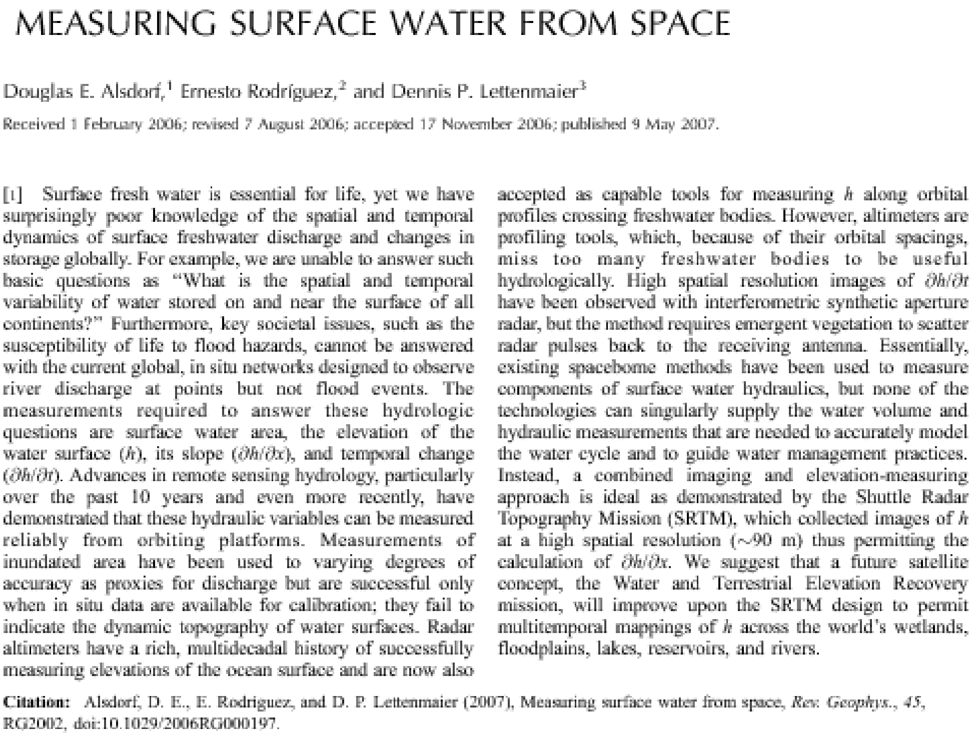
Enhancing in-situ streamflow measurements: needs and opportunities

Balázs M. Fekete

Need for Remote Sensing



MEASURING SURFACE WATER FROM SPACE

Douglas E. Alsdorf,[1] Ernesto Rodríguez,[2] and Dennis P. Lettenmaier[3]

Received 1 February 2006; revised 7 August 2006; accepted 17 November 2006; published 9 May 2007.

[1] Surface fresh water is essential for life, yet we have surprisingly poor knowledge of the spatial and temporal dynamics of surface freshwater discharge and changes in storage globally. For example, we are unable to answer such basic questions as "What is the spatial and temporal variability of water stored on and near the surface of all continents?" Furthermore, key societal issues, such as the susceptibility of life to flood hazards, cannot be answered with the current global, in situ networks designed to observe river discharge at points but not flood events. The measurements required to answer these hydrologic questions are surface water area, the elevation of the water surface (h), its slope ($\partial h/\partial x$), and temporal change ($\partial h/\partial t$). Advances in remote sensing hydrology, particularly over the past 10 years and even more recently, have demonstrated that these hydraulic variables can be measured reliably from orbiting platforms. Measurements of inundated area have been used to varying degrees of accuracy as proxies for discharge but are successful only when in situ data are available for calibration; they fail to indicate the dynamic topography of water surfaces. Radar altimeters have a rich, multidecadal history of successfully measuring elevations of the ocean surface and are now also accepted as capable tools for measuring h along orbital profiles crossing freshwater bodies. However, altimeters are profiling tools, which, because of their orbital spacings, miss too many freshwater bodies to be useful hydrologically. High spatial resolution images of $\partial h/\partial t$ have been observed with interferometric synthetic aperture radar, but the method requires emergent vegetation to scatter radar pulses back to the receiving antenna. Essentially, existing spaceborne methods have been used to measure components of surface water hydraulics, but none of the technologies can singularly supply the water volume and hydraulic measurements that are needed to accurately model the water cycle and to guide water management practices. Instead, a combined imaging and elevation-measuring approach is ideal as demonstrated by the Shuttle Radar Topography Mission (SRTM), which collected images of h at a high spatial resolution (~90 m) thus permitting the calculation of $\partial h/\partial x$. We suggest that a future satellite concept, the Water and Terrestrial Elevation Recovery mission, will improve upon the SRTM design to permit multitemporal mappings of h across the world's wetlands, floodplains, lakes, reservoirs, and rivers.

Citation: Alsdorf, D. E., E. Rodriguez, and D. P. Lettenmaier (2007), Measuring surface water from space, *Rev. Geophys.*, *45*, RG2002, doi:10.1029/2006RG000197.

