Observing Ecohydrological Processes: Challenges and Perspectives

Xin Li, Harry Vereecken, and Chunfeng Ma

Contents

X. Li (✉)
Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China

CAS Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing, China
e-mail: xinli@itpcas.ac.cn

H. Vereecken
Agrosphere Institute (IBG-3), Forschungszentrum Jülich GmbH, Jülich, Germany
e-mail: h.vereecken@fz-juelich.de

C. Ma
Key Laboratory of Remote Sensing of Gansu Province, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China

© Springer-Verlag GmbH Germany, part of Springer Nature 2019

X. Li, H. Vereecken (eds.), *Observation and Measurement of Ecohydrological Processes*, Ecohydrology, https://doi.org/10.1007/978-3-662-48297-1_1

Abstract

The observation and measurement of ecohydrological processes have been witnessed a huge progress in terms of novel ideas, methodologies, and techniques. Many cutting-edge observing techniques, e.g., stable isotope, wireless sensor network, cosmic ray probe, multi-source remote sensing, are continuously introduced and widely applied. As the first chapter of this book, this chapter introduces the progresses, challenges, and perspectives of observing ecohydrological processes. We first introduced the key states and fluxes that control the ecohydrological processes and novel techniques that allow those controlling factors to be quantified. However, we found that knowledge gap remains, including: (1) improving the observation ability to understand and quantify the ecohydrological processes, (2) integrating multisource observations into a dynamics model to accurately estimate the state and flux variables of ecohydrological processes, (3) developing upscaling approaches through system observations to understand the scaling issue, and (4) estimating representativeness error to quantify the uncertainties. To this end, we pointed out the potential directions for filling these gaps, including: (1) to better translate remotely sensed data into information that helps us better understand ecohydrological processes and better inform land-surface models, (2) to better quantify the roles of subsurface processes in ecohydrological processes, (3) to develop observational systems that allow ecohydrological processes to be captured across different scales and across compartments, (4) to use well-instrumented watersheds as test beds of new concept for ecohydrological observations, (5) to combine monitoring and controllable and synthetic observation experiments, (6) to utilize technical advancements in new models, and (7) to integrate observation systems with integrated models, data services, and decision making. Overall, this chapter provides an insight into the-state-of-art of observing ecohydrological processes.

Keywords

Ecohydrological processes · Remote sensing · Uncertainty · Heterogeneity · Scaling

Introduction

Water is among the most essential resources that sustain Earth's ecosystems, and it supports essential ecosystem services, such as food, feed, fiber, and energy. Thus, water can be considered a strategic resource for mankind (Liu et al. 2010). As such, a better understanding of the hydrological processes that control ecosystem services is of great significance. Moreover, our ecosystems are under threat due to a lack of either sufficient water or water of good quality. The need for a better understanding of the roles of water in ecosystem functioning requires an integrated approach between hydrologists and ecologists (Bonacci et al. 2009). A new discipline, ecohydrology, has been proposed to demonstrate the importance of this integrated approach. Ecohydrology was proposed as an independent discipline at the International Conference on Water and the Environment in Dublin in 1992. The results of ecohydrological research have contributed to the better management and preservation of fragile ecosystems (Bonacci et al. 2009; Abbott et al. 2016). Under the continuous support of the International Geosphere-Biosphere Program (IGBP), United Nations Educational, Scientific and Cultural Organization-International Hydrologic Programme (UNESCO-IHP), and other related international organizations, ecohydrology gradually has become a topic of considerable research and a frontier discipline in earth and environmental sciences. Ecohydrology is a key discipline in "Future Earth" (Liverman et al. 2013) and Earth critical zone research (Anderson et al. 2008; Richter and Mobley 2009; Lin et al. 2010; Guo and Lin 2016).

Modeling and observation are the fundamental research methodologies of ecohydrological processes, and both have developed rapidly over the past two decades. This book focuses on the observation of ecohydrological processes.

Progress in the Observation of Ecohydrological Processes

Overview

Ecohydrological processes are controlled by, for example, soil moisture (SM), precipitation, evapotranspiration (ET), runoff, and vegetation through photosynthesis, and the statuses of these processes are characterized by, for example, the leaf area index (LAI). In this chapter, we present different observation technologies that allow these controlling factors to be quantified, including ground-based sensing, airborne remote sensing, and spaceborne remote sensing. Table 1 lists the key variables of ecohydrological processes and observational techniques that will be addressed in this chapter.

Key Factors Controlling Ecohydrological Processes

Precipitation

Precipitation is defined as condensed atmospheric water vapor that falls to Earth's surface in liquid, solid, or combined forms, i.e., rain, snow, drizzle, sleet, and hail. Precipitation is the driving flux for many processes that take place on land surface and is considered the most sensitive but also uncertain input in many ecohydrological models (Chen and Frauenfeld 2014; Liu et al. 2011). Ground-based measurements of precipitation can be obtained using various types of rain gauges and weather radars, and precipitation can be sensed remotely using satellite sensors operating in the near-infrared, thermal infrared, passive microwave, and active microwave bands (Prigent 2010). The most successful satellite missions include the Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM) mission (Hou et al. 2014; Skofronick-Jackson et al. 2017).

Table 1 Key ecohydrological variables and observation techniques and platforms

Variables	Ground measurement	Airborne	Satellite mission
Precipitation	Doppler radar, rain gauge, precipitation particle drop size analyzer	N/A	FY-3, TRMM, GPM
ET	EC, LAS, Lysimeter	Imaging spectrometer, LiDAR, airborne EC	ASTER, MODIS, AATSR, FY-3
Runoff	ADCP, hydrological gauging station, runoff plot	InSAR, Imaging spectrometer	OSTM/Jason-2 Radar Altimeter, ASAR, Altimeter-2, TSX, SWOT
Soil moisture	Site-scale (e.g., TDR, FDR) Footprint scale (e.g., COSMOS, GPR)	Active (e.g., PLIS, AirSAR), passive (e.g., PLMR, PSR)	Active (e.g., SMAP, ENVISAT, ALOS), passive (e.g., SMAP, SMOS, FY-3 MWRI)
Vegetation type	Sampling strip, plot survey	Imaging spectrometer	PROBA CHRIS, HYSPIRI, HJ-1, CBERS
LUCC	Land use survey	Multispectral sensor, imaging spectrometer	Landsat, SPOT, MODIS, HJ-1, CBERS and other multispectral sensors
Photosynthesis and respiration	LI-6400/XT, EC	Airborne-EC	FLEX
LAI	LAI-2000, TRAC, LI-3100	VNIR, LiDAR, low frequency SAR	Landsat, SPOT, MODIS, HJ-1, CBERS and other multispectral sensors

There are several challenges in precipitation measurement. First, in situ observations of precipitation should be bias corrected; in particular, gauge measurements of snowfall are significantly underestimated and require the development of standard correction methods. Therefore, WMO initialized the Solid Precipitation Intercomparison Experiment (SPICE) to undertake a systematic assessment of the reliability of accurately measuring solid precipitation. Second, obtaining high-resolution and reliable precipitation forcings in complex terrains, particularly mountainous regions, remains challenging (Alemohammad et al. 2015; Gottardi et al. 2012; Ward et al. 2011). One promising approach is to combine regional climate modeling with various observations, including those from rain gauges, Doppler radars, and satellite remote sensing, via multiscale data assimilation (Pan et al. 2012, 2017).

Evapotranspiration

Terrestrial ET is composed of the evaporation of water from soils, canopy interception, and waterbodies, whereas transpiration represents the loss of water through stomata. ET can be expressed as either part of the energy balance (latent heat) or a flux in the soil water balance. ET is a key process linking hydrology with ecosystem dynamics from stoma to landscape scales (Wang and Dickinson 2012; Zhu et al.

2016). Ground-based ET measurement techniques include weighing lysimeters, eddy covariance techniques, and scintillometers (Liu et al. 2011). For satellite remote sensing, direct measurements of ET as a water flux remain impossible. ET can be estimated indirectly using the energy balance and Penman-Monteith-based methods (P-M) (for more details, refer to chapters ▶ “Remotely Sensed Evapotranspiration” and ▶ “Micrometeorological Methods to Determine Evapotranspiration”). Various algorithms, such as energy balance based algorithms, including SEBAL (Bastiaanssen et al. 1998), SEBS (Su 2002), and their variants, and algorithms based on plant physiology and ecology, such as P-M, have been developed.

Accurate quantification of ET is challenging due to its strong spatial heterogeneity and scale dependence, which encompasses leaf, canopy, field, and regional scales. Multiscale observational experiments on ET that provide insight into the spatial heterogeneities of ET, explore the energy balance closure problem, and identify scaling effects are needed to address those challenges. These experiments require the provision of ground truth data that correspond to the development of remote sensing models and scale transformation approaches. For example, HiWATER (Heihe Watershed Allied Telemetry Experiment Research) is a multiscale observation experiment designed to capture the heterogeneity of land-surface water and energy fluxes (Li et al. 2013; Xu et al. 2013; Liu et al. 2016).

Streamflow

Streamflow, another significant component of the water cycle and water balance, can be described as the overland flow in streams, rivers, and channels generated by rainfall, snowfall, meltwater, or irrigation water due to gravity and groundwater supplements (Beven et al. 2004). Streamflow feeds rivers and lakes with water that supports many ecosystem services. Streamflow is measured at gauging stations by measuring depth, width, and velocity using traditional methods or Acoustic Doppler Current Profiles (ADCPs). Satellite remote sensing that aims to quantify streamflows shows great potential but is still not operational. The challenge with this technique is determining how to measure streamflow velocity using remote sensing. This challenge will be overcome by the new Surface Water Ocean Topography (SWOT) satellite mission, which uses a Ka-band radar interferometer as the core technology for measuring velocity. The water level will be measured simultaneously by radar altimetry. The spatial resolution (tens of meters) and vertical precision (a few centimeters) of SWOT are also unprecedented (Durand et al. 2010). Therefore, streamflow measurements will be revolutionized through the implementation of the SWOT mission (chapter ▶ “Surface Runoff”).

