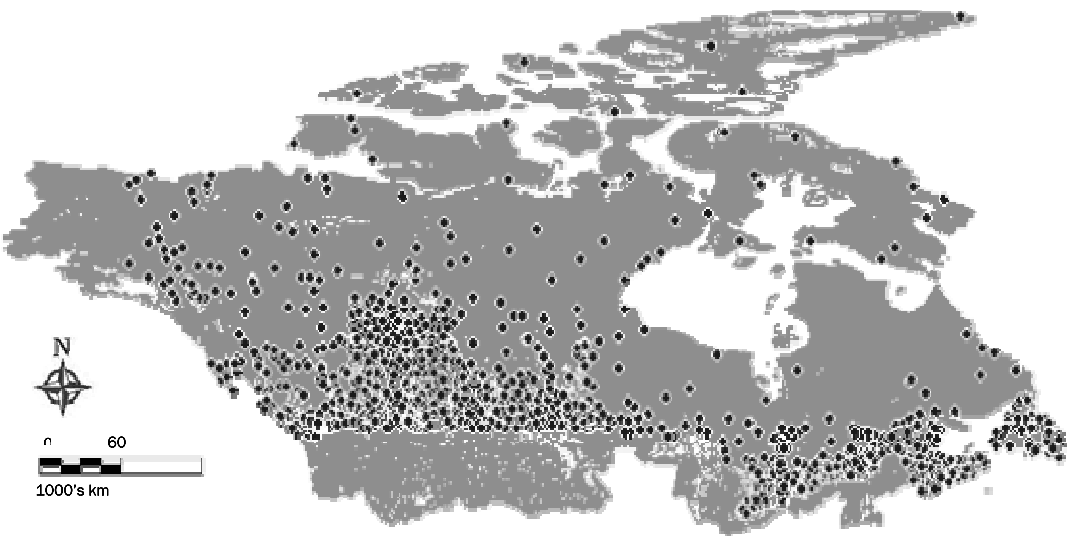

Fig. 1 Distribution of Canadian gauges measuring precipitation superimposed on the continental drainage region that includes all of Canada and part of northern USA.

higher latitudes in the interpolation of the point data to gridded data that is eventually compared to GRACE estimates of water storage. At the time of this paper, the *in situ* database involving Canadian monitoring stations has been completed for the 2003–2005 period.

For this preliminary analysis, time series data of rainfall and snowfall amounts were lumped together into single precipitation quantities. Station locations for precipitation and temperature were imported into ARCMAP to spatially distribute the point data to 1° grids. Temperature was kriged to 1° using Universal Kriging and monthly 1° gridded precipitation totals were created using Inverse Distance Weighting (with a power parameter of 2). Note that the interpolation was only conducted using Canadian monitoring stations; data from relevant northern USA monitoring stations will be incorporated in the final analysis. In future work, temperature along with soil moisture data will be used to estimate actual *ET* in equation (1).

Mass balance control volume: the Nelson Catchment

There are five major ocean drainage areas in Canada, which can be further subdivided into 13 minor drainage catchments. The intent of this research is to conduct the analysis in primarily terrestrial catchments of appropriate size such as the Mackenzie River Basin. The St Lawrence River drainage basin is an exception; it is primarily comprised of the Great Lakes System, which can include other effects besides hydrology in the GRACE signal. This paper will focus on the Nelson Catchment shown in Fig. 2 and focus on the application of equation (1).

The Nelson River Catchment is over 1 000 000 km^2 when it meets Hudson Bay, Canada (IUCN, 2006) with flows in the thousands of cubic metres. It begins at the foothills of the Canadian Rockies, draining forested land, agricultural land, grassland and wetland through Alberta, Saskatchewan, Manitoba, parts of North Dakota,

Fig. 2 Thirteen major drainage catchments in Canada and northern USA.

