Satellite Based Measurements of Global Surface Fresh Waters

Doug Alsdorf, alsdorf@geog.ucla.edu, Department of Geography, 1255 Bunche Hall, UCLA,
Los Angeles, CA 90095-1504

River discharge as well as lake and wetland storage of water are critical elements of land surface hydrology, yet they are poorly observed globally and the prospects for improvement from in-situ networks are bleak. Considering this, the NASA Surface Water Working Group [*Alsdorf et al.,* 2003] is focused on the following science and applications questions: (1) What are the observational and data assimilation requirements for measuring natural and manmade surface storage and river discharge that will allow us to (a) understand the land surface branch of the global hydrologic cycle, (b) predict the consequences of global change, and (c) make assessments for water resources management? (2) What are the roles of wetlands, lakes, and rivers (a) as regulators of biogeochemical and constituent cycles (e.g., carbon, nutrients, and sediments) and (b) in creating or ameliorating water-related hazards of relevance to society?

Global models of weather and climate could be constrained spatially and temporally by stream discharge and surface storage measurements. Yet this constraint is rarely applied, despite weather and climate modeling results showing that predicted precipitation is often inconsistent with observed discharge. Thus, as satellite missions are developed for global observations of critical hydrologic parameters such as soil moisture (i.e., HYDROS, SMOS) and precipitation (i.e., 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. Although off-river-channel environments, such as wetlands, floodplains, and anabranches (e.g., braided channels) are increasingly recognized for their important roles in delaying continental runoff, in biogeochemical cycling of waterborne constituents, and in trace gas exchange with the atmosphere, these environments are not gauged because flow is diffusive (non-channelized). 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 over large spatial domains.

Volumetric measures of surface waters are essential [*Alsdorf & Lettenmaier,* 2003]. Three different approaches have recently emerged to provide these measurements. (1) Interferometric processing of SAR data have provided cm-scale measurements of changes in water levels from environments of inundated vegetation [*Alsdorf et al.,* 2000; 2001]. This approach, however, uses long-wavelength microwaves and relies on a radar pulse travel-path that returns off-nadir-emitted energy to the antennae. Such paths are typically found in flooded forests: the method will not work for open waters, such a river channels. (2) Gravity data from the ongoing GRACE mission and its possible follow-on are expected to provide measurements of the changes in total stored water volumes (i.e., atmospheric, surface, soil, and ground water; *Rodell & Famiglietti* 1999; *Wahr et al.,* 1998), yet the spatial resolution is on the order of 200,000 km^2. While gravimetric data has the potential to address important science issues at the continental and large river basin scale, it most likely will not be applicable for directly measuring the smaller scale hydraulics of individual channels, lakes, and wetlands. (3) The most promising approach combines altimetry with imaging to provide a high-resolution mapping of the water surface elevation. The low spatial resolution of oceanic radar altimeters has already been used to measure water surface elevations of the largest rivers and lakes [*Birkett et al.,* 2002;

Maheu et al., 2003]. Although these studies can only provide a profile of elevations, they demonstrate that the frequencies employed are sufficient for sampling inland waters.

Fortunately, a combination of interferometry and altimetry may provide the necessary spatial resolution [Ernesto Rodriguez of NASA JPL, personal communication]. The instrument is a follow-on to the already NASA-funded Wide-Swath Oceanic Altimeter built by NASA JPL. It essentially combines two k-band altimeters along a short boom, providing a fixed interferometric baseline for the SAR processed altimeter waveforms. Derived spatial resolutions should approach ~10 m with cm-scale accuracies in heights. Such an instrument would provide simultaneous measurements of inundated area and water elevations, which through multi-temporal sampling would provide volumetric measurements of storage changes.

The global observations possible from such platforms will have important implications for global water cycle research. Wetlands cover at least 4% of the Earth's land surface [*Prigent et al.,* 2001] and up to 20% of humid basins such as the Amazon, but are represented poorly or not at all in most global water cycle models. These models also mostly ignore the effects of water management on the redistribution of water over much of the populated part of the globe. The need for better information about the global distribution of surface water resources is particularly acute given pressures of population growth and uneven distribution of water supplies [e.g., *Vörösmarty et al.,* 2000]. This is at a time when concerns about changing weather and climate, and in particular the potential for acceleration of the hydrologic cycle due to greenhouse gas emissions, has heightened [e.g., *Ohmura and Wild,* 2002].

