Space Science Series of ISSI

For other titles published in this series, go to
www.springer.com/series/6592

L. Bengtsson · R.-M. Bonnet · M. Calisto ·
G. Destouni · R. Gurney · J. Johannessen ·
Y. Kerr · W.A. Lahoz · M. Rast
Editors

The Earth's Hydrological Cycle

Previously published in *Surveys in Geophysics*, Volume 35, Issue 3, 2014

Springer

Editors
L. Bengtsson
International Space Science Institute,
Hallerstrasse 6, 3012 Bern, Switzerland
lennart.bengtsson@mpimet.mpg.de

R.-M. Bonnet
International Space Science Institute,
Hallerstrasse 6, 3012 Bern, Switzerland
rmbonnet@issibern.ch

M. Calisto
International Space Science Institute,
Hallerstrasse 6, 3012 Bern, Switzerland
MCalisto@issibern.ch

G. Destouni
Stockholm University, Svante Arrhenius
väg 8, 10691 Stockholm, Sweden
georgia.destouni@natgeo.su.se

R. Gurney
University of Reading, Earley Gate 3,
RG6 6AL Reading, United Kingdom
r.j.gurney@reading.ac.uk

J. Johannessen
Nansen Environmental and Remote
Sensing Center, Thormøhlens gate 47,
5006 Bergen, Norway
johnny.johannessen@nersc.no

Y. Kerr
Center for the Study of the Biosphere
from Space, Avenue Edouard Belin 18,
31401 Toulouse, France
yann.kerr@cesbio.cnes.fr

W.A. Lahoz
Norwegian Institute for Air Research,
Instituttveien 18,
2027 Kjeller, Norway
wal@nilu.no

M. Rast
ESA-ESRIN, Via Galileo Galilei,
00044 Frascati, Italy
Michael.Rast@esa.int

ISSN: 1385-7525
ISBN: 978-94-017-8788-8 ISBN: 978-94-017-8789-5 (eBook)
DOI: 10.1007/978-94-017-8789-5
Springer Dordrecht Heidelberg New York London

Library of Congress Control Number: 2014936873

© Springer Science+Business Media Dordrecht 2014
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Cover illustration: Selected image from "The dramatic retreat of the Aral Sea", released 10/07/2009 10:34 am. See http://www.esa.int/spaceinimages/Images/2009/07/The_dramatic_retreat_of_the_Aral_Sea. Reproduced with the kind permission of ESA © ESA

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Contents

Foreword: International Space Science Institute (ISSI) Workshop on the Earth's Hydrological Cycle
L. Bengtsson **1**

GENERAL SCIENTIFIC OVERVIEW

Review of Understanding of Earth's Hydrological Cycle: Observations, Theory and Modelling
M. Rast · J. Johannessen · W. Mauser **5**

Challenges and Opportunities in Water Cycle Research: WCRP Contributions
K.E. Trenberth · G.R. Asrar **29**

ATMOSPHERE

Physically Consistent Responses of the Global Atmospheric Hydrological Cycle in Models and Observations
R.P. Allan · C. Liu · M. Zahn · D.A. Lavers · E. Koukouvagias · A. Bodas-Salcedo **47**

Quantifying and Reducing Uncertainty in the Large-Scale Response of the Water Cycle
G.M. Martin **67**

LAND SURFACES

Connecting Satellite Observations with Water Cycle Variables Through Land Data Assimilation: Examples Using the NASA GEOS-5 LDAS
R.H. Reichle · G.J.M. De Lannoy · B.A. Forman · C.S. Draper · Q. Liu **91**

Initialisation of Land Surface Variables for Numerical Weather Prediction
P. de Rosnay · G. Balsamo · C. Albergel · J. Muñoz-Sabater · L. Isaksen **121**

Closing the Gaps in Our Knowledge of the Hydrological Cycle over Land: Conceptual Problems
W.A. Lahoz · G.J.M. De Lannoy **137**

OCEANS

Toward Improved Estimation of the Dynamic Topography and Ocean Circulation in the High Latitude and Arctic Ocean: The Importance of GOCE
J.A. Johannessen · R.P. Raj · J.E.Ø. Nilsen · T. Pripp · P. Knudsen · F. Counillon · D. Stammer · L. Bertino · O.B. Andersen · N. Serra · N. Koldunov **175**

Sea Surface Salinity Observations from Space with the SMOS Satellite: A New Means to Monitor the Marine Branch of the Water Cycle
N. Reul · S. Fournier · J. Boutin · O. Hernandez · C. Maes · B. Chapron · G. Alory · Y. Quilfen · J. Tenerelli · S. Morisset · Y. Kerr · S. Mecklenburg · S. Delwart **195**

Role of Ocean in the Variability of Indian Summer Monsoon Rainfall
P.V. Joseph **237**

METHODS AND PROCESS STUDIES

Perspectives in Modelling Climate–Hydrology Interactions
S. Hagemann · T. Blome · F. Saeed · T. Stacke **253**

Downscaling Satellite Precipitation with Emphasis on Extremes: A Variational ℓ_1-Norm Regularization in the Derivative Domain
E. Foufoula-Georgiou · A.M. Ebtehaj · S.Q. Zhang · A.Y. Hou **279**

Global Snow Mass Measurements and the Effect of Stratigraphic Detail on Inversion of Microwave Brightness Temperatures
M. Richardson · I. Davenport · R. Gurney **299**

Glaciers in the Earth's Hydrological Cycle: Assessments of Glacier Mass and Runoff Changes on Global and Regional Scales
V. Radić · R. Hock **327**

Observing Global Surface Water Flood Dynamics
P.D. Bates · J.C. Neal · D. Alsdorf · G.J.-P. Schumann **353**

APPLICATIONS

Arctic Climate and Water Change: Model and Observation Relevance for Assessment and Adaptation
A. Bring · G. Destouni **367**

Irrigation Effects on Hydro-Climatic Change: Basin-Wise Water Balance-Constrained Quantification and Cross-Regional Comparison
S.M. Asokan · G. Destouni **393**

DOI 10.1007/978-94-017-8789-5_1
Reprinted from *Surveys in Geophysics* Journal, DOI 10.1007/s10712-013-9265-8

Foreword: International Space Science Institute (ISSI) Workshop on the Earth's Hydrological Cycle

Lennart Bengtsson

Received: 6 November 2013 / Accepted: 7 November 2013 / Published online: 13 December 2013

Water is a central component in the Earth's system. It is indispensable for life on Earth in its present form and influences virtually every aspect of our planet's life support system. On relatively short time scales, atmospheric water vapor interacts with the atmospheric circulation and is crucial in forming the Earth's climate zones that determine where habitable areas can exist. On the longest time scales of hundreds of millions of years, water contributes to the lubrication of the movements of the tectonic plates, creating a pattern of change that has shaped and is continuing to shape the Earth.

In the atmosphere, water vapor plays a key role in the Earth's energy balance and regulates the Earth's climate in a significant way. Water vapor is the most powerful of the greenhouse gases and serves to enhance the tropospheric temperature because water vapor is physically and dynamically controlled by atmospheric temperature and atmospheric circulation. The total amount of available water on the Earth amounts to some 1.5×10^9 km^3. The dominant part of this, 1.4×10^9 km^3, resides in the oceans. About 29×10^6 km^3 are locked up in the land ice on Greenland and Antarctica, and some 15×10^6 km^3 are estimated to exist as groundwater. If all the ice over the land and all the glaciers were to melt, as has happened several times in the Earth's history, the sea level would rise by some 80 m. In comparison, the total amount of water vapor in the atmosphere is small; it amounts to $\sim$25 kg/m^2, or the equivalent of 25 mm water for each column of air. Yet atmospheric water vapor is crucial for the Earth's energy balance.

The annual mean global values of evaporation and precipitation are $\sim$1,000 mm of water/m^2. However, these values vary enormously in space and time from areas that are almost completely dry to areas where the annual precipitation is more than an order of magnitude larger than the global mean value. An evaporation of 1,000 mm of water/year corresponds to 80 W/m^2 in energy loss for the surface and a corresponding gain for the

---

This Foreword is a slightly amended version of DOI 10.1007/s10712-013-9265-8

L. Bengtsson (✉)
Environmental Systems Science Centre, University of Reading, Reading, West Berkshire RG6 6UR, UK
e-mail: lennart.bengtsson@zmaw.de; lennart.bengtsson@mpimet.mpg.de

atmosphere when condensation takes place. This is the single largest component for heating the atmosphere; it is even larger than the direct solar energy absorbed by the atmosphere. This statement highlights the importance of the hydrological cycle for the energy balance the atmosphere.

As water vapor is also an effective absorber of terrestrial radiation, it contributes significantly to the regulation of the temperature of the lower atmosphere. The greenhouse effect of water vapor is estimated to be ~24 °C. However, water vapor has a residence time of 7–8 days in the atmosphere and responds effectively to temperature through the Clausius–Clapeyron (CC) relation. In the present situation, it is the increase of the long-lasting greenhouse gases, namely CO_2, CH_4, N_2O and the CFCs, that are the drivers of climate change while water vapor generally acts as a positive feedback factor (Lacis et al. 2013). This is a fundamental factor in climate change. Model simulations suggest that water vapor feedback can more than double the initial effect of the long-lasting greenhouse gases.

