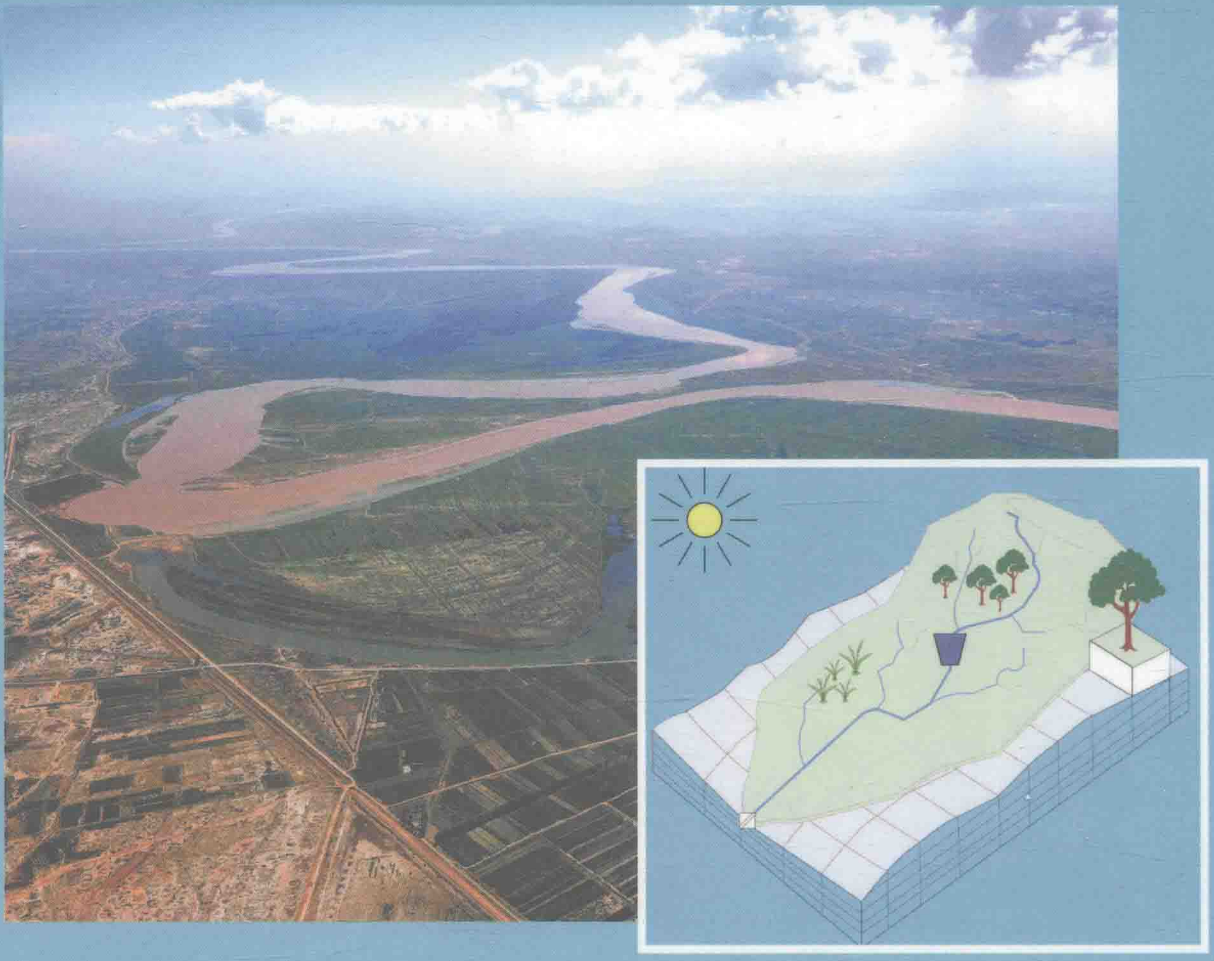
Terrestrial Water Cycle and Climate Change

Natural and Human-Induced Impacts



Qiuhong Tang and Taikan Oki

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Cover images: The main image shows the irrigation area of Jungar Banner along the Yellow River, as photographed by Genwan Li. The inset image gives the schematic figure of the Distributed Biosphere-Hydrological (DBH) model. More details on the DBH model are given in Chapter 10.

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PREFACE

Water is a vital resource for human well-being and ecosystem functioning. The water cycle describes the storage and movement of water on, above, and below the surface of the Earth. Through countless interactions within the Earth system, the water cycle plays a crucial role in the physical, biological, and chemical processes of the planet. The terrestrial water cycle is of paramount importance because it continuously renews water supply for societal and ecological well-being.

Over the past few decades, the terrestrial water cycle has experienced an unprecedented degree of change. Many of the rivers at the middle latitudes have dried up, whereas river discharge across the Eurasian pan-Arctic has significantly increased and changed in the seasonality. In the managed river basins, regulated stream flow has become the new normal: a shift with profound implications for our water supply. The complex change is driven by factors such as the internal variability in the climate system, anthropogenic climate change, and widespread human disturbances.

A better understanding of the change in the terrestrial water cycle is crucial for humans to adapt to the changing environment, and is essential for improved water management to meet society's needs. In the era of the Anthropocene, when human activities are changing the atmospheric and hydrological processes, there is an urgent need for scientists to study not only the natural terrestrial water cycle, but also how humans are increasingly changing it. Investigating the human-altered terrestrial water cycle and assessing the implications of the change in the cycle for society are a major focus of research in hydrology, water resources, climate change, sustainability, and development.