Soil Moisture

Soil moisture is a physical soil state variable that is defined as the water contained in the unsaturated (vadose) soil zone. It represents a key variable in many hydrological, climatological, environmental, and ecohydrological processes (Vereecken et al. 2008). The important role of SM in multidiscipline applications is well recognized (NRC 2007). The approaches for measuring soil moisture include point-measurements, field-scale measurements, ground-based networks, and remotely sensed methods (including satellite-based and airborne-based remote sensing) (Zacharias et al. 2008; Bogena et al. 2012). Soil moisture sensing techniques have progressed considerably over the last 50 years. In particular, the European Spatial Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) (Kerr et al. 2001) and National Aeronautics and Space (NASA) Soil Moisture Active and Passive (SMAP) (Entekhabi et al. 2010) missions are designed to map global soil moisture under the background of climate change.

Soil moisture measurements are challenged by the issues of quantifying the spatial representativeness of in situ measurements and scaling micro-observations to macroscales, such as the pixel resolutions of satellite remote sensing products. The new technologies, which include footprint-scale in situ measurements, such as cosmic-ray probes (Zreda et al. 2012; Andreasen et al. 2017) and wireless sensor networks (Bogena et al. 2010; Jin et al. 2014) provide new opportunities because they can capture spatial variability in soil moisture at multiple scales. By using proper scaling methods, in situ measurements can be scaled to pixel-scale truth data and used to validate remote sensing products (Kang et al. 2015; Jin et al. 2017).

Photosynthesis and Respiration

Photosynthesis is the process by which green plants and other organisms transform sunlight energy into chemical energy. It is a primary life process for green plants and contributes significantly to making terrestrial ecosystems large carbon sinks (Canadell et al. 2000; Eagleson 2002). Through respiration, plants break down carbohydrates to provide energy for metabolism and release CO_2 into the atmosphere (Eagleson 2002). Photosynthesis and respiration are strongly controlled by hydrological states and fluxes. Understanding those relationships can aid in predictions of how hydrological changes affect vegetation and thus both photosynthesis and plant respiration (Running and Gower 1991).

The photosynthesis components of terrestrial plants can be measured by destructive dry matter, gas exchange, isotope, and fluorescence methods (Hunt 2003). Additional details are provided in chapter entitled ▶ "Photosynthesis (NPP, NEP, Respiration)". Photosynthesis components are estimated using light use efficiency or process-based biogeochemical models from satellite remote sensing. The challenge is determining how to measure light use efficiency directly. Solar-induced chlorophyll fluorescences retrieved by high-spectral-resolution (<0.5 nm) remote sensing could shed new light on this challenge (Meroni et al. 2009). In particular, the planned ESA FLuorescence EXplorer (FLEX) mission will usher in a new era of the photosynthesis remote sensing (Drusch et al. 2017).

Leaf Area Index

The leaf area index (LAI) is defined as single-sided green leaf area per unit ground area (Chen and Black 1991) and is a critical parameter in many climate, hydrology, and ecology models. The LAI has been widely used to investigate crop growth, hydrology processes, energy balances, and land-atmosphere exchanges and in other climate change studies (Sellers 1997). The LAI can be measured directly by collecting samples from a plant canopy or indirectly using optical methods. Typical indirect methods include canopy analyzers and the hemispherical photographic method (Jonckheere et al. 2004). Remote sensing is an important and feasible way to acquire the LAI at regional and global scales. However, LAIs estimated from remote sensing should be calibrated and validated with ground observations to ensure reliability (Qu et al. 2012). Additional details are provided in chapter ► "Leaf Area Index: Advances in Ground-Based Measurement".

Main Observation Platforms for Ecohydrological Processes

Ecohydrological processes can be studied using satellite, airborne, and ground-based platforms, as shown in Fig. 1, which represents the HiWATER observational system.

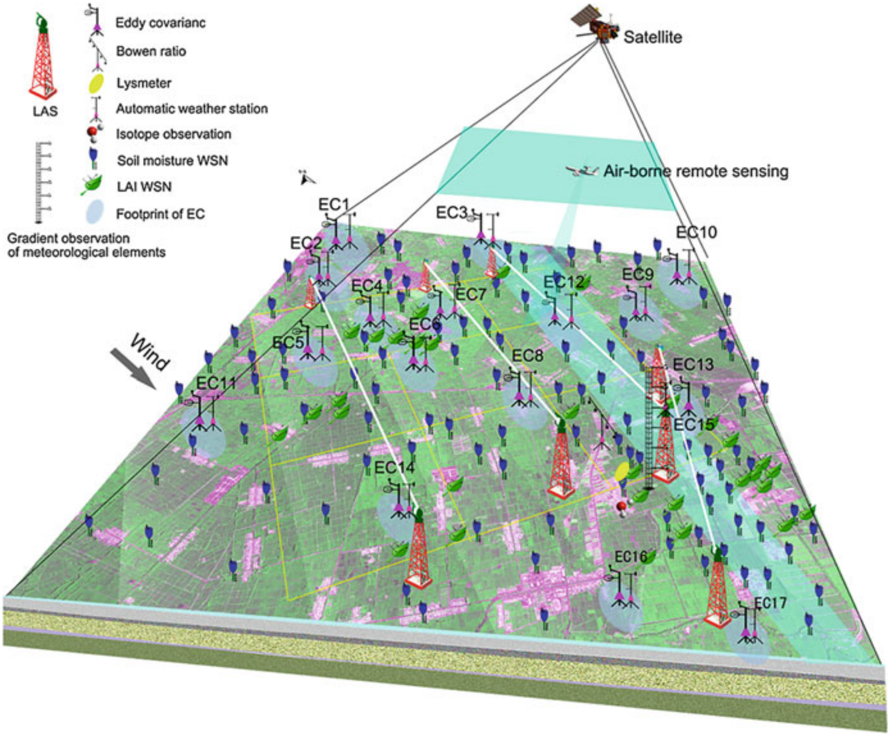

Fig. 1 Multi-platform observing system for ecohydrological processes deployed in the HiWATER observational system, taken as an example. The HiWATER observing system is composed of a flux matrix, a wireless sensor network for measuring soil moisture and the LAI, isotope observations, and airborne remote sensing. Details can be found in Li et al. (2013, 2017); Liu et al. (2016, 2018)

Satellite Observation Platforms

At present, ecohydrological variables largely can be observed or monitored by satellite remote sensing. The main optical-thermal, active and passive microwave satellite/sensors or satellite platforms that can provide observations on ecohydrological variables are listed in Tables 2, 3, and 4, respectively.

Since 2000, several new satellite observation missions have been implemented and can be used to monitor ecohydrological variables globally.

- GPM (Global Precipitation Measurement). The core satellite of the GPM, which was designed and developed jointly by NASA and JAXA, was equipped with both a dual-frequency Ku/Ka-band precipitation radar and a high-resolution, multichannel passive microwave rain radiometer. In addition, through international collaboration, several non-sun-synchronous and sun-synchronous orbit satellites were launched with passive microwave radiometers onboard, making up a satellite constellation. The temporal resolutions of global precipitation observations can reach 3 h (Hou et al. 2014).
- SMOS (Soil Moisture and Ocean Salinity). The SMOS satellite was successfully launched on November 2, 2009, with an L-band passive microwave radiometer. One of the main scientific objectives of SMOS is to monitor surface soil moisture. The spatial resolution is 40 km (Kerr et al. 2010).

Table 2 Main optical-thermal satellite platforms for ecohydrological processes observation

Satellite (Sensors)	Agency (First launch year)	Resolution (m)	Variables that have been observed
TIROs-N/NOAA (AVHRR)	TIROS-n/NOAA, USA (1978)	1100	ET, SM, Chlorophyll, NPP, etc.
Terra/Aqua (MODIS)	NASA, USA (1999)	250–1000	ET, SM, Chlorophyll, biomass, VWC, snow
Landsat (MSS/TM/ETM+/ OLI -TIRS)	USGS, USA (1972)	10–30	SM, biomass, NPP, VWC, snow.
SPOT (VEGETATION)	ESA, Europe (1986)	1.5–20	SM, VWC, biomass, NPP, LUCC, snow.
CBERS	China-Brazil (1999)	2–120	SM, VWC, biomass, NPP.
ALOS/AVNIR	JAXA, Japan (2006)	10–100	SM, VWC, snow.
PROBA-V	ESA, Europe (2013)	3–100	SM, VWC biomass, NPP, LUCC.
FY	China (1988)	250–1250	SM, VWC, biomass, NPP, LUCC, snow.
HJ	China (2008)	1–100	SM, VWC, biomass, NPP.
GF	China (2013)	0.8–16	SM, VWC, biomass, NPP, snow.
Sentine2-3	ESA, Europe (2014/2015)	5–40	ET, SM, VWC, biomass.

- SMAP (Soil Moisture Active Passive). The SMAP satellite, which was developed by NASA, was launched on January 31, 2015 with an integrated active and passive L-band radar and radiometer. As with SMOS, the scientific objectives of SMAP are to map soil moisture and freeze/thaw states. However, the spatial and temporal resolutions of SMAP are 3/9/36 km and 2–3 days, respectively (Entekhabi et al. 2010).

