Large-Scale Terrestrial Freshwater Discharge Estimation using GRACE

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Abstract

A key step towards the closure of large scale water budget is to obtain a holistic estimate of terrestrial freshwater discharge. While often used as surrogate of net outflow in basin-scale water balance studies, in-channel streamflow measured at the gauging stations may in reality represent only a part of the net freshwater flux and are therefore incomplete for budget analysis. Here we present large-scale estimates of freshwater discharge using Gravity Recovery and Climate Experiment (GRACE)-derived monthly terrestrial water storage changes in a combined land-atmosphere water mass balance. The estimates of freshwater discharge are subsequently analyzed in the context of global climate and compared with previously published estimates. This method has been previously tested on the Amazon, Mississippi and several large Arctic river basins. Results and comparisons to observations indicate that the method has important potential for global-scale discharge monitoring of combined surface water and submarine groundwater discharge at near-real time.

Introduction

Terrestrial freshwater discharge is instrumental in integrating an array of complex physical and biogeochemical processes crucial for sustaining ecosystems and influencing climate and related global change. Changes in hydrologic fluxes and states, in response to a progressively warming climate, either by natural variability or anthropogenic influence, have profound societal, environmental and climatic implications through exacerbation of hydrologic extremes, like floods and droughts. A realistic-quantitative knowledge of the various reservoirs and fluxes is of utmost importance for the assessment of current water resources and for reliable projections of water availability in the near future. Currently, there exists no comprehensive global network for monitoring of freshwater discharge into the world oceans (Alsdorf &Lettenmaier, 2003). Here we present independent estimates of freshwater discharge from basins, continents and large ocean draining regions. Excluded from the discharges are contributions from internally draining regions around the world (Fig 1 and 2). The method utilizes observation of land water storage changes from GRACE in a combined Land-Atmosphere Water Balance (LAWB) at monthly and longer time scales . (Syed et al. 2005, 2007).

ATMOSPHERIC MOISTURE BUDGET:

$$\frac{\partial W}{\partial t} = E - P - div\mathrm{Q}$$

$$P - E = -\frac{\partial W}{\partial t} - div\mathbf{Q}$$

TERRESTRIAL WATER BUDGET:

$$\frac{\partial S}{\partial t} = P - E - R$$

LAND-ATMOSPHERE WATER BALANCE : $R = -\frac{\partial W}{\partial t} - div\mathbf{Q} - \frac{\partial S}{\partial t}$

divQ, ∂W/∂t, ∂S/∂t, R, P and E represents atmospheric moisture divergence, changes in total precipitable water, land water storage change, discharge, precipitation and evapotranspiration respectively.

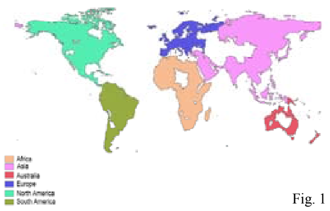

Fig. 1

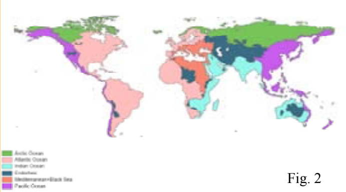

Fig. 2

Figure 1 and 2: Exorheic portions of each continent and ocean draining regions, excluding Greenland and Antarctica. Adapted from STN-30p (Vorosmarty et al. 2000)

Data

1) **GRACE DATA : Consists of JPL RL 03 and GFZ RL03 from Feb, 2003 till Dec, 2005 with the exception of Jun 2003 and Jan 2004.**
2) **OBSERVED STREAMFLOW : For the Arctic rivers streamflow rates were obtained from Arctic RIMS and climatology of discharges for the river basins shown in Fig were obtained from GRDC data archived in http://www. grdc.sr.unh.edu.**
3) **ATMOSPHERIC DATA : Monthly estimates of total column precipitable water (W) and divergence of the atmospheric moisture flux were computed from ECMWF operational forecast analysis and NCEP/NCAR reanalysis (NRA) for the period compatible with the availability of GRACE data. Additionally, it is reasonable to assume that over large regions, such as in Figures 1 and 2, P-E should be positive. Hence, negative P-E values obtained by averaging over continents and large drainage regions , which can produce negative discharge estimates from water balance, are equated to zero.**

Results

- **Figure 3 shows a good correspondence between observed (GRACE) and water balance based estimates of terrestrial water storage.**
- **In Figure 4, except for peak discharges, during spring, in Yenisei and Lena basins, coherence between ECMWF, NRA and observed freshwater fluxes are apparent. Average of ECMWF and NRA values are particularly well correlated with observed discharges.**

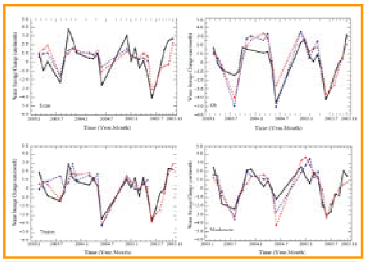

Figure 3: Month-to-month comparison of land water storage changes from GRACE (black) and LAWB using ECMWF (blue) and NRA (red)

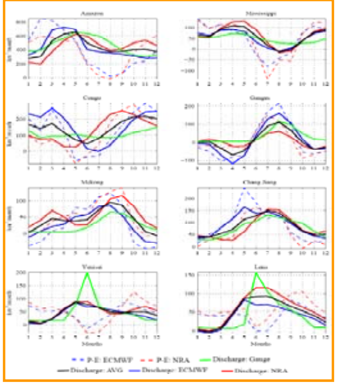

Figure 4: Comparison of discharge climatology in some of the largest river basins also shown are the climatology of P-E (broken lines) estimates from ECMWF and NRA.