GRACE-Based Terrestrial Freshwater Estimate

GRACE-Based Estimates of Terrestrial Freshwater Discharge from Basin to Continental Scales

TAJDARUL H. SYED AND JAMES S. FAMIGLIETTI
Department of Earth System Science, University of California, Irvine, Irvine, California

DON P. CHAMBERS
Center for Space Research, University of Texas, Austin, Texas

(Manuscript received 14 November 2007, in final form 18 April 2008)

ABSTRACT

In this study, new estimates of monthly freshwater discharge from continents, drainage regions, and global land for the period of 2003–05 are presented. The method uses observed terrestrial water storage change estimates from the Gravity Recovery and Climate Experiment (GRACE) and reanalysis-based atmospheric moisture divergence and precipitable water tendency in a coupled land–atmosphere water mass balance. The estimates of freshwater discharge are analyzed within the context of global climate and compared with previously published estimates. Annual cycles of observed streamflow exhibit stronger correlations with the computed discharge compared to those with precipitation minus evapotranspiration ($P - E$) in several of the world's largest river basins. The estimate presented herein of the mean monthly discharge from South America (~846 $\mathrm{km}^3\ \mathrm{month}^{-1}$) is the highest among the continents and that flowing into the Atlantic Ocean (~1382 $\mathrm{km}^3\ \mathrm{month}^{-1}$) is the highest among the drainage regions. The volume of global freshwater discharge estimated here is 30 354 ± 1212 $\mathrm{km}^3\ \mathrm{yr}^{-1}$. Monthly variations of global freshwater discharge peak between August and September and reach a minimum in February. Global freshwater discharge is also computed using a global ocean–atmosphere mass balance in order to validate the land–atmosphere water balance estimates and as a measure of global water budget closure. Results show close proximity between the two estimates of global discharge at monthly (RMSE = 329 $\mathrm{km}^3\ \mathrm{month}^{-1}$) and annual time scales (358 $\mathrm{km}^3\ \mathrm{yr}^{-1}$). Results and comparisons to observations indicate that the method shows important potential for global-scale monitoring of combined surface water and submarine groundwater discharge at near–real time, as well as for contributing to contemporary global water balance studies and for constraining global hydrologic model simulations.

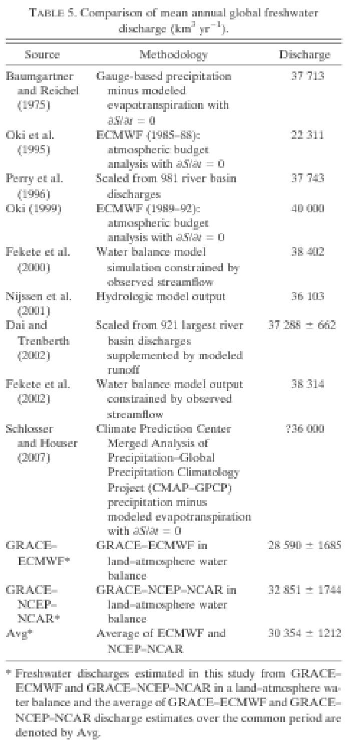


TABLE 5. Comparison of mean annual global freshwater discharge ($\mathrm{km}^3\ \mathrm{yr}^{-1}$).

Source	Methodology	Discharge
Baumgartner and Reichel (1975)	Gauge-based precipitation minus modeled evapotranspiration with $\partial S/\partial t = 0$	37 713
Oki et al. (1995)	ECMWF (1985–88): atmospheric budget analysis with $\partial S/\partial t = 0$	22 311
Perry et al. (1996)	Scaled from 981 river basin discharges	37 743
Oki (1999)	ECMWF (1989–92): atmospheric budget analysis with $\partial S/\partial t = 0$	40 000
Fekete et al. (2000)	Water balance model simulation constrained by observed streamflow	38 402
Nijssen et al. (2001)	Hydrologic model output	36 103
Dai and Trenberth (2002)	Scaled from 921 largest river basin discharges supplemented by modeled runoff	37 288 ± 662
Fekete et al. (2002)	Water balance model output constrained by observed streamflow	38 314
Schlosser and Houser (2007)	Climate Prediction Center Merged Analysis of Precipitation–Global Precipitation Climatology Project (CMAP–GPCP) precipitation minus modeled evapotranspiration with $\partial S/\partial t = 0$	?36 000
GRACE–ECMWF*	GRACE–ECMWF in land–atmosphere water balance	28 590 ± 1685
GRACE–NCEP–NCAR*	GRACE–NCEP–NCAR in land–atmosphere water balance	32 851 ± 1744
Avg*	Average of ECMWF and NCEP–NCAR	30 354 ± 1212

* Freshwater discharges estimated in this study from GRACE–ECMWF and GRACE–NCEP–NCAR in a land–atmosphere water balance and the average of GRACE–ECMWF and GRACE–NCEP–NCAR discharge estimates over the common period are denoted by Avg.

Space-based water discharge

Journal of Hydrology 373 (2009) 508–515

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Evaluation of global land-to-ocean fresh water discharge and evapotranspiration using space-based observations

Ki-Weon Seo[a,*], Duane E. Waliser[b], Baijun Tian[b,c], James S. Famiglietti[d], Tajdarul H. Syed[d,1]

[a] Korea Polar Research Institute (KOPRI), KORDI, 406-840, Republic of Korea
[b] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099, USA
[c] Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles, CA 90095-7228, USA
[d] Earth System Science, University of California, Irvine, CA 92697-3100, USA

ARTICLE INFO

Article history:
Received 9 May 2008
Received in revised form 2 February 2009
Accepted 14 May 2009

