Chapter 92

Large-Scale and Global Hydrology

BY

MATTHEW RODELL, HIROKO KATO BEAUDOING, RANDAL KOSTER, CHRISTA D. PETERS-LIDARD, JAMES S. FAMIGLIETTI, AND VENKAT LAKSHMI

ABSTRACT

Powered by the sun, water moves continuously between and through Earth's oceanic, atmospheric, and terrestrial reservoirs. It enables life, shapes Earth's surface, and responds to and influences climate change. Scientists measure various features of the water cycle using a combination of ground, airborne, and space-based observations, and seek to characterize it at multiple scales with the aid of numerical models. Over time our understanding of the water cycle and ability to quantify it have improved, owing to advances in observational capabilities, the extension of the data record, and increases in computing power and storage. Here we present some of the most recent estimates of global and continental/ocean basin scale water cycle stocks and fluxes and provide examples of modern numerical modeling systems and reanalyses. Further, we discuss prospects for predicting water cycle variability at seasonal and longer scales, which is complicated by a changing climate and direct human impacts related to water management and agriculture. Changes to the water cycle will be among the most obvious and important facets of climate change, thus it is crucial that we continue to invest in our ability to monitor it.

92.1 INTRODUCTION

The perpetual journey of water between and through Earth's oceanic, atmospheric, and terrestrial reservoirs is known as the water cycle. At the global scale, the water cycle is essentially a closed system, save for inputs from the occasional comet and the slow exchange of water between the crust and the mantle (Pearson et al., 2014). The water cycle dictates the distribution of life on land and controls ocean circulations and nutrient availability. Shifts in the water cycle will be the most palpable impacts of climate change.

Despite the fact that the number of stream and river flow observations peaked in 1978 and has continued to decline ever since (GRDC, 2013), the 2000s may someday be characterized as the golden age of global hydrology, owing to the prevalence of satellite-based hydrology data. These include precipitation data from the Tropical Rainfall Measuring Mission (TRMM) and the Global Precipitation Measurement (GPM) Mission, variations in terrestrial water storage (the sum of groundwater, soil moisture, snow and ice, and surface waters) derived from Gravity Recovery and Climate Experiment (GRACE) gravity data, snow observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Microwave Scanning Radiometer (AMSR), and soil moisture data from the Soil Moisture Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) satellites. All of these observations are now being (or will soon be) integrated into data assimilating numerical models, which constrain the observations and fill data gaps using our understanding of the relevant physical processes.

92.2 THE DISTRIBUTION OF WATER ON EARTH

Figure 92.1 illustrates and quantifies the major stocks and fluxes of the global water cycle. Of all the water in and above Earth's crust, about 1,379,400,000 km^3, the vast majority, about 96.8%, is in the oceans. Another 2.1% is frozen in the Antarctic and Greenland ice sheets and in glaciers and permanent snow cover. About 1.1% exists as groundwater, not all of it fresh. At any given time only about $1/40^{th}$ of 1% is active in the water cycle as surface water, soil moisture, biological water, or atmospheric water vapor and clouds. Cataloguing the stocks of freshwater is complicated by a lack of detailed, global measurements of key properties like aquifer and soil porosity, aquifer dimensions, and lake bathymetry. Thus, continental to global scale groundwater and surface water storage were originally estimated decades ago using simplifying assumptions about these properties (e.g., Nace, 1964; Korzoun, 1974). To date, such first order assessments remain the foundation for current estimates of storage in the various stocks (e.g., Shiklomonov, 1993; Oki and Kanae, 2006), including those shown in Fig. 92.1, which were published by Trenberth et al. (2007). Absent a tremendous, coordinated, international data collection campaign, such estimates are unlikely to improve significantly. Further complicating matters, the distinctions between soil moisture, groundwater, and wetland (surface) water storage are not always plain.

