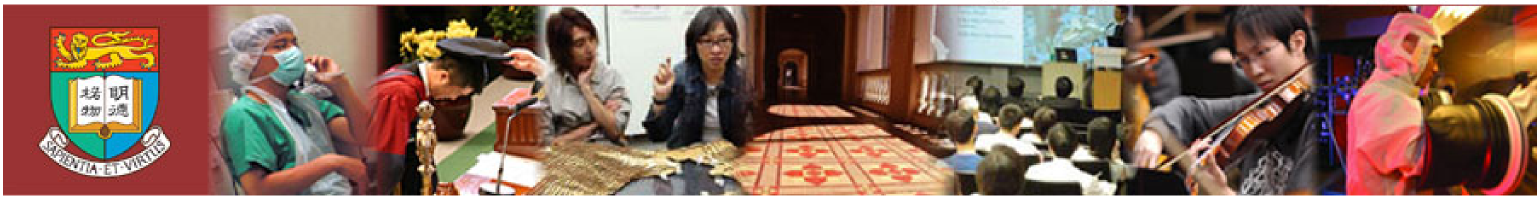

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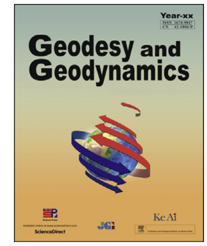

Water storage changes in North America retrieved from GRACE gravity and GPS data

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ABSTRACT

As global warming continues, the monitoring of changes in terrestrial water storage becomes increasingly important since it plays a critical role in understanding global change and water resource management. In North America as elsewhere in the world, changes in water resources strongly impact agriculture and animal husbandry. From a combination of Gravity Recovery and Climate Experiment (GRACE) gravity and Global Positioning System (GPS) data, it is recently found that water storage from August, 2002 to March, 2011 recovered after the extreme Canadian Prairies drought between 1999 and 2005. In this paper, we use GRACE monthly gravity data of Release 5 to track the water storage change from August, 2002 to June, 2014. In Canadian Prairies and the Great Lakes areas, the total water storage is found to have increased during the last decade by a rate of 73.8 ± 14.5 Gt/a, which is larger than that found in the previous study due to the longer time span of GRACE observations used and the reduction of the leakage error. We also find a long term decrease of water storage at a rate of −12.0 ± 4.2 Gt/a in Ungava Peninsula, possibly due to permafrost degradation and less snow accumulation during the winter in the region. In addition, the effect of total mass gain in the surveyed area, on present-day sea level, amounts to −0.18 mm/a, and thus should be taken into account in studies of global sea level change.

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1. Introduction

Surface- and ground-water resources, which have a strong socio-economic impact, are affected by climate change, drought and deluge, increasing water use, land use, and agricultural practices. For example, groundwater depletion in Northwest India probably led to a reduction in agricultural output and a shortage of potable water [1]. Accordingly, it is important to determine the spatial and temporal variability in water storage on continental scale. The present day trend in continental water storage can be obtained from monthly gravity data from the Gravity Recovery and Climate Experiment (GRACE). However, this was limited in formerly glaciated areas such as Antarctica [2] and North America [3,4] due to the interference from the strong signals of glacial isostatic adjustment (GIA) [5–7]. The attempts to separate the hydrologic signal from the background with GIA models are affected by uncertainties in our understanding of the glacial history and mantle viscosity [3] used in the modeling. To overcome this problem so that reliable estimates for the trend of water storage can be obtained, Wang et al. [3] and Lambert et al. [4] proposed separation approaches that are GIA model-independent.

Wang et al. [3] proposed a combination of space-borne gravity and GPS measurements to clearly separate the hydrological signals without any model assumption. They found that central North America had undergone a recovery in terrestrial water storage after the extreme Canadian Prairies drought between 1999 and 2005 [8]. The largest rise in water storage was found southwest of Hudson Bay with maximum magnitudes of 20.0 ± 4.8 mm/a. In total, water storage in central North America increased by 43.0 ± 5.0 Gt/a over the past decade. The results helped uncover the poorly known water storage on the America continent and highlighted once more the capability of the GRACE gravity mission. Jia et al. [9] used GIA models, observed surface gravity and GPS measurements to find that Wahr's relation has an uncertainty of 9.2%–15.0%. However, the work by Wang et al. [3] did not try to reduce the effect due to harmonic truncation and Gaussian filtering for estimation of the hydrology signal.

