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Consistent monitoring of global water cycle and resources variability across scales: Where do we stand?

S. Dietrich, W. Dorigo, V. Aich & et al.

ICWRGC International Centre for Water Resources and Global Change

unesco Centre Under the auspices of UNESCO

bfg Bundesanstalt für Gewässerkunde

TU WIEN GEO

WORLD METEOROLOGICAL ORGANIZATION

Global Water Partnership

GCOS KEEPING WATCH OVER OUR CLIMATE

WMO IOC International Science Council UN environment

Our Team

- Motivated by GCOS
- 32 authors, 16 countries, 29 institutes
- experts for atmospheric, oceanic and terrestrial obervations of the water cycle (in situ and satellite EO)
- Our publication
  - Dorigo, Dietrich et al. 2021 (BAMS), https://doi.org/10.1175/BAMS-D-19-0316.1
  - Key contribution to the GCOS Status Report 2021

BAMS Article

SPECIAL Earth's Energy Imbalance COLLECTION

SPECIAL Global Precipitation Measurement (GPM) COLLECTION

Closing the Water Cycle from Observations across Scales

Where Do We Stand?

Wouter Dorigo, Stephan Dietrich, Filipe Aires, Luca Brocca, Sarah Carter, Jean-François Cretaux, David Dunkerley, Hiroyuki Enomoto, René Forsberg, Andreas Güntner, Michaela I. Hegglin, Rainer Hollmann, Dale F. Hurst, Johnny A. Johannessen, Christian Kummerow, Tong Lee, Kari Luojus, Ulrich Looser, Diego G. Miralles, Victor Pellet, Thomas Recknagel, Claudia Ruz Vargas, Udo Schneider, Philippe Schoeneich, Marc Schröder, Nigel Tapper, Valery Vuglinsky, Wolfgang Wagner, Lisan Yu, Luca Zappa, Michael Zemp, and Valentin Aich

ABSTRACT: Life on Earth vitally depends on the availability of water. Human pressure on freshwater resources is increasing, as is human exposure to weather-related extremes (droughts, storms, floods) caused by climate change. Understanding these changes is pivotal for developing mitigation and adaptation strategies. The Global Climate Observing System (GCOS) defines a suite of essential climate variables (ECVs), many related to the water cycle, required to systematically monitor Earth's climate system. Since long-term observations of these ECVs are derived from different observation techniques, platforms, instruments, and retrieval algorithms, they often lack the accuracy, completeness, and resolution, to consistently characterize water cycle variability at multiple spatial and temporal scales. Here, we review the capability of ground-based and remotely sensed observations of water cycle ECVs to consistently observe the hydrological cycle. We evaluate the relevant land, atmosphere, and ocean water storages and the fluxes between them, including anthropogenic water use. Particularly, we assess how well they close on multiple temporal and spatial scales. On this basis, we discuss gaps in observation systems and formulate guidelines for future water cycle observation strategies. We conclude that, while long-term water cycle monitoring has greatly advanced in the past, many observational gaps still need to be overcome to close the water budget and enable a comprehensive and consistent assessment across scales. Trends in water cycle components can only be observed with great uncertainty, mainly due to insufficient length and homogeneity. An advanced closure of the water cycle requires improved model–data synthesis capabilities, particularly at regional to local scales.

KEYWORDS: Hydrologic cycle; Satellite observations; Surface fluxes; Surface observations; Water masses/storage; Water budget/balance