Several advances have made the study that focuses on the change in the terrestrial water cycle possible. The technological advances in Earth observation produce fairly long-term water-related data needed for characterizing the change in the terrestrial water cycle with unprecedented spatial coverage. The advances in land surface hydrological modeling started to build dynamic connections between hydrology and other components of the Earth system. The models with explicit representation of anthropogenic manipulations can simulate the terrestrial water cycle more realistically. The emerging hydrological data and tools have been used to quantify the water cycle change, identify the impact factors of the change, predict future change, and assess the implications of the change in water management and hazard mitigation. These advances not only deepen our understanding of the terrestrial water cycle, but also contribute to the development of sustainable adaptation strategies for water management.

The objectives of the book are to extend and deepen our understanding of the change in the terrestrial water cycle, and to shed light on the mechanisms of the change and the consequences of the change in water resources and human well-being in the context of global change. This book provides a comprehensive overview and presents the state-of-the-art technology and sciences developed and acquired in the study of the terrestrial water cycle change and the natural and human-induced impacts. The book brings together recent progress and achievements in large-scale hydrological observations and numerical simulations, specifically in areas such as in situ measurement network, satellite remote sensing, and hydrological modeling.

The book contains four parts. Part I presents an overview of the changes in the terrestrial water cycle. It illustrates the global picture of the past and current changes and potential future change under the global warming. Part II covers the human alterations of the terrestrial water cycle. The human influence is highlighted by focusing on various kinds of human activities such as water impoundment, withdrawals, groundwater pumping, and land use/cover change. Part III demonstrates the recent advances in hydrological measurement and observation. Examples from regional and global studies are chosen to show how to apply the advanced satellite remote sensing and ground observation network to quantify hydrological changes. Part IV addresses new achievements in the integrated modeling of the terrestrial water cycle. These modeling efforts integrate knowledge from various aspects in the Earth system to expand and deepen our understanding in the nexus of water, climate, and society.

I hope this book will give the reader clear pictures of the large-scale changes in the terrestrial water cycle, and of the data and tools that are being used to study the natural and human-induced impacts on the cycle. I further hope that the attribution of the change will be an open source of inspirations for study on human, water, and climate interactions.

Qiuhong Tang

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CONTENTS

Part I

Overview of the Changes in the Terrestrial Water Cycle

1

Macroscale Hydrological Modeling and Global Water Balance

Taikan Oki and Hyungjun Kim

ABSTRACT

An overview of the global hydrological cycle, and recent achievements in macroscale modeling are given. Major components of fluxes and storages in the global hydrological cycle are described and quantitatively illustrated based on an off-line simulation framework. Methodologies for estimating fluxes and storage changes are presented from the simple water balance concept to the state-of-the-art numerical models that are capable of incorporating anthropogenic impacts. Efforts made by international research communities on global-scale hydrologic modeling are introduced. Current situations of modeling, research opportunities, and gaps in global hydrology are also identified.

1.1. INTRODUCTION

"Blue Planet" is a frequently used term to describe the Earth, as approximately 70% of its surface is covered by water. Although the water mass constitutes only 0.02% of the total mass of the planet (5.974×10^{24} kg), it is a critical matter for all organisms including humans in their survival [*Oki et al.*, 2004]. Also, its availability has largely affected civilizations in both culture and economy in human history. Therefore, to ensure adequate fresh water supply is essential for human well-being.

The Earth's surface is dominated by various forms of water. The total volume of water on the Earth is estimated to be approximately $1.4 \times 10^{18}\,\mathrm{m}^3$, which corresponds to a mass of 1.4×10^{21} kg. The global hydrologic cycle always includes the oceanic circulation. The proportion of water in the ocean is large (96.5%). Oceanic circulations carry large amounts of energy and water. The surface ocean currents are driven by surface wind stresses, and the atmosphere itself is sensitive to the sea surface temperature. Temperature and salinity together determine the density of ocean water, and both factors contribute to the overturning and the ocean general circulation. Some terrestrial areas are covered by freshwater (lakes and rivers), solid water (ice and snow), and vegetations (which imply the existence of water). Even though the water content of the atmosphere is relatively small (approximately 0.3% by mass and 0.5% by volume), 0.68 (±0.03)% of the area above the Earth is always covered by clouds when considering clouds with optical depth > 0.1 [*Stubenrauch et al.*, 2013].

Water on the Earth is stored in various reservoirs, and water flows from one to another. Water flow per unit time is also called water flux. To understand the global water cycle, the quantification of fluxes and storages with the associated processes is necessary. Figure 1.1 schematically illustrates various water storages and fluxes in the global hydrologic system [revised from *Oki and Kanae*, 2006].

The objective of this chapter is to give a brief overview of research approaches for global water-balance estimation. To provide basic background of the water cycle, in Section 1.2, major components of terrestrial hydrologic processes are briefly explained with quantitative estimations using a global off-line simulation. From Section 1.3 to Section 1.5, the major methodologies for water-balance estimations are described. An early estimation that used reanalysis data set and a simple water-balance equation is introduced, and the development of the model-based macroscale land simulation framework and recent achievements to consider the human impact are covered.

