J9.3 ESTABLISHING THE GLOBAL FRESH WATER CYCLE SENSOR WEB

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1. MEASURING THE GLOBAL WATER CYCLE

This paper presents an approach to measuring the major components of the water cycle from space using the concept of a sensor-web of satellites that are linked to a data assimilation system. This topic is of increasing importance, due to the need for fresh water to support the growing human population, coupled with climate variability and change. The net effect is that water is an increasingly valuable commodity. The distribution of fresh water is highly uneven over the Earth, with both strong latitudinal distributions due to the atmospheric general circulation, and even larger variability due to landforms and the interaction of land with global weather systems. The annual global fresh water budget (e.g. Chahine, 1992; Gleick, 1996) is largely a balance between evaporation, atmospheric transport, precipitation and runoff. Although the available volume of fresh water on land is small, the short residence time of water in these fresh water reservoirs causes the flux of fresh water—through evaporation, atmospheric transport, precipitation and runoff—to be large. With a total atmospheric water store of $\sim 13*10^{12} m^3$, and an annual flux of $\sim 460*10^{12} m^3/y$, the mean atmospheric residence time of water is ~10 days. River residence times are similar, biological are ~1 week, soil moisture is ~2 months, and lakes and aquifers are highly variable, extending from weeks to years. The hypothesized potential for redistribution and acceleration of the global hydrological cycle (e.g. Homberger, 2001 and others) is therefore of concern. This hypothesized speed-up—thought to be associated with global warming—adds to the pressure placed upon water resources by the burgeoning human population, the variability of weather and climate, and concerns about anthropogenic impacts on global fresh water availability.

In the face of these mounting concerns, it is comforting to realize that the capability to measure the full global fresh water cycle and its budget is tantalizingly close. This assessment is based on an evaluation, (Hildebrand, 2004) of present capabilities for measuring water cycle components, including an evaluation of prospects for measuring the remaining water cycle components. The potential is that, if designed as a system of satellites, the full water cycle can be measured with known or planned technologies. Further, the size and scope of the effort is comparable with the size of current space programs and therefore appears to be affordable as an international effort.

2. DEFINING THE REQUIREMENTS FOR OBSERVING THE GLOBAL FRESH WATER CYCLE

Key elements of a full global water cycle measurement system include observation and evaluation of all components of the water cycle in terms of the storage of water—in the ocean, air, cloud and precipitation, soil, ground water, snow and ice, and lakes and rivers—and in terms of the global fluxes between these reservoirs. Each component of the water cycle must be measured at the appropriate temporal and spatial scales. Suggested scales, are presented in Table 1, which is closely based on the outlook for future NASA missions presented in Hildebrand et al (2004), where future measurement needs were considered for a wide range of aspects of earth science, as based on planning activities in individual earth science specialty areas. The observational requirements are based on present observational systems, as modified by expectations for future needs. Also indicated in Table 1 are possible observational approaches for the individual measurements, such as some of the frequencies that have been used for active and passive microwave observations of these quantities. The suggested microwave observations are based on the heritage for such measurements, and some aspects of the recent heritage of these measurement algorithms are listed. Approaches to the development of space systems for measuring the global water cycle can be based on these observational requirements.

The major aspects of a global system for observing the water cycle from space are a) identifying the appropriate remote sensing

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technologies and data analysis algorithms that meet the needs for measurement accuracy, b) designing instruments that meet the spatial/temporal sampling requirements, and c) selection of satellite systems and orbits that support the instruments and enable the appropriate sampling. The sampling requirements and microwave technology approaches listed in Table 1 are approximate and will be updated in the future. They are nevertheless adequate for the following discussion, and will be assumed to be approximately correct.

A major issue in designing a comprehensive global water cycle observational system is the need to make the measurements of water cycle in a manner that meets i) the spatial and temporal sampling requirements as in Table 1, ii) the need for microwave instrument aperture size and scanning capabilities to meet spatial sampling needs, and iii) the selection of orbits that will enable the required temporal sampling.