Table 3 Spaceborne SAR for ecohydrological process observations

Satellite (Band)	Agency (Launch year)	Frequency (GHz)	Resolution (m)	Variables that have been observed
ERS-1/2 (C)	ESA, Europe (1991/1995)	5.25	30	ET, SM, Chlorophyll, NPP, etc.
JERS-1 (L)	JAXA, Japan (1992)	1.275	20	Precipitation, ET, SM, Chlorophyll, biomass, VWC
SIR-C/X-SAR (L, C, X)	NASA/JPL/DLR (1994)	1.25, 5.3, 9.6	30	Precipitation, SM, biomass, NPP, VWC.
Radarsat-1 (C)	Canadian Space Agency (1995)	5.3	10–100	Precipitation, SM, VWC, biomass, NPP, LUCC.
SRTM (C, X)	NASA/JPL/DLR (2000)	5.25, 9.6	30	Snow, SM, biomass
ENVISAT/ASAR (C)	ESA (2002)	5.25	20–100	Precipitation, SM, VWC, biomass, NPP.
ALOS/PALSAR (L)	JAXA, Japan (2006)	1.27	10–100	Precipitation, SM, VWC, snow.
Radarsat-2 (C)	Canadian Space Agency (2007)	5.4	3–100	Precipitation, SM, VWC biomass, NPP, LUCC.
TerraSAR-X (X)	DLR/Astrium, Germany (2007)	9.65	0.24–260	SM, VWC, biomass, NPP, LUCC, snow.
COSMO-SkyMed (X)	ASI, Italy (2007/2010)	9.65	1–100	SM, VWC, biomass, NPP.
TanDEM-X (X)	DLR/Astrium, Germany (2010)	9.65	1–16	SM, VWC, biomass, NPP, snow.
RISAT-1 (C)	Indian Space Agency (2012)	5.35	3/6/9/25/50	SM, VWC, snow, biomass, NPP.
HJ-1C-SAR (S)	CRESDA/CAST/NRSCC, China (2012)	3.2	5/20	SM, VWC, biomass.
ALOS-2/PALSAR-2 (L)	JAXA, Japan (2014)	1.20	1–100	Precipitation, SM, VWC, glacier, snow.
SMAP (L)	NASA/JPL (2015)	1.26	1000–3000	SM, biomass, NPP, freeze and thaw.
Sentinel-1a/b (C)	ESA, Europe (2014/2015)	5.4	5–40	Precipitation, ET, SM, VWC, biomass.
GF-3/SAR (C)	China (2016)	5.4	1–700	SM, VWC, LUCC, biomass.

- Biomass. The Biomass mission was selected as ESA's seventh Earth Explorer in May 2013 (Scipal et al. 2010; Toan et al. 2011). Biomass provides crucial information about the state of forests and how they are changing. The mission also explores the unique sensitivity of P-band SAR together with advanced retrieval methods and generates maps of forest biomass and forest height at a resolution of 200 m. The main goal of the Biomass mission is to understand the carbon cycle and related changes taking place in Earth's ecosystems, e.g., absorption, storage, and release of carbon in forests.

Table 4 Spaceborne radiometers for ecohydrological process observation

Satellite platform (Sensors)	Start-end (Year)	Frequency (GHz)	Spatial resolution (degree)	Temporal resolution (day)	Variables that have been observed
NIMBUS-7 (SMMR)	1978–1987	6.63, 10.69, 18.0, 21.0, 37.0	0.25	2	Precipitation, SM, snow
DMSP-F08 (F08 SSM/I)	1987–2009	19.35, 22.235, 37.0, 85.5	0.25	1	Precipitation, SM, snow.
DMSP-F19 (F19 SSMIS)	2014–	19.35, 22.235, 37.0, 85.5	0.25	1	Precipitation, SM, snow.
TRMM (TMI)	1997–2015	10.7, 19.4, 21.3, 37, 85.5	0.25	1	Precipitation, SM, snow.
WindSat	2003–	6.8, 10.7, 18.7, 23.8, 37.0	0.25	1	Rain rate, SM, snow, cloud liquid water.
EOS-Aqua (AMSR-E)	2002–2011	6.93, 10.65, 18.7, 23.8, 36.5, 89.0	0.25	1	Precipitation, SM, VWC, snow, biomass.
FY-3 (MWRI)	2010–				Precipitation, cloud liquid water, vapor, sea surface temperature.
GCOM (AMSR2)	2012–	6.93, 7.3, 10.65, 18.7, 23.8, 36.5, 89.0	0.25	1	Precipitation, SM, VWC, snow, biomass.
SMOS	2009–	1.4	0.36	1	SM, ocean salinity.
Aquarius	2014–	1.4	0.36	1	SM, SST, SSW.
SMAP	2015–	1.4	0.36	1	ET, SM, VWC, biomass
WCOM	2020	FPIR: 1.2, 2.4, 6.7 PMI: 6.8, 10.65, 18.7, 23.8, 37, 89, 50	FPIR: 50, 30, 15 (km) PMI: 4–50 (km)	1	Precipitation & vapor, ET, SM, sea surface salinity, froze/thaw, SWE.

- FLEX (FLuorescence EXplorer). FLEX is a mission to map vegetation fluorescence to quantify photosynthetic activity initiated by ESA. FLEX will be the first mission designed to observe fluorescence using a novel technique measuring the main part of the chlorophyll fluorescence spectrum that originates from the core of the photosynthetic machinery. The main scientific objectives of FLEX are to assess the quality of the fluorescence-derived photosynthesis data against a classical optical-based method, address temporal and spatial scaling issues in more detail, and indicate potential applications of the novel fluorescence observations.
- GCOM (Global Change Observation Mission). GCOM is a project for the global and long-term observation of Earth initiated by JAXA. GCOM is expected to play an important role in monitoring global water circulation and climate change (Imaoka et al. 2010). The mission consists of two satellite series, GCOM-W and GCOM-C. GCOM-W carries Advanced Microwave Scanning Radiometer 2 (AMSR2), an instrument for observing water-related targets, such as precipitation, water vapor, sea surface wind speed, sea surface temperature, soil moisture, and snow depth. GCOM-C carries a Second Generation Global Imager (SGGI), an instrument for gathering surface and atmospheric measurements of phenomena involved in the carbon cycle and radiation budget, such as clouds, aerosols, ocean color, vegetation, and snow and ice. Global and long-term (10- to 15-year) observations by GCOM will help scientists understand the mechanisms of water circulation and climate change (Imaoka et al. 2010).
- WCOM: The Water Cycle Observation Mission has been proposed by the Chinese Academy of Sciences to improve the capability of synergetic observations of key water cycle variables (Dong et al. 2014; Shi et al. 2014), including soil moisture, ocean salinity, freeze-thaw, and snow water equivalent. The payload configuration of the WCOM satellite is a combination of active and passive wide-frequency-coverage microwave remote sensors with innovative designs, including the L-S-C tri-frequency, Full-Polarized Interferometric synthetic aperture microwave Radiometer (FPIR), the Polarized Microwave radiometric Imager (PMI), which covers a band from 6.6 to 150 GHz, and the X-Ku Dual-Frequency Polarized SCATterometer (DFPSCAT), which has a high spatial resolution. The integration of those payloads can provide global mapping of soil moisture, snow water equivalent, freeze-thaw state, and ET.

Airborne-Based Observation Platforms

Compared to satellite-based remote sensing, airborne-based remote sensing enables a higher spatial resolution and more sensitive observation ability; for example, a super-high spectral resolution can be obtained using airborne sensors. Airborne-based remote sensing is an important complement of satellite-based remote sensing, and the rapid development of UAV remote sensing has enabled lower-cost, more flexible, and more efficient remote sensing experiments. Airborne-based remote sensing plays an important role in ecohydrological process research at the regional

Table 5 Main airborne system used for ecohydrological processes observation

Type	Sensor	Agency/Counry	Band	SR[a] (m)
SAR	C/X-SAR	CCRS/Canada	X/C	0.9,6
	AIRSAR	NASA/USA	C/X/L	0.6,3
	GeoSAR	NASA/JPL	P/X	1.25–3
	PLIS	ARRC/Australia	L	0.2–29
	UAVSAR	NASA/USA	L	1.0,1.8
Radiometer	PSR	NOAA/USA	X/K/Ka	–
	ESTAR	NASA/USA	L	–
	PLMR	NASA/USA	L	–
Spectrometer	AVIRIS	NASA, JPL/USA	360–2500 nm	1-4
	PRISM	NASA/USA	349.9–1053.5 nm	–
	GIFS	NASA/USA	–(multiple sensors)	–

[a] SR = Spatial resolution

and watershed scales. Here we list several representative airborne-based platforms/ sensors to illustrate the characteristics of them (Table 5), almost all of the sensors could provide measurements for key ecohydrological variables.

The main characteristics of airborne-based remote sensing are summarized below.

Controllability

More controllable simultaneous airborne-ground or satellite-airborne-ground observing experiments, in which various observations can be precisely matched in space and time and various parameters can be obtained simultaneously, can be conducted based on airborne remote sensing. Furthermore, airborne-based remote sensing can be used to precisely calibrate satellite-based sensors. These special characteristics of airborne-based remote sensing can provide irreplaceable data for research on ecohydrological processes, model validation, and scale transformations. Therefore, airborne-based remote sensing has played key roles in important observational experiments of the past several decades, including FIFE (Sellers et al. 1987), SMEX (Jackson 2002), CLPX (Cline et al. 2009), WATER (Li et al. 2009), HiWATER (Li et al. 2013), SMAPEx (Panciera et al. 2014), and SMAPVEX (McNairn et al. 2015), and will continue to play more important roles in future observational experiments.

Enabling Scale Transformations

Compared to airborne-based remote sensing, the resolution of satellite-based remote sensing is relatively coarse; therefore, the within-pixel heterogeneity is stronger, and it is relatively difficult to develop accurate and detailed validations for satellite remote sensing. Airborne-based remote sensing allows more flexibility to configure spatial, spectral, and temporal resolutions according to researchers' requirements, and finer observations, with resolutions from centimeters to tens of kilometers, can be obtained. Therefore, airborne-based remote sensing data can be used as homogeneous pixel data for remote sensing validation and can thus play an important role in bridging scaling transformations.

Testing the Observing Ability of Satellite-Based Remote Sensing

Nearly all operational satellite-based sensors and the majority of forward model and inversion approaches are first calibrated and verified using airborne-based remote sensing data. In hydrological applications, comparisons between airborne-based remote sensing data and ground observations are preferred due to the coarse spatial resolutions of satellite-based remote sensing. Thus, airborne-based remote sensing is particularly important for testing the performances of satellite-based sensors. For example, airborne-based sensors have been widely applied in several large-scale ground-based remote sensing experiments.