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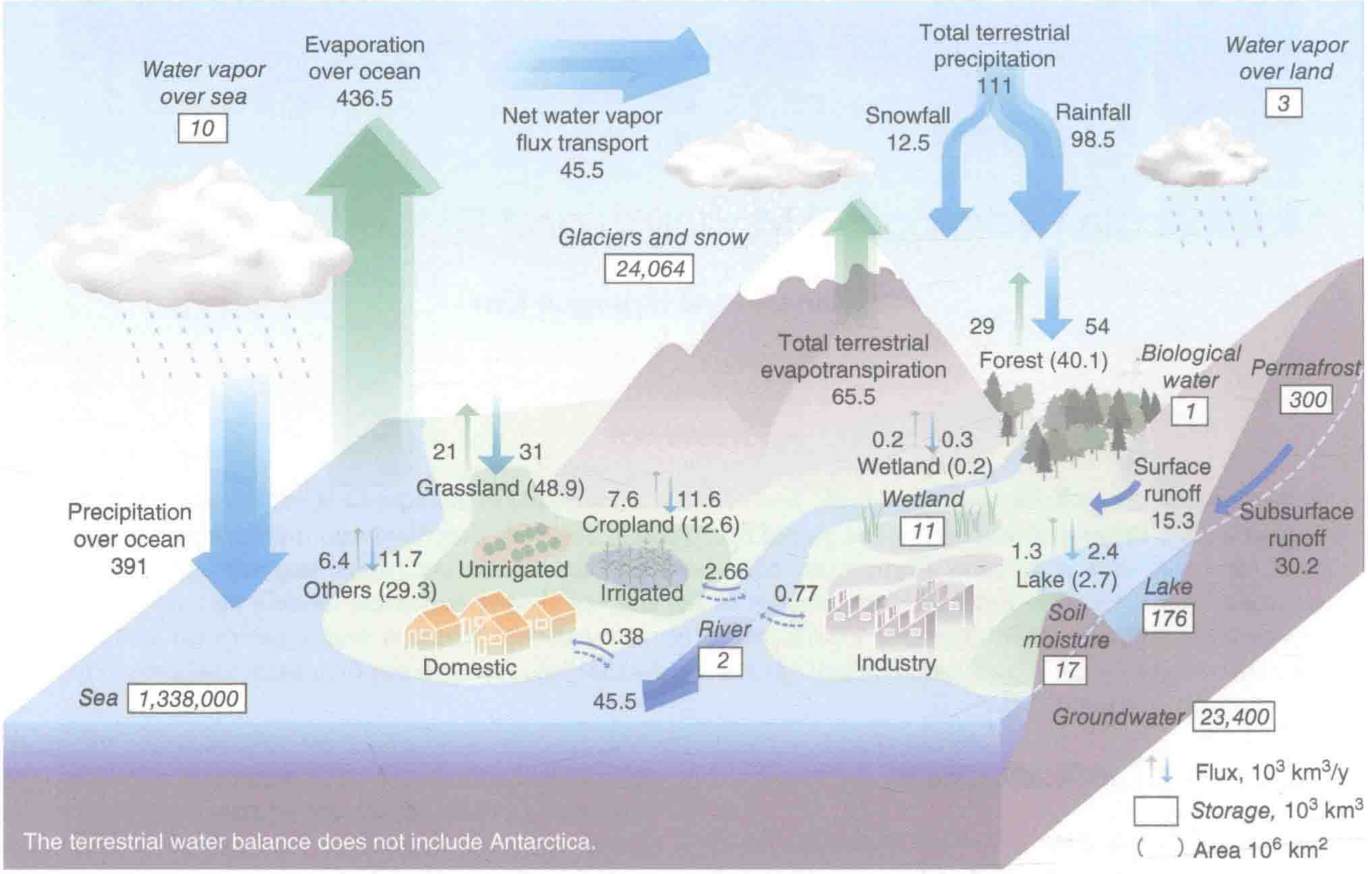

Figure 1.1 Global hydrological fluxes (1000 km^3 yr^{-1}) and storages (1000 km^3) with natural and anthropogenic cycles are synthesized from various sources. Vertical arrows show annual precipitation and evapotranspiration over ocean and land with major landscapes (1000 km^3 yr^{-1}). Parentheses indicate the area (million km^2) [from *Oki and Kanae*, 2006].

Section 1.6 introduces how the science communities have organized international collaborative frameworks. As the last part, prospects for macroscale hydrologic model development in the near future are given in Section 1.7.

1.2. COMPONENTS OF TERRESTRIAL HYDROLOGICAL CYCLES

Precipitation is the water flux from the atmosphere to the land or the ocean surface. It drives the hydrological cycle over the land surface and also changes the ocean surface physical properties (i.e., salinity and temperature), which affect its thermohaline circulation. It is intercepted by vegetation canopy, and the amount exceeding the interception storage reaches the land surface as throughfall. Compared to the other major hydrological fluxes, precipitation behaves in a more variable, intermittent, and concentrated way in time and space. Despite dense gauge station networks, such a highly inhomogeneous spatiotemporal variability makes the observation of precipitation and the aggregation of the process complicated and challenging. In a hybrid product, such as Global Precipitation Climatology Project (GPCP) [*Huffman et al.*, 1997], satellite-based estimates are merged with in situ observational data to fill the observational gaps. Global distribution of precipitation is presented in Figure 1.2a.

Snow has special characteristics compared to rain which refers to the liquid phase of precipitation. When snow accumulates, the surface temperature keeps 0 °C or below until the completion of snow melt. The albedo of new snow can be as high as cloud albedo, and it varies between 0.6 and 0.9 in the aging process (covered with dust). Consequently, the existence of snow significantly changes the surface budget of energy and water. A snow surface typically reduces the aerodynamic roughness, so that it may also have a dynamic effect on the atmospheric circulation and associated local and remote hydrologic cycles.

Evapotranspiration, consisting of evaporation and transpiration, is the flow of water and latent heat energy returning from the surface to the atmosphere. The amount of evaporation is determined by both atmospheric and hydrological conditions. Wetness at the surface influences the partition between latent and sensible heat significantly.