Results (contd.)

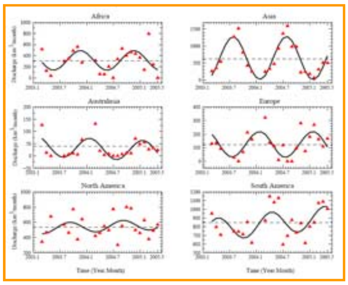

Figure 5: Monthly estimates of discharge (red triangle) from exorheic regions of each continent and their fitted annual cycle (black line). Dashed line represents the mean over the period of study (2003-2005)

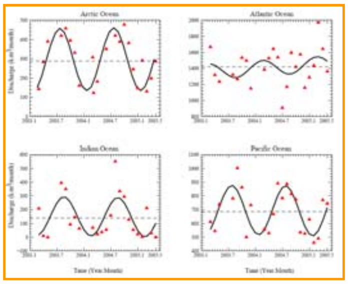

Figure 6: Monthly estimates of discharge (red triangle) into the world ocean basins and their fitted annual cycle (black line). Here, dashed line represents the mean over the study period.

- **Shown in Figure 5 are the monthly variations of continental freshwater flux based on the average of ECMWF and NRA based discharge estimates. While freshwater fluxes from Asia show much higher amplitudes of variability, the mean monthly flux is the highest from South America and is mostly dominated by flows from equatorial river basins (Figure 7).**
- **Figure 6 shows average monthly flows into Atlantic to be the highest ~1400 km³/month and the contributing upward trend from S. America is also reflected in the discharge into the Atlantic Ocean.**
- **Although highly exact in principle the method is primarily limited by errors in P-E and the course resolution of reanalysis data sets which produces continuation of oceanic (negative) P-E patterns across the continental margins. In particular, south-eastern Africa, coastal regions of Australia and central Asia, where largely negative P-E estimates reduce the discharge estimates from these regions.**

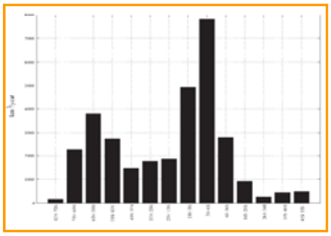

Figure 7. Shows the zonal distribution of terrestrial freshwater discharge excluding those from Greenland. and Antarctica.

- **Zonal distribution of discharge shows the highest values near the equator, highlighting the importance of equatorial river basins (S. America and Africa) in the global freshwater budget.**
- **Discharge estimates for Mediterranean Sea and Indian Ocean shown in Figure 8 are lower than those reported by previous studies. Enhanced evaporative losses in the vast arid and semi-arid areas occupying large portions of the region draining into the Indian Ocean is a primary cause behind the observed low values.**

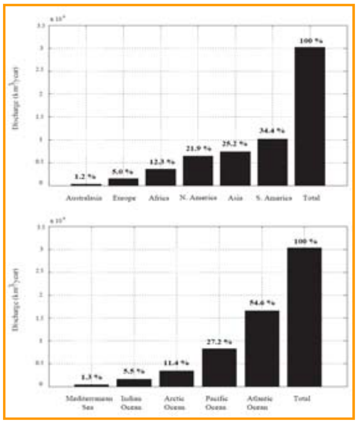

Figure 8. Mean annual discharge from each continent and ocean draining regions expressed as volume and as percentage of global discharge. Mediterranean includes Mediterranean Sea and Black Sea.

Global Water Budget Closure

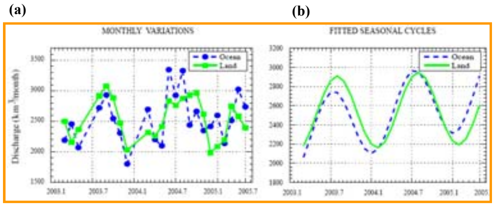

Figure 9: Comparison of monthly (a) estimates of global discharge and their fitted annual cycles (b) obtained from water balance computations over global land and ocean.

- **Good agreement between the two estimates of global discharge at monthly (RMSE=329km³/month) and seasonal times scales (RMSE = 147 km³/month)**
- **Estimates of global discharge obtained from water balance over global ocean area also include flows from Greenland and Antarctica.**

Region	Average	ECMWF	NRA
Global Land	30,354	28,590	32,851
Global Ocean	30,280	27,212	34,063

Table 1: Comparison of global freshwater discharge (km³/year) from water balance over different regions in this study

- **Given the uncertainties in the each of the estimates, comparison of global terrestrial freshwater discharge are very encouraging, even in monthly time scales, in the context of global water budget closure.**

Source	Runoff (km³/year)
Schlosser & Houser 2007	36000
Dai & Trenberth 2002 (extrapolated)	37,228 ± 662
Fekete et al. 2002 (modeled)	38,320
Nijssen et al. 2001(modeled)	36,332
Oki, T. 1999 (modeled)	40,000
Perry et al. 1996 (extrapolated)	37,768
Oki , T. 1995 (ECMWF)	24,568

Table 2: List of global freshwater discharge estimates from previous studies.

Summary & Conclusion

- **Successfully compared with observed river basin discharges at monthly and climatologic time scales**
- **In comparison to the previous studies our estimates of global discharge was on the average less by ~3000km³/yr**
- **Demonstrated deficiencies in the use of P-E as a surrogate of river runoff**
- **Closed global water budget within the limits of accuracy.**

Given the extension of GRACE mission span and possibilities of a follow-on mission, the method holds promise for the contemporary assessment of basin-to-continental scale freshwater discharge over longer time periods.