92.3 THE GLOBAL WATER CYCLE

A complete, well verified, numerical depiction of the fluxes of the global water cycle has been a Holy Grail of hydrology for more than a century. Among the early accomplishments were Loomis's (1882) near-global map of rainfall and Bruckner's (1905) "The Balance of the Circulation of Water on Earth." Both used simple methods and inferences to extrapolate global maps and estimates from a handful of observational datasets. In the 1960s, computers and the first general circulation models facilitated the fusion of available observations with mathematical depictions of physical processes. Recognizing the connection between the terrestrial water cycle and atmospheric prediction, Manabe (1969) incorporated a "bucket model" of land hydrology into the Geophysical Fluid Dynamics Laboratory's general circulation model. That was the first step toward today's land surface models and coupled atmospheric, oceanic, and hydrological Earth system models, which provide estimates of water cycle fluxes through the integration of multiple data streams. Baumgartner and Reichel (1975) presented a comprehensive treatise on the global water balance, and their estimates are still used as benchmarks. A decade later, Eagleson (1986) hailed the "Emergence of Global-Scale Hydrology" and evaluated the state of global hydrological modeling at that time, and Berner and Berner (1987) provided a comprehensive physical and chemical description of the water cycle. Chahine (1992) helped to establish the global

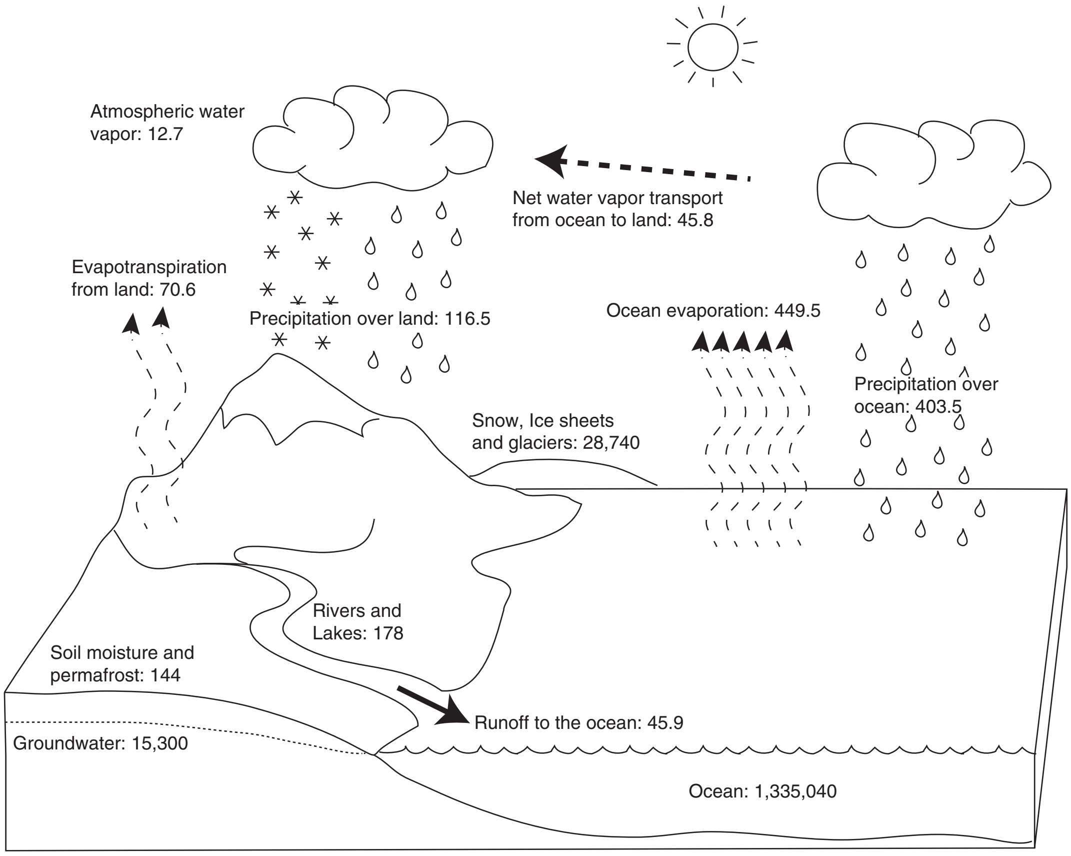

Figure 92.1 Stocks (thousands of cubic kilometers) and fluxes averaged over 2000–2010 (thousands of cubic kilometers per year) of the global water cycle. [*Source: Fluxes from Rodell et al. (2015), Stocks compiled by Trenberth et al. (2007).*]