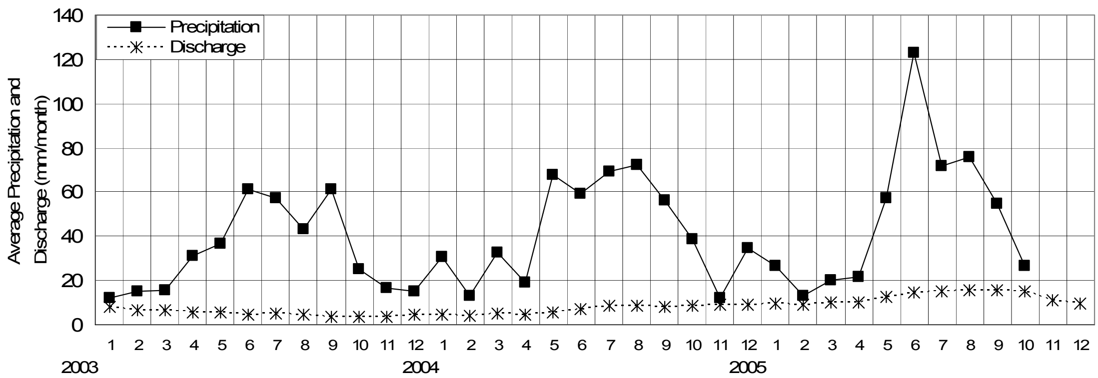

Fig. 3 Precipitation and discharge for the Nelson Catchment.

Minnesota and the Canadian Shield in Ontario (IUCN, 2006). The river is highly regulated with annual mean flows at the outlet of over 2,000 m^3 and has some of the highest water usage in Canada (Statistics Canada, 2007).

As one of the smaller catchments of the 13 minor drainage areas, the Nelson Catchment contains less than 200 grid cells at a 1° resolution. To obtain P in equation (1) a simple average of those cells coincident with the Nelson Catchment is taken. Discharge Q was converted to mm/month by dividing the average monthly flow-rate by the catchment area. Suitable methods for determining actual ET are currently being identified.

Water balance components and GRACE data in the Nelson Catchment

The mean monthly precipitation and monthly discharge for the Nelson Catchment in the study period are shown in Fig. 3. The water equivalent heights determined from the GRACE data using two different Gaussian filters (each having a different half-width) are shown in Fig. 4.

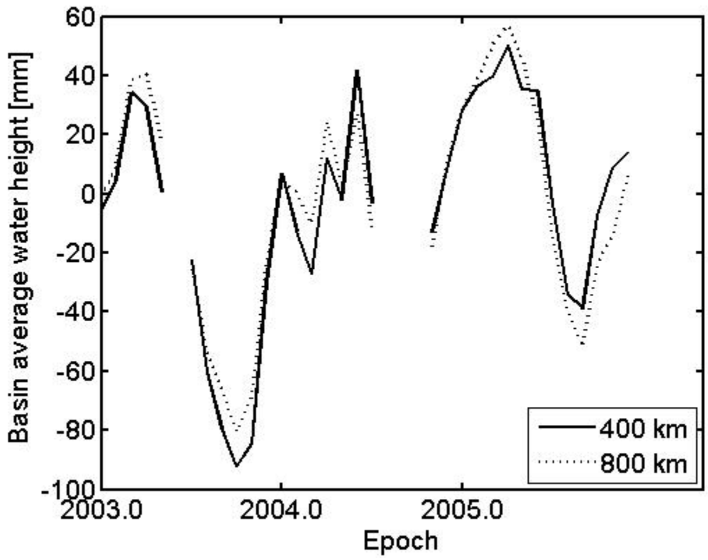

Fig. 4 Basin averaged water equivalent heights for the Nelson Catchment for two Gaussian filters.