Similarly, Lambert et al. [4] investigated the trend of water storage for the Nelson River drainage basin in Canada. They used GRACE gravity data from June, 2002 to October, 2011 and updated GPS vertical velocities. However, in order to remove the GIA signal, the GPS-based velocities were converted to equivalent gravity rate using a transfer function derived from GPS and absolute-g data at co-located sites. Such function may be inevitably affected by the existence of local hydrology signals in the surface gravity measurement. The estimated hydrology signal peaked in the upper Assiniboine River watershed east of Saskatoon with a magnitude of 34 mm/a.

Since the change of water resources may impact the output of agriculture and animal husbandry, it is important to further improve the monitoring of water storage changes. For this study, we employ the separation approach from Wang et al. [3] but use the improved GRACE data of Release 5 (RL05) for a longer time span from August, 2002 to June, 2014. We will see that the new data and longer time span improve the uncertainty of the separated hydrology signal. We focus on water storage changes in North America with emphasis on the trend from March, 2011 to June, 2014 in the study area.

2. Approach to separate hydrology and GIA signals

2.1. Formulas of the separation

According to our previous study [3], the separated hydrology signal (water storage change or the trend rate) at co-latitude θ and longitude ϕ is denoted by the equivalent area density, which can be expressed by spherical harmonic expansion,

$$\sigma(\theta,\phi)=\sum_{l=0}^{\infty}w_l\sum_{m=0}^{l}(c_{lm}\cos m\phi+s_{lm}\sin m\phi)\tilde{P}_{lm}(\cos\theta) \tag{1}$$

where $\tilde{P}_{lm}(\cos\theta)$ is normalized Legendre polynomial function, w_l is the coefficient of Jekeli's Gaussian averaging function for Legendre expansion [10], c_{lm} and s_{lm} are spherical harmonic coefficients, calculated by

$$\begin{cases} c_{lm}=\dfrac{1}{\beta_l}\left[c_{lm}^{\mathrm{GPS}}-\alpha_l c_{lm}^{\mathrm{GRACE}}\right] \\ s_{lm}=\dfrac{1}{\beta_l}\left[s_{lm}^{\mathrm{GPS}}-\alpha_l s_{lm}^{\mathrm{GRACE}}\right]\end{cases} \tag{2}$$

where c_{lm} and s_{lm} with superscripts GPS and GRACE stand for the coefficients of normalized spherical harmonic expansions for GPS radial displacement and GRACE gravity perturbation respectively,

$$u^{\mathrm{GPS}}(\theta,\phi)=\sum_{l=2}^{\infty}\sum_{m=0}^{l}(c_{lm}^{\mathrm{GPS}}\cos m\phi+s_{lm}^{\mathrm{GPS}}\sin m\phi)\tilde{P}_{lm}(\cos\theta) \tag{3}$$

$$\begin{aligned}\delta g^{\mathrm{GRACE}}(\theta,\phi)&=\sum_{l=2}^{\infty}\sum_{m=0}^{l}(c_{lm}^{\mathrm{GRACE}}\cos m\phi+s_{lm}^{\mathrm{GRACE}}\sin m\phi)\tilde{P}_{lm}(\cos\theta)\\&=g_0\sum_{l=2}^{\infty}(l+1)\sum_{m=0}^{l}(C_{lm}\cos m\phi+S_{lm}\sin m\phi)\tilde{P}_{lm}(\cos\theta)\end{aligned} \tag{4}$$

and

$$\alpha_l=\frac{l+1/2}{l+1}\frac{1}{2\pi G\rho_m} \tag{5}$$

$$\beta_l=\frac{3}{\bar{\rho}}\frac{h_l}{2l+1}-\frac{1}{\rho_m}(1+k_l) \tag{6}$$

In equation (4), C_{lm} and S_{lm} are the coefficients as defined in Wahr et al. [10] or the trend rates given by satellite geoid models. In equations (5) and (6), ρ_m is the density of lithosphere with typical values of 3.0gcm^{-3}–3.5 gcm^{-3}. In this study, we follow Wang et al. [3] and use $\rho_m=3.3$ gcm^{-3}. h_l and k_l are the degree l elastic load Love numbers for radial displacement and potential perturbation [11,12]. $\bar{\rho}=5.517$ gcm^{-3} is the average density of the Earth; and G is the gravitational constant.