hydrology community in his review paper on the hydrological cycle and its influence on climate. More recently, Shiklomanov (1998), Oki (1999), Mehta et al. (2005), Oki and Kanae (2006), Trenberth et al. (2007, 2011), and many others have presented analyses of world water balance, with significant overlap of primary data sources. Schlosser and Houser (2007) provided perspective on how estimates of mean annual exchanges of water between the ocean and land (via atmospheric transport or river discharge) have changed over time. In short, the estimates did not converge appreciably over the course of five decades beginning in 1960.

Table 92.1 presents the mean annual rates of precipitation, combined evaporation and transpiration, runoff into the ocean, and atmospheric convergence over the continents and major ocean basins during the first decade of the twenty-first century. The data are presented in units of cm/year, representing the equivalent height of water averaged over the region associated with each flux. Also shown for each continent and the global ocean is the amplitude (maximum minus minimum) of the annual cycle of terrestrial water storage. Data for this analysis were compiled by a large, diverse team of experts supported by NASA's Energy and Water Cycle Study (NEWS) program, and the analysis differed from previous efforts in several respects (Rodell et al., 2015). First, it focused on conditions during roughly the first decade of the twenty-first century, making use of the most modern observational and data-integrating model products. Second, careful assessments of uncertainty in the data products were employed within an optimization algorithm that enforced water balance at multiple scales to compute the final water flux estimates. Third, the energy budget was simultaneously balanced, and consistency between the water and energy budget estimates of evapotranspiration and latent heat flux was ensured. The resulting global water fluxes were shown to agree (within the defined uncertainty bounds) in most cases with other recent estimates from Oki and Kanae (2006) and Trenberth et al. (2011).

Figure 92.2 maps mean annual precipitation, evapotranspiration, and runoff from the land surface. Together with the change in water storage (the mean amplitude of the annual cycle of terrestrial water storage is also mapped in Fig. 92.2) these fluxes are the components of the simple surface water budget equation:

$$\Delta S = P - E - Q, \tag{92.1}$$

where, ΔS is the change in water stored on and beneath the surface, P is precipitation, E is evaporation or the sum of evaporation and transpiration, and Q is total runoff. The maps shown in Fig. 92.2 are derived from some of the best available global datasets: precipitation from the Global Precipitation Climatology Project (GPCP; Huffman et al., 1997; Adler et al., 2003), ocean evaporation from MERRA and land evapotranspiration from MERRA-Land (see the following section), runoff from Fekete et al. (2002), and terrestrial water storage changes from GRACE (Tapley et al., 2004; Landerer and Swenson, 2012). The atmospheric water budget is linked to the terrestrial water budget through $(P - E)$ and is defined as:

$$\Delta W = C - (P - E) \tag{92.2}$$

where, ΔW represents total water (vapor and liquid) in an atmospheric column and C is atmospheric convergence, i.e., the net transport of water into that column. Combining (92.1) and (92.2), it can be seen that

$$\Delta S + Q = C - \Delta W \tag{92.3}$$

which is the water budget equation for the combined atmospheric-terrestrial column.

92.4 NUMERICAL MODELING AND DATA ASSIMILATION

Numerical models of the oceanic, atmospheric, and terrestrial components of Earth's climate system enable the water cycle to be simulated and quantified, based on our knowledge of the relevant processes as represented by systems of physical equations. The simple computer models of atmospheric general circulation first developed in the 1950s have evolved into comprehensive, high resolution Earth system models that form the basis of our operational weather forecasts and climate predictions (e.g., Edwards, 2010). They have

Table 92.1 Mean Annual Fluxes (cm/year) of the Water Cycle Over the Continents and Major Ocean Basins, and the Amplitude of the Annual Cycle of Water Storage (cm), During Roughly 2000–2010

