Contemporary estimates of Pan-Arctic freshwater discharge from GRACE and reanalysis

T. H. Syed,[1] J. S. Famiglietti,[1] V. Zlotnicki,[2] and M. Rodell[3]

[1] Streamflow from Arctic river basins has been increasing in recent decades in response to warming climate. In addition to being a sensitive indicator of global change, Arctic discharge is a critical component of the freshwater budget of the Arctic Ocean, where increasing freshwater flows may slow rates of North Atlantic Deep Water formation and heat transport by the thermohaline circulation. However, quantifying rates of freshwater discharge from the entire Pan-Arctic drainage has been troublesome using traditional stream gauging methods. Here we use satellite measurements of variations in continental water storage from the GRACE mission to present first estimates of monthly freshwater discharge from the entire Pan-Arctic for the period 2003–2005. Results show that rates of Pan-Arctic discharge for this time period ($3588 \pm 257 \text{ km}^3 \text{ yr}^{-1}$) are significantly larger than those suggested by gauge-based estimates ($3238 \text{ km}^3 \text{ yr}^{-1}$), and furthermore, may indicate that discharge rates are accelerating. **Citation:** Syed, T. H., J. S. Famiglietti, V. Zlotnicki, and M. Rodell (2007), Contemporary estimates of Pan-Arctic freshwater discharge from GRACE and reanalysis, *Geophys. Res. Lett.*, *34*, L19404, doi:10.1029/2007GL031254.

1. Introduction

[2] Recently reported changes in the hydrologic regime of the Arctic, including decreasing snow cover, mountain glaciers, permafrost extent and lake area [*Smith et al.*, 2005; *Alley et al.*, 2007], have heightened interest in the terrestrial water cycle of this climatically-sensitive region. These changes may be amplified through increased greenhouse gas emissions associated with increasing active layer thickness and permafrost degradation [*Lawrence and Slater*, 2005; *Zhang et al.*, 2005]. As net precipitation increases and the region thaws in response to progressively warming climate, observed increases in freshwater discharge to the Arctic Ocean [*Peterson et al.*, 2002; *Meier and Carter*, 2006; *McClelland et al.*, 2006] may have important consequences for North Atlantic Deep Water formation and heat transport by the thermohaline circulation [e.g., *Stocker and Raible*, 2005]. Beyond its implications for ocean circulation, Arctic freshwater discharge accounts for 11% of the total global runoff flux [*Shiklomanov et al.*, 2000]. Hence monitoring and understanding variations in Arctic freshwater discharge is essential in order to fully characterize its role in the global water cycle.

[3] In spite of its importance, estimates of freshwater discharge from the Pan-Arctic drainage region (Figure 1) vary considerably (Table 1). Much of the variation can be attributed to problems associated with the three major discharge estimation methods. Some of the estimates in Table 1 are derived from all available, but an incomplete set of measurements [e.g., *McClelland et al.*, 2006], some are based purely on model simulations [e.g., *Oki*, 1999] and still others are derived from the synergistic use of modeled and observed streamflow [e.g., *Fekete et al.*, 2002].

[4] Unfortunately, characterizing freshwater discharge into the Arctic Ocean is not as simple as analyzing in situ stream gauge measurements. First, some 30–40% of the Pan-Arctic drainage area is ungauged [*Shiklomanov et al.*, 2000]. Second, even when gauges are present, a significant volume of discharge may bypass measurement stations as flow in braided channels, inundated floodplain [*Alsdorf and Lettenmaier*, 2003] or as submarine groundwater seepage. Furthermore, freezing of rivers and subsequent flooding due to river-ice break up during late spring impose additional hindrances to monitoring river discharge at high latitudes [*Grabs et al.*, 2000]. Finally, acquiring all Arctic discharge data in near-real time is complicated by varying international standards for data collection and policies for information sharing.