https://doi.org/10.1175/BAMS-D-19-0316.1
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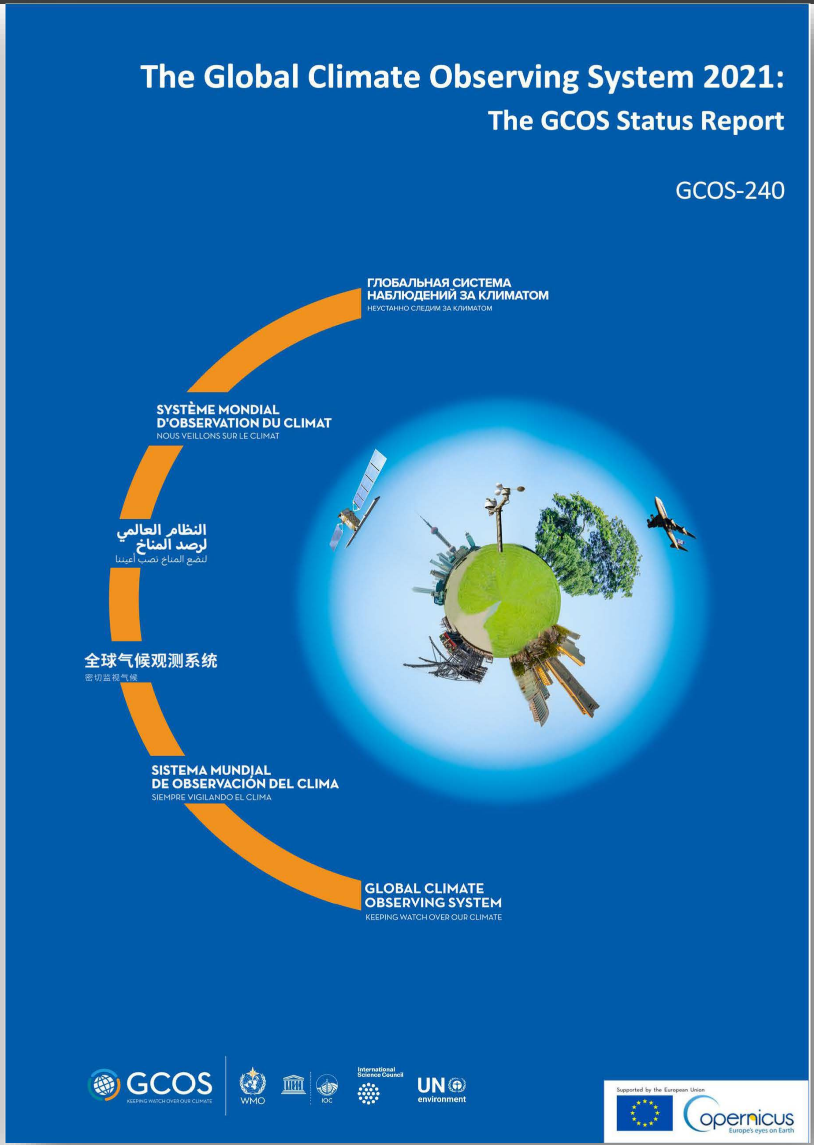
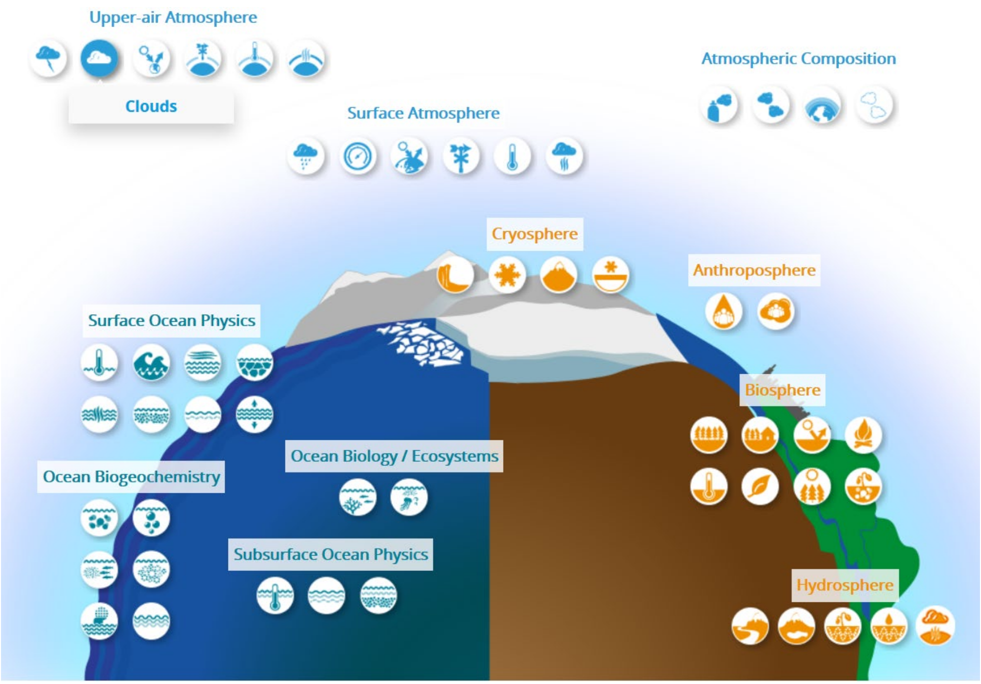
In final form 30 March 2021



Agenda

By assessing the capability of available ground and Earth observations of water cycle ECVs, we

1. provide the **most-recent observation based assessment** of the water cycle and global water storages,
2. **discuss gaps** in existing observation systems,
3. **formulate guidelines** for future water cycle observation strategies.



