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OVERVIEW PAPER

Preface to the Special Issue on "Hydrology from Space"

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Remote sensing instruments aboard Earth-orbiting satellites give excellent new information on water distributed over the Earth—"Hydrology from Space" is the topic of the Special Issue of *Surveys in Geophysics.*

1 Importance of Water in the Earth's System

Terrestrial waters represent less than a mere 1% of the total amount of water on Earth. However, they have crucial impact on terrestrial life and human needs, and play a major role in climate variability. Excluding the ice caps, fresh water on land is stored in various reservoirs: snow pack, glaciers, aquifers and other geological formations, root zone (upper few meters of the soil), and surface waters (rivers, lakes, man-made reservoirs, wetlands and inundated areas). Land waters are continuously exchanged with the atmosphere and oceans through vertical and horizontal mass fluxes (evaporation, transpiration of the vegetation, surface and underground runoff). Terrestrial waters are an integral part of the global climate system with important links and feedbacks generated through their influence on surface energy and moisture fluxes between continental water, atmosphere and oceans. Analysis of the flow and storage of water in the global water balance is therefore, a key issue for the understanding of the water cycle. It is also essential for making an inventory of, and for managing, water resources. However, the global distribution and spatio-temporal variations of continental waters are still poorly known because routine in situ observations are not available globally.

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2 Inadequacy of Observation Networks

In situ gauging networks have been installed for several decades in many river and lake basins, distributed non-uniformly around the world. In situ measurements provide time series of water levels and discharge rates, which are used for studies of regional climate variability as well as for socio-economic applications (e.g. water resources allocation, navigation, land use, infrastructures, hydroelectric energy and flood hazards) and environmental studies (rivers, lakes, wetlands and floodplains hydro-ecology). Indeed the systematic and global monitoring of these water bodies is becoming a fundamental objective of the international community (as recognised by United Nations organisations, numerous governments, and other public or private institutions), but the decline in ground-based gauge information has dramatically increased during the last decade. In many regions, the expense of data collection is limited due to economic reasons, or the diffusion of collected data restricted, being considered as sensitive national information. The physical removal of gauges from many lake or river basins is a common, yet most unfortunate, situation in many parts of the world.

Concerning water storage in soil and aquifers, soil moisture networks are very limited in extent. The situation is even worse for underground waters. Until recently, global estimates of spatio-temporal changes of land water storage (soil and underground waters) have essentially relied on hydrological models, either coupled with atmosphere/ocean global circulation models and/or forced by observations. However, hydrological phenomena are so complex that it is very difficult to represent the hydrological system in a simple way. At the very least it requires the acquisition of a huge amount of data and their assimilation into complex climatological models. Therefore, our ability to measure, monitor, and forecast supplies of fresh water using in situ methods is facing considerable difficulties, at least on the global/continental scale.

3 Sensing Hydrological Processes from Space

In recent years, remote sensing techniques have clearly shown their capabilities for monitoring components of the water balance of large river basins on time scales ranging from months to decades. For example, satellite altimetry from the Topex/Poseidon, Jason-1, ERS and ENVISAT missions has been used for systematic monitoring of the water levels of large rivers, lakes and floodplains. Approximately 15-year long water level time series are now available worldwide. Combined with radar and/or visible imagery, satellite altimetry can also provide quantitative estimates of surface water volume changes during the flooding season.

For quite some time, researchers have tried to obtain information on soil moisture from space, but this has been extremely difficult. One of the more promising remote sensing techniques is to use microwaves for sensing soil moisture, but a successful method will probably depend on a combination of techniques. Passive microwaves from in-orbit radiometers have been used to give information on snow pack, both on snow extent and thickness.

Very promising is the gravity mission GRACE, launched in 2002, which offers for the first time the possibility of directly measuring the spatio-temporal variations of the total (i.e. vertically integrated) terrestrial water storage, consisting of underground waters, soil waters, surface waters and snow pack. Combined with other remote sensing data, GRACE can also be used to estimate additional hydrological parameters, for example mean evaporation over river basins. GRACE products have a growing interest for modellers since they can validate hydrological models. Preliminary attempts to assimilate GRACE products into the models appear highly promising.

By complementing in situ observations and hydrological modelling, space observations have the potential to improve significantly our understanding of hydrological processes at work in large river basins and their influence on climate variability and socio-economic life. Unprecedented information can be expected by synergistically using data from different sensors in orbit, and by combining model outputs and in situ measurements with observations from space. This is because the latter offer global geographical coverage, rather good spatio-temporal sampling, quasi-continuous monitoring in time, and the capability of measuring water mass changes occurring at or below the Earth's surface.

4 This Special Issue

The objective of this thematic issue is to provide an overview of recent progress accomplished in continental-scale hydrology using remote sensing observations. Different papers concentrate on different parts of the water balance. The terrestrial water balance can be written as:

$$\frac{\mathrm{dS}}{\mathrm{d}t} = P - E - Q$$

where S stands for the stock, P for the precipitation, E for the evaporation and Q for the runoff. Because water is almost incompressible, these parameters are generally expressed as a volume per unit surface area, although they can also be expressed as mass per unit area. Hence the stock has the dimensions of length [L] and reflects all forms of water storage, including groundwater storage S_g, unsaturated zone storage S_u, surface water storage S_w, ice pack S_i, and interception storage S_s. The precipitation is similarly expressed as a flux per unit surface area [LT^{-1}]; it includes all forms of precipitation, such as rainfall, snow, dew and hail. Evaporation is the transfer of liquid water to vapour, expressed in [LT^{-1}], and includes all forms of evaporation, such as evaporation from the interception stock, transpiration and soil evaporation from the unsaturated zone stock, and open water evaporation from the surface water stock. The runoff is the total amount of water leaving the area under consideration, which consists of all lateral fluxes, including surface water and groundwater flows.