Abstract for the 14th meeting of the Strategic Implementation Team, Committee on Earth Observation Satellites, Rome, May 25, 2004

References Cited:

Alsdorf, D.E, and D. Lettenmaier, Tracking fresh water from space, *Science, 301,* 1485-1488, 2003. [Note: A senior editor invited this "Perspective"]

Alsdorf, D.E., D. Lettenmaier, C. Vörösmarty, and The NASA Surface Water Working Group, The need for global, satellite-based observations of terrestrial surface waters, *EOS Transactions AGU, 84,* 269-276, 2003. [Note: this was the lead, top-front page article of the issue.]

Alsdorf, D., C. Birkett, T. Dunne, J. Melack, and L. Hess, Water level changes in a large Amazon lake measured with spaceborne radar interferometry and altimetry, *Geophysical Research Letters, 28,* 2671-2674, 2001.

Alsdorf, D.E., J. M. Melack, T. Dunne, L.A.K. Mertes, L.L. Hess, and L.C. Smith, Interferometric radar measurements of water level changes on the Amazon floodplain, *Nature, 404,* 174-177, 2000.

Birkett, C.M., L.A.K. Mertes, T. Dunne, M.H. Costa, and M.J. Jasinski, Surface water dynamics in the Amazon Basin: Application of satellite radar altimetry, *Journal of Geophysical Research, 107,* 10.1029/2001JD000609, 2002.

Maheu, C., A. Cazenave, and C.R. Mechoso, Water level fluctuations in the Plata Basin (South America) from Topex/Poseidon Satellite Altimetry, *Geophysical Research Letters, 30,* 10.1029/2002GL016033, 2003.

Ohmura, A. and M. Wild, Is the hydrological cycle accelerating?, *Science, 298,* 1345-1346, 2002.

Prigent, C., E. Matthews, F. Aires, and W. Rossow, Remote sensing of global wetland dynamics with multiple satellite data sets, *Geophysical Research Letters, 28,* 4631-4634, 2001.

Rodell, M. and J.S. Famiglietti, Detectability of variations in continental water storage from satellite observations of the time dependent gravity field, *Water Resources Research, 35,* 2705-2723, 1999.

Vörösmarty, C.J., P. Green, J. Salisbury, and R.B. Lammers, Global water resources: Vulnerability from climate change and population growth, *Science, 289,* 284-288, 2000.

Wahr, J., M. Molenaar, and F. Bryan, Time-variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE, *Journal of Geophysical Research, 103,* 30,205-30,230, 1998.

the spindle in the stem cells appears to be set up early during interphase, because the single centrosome present shortly after cell division is already found consistently localized to a cortical region of the stem cell next to the hub. Upon duplication, one centrosome remains at the hub while the other migrates to the opposite side of the cell to set up the mitotic spindle. This is in contrast to all other well-studied examples of oriented cell division. Such examples include division of another type of *Drosophila* stem cell, the neuroblast, and the first divisions of the *Caenorhabditis elegans* embryo—here, the spindle is formed before it rotates 90° into its final position during mitosis (see the figure) (*5*). The Yamashita *et al.* findings in *Drosophila* germline stem cells suggest a new mechanism of asymmetric cell division.

Germline stem cells in *Drosophila* testes that carry a mutation in centrosomin, an integral centrosome component, provide clues as to how the spindle-positioning mechanism may operate. These mutant stem cells display defects in positioning of the centrosomes during interphase, and the resultant mitotic spindles are often misoriented. This is consistent with a direct role for the centrosomes in setting up the division plane, as suggested by the early localization of the centrosomes during interphase. Strikingly, the number of stem cells in the testes of the centrosomin mutant flies increases significantly. These stem cells become crowded around the hub, presumably because of the symmetric divisions of stem cells that have misoriented spindles. It thus appears that in *Drosophila* testes, the balance between stem cell self-renewal and differentiation is not dictated entirely by the amount of available space in the niche; rather, this balance is influenced directly by the orientation of stem cell division. The authors observe a similar misorientation of mitotic spindles and increase in stem cell number in flies with mutations in the *Drosophila* homologs of the mammalian adenomatous polyposis coli (APC) tumor suppressor protein, which has been implicated in spindle orientation and cell adhesion (*6*, *7*). Because these fly APC proteins are enriched at the cell cortex and at the centrosome during cell division, the authors propose that they may play a structural role in linking the centrosome to the cell adhesion molecule E-cadherin, which they find enriched at the stem cell–hub interface. APC is also an integral component of the Wnt signaling pathway, which participates in the regulation of stem cell division (*8*, *9*). It will be interesting to determine whether Wnt signaling is important for stem cell division in the testis, contributing to the phenotypes observed in the APC mutant flies.

