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 km³, 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 1/40th 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., Shiklomanov, 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 Beven’s (1969) incorporation of 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 Rechel (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
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, \(\Delta S\) 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 (92.1) and is defined as:
\[
\Delta W = C - (P - E) \tag{92.2}
\]
where, \(\Delta W\) 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

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 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:
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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

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

[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 (Landerser and Swenson, 2012).
benefited from advances in computing power and storage, the implementa-
tion of extensive in situ measurement networks and satellite based observa-
tions, 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 inte-
grator, 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 hydrologi-
cal analysis. For example, Roads and Betts (2000) reported that precipitation
and runoff in the NCEP/NCAR Reanalysis were too small 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 underpin 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 simula-
tions. These have been developed for several regions and at the global scale to
integrate ground and space based observations within sophisticated land sur-
face 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 collabo-
ration of land surface modeling groups from NOAA, NASA, Princeton
University, and the University of Washington. Its objectives included inter-
comparison of four separately developed land surface models that were
parameterized and forced (see Table 92.2) by a common set of 0.125° resolu-
tion, near-real time, observation-based meteorological inputs of unprecedent-
ed 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;
Jimenez 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 resour-
ces 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 per-
formance 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 inte-
grating 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 subsys-
tem (Kumar et al., 2008) for use with satellite derived soil moisture, snow
cover, and terrestrial water storage. NL-DAS 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 impor-
tant to society as the long-term mean fluxes themselves. Droughts can
Table 9.2 Static and Time Varying Inputs, Observables that May Be Incorporated via Data Assimilation, and Outputs of a Typical Land Data Assimilation System

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

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 measurable. 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 km³, 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 km³ 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 downward (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). Kornikow (2011) estimated that removal of 4500 km³ 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 km³/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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