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The Need for Global, Satellite-based Observations of Terrestrial Surface Waters

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River discharge as well as lake and wetland storage of water are critical terms in the surface water balance, yet they are poorly observed globally and the prospects for improvement from in-situ networks are bleak [e.g., *Shiklomanov et al.*, 2002; *IAHS*, 2001; *Stokstad*, 1999]. Indeed, given our basic need for fresh water, perhaps the most important hydrologic observations that can be made in a basin are of the temporal and spatial variations in discharge. Gauges measuring discharge rely on flow converging from the upstream catchment to a singular in-channel cross section. This approach has successfully monitored many of the world's densely inhabited and typically heavily engineered basins for well over a century. However, much of the globally significant discharge occurs in sparsely gauged basins, many with vast wetlands that lack flow convergence (e.g., Figures 1 and 2); thus leading to poorly defined values of runoff at local, regional, and continental scales.

The Surface Water Working Group is funded by NASA's Terrestrial Hydrology Program and is an outgrowth of a mission planning process summarized in a July 1999 white paper [*Vörösmarty et al.*, 1999]. Based on the white paper and discussions at meetings over the last 2 years, the working group is focused on the following critical hydrologic questions. (1) What are the observational and data assimilation requirements for measuring surface storage and river discharge that will allow us to understand the dynamics of the land surface branch of the global hydrologic cycle, and in particular, to predict the consequences of global change on water resources? (2) What are the roles of wetlands, lakes, and rivers as regulators of biogeochemical cycles (e.g., carbon and nutrients), and in creating or ameliorating water-related hazards of relevance to society?

Open Hydrologic Questions Resulting from the Lack of Globally Measured Runoff

An understanding of the dynamics of the land surface branch of the global water cycle is in its infancy, and only in a few cases has moved beyond the gross budget analyses reported in most basic textbooks. Although the space-time distribution of precipitation is reasonably well known in those parts of the world with dense gauge measurements (mostly industrialized portions of the northern hemisphere), similar distributions of soil moisture are largely unknown. An active community, which developed the proposal for spaceborne soil moisture measurement missions in Europe (Soil Moisture and Ocean Salinity, SMOS) and the U.S. (the Hydrospheric States mission, Hydros), as well as the potential of the current gravity mission GRACE (Gravity Recovery and Climate Experiment), show promise of making headway on this problem. On the other hand, the large-scale dynamics of water storage in lakes, reservoirs, and wetlands is largely unknown. For example, the total interseasonal variability of the five largest lakes and wetlands in Africa, based on Topex/POSEIDON altimetry data [*Birkett*, 1998] is about 14 mm averaged over the entire continent. This is over one quarter of the model-based estimate of 50 mm for continental interseasonal soil moisture storage variability. The contribution of the many smaller lakes is unknown, but may well be of the same order as that from the largest lakes.

Global models of weather and climate could be constrained spatially and temporally by stream discharge and surface storage measurements. Stream discharge, in particular, is an appealing component of the surface hydrologic cycle to measure, because it represents a spatial integration of watershed processes. Yet this constraint is rarely applied, despite weather and climate modeling results showing that predicted precipitation is often inconsistent with observed discharge. For example, *Roads et al.* [2003], using data over the continental U.S. from various climate models, found that model predictions of runoff are

Fig. 1. Inundated floodplain of the Amazon River (scale is about 1 km across the foreground). Singular gauges are incapable of measuring the flow conditions and related storage changes implied by this photo, whereas complete gauge networks are cost-prohibitive. The ideal solution is a spatial measurement of water heights from a satellite platform. (Photo by Laura Hess).

BY DOUG ALSDORF, DENNIS LETTENMAIER, CHARLES VÖRÖSMARTY, AND THE NASA SURFACE WATER WORKING GROUP

often in error by 50%, and even 100% mismatches with observations were not uncommon. *Coe* [2000] found similar results for many of the world's large river basins.