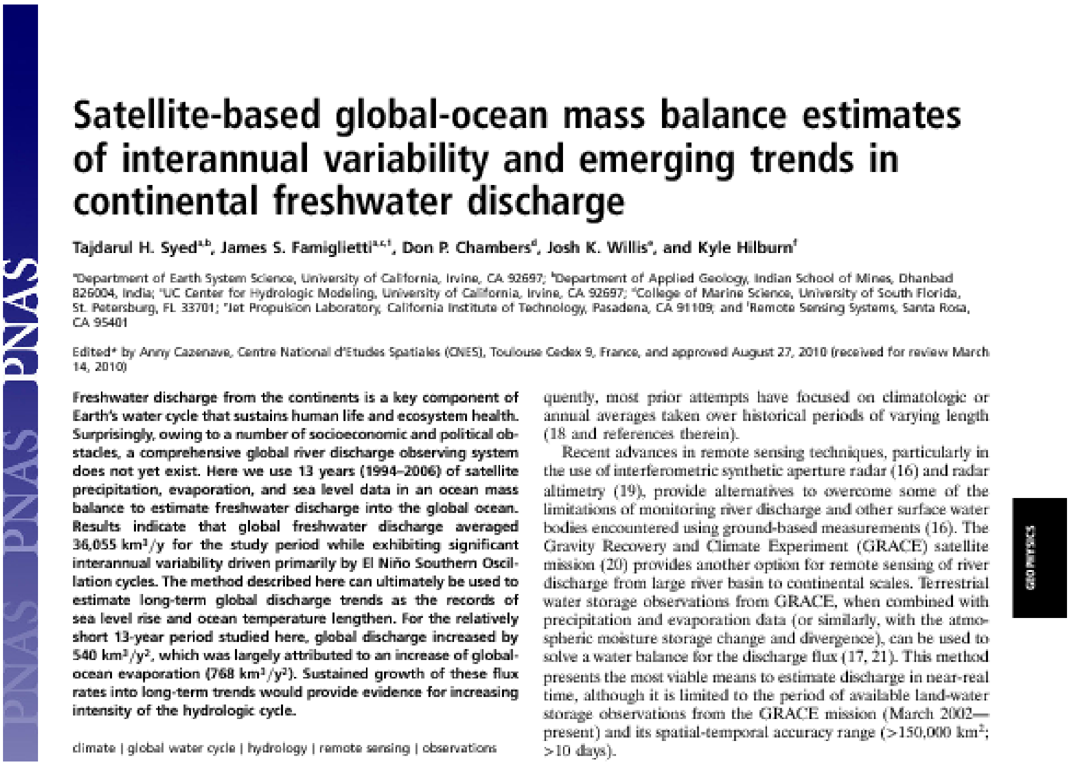
This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of V. Lakshmi, Associate Editor

Keywords:
River discharge
Evapotranspiration
Remote sensing
GRACE

SUMMARY

We estimate global fresh water discharge from land-to-oceans (Q) and evapotranspiration (ET) on monthly time scales using a number of complimentary hydrologic data sets. This estimate is possible due to the new capability of measuring oceanic and land water mass changes from GRACE as well as the space-based measurements of oceanic and land precipitation (P_l) and oceanic evaporation. Monthly time series of Q show peaks in July and January, and those of ET show peaks in March, May and August. Our estimates of Q and ET are correlated with P_l indicating qualitatively that our estimates capture temporal patterns of Q and ET reasonably well. Comparison of our Q with two other previous estimates based on the Global Runoff Data Centre (GRDC) river gauges network shows that our maximum peak in Q occurs about a month later than previous estimates. In addition, we compare our estimation of Q and ET to 20th century simulations from the WCRP CMIP3 multi-model archive assessed in the IPCC 4th Assessment Report. Runoff (R) and ET from AOGCMs tend to only exhibit the annual cycle, but the Q estimated in this study exhibits additional semi-annual variations that exists in P_l as well. In addition, R from the models shows a maximum peak 2 months earlier than the estimated Q, which is due partly to the river discharge time lag that most AOGCMs do not take into account. These results indicate that current AOGCMs exhibit basic shortcomings in simulating Q and ET accurately. The new method developed here can be a useful constraint on these models and can be useful to close budget of global water balance.

PNAS Satellite-based Ocean Mass Balance



Satellite-based global-ocean mass balance estimates of interannual variability and emerging trends in continental freshwater discharge

Tajdarul H. Syed[a,b], James S. Famiglietti[a,c,1], Don P. Chambers[d], Josh K. Willis[e], and Kyle Hilburn[f]

[a]Department of Earth System Science, University of California, Irvine, CA 92697; [b]Department of Applied Geology, Indian School of Mines, Dhanbad 826004, India; [c]UC Center for Hydrologic Modeling, University of California, Irvine, CA 92697; [d]College of Marine Science, University of South Florida, St. Petersburg, FL 33701; [e]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; and [f]Remote Sensing Systems, Santa Rosa, CA 95401

Edited* by Anny Cazenave, Centre National d'Etudes Spatiales (CNES), Toulouse Cedex 9, France, and approved August 27, 2010 (received for review March 14, 2010)

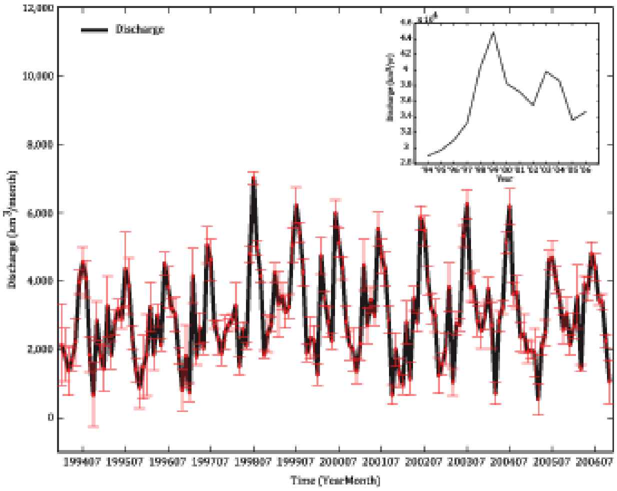
Freshwater discharge from the continents is a key component of Earth's water cycle that sustains human life and ecosystem health. Surprisingly, owing to a number of socioeconomic and political obstacles, a comprehensive global river discharge observing system does not yet exist. Here we use 13 years (1994–2006) of satellite precipitation, evaporation, and sea level data in an ocean mass balance to estimate freshwater discharge into the global ocean. Results indicate that global freshwater discharge averaged 36,055 km^3/y for the study period while exhibiting significant interannual variability driven primarily by El Niño Southern Oscillation cycles. The method described here can ultimately be used to estimate long-term global discharge trends as the records of sea level rise and ocean temperature lengthen. For the relatively short 13-year period studied here, global discharge increased by 540 km^3/y^2, which was largely attributed to an increase of global-ocean evaporation (768 km^3/y^2). Sustained growth of these flux rates into long-term trends would provide evidence for increasing intensity of the hydrologic cycle.

