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Assessment of water budget for sixteen large drainage basins in Canada

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SUMMARY

This study represents the first attempt to examine the spatial and seasonal variations of the surface water budget by using state-of-the-art datasets for sixteen large Canadian drainage basins with a total area of 3.2 million km^2. The datasets used include two precipitation grids produced using measurements and reanalysis models, land surface evapotranspiration and water surface evaporation estimated using the EALCO model, streamflow measured at hydrometric stations, and total water storage change derived from GRACE satellite observations. The monthly water imbalance resulted from these datasets varied from 7.0 mm $month^{-1}$ to 21 mm $month^{-1}$ among the studied basins, which was 30% on average of the corresponding monthly precipitation. The accumulated water budget imbalance over the 7 years of 2002–2008 varied from close to zero to ±10 mm $month^{-1}$. The positive and negative imbalances among the sixteen basins were largely offset and the all-basin imbalance was very close to 0. The uncertainties in precipitation, streamflow, evapotranspiration and total water storage change all contributed to the water budget imbalance and their relative magnitudes were found to vary with basin and season. In most cases, precipitation showed the largest uncertainties, which had similar magnitudes to the water budget imbalances. While improvements are noted in comparison with previous water budget studies over the regions, the water imbalance obtained for some basins is quite large, suggesting that considerable improvements in both the observation networks and models are necessary before the water budget closure can be substantially improved over this region.

1. Introduction

A water budget is the quantitative accounting of the amount of water entering, stored within, and leaving a hydrologic system. Understanding the regional water budget is essential in water resources management, particularly for irrigation planning, drought, flood and pollution control, drainage system design, and groundwater recharge estimation. Knowledge of the water budget at a monthly time scale helps understand the basin water annual cycles and dynamics, such as the recharge and discharge time and rates of a basin. Assessment of water budget closure at a monthly time scale helps understand the error sources and uncertainties of the water budget components as well as their seasonal distributions.

For a drainage basin, the water budget involves various components of the water cycle which can be written as,

$$P - (1.0 - \alpha)\mathrm{ET} - \alpha E0 - Q - \Delta\mathrm{TWS} = \varepsilon \qquad (1)$$

where P is precipitation, ET is land surface evapotranspiration, $E0$ is water surface evaporation, Q is streamflow (including both surface runoff and base flow), ΔTWS is total water storage (TWS) change (including vegetation storage, soil water, groundwater, snow, glaciers and surface water bodies such as lakes, wetlands and rivers), ε is the water budget imbalance, and α is a parameter representing the water surface (e.g., rivers and lakes) fraction over a drainage basin.

Eq. (1) is often used to calculate one variable from others by assuming perfect water budget closure (i.e., $\varepsilon = 0$). For example, Wang and Alimohammadi (2012) calculated the annual ΔTWS for 277 watersheds in the United States, Donohue et al. (2010) assessed annual ΔTWS for 221 watersheds in Australia, Milly and Dunne (2002) calculated annual ET for 175 large basins worldwide, among others (e.g., Ohta et al., 2008; Rodell et al., 2011). In fact, estimating the variables in Eq. (1) often involves significant uncertainties especially for large drainage basins with non-homogeneous climate and surface conditions and sparse observational networks. This usually results in the non-closure or imbalance (ε)

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of the water budget estimate for the specific data used. Treating $\varepsilon = 0$ will transfer these uncertainties to the target variable to be calculated which may lead to serious errors particularly when the magnitude of the target variable is small by nature (e.g., annual ΔTWS). Indeed, significant imbalances have been reported in the water budget estimates for a wide variety of basins throughout the world. For example, Marengo (2005) studied the water budget over the Amazon region and showed an average imbalance of almost 50% of the observed *Q* for the datasets they used. Flerchinger and Cooley (2000), Sheffield et al. (2009), Gao et al. (2010), Landerer et al. (2010), Troy et al. (2011) reported similar imbalances for basins in the USA and Eurasia.