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Closing the water cycle from observations across scales: Where do we stand?

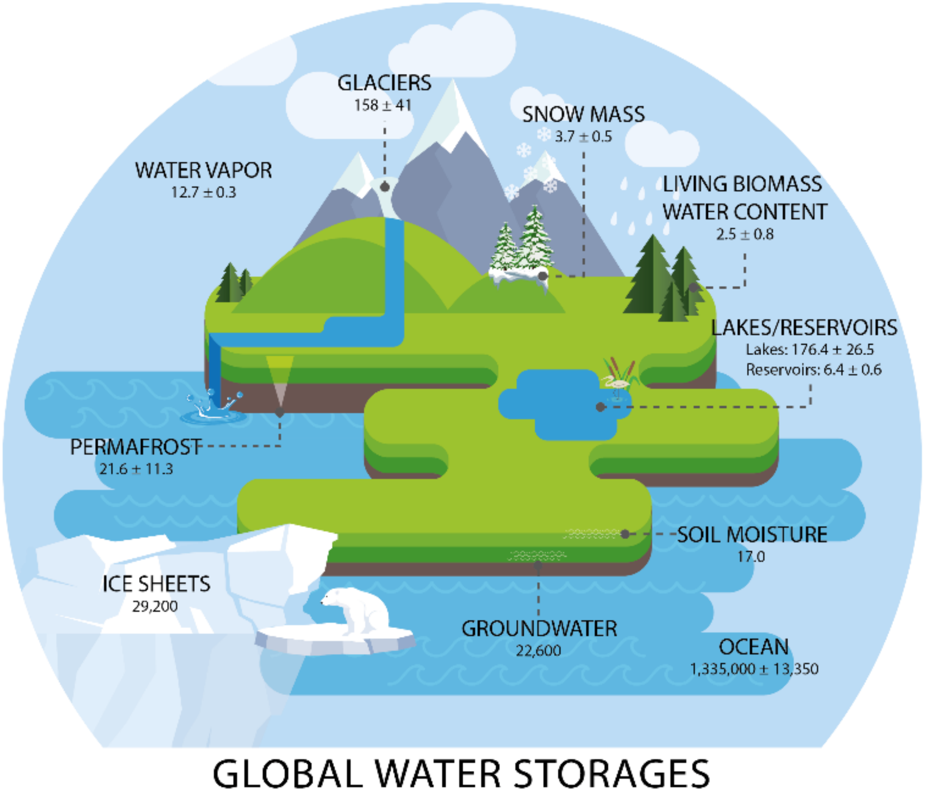

Fig. 1. Observed estimates of global water cycle storages (in 10^3 km^3) and their uncertainties.