[5] Despite major advances in land surface models, many remain deficient in representing hydrologic processes in regions with perennial-to-intermittent frozen ground, and often overestimate even basin-scale outflows [e.g., *Prowse and Flegg*, 2000]. In addition to gauge- and model-driven uncertainties in Pan-Arctic discharge estimates, the definition of the geographic extent of the region also varies and explains in part the range of values in Table 1.

[6] Given the shortage of streamflow measurements in the region, all of the above methods are valid, but lead to high uncertainty and the large range of estimates shown in Table 1. New methods are therefore required to characterize freshwater discharge from the Pan-Arctic drainage region into the Arctic Ocean.

[7] Recently, *Syed et al.* [2005] used Gravity Recovery and Climate Experiment (GRACE) [*Tapley et al.*, 2004] satellite-based estimates of terrestrial water storage changes and atmospheric reanalysis data in a combined land-atmosphere water balance to estimate freshwater discharge from the Amazon and Mississippi river basins. Results were promising and suggested that application to larger regions such as the Pan-Arctic, which typically include a significant amount of ungauged area, would be feasible.

[8] Here we present contemporary (2003–2005) estimates of monthly freshwater discharge from four of the

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[1]Department of Earth System Science, University of California, Irvine, California, USA.

[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

[3]Hydrologic Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
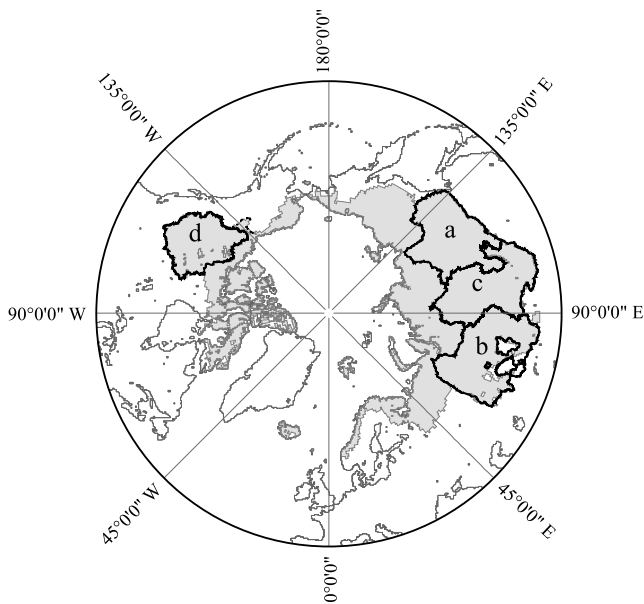
Figure 1. Pan-Arctic drainage region (in grey, modified from http://www.wsag.unh.edu/data.html to exclude Greenland) and river basins for which total basin discharge was estimated. Basin boundaries are delineated to gauging stations http://gtn-r.bafg.de): (a) Lena basin draining into Kusur (2.413 × 10^6 sq km); (b) Ob basin draining into Salekhard excluding the internally draining regions (2.678 × 10^6 sq km); (c) Yenisei basin draining into Igarka (2.454 × 10^6 sq km); and (d) Mackenzie basin draining into Arctic Red River (1.665 × 10^6 sq km).

largest Arctic river basins and from the entire Pan-Arctic drainage region (Figure 1). The key contributions of this work are that our estimates represent total basin discharge [*Syed et al.*, 2005] (both surface and groundwater) from the entire river basin or drainage region (including ungauged areas). The estimated discharge directly reflects changes in land water storage (before GRACE, terrestrial water storage changes were typically assumed equal to zero on annual time scales), and the estimates can be made in near-real time. To our knowledge, the method presented here may be the only currently viable approach for estimating monthly freshwater discharge from the entire Pan-Arctic region without the need for land surface modeling or scaling of stream gauge measurements to account for insufficient spatial coverage.

2. Data and Methods

[9] GRACE provides highly accurate maps of Earth's gravity field at monthly intervals over spatial scales of several hundred kilometers and larger. Time variations of Earth's gravity field, obtained by differencing monthly GRACE solutions, can be effectively used to infer global redistribution of water mass [*Tapley et al.*, 2004]. Over land, this time-varying component of Earth's gravity field is dominated by mass change signals related to land surface hydrology [*Wahr et al.*, 2004]. Note that GRACE provides a column-integrated measure of water mass change and, therefore, cannot differentiate amongst mass change signals above and below the surface.