	Precipitation	Evoporation & Transpiration	Runoff in the ocean	Atmospheric convergence	Water storage annual amplitude
North America	73.9	41.3	32.7	32.6	10.7
South America	166.7	97.5	69.3	69.3	17.0
Eurasia	72.3	42.3	30.0	29.9	3.8
Africa	69.0	56.2	12.8	12.8	2.9
Australia and islands	84.5	44.0	40.5	40.6	5.6
Mainland Australia	51.8	33.9	17.8	17.9	5.6
Australasian and Indonesian Islands	251.3	95.1	156.3	156.2	5.4
Antarctica	19.1	1.0	18.0	18.1	2.5
World land	79.4	48.2	31.3	31.3	5.1
Arctic	34.0	12.6		21.3	
North Pacific	145.8	133.1		12.8	
South Pacific	109.6	125.0		−15.4	
North Atlantic	106.0	124.2		−18.2	
South Atlantic	73.1	104.8		−31.7	
Indian	112.5	133.5		−20.9	
Carribean sea	106.9	157.4		−50.5	
Mediterranean sea	57.3	142.5		−85.1	
Black sea	69.5	109.9		−40.4	
World ocean	110.7	123.3	12.6	−12.6	2.1
World surface	101.7	101.7			0.0

[Source: Data from Rodell et al. (2015)]