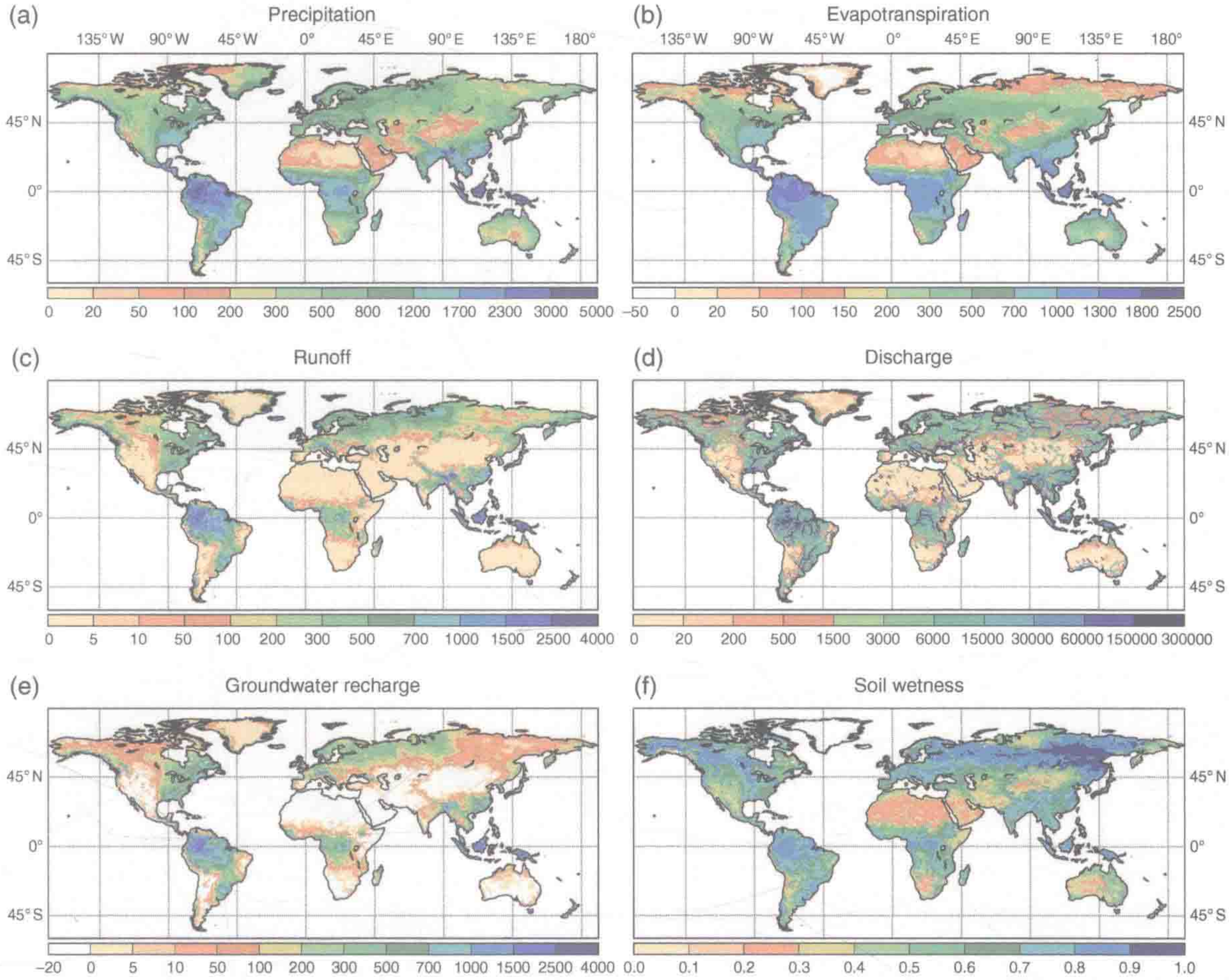

Figure 1.2 Global distribution of long-term (1979–2013) annual mean of (a) precipitation (mm yr^{-1}) from the GPCC [*Schneider et al.*, 2014], (b) evapotranspiration (mm yr^{-1}), (c) runoff (mm yr^{-1}), (d) river discharge (m^3 yr^{-1}), (e) groundwater recharge (mm yr^{-1}), and (f) soil wetness (-) from off-line hydrological simulations by Ensemble Land Surface Estimator (ELSE) [*Kim and Oki*, 2014].

The ratio of actual evaporation to potential evaporation is reduced due to drying stress near the surface. The stress is sometimes formulated as a resistance under which evaporation is classified as hydrology-driven (soil-controlled). If the land surface is wet enough compared to available energy for evaporation, the condition is classified as radiation driven (atmosphere controlled).

Transpiration is the release of water vapor from the stomata of leaves. It is distinguished from evaporation from soil surfaces in two aspects. One is that the resistance of stomata does not relate only to the soil dryness but also to the physiological conditions of vegetation through the opening and closing of stomata. The other is that roots can transfer water from deeper soil layers in contrast to evaporation over bare soil. Vegetation also modifies the balance of surface energy and water by altering surface albedo and by intercepting and evaporating a part of precipitation. The global distribution of total evapotranspiration is shown in Figure 1.2b.

Runoff (Fig. 1.2c) carries water back to the ocean from the land. Without rivers, global hydrologic cycles on the Earth are not closed. Runoff into the ocean also plays a role in the freshwater balance and the salinity of the ocean. Rivers carry not only water but also sediments, chemicals, and various nutrient materials from continents to seas. Runoff at the hillslope scale is a nonlinear and complex process. Surface runoff can be generated when the intensity of rainfall or snowmelt exceeds the infiltration capacity of the soil (Hortonian runoff), or when rain falls on the saturated land surface (Dunne runoff).