[10] We used 24 consecutive months of GRACE data, using different releases (RL), i.e. processing standards, from the three science data centers, Center for Space Research RL01, Geo Forschungs Zentrum RL03 and Jet Propulsion Laboratory RL02, over the period of March 2003 to November 2005 [http://gracetellus.jpl.nasa.gov/month_mass.html]. In this work we take an average of the three data sets in order to obtain a robust estimate of terrestrial water storage changes [*Chambers*, 2006].

Table 1. Estimates of Mean-Annual Freshwater Discharge Into the Arctic Ocean

Reference	Discharge Volume, km^3 yr^{-1}	Contributing Area, km^2	Runoff, mm yr^{-1}	Period
		Observed		
McClelland et al. [2006][a]	2420 (3238)	12.1 × 10^6	200	1964–2000
Grabs et al. [2000]	2603	12.8 × 10^6	203	
Prowse and Flegg [2000][b]	3299	15.5 × 10^6	213	1975–1984
Shiklomanov et al. [2000][c]	4300	18.8 × 10^6	229	1921–1996
Lammers et al. [2001]	4749	22.4 × 10^6	212	1960–1989
		Modeled		
Baumgartner and Reichel [1975]	2600			
Su et al. [2005]	3596	16.4 × 10^6	219	1979–1999
Oki [1999]	4500			
		Combined Observed and Modeled		
Fekete et al. [2002]	3268	17.0 × 10^6	192	
Dai and Trenberth [2002]	3658	16.9 × 10^6	216	
		This Study		
GRACE-ERA	3446 ± 365	16.7 × 10^6	206	2003–2005
GRACE-NRA	3730 ± 363	16.7 × 10^6	223	2003–2005
AVERAGE	3588 ± 257	16.7 × 10^6	214	2003–2005

[a]Volume in parentheses is scaled to the entire Pan-Arctic drainage region and projected to 2004 using trends from *McClelland et al.* [2006].
[b]Includes parts of Northern Greenland.
[c]Includes Greenland.

[11] The land-atmosphere water balance is given by

$$R = -\frac{\partial S}{\partial t} - \frac{\partial W}{\partial t} - div\, \mathbf{Q} \qquad (1)$$

where R is total basin discharge and $\frac{\partial S}{\partial t}$ is the change in terrestrial water storage obtained from GRACE. The $\frac{\partial W}{\partial t}$ and $div\, \mathbf{Q}$ terms are the precipitable water tendency and horizontal divergence of atmospheric moisture content computed from reanalyses. Note that $(-\frac{\partial W}{\partial t} - div\, \mathbf{Q})$ is equivalent to precipitation (P) minus evapotranspiration (E) in the terrestrial water balance.

[12] Reanalysis data sets used in this study are from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NRA) [*Kalnay et al.*, 1996] and the European Centre for Medium-Range Weather Forecasts operational forecast analysis (ERA) (http://www.ecmwf.int/research/ifsdocs/CY25r1/index.html). The limitations of reanalyses [*Cullather et al.*, 2000] notwithstanding, the $(-\frac{\partial W}{\partial t} - div\, \mathbf{Q})$ term is an extensively used alternative to P−E in regional and global water balance studies [e.g., *Dai and Trenberth*, 2002; *Serreze et al.*, 2003] owing to the assimilation of observed wind, temperature and humidity profiles. The availability of additional meteorological data from the dense rawinsonde network makes the assimilation even more effective in the Pan-Arctic region [*Serreze et al.*, 2003]. In contrast, observed precipitation in the Arctic often contains large errors [*Yang et al.*, 2001], and observations of evapotranspiration are significantly lacking.