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In equation (5), α_l is given by Wahr et al. [13] and used in this study although alternatively $\alpha_l = (a/g_0)(1.1677\,l - 0.5233)/(l+1)$ was recently introduced by Purcell et al. [14], where a is the Earth's radius and g_0 is the surface gravity.

After the hydrology signals have been separated, the contributions to elastic radial displacement in the GPS measurement and to gravity perturbation in the GRACE measurement can be calculated respectively by

$$u^e(\theta,\phi) = \frac{3}{\bar{\rho}}\sum_{l=0}^{\infty} w_l \frac{h_l}{2l+1}\sum_{m=0}^{l}(c_{lm}\cos m\phi + s_{lm}\sin m\phi)\tilde{P}_{lm}(\cos\theta) \tag{7}$$

$$\delta g^e(\theta,\phi) = 4\pi G\sum_{l=0}^{\infty} w_l \frac{l+1}{2l+1}(1+k_l)\sum_{m=0}^{l}(c_{lm}\cos m\phi + s_{lm}\sin m\phi) \times \tilde{P}_{lm}(\cos\theta) \tag{8}$$

The GIA signals can be obtained from the residues of the measurements with these elastic effects removed.

Note that for the separation approach as stated above, the GPS displacement and the GRACE gravity perturbation should be measured during the same time span. However, monthly GRACE data with good quality are available from August, 2002 to June, 2014 while the trend rates of radial displacement [15] were derived from GPS measurements during the period from 1993 to 2006 in North America. According to Wang et al. [3], it is reasonable to assume that the hydrological contribution to the GPS signal is much smaller than the GIA contribution during the same period. Therefore, we assume that the GPS signals are caused by GIA alone. The separation approach is still valid except that the first term of the right side of equation (6) needs to be crossed out.

Water storage change or the trend rate computed by equation (1) is usually expressed by the change of equivalent water thickness (EWT) or the trend. EWT change or EWT rate is calculated by the area density of equation (1) divided by the water density.

It should be noted that the EWT change or the trend calculated by equation (1) at an observer is unavoidably impacted by the truncation of the summation and Gaussian filtering respectively causing the leakage and smooth of the signal. However, for a selected surveyed region, the total EWT change or the trend calculated by equation (1) can be further multiplied by a scale factor in order to recover its realistic value. For calculating the scale factor, we assume that the EWT signals (or region function) are 1 and 0 within and outside the region, respectively. The signals are truncated at degree 60 and smoothed by Gaussian filtering. The scale factor K is then the inverse of the average residual signal over the region.

2.2. *Uncertainty of the separation*

The uncertainty for EWT change or the EWT trend rate can be computed by the variance formula,

$$\mathrm{var}[\sigma(\theta,\phi)] = \sum_{l=2}^{\infty} w_l^2 \sum_{m=0}^{l}[\mathrm{var}(c_{lm})\cos^2 m\phi + \mathrm{var}(s_{lm})\sin^2 m\phi] \times \tilde{P}_{lm}^2(\cos\theta) + \mathrm{var}[\sigma_{SP}(\theta,\phi)] \tag{9}$$

where $\mathrm{var}[\sigma_{SP}]$ is the variance contribution from the separation approach itself, $\mathrm{var}(c_{lm})$ and $\mathrm{var}(s_{lm})$ are the variances of coefficients in equation (1) which can be calculated by

$$\begin{bmatrix}\mathrm{var}(c_{lm})\\ \mathrm{var}(s_{lm})\end{bmatrix} = \frac{1}{(1+k_l)^2}\left\{\left(\frac{1}{2\pi G}\frac{l+1/2}{l+1}\right)^2\begin{bmatrix}\mathrm{var}(c_{lm}^{GRACE})\\ \mathrm{var}(s_{lm}^{GRACE})\end{bmatrix} + \rho_m^2\begin{bmatrix}\mathrm{var}(c_{lm}^{GPS})\\ \mathrm{var}(s_{lm}^{GPS})\end{bmatrix}\right\} \tag{10}$$

here, $\mathrm{var}(c_{lm}^{GRACE})$ and $\mathrm{var}(s_{lm}^{GRACE})$ are the variances of harmonic coefficients of the GRACE gravity perturbation trend, and $\mathrm{var}(c_{lm}^{GPS})$ and $\mathrm{var}(s_{lm}^{GPS})$ are the variances of harmonic coefficients of GPS vertical motion trend, which can be all computed based on the propagation law of the measurement errors for the GRACE gravity perturbation trend and the GPS vertical motion trend, or given by corresponding least-square fitting for time series of the two types of data like in this work. σ_{SP} can be estimated by the simulated separation based on a given GIA model and a hydrology model. According to Jia et al. [9], we set $\sigma_{SP} = 15\%\sigma$.