The study by Yamashita *et al.* raises a number of intriguing questions for further investigation. Although the authors do not observe symmetric divisions in wild-type *Drosophila* male germline stem cells, can such divisions take place and replenish a niche depleted of stem cells, as found in the *Drosophila* ovary (*10*)? How is the specialized cortical region recognized by the centrosome established? The authors suggest that homotypic interactions between cadherins at the germ cell–hub interface may be involved. If this is indeed the case, something must be preventing these interactions at interfaces between the germ cells and the somatic cyst cells that flank them. Given that after centrosome separation only one centrosome migrates away to the opposite cortex, how are the differences between the two centrosomes established and recognized? A recent study suggests that the mother and daughter centriole differ substantially in the degree to which they associate with microtubules and move within the cell (*11*). Such a mechanism might be used to differentiate between the duplicated centrioles in the *Drosophila* germline stem cells. It will be interesting to determine whether the centrosome differences observed are further exploited by testis stem cells to deliver cell fate information to the daughter cells (*12*). The Yamashita *et al.* study points to previously unappreciated mechanisms within stem cells that orient their divisions. Together with external cues, these mechanisms regulate the balance between stem cell self-renewal and differentiation.

References

1. A. Spradling *et al.*, *Nature* **414**, 98 (2001).
2. Y. M. Yamashita, D. L. Jones, M. T. Fuller, *Science* **301**, 1547 (2003).
3. A. A. Kiger *et al.*, *Science* **294**, 2542 (2001).
4. N. Tulina, E. Matunis, *Science* **294**, 2546 (2001).
5. C. Q. Doe, B. Bowerman, *Curr. Opin. Cell Biol.* **13**, 68 (2001).
6. B. M. McCartney *et al.*, *Nature Cell Biol.* **3**, 933 (2001).
7. B. Lu *et al.*, *Nature* **409**, 522 (2001).
8. X. Song, T. Xie, *Development* **130**, 3259 (2003).
9. T. Reya *et al.*, *Nature* **423**, 409 (2003).
10. C. H. Zhu, T. Xie, *Development* **130**, 2579 (2003).
11. M. Piel *et al.*, *J. Cell Biol.* **149**, 317 (2000).
12. J. D. Lambert, L. M. Nagy, *Nature* **420**, 682 (2002).

GEOPHYSICS

Tracking Fresh Water from Space

Douglas E. Alsdorf and Dennis P. Lettenmaier

Fresh water is a basic requirement for terrestrial life, yet knowledge of changes in the volume of water stored and flowing in rivers, lakes, and wetlands is poor. Recent developments in satellite remote sensing promise more accurate monitoring of freshwater resources and better prediction of floods and droughts.

Stream flow is traditionally estimated by measuring the water level and converting it to river discharge using an empirical relationship of level versus discharge. Similarly, water level in lakes and reservoirs is converted to storage volume via level-volume relationships. Gauge measurements have helped to quantify flow in river channels. However, the gauging networks used for the level measurements are in decline globally, and gauges are particularly sparse outside of industrialized regions (*1*).

Furthermore, estimates of the amount of surface water leaving a drainage basin assume that all the runoff generated upstream flows past a single downstream point. This is often not the case: Many river basins are marked by extensive wetlands and floodplains in which flow is diffuse and not flowing in a channel (see the first figure). Braided rivers are also problematic because their multiple, intertwined channels are constantly shifting, resulting in new channels with ungauged flows. Costs and logistics prohibit the installation of numerous gauges to characterize the flow dynamics in these environments.