[13] We obtain monthly estimates of total basin discharge by solving (1) using the data sets described above. Daily ERA and NRA data were aggregated to monthly values for consistency with the GRACE data, as outlined by *Syed et al.* [2005]. Uncertainties in the monthly discharge estimates are computed by error propagation through equation (1) at the 95% confidence level [*Syed et al.*, 2005]. Errors in GRACE-derived storage changes are estimated using a least squares fit, consisting of annual, semiannual and linear terms, to monthly estimates of basin-averaged water storage. The Root Mean Square (RMS) of the residuals from the least squares fit is then used as a conservative estimate of the upper bound of error in water storage change estimates observed by GRACE [*Wahr et al.*, 2006]. We assume a value of 10% for the accuracy of divQ and $\frac{\partial W}{\partial t}$ because no published estimates are available. The actual errors may in reality be higher and would yield larger discharge errors than those shown in Table 1. The difference between the atmospheric moisture terms in the NRA and ERA can also serve as a measure of their uncertainty [*Rodell and Famiglietti*, 1999].

3. Results

[14] Monthly estimates of total basin discharge and observed streamflow, along with their fitted seasonal cycles, are shown in Figure 2 for the Lena, Ob, Yenisei and Mackenzie river basins. Before computing the discharge time series shown in Figure 2, GRACE-derived storage changes were first compared to those estimated from a land-atmosphere water balance, with good results. See auxiliary material for additional details.[1]

[15] In general, temporal variations of the fitted seasonal cycles of total basin discharge estimates are in very good agreement (R > 0.8, p < 0.001) with those of observed streamflow. Large overestimates of total basin discharge are noted in the Ob basin. Here, in contrast to the other three river basins, significantly less permafrost extent (∼4%−10% of the drainage area), an appreciably greater number of snow-free days and the highest percentage of wetland cover result in relatively higher ET rates (∼74% of annual precipitation) [*Serreze et al.*, 2003] which are poorly captured by ERA and NRA.

[16] While estimated and observed peak flows are similar in magnitude in all basins, estimated winter low flows are consistently higher than those observed in the streamflow record. This unconformity is best explained by the fact that estimated total basin discharge, as previously discussed, encapsulates all forms of water mass losses, including all of gauged and ungauged discharge. Additionally, observed low flows during winter are far more prone to measurement errors relative to peak flows, due to ice jams and river freeze-up, with potential errors ranging between ∼15% and ∼30% [*Grabs et al.*, 2000; *Serreze et al.*, 2003].

[17] Results from the comparisons shown above give sufficient confidence in the methodology such that we apply it to estimate total basin discharge for the entire Pan-Arctic drainage area. Monthly estimates of Pan-Arctic (Figure 1) total basin discharge are shown in Figure 3. Both the estimates of freshwater discharge are in general agreement with each other. However, peak flows of the fitted seasonal cycles for NRA-based discharge (mean = 310.87 km^3 month^{-1}) are larger in magnitude when compared to ERA-based estimates (mean = 287.15 km^3 month^{-1}), primarily due to intermodel differences in the reanalysis moisture divergence and precipitable water tendencies.

[18] We compare our annual estimates of total basin discharge into the Arctic Ocean with those of several previous studies shown in Table 1. For the 2003−2005 period, we estimate Pan-Arctic discharge rates of 3446 ± 365 km^3 yr^{-1} (ERA-based) and 3730 ± 363 km^3 yr^{-1} (NRA-based). Our estimates are in the mid-range of those reported, and our errors are consistent with the ∼10%−20% error in gauge measurements [*Fekete et al.*, 2002].

[19] We previously noted variations in estimation methods and the definition of contributing drainage area, both of which will significantly affect Pan-Arctic discharge rates. In order to perform a more direct comparison of our Pan-Arctic discharge estimates with those shown in Table 1, we concentrate only on the observation-based estimates. We make no attempt here to perform a more detailed comparison with model-based, or combined model/observation-based Pan-Arctic discharge estimates. For the purposes of this study, we characterize our estimates as primarily observation based. Although the atmospheric moisture terms in (1) are derived from reanalysis, recall that the numerical weather prediction models used here assimilate observed profiles of wind, temperature and humidity.