With a population that has increased more the fourfold over the last 100 years and with an infrastructure that has grown by more than a factor of ten, society at large has become more exposed, in particular, to extremes in precipitation with associated flooding damages. Society has also over time significantly increased the amount of water that is needed, primarily for agriculture as well as for different kinds of industrial usage. This has contributed to a severe lack of water in exposed regions, even affecting major water bodies such as the Aral Sea and Lake Chad that have almost dried up completely during the last decades because of excessive extraction of water.

Other potential problems are disruptions related to climate change. The most severe prospects are systematic changes in weather zones such as a tendency for a poleward shift of the extra-tropical storm tracks that is indicated in climate simulation studies; others are the likelihood of more intense precipitation that will increase severe flooding. The poleward shift of weather systems is expected to create regional water problems with increased precipitation in some areas and decreased precipitation in other regions. Most severe here are the increasing risks of persistent periods of droughts, preferentially in the subtropics of both hemispheres (IPCC 2013).

In summary, society will have to cope with a multitude of disruptive events related to the water cycle due both to natural and anthropogenic effects such as (1) extreme events of heavy and persistent precipitation as well as extended periods of drought, which are all possible within the present climate, (2) anthropogenic actions unrelated to weather and climate, such as large-scale environmental changes caused by changing practices in large-scale agriculture and forestry, and (3) changes in the water cycle as a consequence of climate change. Presently the first two are dominant but gradually, as the climate system is getting warmer, the third factor is expected to be of increasing importance.

A scientific assessment of the Earth's hydrological cycle is a complex task which covers a multitude of areas and applications. The scientific papers in the present volume address a broad area of research related to the Earth's Hydrological Cycle. They represent the outcome of the third workshop within the ISSI Earth's Science Programme. The workshop took place from 6 to 10 February, 2012, in Bern, Switzerland, with the objective of providing an in-depth overview of the Earth's hydrological cycle. The participants in the workshop were experts in a wide range of disciplines; they included geophysicists, meteorologists, hydrologists, oceanographers and climate modelers.

The increase in the world's population and the increasing need for food, energy and natural resources have put increasing stress on the water requirements.

Perhaps the most extreme effect of such a water stress is the almost complete destruction of the world's previously fourth largest lake, the Aral Sea. This is one of the planet's worst environmental disasters. Over a period of some 40 years, the lake has lost more than 90 % of its area. The most likely reason for this is the massive agricultural developments that have used more and more of the water in the catchment areas of the Amu Darya and Syr Darya (Asokan and Destouni 2014).

As the extreme opposite effect, excessive flooding in rivers and in coastal areas is causing significant economic costs and hardship to their populations. Two kinds of events stand out. The first is mostly coupled to excessive precipitation in river catchments. This occurs over all continents during the rainy season, often with devastating consequences. The main cause is not necessarily higher precipitation but enhanced exposure to heavy precipitation mainly due to increased population and increased occupation in exposed areas. The second most important cause is related to coastal flooding that occurs in relation to intense weather systems, in particular tropical cyclones. The coastal flooding in New Orleans in 2005 and in New York in 2012 are prime examples of such events. Fortunately due to the advances made in weather prediction in recent decades, the public was warned several days in advance and evacuated the areas most at risk.

There is overwhelming evidence from theory (Held and Soden 2006, Stevens and Bony 2013) and from empirical and model studies (e.g., Allan 2014) that the atmospheric water vapor content increases with increasing temperature since it varies according to the CC relation. It also follows from theory that the horizontal transport of water vapor also scales with the CC. This is a serious consequence, as it will affect regional precipitation; in areas of convergence (such as the tropical convergence zone and at high latitudes), there will be increased precipitation. Alternatively, it will also affect areas of divergence (such as the subtropical regions), with the consequence of reduced precipitation. This response of the water cycle to climate warming is probably one of the most severe consequences of climate change, as it will amplify the extremes of the hydrological cycle. So far, because of the large variability of precipitation in time and space, we are not yet able to show this from observations but model results demonstrate this response clearly (e.g., Bengtsson 2011).

Even ocean circulation is affected as heavy precipitation will reduce salinity and thus diminish ocean convection. And, in an analogous way, reduced precipitation over ocean areas will increase salinity and increase ocean convection. Observations from ESA's Soil Moisture and Ocean Salinity satellite (SMOS) are providing new and exciting knowledge (Reul et al. 2014) in this area. There is a wide range of methodological studies, mainly related to the handling of the water cycle in climate models due to the fine structure of precipitation processes in the atmosphere that present climate models cannot handle very well (Foufola-Giorgiou 2014). Both satellite and ground-based radar information are of special importance here and highlight the need for higher resolution in weather and climate models.

References

Allan R (2014) Physically consistent responses of the global atmospheric cycle in models and observations. Surv Geophys (this issue)

Asokan S, Destouni G (2014) Irrigation effects on hydro-climatic change: basin-wide water balance-constrained quantification and cross-regional comparison. Surv Geophys (this issue)

Bengtsson L (2011) The global atmospheric water cycle, Environ Res Lett, 5:025001 (8 pp) doi:10.1088/1748-9326/5/2/025001, 2010

Foufola-Giorgiou E (2014) Downscaling satellite precipitation with emphasis on extremes, Surv Geophys (this issue)

Held I, Soden B (2006) Robust response of the hydrological cycle to global warming. J Climate 19:5686–5699

Intergovernmental Panel on Climate Change, IPCC (2013), Climate Change 2013: the physical science basis, Working Group I Contribution to the IPCC Fifth Assessment Report

Lacis A, Hansen J, Jonas J, Oinas V, Russell G (2013) The role of long-lived greenhouse gases as principal LW control knob that governs the global surface temperature for past and future climate change. Tellus (accepted)

Reul N, Fournier S, Boutin J, Hernandes O, Maes C, Chapron B, Alory G, Quilfen Y, Tenerelli J, Morisset S, Kerr Y, Mecklenburg S, Delwart S (2014) Sea surface salinity observations from space with SMOS satellite: new tool to better monitor the marine branch of the water cycle. Surv Geophys (this issue)

Stevens B, Bony S (2013) What are climate models missing? Science 340:1053–1054

DOI 10.1007/978-94-017-8789-5_2
Reprinted from *Surveys in Geophysics* Journal, DOI 10.1007/s10712-014-9279-x

Review of Understanding of Earth's Hydrological Cycle: Observations, Theory and Modelling

Michael Rast · Johnny Johannessen · Wolfram Mauser

Received: 20 January 2014 / Accepted: 22 January 2014 / Published online: 11 March 2014

Abstract Water is our most precious and arguably most undervalued natural resource. It is essential for life on our planet, for food production and economic development. Moreover, water plays a fundamental role in shaping weather and climate. However, with the growing global population, the planet's water resources are constantly under threat from overuse and pollution. In addition, the effects of a changing climate are thought to be leading to an increased frequency of extreme weather causing floods, landslides and drought. The need to understand and monitor our environment and its resources, including advancing our knowledge of the hydrological cycle, has never been more important and apparent. The best approach to do so on a global scale is from space. This paper provides an overview of the major components of the hydrological cycle, the status of their observations from space and related data products and models for hydrological variable retrievals. It also lists the current and planned satellite missions contributing to advancing our understanding of the hydrological cycle on a global scale. Further details of the hydrological cycle are substantiated in several of the other papers in this Special Issue.

Keywords Earth observation · Satellite remote sensing · Water cycle · Hydrological cycle

1 Introduction

The water cycle of the Earth system and its variability at global, regional and local scales are influenced by a range of processes and mutual interactions, feedback mechanisms and