3. MEASUREMENT OF WATER CYCLE COMPONENTS

The following discussion will concentrate on instrumentation approaches that can be expected to meet the spatial/temporal sampling needs of the difference major components of the water cycle. The discussion will present the required temporal sampling, and the spatial sampling, including the vertical in the case of profiles. The needed measurement precision will be expressed, and in many cases, only as a fraction of the total, rather than a specific amount. Additional details are needed, including improved description of the precision and the required minimum and maximum intensities. Details of the instrumentation are largely omitted at this point, except to present concepts for instruments and orbits that could support measurement of each component of the water cycle. A discussion of how to integrate these instruments and orbit requirements will be presented in section 4.

3.1. Precipitation

The sampling of global precipitation can be accomplished with an upgraded GPM-type mission consisting of one or more core LEO satellites containing a multi-frequency precipitation radar and a multi-frequency radiometer system, plus a 6-8 passive microwave satellite instruments, all at LEO. The successes of TRMM give good reason to assume this approach will work; however, measurement of snow, particularly over land, and all high latitude precipitation remain a research problem. Measurement of cloud water will likely require a 94 GHz radar system in addition to the 14 and 35 GHz precipitation radars. The major sampling goals for accurate monitoring of precipitation (Table 1) indicate requirements for ~5 km horizontal and ~0.5 km vertical sampling, with an update rate of about 3 hours. The requirements for measurement precision are less precisely expressed as a range or percentage of the total precipitation rate.

3.2. Surface Evaporation.

The sampling of oceanic surface evaporation or of latent heat flux is presently based on estimates of surface humidity and winds that are provided by LEO polar orbiters, plus the evaluations from GCMS. Present ocean wind measurement satellite systems are improving the wind component of these calculations, and future upgrades can come from improved algorithms, and possibly from future sea surface salinity measurements, which when coupled with rainfall, might provide another approach for estimation of evaporation.

Measurement of evapotranspiration is a considerably more difficult problem due to the combined complexity of the topography, soil type and soil moisture, and vegetation. The evapotranspiration goals listed in Table 1 may possibly be addressed with the future NPOESS LEO sensors, plus high quality land data assimilation approaches that include high resolution topography and soil type, plus a soil moisture mission.

3.3. Water vapor transport

Present capabilities for satellite measurement of water vapor profiles using AIRS are more accurate than for most other water cycle components, and can be expected to be improved along the path to NPOESS. The major area for improvement of water vapor transport will be in the area of improved global tropospheric wind measurements, which are of extremely high priority for many other reasons. Candidate tropospheric wind measuring systems include Doppler lidar. Additionally, feature tracking approaches such as the water vapor winds, have been suggested by Riishojgaard (2005), either from a geostationary or a Molniya orbit, and would require two or more such systems, depending on the selected orbit.

3.4. Continental discharge

Accurate measurement of continental discharge of fresh water into the ocean represents a serious gap in our knowledge of the global fresh water cycle. The proposed surface water satellite mission (Alsdorf and Lettermaier, 2002; Alsdorf, et al, 2003) present a clear means of addressing this need by using high resolution satellite altimeters to monitor global surface water levels and stream flow rates. Candidate instrumentation includes laser altimetry, such as with IceSAT (Zwally et al, 2002), or interferometric synthetic aperture radar (inSAR) altimeters. Measurement requirements include altimetry accuracy of ~10cm over spot sizes of ~50m. These systems have somewhat different attributes and capabilities; however, each would support other important water cycle needs, plus additional important measurements. These measurements could be provided by single LEO satellites.

3.5. Ice Sheets, Glaciers and Sea Ice

Accurate ice sheet altimetry, provided by IceSAT (Zwally et al, 2002), has met the needs to measure ice sheet altimetry to better than the designed 10 cm accuracy. This technology also has application to glaciers and sea ice. There also are applications to vegetation structure and, as noted above, to continental discharge. There are remaining technological issues, including achieving the required small spot size. Although single LEO spacecraft could meet these sampling goals, creative orbit determination or possible use of more than one satellite will be required to meet the global sampling requirements.