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL031254.
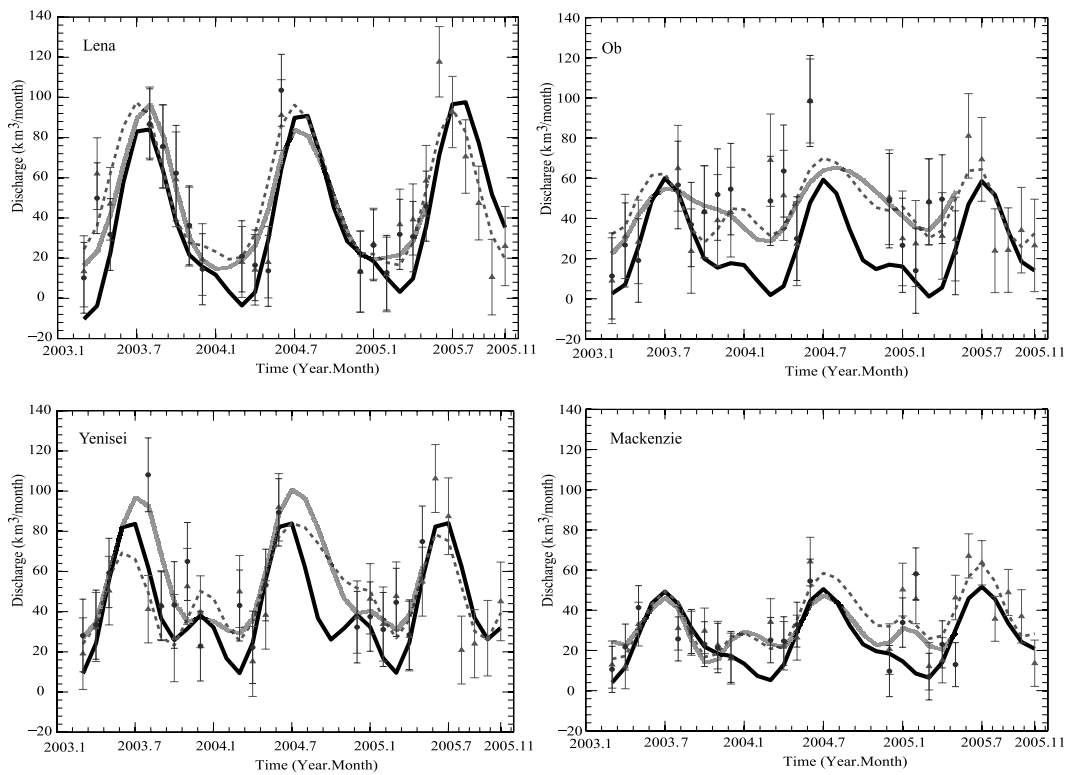
Figure 2. Time series of estimated total basin discharge and observed streamflow in km^3 month^{-1}. Fitted seasonal cycles of estimated total basin discharge using ERA (solid grey line) and NRA (broken grey line) and of observed streamflow (solid black line). Monthly estimates of total basin discharge using ERA (sphere) and NRA (triangle) with errors.