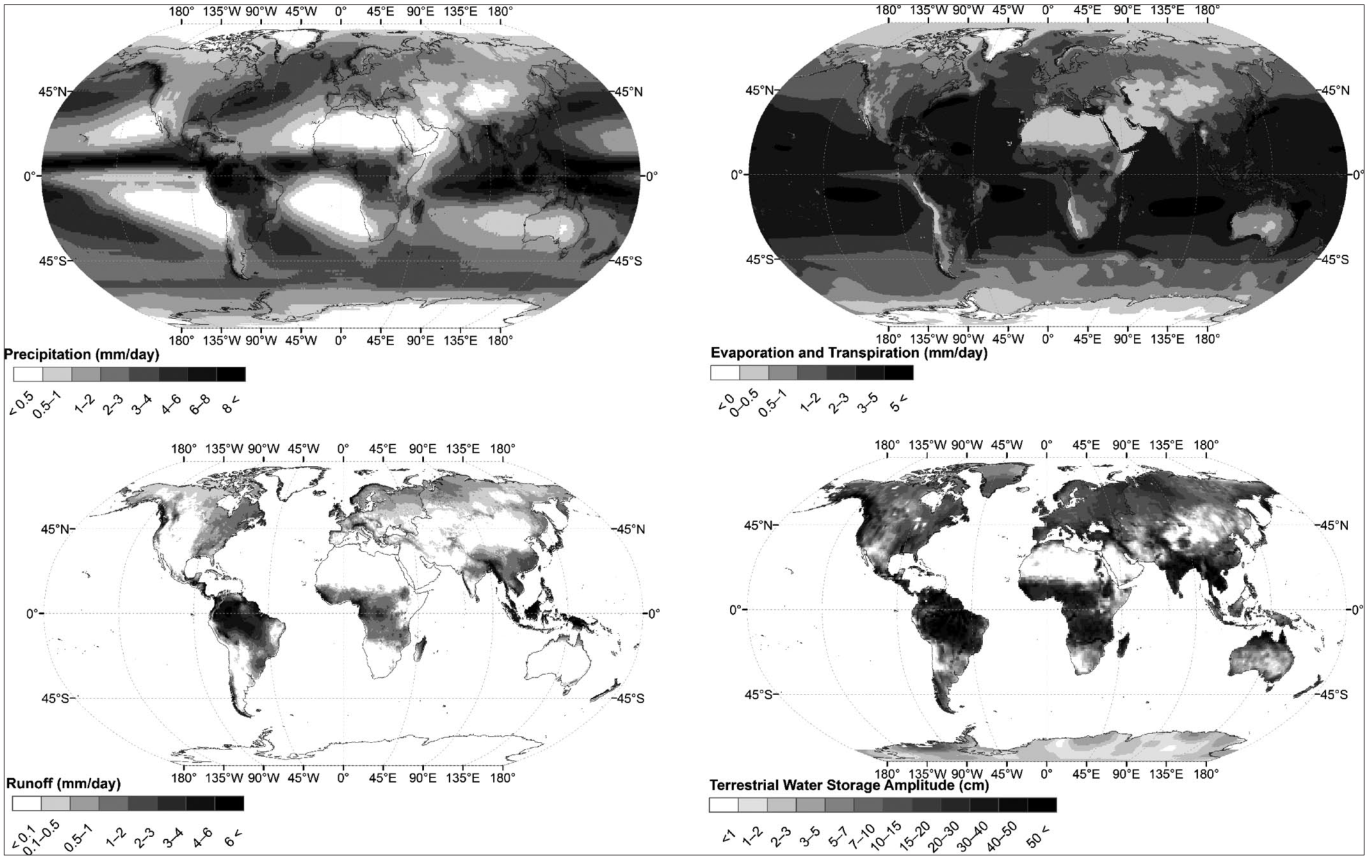

Figure 92.2 Annual mean rates of precipitation, ocean evaporation and land evapotranspiration, and surface runoff that reaches the ocean, and the amplitude of the annual cycle of terrestrial water storage. Precipitation from GPCP (Huffman et al., 1997; Adler et al., 2003), ocean evaporation from MERRA (Rienecker et al., 2011) and land evapotranspiration from MERRA-Land (Reichle et al., 2011; Reichle, 2012), runoff from Fekete et al. (2002), and terrestrial water storage from GRACE (Landerer and Swenson, 2012).

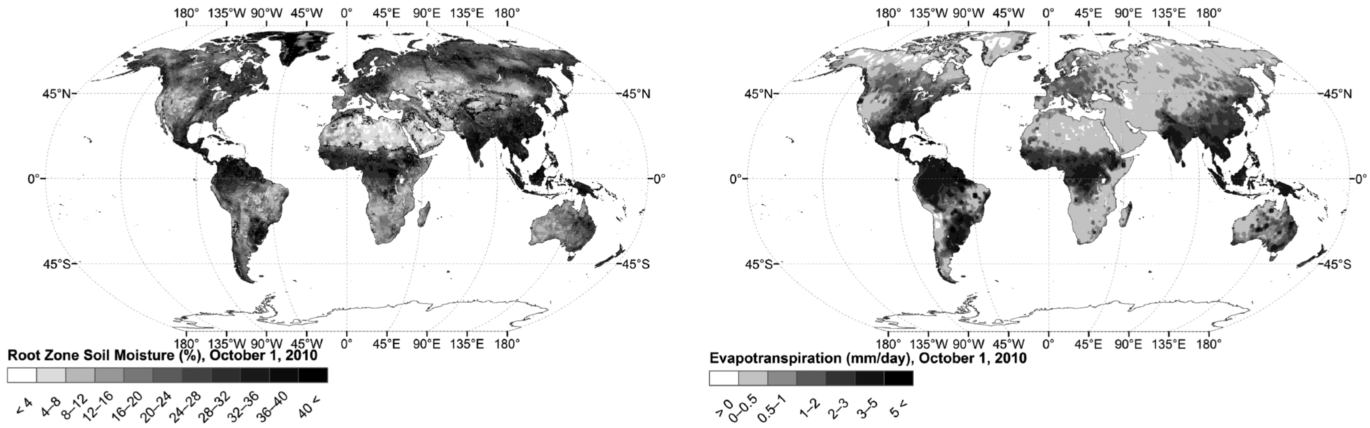

Figure 92.3 Root zone soil moisture and evapotranspiration on October 1, 2010, output from GLDAS (Rodell et al., 2004) running the Noah land surface model (Ek et al., 2003) with inputs from the Princeton meteorological forcing dataset (Sheffield et al., 2006).

benefitted from advances in computing power and storage, the implementation of extensive in situ measurement networks and satellite based observations, and consequent improvements in our understanding of geophysical processes. Models that focus on particular aspects of the Earth System, such as land surface models, are continually being developed offline (decoupled from the comprehensive Earth system model), improved by the addition of more complex physics and through validation and calibration exercises, and later reintroduced or appended to the fully coupled systems.