3.6. Soil Moisture

Although soil moisture remains largely not measured globally, the upcoming NASA/HYDROS and European/SMOS satellites will quickly change knowledge of global soil moisture, once they are launched. In the longer term, soil moisture measurements will be available from a single LEO instrument that measures L-band emission and backscatter from the soil and vegetative ground cover. Optimally speaking, these soil moisture measurements will greatly benefit from integration with land data assimilation systems that include knowledge of topography, soil type, vegetation, etc.

3.7. Ground Water

The current GRACE mission is significantly improving our ability to resolve and understand variability in the earth's gravity field and ground water. Future satellite technologies should significantly improve the precision and spatial resolution of these measurements.

3.8. Seasonal Snow

Snow extent can be measured with visible band satellite imagery, e.g. MODIS (Hall, et al, 2002) and at lower resolution by microwave instruments. Measurement of snow water equivalent, however, remains elusive, due to the effects of terrain, vegetation, and the constantly varying nature of seasonal snow pack. It is reasonable to expect that these measurements will soon be available from a combination of visible, passive microwave and high resolution altimeter systems, all coupled with land data assimilation systems.

3.9. Land Data Assimilation Modeling

As noted above, data assimilation models, e.g. the land data assimilation model described by Mitchell et al (2004) are expected to form a critically important portion of all land fresh water cycle measurements. Through ingesting and interpreting the data from the various satellite sensors, these models form a key portion of the global fresh water cycle sensor web.

4. THE GLOBAL FRESH WATER SATELLITE NETWORK

Examination of the global fresh water cycle measurements discussed above indicates that these observations can be gathered with satellites that are now familiar to us, for they are all based on current Earth observational satellite systems. These present satellite systems have primarily been designed for specialized operational and research measurements of weather and climate on Earth. Due to these advances, the opportunity now exists to design a complete global water cycle observational system which would consist of about two dozen satellites: 5-6 GEO, 8 LEO and 10 Specialized satellites. Foreseeable upgrades to present capabilities will enable measurement of the full global water cycle with an accuracy that resolves annual and short term climate variability in the rate of the water cycle.

The concept is to sort the measurement systems on the basis of the required orbits, the required temporal update rates, and on the basis of required antenna sizes as determined by observational wavelength and beamwidth. These considerations dictate a particular set of measurement possibilities for any orbit which can then be matched to the sampling requirements.

Using this approach, observations requiring high temporal sampling rates, which can also use short observational wavelengths can be made from ~5-6 geostationary satellites (these are represented as "S" in Table 1) and include passive, short wavelength microwave and near-optical measurement of temperature and humidity profiles, color measurements of vegetation and other variables, and some short microwave wavelength measurement of other variables. Wind profiles can be calculated based on a combination of feature tracking in the temperature, humidity, or water vapor profiles, as was planned for GIFTS, (or suggested for a Molniya orbit by Riishojgaard, 2005 – "S" in Table 1), plus use of cloud winds (as in AVHRR) in a data assimilation framework. All these measurements could be produced on hourly or shorter time scales. A major issue in developing these geostationary observational systems will be implementation of large apertures (for small spot size) plus scanning beams that can cover the full Earth.

The low Earth orbit (LEO) satellite systems can be divided into a LEO constellation (L in Table 1), plus a few special purpose observational systems (S in Table 1), which would mostly be at LEO. The LEO constellation will can be an upgraded version of presently planned future polar orbiters, using active and passive microwave observations above about 6 GHz, plus near visible and possibly lidar observations to provide detailed global precipitation and vegetative state observations, plus measurements of Earth surface processes. A constellation of 8 satellites will provide ~ 3 hourly global observations. Major issues will be the design of simple wide-track scanning remote sensing systems that include narrow beams and the beam-sharpening approaches needed to meet the spatial sampling requirements.