---

M. Rast (✉)
ESA/ESRIN, Frascati, Italy
e-mail: Michael.Rast@esa.int

J. Johannessen
Nansen Environmental & Remote Sensing Center (NERSC), Bergen, Norway

W. Mauser
Ludwig Maximilian University of Munich, Munich, Germany

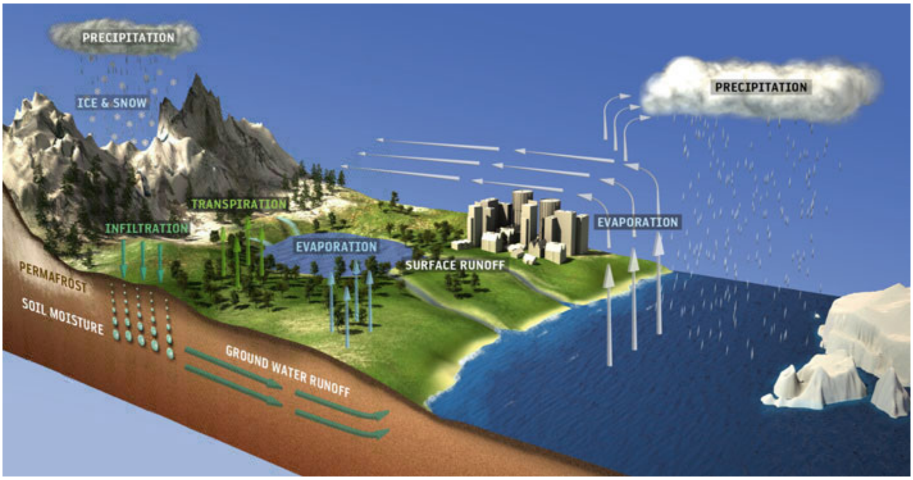

Fig. 1 Schematic illustration of the hydrological cycle (courtesy of European Space Agency, Earth Observation Graphic Bureau)

as well as affected by anthropogenic processes. The scales at which processes interact both spatially and temporally vary across the atmosphere, the hydrosphere, the cryosphere and the biosphere in a complex manner. The hydrological cycle is composed of different components, which include evaporation from water surfaces and bare soil, evapotranspiration from vegetated land, transport of water vapour in the atmosphere, cloud droplet formation and cloud dynamics, the mechanisms leading to liquid and solid precipitation, the movement of water and change in soil moisture in the unsaturated soil, including root dynamics, surface and river run-off, and groundwater flow as schematically illustrated in Fig. 1. Oki and Kanae (2006) give an overview of current knowledge on the world water resources.

The hydrological cycle is the basic purification mechanism for water on Earth as any water constituents are left behind during the phase change from liquid water to water vapour. For billions of years, this process supplied the land surface with freshwater, which was and is the basis for life. The precipitated water dissolved minerals on its way through the hydrological compartments to the oceans and thereby gradually increased ocean salinity. Reliable and adequate supply of clean freshwater is essential to the survival of humankind as well as to the maintenance of terrestrial biotic systems worldwide. However, the rapidly growing human population increasingly stresses available water resources (Ferguson and Maxwell 2012). Human water demand consists of (1) drinking water, (2) sanitation and (3) industrial water and agricultural water to produce biomass for food, fibre, energy and industrial materials. On the global average, the ratio between these three sources of human water demand is approximately 3:4:92 (Turner et al. 2004). Human-induced stresses on available water resources therefore are mainly connected to biomass production through agriculture. Human biomass demand as well as the closely linked agricultural water demand is expected to double by 2050 in order to supply a growing and more prosperous global population with food, fibre, energy and industrial materials (Alexandratos and Bruinsma 2012; Mauser 2009). At this point, it becomes clear that agricultural activities modify the closely coupled global hydrological and carbon cycle through land-use changes, optimization of rainwater use by plants, irrigation, emission of greenhouse gases, changing seasonal albedo and changing plant physiology caused by fertilizers.

Importantly, the expected increase in human water demand and the related change in land use seem to occur faster than any anticipated effect of a changing climate on the availability of freshwater (Piao et al. 2007). To comprehend the combined effect of (and interactions between) increasing human stresses on water supplies, land use and climate change, the understanding of the hydrological cycle needs to be advanced on all interconnected scales from local to global.

Many regional and local studies already exist on how climate change is expected to impact the different compartments of the hydrological cycle and how societies may best adapt to these changes by changing land use, water storage or even water use itself (Ludwig et al. 2008; Christensen et al. 2004; Fowler et al. 2007; Ludwig et al. 2008; Prasch et al. 2013). The majority of these hydrological cycle studies, with few exceptions (e.g., Strengers et al. 2010; Zabel and Mauser 2013), treat this issue as a unidirectional cause–effect chain, where a changing climate influences the regional and local hydrological cycle and thereby affects water availability. Possible effects of dynamic, human-induced land surface changes on the carbon cycle and regional and global water cycle, which in turn may result in a changing climate, are, however, neglected here.

All components of the hydrological cycle are involved in different ways in climate change, either by causing it or by reacting to it, sometimes amplifying each other's action, sometimes giving rise to negative feedbacks such as atmospheric cooling through larger Sun shielding cloud formations from increased evaporation. Variations in the hydrological cycle often take place at regional or even local scale (such as orographic variations in precipitation, small-scale variations of soil physical properties, ecosystem composition or run-off processes), but can still trigger modifications that have an upscale effect possibly leading to global changes in the hydrological cycle. The mechanisms and magnitudes of the feedbacks of local interferences with the hydrological cycle with the regional and global hydrological cycle are complex, largely unknown and cannot satisfactorily be explored with current Earth system models. The feedbacks, e.g., between precipitation, land use, soil moisture and the resulting evapotranspiration, are especially challenging and exhibit strong intermittency and interactions at all scales, which makes them often hard to model with contemporary Earth system models. The strong, small-scale and nonlinear dependency of the participating processes on topography, soil physical properties and plant physiology makes it also hard to estimate their magnitudes from sparse rain gauge, sparser soil moisture and even sparser evapotranspiration measurement networks.

Nevertheless, there are important research issues waiting to be addressed, which are related to the hydrological cycle and its relation both to the carbon cycle and the global climate system. They centre on the feedbacks between the accumulated effects of increasing local human interferences with the hydrological cycle through more intense agricultural use and the global climate system. Most relevant and probably most difficult to understand and model is a possible change in precipitation patterns, which results from land use and evapotranspiration changes in one region and which affects the local and regional hydrological cycle as well as the water availability elsewhere through teleconnections in the global circulation. The described mechanism may be of extreme relevance to the affected region in cases when rainfall is reduced below a critical value, where agriculture becomes impossible. Besides the global climate, a substantial part of the global population may thereby indirectly be affected by collective land-use activities in another part of the globe. Current understanding of the hydrological cycle, its components and the feedbacks with the carbon cycle and the climate system is not sufficient to approach this and similar research questions related to the multi-scale hydrological cycle. Currently available Earth system models both lack spatial resolution to be able to accumulate the nonlinear effects of the local human interferences with the hydrological cycle through land-use changes and do not contain a detailed and realistic representation especially of the terrestrial hydrological cycle and the strongly nonlinear response mainly of its components soil and vegetation during times of water shortage. These important research issues can hardly be addressed by most present hydrological models, which are often conceptual in nature, calibrated to measured data to various degrees and often data poor in design. This is the underlying reason why several authors recently suggest developing new hyper-resolution hydrological land surface models, which can be fully coupled to regional and global climate models to combine global with regional hydrology. These models should be based on first-order principles, close the terrestrial energy, water and carbon balance at all scales, should be able to overcome these scale issues by coupling the very small with the very large processes and should be able to tap the rich global data archives available through remote sensing (Hibbard et al. 2010; Wood et al. 2011; Mauser and Bach 2009; Su et al. 2010).

However, research on these multi-scale issues is currently also severely hampered by the lack of observations of key variables with adequate resolution related to hydrological cycle change in space and time. The measurement of precipitation, for instance, either by ground stations, radars or satellites, is still a challenging task at all spatial and temporal scales that could hamper efforts devoted to understanding and modelling the hydrological cycle and its variability. Surface soil moisture is one of the least observed variables and only recently, with the advent of ESA’s Soil Moisture and Ocean Salinity (SMOS) mission, became accessible to global spatio-temporal measurements with a very coarse spatial but almost adequate temporal resolution.

Vegetation response to water stress and its effect on water release to the atmosphere has to be inferred from models, which simulate evapotranspiration and vegetation surface temperature, which can then be compared to remote sensing measurements under cloud-free conditions. Moreover, the terrestrial snow and ice masses are important components of the global climate system. Snow and ice influence the radiation and surface energy budget, the moisture balance, gas and particle fluxes, precipitation, hydrology, and atmospheric and oceanic circulation. These processes are coupled with the global climate system through complex feedbacks that are not yet well understood. Improved observational data are therefore needed for a better understanding and accurate quantification of the main cryospheric processes and the corresponding representation of the cryosphere in climate models (Lemke et al. 2007).

Remote sensing offers the possibility of delivering the kind of data that allows observing with adequate resolution how key variables related to hydrological cycle change in space and time. Most remote sensing measurements indirectly observe the hydrological cycle and can only be utilized to their full potential when assimilated into appropriate hydrological models. Some recent hydrological model developments have taken up this task (Mauser and Bach 2009) and have shown how to assimilate remote sensing data streams into hydrological models (Bach 2003). Nevertheless, hydrological land surface models face the challenge of a future data-rich environment. They have to learn how to assimilate on all scales globally available, high spatial resolution, frequent coverage remote sensing data, e.g., from the operational Sentinel satellites of the European Commission - European Space Agency (EC-ESA) Copernicus program. This is expected to generate the necessary knowledge to successfully approach issues of the local to global hydrological cycle as outlined above. Critical elements to accomplish this are related to (1) the quality of the observing system, jointly combining the ground-based network and the Earth observation (EO); (2) removal of major knowledge gaps; and (3) development and implementation of high-quality hydrological models with the ability to assimilate EO data.