Hydrologists recognize the great potential of this constraint; and such research is underway, but is limited to historical periods, and by the absence of consistent observation records of river discharge globally. So, although global Earth system models continue to improve through incorporation of better soils, topography, and land-use land cover maps, these models are now becoming limited as a consequence of the decline in observations of discharge and water storage. Thus, as NASA and other space agencies develop missions for global observations of critical hydrologic parameters such as soil moisture (e.g., Hydros) and precipitation (e.g., Global Precipitation Measurement mission, GPM), the lack of concomitant measurements of runoff and surface water storage at compatible spatial and temporal scales may well result in inconsistent parameterizations of global hydrologic, weather, and climate models.

Global observations of wetland, lake, and river hydrology also provide the scientific underpinnings for our comprehension of land surface hydrological processes. For the past ~100 years, our understanding of the hydraulic characteristics and hydrologic mass-balances of surface water runoff have largely been derived from discharge measurements at in-channel gauging stations. Measurement of in-channel discharge unfortunately does not provide the information necessary for understanding flow and storage in off-river-channel environments, such as wetlands, floodplains, and anabranches (e.g., braided channels). These environments are increasingly recognized for their important roles in biogeochemical cycling of waterborne constituents, and in trace gas exchange with the atmosphere. Wetlands and surface water cover at least ~4% of the Earth's landmass [*Prigent et al.*, 2001], yet these environments are disproportionately important in global budgets of atmospheric carbon dioxide and methane [*Richey et al.*, 2002].

For example, the mean annual area of flooded wetlands in the central Amazon Basin is 250,000 km² [*Richey et al.*, 2002], which, extrapolated to all of the tropical lowlands of South America, is estimated at 0.73 million km², or 14% of the total land lying below an elevation of 500 m. Most of this area is floodplain that is hydrologically connected to the major rivers. Rather than fixed station measurements, remote sensing offers the only practical way to determine the spatial and temporal patterns of inundation and water storage of these areas (e.g., Figure 1).

In addition to the scientific interests and challenges that could be addressed by global remote sensing of surface water storage and discharge, there are important practical implications as well. For instance, *Vörösmarty et al.* [2000] describe the global societal effects from increasing demands for fresh water. These demands will place a premium on better management of water resources, especially in parts of the world where surface networks are sparse or non-existent. There are related national security issues associated with the management of water in parts of the world where information about surface water is unavailable. Furthermore, with population growth and economic expansion, society is increasingly at risk from potentially more severe water-related extremes in weather, which include not only flooding, but drought as well [*van der Wink et al.*, 1998].