Without comprehensive measurements of surface water storage and discharge, the availability of freshwater resources cannot be predicted with confidence. The performance of climate models with respect to land surface hydrology also cannot be evaluated. Comparison of model-derived flows with observations typically shows large modeling errors, sometimes greater than 100% (*2*). Such comparisons are only possible where there are stream gauges to verify discharge. Yet, in many areas—including much of Africa and the Arctic—surface water flow is not measured (*1*).

Knowledge of flow through nonchanneled environments such as wetlands and floodplains is particularly poor. Wetlands cover at least 4% of Earth's land surface (*3*)

D. E. Alsdorf is in the Department of Geography, University of California Los Angeles, Los Angeles, CA 90095, USA. E-mail: alsdorf@geog.ucla.edu D. P. Lettenmaier is in the Department of Civil and Environmental Engineering, University of Washington, Seattle, WA 98195, USA. E-mail: denisl@u.washington.edu

The Amazon floodplain near Manaus, Brazil. Nearly 100% of the area is inundated, despite the lack of visible open water. Furthermore, much of the flow occurs outside the channel (photo center), making a single gauge nearly useless for measuring discharge. A series of water surface elevation maps would show how the volume of stored water changes with time.

and up to 20% of humid basins such as the Amazon, but are represented poorly or not at all in most global climate models. In addition, these models generally ignore the effects of water management on the redistribution of water over much of the populated part of the globe.

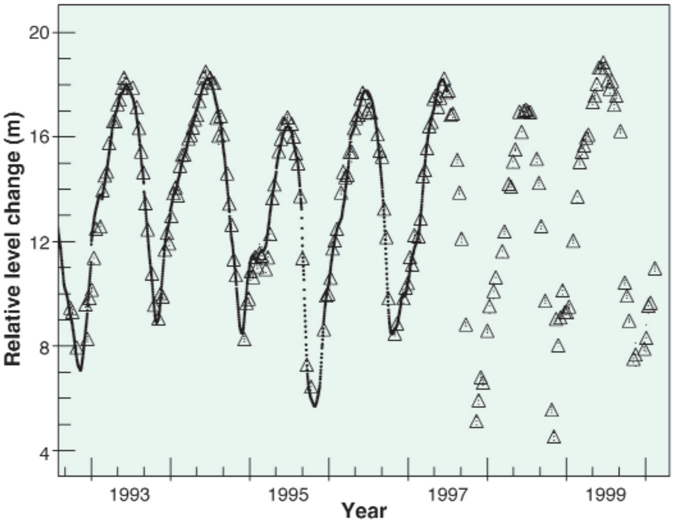
The need for better knowledge of the global distribution of surface water resources is particularly acute, given population growth and the uneven distribution of water supplies (*4*). Furthermore, changing weather and climate may accelerate the hydrologic cycle, with unknown effects on freshwater resources (*5*).

Satellite measurements may enable hydrologists to move beyond the point-based observations provided by gauge networks to basin-wide measurements of discharge and storage. For example, areas inundated by floodwaters have been measured with Landsat imagery (*6*). However, clouds and vegetation can easily mask the underlying water, a problem that is common to all systems operating in the visible spectrum (see the first figure). Microwave radar [such as synthetic aperture radar (SAR)] overcomes this problem by penetrating clouds and canopy (*7*).

Remotely measuring surface water area is much easier than monitoring changes in the water volume over space and time. There are three different satellite-based approaches to calculating volume changes. The most straightforward method is to simultaneously measure water surface area and elevation; from a series of such maps, one can then calculate the volume gained or lost. A first step toward such measurements has come from radar altimeters, which were originally designed for use over the open ocean or ice sheets (see the second figure) (*8*).

Altimeters measure the elevation of the water surface relative to a reference ellipsoid. Over the ocean surface, the elevation accuracy is on the order of a few centimeters, but two factors reduce the accuracy to tens of centimeters over terrestrial water bodies. First, terrestrial water bodies do not provide a sufficiently large surface area for averaging the multiple radar pulses used in ocean applications. Second, the shape of the returned radar pulse from the water surface deviates from the shape of a typical ocean-like echo. Today's altimeters provide only an elevation profile, yet ideal future instruments would also include area. Radar altimetry has been used to measure river surface slopes (*8*), which should be related to velocity and hence discharge.