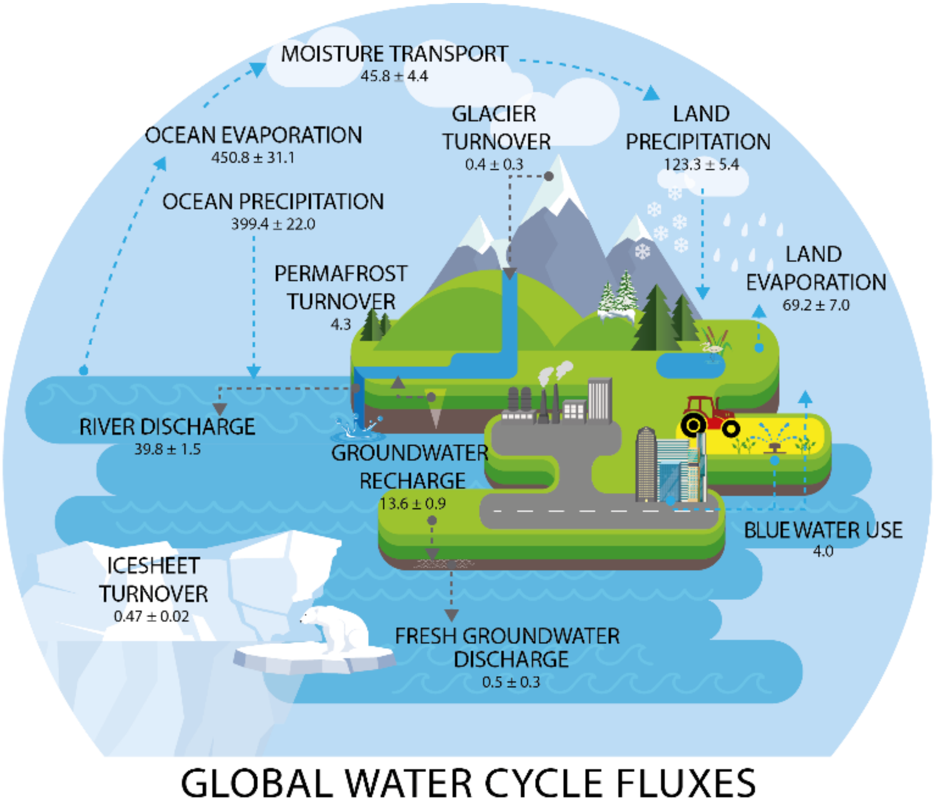

Fig. 2. Observed estimates of annual global water cycle fluxes in 10^3 km^3 .

Dorigo et al. (2021/BAMS)

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Gaps in existing observation systems

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Global Terrestrial Network – Hydrology: a network of operational global data centers of essential water variables

GTN-H

Network of the global water data centres, most of them operating under the umbrella of UN organizations, mostly in situ obs.

Joint project of the World Meteorological Organization (WMO) and the Global Climate Observing System (GCOS); implemented in 2001

9 experts from GTN-H data centres contributed to this study.

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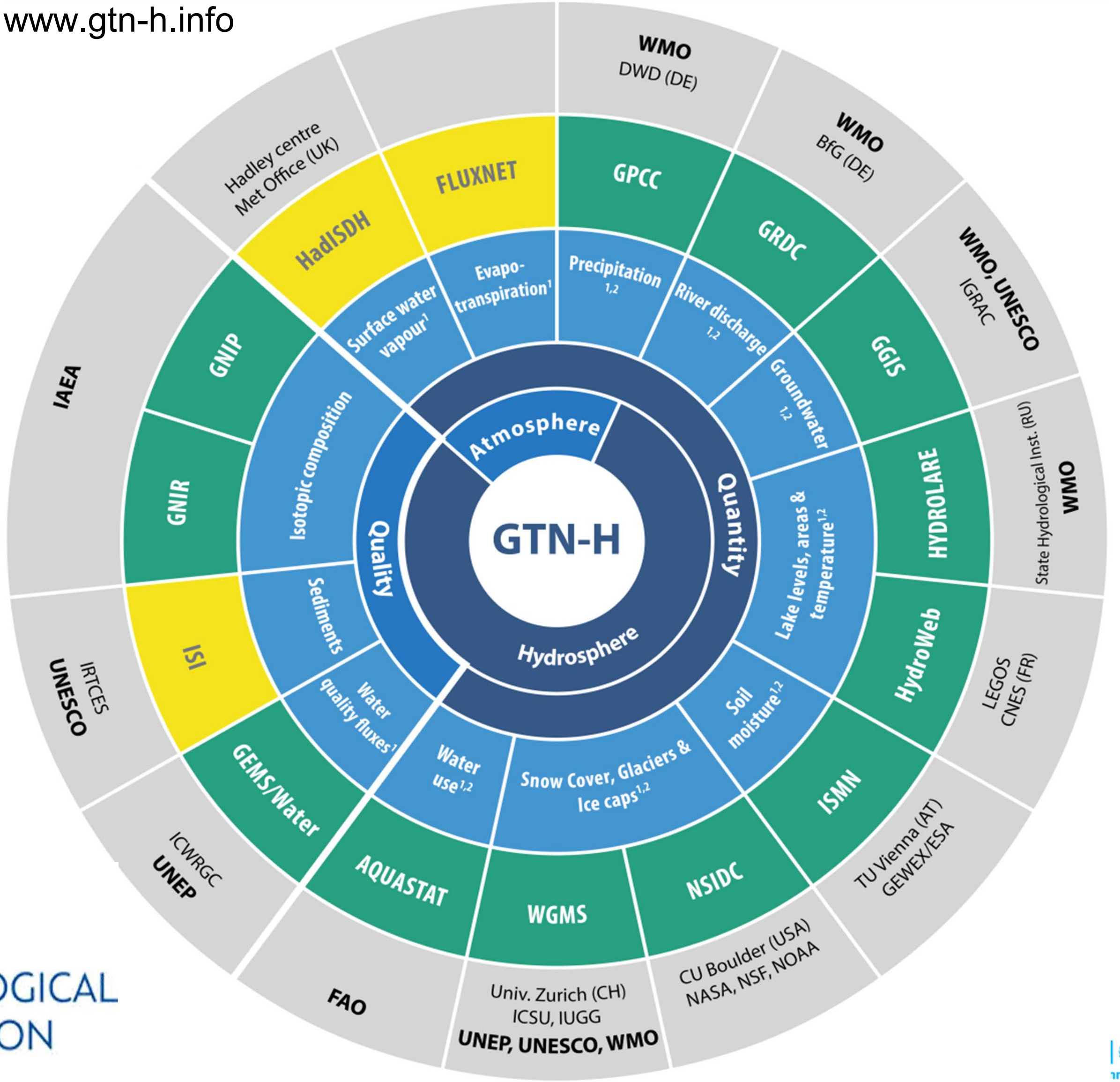
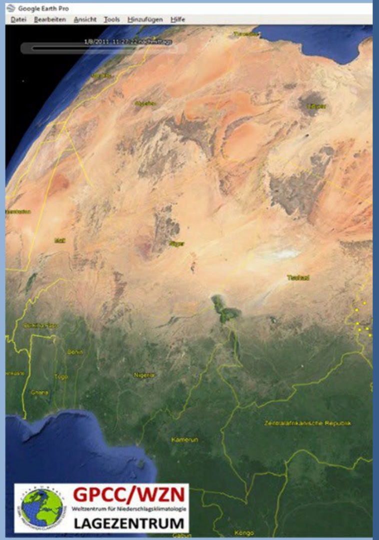
www.gtn-h.info