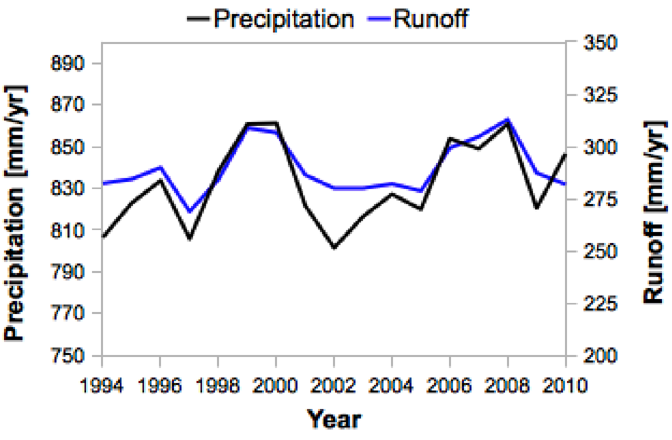
climate | global water cycle | hydrology | remote sensing | observations

quently, most prior attempts have focused on climatologic or annual averages taken over historical periods of varying length (18 and references therein).

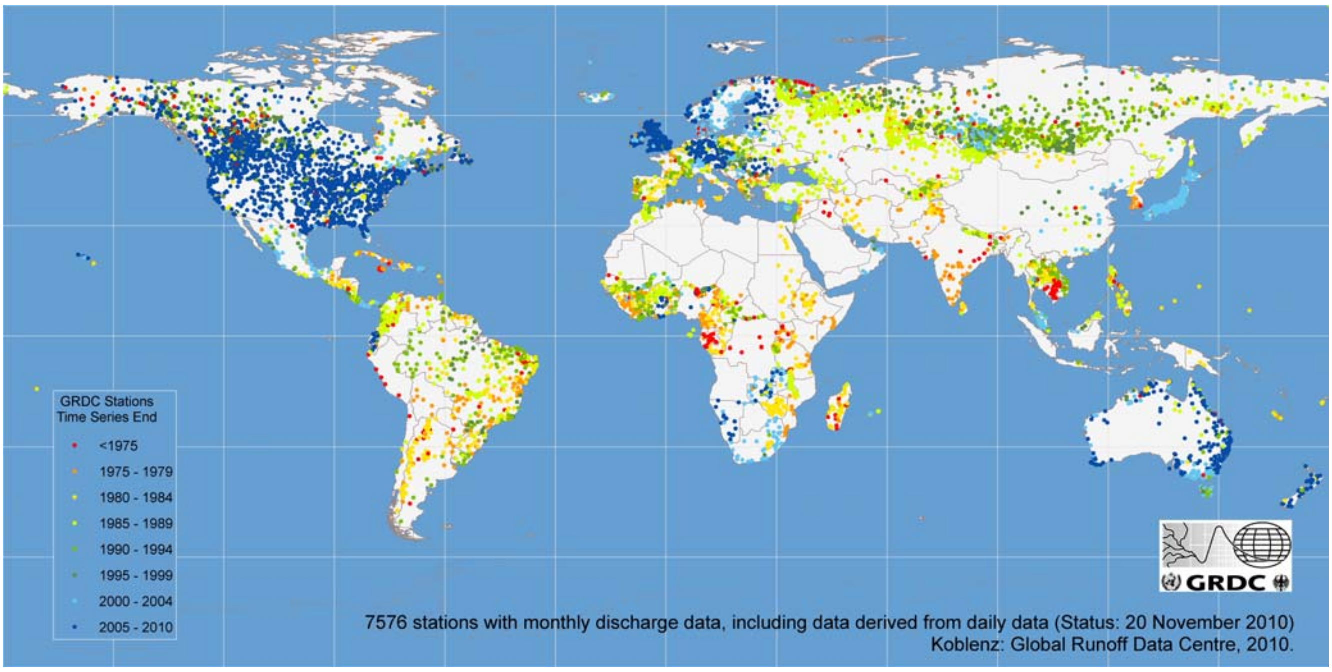
Recent advances in remote sensing techniques, particularly in the use of interferometric synthetic aperture radar (16) and radar altimetry (19), provide alternatives to overcome some of the limitations of monitoring river discharge and other surface water bodies encountered using ground-based measurements (16). The Gravity Recovery and Climate Experiment (GRACE) satellite mission (20) provides another option for remote sensing of river discharge from large river basin to continental scales. Terrestrial water storage observations from GRACE, when combined with precipitation and evaporation data (or similarly, with the atmospheric moisture storage change and divergence), can be used to solve a water balance for the discharge flux (17, 21). This method presents the most viable means to estimate discharge in near-real time, although it is limited to the period of available land-water storage observations from the GRACE mission (March 2002—present) and its spatial-temporal accuracy range (>150,000 km^2; >10 days).