A second approach provides simultaneous measurements of water surface area and elevation change to yield temporal variations in water storage. A first step toward such simultaneous imaging has recently come from interferometric SAR (*9*). This method is commonly used to generate maps of seismic deformation and glacial flow. Because water is highly reflective, microwave pulses from off-nadir imaging SARs reflect away from the SAR antennae, unless intercepted by vegetation. Thus, subtle height fluctuations across a floodplain's water surface can be mapped interferometrically with centimeter-scale accuracy. Such accuracy is required for understanding flow volumes across lowland floodplains. For example, an elevation change of only a few centimeters in the Amazon can be equivalent to flows greater than the average discharge of the Mississippi River.



Relative elevations of the Amazon River near Manaus (*8*). The TOPEX/POSEIDON radar altimetry measurements (triangles) agree closely with stream gauge observations (solid line). Spaceborne measurements are particularly valuable when gauge data are no longer available (for example, after 1997).

Instead of directly measuring spatial and height changes of a water surface, one may also measure the change in mass resulting from volumetric gains or losses in terrestrial water. Starting in 2004, the Gravity Recovery and Climate Experiment (GRACE) satellites will provide monthly global measurements of Earth's gravity field (*10*). On this time scale, most gravitational variations over the land surface result from mass changes in the total water column (*11*, *12*). The column total is the sum of atmospheric, surface, soil, and ground water volumes. However, because a mass's gravity field decreases rapidly with observing distance, GRACE is only sensitive to basins greater than about 200,000 km^2 (*11*, *12*).

By themselves, none of these technologies supply the water volume measurements needed to accurately model the water cycle and to guide water management (*13*). However, they provide a conceptual framework for a surface water satellite mission that could provide the required information.

Such a mission—assuming that it passes careful model-based evaluation—would need to have the following attributes: (i) sufficient spatial resolution (~100 m) to resolve channels, floodplains, and lakes contributing most of a basin's discharge; (ii) sufficient temporal resolution (a few days) to capture short flood events; and (iii) sufficient vertical resolution (a few centimeters) to measure subtle height changes responsible for significant discharge. Surface velocities might be helpful, but surface slope could be used as a surrogate, especially because surface velocity observations are often corrupted by wind ef-

CREDITS: TOP, LAURA HESS; BOTTOM, REPRODUCED FROM (8) WITH PERMISSION OF THE AMERICAN GEOPHYSICAL UNION

fects. In effect, the mission would be a topographic imager that would yield a water map of volumetric gain or loss after each overpass (*14*).

Such a satellite mission would enable hydrologists to move beyond the point-based gauging methods of the past century to measurements of the spatial variability inherent in surface water hydrology. Global coverage would ensure that, despite local economic and logistic problems, all countries could access measurements critical for forecasting floods and droughts, both of which have dramatic economic and human impacts.

References and Notes

1. A. I. Shiklomanov, R. B. Lammers, C. J. Vörösmarty, *EOS Trans. AGU* **83**, 13 (2002).
2. J. Roads *et al.*, *J. Geophys. Res.* **108** (D16), 8609, 10.1029/2002JD002583 (2003).
3. C. Prigent, E. Matthews, F. Aires, W. Rossow, *Geophys. Res. Lett.* **28**, 4631 (2001).
4. C.J. Vörösmarty, P. Green, J. Salisbury, R. B. Lammers, *Science* **289**, 284 (2000).
5. A. Ohmura, M. Wild, *Science* **298**, 1345 (2002).
6. L. C. Smith, *Hydrol. Process.* **11**, 1427 (1997).
7. An outstanding effort to measure inundated areas throughout the world has been constructed by the Global Rain Forest Mapping project using SAR images collected by the Japanese Earth Resources Satellite (JERS-1) (*15*).
8. C. M. Birkett, L. A. K. Mertes, T. Dunne, M. H. Costa, M. J. Jasinski, *J. Geophys. Res.* **107** (D20), 10.1029/2001JD000609 (2002).
9. D. E. Alsdorf *et al.*, *Nature* **404**, 174 (2000).
10. B. Tapley, personal communication.
11. J. Wahr, M. Molenaar, F. Bryan, *J. Geophys. Res.* **103**, 30205 (1998).
12. M. Rodell, J. S. Famiglietti, *Water Resour. Res.* **35**, 2705 (1999).
13. D. Alsdorf, D. Lettenmaier, C. Vörösmarty, the NASA Surface Water Working Group, *EOS Trans. AGU* **84**, 269 (2003).
14. An instrument that matches these requirements has been sketched by E. Rodriguez of NASA's Jet Propulsion Laboratory, based on the Shuttle Radar Topography Mission (SRTM).
15. A. Rosenqvist *et al.*, *Int. J. Remote Sens.* **23**, 1215 (2002).