Important Component of Watershed Observation Systems

Although the resolution of satellite-based remote sensing has increased considerably, particularly for satellite-based multispectral and SAR remote sensing techniques, the same resolutions cannot yet be achieved by hyperspectral/hyperspectral and laser radar satellites. The latter play a critical role in research in watershed hydrological and ecological sciences, such as in measurements of forest and crop structure parameters. Therefore, airborne-based remote sensing is not only a scientific experimental approach but also an important component of watershed observing systems.

Ground-Based Observation Platforms

Traditionally, the key ecohydrological elements have mainly been observed using point-scale equipment that does not adequately capture scale-related heterogeneities in the variables. The upscaling of ecohydrological observations is described and analyzed in detail in chapter entitled ▶ "Upscaling Issues in Ecohydrological Observations." The next generation of ground-based observation networks is presented below.

- WSNs (Wireless sensor networks): WSNs integrate sensor, automatic control, wireless transmission, data storage, pre-processing, and visualizing technologies. Each node in a network consists of one or more sensors, data loggers, transceivers, and energy supply systems (solar, wind or battery) that in turn constitute an intelligent and automate observation network (Gong 2010; Delin et al. 2005). In hydrological applications, various types of sensors, such as soil moisture and temperature sensors, have become increasingly more sophisticated, lower cost, and more reliable and have lower power consumptions, making deployments of large numbers of these sensors possible and applicable. Unprecedented increases in sensor networks have enabled us to capture spatial variations in observational variables at the river basin scale. However, observations from WSNs are more objective than manual observations. Thus, WSNs have become a bridge to fill the gaps between the traditional single-point observations and remote sensing pixel observations, thus playing an important role in remote sensing validation and scaling-related research (Kang et al. 2014; Jin et al. 2014; Hart and Martinez 2006; van Zyl et al. 2009; Qu et al. 2014).

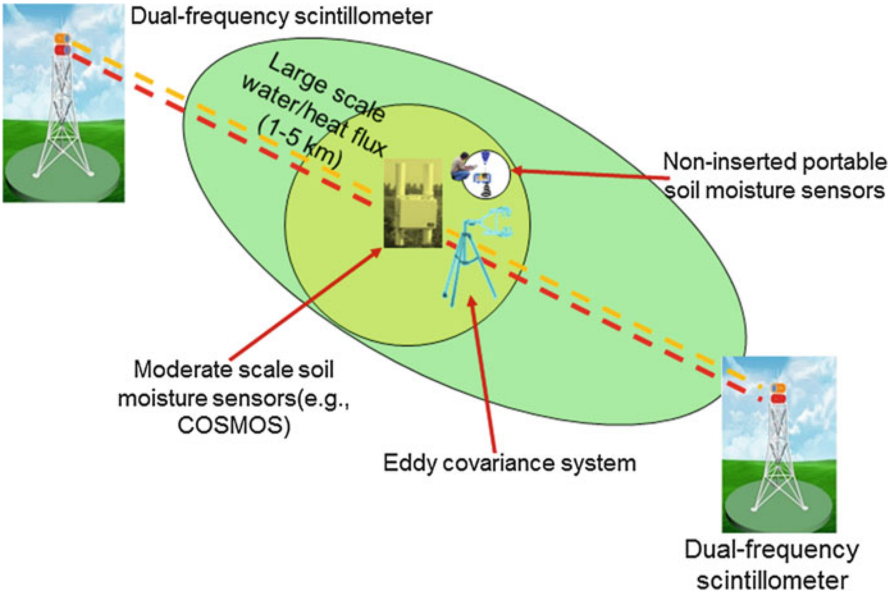

Fig. 2 Typical configuration of a multiscale ground-based observation system for energy balance and soil moisture (Liu et al. 2016; Li et al. 2017). Dual-frequency scintillometers (an infrared scintillometer for measuring sensible heat flux and a microwave scintillometer for measuring latent heat flux) are installed with a separation of approximately 1–5 km. An eddy covariance system is mounted between them, and a wireless sensor network is installed around the EC system, with a cosmic-ray probe in the center

- Large-scale flux and footprint-scale observations (Fig. 2): An eddy covariance (EC) system is a main approach for directly measuring sensible heat and latent heat flux at measurement scales ranging from tens of meters to hundreds of meters. However, EC energy disclosures have been found in nearly all field experiments, possibly because EC systems could not capture large-scale eddies using a single EC set (Foken 2008; Liu et al. 2013). Since the 1990s, optical large aperture scintillometers (LASs) have attracted considerable attention and have been widely used in field experiments (Kleissl et al. 2008; DeBruin 2009; Liu et al. 2011, 2013). LASs can measure sensible heat fluxes on scales of a hundred meters to several kilometers. In recent years, combinations of optical and microwave scintillometers that can measure area sensible heat and latent heat flux directly have been commercialized (Ludi et al. 2005). Their use also makes flux observations easier than medium-resolution satellite remote sensing, such as MODIS and MERIS. In addition, various footprint-scale ground-based observation techniques are widely used in observations of ecohydrological processes. Cosmic-ray probes are the most typical type of equipment; they utilize fast neutrons to detect variations in hydrogen atoms in the soil and atmosphere, thus enabling calculations of soil moisture and snow water equivalent at large scales (Zreda et al. 2012; Han et al. 2014, 2016).

- Many of the newer sensors have developed rapidly and have been widely used for ecohydrological observations. These new sensors include distributed water temperature observation techniques, GPS/GNSS hydrological observations, cosmic rays, isotope methods, new-generation weather radars, ground-based lidar technology, Acoustic Doppler current profiles (ADCPs), the time domain transient electromagnetic method (TDEM), and many other new technologies.

These new observation methods greatly enhance the observability of large-scale ecohydrological processes and enable distributed ground observations.

Challenges in Observing Ecohydrological Processes

Improving the Observation Ability for Ecohydrological Processes

It is critical to continue to develop remotely sensed observation systems that allow for the observation and quantification of ecohydrological processes. There are several challenges to improving observational capability. First, high-resolution remote sensing in space and time is needed to better quantify land-surface heterogeneities and processes occurring at short time scales. Second, better ground-based observational platform designs are needed in terms of measuring ecohydrological processes. In many cases, only variables in specific compartments are measured without considering the complex interactions between hydrology and ecology across all compartments of the land surface. Third, continuous improvements in our ground-based measuring capabilities are needed to allow ecohydrological processes to be quantified.

Integrating Multisource Observations into a Dynamic Model

Integrating multisource observations, e.g., ground- and remote sensing-based observations, into dynamic models to accurately estimate the state and flux variables of ecohydrological processes remains a challenge. Data assimilation is the most promising approach to combine the strengths of multisource observations and dynamic simulations to improve estimations of ecohydrological processes (Han et al. 2013; Huang et al. 2016). However, new assimilation approaches and strategies that are more effective and efficient for improving the estimation of ecohydrological processes and that account for the inherent heterogeneities of land surfaces and upscaling must be developed.

Deriving Upscaling Approaches Through System Observations

Observations of ecohydrological processes must address the scaling issue, a complex problem that is intertwined with the nonlinearities and heterogeneities of ecohydrological processes (Li 2014). Scaling is challenging within all branches of land-surface sciences, including hydrology (Vereecken et al. 2007; Blöschl and Sivapalan 1995; Blöschl 2001), ecology (Wiens 1989), soil science (Lin et al. 2005), and boundary layer meteorology (Raupach and Finnigan 1995), and becomes increasingly prominent as increasing amounts of observational data become available. Multiscale observations must be obtained to further improve our understanding of the scaling issue and validate upscaling methods.

Over the last few years, data availability has increased considerably due to state-of-the-art in situ and remote sensing observations and data acquisition techniques. Moreover, multiscale land-surface observation experiments have been implemented globally within the last decade (Vereecken et al. 2008; Jensen and Illangasekare 2011; Debeer et al. 2015; Li et al. 2013; Yang et al. 2013; Bogena et al. 2012; Zacharias et al. 2008). Those experiments have provided a promising method for bridging knowledge gaps among microscopic-, mesoscopic-, and macroscopic-scale understandings.

Ecohydrological processes are highly controlled by heterogeneities in states and parameters, and assessing the impacts of small-scale heterogeneity on larger-scale behaviors remains a challenge. Thus, how to capture and quantify spatiotemporal heterogeneities of states and parameters across scales is an important issue to resolve.

Overall, upscaling and heterogeneity issues are related to the quantification of uncertainty. Such quantification is extremely complex when observing ecohydrological processes at multiple scales. Thus, the scaling and heterogeneity issues are among the most challenging problems in ecohydrological observation.

Estimating Representativeness Error

Measurements are subject to instrument and representativeness errors, which are independent of each other. However, representativeness error, which is scale dependent, is considerably more difficult to quantify (Li 2014). From a mathematical perspective, the spatial representativeness errors of observations should be made statistically unbiased, and their variances should be as small as possible.

New-generation observing techniques, e.g., those introduced in the section above, are reliable for direct measurements. However, in terms of spatial representativeness, which requires appropriate scaling, both remote sensing and in situ observations exhibit greater uncertainties. In terms of the reliabilities of retrieval and estimation models, which transform direct measurements into the necessary hydrological and ecological variables or parameters, those observations also exhibit considerable uncertainties. Thus, although the original measurements capture the heterogeneities, translating those measurements into useful information for understanding ecohydrological processes requires appropriate scaling schemes and carefully developed models that can provide reliable retrievals. In turn, optimal observation network designs and sampling strategies as well as suitable approaches to quantify the uncertainties associated with scaling and estimation/retrieval models are needed.

Outlook and Perspectives

Advances in ecohydrological observation, both ground-based and remotely sensed, have contributed significantly to understandings of ecohydrological processes. In the future, these new observational technologies and methods should be fully employed to further benefit ecohydrological science.