Saturation at the land surface mostly occurs along the hill slopes according to the topographic concentration mechanism. Infiltrated water in the upper part of the hill slope flows down the slope and discharges at the bottom of the hill. Because of the high heterogeneity of topography, soil properties (such as hydraulic conductivity and porosity), and precipitation, basic equations such as Richard's equation, which can be valid fairly well at a point scale or hillslope scale, cannot be directly applied in the macroscale using the mean quantities because of the nonlinearity involved. The river discharge accumulates total runoff generated in upstream watershed. The global distributions of runoff and river discharge are illustrated in Figure 1.2c and d.

Groundwater is the subsurface water in the saturated zone. It contributes to the runoff in the low-flow regime between storm events, that is, during a dry spell. Deep groundwater may also reflect the long-term climatological condition. The groundwater quantity in Figure 1.1 considers both gravitational and capillary water, but groundwater in Antarctica (roughly estimated as $2 \times 10^6 \text{km}^3$) is excluded. Gravitational water is the water in the unsaturated zone (vadose zone), which moves downward by gravity. Capillary water is the water that moves upward due to capillary diffusion. Implementing macroscale groundwater dynamics, *Koirala* [2010] estimated groundwater recharge flux as $31{,}789\,\text{km}^3\,\text{yr}^{-1}$, which is close to the flux of subsurface runoff in Figure 1.1 ($30{,}200\,\text{km}^3\,\text{yr}^{-1}$). The global distribution of model-simulated groundwater recharge is illustrated in Figure 1.2e.

The global distribution of soil wetness is shown in Figure 1.2f. Soil moisture is the water being held above the groundwater table. It influences the energy balance at the land surface by affecting evapotranspiration (which consists of soil evaporation, plant transpiration, and interception loss) and changing surface albedo. Soil moisture also alters the fraction of precipitation partitioned into direct runoff and infiltration. When the temperature of the soil column keeps at or below 0 °C for more than two consecutive years, the condition is called permafrost. During the summer season, the upper part of the soil column thaws and the melting water infiltrates downward, but the permafrost layer is still impermeable like a bedrock. Figure 1.3 indicates the global estimation of evapotranspiration and runoff. Approximately one third of precipitation turns to runoff and one third of the runoff is estimated to be surface runoff. The shares of transpiration, canopy infiltration, and bare soil evaporation are close on global average.

Major reserves other than the ocean are solid waters on the continent, including glaciers and permanent snow cover. Glaciers are ice accumulations originated from the atmosphere, and they move slowly on land over a long time period. Glaciers form U-shaped valleys over land and leave moraine deposits when they retreat. If a glacier "flows" into an ocean, it often turns into an iceberg. Glaciers evolve in a relatively longer timescale in comparison to climatic change. They can also induce isostatic responses of continental-scale upheavals or subsidence in even longer timescales. Even though it was believed that the thermal expansion of oceanic water dominated the anticipated sea level rise due to global warming, glaciers over land are also a major concern as the cause of sea level rise associated with global warming in the coming decades.

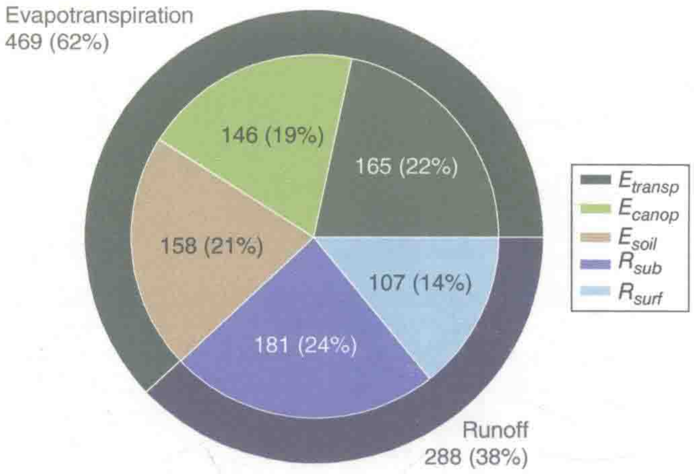

Figure 1.3 Global water balance and partitioning between the components of evapotranspiration (E_{transp}: transpiration, E_{canop}: interception-loss, and E_{soil}: evaporation from bare soil) and runoff (R_{surf}: surface runoff, R_{sub}: base flow) based on the estimation by *Kim and Oki* [2014].

1.3. GLOBAL WATER BALANCE IN EARLY ERA

The 1980s was the dawn of four-dimensional data assimilation (4DDA) of the global atmosphere. *Oki et al.* [1995] were one of the first to demonstrate the potential capability of 4DDA data to estimate terrestrial water balances using global precipitation observations and large basin river discharges based on the atmospheric water balance (AWB) method. Water balance over land and combined water balance are schematically illustrated in Figure 1.4.