observational gaps: some examples from in-situ obs

Precipitation

Global Precipitatio
Climatology Centre

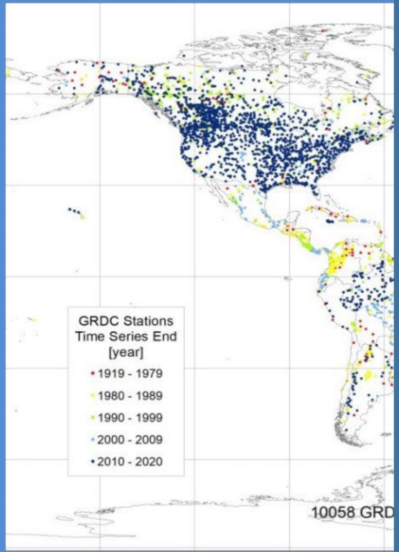


GPCC Precipitat

Discharge

Global Runoff Data

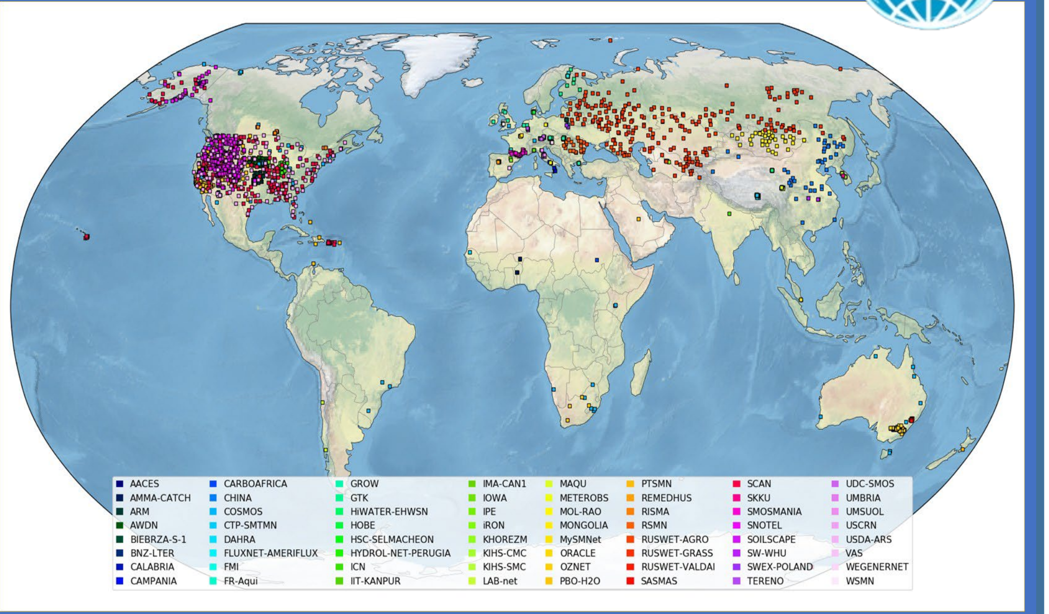
Operational since 1988 ur



Soil Moisture

International Soil Moisture Network (ISMN)