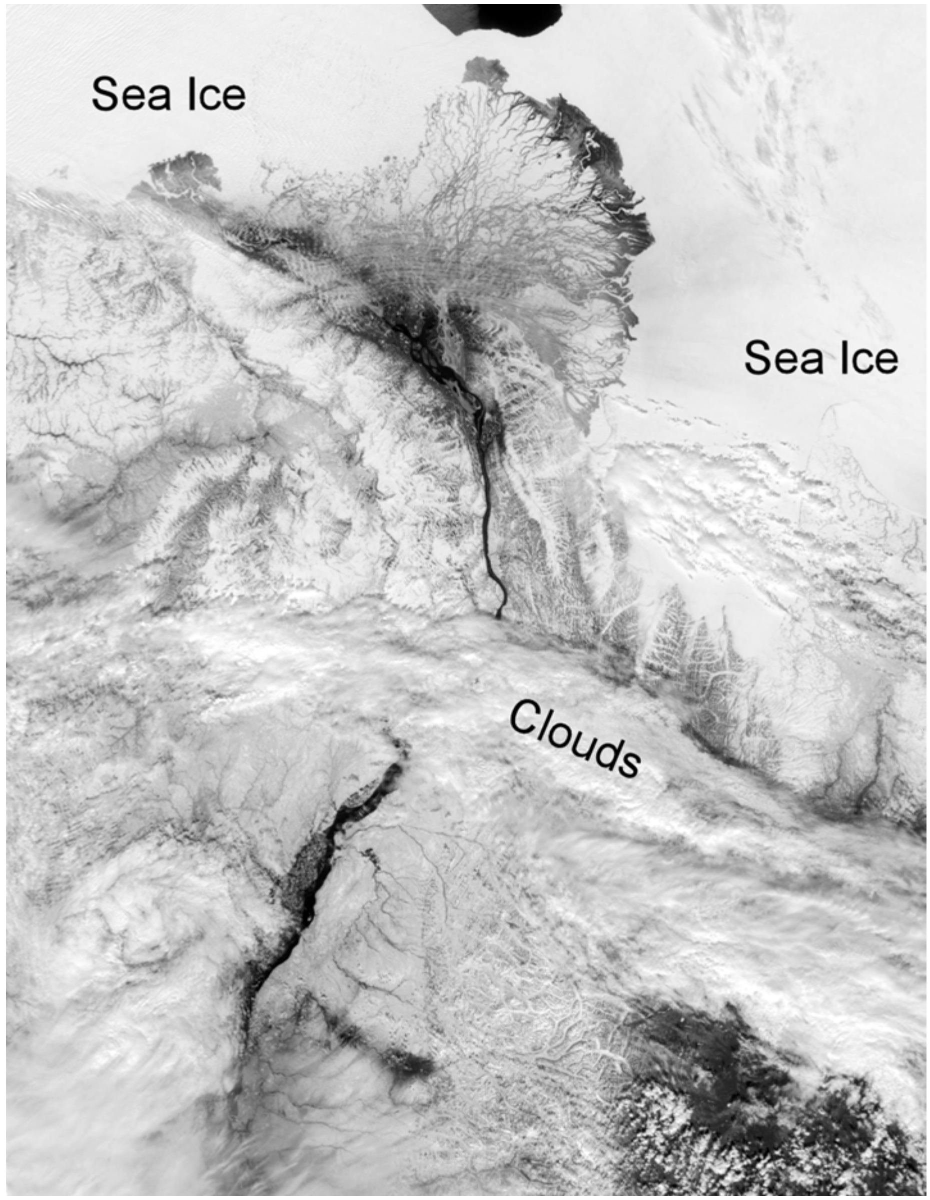

Fig. 2. Lena River and delta, Siberia. This 500 km x 650 km MODIS image from June 2002 illustrates a small portion of the vast, seasonally snow-covered Arctic area available for snowmelt runoff, and the difficulty in using optical wavelengths to image or profile beneath clouds (note the disappearance of the Lena beneath the clouds). Unfortunately, the number of upstream, within-basin gauges is severely limited to non-existent; thus, climate model predictions for much of Siberia are poorly constrained. (MODIS image from visibleearth.nasa.gov).

How Can Satellite-based Observations Answer These Questions?

There are great opportunities on the horizon for answering these questions. For example, members of our working group have utilized various satellite data sets to derive braided river discharge [*Smith et al.*, 1996], river and lake water heights [*Birkett*, 1998], and floodplain storage changes [*Alsdorf et al.*, 2000]. Although none of these approaches is ideal, in part because they all rely on instruments and platforms designed for other purposes, we believe the advances based on this research provide direction for instrument improvements.

For example, at our most recent meeting in November 2002, two working group members (Ernesto Rodriguez and Yunjin Kim of JPL) sketched out a small, cost-effective interferometric SAR that may be able to provide measurements of water heights and flow velocities. Other instruments, such as lidar systems, also need investigation. A set of stream and lake targets at which ICESat's GLAS observations

(Ice, Cloud and land Elevation Satellite, Geoscience Laser Altimeter System) will be collected during a test period in mid-2003 will provide preliminary observations for analyses.

In summary, a global, systematically collected data set of fresh water storage changes and discharge is required to answer these presently open hydrologic questions. Although gauging networks provide valuable measurements of channelized environments, only satellite-based measurements, can provide hydrologic measurements over the Earth's vast wetlands where diffusive flow conditions prevail.

Future directions for the working group are focused on modeling the spatial and temporal limits of these much-needed hydrologic measurements, and determining the technologies capable of meeting these requirements. We strongly encourage anyone interested in these problems to participate in our working group.