Table 1 GCOS essential climate variables, variables directly related to the hydrological cycle are marked in italics

Atmosphere	
Surface	Air temperature; *precipitation* Air pressure; Surface radiation budget; Wind speed and direction; *water vapour*
Upper air	Earth radiation budget; Upper air temperature; *Water vapour;* *Cloud properties*; Wind speed and direction
Composition	Carbon dioxide, methane and other greenhouse gases (GHGs); Ozone; Aerosol properties
Ocean	
Surface	Sea-surface temperature, *sea-surface salinity*, *sea level*, sea state, *sea ice*, ocean colour; Carbon dioxide partial pressure
Sub-surface	Temperature, salinity; current; nutrients; carbon; ocean tracer; phytoplankton
Terrestrial	*Lake level; snow cover; glacier and ice caps; albedo*; land-cover fraction of absorbed photo-synthetically active radiation; *Leaf Area Index (LAI) biomass, fire disturbance; soil moisture* *Water use, ground water, river discharge* *Permafrost and seasonally frozen ground*

The usefulness of remote sensing for assessing products beneficial for hydrological monitoring dates back to the 1970s, when the potential of the infrared geostationary data for rainfall and vegetation monitoring was first demonstrated as an important technology for complementing and enhancing information from in situ observational systems. Over the last three decades, the amount of relevant hydrological products derived from satellites has increased, and they have been implemented in derivation of the majority of the Global Climate Observing System's (GCOS) and the Global Terrestrial Observing System's (GTOS) terrestrial and atmospheric Essential Climate Variables (ECVs) (see Table 1). These include, in accordance with GCOS recommendations, precipitation, water vapour, cloud properties, soil moisture, leaf area index, water level and estimates of ground water, evapotranspiration, river discharge, ocean salinity, snow cover, albedo, glaciers and ice caps, ice sheets, permafrost extent and seasonally frozen ground (GCOS 2003).

Each of these variables shown in italics can currently be estimated with the use of at least one Earth observation system although possibly not in all cases with the requisite spatial and temporal resolution for advancing the understanding of local to global feedbacks in the hydrological cycle. However, adequate validation of the satellite data is challenging and often limited implying retrievals lacking satisfactory uncertainty estimates. Commonly, several systems have capabilities to derive identical parameters, and implementation techniques for their merging and blending were suggested. As a result, new integrated, multi-year data sets are being generated, taking advantage of the opportunity presented by the simultaneous operation of key satellites by Europe, Japan and the USA. For instance, the ESA Climate Change Initiative (CCI) aims to demonstrate the full potential of the long-term global Earth Observation archives as a significant and timely contribution to the GCOS Essential Climate Variables (ECVs) databases required by UNFCCC (United Nations Framework for Combating Climate Change). In its first phase, the initiative is targeting the following hydrology-related variables: sea level, sea ice, glaciers and ice caps, ice sheets and clouds. The ongoing discussion on possible operations of convoys and constellations is also expected to strengthen the value and use of the satellite data for understanding and monitoring of the hydrological cycle.

The state-of-the-art overview of currently available EO products for hydrological monitoring and modelling is provided in the following. Importantly, it is not aimed for listing methodologies on how to implement such products in models, as this have been extensively summarized elsewhere (Van Dijk and Renzullo 2011), but it clearly emphasizes the multidisciplinary aspects and complexity that jointly with the wide range of spatial and temporal scales establish a significant demand on the observing system. The individual papers presented in this issue provide further quantitative evidence of the capability and limitation of the observing system.

2 Clouds and Precipitation

Cloud and precipitation systems tend to be somewhat random in character, and they are usually small scale and also evolve very rapidly, especially during the summer in convection regimes. These factors make clouds and precipitation difficult to quantify. Reliable ground-based precipitation measurements are difficult to obtain over regional and global scales because more than 70 % of the Earth's surface is covered by ocean and lakes, and additionally many countries are not equipped with precise rain measuring sensors (i.e., rain gauges and/or radars). In such regions, regional and global scale precipitation measurements from Earth Observation satellite systems are extremely valuable.

Over its lifetime of more than 15 years, the Tropical Rain Monitoring Mission (TRMM) satellite has provided a wealth of information on tropical cyclones and short-duration climate shifts such as El Niño (Curtis et al. 2007) and has proved to be an essential tool for the measurement of precipitation. Current operational and research platforms form a constellation that can be used for the routine generation of precipitation with nominal 3-h temporal and 0.25-degree spatial resolution. Estimates derived at full resolution (4 km) are available up to instantaneously, albeit more sporadically. However, TRMM misses low-rate precipitation, e.g., drizzle, which is expected to contribute significantly to the total precipitation in regions with low rainfall amounts. The upcoming Global Precipitation Measurement (GPM) mission [e.g., http://pmm.nasa.gov/GPM] is a network of satellites and will provide solid and liquid precipitation, including light precipitation. Full vertical profiles of clouds and light and solid precipitation are being observed by CloudSat [http://cloudsat.atmos.colostate.edu/] and will be further improved by EarthCARE (see, e.g., http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Earth_Explorers/EarthCARE/ESA_s_cloud_aerosol_and_radiation_mission). EarthCARE will provide extended vertical cloud profiles with significantly higher sensitivity compared to CloudSat and added Doppler capability for observation of vertical motion within clouds. Solid precipitation and light precipitation will be measured together with full cloud profiles, and heavy precipitation will be detected. In contrast to TRMM and GPM radar satellites, CloudSat and EarthCARE which travel on polar orbits provide full global coverage.

The usefulness of radar systems capable of measuring precipitation (e.g., TRMM Precipitation Radar and CloudSat Cloud Profiling Radar) has been demonstrated (Lonfat et al. 2004). They provide a unique and crucial addition to our observational capabilities for precipitation. The retrieval of precipitation at higher latitudes remains an open challenge. Problems include contamination by the surface background and low-level, frozen precipitation.

In the tropical oceans, large vertical salinity gradients can develop in the upper few metres of the ocean after heavy rainfall as evidenced by Soloviev and Lukas (1996); Schlüssel et al. (1997); and Wijesekera et al. (1999). Signatures of these intense precipitation regimes can be detected in the SMOS Sea-Surface Salinity (SSS) data in the form of freshwater patches, as clearly shown by Reul et al. (2013).

3 Soil Moisture

Numerous soil moisture products are available from active experiments (ERS, ASCAT) (Naeimi et al. 2009; Wagner et al. 1999; Loew et al. 2006), or from passive sensors (AMSR-E, SMOS) (Kerr et al. 2010; Njoku et al. 2003; Loew et al. 2013) and will be available as well from combined passive/active microwave remote sensors (e.g., the planned Soil Moisture Active Passive (SMAP) mission). These operate at coarser (>25 km) resolutions and span altogether more than three decades of data. Recently, a multi-decadal blended dataset was developed that is expected to further enhance the understanding of the water balance in hydrological models (Dorigo et al. 2012; Liu et al. 2011).

The application of coarse resolution soil moisture data in hydrological models is controversial. There seems to be no obvious approach in river run-off studies that would explain under which conditions an improvement could be achieved. Recently, however, several studies demonstrated positive impact when Soil Water Index (SWI) was assimilated (Brocca et al. 2010a, b; Matgen et al. 2011; Meier et al. 2011; Wagner et al. 1999). SWI represents the profile of soil moisture in the root zone which is the hydrological most important zone in terms of run-off generation (Parajka et al. 2006).

Semi-operational products are also available at medium-resolution scale (>1 km) (Pathe et al. 2009). Nevertheless, assimilation of such data into models was restricted by poor radiometric resolution and revisit period. A soil moisture product from Sentinel-1 has been foreseen with coverage every 6 days globally, nearly daily over Europe and Canada (depending on latitude) (Hornacek et al. 2012). With its remarkably improved radiometric accuracy, it has the potential to be of great benefit for data assimilation, anomaly and threshold detection as well as direct input into models operating at medium-resolution scales (Doubková et al. 2012).

4 Evapotranspiration

Neither evapotranspiration (ET) nor any of its components can be directly sensed from satellites, as heat fluxes do not absorb nor emit electromagnetic signals directly. Nonetheless, the last three decades have seen substantial progress in the combined field of evaporation and remote sensing. Current methodologies concentrate on the derivation of ET by combining some of the satellite-observable physical variables that are linked to the evaporation process. Some of the existing algorithms differ in their purpose of application, which to a certain extent defines the type of remote sensing data used and the amount of required ancillary data. The majority use some form of thermal and visible data, with only a few applying microwave observations. Some of these methodologies are fully empirical, and others are based on more physically based calculations of ET via formulations like the ones of Penman (1948), Monteith (1965), and Priestley and Taylor (1972), or focus on solving the surface energy balance targeting the accurate determination of the sensible heat flux (H). Most of the early methods were designed for local-scale studies and agricultural and water management practices, while more recent methodologies have started to pursue the coverage of the entire globe. A general review of these methodologies can be found in Courault et al. (2005); Kalma et al. (2008); Wang and Dickinson (2012) and Su et al. (2010). Notice also that other methodologies based on relatively complex land surface models are also producing global ET estimates for climatological applications (Strengers et al. 2010; Zabel and Mauser 2013). Currently, they use remote sensing-derived parameter fields in a rudimentary way, usually as temporally irregular medium spatial resolution land use, the fraction of Absorbed Photosynthetically Active Radiation (fAPAR) or LAI fields from the MODIS or MERIS instruments. With the advent of higher spatial resolution imaging spectrometers like the German Environmental Mapping and Analysis Program (EnMAP), the assimilation of higher accuracy and more physiological parameters like, e.g., chlorophyll content from remote sensing sources will potentially improve vegetation parameterization (Rodriguez et al. 2011).