While a direct observation of any water cycle state (e.g., soil moisture) or flux (e.g., evapotranspiration) is preferable to a model estimate, numerical models provide superior spatial and temporal continuity and also enable the quantification of states and fluxes at a tiny fraction of the cost of installing and maintaining networks to measure the same processes with conventional or remote sensing techniques. However, model simulations contain random and systematic errors, which stem from the parameterizations and simplifying assumptions employed to represent complex physical processes that occur on all scales from global to molecular. Data assimilation systems that synthesize multiple streams of observational data, using numerical models as the integrator, are an appealing option for generating regional or global fields of water and energy cycle states and fluxes, which are both continuous in space and time and anchored in reality.

Chief sources of large scale hydrological data are regional and global reanalyses, which begin with the assimilation of huge quantities of satellite and ground-based meteorological observations into the operational weather prediction models of various government agencies and research laboratories. Scientists then attempt to identify and remove biases, discontinuities, and spurious trends that result from model deficiencies and changes in the input data streams. Among the first of these were the NCEP/NCAR 40-Year Reanalysis (Kalnay et al., 1996) and the ECMWF 15-Year Reanalysis (ERA-15; Gibson et al., 1999). The water budgets depicted by these early reanalyses were flawed in ways that limited their application for quantitative hydrological analysis. For example, Roads and Betts (2000) reported that precipitation and runoff in the NCEP/NCAR Reanalysis were too large while runoff was too small in ERA-15, and Rodell and Famiglietti (1999) found that terrestrial water storage variations were too small in ERA-15 and too tightly constrained to a prescribed climatology in the NCEP/NCAR Reanalysis. Further, data assimilation causes imbalances in the water and energy budgets (e.g., Roads et al., 2002) that must be resolved via bias correction or distribution of the analysis increments into the physical terms of the budget equations (Bosilovich and Schubert, 2001) before the reanalysis data are suitable for comparison with measured quantities or detailed water balance analysis. Nevertheless these two reanalyses underpinned a renaissance of global water cycle studies in the late 1990s and early 2000s.

Subsequent generations of reanalyses have improved the realism of water cycle processes and quantities, and they continue to evolve. At the time of writing, two of the most modern reanalyses were ERA Interim (Dee et al., 2011) and NASA's Modern Era Retrospective-analysis for Research and Applications (MERRA; Rienecker et al., 2011). Figure 92.2 includes maps of ocean evaporation from MERRA and land evapotranspiration from MERRA-Land (Reichle et al., 2011; Reichle, 2012). The latter provides enhanced land surface hydrology estimates based on a land-only GEOS-5 simulation with bias-corrected precipitation as a meteorological input. MERRA was an important source of gap-filling data for the NEWS water budget analysis described above (Rodell et al., 2015).

Land data assimilation systems (LDAS) that are not coupled to atmospheric models can ingest observation based meteorological inputs to drive them forward in time, thus avoiding biases that often exist in atmospheric simulations. These have been developed for several regions and at the global scale to integrate ground and space based observations within sophisticated land surface models, for the purpose of producing high-resolution gridded fields of the stocks and fluxes of the terrestrial water and energy cycles (examples are shown in Figure 92.3). The first LDAS was the North American LDAS (NLDAS; Mitchell et al., 2004), which originated in 1998 through the collaboration of land surface modeling groups from NOAA, NASA, Princeton University, and the University of Washington. Its objectives included intercomparison of four separately developed land surface models that were parameterized and forced (see Table 92.2) by a common set of 0.125° resolution, near-real time, observation-based meteorological inputs of unprecedented quality over central North America. The first phase of NLDAS demonstrated that there were substantial differences among the four models in simulated evaporation, runoff, soil moisture, snowpack, and land surface temperature, despite the uniformity of the inputs (Mitchell et al., 2004). Results of this and similar intercomparison studies (e.g., Dirmeyer et al., 1999; 2006; Jiminez et al., 2011; Mueller et al., 2011) have stimulated continued refinement and increasing complexity of land surface models, while substantiating the need for multivariate data assimilation as an approach for overcoming model deficiencies.