Canada covers a land area of 9.1 million km^2 with inland water bodies of almost 0.9 million km^2. Of this total area, 75% drains northward into Hudson Bay and the Arctic Ocean and 15% drains into the Atlantic Ocean; the rest mainly drains into the Pacific Ocean. In total, Canadian rivers discharge about 8% of the world's renewable water supply (Healey and Wallace, 1987). This makes it extremely important to improve our understanding of Canada's water budget. On the other hand, the climate, vegetation, soil, terrain topography and the geology of aquifers vary substantially over this large landmass (Wang et al., 2013), but the hydrometeorological observations are sparse and less accurate in northern Canada (Hare and Hay, 1971; Lammers et al., 2001). These pose significant challenges in accurately quantifying the water budget. Understanding the water budget and its closure for the Mackenzie River Basin (MRB) was one of the focuses of the Mackenzie GEWEX Study (MAGS) – one of the largest hydro-climatology projects in the Canadian history (Woo, 2008a, b). Various model assimilated datasets, including the National Centers for Environmental Prediction Global Reanalysis 2 (NCEP-R2), the global 40-yr European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-40), the NCEP North American Regional Reanalysis (NARR), and the Canadian Meteorological Centre (CMC) operational regional analysis, as well as results from the Canadian Regional Climate Model (CRCM) simulations, were used to assess the water budget closure for the MRB in that study (Szeto et al., 2008). It was found that the regional water budget for the MRB was closed within 6% (ERA-40/NARR), 8% (CMC) and 10% (CRCM) of the observed *Q* by using the atmosphere moisture flux convergence from the respective models. These were substantial improvements over the closure of 26% assessed by using the previous generation CMC analysis dataset (Strong et al., 2002), and these improvements possibly reflect the recent advances in the modeling of atmospheric water cycling processes for the region. Note that the water budget closure in the above study was assessed at multiyear time scale by assuming negligible long-term changes in the atmospheric and surface water storage, so that the atmosphere moisture flux convergence can be regarded as equal to *P*-ET, or *Q*. Another limitation is that by using the atmosphere moisture flux convergence as the surface *P*-ET, it is difficult to assess separately the uncertainties in *P* and ET and their impacts on the water budget imbalance. Moreover, *P* and ET are highly coupled and dependent on each other in atmosphere models. Water imbalance estimated using *P*-ET from one model, instead of *P* and ET from independent data sources, is unlikely to reflect the actual biases in *P* and ET due to their at least partial cancel-out.

Using a similar approach and datasets to the above studies, Szeto (2007) also analysed the surface water budget for the Saskatchewan River Basin (SRB). The *P*-ET estimated as the atmosphere moisture flux convergence from the above model-assimilated datasets was found in general many-fold larger than the observed *Q*. This was attributed to the characteristics of the Prairie landscape of the SRB which contains large internal drainage areas and the streamflow in the region is influenced by glacier melt water from the Rockies. These factors were deemed to make their approach for closing the water budget of the region inappropriate (Szeto, 2007).

The water budget assessment for the MRB has also been included in several other studies in the context of large global river basins. Serreze et al. (2003) analysed the long-term water budget for the MRB using observed *P* and *Q*, and NCEP reanalysis-based ET. They reported a water imbalance of 29 mm $year^{-1}$, or 7% of its annual *P*. Sahoo et al. (2011) used multiple satellite and non-satellite *P*, ET and ΔTWS, and observed *Q*, in their water budget assessment for the MRB. They reported monthly water imbalances ranging from −18 to 32 mm $month^{-1}$ for 2003–2006. Note that Sahoo et al. (2011) used the ΔTWS derived from observations by the GRACE satellite system, which made the assessment of water budget closure at a monthly time scale possible. Without the observed ΔTWS made available by GRACE, assessments of water budget closure at sub-annual time scales for large basins have to rely on modeled ΔTWS (e.g., Szeto, 2007; Szeto et al., 2008), which is typically a poorly constrained variable in climate models and reanalysis datasets.

In this study, the water budget variables were first characterised for sixteen large drainage basins in Canada. These basins cover a total area of 3.2 million km^2, which is close to one third of the entire Canadian landmass. State-of-the-art datasets covering up to 30 years from 1979 to 2008 for the basins were used, which include two *P* datasets that were produced independently using in situ measurements and reanalysis models (Sheffield et al., 2006; McKenney et al., 2011), the land surface ET and water surface evaporation (*E*0) obtained by the remote sensing-based model EALCO (Wang et al., 2013; Wang, 2011), the *Q* observed at hydrometric stations of the Water Survey of Canada, and the ΔTWS retrieved from GRACE observations (Huang et al., 2012). Spatial and seasonal variations and uncertainties of the water budget variables were discussed. The water budget closure was then assessed for each of the basins at a monthly time scale when all the data are available. The possible sources of errors to the water imbalance were discussed. This study represents the first attempt to address surface water budget closure at this large spatial coverage for the Canadian landmass. The datasets used are independent and represent the latest developments in producing measurement-based national-scale water data for Canada. It is the first time to use GRACE observations to assess the water budget closure at a monthly time scale for the sixteen drainage basins. The high spatial resolution (5-km) of the datasets for *P*, ET and *E*0 also provides advantages for recognising their variations in space within a large basin. The results will be beneficial for the further improvements of observations and models that ultimately lead to the reduction in water imbalance.

2. Methods and data

2.1. Drainage basins and streamflow (Q)

The 1:1 million National Scale Frameworks Hydrology (Atlas of Canada, 2003) was used to create the drainage basin boundaries for the selected hydrometric stations. A total of sixteen large drainage basins were delineated for this study, as shown in Fig. 1 and Table 1. These include all the drainage basins in Canada that meet the criteria of drainage areas >90,000 km^2 (to be compatible with the spatial scale of GRACE data, see Section 2.4), and have continuous *Q* measurements available during the study period. This study is focused on the drainage basins over the Canadian landmass. Stations for which *Q* contains substantial flows from the USA (e.g., the Red River and St. Lawrence River) are not included. The sixteen studied basins cover a total area of 3.2 million km^2, which is close to one third of the entire Canadian landmass.