DISCUSSION

Water balance components

The precipitation pattern shows the typical seasonal cycle expected at the monthly scale. The discharge curve *Q* shown in Fig. 3 shows very little amplitude and reflects the nature of this regulated catchment as having a slow response time to average precipitation for the area and provides some idea of total storage in the catchment. If the catchment is viewed as a simple linear reservoir, then discharge *Q* increases with storage *S*, implying that 2005 should show an increase in storage in mid to late 2005. Thus, it is likely that the changes in storage $\Delta S/\Delta t$ are positive for summer months in 2005, and this should be reflected in the GRACE estimates of average water height as well as the *in situ* data of the soil moisture level. Precipitation shows a peak in the summer months for this prairie catchment. The discharge *Q*, which is a reflection of storage, shows a lag in peak of 1 to 2 months in comparison to the peaks shown in *P*. This lag should also be reflected in the GRACE data. Discharge also indicates eventual losses if *P* drops and thus, GRACE data should show drops in water equivalent in the fall months.

Actual *ET* is one of the most problematic quantities to estimate in most terrestrial mass balance calculations and will produce the greatest source of uncertainty in the analysis. Several methods exist for computing actual evapotranspiration and future directions will look toward to estimating actual *ET* with these methods. Future considerations will also focus on seasonal snow-loading effects, and the timing of snowmelt throughout the catchment. These are significant issues for a catchment of this size, as the snowpack introduces lags in response to precipitation measured at ground monitoring stations. These effects need to be quantified to permit a proper comparison between $\Delta S/\Delta t$ and basin-average water equivalent heights derived from the GRACE data.

GRACE data and comparison with *in situ* data

GRACE data undergo a complicated process of filtering to remove errors and noise and the resulting data have been smoothed in the process. Generally, the filter and smoothing process applied to the GRACE data should also be applied to the *in situ* data. This can be done in the interpolation process from point data to gridded surfaces. The data produced in Fig. 4 were produced using a Gaussian filter, and Gaussian functions may be used in the gridding process for the *in situ* data. In this work, the *in situ* data are smoothed through the interpolation process and are areally averaged. The effect of the de-striping filter on the *in situ* data is not investigated.

As previous work has shown (Rangelova *et al*., 2007), snow signals are large in the Rocky Mountains and the Nelson Catchment borders the eastern side of the Rockies. Because of the nature of the gravity data and the smoothing process, the surrounding gravity signal can "leak" into the Nelson Catchment average. In Fig. 4, the annual signal is characteristic of snow accumulation in winter and spring melt, reflecting either the dominant gravitational signature of the seasonal snowpack in the western portion of the Nelson Basin, or the leakage of the seasonal snow load from the mountain regions west of the basin.

The effect of the two different smoothing radii (the two half-widths) shown in Fig. 4 demonstrate that the pattern is stable, but peaks affected by snowmelt are diminished by the smaller radius and processes relevant to just the Nelson Catchment are more pronounced (note the peak in the autumn of 2005). The Nelson Catchment is one of the smaller drainage areas in the Canadian drainage system, but the size is less of a problem in comparison to the fact that it is adjacent to one of the strongest annual signals in North America.

The fact that the Nelson Catchment only contains 200 interior grid cells implies that areal averages are affected by errors in boundary location. Future directions will involve error analysis to determine boundary effects. Corrections for boundary effects (particularly at the Rocky Mountain side) in the data may involve auxiliary data or models to remove the signal from outside the study area.

CONCLUSIONS

The database provided presents certain advantages in that it is based on *in situ* data and not global hydrological models that carry a great deal of uncertainty. Preliminary results for the Nelson catchment indicate that GRACE sees the large hydrological signal of the seasonal snowpack on the western side of the basin, likely including snow-loading from outside the catchment boundaries. Future work will focus on efforts to close the water balance using *in situ* data and make GRACE estimates less sensitive to effects outside the basin. A tapered filter can also be introduced to explicitly model the storage signal from adjacent regions. Both approaches need to be considered to further the application and utility of GRACE data in large-scale hydrological research.

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