In the framework of the Global Energy and Water Cycle Experiment (GEWEX) Data Assimilation Panel (GDAP) LandFlux-Eval initiative, the first satellite-based ET products (reported as latent heat fluxes) and these other estimates have been inter-compared (Jiménez et al. 2011; Mueller et al. 2013). As a contribution to LandFlux, the ESA WACMOS-ET (WAter Cycle Multi-mission Observation Strategy-EvapoTranspiration) project aims at advancing the improvement and characterization of ET estimates from satellite observations, both at continental and regional scales. To this end, a cross-comparison, error assessment and validation exercise of a selection of state-of-art algorithms will be undertaken at different spatial domains and resolutions (Mueller et al. 2013).

Over the ocean, changes in the evaporation can be indirectly inferred from observed changes in sea-surface salinity derived from SMOS and Aquarius in areas of strong precipitation. Further details on this are found in Reul et al. (2013).

5 Ground Water Observations

An emerging application area is the use of the GRACE satellite mission, and its gravimetric measurements of mass changes, which are being used to quantify changes in groundwater storages (Rodell and Famiglietti 2002) as well as melting of ice sheets and glaciers. Plans are currently being formulated for GRACE Follow On and GRACE-II missions, and it is expected that this area of research will continue to expand. The multiple applications of GRACE data were summarized by Cazenave and Chen (2010).

6 Water Extent and Levels

Optical (MERIS, MODIS and AVHRR), active (ERS and Envisat) as well as passive (SSM/I) microwave data were employed to estimate the extent of water bodies, floods and volumes (Prigent et al. 2007), and the first global estimate of wetland extent and dynamics over almost a decade was presented. Importantly, it was the combination of several observation techniques and capitalizing on the strength of each of them that allowed extracting the most from inundation characteristics.

Several semi-operational products exist at local to regional scales ($\sim$100 m–5 km) mostly derived from synthetic aperture radar (SAR) sensors (ESA 2013). SAR sensors demonstrated a great potential for the monitoring of open water bodies at medium-resolution scale (Bartsch et al. 2007). Nevertheless, there is no operational product providing water body extent. In addition, the potential of monitoring inland water levels by using radar altimeters mainly from ERS and Envisat became apparent to the extent that river and lake heights have been produced on a global scale (ESA 2013).

Given the high revisit period, the Sentinel-1 sensor, which is planned to be launched towards the end of 2014, holds a great potential for high-resolution water extent mapping (http://www.esa.int/Our_Activities/Observing_the_Earth/GMES/Sentinel-1).

As for the oceans, areas of interest including the use of optical wavelengths to assess ocean colour, i.e., phyto-plankton and other water borne materials (e.g., MERIS, MODIS, SeaWIFS), and the exploration of radar altimetry to measure water levels in lakes and rivers are aimed to be continued into the future. Regarding the latter, our knowledge of the global dynamics of terrestrial surface waters and their interactions with coastal oceans in estuaries is expected to significantly advance with the planned launch of the joint NASA–CNES–CSA Surface Water Topography Mission (SWOT) in 2020 (http://swot.jpl.nasa.gov/). By measuring water storage changes in all wetlands, lakes and reservoirs and making it possible to estimate discharge in rivers more accurately, SWOT will contribute to a fundamental understanding of the terrestrial branch of the global water cycle. SWOT will also map wetlands and non-channelized flow.

7 Vegetation Stage

Optical vegetation indices and land-cover classifications, as well as passive and active microwave derived estimates of vegetation water content, biomass and vegetation structure can be used to initialize hydrological models. There seems to be a good understanding and variety of independent algorithms that estimate vegetation stage by using data acquired in optical, near-infrared and thermal-infrared spectrum or derived products such as fPAR or LAI. Also, a variety of land-cover classification approaches have been employed in land surface models that implement Normalized Difference Vegetation Index (NDVI) data from AVHRR or SPOT/Vegetation. (DeFries 2008) gives an excellent review of the current status and role of remote sensing on observing the terrestrial vegetation.

Synthetic data experiments undertaken with simulated Sentinel-2 data showed a reduction in the uncertainty in Leaf Area Index (LAI) (Richter et al. 2012; Bach et al. 2012). Severe improvements are expected also in the land-cover classification in the future.

A variety of products is also derived from passive and active microwave observations that include estimates of vegetation water content, biomass, or vegetation height and structure. The latter can be used to estimate variables such as emissivity, canopy conductance and vegetation roughness, which affect the partitioning of radiation into ET and other terms (Van Dijk and Renzullo 2011). Further potentials for greater use of satellite microwave observations include parameterization of biomass, height or aerodynamic roughness. The possibility to observe forest biomass has been proposed by the new Earth Explorer Mission Biomass that uses P-band synthetic aperture polarimetric radar (ESA 2012).

Lastly, to gain a detailed knowledge about the observed medium and to improve understanding of upcoming high-resolution Sentinel and potential Biomass mission, a combination of airborne and terrestrial LiDAR observations is investigated (ESA 2012).

8 Water Vapour

A large variety of space-borne sensors are used to retrieve atmospheric profiles of humidity or the water vapour column amount (microwave, infrared, optical, UV). SSM/I total column water vapour over ocean is mature for climate analysis. In addition, MERIS observations have shown over time a significant potential for high spatial resolution total column water vapour over land during daytime in clear sky, e.g., ESA DUE (Data User Element) GlobVapour.

UV/VIS instruments provide independent means for total column water vapour retrievals, but these measurements are biased towards clear sky. Upper tropospheric humidity (UTH) data sets provide a data source with high value for climate research.

Microwave sounding data sets from AMSU-B, MHS and SSM/T2 hold a great potential to improve our knowledge on UTH—also allowing estimates of absolute humidity. The availability of atmospheric temperature and humidity profiles for more than 30 years has been identified as a critical issue (see, e.g., WMO, 2012 [http://www.wmo.int/pages/prog/www/OSY/Meetings/Wshop-Impact-NWP-5/index.html).

9 Snow

Snow plays an important role in the regional and global hydrological system, since it acts as temporary water storage. As a cause of large land surface albedo changes and because it is highly variable both in time and space, dedicated measurements/monitoring systems are needed. Satellite products have advantage over point-based measurements of the snow-related parameters, especially due to their spatial coverage. The mass of seasonal snow (the snow water equivalent, SWE) accumulated on land surfaces and the extent of the snow-covered area are the principal variables in hydrology and for water resources applications (Rott 2013). They are also essential for determining and modelling surface/atmosphere exchange of mass and energy, and therefore of great importance for numerical weather prediction. Satellite-based snow sensing techniques use visible/infrared (optical), active microwave (SAR) and passive microwave sensing techniques (Frei et al. 2012; Botteron et al. 2013).

Operational snow cover products are commonly related to the fractional snow cover (percentages of the coverage) and snow albedo. They are derived from operational geostationary and numerous polar-orbiting satellite sensors, e.g., AVHRR, MODIS and VIIRS. The use of active microwave (SAR) on ENVISAT and RADARSAT enables the detection of wet snow, indicating melting processes. This information can be integrated in regional hydrological monitoring activities (Bach et al. 2010). Imaging microwave radiometry (SSM/I, AMSR-E) allows the global snow mass to be mapped every day or two at a spatial resolution of about 25 km. SWE retrieval exploits the scattering losses in the (dry) snow pack of the microwave radiation emitted by the soil below snow. The accuracy of SWE retrieval is impaired by uncertainty in snow morphology (grain size, stratification). Satellite scatterometer measurements at Ku-band are also sensitive to morphology of the snow volume (Nghiem and Tsai 2001), suggesting that the active microwave measurements support the characterization of snow scattering properties and thus improve the retrieval of SWE by means of microwave radiometry. The Ku-band scatterometer aboard flying with the second generation MetOp satellite is also used to measure ice sheet snow accumulation, for the measurement of land snow mass at medium/low spatial resolutions and for the characterization of the soil freeze/thaw cycle.

In order to account for improve remote sensing capabilities to measure snow parameters, the validation with ground-based measurements and regional optimized algorithms to account for variable landscape and physical properties effects are still a scientific challenge (IGOS 2007). It is expected that the Sentinels will be beneficial due to their increased temporal coverage, accessibility and ability to monitor snow cover and snow melting process.

10 Permafrost

In the Northern Hemisphere, permafrost regions extend over about 23 million km^2 (Zhang et al. 2001).