3. GRACE and GPS data

The GRACE gravity perturbation trends are computed from RL05 monthly gravity solutions between August, 2002 and June, 2014, which consists of a series of monthly spherical harmonic coefficients that extend to degree and order 90, provided by Center for Space Research (CSR), University of Texas at Austin. The C_{20} term for these solutions was substituted with that from satellite laser ranging [16]. The trend rates of C_{21}, S_{21}, C_{30}, and C_{40} that were removed in the RL05 standard processing procedures [17] are now added back to their respective coefficients.

We take two measures to reduce the two types of noises found in the GRACE gravity field. For stripe errors caused by correlation among the coefficients of the same parity in degrees for a certain order [18], following Chambers [19] we use a third-order polynomial fitted to all the coefficients of the same parity in degrees larger than 10 from orders larger than 3, and the coefficients used in fitting are subtracted by the fitting values. Therefore, the stripe errors can be suppressed efficiently. For the high order measure errors, we implement a filtering with an isotropic Gaussian filter with 340 km average radius.

We estimate the linear trend of coefficients of geoid models or gravity perturbations by including periodic signals due to annual, 2.5 year and S_2-tide (161 days) variations [20]. The trend rates of GPS radial displacement are derived from GPS measurements from 1993 to 2006 in North America [15]. The trend rates are developed into spherical harmonics from degree 2 to 60.

Since GPS data are not available in regions outside of the used GPS network, we assume that GIA dominates the geodynamic signal there. Trends of radial displacement can then be transformed from the trends of gravity perturbation from GRACE through Wahr's relation [13] in order to reduce the effects of the GPS data blanking on the separated hydrology signal within the network. However, this also means that

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any result from the separation is invalid beyond the GPS network.

The computed rates of gravity perturbation and radial displacement are shown in Fig. 1. The GRACE signals mainly reflect the GIA signal in North America but also include the contribution from hydrology. The maximum signal is found in the southeast of Hudson Bay with a magnitude of 1.6 μGal/a. A GIA signal larger than that to the west of Hudson Bay as predicted by ICE-5G GIA model [21] is not visible. This implies an overestimate of the ice thickness in the area by this particular GIA model and confirms the results of Wang et al. [3]. The GPS signals within the GPS network also peak in the southeast of Hudson Bay with a magnitude of 11 mm/a. The pattern outside the GPS network results from the transformation of GRACE signals and is thus similar to the GRACE signals. As found in the next, we can reasonably assume that the GPS signals are completely attributed to GIA.

4. Results and analysis

The results of the separated hydrology signals and the uncertainties are shown in Fig. 2a and b, respectively. Note that only results within the marked area are reliable and will be discussed. In Fig. 2a, we find two pronounced hydrology signals. The larger one is a positive signal with a magnitude of 20.2 ± 4.2 mm/a, located in the Canadian Prairies (mostly including Southern Alberta, Saskatchewan and Manitoba) and also enveloping the Great Lakes area. The peak is found to be the west of Lake Winnipeg. Another one is a negative signal with a magnitude of −9.7 ± 3.9 mm/a, located in Ungava Peninsula to the east of Hudson Bay. The estimated uncertainties are between 2.8 and 4.0 increasing from south to north except to the west of Lake Winnipeg where they are locally increased to 4.2 mm/a mainly due to the approximation of the separation approach.