[20] Because observation-based studies differ significantly in their contributing land areas, direct comparison of our estimates with those listed in Table 1 is still challenging. For instance, *Grabs et al.* [2000] estimated a mean annual flow of 2603 km^3 yr^{-1} from gauged streamflow estimates of 35 rivers that accounted for about 70% of the Pan-Arctic drainage area. However, the Yukon was included among the 35 rivers when it actually drains into the Bering Strait. *Shiklomanov et al.* [2000] included all of Greenland and used several approximate methods to estimate streamflow
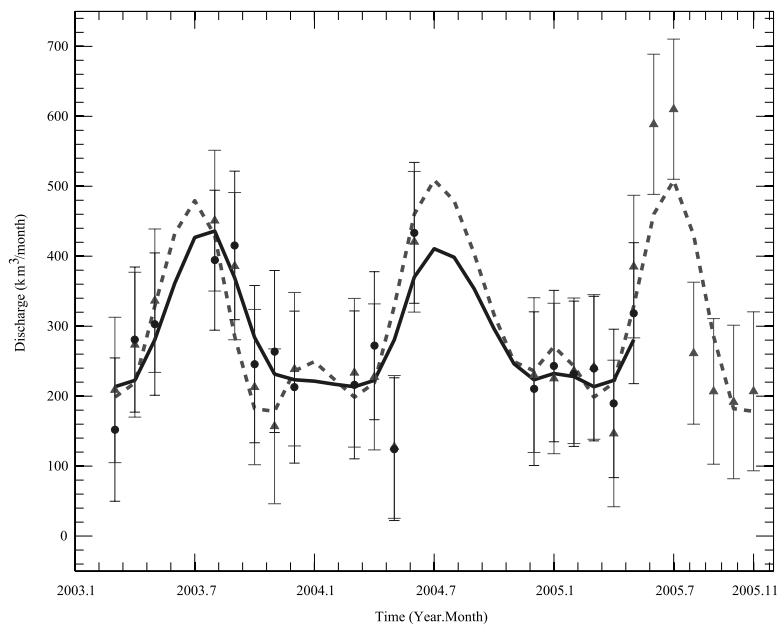
Figure 3. Monthly estimates of total basin discharge for the Pan-Arctic drainage region (Figure 1) using ERA (black sphere) and NRA (grey triangle) and computed 95% confidence intervals. Seasonal cycles of ERA estimates shown as solid black line, and of NRA estimates as the broken grey line.

records from missing gauges. *Lammers et al.* [2001] considered a significantly larger contributing area than the other studies shown in the table. *Prowse and Flegg* [2000] included flows from Northern Greenland, while ignoring contributions from the Arctic Archipelago.

[21] Additionally, the majority of the previous studies only reported mean-annual discharge estimates averaged over long time periods. Without a reported long-term trend, projection forward in time for further comparison with our 2003–2005 estimates is not feasible. Only *McClelland et al.* [2006] give the most recent, fully gauge-based estimate of Pan-Arctic discharge and its long-term trend, but only representing 74% and 85% of the Eurasian and N. American discharge into the Arctic Ocean.

[22] In order to compare our Pan-Arctic discharge estimates with those of *McClelland et al.* [2006] we first scaled up their estimates from Eurasia and N. America, by 26% and 15% respectively, to account for discharge from ungauged regions. We next applied their trend estimate (7.4 km^3/yr/yr) to extrapolate in time through the year 2004, which yields a discharge rate of ∼3238 km^3 yr^{-1}. Our estimates of Pan-Arctic total basin discharge are significantly higher than this projected value: the average of our ERA- and NRA-based estimates exceeds the projected estimate of *McClelland et al.* [2006] by 350 km^3 yr^{-1} (the lower ERA-based estimate is 208 km^3 yr^{-1} greater and the larger NRA-based estimate is 492 km^3 yr^{-1} greater). This comparison suggests that contemporary Pan-Arctic discharge continues to increase, and is greater than that estimated by the extrapolation of gauged streamflow. This is consistent with observed and modeled changes in the cryosphere [*Lawrence and Slater*, 2005; *Alley et al.*, 2007], the natural result of which is increasing drainage from the continents.

4. Discussion

[23] The significant deviation of our estimates from the linear extrapolation of the *McClelland et al.* [2006] estimate (the deviations are similar in magnitude to recent reports of mass loss from the Antarctic [*Velicogna and Wahr*, 2006a] and Greenland [*Velicogna and Wahr*, 2006b] ice sheets) points to either one of two possibilities. First, the trend in total basin discharge may be similar to that of observed streamflow, but the magnitude of the annual total basin discharge is larger than could be anticipated from simply scaling streamflow estimates to account for ungauged regions. Alternatively, freshwater drainage from the Pan-Arctic may in fact be accelerating in response to Arctic thawing and other changes in high latitude hydrology.