The success of NLDAS soon led to the development of a Global LDAS (GLDAS; Rodell et al., 2004), which drove multiple land surface models at 0.25° and 1.0° resolutions using a combination of observation-based and global atmospheric analysis-based forcing fields. The GLDAS dataset now extends back to 1948, relying on the Princeton University Meteorological Forcing Dataset (Sheffield et al., 2006) for input during the period prior to 2000. At the time of writing it continued to serve 400–1200 distinct users per month, including water cycle scientists and students, educators, water resources managers, agricultural productivity forecasters, and insurers, and among others. Other LDASs have been developed and optimized for various regional efforts over the years, including South American LDAS (de Goncalves, 2006), European LDAS (van den Hurk, 2002), the LDAS of the University of Tokyo (Yang et al., 2007), and MERRA-Land (Reichle et al., 2011; Reichle, 2012).

In 2002, the software that drove GLDAS became the basis for a high performance computing initiative known as the Land Information System (LIS; Kumar et al., 2006; Peters-Lidard et al., 2007). LIS is a flexible land surface modeling and data assimilation framework developed with the goal of integrating satellite and ground based observational data products using advanced modeling techniques to produce spatially and temporally coherent estimates of land surface conditions. LIS has a comprehensive data assimilation subsystem (Kumar et al., 2008) for use with satellite derived soil moisture, snow cover, and terrestrial water storage. NLDAS and GLDAS have both adopted LIS as their software infrastructure, and it has been widely distributed for use in hydrological studies that range in scale from local to global.

92.5 GLOBAL WATER CYCLE VARIABILITY, PREDICTABILITY, AND CHANGE

In some ways the variability of a region's water cycle—interannual swings, for example, in precipitation and thus in water availability—are as important to society as the long-term mean fluxes themselves. Droughts can

Table 92.2 Static and Time Varying Inputs, Observables that May Be Incorporated via Data Assimilation, and Outputs of a Typical Land Data Assimilation System

Static parameter fields	Meteorological forcing fields	LDAS outputs
Elevation	Precipitation	Soil moisture profile
Vegetation/Land use type	Downward shortwave radiation	Fractional snow coverage
Vegetation height	Downward longwave radiation	Snow depth and water equivalent
Leaf area index	Near-surface air temperature	Plant canopy water storage
Surface roughness	Near-surface specific humidity	Soil temperature profile
Root depth & density	Near-surface wind speed	Surface temperature
Soil texture	Near-surface wind direction	Surface and Subsurface runoff
Minimum stomatal conductance	Surface pressure	Evaporation from soil, snow, and vegetation
Surface albedo		Canopy transpiration
Thermal inertia	State observations	Latent, sensible, and ground heat fluxes
Emissivity	Vegetation fractional coverage	Snow phase change heat flux
	Leaf area index	Snowmelt
	Fractional snow coverage	Snowfall and rainfall
	Snow cover and water equivalent	Net surface shortwave radiation
	Surface soil moisture	Net surface longwave radiation
	Terrestrial water storage	Aerodynamic conductance
	Surface albedo	Canopy conductance
	Surface temperature	Surface albedo

cripple agricultural production, and pluvial periods often induce flooding. Even small variations in yearly precipitation can have important implications for water management. A true understanding of the global water cycle requires knowledge of the roots of its variability, with an eye toward predicting extremes in a timely manner.

The numerical Earth system models discussed earlier can serve as useful, if imperfect, laboratories for examining this variability. Through analysis of parallel climate simulations with such a model, one simulation serving as a control and another (otherwise equivalent) simulation featuring an imposed change in the treatment of some specific physical mechanism, the impact of that mechanism on the water cycle and its variability can be quantified (e.g., Delworth and Manabe 1989; Douville et al., 2002). Koster et al. (2000), for example, illustrated with global simulations that tropical rainfall variability is controlled mostly by sea surface temperature (SST) variations, whereas mid-latitude rainfall variability is affected much more by unpredictable chaotic noise, though with some potential for prediction creeping in, in certain regions, from knowledge of soil moisture state. Such studies are limited by the biases inherent in the models, but as long as these biases are kept in mind, such modeling studies can prove enlightening.