Annual Discharge



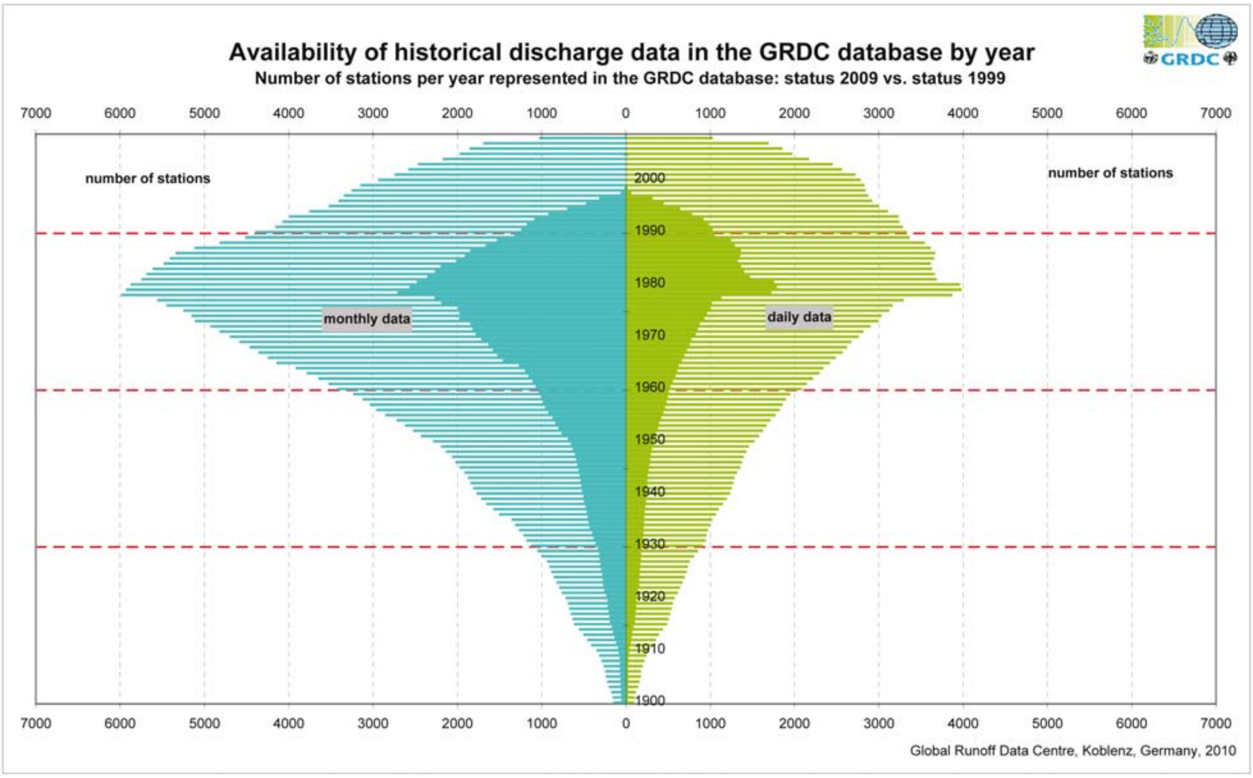


Discharge Monitoring Infrastructure



7576 stations with monthly discharge data, including data derived from daily data (Status: 20 November 2010)
Koblenz: Global Runoff Data Centre, 2010.

Tornado Graph of GRDC's Data Archive



Availability of historical discharge data in the GRDC database by year

Number of stations per year represented in the GRDC database: status 2009 vs. status 1999

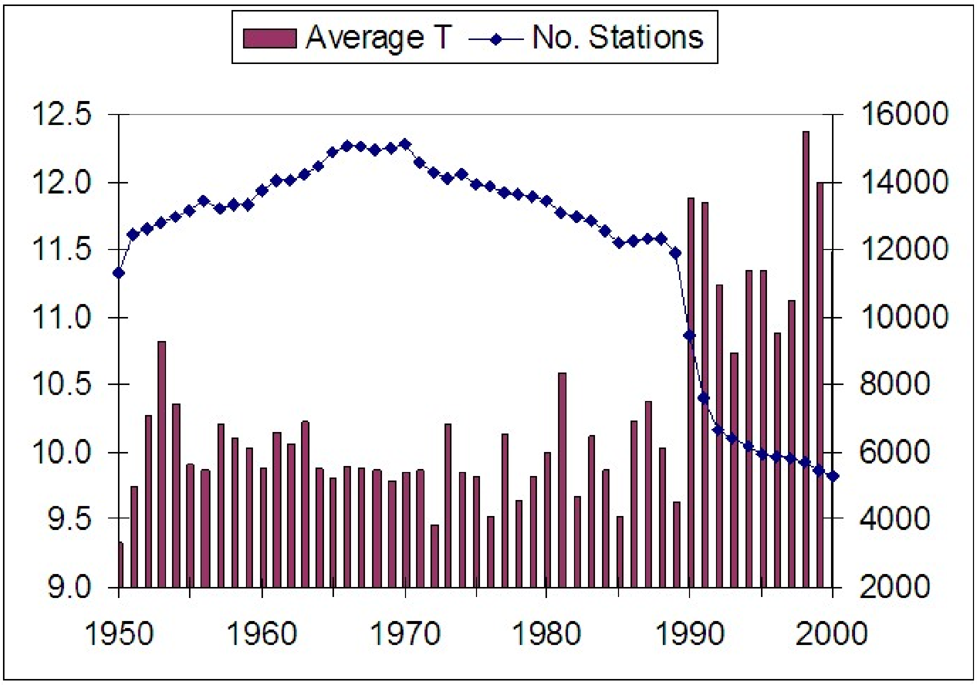
Global Runoff Data Centre, Koblenz, Germany, 2010