The water balance over land is described as equation (1.1) where P, E, R, and S are precipitation, evapotranspiration, runoff, and terrestrial water storage, respectively, within an arbitrary boundary as illustrated in Figure 1.4a:

$$\frac{dS}{dt} = P - E - R \tag{1.1}$$

Atmospheric water vapor flux convergence contains water balance information in addition to the traditional hydrological elements such as precipitation, evapotranspiration, and discharge. The basic concepts as well as the application of atmospheric data to estimate terrestrial water balance were first presented by *Starr and Peixöto* [1958]. The atmospheric water balance for a column of atmosphere from the bottom at land surface to the top of the atmosphere is described by the equation,

$$\frac{dW}{dt} = Q + (E - P) \tag{1.2}$$

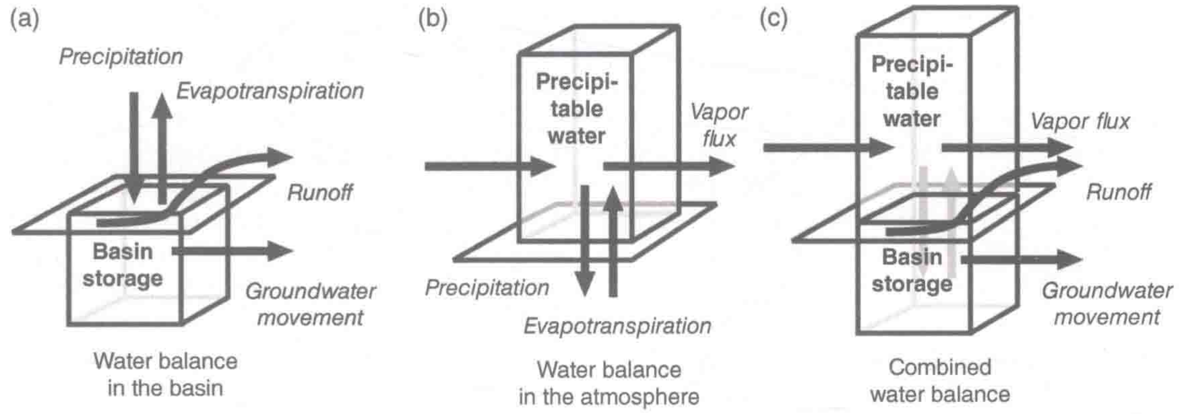

Figure 1.4 Schematic diagram for (a) terrestrial water balance, (b) atmospheric water balance, and (c) combined atmosphere–land surface water balance corresponding to equations (1.1), (1.2), and (1.3), respectively [*Oki et al.*, 1995].

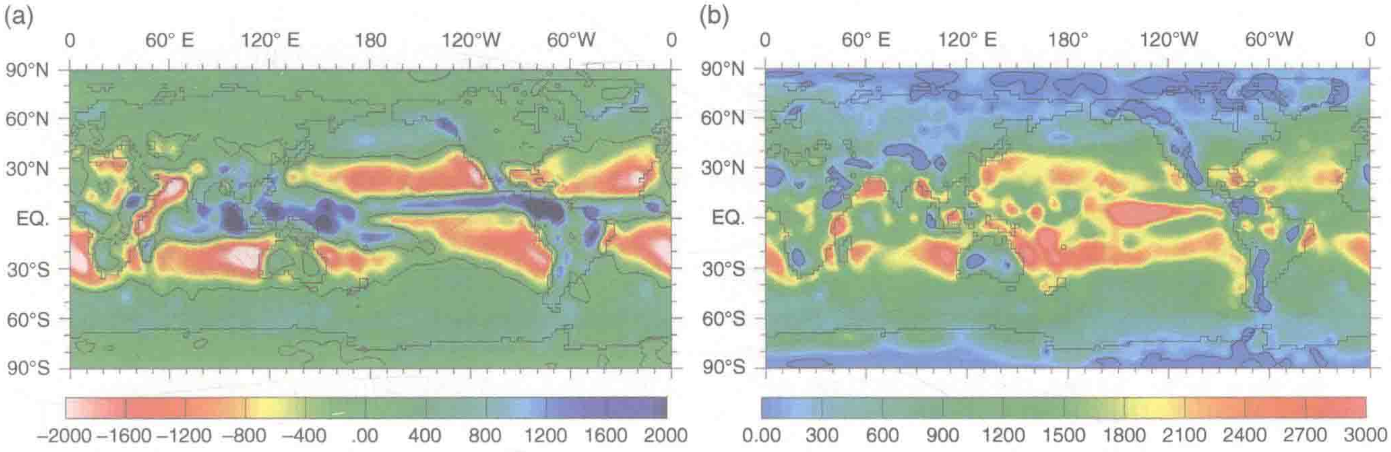

Figure 1.5 Atmospheric water balance approach using (a) annual vapor-flux convergence (mm yr^{-1}) from European Centre for Medium-Range Weather Forecast (ECMWF) global analysis [*Hoskins*, 1989] based on *Oki et al.* [1995] to estimate (b) annual mean evapotranspiration (mm yr^{-1}) for 1989–1992 as a residual of (a) and precipitation corresponding to the period.

where W represents the precipitable water (i.e., column integrated water vapor), and Q is the water vapor flux convergence in the atmosphere (Fig. 1.5a); all fluxes given in the unit volume of per time step). Since the atmospheric water content in both solid and liquid phases is generally small, only the water vapor is considered in equation (1.2). Figure 1.4b shows that the water storage in an atmospheric column is increased by the lateral convergence of water vapor and evapotranspiration from the bottom of the column (i.e., land surface), and decreases due to the precipitation falling from the bottom of the atmosphere column to the land.