Forecasts of water cycle variations are, of course, of particular interest. For years, water and agricultural managers in tropical areas have been using SST variations, particularly the state of the El Nino cycle, to help with seasonal planning (Babkina, 2003). Koster et al. (2011) demonstrated that accurate soil moisture initialization has a slight but statistically significant impact on the skill of subseasonal (out to 2 months) precipitation forecasts in some areas, and Waliser et al. (2006) pointed out that subseasonal precipitation forecasts may also benefit from the accurate prediction of the Madden–Julian oscillation (MJO). Accurate soil moisture and snow information can provide significant skill to the prediction of streamflow on seasonal time scales (Pagano et al., 2009; Mahanama et al., 2012).

Climate change adds substantial complexity to the study of hydroclimate variability and predictability. Changes to the water cycle will indeed be among the most obvious and important facets of climate change. As the Earth warms, the water cycle will respond, in some cases damping the warming (e.g., if cloud cover increases), and in other cases enhancing it (e.g., reduced snow cover and ice sheet extent increase the absorption of solar radiation). The consensus prediction of current climate models is that, at the global scale, wet regions generally will become wetter and arid regions generally will become drier, with an acceleration of the water fluxes and more frequent and extreme floods and droughts (Bosilovich et al., 2005; Held and Soden, 2006; Famiglietti and Rodell, 2013). Such changes are already complicating the jobs of water managers, who for decades depended upon assumptions of stationarity (Milly et al., 2008).

In addition, direct human impacts on the global water cycle are measureable. The installation of dams, which allows society to smooth out the seasonal cycle of renewable water and sustain itself through dry periods, is one of the first and most obvious examples. Chao et al. (2008) estimated total global impoundment of water in artificial reservoirs to be 10,800 km^3, enough to cause 30 mm of sea level rise if it were all to be released. Increased greenness of the land surface due to crop irrigation can be seen from an altitude of 30,000 feet during air travel and from space. Globally, irrigation requires 2.7 thousand km^3 of water per year, accounting for about 69% of total water usage (FAO, 2014). A large proportion of that water becomes evapotranspiration. Ozdogan et al. (2010) estimated that irrigation increases evapotranspiration by about 4% averaged over the contiguous U.S. Hence irrigation can have a significant impact on the water cycle and atmospheric processes, including increasing precipitation and streamflow downwind (DeAngelis et al., 2010; Kustu et al., 2011; Lo and Famiglietti, 2013).

Aquifers are the main sources of water for irrigation in regions where surface water is not sufficiently abundant. In certain regions the rates of withdrawal exceed the rates of recharge, causing groundwater levels to decline. Where groundwater depletion is significantly severe and widespread, it causes changes in the gravity field that can be monitored from space. GRACE satellite observations have been used to quantify groundwater depletion in the Central Valley (Famiglietti et al., 2011) and High Plains (Strassberg et al., 2007) aquifers in the U.S., in Northern India (Rodell et al., 2009; Tiwari et al., 2009), in the Middle East (Voss et al., 2012), and in the North China Plain (Feng et al., 2013). Konnikow (2011) estimated that removal of 4500 km^3 of water from aquifer storage had contributed 12.6 mm to sea level rise since 1900, and that the rate of depletion had increased to 145 km^3/yr during 2000–2008.

Climate change and direct human impacts are changing the water cycle at all scales, and the pressures of population increase and economic development are straining water resources in much of the world. Thus it is critical that we continue to monitor and understand changes in the stocks and fluxes of the water cycle. Considering that costs, labor, and political boundaries restrict our ability to monitor water resources and the water cycle adequately at regional to global scales, it will be imperative that investments in remote sensing capabilities and numerical modeling continue to grow in order to provide the data necessary to plan for and respond to water cycle variability and change.

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