Existing Realtime Reporting Discharge Gauges

	Realtime	Archive
United States	9230	25300
Canada	1700	5607
European Union		3800

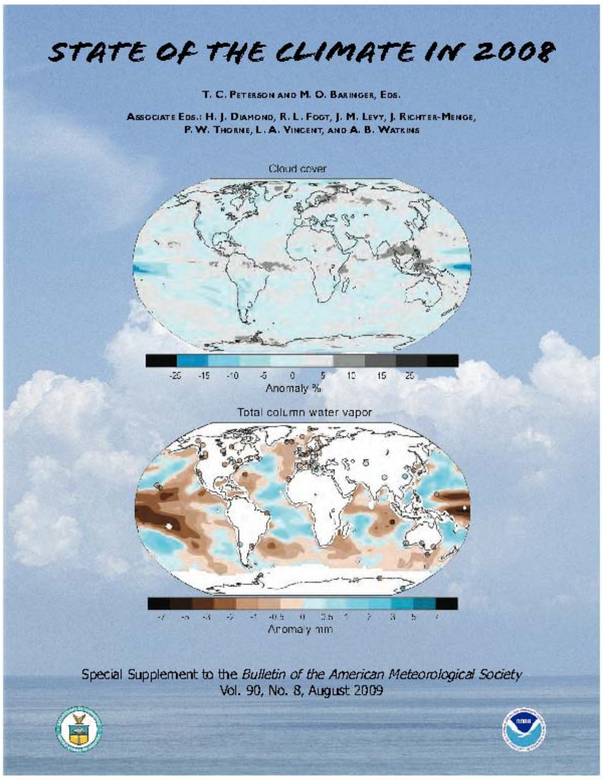
GRACE Spatial Resolution is the equivalent of operating 750 stations

Temperature Stations in NCDC



D'Aleo and Watts, 2010

Past Issues

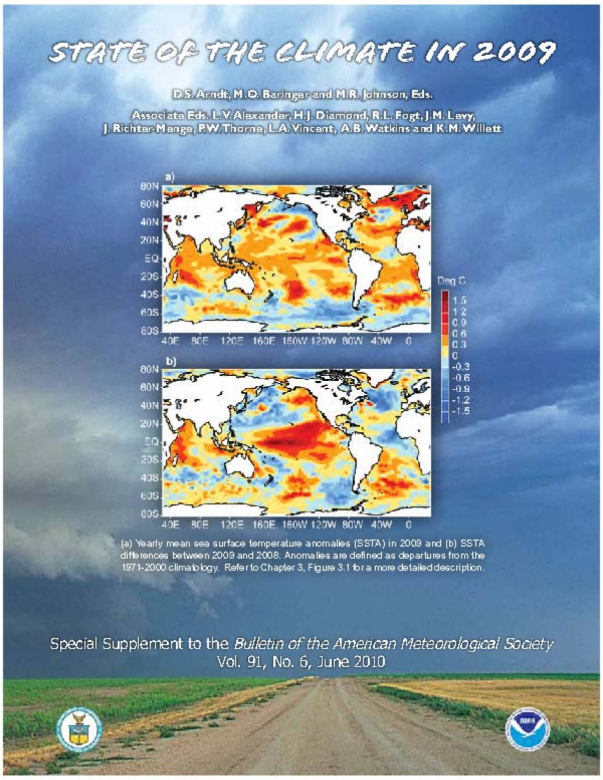


STATE OF THE CLIMATE IN 2008

T. C. PETERSON AND M. O. BARINGER, EDS.

ASSOCIATE EDS.: H. J. DIAMOND, R. L. FOGT, J. M. LEVY, J. RICHTER-MENGE,
P. W. THORNE, L. A. VINCENT, AND A. B. WATKINS

Special Supplement to the *Bulletin of the American Meteorological Society*
Vol. 90, No. 8, August 2009



STATE OF THE CLIMATE IN 2009

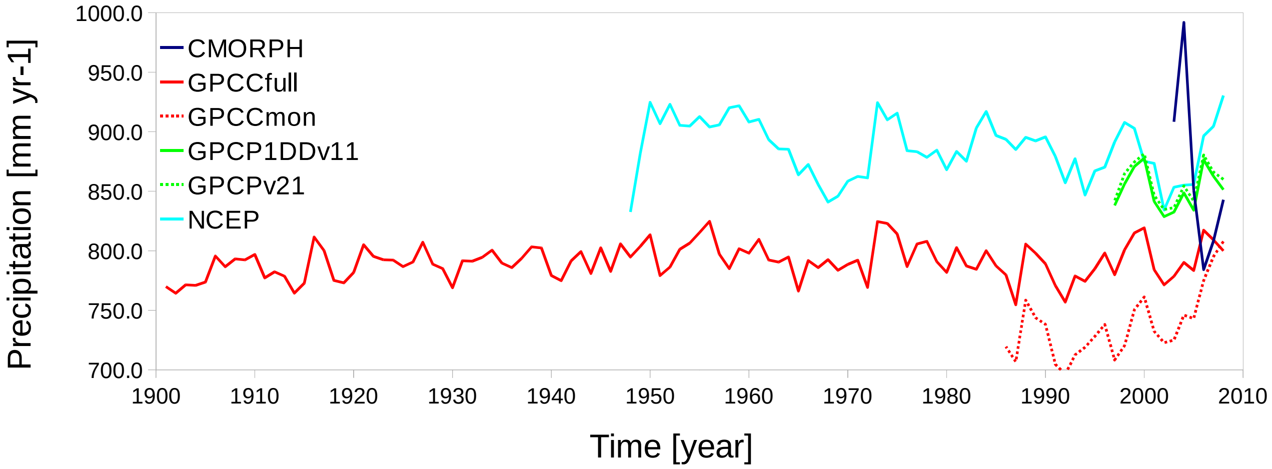
D.S. Arndt, M.O. Baringer and M.R. Johnson, Eds.

Associate Eds. L.V. Alexander, H.J. Diamond, R.L. Fogt, J.M. Levy,
J. Richter-Menge, P.W. Thorne, L.A. Vincent, A.B. Watkins and K.M. Willett

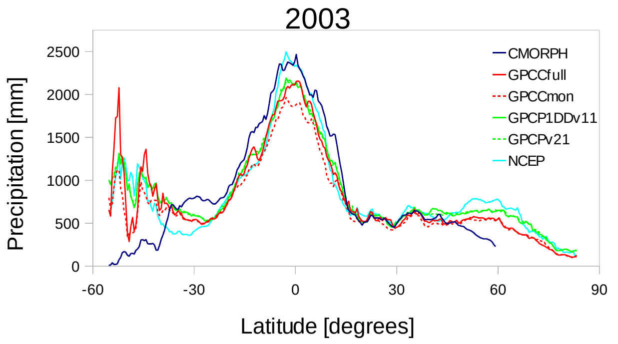
(a) Yearly mean sea surface temperature anomalies (SSTA) in 2009 and (b) SSTA differences between 2009 and 2008. Anomalies are defined as departures from the 1971-2000 climatology. Refer to Chapter 3, Figure 3.1 for a more detailed description.