Since there are common terms in equations (1.1) and (1.2), they can be combined into:

$$-\frac{dW}{dt}+Q=\left(P-E\right)=\frac{dS}{dt}+R \tag{1.3}$$

Figure 1.4c illustrates the balance in this equation. The difference of precipitation and evapotranspiration is equal to the sum of the decrease of atmospheric water vapor storage and lateral (horizontal) convergence, and is also equal to the sum of the increase of water storage over the land and runoff. Theoretically, equation (1.3) can be applied for any control volume of the land area combined with the atmosphere above, however, the practical applicability depends on the accuracy and availability of atmospheric and hydrologic information. The global distribution of total evapotranspiration is shown in Figure 1.5b, which is estimated using the atmospheric water balance. *Trenberth et al.* [2007] used 40 yr ECMWF Re-Analysis [ERA-40; *Uppala et al.*, 2005] to compute the atmospheric moisture budget (i.e., *E–P*) and calculated global evapotranspiration as a residual of the precipitation and runoff (i.e., *P–E*) using gauged streamflow data of the largest 921 rivers in the world. This approach has been extended combining terrestrial water storage variability (obtained from remote sensing data by Gravity Recovery and Climate Experiment, GRACE; *Tapley et al.*, 2004) and satellite altimetry-based ocean mass change observation to estimate basin-scale evapotranspiration [*Rodell et al.*, 2004], global terrestrial discharges [*Syed et al.*, 2010], and discharges in continents and large river basins [*Syed et al.*, 2009].

1.4. MACROSCALE MODELING FOR WATER CYCLE IN NATURE

Macroscale hydrological models have been developed in response to societal expectations for solving current and future world water issues. There is an increasing demand for information on water resources and the prediction of their future changes. Conventionally, available freshwater resources are commonly defined as annual runoff estimated by historical river discharge data or water-balance calculation [*Baumgartner and Reichel*, 1975; *Korzun*, 1978]. Such an approach has been used to provide valuable information on annual freshwater resources in many countries. Atmospheric water balance using the water vapor flux convergence could alternatively be used to estimate global distribution of runoff based on the atmospheric reanalysis and data assimilation system [*Oki et al.*, 1995].

In the early 1990s, during the planning stage of the GEWEX Asian Monsoon Experiment (GAME), the topic "how to develop macroscale hydrological models" was discussed among Japanese scientists based on land-atmosphere interaction studies. Two approaches were identified. The first approach was to extend a conventional microscale rainfall-runoff hydrological model to a macroscale model that could run on the continental scale with a detailed energy balance and vegetation representation. The other approach was to enhance hydrological processes in land surface models (LSMs) and couple them with horizontal water flow processes, particularly with river flow.

The land surface model was originally devised as a physical scheme of a GCM to provide appropriate lower boundary conditions of land grid boxes [*Pitman*, 2003]. The first implementation, the so-called bucket model, has a globally constant soil depth and moisture-holding capacity, and determines the Earth's surface temperature using a simple heat balance equation [*Manabe* 1969]. Evaporation in the bucket model is simply determined by a linear relationship with soil moisture availability. *Deardorff* [1978] used the "force-restore" method for soil scheme and proposed a "big leaf" type for vegetation representation that has a single layer canopy for heat and moisture exchanges characterized by the micrometeorological bulk parameters. The big leaf canopy model has been broadly adopted in so-called second generation LSM including the Biosphere Atmosphere Transfer Scheme [BATS; *Dickinson et al.*, 1986] and Simple Biosphere Model [SiB; Sellers *et al.*, 1986]. After a major advance of the second generation LSMs, which explicitly considered a vegetation cover on the Earth's surface, LSMs were able to simulate the carbon cycle. Representation of plant physiology enabled LSMs such as SiB2 [*Sellers et al.*, 1996a] to control carbon and water fluxes simultaneously, taking into account light, carbon dioxide, and water stresses. Although third generation LSMs tended to employ multiple soil layers and simulated better underground processes of vertical heat and moisture transfer, intergrid exchanges such as "river", a horizontal redistribution of water, were not considered.

Oki and Sud [1998] developed a global river channel network named Total Runoff Integrating Pathway (TRIP). *Oki et al.* [1999] proposed a framework for evaluating global water cycles via off-line (uncoupled with atmosphere) simulation of LSMs combined with river routing schemes as a post-processors. The accuracy of global water balance estimated by 11 land surface models (LSMs) was validated by river discharge utilizing TRIP. The framework is also useful for translating climate change–driven changes in hydrological cycles (projected by GCMs) into socially relevant information, such as changes in future world-water resources and the frequency of flood and drought [e.g., *Nohara et al.*, 2006; *Hirabayashi et al.*, 2008; *Hirabayashi and Kanae*, 2009; *Hirabayashi et al.*, 2013]. The second phase of the Global Soil Wetness Project (GSWP2) also utilized such framework [*Dirmeyer et al.*, 2006]. A comprehensive review of the global hydrologic cycle was done and world-water resources were estimated. TRIP and the river routing scheme were widely adopted by several GCMs in the world, including the European Centre for Medium-Range Weather Forecasts (ECMWF) for flood forecasting applications [*Pappenberger et al.*, 2010]. Six out of 23 future projections in the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) utilized TRIP to identify the impact of climate change on hydrological cycles [*Faloon and Betts*, 2006]. The global river-routing scheme, TRIP, was fundamentally revised recently. The new scheme, named CaMa-Flood, which adopts the diffusive equation as its principal equation, has the capability to represent natural inundation processes [*Yamazaki et al.*, 2011]. However, its couplings with large water bodies (e.g., lakes), human interventions (e.g., reservoir operations), and evaporation from water surfaces are still under development.