[24] Monitoring accelerations of the Arctic hydrologic cycle is particularly challenging given the questionable accuracy of precipitation measurements in the region and the difficulties in comprehensively measuring freshwater discharge as discussed earlier. The Pan-Arctic discharge estimates presented here provide a direct measure of hydrologic response to anthropogenic global warming in a more spatially- and temporally-comprehensive way than has been previously possible. While GRACE-based estimates of total basin discharge will not provide insight into the lateral distribution of terrestrial surface waters such as that

from a hydrology-specific altimetry mission [*Alsdorf and Lettenmaier*, 2003], they will provide important information about large-scale freshwater discharge fluxes at monthly and longer time intervals.

References

Alley, R., et al. (2007), Summary for policymakers, in *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Forth Assessment Report of the IPCC*, edited by S. Solomon et al., pp. 1–18, Cambridge Univ. Press, Cambridge, U. K.

Alsdorf, D. E., and D. P. Lettenmaier (2003), Tracking fresh water from space, *Science*, 301, 1491–1494.

Baumgartner, A., and E. Reichel (1975), *The World Water Balance*, 179 pp., Elsevier, New York.

Chambers, D. P. (2006), Evaluation of new grace time-variable gravity data over the ocean, *Geophys. Res. Lett.*, 33, L17603, doi:10.1029/2006GL027296.

Cullather, R. I., D. H. Bromwich, and M. C. Serreze (2000), The atmospheric hydrologic cycle over the Arctic basin from reanalyses. Part I: Comparison with observations and previous studies, *J. Clim.*, 13, 923–937.

Dai, A., and K. E. Trenberth (2002), Estimates of freshwater discharge from continents: Latitudinal and seasonal variations, *J. Hydrometeorol.*, 3, 660–687.

Fekete, B. M., C. J. Vörösmarty, and W. Grabs (2002), High-resolution fields of global runoff combining observed river discharge and simulated water balances, *Global Biogeochem. Cycles*, 16(3), 1042, doi:10.1029/1999GB001254.

Grabs, W. E., F. Portmann, and T. D. Couet (2000), Discharge observation networks in Arctic regions: Computation of the river runoff into the Arctic ocean, its seasonality and variability, in *Freshwater Budget of the Arctic Ocean*, NATO Sci. Ser., vol. 70, edited by E. L. Lewis et al., pp. 249–267, Kluwer Acad., Dordrecht, Netherlands.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, 77, 437–470.

Lammers, R. B., A. I. Shiklomanov, C. J. Vörösmarty, B. M. Fekete, and B. J. Peterson (2001), Assessment of contemporary Arctic river runoff based on observational discharge records, *J. Geophys. Res.*, 106, 3321–3334.

Lawrence, D. M., and A. G. Slater (2005), A projection of severe near-surface permafrost degradation during the 21st century, *Geophys. Res. Lett.*, 32, L24401, doi:10.1029/2005GL025080.

McClelland, J. W., S. J. Déry, B. J. Peterson, R. M. Holmes, and E. F. Wood (2006), A Pan-Arctic evaluation of changes in river discharge during the latter half of the 20th century, *Geophys. Res. Lett.*, 33, L06715, doi:10.1029/2006GL025753.

Meier, M. F., and C. L. Carter (2006), Observational evidence of increases in freshwater inflow to the Arctic Ocean, *Arct. Antarct. Alp. Res.*, 36, 117–122.

Oki, T. (1999), The global water cycle, in *Global Energy and Water Cycles*, edited by K. A. Browning and R. J. Gurney, pp. 10–29, Cambridge Univ. Press, Cambridge, U. K.

Peterson, B. J., R. M. Holmes, J. W. McClelland, C. J. Vörösmarty, R. B. Lammers, A. I. Shiklomanov, I. A. Shiklomanov, and S. Rahmstorf (2002), Increasing river discharge to the Arctic ocean, *Science*, 298, 2171–2173, doi:10.1126/science.1077445.