16. We acknowledge the constructive comments of C. Birkett, T. Dunne, J. Famiglietti, J. Melack, L. Smith, and C. Vörösmarty. D. Lettenmaier is funded by NASA under NAG5-9454 and NAG5-9416. D. Alsdorf is funded by NASA under NAG5-12740, NAG5-13461, and NAG5-10685.

COMPUTER SCIENCE

The Power of Speech

Lawrence Rabiner

In the next few decades, advances in communications will radically change the way we live and work. The concept of "going to work" will change from commuting to a particular place to get things done, to "getting things done" no matter where you are. Life at home will also change radically as communications between individuals become multimodal (using voice, visual, and tactile modes) and multimedia (with sharing of text, data, audio, images, video, and other forms of information). For example, you will be able to control virtually any device in the home—such as the family home entertainment center—by pointing to it with your finger and issuing voice commands such as "find me a good classical music station."

The driving force for these changes is the seamless integration of real-time communications (voice, audio, video, virtual reality) and data (text, images, files) into a single network that can be accessed anywhere, anytime, and by a wide range of devices. Speech and language processing plays a crucial role in this network by enabling enhanced services and providing seamless access to new services (*1*).

Traditional speech and audio coding and compression will remain important even as bandwidth increases dramatically to the home, to the office, and in wireless environments. The need for high-quality, low-delay streaming of voice, CD-quality audio, and HDTV-quality video is a driving force for advanced coding research. Advanced coding and compression technologies enable networks to provide high signal quality at low delays without requiring excessive network resources.

Speech and language processing is also crucial for seamless user access to new and advanced services. As communication devices become ever smaller, the ability to provide and use keyboards and pointing devices (such as the mouse) becomes limited and problematic, and voice access to services becomes an essential component of the user interface. To access services on such devices, we will increasingly rely on speech recognition and speech understanding to command and control machines, and on speech synthesis to respond back to the user.

A third opportunity for speech processing is in user authentication. Speaker verification technology is a convenient and accurate method for authenticating the claimed identity of a user for access to secure or restricted services. It has the potential to be much more robust and reliable than conventional log-ons and passwords.

Finally, the opportunities for speech and language processing in services and operations are almost limitless. Voice commands may be used to access movie schedules or airline schedules or to add new people to a teleconference, whereas text-to-speech synthesis can be used to convert a text message to a voice message. At help desks or in customer care, voice processing can act as a surrogate for an attendant or an operator in handling routine transactions.

The speech dialog circle (see the figure) illustrates the speech-processing technology that enables voice conversations between humans and machines. Its major elements are speech recognition, spoken-language understanding, dialog management, and text-to-speech synthesis. In addition to these basic speech-processing technologies, two other key technologies, speech coding and speaker verification, are used in multimedia communications.

Speech Coding

Speech coding has existed for more than 60 years, beginning with the classic work of Dudley on the "vocoder" (*2*). The original goal of speech coding was to provide a compression technology that would enable existing copper wires to handle the continual growth in voice traffic without having to continuously add new lines. Recently, the need for speech coding has grown because of the rapid growth in wireless systems and in the transmission of voice signals over data networks, where speech is just one (very important) data type.

The goal of speech coding (*3*) is to compress the speech signal—that is, to reduce the bit rate necessary to accurately represent the speech signal—without distorting it excessively. Two main techniques have been used in speech coding. Waveform coding tries to match waveform characteristics directly, whereas model-based coding tries to match spectral and source-excitation characteristics of speech.