- To better translate remotely sensed data into information that helps us better understand ecohydrological processes and better inform land-surface models. We should move toward mechanistic models that allow remote sensing measurements to be predicted, e.g., to mechanistically predict vegetation canopy fluorescence, and use those models to estimate parameters that are critical in ecohydrological processes through inverse estimation.
- To better quantify the roles of subsurface processes in ecohydrological processes. Data assimilation can play an important role by integrating different types of data with varying spatial and temporal resolutions. Remotely sensed data are critical because they provide global spatial coverage at different spatial resolutions. Remote sensing techniques that allow ecohydrological processes to be better captured are urgently needed. Recent steps have been undertaken, but considerable work remains to be done.
- To develop observational systems that allow ecohydrological processes to be captured across different scales and across compartments. This goal will require the integration of different sensing systems at selected locations to capture nonlinearities and feedback processes among the subsurface, vegetation, and atmosphere.
- To use well-instrumented watersheds as test beds of new concept for ecohydrological observations. In designing this type of a watershed observation system, multiscale heterogeneity must be considered such that the knowledge obtained can eventually be scaled up to the basin, regional, and global scales.
- To combine monitoring and controllable and synthetic observation experiments. Earth science begins with observations rather than controlled experiments. Nevertheless, as earth science became an experimental science, controllable experiments, the goals of which are to verify scientific hypotheses, were advocated. Accordingly, synthetic observation experiments consisting of monitoring and controlled experiments have become more important.
- To utilize technical advancements in new models. Modeling is lagging behind new observational techniques. Modeling strategies must shift from being spatially explicit to being scale explicit. Data assimilation methods will play a key role in this shift. However, determining how to effectively combine modeling and observation using data assimilation methods remains a considerable challenge that must be addressed.
- To integrate observation systems with integrated models, data services, and decision-making. Observation systems should be fully coupled with data systems and fully used in ecohydrological modeling to gain understandings of ecohydrological processes and to support decision-making by water resources

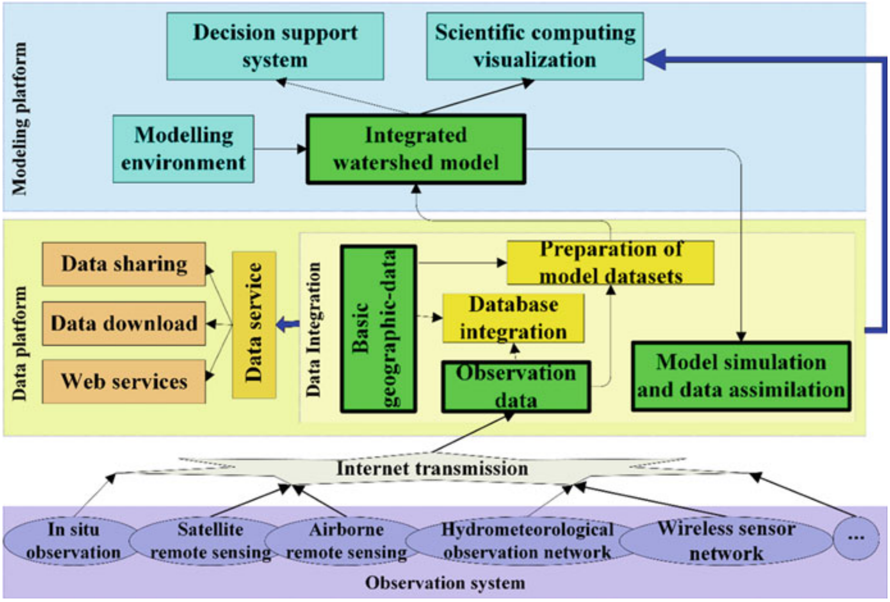

Fig. 3 Integration of multisource observations, integrated models, and information technologies to understand ecohydrological processes

and ecosystem management (Fig. 3). Automatic data collection, data transfer, and the remote control of observational nodes can be realized using the Internet of Things technologies. In addition, various observations at different scales and from different sources should be assimilated into integrated ecohydrological models to provide better estimates of ecohydrological state variables.

Summary of the Contents of this Book

This book is organized with the aim of introducing the state of the art of technologies and measurement methods of ecohydrological processes.

The first chapter provides an overview of the progress, challenges, and perspectives of observing ecohydrological processes. It demonstrates that observations of ecohydrological processes have developed considerably in terms of observation techniques, sensor design and application, and observing platforms (ground-, airborne-, and satellite-based). In particular, applications of next-generation information, communications, and sensor techniques have improved our ability to observe ecohydrological processes considerably. For example, the development and application of wireless sensor networks make it easier for scientists and engineers to collect, control, monitor, and visualize observational data. Nevertheless, problems and challenges remain and must be resolved. The mechanism of the scaling issue remains unclear, and methodologies for scaling transformations must be investigated. Thus, observational experiments must be conducted, and world-class observing systems that can capture heterogeneity, quantify uncertainty, and combine observations and modeling to develop advanced ecohydrological data assimilation systems must be developed.

Chapter ▶ "Ground-Based Soil Moisture Determination" introduces the estimation of soil moisture by ground-based approaches and provides an analysis of the advantages and limitations of each technique. The state of the art in ground-based observation sensors and estimation approaches for soil moisture are highlighted. Spatial scale remains the main issue throughout the chapter. Taking different spatial scales as the breakthrough point, the ground-based techniques of soil moisture are discussed from the point scale to the field scale. Point-scale measurements provide observations with high temporal resolutions, but they have limited spatial representativeness. The application of wireless sensor networks provides multitudes of soil moisture measurements that can capture spatial heterogeneity and allow estimates of soil moisture uncertainty to some extent. Several field-scale observational techniques, such as ground-penetrating radar, ground-based L-band radiometry, cosmic-ray probes, and global navigation satellite system reflectometry, are introduced in detail. The authors also expect to develop new instruments with higher accuracies and spatiotemporal resolutions for soil moisture measurements.

Chapter ▶ "Airborne and Spaceborne Passive Microwave Measurements of Soil Moisture" introduces the basic theories and methodologies of airborne and spaceborne microwave remote sensing for soil moisture, surface roughness, and vegetation parameters. Numerous international missions designed for soil moisture monitoring and mapping continue to be carried out, including the ESA/SMOS, NASA/SMAP, JAXA/GCOM-W, and China/WCOM missions. Surface roughness and vegetation effects are the main uncertainty sources for soil moisture estimation; thus, determining how to estimate those effects remains a challenge. The chapter describes related models and algorithms that attempt to solve the problem by proposing parameterized models and microwave vegetation indices (MVIs). The newly launched SMOS and SMAP satellites provide global soil moisture products for hydrological, meteorological, and climatological applications. However, current soil moisture products continue to have large uncertainties, and their spatial resolutions are coarse. The retrieval accuracy can be increased by combining the L-and S-bands; this finding will be utilized in the upcoming WCOM mission.

Chapter ▶ "Remote Sensing Precipitation: Sensors, Retrievals, Validations, and Applications" systematically introduces the ground-based sensing, retrieval, validation, and remote sensing of precipitation. The authors review the sensors and precipitation retrievals from two aspects of ground- and satellite-based platforms. Full-band remote sensing from visible/infrared to microwave satellite sensors and ground-based weather radars are widely used in precipitation sensing and retrieval. The former provide rainfall estimates best from space, whereas the latter accurately provide estimates of precipitation on the ground; thus, high-quality precipitation estimates can be generated by combining satellite-based sensors with ground-based radars and rain gauges. Global precipitation products, validation, and application are introduced in detail. Single sensors or individual satellites cannot provide adequate precipitation estimates; thus, numerous multi-satellite precipitation products have been developed and applied. The products can typically provide both near-real-time and post-real-time datasets for climatology, meteorology, and hydrology applications. Validations of remotely sensed precipitation products suggest that large uncertainties remain and that the products must be further improved.

Chapter ▶ "Inhomogeneity in Winter Precipitation Measurements" introduces precipitation measurement-related topics, mainly focusing on ground-based measuring methods. The precipitation gauge is regarded as one of the most important and direct measuring tools; this tool is not only the standard of ground-based precipitation measurements but also provides ground truth for validating remotely sensed precipitation estimates. Various types of precipitation gauges as well as their advantages and disadvantages are comprehensively introduced. With the advances of sensor techniques, various new instruments have been developed and applied in precipitation measurements, such as snow pillow, gamma radiation system, and disdrometer methods. The authors demonstrate that identifying the precipitation phase is very important for the functioning of models in many discipline applications, and thus, they provide several methods to identify the precipitation type. Finally, the authors point out the biases that exist in the precipitation observations and propose several methods to correct these biases.

Chapter ▶ "Remotely Sensed Evapotranspiration" introduces the quantification of land surface evapotranspiration based on remote sensing approaches. Three typical methods for evapotranspiration estimation, including surface energy balance models, vegetation index-land surface temperature space approaches, and the Penman-Monteith equation, are presented. Based on an actual experimental example, the authors comprehensively compare the advantages and drawbacks of the three methods. The spatio-temporal scaling and global remote sensing products of evapotranspiration are introduced. The authors believe that great achievements have been made in evapotranspiration estimation, but a tremendous challenge remains. These researchers propose one potential solution to incorporate the evapotranspiration equation into hydrological models to close the water balance within a given domain.