Permafrost is currently monitored mainly by means of ground-based point measurements. Remote sensing systems are used as complementary tools, to map surface features of permafrost terrain and monitor their changes driven by climate warming. Surface indicators of permafrost terrains that can be identified by remote sensing images include pingos, thaw lakes and basins, retrogressive thaw slumps, thermo-erosional valleys, thermokarst mounds, ice wedge polygons, beaded drainage, palsa fields, slope failures, and rock glaciers (IGOS 2007). Precise topographical data are required for accurate geocoding of the remote sensing imagery (optical and SAR) so that changes in permafrost features can be tracked accurately. High resolution Digital Elevation Models (DEMs) are also required for modelling hydrology, permafrost distribution, erosion and matter fluxes resulting from permafrost degradation (McNamara et al. 1999). DEMs derived from current satellite systems (e.g., ASTER DEM) are lacking the accuracy needed for these tasks.

11 Glaciers and Ice Caps

Precise data on surface topography of mountain glaciers, ice caps and outlet glaciers of ice sheets are needed as basic information for ice dynamic models, mass balance models, and regional hydrological and climate models. Vertical accuracy on the order of 5 m is acceptable for most of these applications, except for some special ice dynamic models. The requirements in vertical accuracy are more stringent for measuring changes in surface topography to infer glacier mass balance through annual (goal) or multi-annual volume changes. The typical requirement in vertical accuracy for this application is ≤ 1 m (elevation change). There is still high uncertainty in the mass balance of the world's glaciers and ice caps (Lemke et al. 2007). This is due to the fact that accurate mass balance measurements are made only on few glaciers worldwide (Dyurgerov et al. 2005). The representativeness of this small sample is rather questionable, as there is a strong bias towards small glaciers that are easily accessible. Extrapolating from these glaciers to global numbers causes large uncertainty. To overcome this deficit requires spatially detailed, precise repeat measurements of temporal changes in glacier surface topography for a large sample of the glaciers worldwide. For calving glaciers, these measurements need to be complemented by estimates of the calving flux to obtain the mass balance. In this context, radar altimetry and SAR interferometry are providing highly important observations. The sustainability of these observations is also promising in view of the Sentinel-1 and Sentinel-3 missions. The limiting factor for use of SAR interferometry is the temporal variability of the radar signals due to snow fall, drift and melting (Rott and Siegel 1997) as well as due to signal decorrelation in zones of strong sea ice deformation such as along glacier margins.

12 Ice Sheet

Radar altimetry (ERS-RA, Envisat-RA), IceSat-1 and CryoSat 2 have been the main sensors for precise measurements of surface topography on the ice sheets for estimating volume changes. Because the accumulation rate on the main accumulation zones of the ice sheets is rather small, the requirements in vertical accuracy of the repeat measurements are rather high (≤10 cm/year minimum, ≤5 cm/year goal). Uncertainty of radar signal penetration in firn and temporal trends in firn properties are reasons for differences in surface elevation measured by radar and lidar (Brenner et al. 2007). Further uncertainties in computing mass changes of the ice sheets result from variability of firn layer thickness, caused by regional variability of accumulation and temperature (Helsen et al. 2008). These are reasons for the rather large error bars in the mass balance estimates for Antarctica and Greenland in the IPCC report (Lemke et al. 2007). Significant reduction in the uncertainty can be expected by applying different altimetric systems in synergy.

A combination of SAR interferometry and satellite altimetry strengthens the retrieval method and reduces the uncertainties that in turn allows for more detailed studies of topographical and mass changes as well as surface velocity and associated deformation as reported by Rignot et al. (1998) and Shepherd and Wingham (2002) showing that dynamically related thinning is penetrating deep into the interior of the West Antarctic, Pine Island and Thwaites drainage basins. The temporal variability and corresponding signal decorrelation time are again a limiting factor regarding appropriate use of interferometry.

CryoSat (Wingman et al. 2006) is a separate mission developed mainly for measuring ice sheet elevation and sea ice thickness and their changes. By accurately measuring thickness change in both types of ice, CryoSat-2 will provide information to complete the picture and lead to a better understanding of the role ice plays in the Earth system.

The planned Sentinel-1 mission is expected to offer unique operational and scientific capacity due to its increase revisit period. Also, by a synergistic use of Sentinel-1 and the other space-borne SAR missions, often operating at different wavelengths and modes, certain ice types can be easily identified.

13 Sea Ice

Microwave satellite observations are routinely providing essential data on large-scale ice concentration, area, type and large-scale motion. Moreover, measurement of the vertical dimension of sea ice (ridges, freeboard, thickness, snow thickness) and thermodynamic properties (temperature, heat flux) is possible by use of altimeters (e.g., IceSAT, CryoSat 2 for sea ice thickness >0.5 m) and infrared/microwave radiometers (e.g., SMOS for sea ice thickness <0.5 m), although at varying degree of maturity with respect to retrieval accuracies. Many small-scale processes and phenomena related to sea ice deformation and marginal ice zone thermodynamics can also be observed by high-resolution SAR (coupled with optical/infrared images under cloud-free conditions), but there are no systematic and long-term observations because the data coverage is insufficient. Snow depth and snow water equivalent are also important variables in the presence of sea ice that need to be retrieved more reliably from satellites. Data on snow depth can be obtained from satellite sensors such as by combined use of IceSAT and CryoSat, and from optical (snow cover) and passive microwave data (snow depth), or higher frequency (Ka band) SAR data, but the methods are not adequately validated and need to be further carefully examined and improved.

14 Sea Level

Sea levels are rising in several places around the world potentially impacting human populations (e.g., those living in coastal regions and on islands) and the natural environment (e.g., marine ecosystems). Global average sea level rose at an average rate of around

1.7 mm per year in the twentieth century and at a satellite-measured average rate of about 3.2 mm per year from 1993 to 2009 (Meyssignac and Cazenave 2012), but no acceleration has been noted in the period 1993–2013. It is unclear whether the increased rate reflects an increase in the underlying long-term trend. Two main factors contribute to the observed sea-level rise, notably thermal expansion from general warming of the ocean and enhanced freshwater run-off from land-based ice due to increased melting. As such, long-term observations of the global mean and spatial sea-level change jointly with mass changes of the ice sheets and glaciers become of paramount importance for monitoring of the hydrological cycles and constraining of the water budget between the glaciers and the ocean.

15 Sea-surface Salinity

A total of 86 % of the total global evaporation and 78 % of the precipitation occur over the ocean (Schmitt 1995). As such, the ocean surface salinities have proven to be a much more reliable indicator of the water cycle than many of the land-based measurements. Salinity, moreover, is a fundamental ocean state variable and a major determinant, along with Sea-Surface Temperature (SST), of the density of seawater; hence it is a crucial factor in ocean circulation, which in turn has a major impact on climate (Schmitt 2008). Salinity variability at the sea surface also modulates or is modulated by heat, momentum and CO_2 exchange between the ocean and atmosphere. Salinity is an important constraint in ocean models and an indicator of freshwater capping. Sea-surface salinity (SSS) is correlated with differences between precipitation and evaporation (P–E), and improved knowledge of P–E would provide a better estimation of latent heat flux and improve characterization of stratification of the near-surface ocean layer. Besides, SSS variability is also related to the freezing and melting of sea ice and to freshwater river run-off. A better understanding of all these phenomena will be fostered by the recent availability of synoptic measurements of SSS thanks to the ESA SMOS (Font 2010) and NASA/CONAE Aquarius (Le Vine et al. 2010) satellites. Concurrently with the continuous improvements in the accuracy and reliability of these data, a routine monitoring of Sea Surface Salinity (SSS) is becoming possible for the first time thus allowing a quantitative characterization of the above-mentioned processes and their mutual relationships in the context of the hydrological cycle.

16 Freshwater Discharge for Large Mid-Latitude and Tropical Rivers

Occurrences of low salinity surface patches in tropical regions are closely related to the presence of the estuaries of the world's largest rivers in terms of fresh-water discharge (Amazon, Congo, Orinoco, Niger) and the subsequent spreading of freshwater by the surface oceanic circulation. The largest tropical river discharge regions have been studied using satellite altimetry, SST and ocean colour, but each technique has limits in these fresh pool regions, since salinity is the main controller of surface density in those areas. Now the satellite sea surface salinity (SSS) missions bring the unique capability to directly detect and track freshwater spatial gradients and lateral advection across the tropical oceans. The spatial extent of the buoyant plumes of freshwater that form in the tropical seas due to discharges from these world largest rivers can thus be temporally traced by SMOS/Aquarius imagery with an unprecedented resolution (Reul et al. 2013) In particular, river-influenced low salinity waters behave as excellent tracers of the local oceanic circulation and can be a very interesting proxy of subsurface properties (stratification, ocean heat content).