Prowse, T. D., and P. O. Flegg (2000), Arctic river flow: A review of contributing areas, in *Freshwater Budget of the Arctic Ocean*, NATO Sci. Ser., vol. 70, edited by E. L. Lewis et al., pp. 269–279, Kluwer Acad., Dordrecht, Netherlands.

Rodell, M., and J. S. Famiglietti (1999), Detectability of variations in continental water storage from satellite observations of the time dependant gravity field, *Water Resour. Res.*, 35, 2705–2723.

Serreze, M. C., D. H. Bromwich, M. P. Clark, A. J. Ertringer, T. Zhang, and R. Lammers (2003), Large-scale hydro-climatology of the terrestrial Arctic drainage system, *J. Geophys. Res.*, 108(D2), 8160, doi:10.1029/2001JD000919.

Shiklomanov, I. A., A. I. Shiklomanov, R. B. Lammers, B. J. Peterson, and C. J. Vörösmarty (2000), The dynamics of river water inflow to the Arctic ocean, in *Freshwater Budget of the Arctic Ocean*, NATO Sci. Ser., vol. 70, edited by E. L. Lewis et al., pp. 281–296, Kluwer Acad., Dordrecht, Netherlands.

Smith, L. C., Y. Sheng, G. M. MacDonald, and L. D. Hinzman (2005), Disappearing Arctic lakes, *Science*, *308*, 1429, doi:10.1126/science.1108142.

Stocker, T. F., and C. C. Raible (2005), Water cycle shifts gear, *Nature*, *434*, 830–832, doi:10.1038/434830a.

Su, F., J. C. Adam, L. C. Bowling, and D. P. Lettenmaier (2005), Streamflow simulations of the terrestrial Arctic domain, *J. Geophys. Res.*, *110*, D08112, doi:10.1029/2004JD005518.

Syed, T. H., J. S. Famiglietti, J. Chen, M. Rodell, S. I. Seneviratne, P. Viterbo, and C. R. Wilson (2005), Total basin discharge for the Amazon and Mississippi river basins from GRACE and a land-atmosphere water balance, *Geophys. Res. Lett.*, *32*, L24404, doi:10.1029/2005GL024851.

Tapley, B. D., S. Bettadpur, J. C. Ries, P. F. Thompson, and M. M. Watkins (2004), GRACE measurements of mass variability in the Earth system, *Science*, *305*, 503–505.

Velicogna, I., and J. Wahr (2006a), Measurements of time-variable gravity show mass loss in Antarctica, *Science*, *311*, 1754–1756.

Velicogna, I., and J. Wahr (2006b), Acceleration of Greenland ice mass loss in spring 20 04, *Nature*, *443*, 329–331, doi:10.1038/nature05168.

Wahr, J., S. Swenson, V. Zlotnicki, and I. Velicogna (2004), Time-variable gravity from GRACE: First results, *Geophys. Res. Lett.*, *31*, L11501, doi:10.1029/2004GL019779.

Wahr, J., S. Swenson, and I. Velicogna (2006), Accuracy of GRACE mass estimates, *Geophys. Res. Lett.*, *33*, L06401, doi:10.1029/2005GL025305.

Yang, D., B. Goodison, J. Metcalfe, P. Louie, E. Elomaa, C. Hanson, V. Golubev, T. Gunther, J. Milkovic, and M. Lapin (2001), Compatibility evaluation of national precipitation gage measurements, *J. Geophys. Res.*, *106*(D2), 1481–1492.

Zhang, T., et al. (2005), Spatial and temporal variability in active layer thickness over the Russian Arctic drainage basin, *J. Geophys. Res.*, *110*, D16101, doi:10.1029/2004JD005642.

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J. S. Famiglietti and T. H. Syed, Department of Earth System Science, University of California, Irvine, Irvine, CA 92697, USA. (tsyed@uci.edu)

M. Rodell, Hydrologic Sciences Branch, NASA Goddard Space Flight Center, Code 974.1, Greenbelt, MD 20771, USA.

V. Zlotnicki, Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 300-323, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.