Chapter ▶ "Micrometeorological Methods to Determine Evapotranspiration" introduces the observation of evapotranspiration by micrometeorological methods. The Bowen ratio, eddy covariance, and scintillometer methods are described in detail from the aspects of theory, installation, maintenance, data processing, and footprint source analysis. The Bowen ratio is simple and can integrate latent heat fluxes over large areas and observe fluxes on fine time scales; however, it is overly sensitive to the instrument bias and requires an adequate upwind source area to establish an equilibrium. The eddy covariance method, which is based on the premise of Taylor's frozen turbulence hypothesis, is the most accurate method for measuring water, heat, and carbon dioxide fluxes at fine spatial and temporal resolutions. However, the method requires careful footprint source analysis and data processing. Scintillometers measure areal average sensible and latent heat fluxes based on the Monin-Obukhov similarity theory. Scintillometers have the potential to bridge the gap between point-scale observations and satellite pixel or model grid scales because they can provide average fluxes measurements over hundreds of meters to several kilometers. Furthermore, typical evapotranspiration observation systems and experiments, such as FLUXNET, NEON, CZO, TERENO HOBE, FIFE, WATER, and HiWATER, are reviewed. The scaling mismatch between ground- and remotely sensed-based measurements is the main problem and challenge to be overcome. Scientists and engineers should focus on developing large-scale ET observational methods, such as airborne EC and multiband LAS.

Chapter ► "Surface Runoff" introduces four kinds of measurement techniques for surface runoff, namely, the runoff plot method, curve number method, isotopic tracer method, and salt solution method. First, the definition and formation mechanism of surface runoff are introduced. The authors focus on the analysis of four observation methods for surface runoff and demonstrate the following: (1) the runoff plot method is a prerequisite of watershed scale investigations and is widely used to evaluate the rainfall–runoff processes with better controllability and is also a prerequisite for developing the regional hydrological model; (2) the curve number method depends on using the measured watershed runoff and rainfall data and has been widely applied by the engineers and hydrologists as a simple watershed model; (3) the isotopic tracer method is based on the mass balance of stable isotopes, which could provide comprehensive insights into runoff processes; and (4) the principle of the salt solution method is to measure the shallow water flow by detecting the movement of salt. The modeling methods and vegetation effects of surface runoff are also briefly introduced. Finally, challenges regarding the measurement and simulation of surface runoff are presented.

Chapter ► "Subsurface Flow" provides an overview of current research on subsurface flow, including the concept, theoretical development, classification, controlling factors, and main measurement methods of subsurface flow. The connection between subsurface flow and ecohydrological processes is highlighted, and future research directions are proposed. Physical-based direct observations, isotope tracers, and model simulations are the main methods for subsurface runoff estimation. Direct observation is highly effective but based on collecting water. Isotope tracers and other novel techniques are extensively used but remain underdeveloped in terms of detailed processes, and the precise transport method remains poorly understood. Thus, future directions in subsurface flow research must focus on the understanding of subsurface flow processes, obtaining high-precision and systematic field datasets, extracting commonalities from multiple different well-instrumented sites, testing models, and assessing uncertainties.

Chapter ► "Photosynthesis (NPP, NEP, Respiration)" systematically introduces the measurement and modeling methods for carbon fluxes from field to regional or global scales. The state of the art in carbon flux estimation is reviewed, and challenges are analyzed. Remote sensing-based light use efficient models, process-based ecosystem models, and upscaling approaches are the main methods for estimating terrestrial carbon fluxes. The authors demonstrate that assimilating multisource observations, including remote sensing and field measurements, into dynamic ecosystem models could allow for accurate carbon flux estimation at regional or global scales.

Chapter ► "Leaf Area Index: Advances in Ground-Based Measurement" systematically reviews the main methods for LAI measurements and emphasizes newly advanced methods, namely, LAINet and LAISmart, which are based either on WSNs or mobile computing platform techniques for measuring LAI at high efficiencies and low costs. The former can reduce field data collection costs, and the latter can provide automatic measurements using mobile applications deployed on smartphones. Integrating passive and active optical signals for LAI measurement may be a future trend in this field.

Chapter ► "Radar Remote Sensing of Land Surface Parameters" reviews and analyzes the advantages and limitations of radar remote sensing in land cover and agriculture applications. In particular, the use of PolSAR and InSAR techniques is useful in land cover monitoring, classification, parameter estimation, and crop and forest height retrieval. SAR polarimetry and interferometry should also be employed to separate different elemental scattering processes, which will improve classification and allow for the development of temporal series analysis to obtain multisource information for boosting classification.

Chapter ► "Root Processes Affecting Soil Moisture Patterns in Ecohydrology" introduces the effects of vegetation (especially the plant root processes) on the soil moisture distribution pattern. The root growth, root water uptake and transpiration, plant competitions and rhizosphere properties are identified as the potential drivers of the soil moisture content variability. The authors find that high transpiration, root growth, and root water uptake generally tend to increase the vertical variability for drying conditions in wet soils. These authors also indicate that mechanistic models might help investigate how such interactions control the shape of soil moisture relations in a quantitative manner.

Chapter ► "Upscaling Issues in Ecohydrological Observations" describes the upscaling of soil water processes and hydraulic properties in the vadose zone as well as the upscaling of soil water-plant processes. Applications of data assimilation to estimate the ecohydrologically relevant parameters and novel observational platforms and techniques are also introduced in detail. The integration of novel upscaling approaches and sensing techniques will provide insights into understandings of ecohydrological processes.

Chapter ► "Field Experimental Design for a Watershed Observing System" introduces a field experimental design and watershed observation system for ecohydrological processes. The watershed observation system should be capable of observing water and energy cycles, ecological processes, and socioeconomic activities with state of science. The observation system should be able to capture spatial and temporal heterogeneities and variabilities in ecohydrological variables as well as quantify uncertainties. Taking the WATER and HiWATER experiments as case studies, the design and conduct of a field experiment and establishment of a watershed observation system are described in detail from the perspectives of thematic experiments, observation system establishment, scaling transformation, remote sensing products, data information systems, and data curation and sharing systems.

Acknowledgments This work was supported by the National Natural Science Foundation of China (Grant No. 91425303), and the Strategic Priority Research Program of the Chinese Academy of Sciences, Grant No. XDA20100104.

References

B.W. Abbott, V. Baranov, C. Mendoza-Lera, M. Nikolakopoulou, A. Harjung, T. Kolbe, M.N. Balasubramanian, T.N. Vaessen, F. Ciocca, A. Campeau, M.B. Wallin, P. Romeijn, M. Antonelli, J. Goncalves, T. Datry, A.M. Laverman, J.R. de Dreuzy, D.M. Hannah, S. Krause, C. Oldham, G. Pinay, Using multi-tracer inference to move beyond single-catchment ecohydrology. Earth Sci. Rev. **160**, 19–42 (2016)

S.H. Alemohammad, D.B. McLaughlin, D. Entekhabi, Quantifying precipitation uncertainty for land data assimilation applications. Mon. Weather Rev. **143**, 3276–3299 (2015)

S.P. Anderson, R.C. Bales, C.J. Duffy, Critical zone observatories: building a network to advance interdisciplinary study of Earth surface processes. Mineral. Mag. **72**, 7–10 (2008)

M. Andreasen, K.H. Jensen, D. Desilets, T.E. Franz, M. Zreda, H.R. Bogena, M.C. Looms, Status and perspectives on the cosmic-ray neutron method for soil moisture estimation and other environmental science applications. Vadose Zone J. **16** (2017). https://doi.org/10.2136/vzj2017.04.0086

W.G.M. Bastiaanssen, M. Menenti, R.A. Feddes, A.A.M. Holtslag, A remote sensing surface energy balance algorithm for land (SEBAL) - 1. Formulation. J. Hydrol. **212**, 198–212 (1998)

K. Beven, Robert E. Horton's perceptual model of infiltration processes. Hydrol. Process. **18**, 3447–3460 (2004)

G. Blöschl, Scaling in hydrology. Hydrol. Process. **15**, 709–711 (2001)

G. Blöschl, M. Sivapalan, Scale issues in hydrological modelling: A review. Hydrol. Process. **9**, 251–290 (1995)

H.R. Bogena, M. Herbst, J.A. Huisman, U. Rosenbaum, A. Weuthen, H. Vereecken, Potential of wireless sensor networks for measuring soil water content variability. Vadose Zone J. **9**, 1002–1013 (2010)

H. Bogena, R. Kunkel, T. Puetz, H. Vereecken, E. Kruger, S. Zacharias, P. Dietrich, U. Wollschlager, H. Kunstmann, H. Papen, H.P. Schmid, J.C. Munch, E. Priesack, M. Schwank, O. Bens, A. Brauer, E. Borg, I. Hajnsek, TERENO – long-term monitoring network for terrestrial environmental research. Hydrol. Wasserbewirtsch. **56**, 138–143 (2012)

O. Bonacci, T. Pipan, D.C. Culver, A framework for karst ecohydrology. Environ. Geol. **56**, 891–900 (2009)

J.G. Canadell, H.A. Mooney, D.D. Baldocchi, J.A. Berry, J.R. Ehleringer, C.B. Field, S.T. Gower, D.Y. Hollinger, J.E. Hunt, R.B. Jackson, S.W. Running, G.R. Shaver, W. Steffen, S.E. Trumbore, R. Valentini, B.Y. Bond, Carbon metabolism of the terrestrial biosphere: A multitechnique approach for improved understanding. Ecosystems **3**, 115–130 (2000)

J.M. Chen, T.A. Black, Measuring leaf area index of plant canopies with branch architecture. Agric. For. Meteorol. **57**, 1–12 (1991)

L. Chen, O.W. Frauenfeld, A comprehensive evaluation of precipitation simulations over China based on CMIP5 multimodel ensemble projections. J. Geophys. Res.-Atmos. **119**, 5767–5786 (2014)

D. Cline, S. Yueh, B. Chapman, B. Stankov, A. Gasiewski, D. Masters, K. Elder, R. Kelly, T.H. Painter, S. Miller, NASA cold land processes experiment (CLPX 2002/03): airborne remote sensing. J. Hydrometeorol. **9**, 1427–1433 (2009)

C.M. Debeer, H.S. Wheater, W.L. Quinton, S.K. Carey, R.E. Stewart, M.D. Mackay, P. Marsh, The changing cold regions network: observation, diagnosis and prediction of environmental change in the Saskatchewan and Mackenzie River Basins, Canada. Sci. China Earth Sci. **58**, 46–60 (2015)