17 Conclusions and Observational Needs for the Future

Since the first experiments performed on assimilating data products derived from EO data into hydrological modelling for practical purposes of water resources management in the early 1980s (Ramamoorthi 1983), there seemed to be a prolonged pause. It is only now, more than 30 years later, that there are signs that application into operational hydrological models progresses rapidly (Van Dijk and Renzullo 2011). This is due to the fact that remote sensing data availability for the complex and interdisciplinary task of hydrology has long remained subcritical to capture the key multidisciplinary variables and their mutual interactions and feedback. EO data availability is now, especially with the prospect of the high-frequency global coverage with high-resolution satellite data, such as the ones from the Sentinels, approaching a point where monitoring of the hydrological variability in the context of a balanced Earth system approach is gradually becoming feasible (see Table 2). Also, hydrological models of operational character and spanning longer time intervals are increasingly becoming available. These models are optimized more and more for the use and assimilation of EO products.

Nevertheless, still today, the main shortcomings in many cases are that derived hydrological indices from so-called black-box models or conceptual models are not based on physical principles and relationships. These black-box models have to be calibrated to unknown and unconsidered circumstances in local and regional watersheds. Because of calibration with historical data, they more or less lack predictive power. This makes their use for any kind of long-range forecast difficult and for the necessary formulation of a global hydrology impossible. In addition, the climate system is governed by the global water and energy cycle, which is constituted of many interdependent and complex processes, interactions and mutual feedbacks in the atmosphere, hydrosphere, cryosphere and biosphere. Only a sound understanding of these processes will allow a quantitative and accurate determination of hydrological variables from satellites. The new wealth of data relevant for hydrological land surface processes studies, which originates from remote sensing sources in turn allows us to abandon conceptual model approaches and further develop hydrological models, which are based on first-order principles in the representation of hydrological land surface processes both in the physical and physiological domain.

The understanding of the complex hydrology of the Earth and its linkage with the carbon cycle and the atmosphere will drive our ability to realistically model the local, regional and global water cycle with high predictive skill and to thereby further reduce uncertainties in climate and Earth system models. Besides the general need for better and longer-term global data coverage at higher temporal and spatial resolutions to constrain model projections, observational needs and areas of continuing difficulties to obtain consistent observations and measurements include

- Improved observations of precipitation as the basic driver both for numerical weather prediction and hydrological land surface models to quantify global and regional trends,
- Increased and continuous precipitation observations over the oceans,
- Improved satellite-based global measurements of land surface parameters and their assimilation into dedicated high spatial resolution hydrological land surface models to better quantify stream flow, soil moisture and evapotranspiration and the carbon cycle,

Table 2 Availability of in situ and remotely sensed data products for hydrological variable retrievals and their status

Variable	In situ	Remote sensing	Product	Status
Soil moisture	Mesonets, climate reference networks, regional soil moisture networks	SMMR, AMSR, HYDROS, SMOS, *ASCAT* METOP-A, *ERS-Scat*	Surface soil moisture (SSM) Root-zone soil moisture Global Soil Wetness Project (GSWP) and Land Data Assimiliation Schemes (LDAS) Products	Products available from a) active (scatterometers and radars), b) passive (radiometers) microwave remote sensors and c) blended soil moisture product Global operational products available at coarse resolution scale (>25 km) Semi-operational, regional, products available at medium-resolution scale (>1 km) 30+ year historical soil moisture product available for long-term analyses (WACMOS) Potential future mission to deliver operational soil moisture SAR product from Sentinel-1
Sea-surface salinity	ARGO profilers, mooring networks, drifters, gliders, cruises, voluntary observing ships (VOS)	SMOS, Aquarius	Sea-Surface Salinity (SSS)	First ever synoptic monitoring for large-scale oceanography Large-scale river plumes and their extension into the open ocean tracking Freshwater barrier layers in tropical regions of intense rain detection Large-scale ocean currents and their salinity fronts characterization Surface processes monitoring in strong evaporation areas
Evapotranspiration	Flux Towers, Flux measurement aircraft, gradient observations, pan evaporation networks	Derived from models by inputting or assimilating vegetation indices from environmental satellites (MODIS, MERIS) and polar meteorological satellites (SUOMI NPP, EPS) as well as land surface temperature (AMSR), soil moisture (AMSR) and precipitation (NOAA's CMORPH technique)	No direct estimate of evapotranspiration	High spatial and temporal resolution product available (WACMOS) Global product available from MODIS and GLEAM

Table 2 continued

Variable	In situ	Remote sensing	Product	Status
Water level	Coastal gauge stations	Radar Altimeters	Satellite altimetry measures water level in large water bodies Optical, active and passive microwave RS data measure the extent of water bodies, floods and volumes	No operational product existing for water bodies extent Semi-operational products exist at local to regional scales (~ 100 m to 5 km)
Estimates of groundwater	Monitoring bores	A residual product of GRACE total water storage (TWS) after removal of other factors (i.e., SSM, ice) Interpretative use of optical and microwave data (e.g., thermal anomalies)	No direct measurement of groundwater	It is essential to have a good estimate of TWS errors to derive a good groundwater estimates GRACE provides an estimate of all water storages; GOCE complements GRACE to derive improved model of geoid
Vegetation stage	Field surveys, Aircraft surveys	Environmental satellites (MODIS, MERIS, MISR, SPOT, Landsat, Sentinels)	Optical vegetation indices (fPAR and LAI) passive or active microwave derived estimates of vegetation water content, biomass, vegetation structure Land-cover classifications	Open opportunities in use of radar and microwave data to estimate biomass and canopy height A good understanding and numerous algorithms for optical vegetation greenness indices
Precipitation	Surface Gages (manual and automatic)	SSM/I, TRMM, AMSR, AMSR-E, Geostationary environmental satellites, polar-orbiting meteorological satellites, GPM, NPOESS, Doppler radar	A routine generation of precipitation products—hourly 0.25-degree resolution via operational and research platforms Estimates from full-resolution observations available up to instantaneous, 4 km resolution, albeit more sporadically. Corrected numerical weather prediction (NWP) derived fields for structure and distribution	The Radar systems (e.g., TRMM PR and CloudSat CPR) provide a unique and crucial addition to our observational capabilities for precipitation. A retrieval at higher latitudes remains an open challenge due to contamination by the surface background as well as by the detection of light intensity, low-level, frozen precipitation.

Table 2 continued

Variable	In situ	Remote sensing	Product	Status
Clouds	Radiosondes, meteorological surface networks	Meteorological geostationary satellites, e.g., Meteosat Second Generation (MSG) Spinning Enhanced Visible and InfraRed Imager (SEVIRI), complemented by lower orbiting satellites (CloudSat, Calipso)	Cloud mask, cloud classification, cloud optical depth, liquid and ice water path, cloud top temperature and infrared emissivity	High spatiotemporal retrievals from SEVIRI provide powerful means to analyse model performance, in particular, the diurnal cycle New observations from CloudSat and Calipso provide powerful tools to validate other instruments series and also improve model parameterizations However, major efforts are needed to make cloud Climate Data Records (CDRs) fit for climate trend analysis Upcoming sensors include EarthCARE at 0.5 km resolution
Water vapour	Radiosondes, meteorological surface networks	A variety of space-borne sensors are used to retrieve atmospheric profiles of humidity or the column amount (microwave, infrared, optical, UV)	Atmospheric profiles of humidity or the column amount	SSM/I total column water vapour over ocean is mature for climate analysis MERIS observations have a significant potential for high spatial resolution total column water vapour over land during daytime in clear sky, e.g., ESA DUE GlobVapour. UV/VIS instruments provide independent means for total column water vapour retrievals but these measurements are biased towards clear sky Upper Tropospheric Humidity (UTH) data sets provide a data source with high value for climate research Microwave sounding data sets from AMSU-B, MHS and SSM/T2 hold a great potential to improve our knowledge on UTH—also allowing estimates of absolute humidity. The availability of atmospheric temperature and humidity profiles for 30 and more years is a critical issue The GEWEX Radiation Panel plans to carry out an intercomparison exercise

Table 2 continued

Variable	In situ	Remote sensing	Product	Status
Streamflow	Streamflow gages, field observation, global runoff data centre	Laser, radar altimeter, InSAR systems	River runoff	Experimental
Water quality	In stream sampling Buoys	MERIS, MODIS, SeaWIFS, Landsat	Ocean Colour, water quality indicators	Semi-operational coastal water quality assessments
Snow	Snow pillow networks, snow surveys	Geostationary environmental satellites, polar-orbiting meteorological satellites ATSR-2/ATSR, MERIS, MODIS, SSM/I, AMSR, NPOESS	Snow cover and snow water equivalent water storage from optical and passive microwave observations	Experimental
Permafrost	Temperature- and moisture probes	Only indirect, complementarity through SAR interferogrammes together with high precision digital elevation models (DEMs) and Thermal InfraRed (TIR) observations	Differential Interfergrammes, TIR maps	Experimental, terrain movement observations over time

Sources CEOS handbook (2013); Doubková et al. (2011); Van Dijk and Renzullo (2011)

- Enhanced ground water monitoring from satellite gravity observations,
- Enhanced monitoring of water quality, not only in coastal zones, but also over inland water bodies and large rivers,
- Improved inputs from higher resolution space data for land snow- and ice inventories as important water storage and frozen soil/permafrost monitoring,
- Inventories of data needed to do broad assessments of socio-economic trends of water use (e.g., agricultural water demands),
- Improved assessment of the insights offered by the recent satellite monitoring of sea-surface salinity regarding the oceanic branch of the hydrological cycle,
- Improved quantitative observation of river discharge,
- Enhanced monitoring of the surface albedo (from changes in snow, cover, sea ice extent) and its influence on evaporation, cloud formation and precipitation.