In Fig. 3, we show the separated hydrology and GIA contributions in the GRACE and GPS measurements. In Fig. 3a, the hydrology contributions in GRACE have the same pattern as the separated hydrology signals (Fig. 2a) since they are mainly due to the Newtonian attraction of increased or decreased water mass and less due to the loading induced mass redistribution of the crust and mantle. In Fig. 3b, the GIA contributions in the GRACE measurements have the same pattern as the GPS signals (Fig. 1b) because they are related by Wahr's transformation relation [13]. Comparing Fig. 3a,b and Fig. 1a we find that

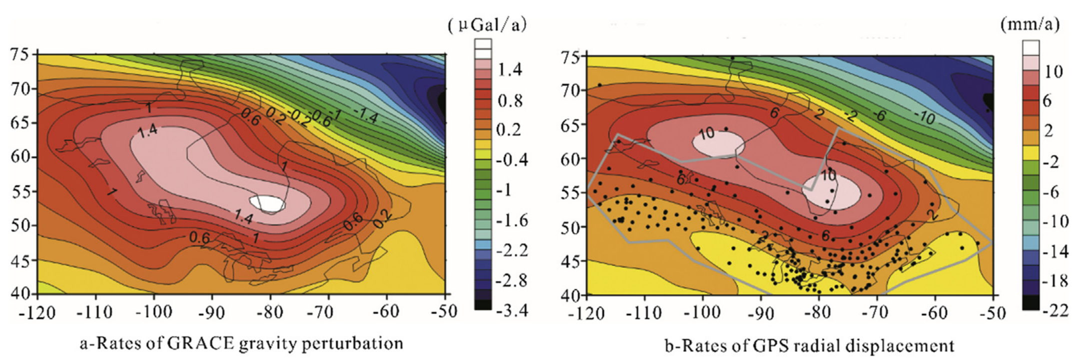

Fig. 1 – GRACE and GPS data used for separating the hydrology signal in North America. a – Trend rates of gravity perturbation from CSR RL05 GRACE monthly data (degree 2 to 60) from August, 2002 to June, 2014; b – Trend rates of radial displacement (degree 2 to 60) derived from the GPS observations from 1993 to 2006 [15]. Thick light gray line surrounds the investigation area which depends on a dense GPS network. The black dots denote the GPS sites.

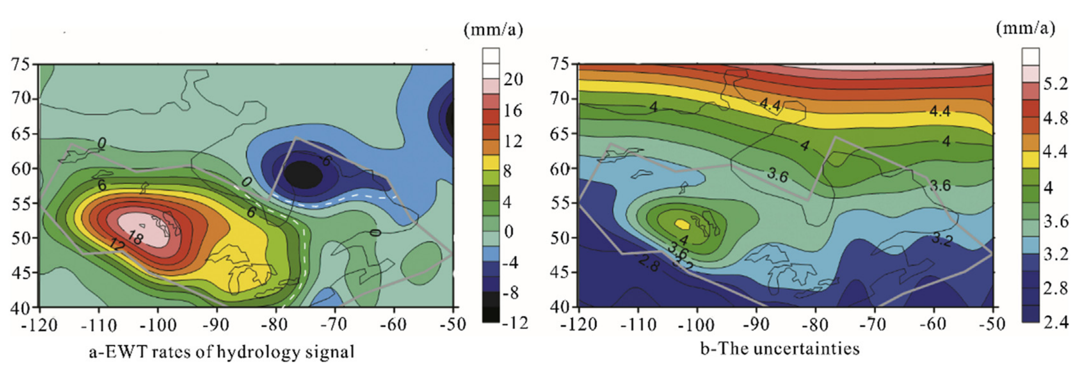

Fig. 2 – Trend rates a – of separated hydrology signal from August, 2002 to June, 2014 and the uncertainties b – in North America using GRACE and GPS data. In Fig. 2a, the positive signal is delimited by the GPS network boundary lines (light gray lines) and the white dashed lines in the Canadian Prairies and the Great Lakes area. Similarly for the negative signal in Ungava Peninsula. The white dashed lines mean the contours of ± 2 mm/a.