Today, speech can be coded down to bit rates of about 8000 bps, with intelligibility and quality approaching that of telephone-bandwidth speech (which has a bit rate of about 64,000 bps). The challenge for the next few years is to lower the bit rate by a factor of 2 without seriously lowering the quality of the resulting speech. Achieving this goal requires improved signal processing for accurately representing the excitation source and the short-time spectrum properties of the time-varying speech signal.

Text-to-Speech Synthesis

Text-to-speech synthesis aims to convert an ordinary text message into an intelligible, natural-sounding speech utterance, thus giving machines the ability to "speak" (*4*, *5*). Two approaches have been proposed

---

The author is in the Center for Advanced Information Processing, Rutgers University, Piscataway, NJ 08854, USA. E-mail: lrr@caip.rutgers.edu

EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 84 NUMBER 29
22 JULY 2003
PAGES 269–280

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

PAGES 269, 275–276

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 km^2 [*Richey et al.*, 2002], which, extrapolated to all of the tropical lowlands of South America, is estimated at 0.73 million km^2, 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].

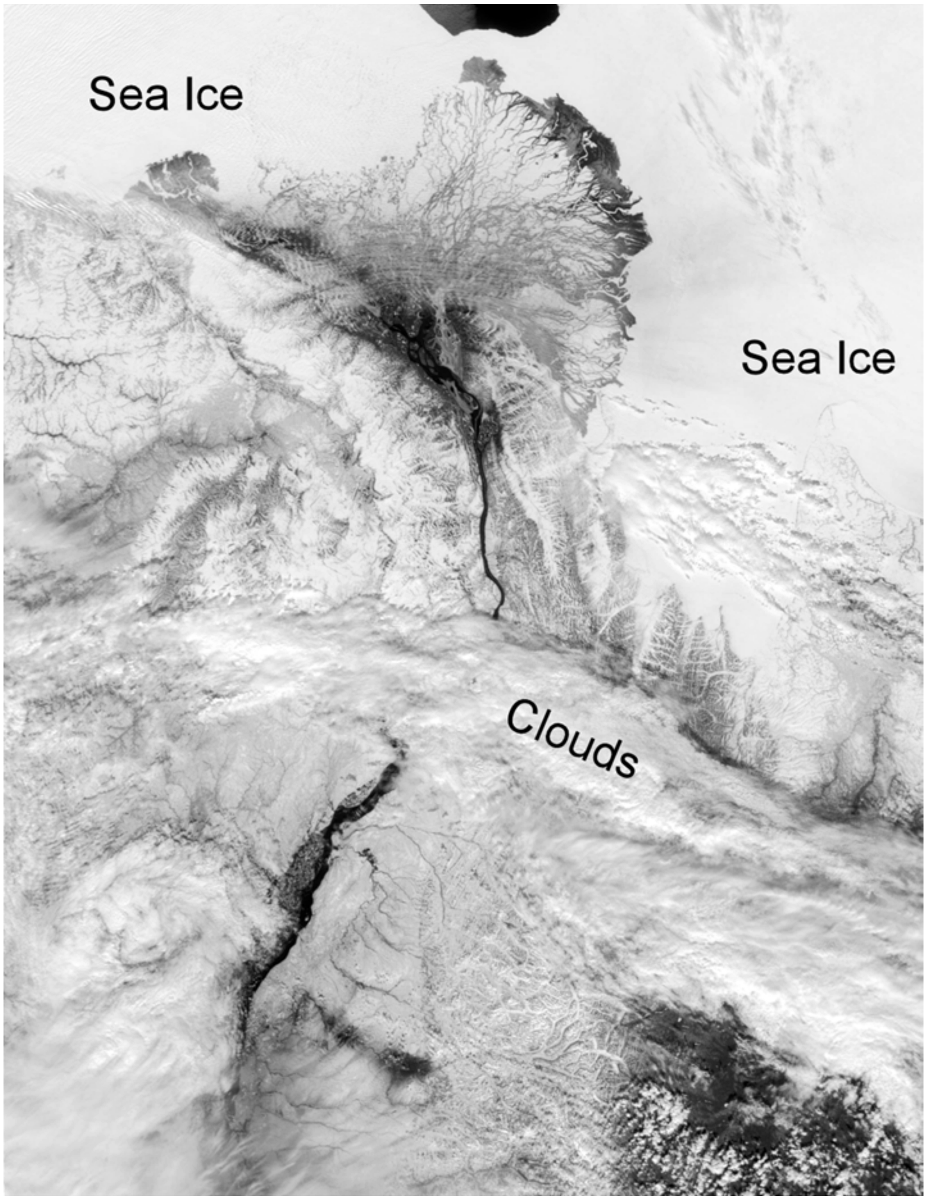


Fig. 2. Lena River and delta, Siberia. This 500 km x 650 km MODIS image from June 2002 illustrates a small portion of the vast, seasonally snow-covered Arctic area available for snowmelt runoff, and the difficulty in using optical wavelengths to image or profile beneath clouds (note the disappearance 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.

Acknowledgments

We thank all of the working group members for their input. Contact Doug Alsdorf (alsdorf @geog.ucla.edu), Dennis Lettenmaier (dennisl @u.washington.edu), or Charles Vörösmarty (Charles.vorosmarty@unh.edu) for more information. Our Web page, www.swa.com/ hydrawg, provides significant additional information.

References

Alsdorf, D. E., J. M. Melack, T. Dunne, L. A. K. Mertes, L. L. Hess, and L. C. Smith, Interferometric radar measurements of water level changes on the Amazon floodplain, *Nature, 404*, 174–177, 2000.

Birkett, C. M., Contribution of the TOPEX NASA radar altimeter to the global monitoring of large rivers and wetlands, *Water Resour. Res., 34*, 1223–1239, 1998.