H.A.R. DeBruin, Time to think: reflections of a pre-pensioned scintillometer researcher. Bull. Am. Meteorol. Soc. **90**, Es17–Es26 (2009)

K.A. Delin, S.P. Jackson, D.W. Johnson, S.C. Burleigh, R.R. Woodrow, J. Michael Mcauley, J.M. Dohm, F. Ip, T.P.A. Ferré, D.F. Rucker, Environmental studies with the sensor web: principles and practice. Sensors **5**, 103–117 (2005)

Dong, X., H. Liu, Z. Wang, J. Shi, and T. Zhao, COM: the mission concept and payloads of a global water cycle observation mission, in *2014 IEEE Geoscience and Remote Sensing Symposium* (2014), pp. 3338–3341

M. Drusch, J. Moreno, U. Del Bello, R. Franco, Y. Goulas, A. Huth, S. Kraft, E.M. Middleton, F. Miglietta, G. Mohammed, L. Nedbal, U. Rascher, D. Schttemeyer, W. Verhoef, The FLuorescence EXplorer mission concept-ESA's Earth Explorer 8. IEEE Trans. Geosci. Remote Sens. **55**, 1273–1284 (2017)

M. Durand, L.L. Fu, D.P. Lettenmaier, D.E. Alsdorf, E. Rodriguez, D. Esteban-Fernandez, The surface water and ocean topography mission: observing terrestrial surface water and oceanic submesoscale eddies. Proc. IEEE **98**, 766–779 (2010)

P.S. Eagleson, *Ecohydrology: Darwinian expression of vegetation form and function* (Cambridge University Press, Cambridge, 2002)

D. Entekhabi, E.G. Njoku, P.E. O'Neill, K.H. Kellogg, W.T. Crow, W.N. Edelstein, J.K. Entin, S.D. Goodman, T.J. Jackson, J. Johnson, J. Kimball, J.R. Piepmeier, R.D. Koster, N. Martin, K.C. McDonald, M. Moghaddam, S. Moran, R. Reichle, J.C. Shi, M.W. Spencer, S.W. Thurman, L. Tsang, J. Van Zyl, The soil moisture active passive (SMAP) mission. Proc. IEEE **98**, 704–716 (2010)

T. Foken, The energy balance closure problem: an overview. Ecol. Appl. **18**, 1351–1367 (2008)

P. Gong, Progress in recent environmental applications of wireless sensor networks. J. Remote Sens. **14**, 153–157 (2010)

F. Gottardi, C. Obled, J. Gailhard, E. Paquet, Statistical reanalysis of precipitation fields based on ground network data and weather patterns: application over French mountains. J. Hydrol. **432**, 154–167 (2012)

L. Guo, H. Lin, Critical zone research and observatories: current status and future perspectives. Vadose Zone J. **15**(9) (2016). https://doi.org/10.2136/vzj2016.06.0050

X.J. Han, H.J.H. Franssen, X. Li, Y.L. Zhang, C. Montzka, H. Vereecken, Joint assimilation of surface temperature and L-band microwave brightness temperature in land data assimilation. Vadose Zone J. **12**(3), 155–175 (2013)

X.J. Han, R. Jin, X. Li, S.G. Wang, Soil moisture estimation using cosmic-ray soil moisture sensing at heterogeneous farmland. IEEE Geosci. Remote Sens. Lett. **11**, 1659–1663 (2014)

X.J. Han, H.J.H. Franssen, M.Á.J. Bello, R. Rosolem, H. Bogena, F.M. Alzamora, Simultaneous soil moisture and properties estimation for a drip irrigated field by assimilating cosmic-ray neutron intensity. J. Hydrol. **539**, 611–624 (2016)

J.K. Hart, K. Martinez, Environmental sensor networks: a revolution in the earth system science? Earth Sci. Rev. **78**, 177–191 (2006)

A.Y. Hou, R.K. Kakar, S. Neeck, A.A. Azarbarzin, C.D. Kummerow, M. Kojima, R. Oki, K. Nakamura, T. Iguchi, The global precipitation measurement mission. Bull. Am. Meteorol. Soc. **95**, 701–722 (2014)

C.L. Huang, W.J. Chen, Y. Li, H.F. Shen, X. Li, Assimilating multi-source data into land surface model to simultaneously improve estimations of soil moisture, soil temperature, and surface turbulent fluxes in irrigated fields. Agric. For. Meteorol. **230–231**, 142–156 (2016)

S. Hunt, Measurements of photosynthesis and respiration in plants. Physiol. Plant. **117**, 314–325 (2003)

K. Imaoka, M. Kachi, H. Fujii, H. Murakami, M. Hori, A. Ono, T. Igarashi, K. Nakagawa, T. Oki, Y. Honda, H. Shimoda, Global change observation mission (GCOM) for monitoring carbon, water cycles, and climate change. Proc. IEEE **98**, 717–734 (2010)

T. Jackson, Soil Moisture Experiments in 2002 and 2003. American Geophysical Union Meeting. May 28–31, 2002. Washington, DC, EOS Trans. of AGU,83:S191

K.H. Jensen, T.H. Illangasekare, HOBE: a hydrological observatory. Vadose Zone J. **10**, 1–7 (2011)

R. Jin, X. Li, B.P. Yan, X.H. Li, W.M. Luo, M.G. Ma, J.W. Guo, J. Kang, Z.L. Zhu, S.J. Zhao, A nested ecohydrological wireless sensor network for capturing the surface heterogeneity in the midstream areas of the Heihe River Basin, China. IEEE Geosci. Remote Sens. Lett. **11**, 2015–2019 (2014)

R. Jin, X. Li, S.M. Liu, Understanding the heterogeneity of soil moisture and evapotranspiration using multiscale observations from satellites, airborne sensors, and a ground-based observation matrix. IEEE Geosci. Remote Sens. Lett. **14**, 2132–2135 (2017)

I. Jonckheere, S. Fleck, K. Nackaerts, B. Muys, P. Coppin, M. Weiss, F. Baret, Review of methods for in situ leaf area index determination – part I. theories, sensors and hemispherical photography. Agric. For. Meteorol. **121**, 19–35 (2004)

J. Kang, X. Li, R. Jin, Y. Ge, J.F. Wang, J.H. Wang, Hybrid optimal design of the eco-hydrological wireless sensor metwork in the middle reach of the Heihe River Basin, China. Sensors **14**, 19095–19114 (2014)

J. Kang, R. Jin, X. Li, Regression Kriging-based upscaling of soil moisture measurements from a wireless sensor network and multiresource remote sensing information over heterogeneous cropland. IEEE Geosci. Remote Sens. Lett. **12**, 92–96 (2015)

Y.H. Kerr, P. Waldteufel, J.P. Wigneron, J. Martinuzzi, J. Font, M. Berger, Soil moisture retrieval from space: the soil moisture and ocean salinity (SMOS) mission. IEEE Trans. Geosci. Remote Sens. **39**, 1729–1735 (2001)

Y.H. Kerr, P. Waldteufel, J.P. Wigneron, S. Delwart, F. Cabot, J. Boutin, M.J. Escorihuela, J. Font, N. Reul, C. Gruhier, S.E. Juglea, M.R. Drinkwater, A. Hahne, M. Martin-Neira, S. Mecklenburg, M. Martı, The SMOS mission: new tool for monitoring key elements of the global water cycle. Proc. IEEE **98**, 666–687 (2010)

J. Kleissl, J. Gomez, S.H. Hong, J.M.H. Hendrickx, T. Rahn, W.L. Defoor, Large aperture scintillometer intercomparison study. Bound.-Layer Meteorol. **128**, 133–150 (2008)

X. Li, Characterization, controlling, and reduction of uncertainties in the modeling and observation of land-surface systems. Sci. China Earth Sci. **57**, 80–87 (2014)

X. Li, X.W. Li, Z.Y. Li, M.G. Ma, J. Wang, Q. Xiao, Q. Liu, T. Che, E.X. Chen, G.J. Yan, Z.Y. Hu, L.X. Zhang, R.Z. Chu, P.X. Su, Q.H. Liu, S.M. Liu, J.D. Wang, Z. Niu, Y. Chen, R. Jin, W.Z. Wang, Y.H. Ran, X.Z. Xin, H.Z. Ren, Watershed allied telemetry experimental research. J. Geophys. Res.-Atmos. **114** (2009). https://doi.org/10.1029/2008JD011590

X. Li, G.D. Cheng, S.M. Liu, Q. Xiao, M.G. Ma, R. Jin, T. Che, Q.H. Liu, W.Z. Wang, Y. Qi, J.G. Wen, H.Y. Li, G.F. Zhu, J.W. Guo, Y.H. Ran, S.G. Wang, Z.L. Zhu, J. Zhou, X.L. Hu, Z.W. Xu, Heihe Watershed Allied Telemetry Experimental Research (HiWATER): scientific objectives and experimental design. Bull. Am. Meteorol. Soc. **94**, 1145–1160 (2013)

X. Li, S.M. Liu, Q. Xiao, M.G. Ma, R. Jin, T. Che, W.Z. Wang, X.L. Hu, Z.W. Xu, J.G. Wen, L.X. Wang, A multiscale dataset for understanding complex eco-hydrological processes in a heterogeneous oasis system. Sci Data **4**, 170083 (2017). https://doi.org/10.1038/sdata.2017.83

H.S. Lin, D. Wheeler, J. Bell, L. Wilding, Assessment of soil spatial variability at multiple scales. Ecol. Model. **182**, 271–290 (2005)

H. Lin, H.J. Vogel, J. Seibert, Towards holistic studies of the Earth's critical zone: hydropedology perspectives' preface. Hydrol. Earth Syst. Sci. **14**, 479–480 (2010)

C.M. Liu, Y.N. Chen, Z.X. Xu, Eco-hydrology and sustainable development in the arid regions of China preface. Hydrol. Process. **24**, 127–128 (2010)