The Specialized satellites (S) will be used for the lower update rate measurements of processes such as soil moisture, ocean salinity, glacial and polar ice, sea ice, etc. These observations can be made on a weekly basis, mostly from LEO, using single observational platforms that are dedicated to specific observational issues. On the order of ten Specialized satellites would be needed, for the purposes of cloud and precipitation (2), tropospheric winds (2-4), soil moisture and salinity (1-2), altimetry for runoff, ice and snow (2), and gravity (1). Due to their specialized instrumentation and unique orbits, these tasks would be most economically performed on dedicated satellites.

5. THE OBSERVATIONAL SENSOR WEB

The volume of global water cycle observational data can be expected to grow significantly over the next decade, as measurement system such as are described herein are developed. The networks of satellite instrumentation systems—in geostationary orbit, in low Earth orbit, and the special-purpose LEO satellites—will provide a diverse set of measurements. The variations in instrument characteristics, the placement, and calibration of remote sensing and in-situ observations will need to be quantified at the computational nodes where the full dataset is assembled and end-user data products can be generated.

The overall usefulness of the water cycle observational system will be limited by the ability to communicate, integrate and analyze this diverse set of water cycle information in a computational framework. Major development issues will include the data communications and pathways, the multi-dimensional data assimilation approaches, and the final reduction and delivery of data products in a manner suitable for use by diverse, non-technical users.

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Table 1. Components of the global water cycle and estimates of the spatial and temporal resolution required to provide adequate observations of water cycle processes. Possible orbits are noted as LEO (L), GEO (G) and specialized LEO/MEO/Molniya (S). Candidate active and passive observational frequencies are presented, along with examples of the observational heritage for the measurements, and possible additional measurement approaches. In-situ, ground-based validation measurements, located at carefully selected locations will be an important part of the system.

	Spatial Sampling	**Temporal Sampling**	**Precision**	**Orbit**	**Observational Frequency (GHz)**		**Heritage**	**Other Obs Technology**
	(km)				Passive	Active		
				Precipitation & Cloud				
Rainfall	5	3h	5-10mm/h 0.5 km (z)	L,S	6–89	14, 35	SSM/I, TRMM	
Falling snow	5	3h	5% 0.5 km (z)	L,S	6–150	14, 35	–	
Cloud water	5	3h	5% 0.5 km (z)	L,S	89–150	94	Cloudsat, TRMM	
				Profiles				
Temperature profiles	5	1-3h	1 C (T) 0.5 km (z)	G,S	50	–	SSM/T, EOS	
Humidity profiles	5	1-3h	1 C (Td) 0.5 km (z)	G,S	183	–	AIRS, SSM/I, SSM/T2, GPS	
Wind profiles	5	1-3h	1 m/s 0.5 km (z)	G,S	50–183	–	–	Feature Tracking or Lidar
				Land Surface & Storage				
Ground water	50	Month	–	S	–	–	GRACE	Gravity
Soil moisture	1	Day	10%	S	1.4, 6	1.2	EOS, HYDROS	
Freeze/thaw state	1	Day	–	L	6, 14	14, 35	EOS	
Vegetation state/condition	0.1	Monthly	20%	G	–	–	CZCS, SeaWiFS,MODIS	
Evapo-transpiration	1	3h	20%	L	–	–	MODIS	Data Assim
Lakes & streamflow	0.05	Day	10 cm	L	–	–	–	Lidar / inSAR
Snow cover & SWE	1	Day	–	L,G	19, 37		MODIS, EOS	Altimetry
Glacial & polar ice	0.05	Week	10 cm	S	–	–	IceSAT	Lidar / inSAR
				Ocean				
Sea ice	5	Monthly	5 cm	L,G	6, 19, 37	18 (SAR)	SSM/I, EOS	Lidar / inSAR
Ocean evap. rate	10	Day	5%	L				
SST	10	Week	0.1 C	L,G	11,18,37,85		SMMR, TMI, AMSR	AVHRR
Sea sfc winds	10	Week	1 m/s	L	6–37	5 - 14	SSM/I, EOS	QuickScat
Sea sfc salinity	10	Week	0.2 psu	S	1.4	1.2	AQUARIUS	
Ocean mixed layer depth	10	Week	10%	–	–	–	–	Data Assim