The new generation of operational satellites is expected through their increased coverage and temporal repeat observation capability to augment data availability and as such further our understanding of the hydrological cycle, also helping to move towards a quantitative closure of the water budget. Here, increased international collaboration and the use of observations from many satellites and/or satellite constellations will constitute important assets.

Acknowledgments The authors gratefully acknowledge the contributions by Florian Appel, Heike Bach, Marcela Doubkova, Diego Fernández-Prieto, Paul Ingmann, Roberto Sabia and Tobias Wehr.

References

Alexandratos N, Bruinsma J (2012) World agriculture towards 2030/2050, ESA Working paper No. 12–03, Agricultural Development Economics Division, Food and Agricultural Organisation of the United Nations, June 2012

Bach H, Mauser W (2003) Methods and examples for remote sensing data assimilation in land surface process modelling. IEEE Trans Geosci Remote Sens (TGARSS) 41(7):1629–1637

Bach H, Appel F, Rust F, Mauser W (2010) Polar View Snow Service—operational snow cover mapping for downstream Runoff modeling and hydropower predictions. Proceedings of the ESA Living Planet Symposium. ESA Special Publication SP-686, CD-Rom

Bach H, Migdall S, Spannraft K, Hank T, Mauser W (2012) Potential and challenges of using sentinel-2 for smart farming; sentinel-2 preparatory symposium, ESA–ESRIN, Frascati, Italy, 23–27

Bartsch A, Kidd RA, Pathe C, Scipal K (2007) Satellite radar imagery for monitoring inland wetlands in boreal and sub-arctic environments. Methods 317(3):305–317. doi:10.1002/aqc.836

Botteron C, Dawes N, Leclère J, Skaloud J, Weijs SV, Farine P-A (2013) Soil moisture and snow properties determination with GNSS in alpine environments: challenges, status, and perspectives. Remote Sens 5:3516–3543

Brenner AC, DiMarzio JP, Zwally HJ (2007) Precision and accuracy of satellite radar and laser altimeter data over the continental ice sheets. IEEE Trans Geosci Remote Sens 45(2). doi:10.1109/TGRS.2006.887172

Brocca L, Melone F, Moramarco T, Morbidelli R (2010a) Spatial-temporal variability of soil moisture and its estimation across scales. Water Resour Res, 46(2), art. no. W02516

Brocca L, Melone F, Moramarco T, Wagner W, Naeimi V, Bartalis Z, Hasenauer S (2010b) Improving runoff prediction through the assimilation of the ASCAT soil moisture product. Hydrol Earth Syst Sci Dis 14(10):1881–1893. doi:10.5194/hess-14-1881-2010

Cazenave A, Chen J (2010) Time-variable gravity from space and present-day mass redistribution in the Earth system. Earth Plan Sci Lett 298(3–4):263–274. doi:10.1016/j.epsl.2010.07.035

CEOS (2013) The Earth observation handbook—special edition for rio + 20 Updated for 2014. http://www.eohandbook.com

Christensen NS, Wood AW, Voisin N, Lettenmaier DP, Palmer RN (2004) The effects of climate change on the hydrology and water resources of the colorado river basin. Clim Change 62:337–363

Courault D, Seguin B, Olioso A (2005) Review on estimation of evapotranspiration from remote sensing data: from empirical to numerical modelling approaches. Irrigat Drain Syst 19(3):223–249

Curtis S, Salahuddin A, Adler RF, Huffman GJ, Gu G, Hong Y (2007) Precipitation extremes estimated by GPCP and TRMM: ENSO relationships. J Hydrometeorol. doi:10.1175/JHM601.1

DeFries R (2008) Terrestrial vegetation in the coupled human-Earth system: contributions of remote sensing. Ann Rev Environ Resour 2008(33):369–390. doi:10.1146/annurev.environ.33.020107.113339

Dorigo WA, De Jeu R, Chung D, Parinussa R, Liu Y, Wagner W, Fernández-Prieto D (2012) Evaluating global trends (1988–2010) in harmonized multi-satellite surface soil moisture. Geophys Res Lett 39:L18405. doi:10.1029/2012GL052988

Doubková M, Wagner W, De Jeu RAM (2011) Water from space: soil moisture and landscape dynamics. WIRADA Science Symposium, Melbourne

Doubková M, Van Dijk AIJM, Sabel D, Wagner W, Blöschl G (2012) Evaluation of the predicted error of the soil moisture retrieval from C-band SAR by comparison against modelled soil moisture estimates over Australia. Remote Sens Environ 120:188–196

Dyurgerov MB, Mark FM (2005) Glaciers and the changing Earth system: a 2004 Snapshot. Institute of Arctic and Alpine Research. Occasional paper 58

ESA (2012) The biomass mission. Report for mission selection—ESA SP-1324/1. http://esamultimedia.esa.int/docs/EarthObservation/SP1324-1_BIOMASSr.pdf

ESA (2013) ERS missions, 20 years of observing Earth. ESA SP-1326, ESA Communications, Fletcher K (ed), ISBN 978-92-9221-424-1, Leiden July 2013

Ferguson IM, Maxwell RM (2012) Human impacts on terrestrial hydrology: climate change versus pumping and irrigation. Environ Res Lett 7(2012) 044022 (8pp). doi:10.1088/1748-9326/7/4/044022

Font J, Camps A, Borges A, Martín-Neira M, Boutin J, Reul N, Kerr YH, Hahne A, Mecklenburg S (2010) SMOS: the challenging sea surface salinity measurement from space. Proc IEEE 98:649–665

Fowler HJ, Blenkinsop S, Tebaldi C (2007) Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling—review. Int J Climatol 27:1547–1578. doi:10.1002/joc.1556

Frei A, Tedesco M, Lee S, Foster J, Hall DK, Kelly R, Robinson DA (2012) A review of global satellite-derived snow products. Adv Space Res 50:1007–1029

GCOS (2003) The second report on the adequacy of the global observing systems for climate in support of the UNFCCC. GCOS– 82 (WMO/TD No. 1143) April 2003. (http://www.wmo.int/pages/prog/gcos/Publications/gcos-82_2AR.pdf)

Helsen MM, van den Broeke MR, van de Wal RSW, van de Berg WJ, van Meijgaard E, Davis CH, Li Y, Goodwin I (2008) Elevation changes in Antarctica mainly determined by accumulation variability. Science 320:1626–1629

Hibbard K, Janetos A, van Vuuren DP, Pongratz J, Rose SK, Betts R, Herold M, Feddema JJ (2010) Research priorities in land use and land-cover change for the Earth system and integrated assessment modelling. Int J Climatol 30: 2118–2128. doi:10.1002/joc.2150

Hornacek M, Wagner W, Sabel D, Truong H, Snoeij P, Hahmann T, Diedrich E et al (2012) Potential for high resolution systematic global surface soil moisture retrieval via change detection using sentinel-1. IEEE J Sel Top Appl Earth Observation Remote Sens 5(4):1303–1311

IGOS (2007) Integrated Global Observing Strategy Cryosphere Theme Report, August 2007, WMO/TD No 1405

Jiménez C et al (2011) Global intercomparison of 12 land surface heat flux estimates. J Geophys Res 116:D02102. doi:10.1029/2010JD014545

Kalma JT, McVicar M, McCabe M (2008) Estimating land surface evaporation: a review of methods using remotely sensed surface temperature data. Surveys Geophys 29(4):421–469

Kerr YH, Waldteufel P, Wigneron JP, Delwart S, Cabot F, Boutin J, Escorihuela MJ et al (2010) The SMOS L: new tool for monitoring key elements of the global water cycle. Proc IEEE 98(5):666–687

Le Vine DM, Lagerloef GSE, Torrusio SE (2010) Aquarius and remote sensing of sea surface salinity from Space. Proceedings of the IEEE 98(5) 688–703. doi:10.1109/JPROC.2010.2040550

Lemke P, Ren J, Alley RB, Allison I, Carrasco J, Flato G, Fujii Y, Kaser G, Mote P, Thomas RH, Zhang T (2007) Observations: changes in snow, ice and frozen ground. Climate Change: the physical science basis; summary for policymakers, technical summary and frequently asked questions. Part of the Working Group I contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, ISBN: 92-9169-121-6. hdl:10013/epic.30870

Liu YY, Parinussa RM, Dorigo WA, De Jeu RAM, Wagner WM, Van Dijk AIJ, McCabe MF et al (2011) Developing an improved soil moisture dataset by blending passive and active microwave satellite-based retrievals. Hydrol Earth Syst Sci 15(2):425–436