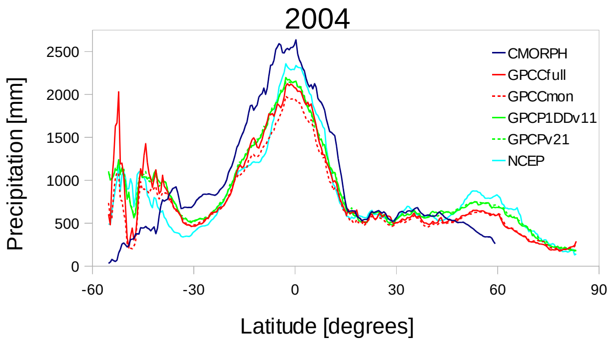
Special Supplement to the *Bulletin of the American Meteorological Society*
Vol. 91, No. 6, June 2010

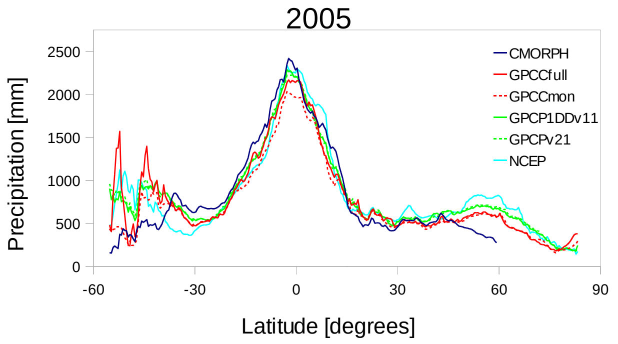
Continental Precipitation

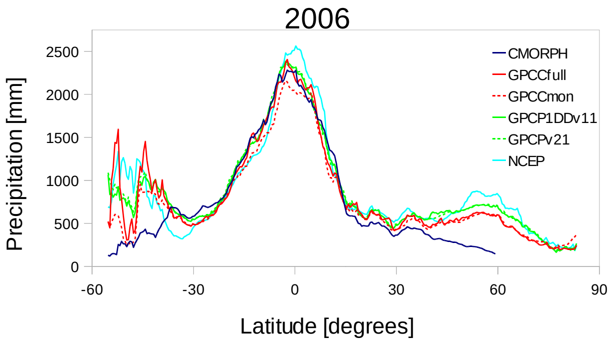


Annual Precipitation Profiles

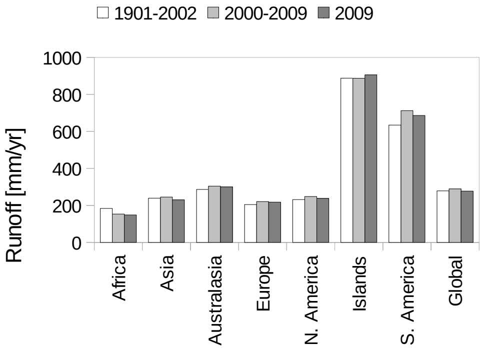


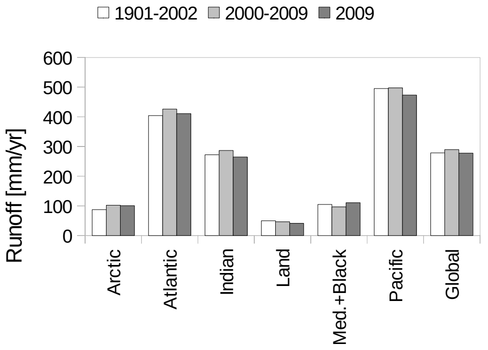




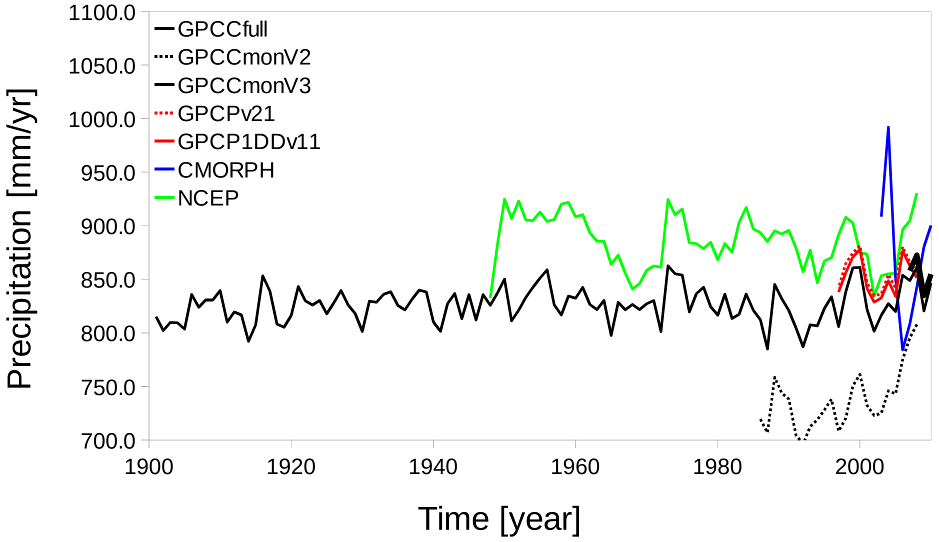


Continental Runoff

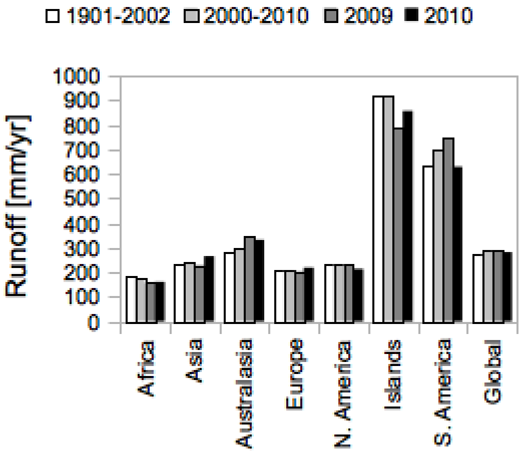


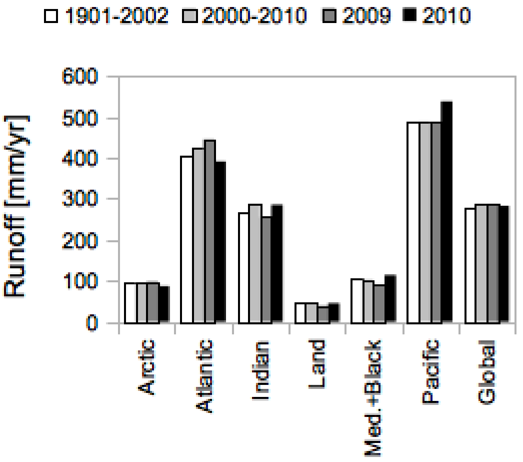