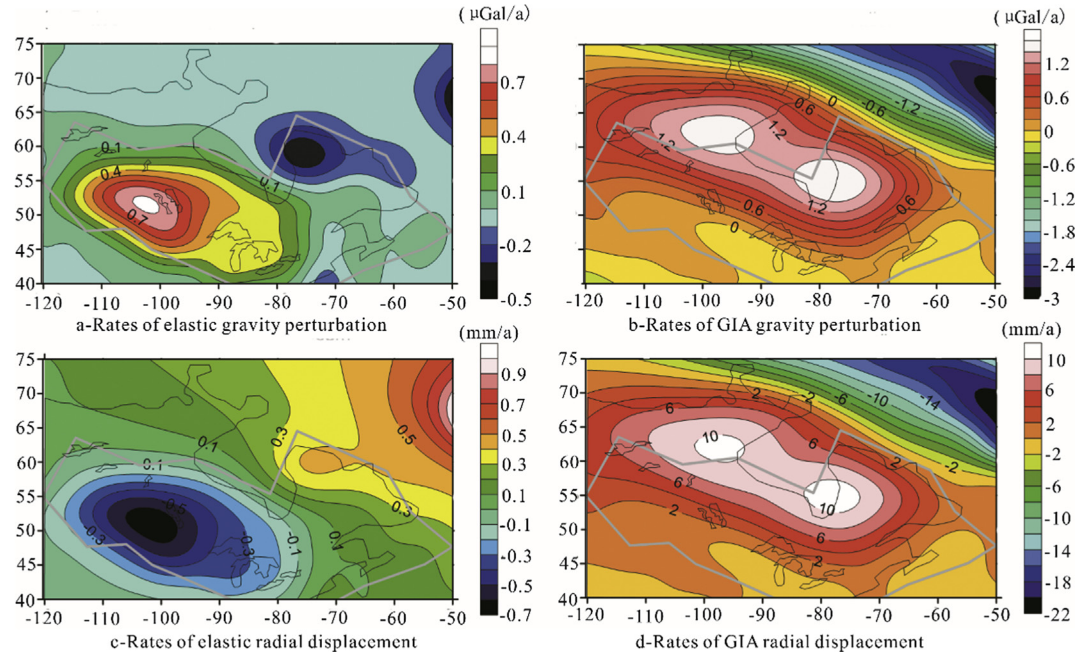

Fig. 3 – Separated hydrology and GIA contributions in GRACE and GPS measurements in North America. a – Hydrology contribution in GRACE measurements; b – GIA contribution in GRACE measurements; c – Hydrology contribution in GPS measurements; d – GIA contribution in GPS measurements.

although the hydrology signals in the GRACE measurements are aside the GIA centers, they are still covered by the strong GIA background signal. As shown in Fig. 3a,b, the contributions of two hydrology signals to the GRACE measurements in the Canadian Prairies and the Great Lakes area, as well as the Ungava Peninsula are found to be as large as 0.8 μGal/a and −0.4 μGal/a, respectively, while the GIA contributions are about 1.6 μGal/a. In Fig. 3c,d, the contributions of the two hydrology signals to the GPS measurements are as large as −0.6 mm/a and 0.5 mm/a, while the GIA contributions are up to 10.8 mm/a.

As in Fig. 2, the two regions with the positive signal and negative signal, that cover an area of 4965120 km^2 and 938623 km^2 respectively, are delimited by the GPS network boundary and the dashed line. The total EWT trend rates are found to be 55.9 ± 11.2 Gt/a and −6.4 ± 2.3 Gt/a, respectively, before the scale factor calibrations. Since the scale factors for the two regions are 1.32 and 1.87, the calibrated results of the total EWT trend rates are 73.8 ± 14.5 Gt/a and −12.0 ± 4.2 Gt/a, respectively. For the GPS surveyed area, the total EWT trend rate is therefore 61.8 ± 15.0 Gt/a, which may cause a global sea level fall of 0.18 mm/a.

Figs. 4 and 5 compare the separated hydrology and the original GRACE signals converted to EWT at the two hydrology extrema in Fig. 2a, which are located in central Saskatchewan to the west of Lake Winnipeg, and in Ungava Peninsula respectively. In Fig. 4a, the EWT trend rate observed by GRACE is 25.8 ± 1.0 mm/a and the separated hydrology signal accounts for 20.2 ± 4.2 mm/a. In Fig. 5, the EWT trend rate observed by GRACE is 20.0 ± 0.7 mm/a but the separated hydrology signal accounts for −9.7 ± 3.9 mm/a together with a larger GIA signal. In Fig. 4b, the time series of separated hydrology signal is compared with an averaged variation of 20 groundwater well data in central Saskatchewan from August, 2002 to March, 2011 [22], showing reasonable agreement. For the well table variation and the separated hydrology signal, the EWT trend rates are 166.5 ± 9.1 mm/a and 20.2 ± 4.2 mm/a, respectively, apparently showing a large difference. The reason is that groundwater is stored in the pores of the rocks and soil; so, a meter rise in groundwater (outside the water wells) has EWT change of P meters if the rocks and soil are water saturated and has an average porosity P. The ratio between the two numbers implies that P has a value of about 12% in the region.