Different papers in this Special Issue address the estimation of different elements of the water balance. Most papers concentrate on determining stock estimates (Calmant et al., Ramillien et al., Klees et al., Le Jeu et al., Güntner et al., Kouraev et al., Papa et al.), while one paper concentrates on the evaporation fluxes (Kalma et al.).

4.1 Remotely Sensed Hydrological Stocks and Stock Variations

Calmant et al. (2008) review the capability of nadir-viewing radar altimetry to measure water level variations for rivers and lakes. Additional products can also be derived, such as water level slopes of rivers, discharges and surface water volumes. A discussion about the limitations of current altimetry missions is provided. The first space mission (SWOT) dedicated to studying surface waters is briefly presented.

Kouraev et al. (2008) use radar altimetry and passive radiometry over the Caspian and Aral seas, Ladoga and Onega lakes, allowing them to study the ice regime of these large water bodies. They also address the potential of passive microwaves observations to measure snow depth.

Papa et al. (2008) used a multi-satellite technique to monitor flood extents on the basis of passive and active microwave combined with visible and infrared observations, developed to estimate monthly inundation extent on the global scale. They applied this to determine the flood extent and discharge variations in the large Siberian rivers.

Schmidt et al. (2008) give an overview of the basic features of the space gravimetry mission GRACE. They discuss the gravity recovery process and the derived gravity products as well as the interpretation of the GRACE gravity data, with a focus on detecting hydrological signals.

Klees et al. (2008) compare different global and regional methods to interpret GRACE data, using some of the more widely used regional and global methods currently available. The regional techniques tested make use of spherical radial basis functions or single layer densities (i.e. mascons), while the global solutions have been obtained from various major processing centres. In comparing these methods, their capacities to identify hydrological stock variations are assessed.

Ramillien et al. (2008) discuss the applications of GRACE to the monitoring of water storage in large river basins. They present several examples of major contributions of GRACE to global and regional hydrology.

Güntner et al. (2008) show how GRACE data can be used to improve global hydrological models developed for climate research and water resources management. They summarize a number of GRACE products and model output comparisons, and discuss the potential of GRACE for improving these models through data assimilation.

De Jeu et al. (2008) concentrate on the observation of soil moisture. They compare two products that are used to infer global soil moisture patterns from observations with space-borne microwave radiometers and scatterometers.

4.2 Remotely Sensed Hydrological Fluxes

In general, one should say that hydrological fluxes cannot be measured directly by remote sensing. All methods to determine these fluxes are based on semi-empirical relations that relate observed state variables to fluxes. Several products exist to describe global rainfall, such as the tropical rainfall measuring mission TRMM (Huffman et al. 2007), which are still under development and are very promising as inputs to hydrological models. The second largest hydrological flux at a global scale is evaporation. A well-known method to determine evaporation is SEBAL (Bastiaanssen et al. 1998), which is based on remotely sensed components of the energy balance. Space-based estimation of evaporation could be one of the most promising instruments to enhance hydrological prediction in ungauged basins (Winsemius et al. 2008).

Kalma et al. (2008) compared different methods for estimating land surface evaporation based on remotely sensed surface temperature. The paper reviews methods for estimating evaporation from landscapes, regions and larger geographic extents, with remotely sensed surface temperatures. Particular attention is given to the validation of such approaches against ground based flux measurements.

4.3 Outlook

For 2009, the launch of the first dedicated hydrological satellite has been planned by the European Space Agency, namely the Soil Moisture and Ocean Salinity satellite (SMOS).

All hydrological applications of satellite observations have, until now, consisted of the opportunistic use of satellites that were designed for non-hydrological purposes. Good examples are the development of evaporation estimates on the basis of standard optical/thermal imagery (Bastiaanssen et al. 1998) and the use of scatterometers for soil moisture status estimates (Wagner et al. 1999). SMOS will use L-Band radiometry to measure soil moisture around the globe. From laboratory and field studies, it has been known for a long time that passive L-band is the single most sensitive instrument with respect to soil moisture. It is clear that soil moisture is the key state variable for a better understanding of global and regional hydrology. Energy partitioning between evaporation and sensible heat flux depends on soil moisture, as does the partitioning of rainfall between surface runoff, groundwater recharge, and vadose zone replenishment.

Passive L-band is a new space sensor that needs calibration and validation. SMOS pixels will have a size of 40 $\times$ 40 km, which is not easy to relate to directly observable soil moisture measurements on the ground. The impact of vegetation, surface roughness, and dielectric constant of the surface are, in principle, understood but will need field work as well to tie everything together. Although it is well understood that many research questions need to be answered before reliable soil moisture fields can be produced, the perspective that SMOS offers is a solid global estimate of soil moisture. In turn, this may relate to mainstream surface hydrological feedback in weather and climate models. It is, therefore, good to know that the NASA initiative concerning an American soil moisture satellite has received a second life. Originally, the NASA soil moisture mission was known as Hydros but it has been renamed Soil Moisture Active/Passive (SMAP) (Entekhabi et al. 2008). As the name suggests, SMAP will use both passive and active L-band observations. SMAP has been scheduled for launch in 2012. As such, the delay in the Hydros-SMAP mission may be a blessing in disguise as it may provide the hydrological community with continuous long-term global soil moisture observations.

Finally, a second interesting American initiative is underway in the form of the Surface Water Ocean Topography (SWOT) mission (Alsdorf et al. 2007). This satellite will measure both the water level and slope of all open water bodies. If successful, SWOT will provide a wealth of information concerning the runoff through rivers around the world.

Finally, hydrological satellite observations are now coming of age. They will prove to be essential in our understanding of the relation between global change and changes in the hydrological cycle.

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