Precipitation Monitoring

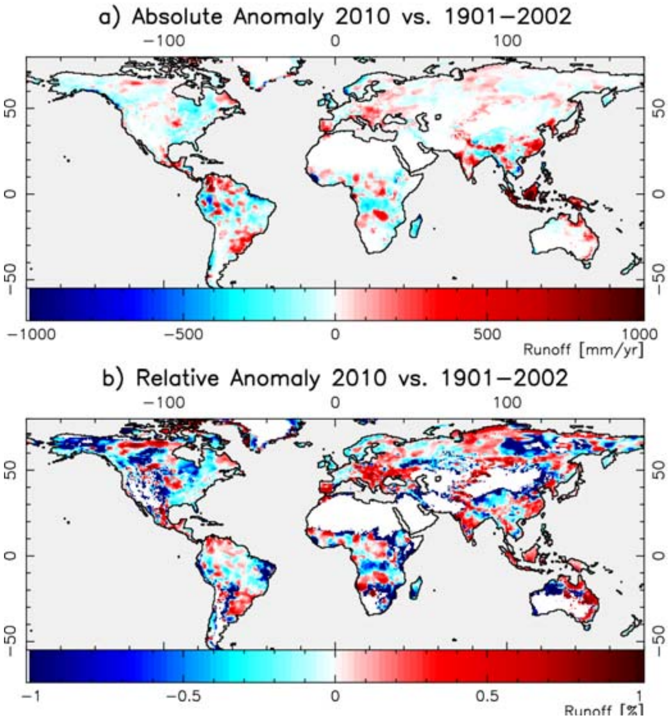


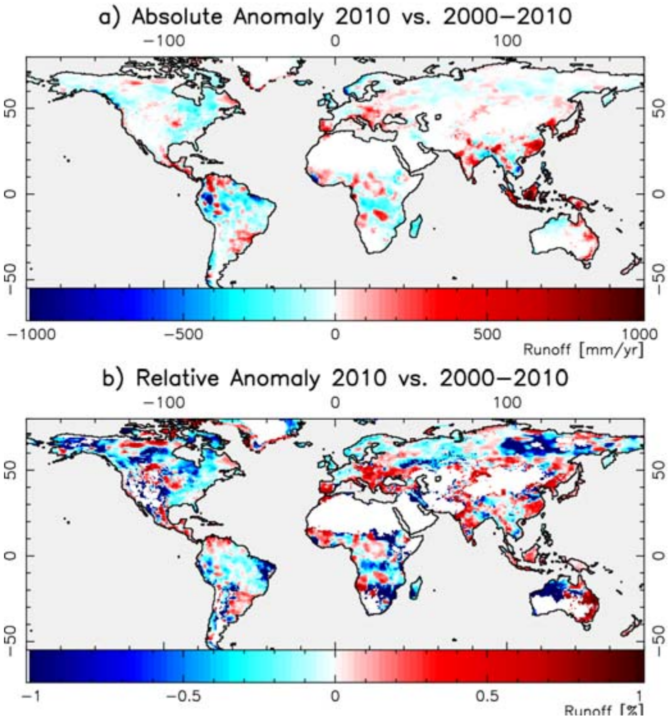
Continental Runoff Fluxes in 2010





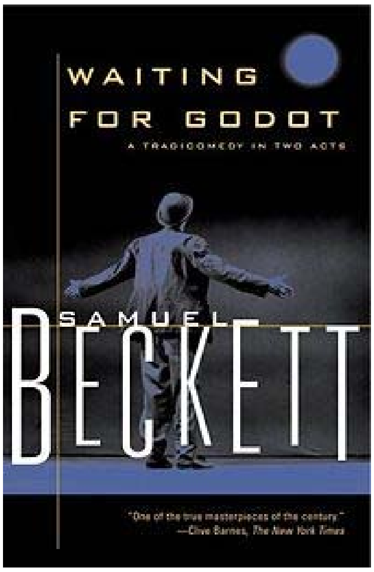
Runoff Anomalies





Conclusions

- How our descendent will know what was the Earth like in our time?
- What kind of observing system we need to operate?
  - What do we want to measure?
  - How can we measure (*in-situ* vs. satellite?
  - How we can provide seamless access to observations?



"Ceterum censeo Carthaginem esse delendam..."
Cato, A.D. 234-149