Coe, M. T., Modeling terrestrial hydrological systems at the continental scale: Testing the accuracy of an atmospheric GCM, *J. Clim., 13*, 686–704, 2000.

IAHS Ad Hoc Group on Global Water Data Sets, Global water data: A newly endangered species, *Eos Trans., AGU, 82*, 54–58, 2001.

Prigent, C., E. Matthews, F. Aires, and W. Rossow, Remote sensing of global wetland dynamics with multiple satellite data sets, *Geophys. Res. Lett., 28*, 4631–4634, 2001.

Richey, J. E., J. M. Melack, A. K. Aufdenkampe, V. M. Ballester, and L. L. Hess, Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO_2, *Nature, 416*, 617–620, 2002.

Roads, J. et al., GCIP Water and Energy Budget Synthesis (WEBS), *J. Geophys. Res.*, in press.

Stokstad, E., Scarcity of rain, stream gages threatens forecasts, *Science, 285*, 1199, 1999.

Shiklomanov, A. I., R. B. Lammers, and C. J. Vörösmarty, Widespread decline in hydrological monitoring threatens Pan-Arctic research, *Eos Trans., AGU, 83*, 13–16, 2002.

Smith, L. C., B. L. Isacks, A. L. Bloom, and A. B. Murray, Estimation of discharge from three braided rivers using synthetic aperture radar (SAR) satellite imagery: Potential application to ungaged basins, *Water Resources Res., 32*, 2021–2034, 1996.

van der Wink, G., R. M. Allen, J. Chapin, M. Crooks, W. Fraley, J. Krantz, A. M. Lavigne, A. LeCuyer, et al., Why the United States is becoming more vulnerable to natural disasters, *Eos Trans., AGU, 79*, 533–537, 1998.

Vörösmarty, C. J., P. Green, J. Salisbury, and R. B. Lammers, Global water resources: Vulnerability from climate change and population growth, *Science, 289*, 284–288, 2000.

Vörösmarty, C. J., C. Birkett, L. Dingman, D. P. Lettenmaier, Y. Kim, E. Rodriguez, and G. D. Emmitt, NASA Post-2002 Land Surface Hydrology Mission Component for Surface Water Monitoring: HYDRA-SAT HYDRlogical Altimetry SATellite, A report from the NASA Post-2002 Land Surface Hydrology Planning Workshop, Irvine, Calif., 12–14 April 1999 (available from our Website, www.swa.com/hydrawg).

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

PAGES 269, 274

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 $\mathbf{B}$ with velocity $\mathbf{V}$ ($\mathbf{V} = \mathbf{E} \times \mathbf{B}/B^2$, where $\mathbf{E}$ 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