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Observing the Global Water Cycle from Space

Peter H. Hildebrand, Paul Houser, and C. Adam Schlosser
Laboratory for Hydrospheric Processes, NASA Goddard Space Flight Center
Greenbelt, MD 20771

1. THE GLOBAL WATER CYCLE

Although there is considerable water on Earth, only about 2.5% is in the form of fresh water. Of the fresh water, ~69% is unavailable as it is locked in permanent ice and snow, ~30% is stored in ground water, and only the small remaining amount is available in lakes, rivers, etc. (Table 1). 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.

Table 1. Distribution of water on Earth (Gleick, 1996)

	Volume	Total Water	Fresh Water
	(10^{15} m^3)	(%)	(%)
Oceans seas & bays	1338	96.5	--
Ice caps, glaciers & permanent snow	24	1.73	68.7
Ground water (fresh)	10	0.76	30.1
Ground water (saline)	12	0.93	--
Soil moisture	0.016	0.001	0.050
Ground Ice & Permafrost	0.300	0.022	0.860
Lakes (fresh)	0.091	0.007	0.260
Lakes (saline)	0.085	0.006	--
Atmosphere	0.013	0.001	0.040
Swamps	0.011	0.001	0.030
Rivers	0.002	0.000	0.006
Biological water	0.001	0.000	0.003
Total	1386	100	100

The annual global fresh water budget (Chahine, 1992; Gleick, 1996) is largely a balance between evaporation, precipitation and runoff. Although the available volumes of fresh water are small, the movement of fresh water through evaporation, atmospheric transport, precipitation and runoff is considerably larger (Table 2), due to the short residence time of water in these fresh water reservoirs. With a total atmospheric water store of ~$13*10^{12}$m^3, and an annual flux of ~$460*10^{12}$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 many years.

Table 2. Land-ocean gross water budget. The flux estimates are from Peixoto and Kettani, (1973) and Baungartner and Reichel, (1975)

	Land Water Budget	Ocean Water Budget
	(10^{12} m^3 / y)	(10^{12} m^3 / y)
Evaporation (ocean)		-361 to -424
Evaporation (land)	-62 to -71	
Precipitation (ocean)		324 to 385
Precipitation (land)	99 to 111	
Runoff	-37 to -40	37 to 40

The potential for redistribution and acceleration of the global hydrological cycle has been hypothesized (Hornberger, 2001 and others) to be associated with global warming and anthropogenic modification of the climate system. Additional pressure is 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.

2. OBSERVATIONAL REQUIREMENTS

This paper presents an approach to measuring all major components of the water cycle from space. The goal of the paper is to explore the concept of using a sensor-web of satellites to observe the global water cycle. The details of the required measurements and observation systems are therefore only an initial approach and will undergo future refinement, as their details will be highly important.

[1] *Corresponding author address:* Peter Hildebrand, NASA Goddard Space Flight Center, Greenbelt, MD 20771, 301-614-5671, peter.hildebrand@nasa.gov.

Key elements 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.

For each component of the water cycle that must be observed, the appropriate temporal and spatial scales of measurement are estimated in Table 3, along with the some of the frequencies that have been used for active and passive microwave observations of the quantities. The suggested types of microwave observations are based on the heritage for such measurements, and some aspects of the recent heritage of these measurement algorithms are listed. The observational requirements are based on present observational systems, as modified by expectations for future needs. Approaches to the development of space systems for measuring the global water cycle can be based on these observational requirements.

Table 3. 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 special Leo (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**		**Orbit**	**Observational Frequency**		**Heritage**	**Other Obs Technology**
	(km)	hours, days, weeks	days		Passive (GHz)	Active (GHz)		
Surface & Storage								
Ground water	50	month	30.00	S	--	--	GRACE	gravity
Soil moisture	10	3 days	3.00	S	1.4, 6	1.2	EOS, HYDROS	
Sea surface salinity	10	1 week	7.00	S	1.4	1.2	AQUARIUS	
Freeze/thaw state	1	1d	1.00	L	6 - 14	14, 35	EOS	
Vegetation				G	--	--	CZCS, SeaWiFS,MODIS	
Evapo-transpiration	5	3h	0.13	--	--	--	--	Data Assim
Lakes & streams	0.1	1d	1.00	L	--	--	--	lidar
Stream flow				L	--	--	--	lidar
Snow: SWE	1	1d	0.13	L,G	10 - 90		EOS	
Glacial & polar ice	10	week	7.00	L	--	--	IceSAT	lidar / SAR
Sea ice	1	week	7.00	L,G	6, 18, 85	18 (SAR)	SSM/I, EOS	lidar
SST	10	1 week	7.00	L,G	15 - 19 - 85		EOS	AVHRR
Sea surface winds	10	1 week	7.00	L	6 - 37	5 - 14	SSM/I, EOS	QuickScat
Ocean Mixed layer	10	1 week	7.00	--	--	--	--	Data Assim
Profiles								
Temperature profiles	20	3h	0.13	G	50	--	SSM/T, EOS	
Humidity profiles	20	3h	0.13	G	183	--	SSM/T2, EOS	
Wind profiles	20	3h	0.13	G	50 - 183	--	EOS	lidar
Precipitable water	10	3h	0.13	G,L	6 - 37		EOS	
Water vapor	10	3h	0.13	G,L	6 – 22 - 37		SSM/I, EOS	
Precipitation & cloud								
Rainfall	5	3h	0.13	L,S	6 - 89	14, 35	SSM/I, TRMM	
High latitude & light rainfall	5	3h	0.13	L,S	6 - 89	14, 35	SSM/I	
Falling snow	5	3h	0.13	L,S	6 - 89 - 150	14, 35	--	
Cloud water	5	3h	0.13	L,S	89 - 150	94	Cloudsat, TRMM	

3. MEASUREMENT OF THE WATER CYCLE FROM SPACE

The major aspects of a global system for observing the water cycle from space are a) identifying the appropriate remote sensing 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 3 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 3, 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.

Examination of the required measurements and their characteristics indicates the global water cycle observations can be gathered with a network of satellites similar to the Earth observational satellite systems that presently provide operational and research measurements of weather and climate on Earth. The selection of orbits can be based on the required temporal update rates, plus antenna size/beamwidth considerations. These considerations dictate a particular set of measurement possibilities for any orbit which can then be matched to the sampling requirements.

Observations requiring high temporal sampling rates, which can also use short observational wavelengths can be made from five geostationary satellites (S in Table 3). These can be upgraded versions of present geostationary systems (i.e. GOES, METEOSAT, etc.), that 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 and humidity profiles (as was planned for GIFTS), plus use of cloud winds (as in AVHRR) in a data assimilation framework. All these measurements can 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 (~18° to cover the full Earth).

The low Earth orbit (LEO) satellite systems can be divided into a LEO constellation (L in Table 3), plus a few special purpose observational systems (S in Table 3), also at LEO. The LEO constellation will can be an upgraded version of the 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 LEO special purpose 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—salinity, soil moisture, glacial and polar ice, sea ice, sea surface temperature and winds—can be made on a weekly basis using single observational platforms that are dedicated to specific observational issues.

Additional LEO special purpose satellites will provide confirmatory calibration measurements of processes such as global precipitation, that can benefit from more complex active measurement systems. One or more, multi-wavelength (14-94 GHz) radar systems based on TRMM and CloudSat heritage, that also provide a spectrum of passive microwave measurements, will provide calibrated measurements of clouds and precipitation. Another LEO special purpose satellite will provide lidar measurements of clouds and ice topography in a manner similar to IceSAT. These satellites will provide observations at a weekly update rate.

4. 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 some 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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