Kim et al. [2009] suggested another framework to evaluate off-line hydrological simulations not only using single flux term (i.e., discharge) but also including total terrestrial water storage (TWS) variations, which consist

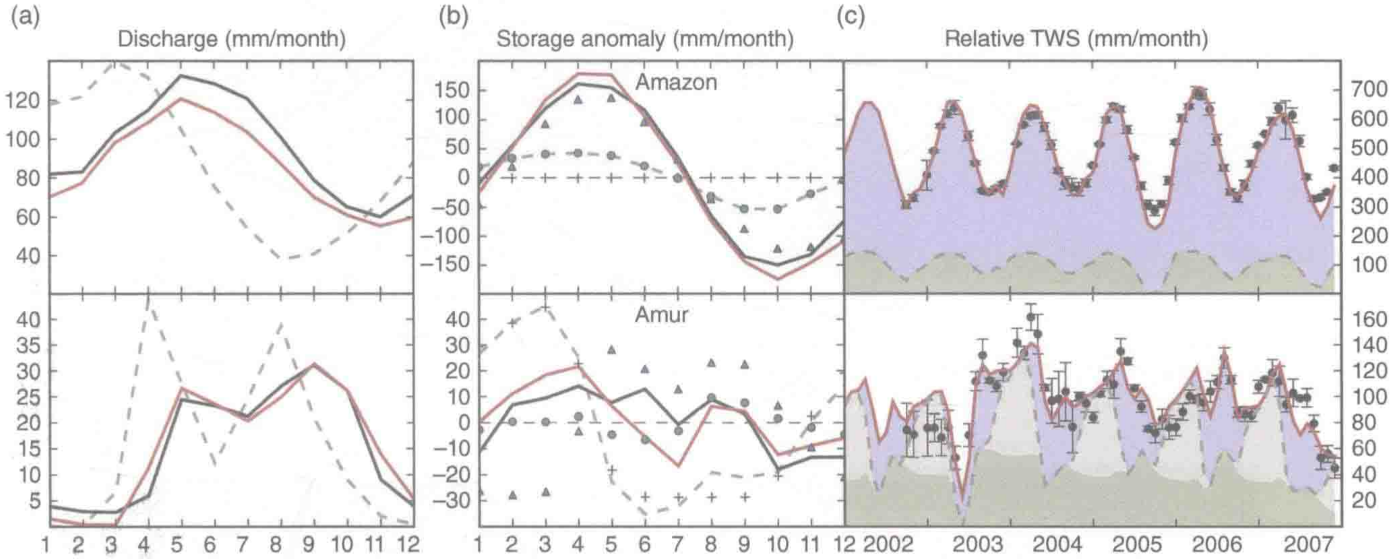

Figure 1.6 Basinwise validation for a macroscale hydrological simulation using the gauged Global Runoff Data Center (GRDC) discharge and the observed TWSA by GRACE. It shows (a) seasonal variations of GRDC discharge (black solid line), simulated discharge (red solid line), and runoff without routing (gray dashed line); (b) seasonal variations of GRACE observed TWSA (black solid line), simulated TWSA with river storage (red solid line), simulated TWSA without river storage (gray dashed line), and the major water storage components in TWS; and (c) interannual variations of relative TWS: the GRACE observation (black dot), simulation with river storage (red solid line), and simulation without river storage (gray dashed line). Gray crosses and shade, green circles and shade, and blue triangles and shade in (b) and (c) represent the individual storage component of snow water, soil moisture, and river storage, respectively [from *Kim et al.*, 2009].

of soil moisture, snow water, and river water (Fig. 1.6). As the satellite mission GRACE has monitored TWS with unprecedented accuracy since 2002, it became feasible to validate the partition of terms in terrestrial water balance [*Famiglietti and Rodell*, 2013]. Also, it was found that river storage not only explains different portions of total TWS variations but also plays different roles in different climatic regions. River is the most dominant water-storage component in wet basins (e.g., Amazon) in terms of amplitude and acts as a "buffer" which smooths the seasonal variation of total TWS especially in snow-dominated basins (e.g., Amur, Lena, Yenisei).

The model simulation of TWS may not be able to reproduce the amplitude and seasonal pattern of observed TWS variations by GRACE without an appropriate representation of a river storage component. Also, using a geodesy approach, *Han et al.* [2009] employed a set of TRIP simulations using different effective velocities in the Amazon River Basin and its vicinity. The model simulations were compared to the residual of GRACE L1b measurements derived from removing all the gravity-influencing factors except for the lateral redistribution of water storage in the Amazon river network. They demonstrated that the optimal flow velocity of TRIP in the Amazon varies between rising and falling water levels.

The global off-line hydrological modeling framework has been used to estimate large-scale water cycles since it is still the only available methodology that covers the global area for a sufficient time span without any gap. To reduce or estimate simulation uncertainties, approaches such as data model integration (e.g., data assimilation) and multimodel ensemble (MME) have been proposed. The Making Earth System Data Records for Use in Research Environments (MEaSUREs) project compiled various sources of data set including remote sensing, atmospheric reanalysis and model simulations, and optimized sets of flux terms using a data assimilation technique [*Rodell et al.*, 2015]. MME approach has been frequently performed as a community effort. International model intercomparison projects (MIPs) such as Global Soil Wetness Project [GSWP; *Dirmeyer et al.*, 2006; *Dirmeyer*, 2011] and Water Model Intercomparison Project [WaterMIP; *Haddeland et al.*, 2011] are good examples adopting MME approach to quantify the fluxes of water cycles globally, and they are introduced in Section 1.6 with more details. Table 1.1 compares recent studies that estimate global water balance using different approaches.

1.5. CLIMATE CHANGE AND HUMAN IMPACT

Global concentrations of carbon dioxide and methane have grown from the latter part of the eighteenth century. Since then it has been called the "Anthropocene"