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Author Information

Doug Alsdorf, University of California, Los Angeles; Dennis Lettenmaier, University of Washington, Seattle; Charles Vörösmarty, University of New Hampshire, Durham; and the NASA Surface Water Working Group

Chapman and Alfvén: A Rigorous Mathematical Physicist Versus an Inspirational Experimental Physicist

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Modern magnetospheric physics owes its initial development to two great pioneers: Sydney Chapman and Hannes Alfvén (Figure 1), who took very different and contrasting approaches to their research activities. This caused one of the most memorable controversies in space physics during the 20th century.

The controversy was initiated formally by *Alfvén* [1951] when he criticized a paper by D. F. Martyn entitled, "The Theory of Magnetic Storms and Auroras," published in *Nature* in 1951. Alfvén stated: "Dr. Martyn's treatment is founded on Chapman-Ferraro's theory of magnetic storms. It is not my intention to review here the objections to this theory, objections which I believe to be fatal—nor is it worthwhile to discuss the curious super structure which Dr. Martyn tried to erect on this weak ground." Alfvén's objections will be described after briefly providing the background on which the Chapman-Ferraro theory was constructed. It may be mentioned at the outset that Chapman, together with T. G. Cowling, was well recognized by his publication of a classical treatise, "The Mathematical Theory of Non-Uniform Gases" in 1953; and also, with J. Bartels, of "Geomagnetism" in 1940, while Alfvén established himself by the publication of an inspirational book, "Cosmical Electrodynamics" in 1950.

By Syun Akasofu

Chapman published one of his first papers on magnetic storms under the title, "An Outline of a Theory of Magnetic Storms" in 1918. Recollecting about it in 1967, he stated, "I certainly misnamed this paper in calling it 'An Outline of a Theory of Magnetic Storms.' The observational part was useful, the theory was quite phony...." The observational part put the foundation on the present morphology of magnetic storms; terms such as Dst and DS were introduced. In this theory, he assumed a stream of ions or electrons from the Sun, which was supposed to cause atmospheric motions after entering there. His paper was immediately criticized by F. A. Lindeman who pointed out that a stream of ions or electrons will be dispersed laterally into space by their electrostatic force before reaching Earth. However, he suggested that the stream should consist of an equal number of ions and electrons. Such a gas is now called plasma.

Chapman took Lindeman's suggestion seriously, and he and his graduate student, Vincenzo Ferraro, formulated their problem in terms of the interaction between superconducting diamagnetic plasma and a magnetic dipole; *Chapman and Ferraro* [1931] derived an equation similar to the Debye length, a measure of the shielding distance of plasma cloud, and confirmed that the stream must be treated as plasma in dealing with the interaction with the Earth's magnetic field, as we define it today. Their theory provided a sort of skeleton configuration of the magnetosphere. Because the electrostatic force among ions and electrons in the stream is such a fundamental point in dealing with the solar wind, Chapman could not accept any theory that was not explicitly treating the solar wind as plasma.

In 1939 and 1940, Alfvén published his theory of magnetic storms. In his theory, both ions and electrons drift in the interplanetary magnetic field $\boldsymbol{B}$ with velocity $\boldsymbol{V}$ ($\boldsymbol{V} = \boldsymbol{E} \times \boldsymbol{B}/B^2$, where $\boldsymbol{E}$ denotes electric field). They have different drift paths near Earth (Figure 2) and, as a result, electrical discharge between the dawn and dusk occurs along the geomagnetic field lines. This situation may resemble the motions of ions and electrons toward Earth from the plasma sheet; ions tend to drift toward the dusk sector, while electrons tend to drift toward the dawn sector. Chapman refused to entertain Alfvén's theory on the basis that ions and electrons have semi-independent drift paths.

In responding to Alfvén's criticism in 1951, *Chapman* [1951] commented: "A theorist in such a field must select what he considers the initial bases as accurately as possible; and then develop it from these premises as accurately as possible..."

Alfvén's criticism of the Chapman-Ferraro theory consists of two parts and is better expressed in his later publications. *Alfvén* [1975] expressed the first part by stating: "The first approach to magnetospheric theory was based on a mathematically elegant formulism which, however, was highly idealized and derived without contact with experiments. It led to the Chapman-Ferraro theory...." He went on to say that Chapman-Ferraro plasma is vastly different from the real plasma, which exhibits plasma oscillations, double layers and others, and thus the transfer