S.M. Liu, Z.W. Xu, W.Z. Wang, Z.Z. Jia, M.J. Zhu, J. Bai, J.M. Wang, A comparison of eddy-covariance and large aperture scintillometer measurements with respect to the energy balance closure problem. Hydrol. Earth Syst. Sci. **15**, 1291–1306 (2011)

S.M. Liu, Z.W. Xu, Z.L. Zhu, Z.Z. Jia, M.J. Zhu, Measurements of evapotranspiration from eddy-covariance systems and large aperture scintillometers in the Hai River Basin, China. J. Hydrol. **487**, 24–38 (2013)

S.M. Liu, Z.W. Xu, Q.Y. Zhao, T.R. Xu, Y. Ge, Y.F. Ma, L.S. Song, Z.L. Zhu, Z.Z. Jia, F. Zhang, Upscaling evapotranspiration measurements from multi-site to the satellite pixel scale over heterogeneous land surfaces. Agric. For. Meteorol. **230**, 97–113 (2016)

S.M. Li, X. Li, Z.W. Xu, The Heihe integrated observatory network: a basin-scale land surface processes observatory in China. Vadose Zone J., under review (2018)

D. Liverman, J. Rockström, M. Visbek, R. Leemans, T. Abrahamse, B. Becker, R. D'Sousa, K. Jones, H. Mooney, I. Niang, *Future Earth initial design* (International Council for Science, Future Earth, Interim Secretariat, Paris, 2013)

A. Ludi, F. Beyrich, C. Matzler, Determination of the turbulent temperature-humidity correlation from scintillometric measurements. Bound.-Layer Meteorol. **117**, 525–550 (2005)

H. McNairn, T.J. Jackson, G. Wiseman, S. Belair, A. Berg, P. Bullock, A. Colliander, M.H. Cosh, S.B. Kim, R. Magagi, M. Moghaddam, E.G. Njoku, J.R. Adams, S. Homayouni, E.R. Ojo, T.L. Rowlandson, J.L. Shang, K. Goita, M. Hosseini, The soil moisture active passive validation experiment 2012 (SMAPVEX12): prelaunch calibration and validation of the SMAP soil moisture algorithms. IEEE Trans. Geosci. Remote Sens. **53**, 2784–2801 (2015)

M. Meroni, M. Rossini, L. Guanter, L. Alonso, U. Rascher, R. Colombo, J. Moreno, Remote sensing of solar-induced chlorophyll fluorescence: review of methods and applications. Remote Sens. Environ. **113**, 2037–2051 (2009)

NRC, *Earth science and applications from space: national imperatives for the next decade and beyond* (National Academy Press, Washington, DC, 2007)

X.D. Pan, X.J. Tian, X. Li, Z.H. Xie, A.M. Shao, C.Y. Lu, Assimilating Doppler radar radial velocity and reflectivity observations in the weather research and forecasting model by a proper orthogonal-decomposition-based ensemble, three-dimensional variational assimilation method. J. Geophys. Res.-Atmos. **117** (2012). https://doi.org/10.1029/2012jd017684

X.D. Pan, X. Li, G.D. Cheng, Y. Hong, Effects of 4D-Var data assimilation using remote sensing precipitation products in a WRF model over the complex terrain of an arid region river basin. Remote Sens. **9**, 963 (2017). https://doi.org/10.3390/rs9090963

R. Panciera, J.P. Walker, T.J. Jackson, D.A. Gray, M.A. Tanase, D. Ryu, A. Monerris, H. Yardley, C. Rudiger, X.L. Wu, Y. Gao, J.M. Hacker, The soil moisture active passive experiments (SMAPEx): toward soil moisture retrieval from the SMAP mission. IEEE Trans. Geosci. Remote Sens. **52**, 490–507 (2014)

C. Prigent, Precipitation retrieval from space: an overview. Compt. Rendus Geosci. **342**, 380–389 (2010)

Y.H. Qu, Y.Z. Zhang, J.D. Wang, A dynamic Bayesian network data fusion algorithm for estimating leaf area index using time-series data from in situ measurement to remote sensing observations. Int. J. Remote Sens. **33**, 1106–1125 (2012)

Y.H. Qu, Y.Q. Zhu, W.C. Han, J.D. Wang, M.G. Ma, Crop leaf area index observations with a wireless sensor network and its potential for validating remote sensing products. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sen. **7**, 431–444 (2014)

M.R. Raupach, J.J. Finnigan, Scale issues in boundary-layer meteorology: surface energy balances in heterogeneous terrain. Hydrol. Process. **9**, 589–612 (1995)

D.D. Richter, M.L. Mobley, Monitoring Earth's critical zone. Science **326**, 1067–1068 (2009)

S.W. Running, S.T. Gower, A general model of forest ecosystem processes for regional applications.2. Dynamic carbon allocation and nitrogen budgets. Tree Physiol. **9**, 147–160 (1991)

K. Scipal, M. Arcioni, J. Chave, J. Dall, F. Fois, T. Le Toan, C.C. Lin, K. Papathanassiou, S. Quegan, F. Rocca, S. Saatchi, H. Shugart, L. Ulander, M. Williams, The BIOMASS mission 2014; an ESA Earth explorer candidate to measure the BIOMASS of the earth's forests, in *2010 IEEE International Geoscience and Remote Sensing Symposium* (2010), pp. 52–55

P.J. Sellers, Modeling the exchanges of energy, water, and carbon between continents and the atmosphere. Science **275**, 502–509 (1997)

P.J. Sellers, F.G. Hall, G. Asrar, D.E. Strebel, R.E. Murphy, The First ISLSCP field experiment (FIFE). Bull. Am. Meteorol. Soc. **69**, 22–27 (1987)

J.C. Shi, X.L. Dong, T.J. Zhao, J. Y. Du, L. M. Jiang, Y. Du, H. Liu, Z. Wang, D. B. Ji, C. Xiong, WCOM: the science scenario and objectives of a global water cycle observation mission, in *2014 IEEE Geoscience and Remote Sensing Symposium* (2014), pp. 3646–3649

G. Skofronick-Jackson, W.A. Petersen, W. Berg, C. Kidd, E.F. Stocker, D.B. Kirschbaum, R. Kakar, S.A. Braun, G.J. Huffman, T. Iguchi, P.E. Kirstetter, C. Kummerow, R. Meneghini, R. Oki, W.S. Olson, Y.N. Takayabu, K. Furukawa, T. Wilheit, The global precipitation measurement (GPM) mission for science and society. Bull. Am. Meteorol. Soc. **98**, 1679–1695 (2017)

Z. Su, The surface energy balance system (SEBS) for estimation of turbulent heat fluxes. Hydrol. Earth Syst. Sci. **6**, 85–99 (2002)

T. Le Toan, S. Quegan, M.W.J. Davidson, H. Balzter, P. Paillou, K. Papathanassiou, S. Plummer, F. Rocca, S. Saatchi, H. Shugart, L. Ulander, The BIOMASS mission: mapping global forest biomass to better understand the terrestrial carbon cycle. Remote Sens. Environ. **115**, 2850–2860 (2011)

T.L. van Zyl, I. Simonis, G. McFerren, The sensor web: systems of sensor systems. Int. J. Digital Earth **2**, 16–30 (2009)

H. Vereecken, T. Kamai, T. Harter, R. Kasteel, J. Hopmans, J. Vanderborght, Explaining soil moisture variability as a function of mean soil moisture: a stochastic unsaturated flow perspective. Geophys. Res. Lett. **34**, 315–324 (2007)

H. Vereecken, J.A. Huisman, H. Bogena, J. Vanderborght, J.A. Vrugt, J.W. Hopmans, On the value of soil moisture measurements in vadose zone hydrology: a review. Water Resour. Res. **44**, 253–270 (2008)

K. Wang, R.E. Dickinson, A review of global terrestrial evapotranspiration: observation, modeling, climatology, and climatic variability. Rev. Geophys. **50**(2), RG2005 (2012). https://doi.org/10.1029/2011RG000373

E. Ward, W. Buytaert, L. Peaver, H. Wheater, Evaluation of precipitation products over complex mountainous terrain: a water resources perspective. Adv. Water Resour. **34**, 1222–1231 (2011)

J.A. Wiens, Spatial scaling in ecology. Funct. Ecol. **3**, 385–397 (1989)

Z.W. Xu, S.M. Liu, X. Li, S.J. Shi, J.M. Wang, Z.L. Zhu, T.R. Xu, W.Z. Wang, M.G. Ma, Intercomparison of surface energy flux measurement systems used during the HiWATER-MUSOEXE. J. Geophys. Res. Atmos. **118**, 13,140–13,157 (2013)

K. Yang, J. Qin, L. Zhao, Y.Y. Chen, W.J. Tang, M.L. Han, Z. Lazhu, Q. Chen, N. Lv, B.H. Ding, H. Wu, C.G. Lin, A multi-scale soil moisture and freeze-thaw monitoring network on the Third Pole. Bull. Am. Meteorol. Soc. **94**, 1907–1916 (2013)

S. Zacharias, P. Dietrich, H.J. Vogel, R. Seppelt, D. Borchardt, S. Klotz, F. Messner, G. Teutsch, TERENO – methodical approach for the implementation of a terrestrial observatory for Environmental Research in Central Germany, *Consoil 2008*: *Theme B – Functions and Values of Soil-Water Systems; Understanding of Processes* (2008), pp. 85–89

G.F. Zhu, X. Li, K. Zhang, Z.Y. Ding, T. Han, J.Z. Ma, C.L. Huang, J.H. He, T. Ma, Multi-model ensemble prediction of terrestrial evapotranspiration across North China using Bayesian model averaging. Hydrol. Process. **30**, 2861–2879 (2016)

M. Zreda, W.J. Shuttleworth, X. Zeng, C. Zweck, D. Desilets, T.E. Franz, R. Rosolem, COSMOS: the COsmic-ray soil moisture observing system. Hydrol. Earth Syst. Sci. **16**, 4079–4099 (2012)