Wang et al. [8] found a recovery in terrestrial water storage from August, 2008 to March, 2011, that was observed by GRACE and GPS after the extreme Canadian Prairies drought between 1999 and 2005. From Fig. 4b, it can be seen that the water storage continued to rise from March, 2011 to June, 2014. In Ungava Peninsula to the east of Hudson Bay, the long term decrease of the hydrology signal is assumed to be caused by permafrost degradation and less snow accumulation in winter, which was neglected in Wang et al. [3]. This needs to be validated by dedicated observations in the future.

5. Conclusions

We have used the new GRACE RL05 gravity data set together with GPS data in North America to separate

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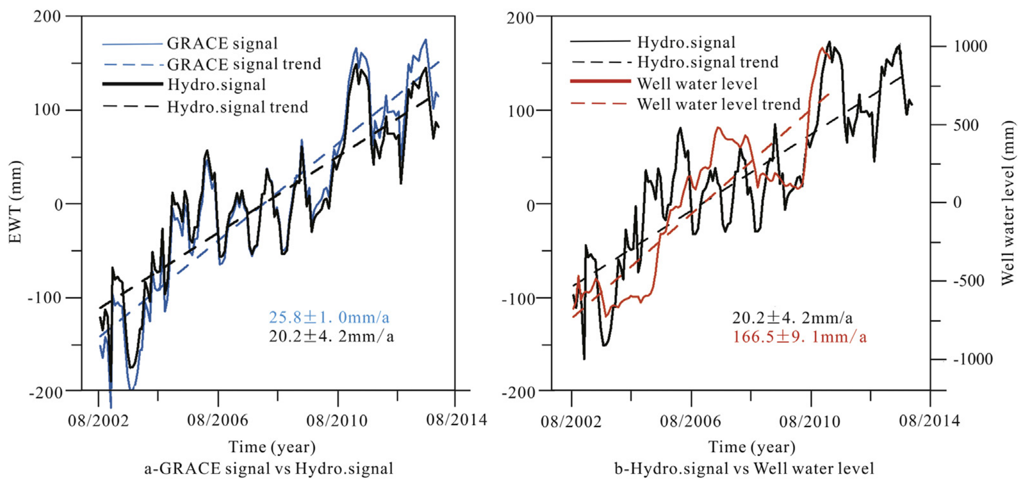

Fig. 4 — Time series of the separated hydrology signal (black), the GRACE signal (blue) and the well water level (red) in central Saskatchewan. The dashed lines denote the linear trends of the curves with the same colors. The numbers with uncertainties denote the rates of corresponding linear trends. The well water level is an averaged variation from 20 groundwater well data in central Saskatchewan [22].

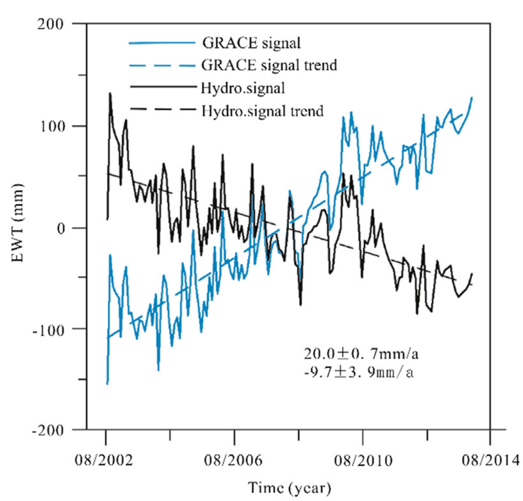

Fig. 5 — Time series of separated hydrology signal (black) together with GRACE signal (blue) in Ungava Peninsula to the east of Hudson Bay. The long term decrease of the hydrology signal implies permafrost degradation and less snow accumulation in winter.

hydrology signals using the separation approach introduced by Wang et al. [3]. We found that the water storage in the Canadian Prairies increased by a rate of 73.8 ± 14.5 Gt/a from August, 2002 to June, 2014 after the extreme Canadian Prairies drought between 1999 and 2005. For the first time, we indicated that the water storage in Ungava Peninsula decreased by a rate of −12.0 ± 4.2 Gt/a during the past 12 years, possibly due to permafrost degradation and less snow accumulation in winter in the area under an increasingly warmer climate. Due to the water storage changes in the study area, the velocity of present-day global sea level rise has been reduced by a rate of 0.18 mm/a.

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