- *Dorigo et al., (2021, HESS):* The international Soil Moisture Network (ISMN): *serving Earth system science for over a decade".*
- *ESA funded since 2009 (soft money)*
- *In transfer for permanent operation from TU Wien to ICWRGC/BfG (Germany)*
- *Financed by German Federal Ministry for Digital and Transport*



*Soil moisture observation networks contributing to the **ISMN***

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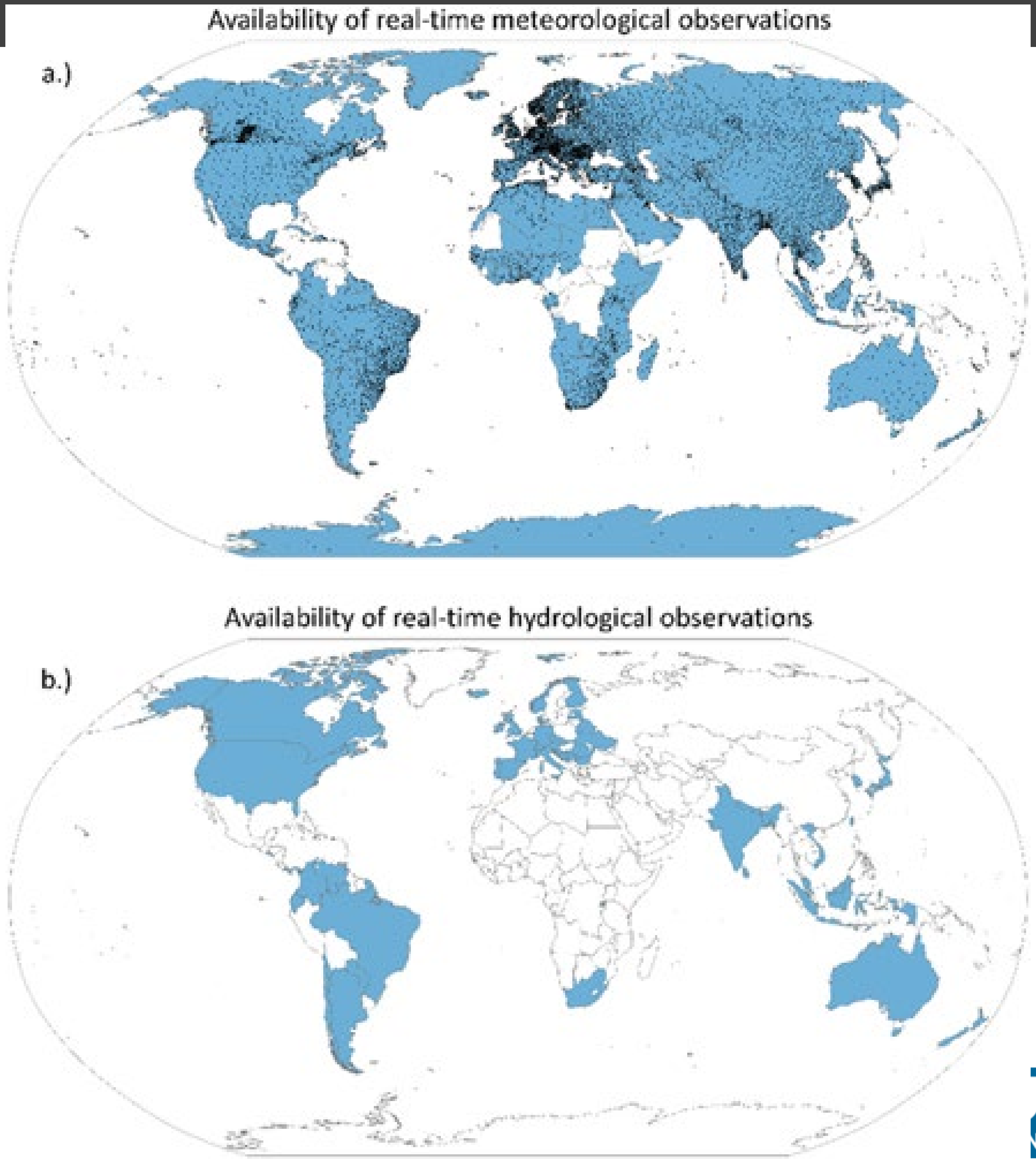
Hydrological data exchange



Call for action:
Timely exchange of hydrological data

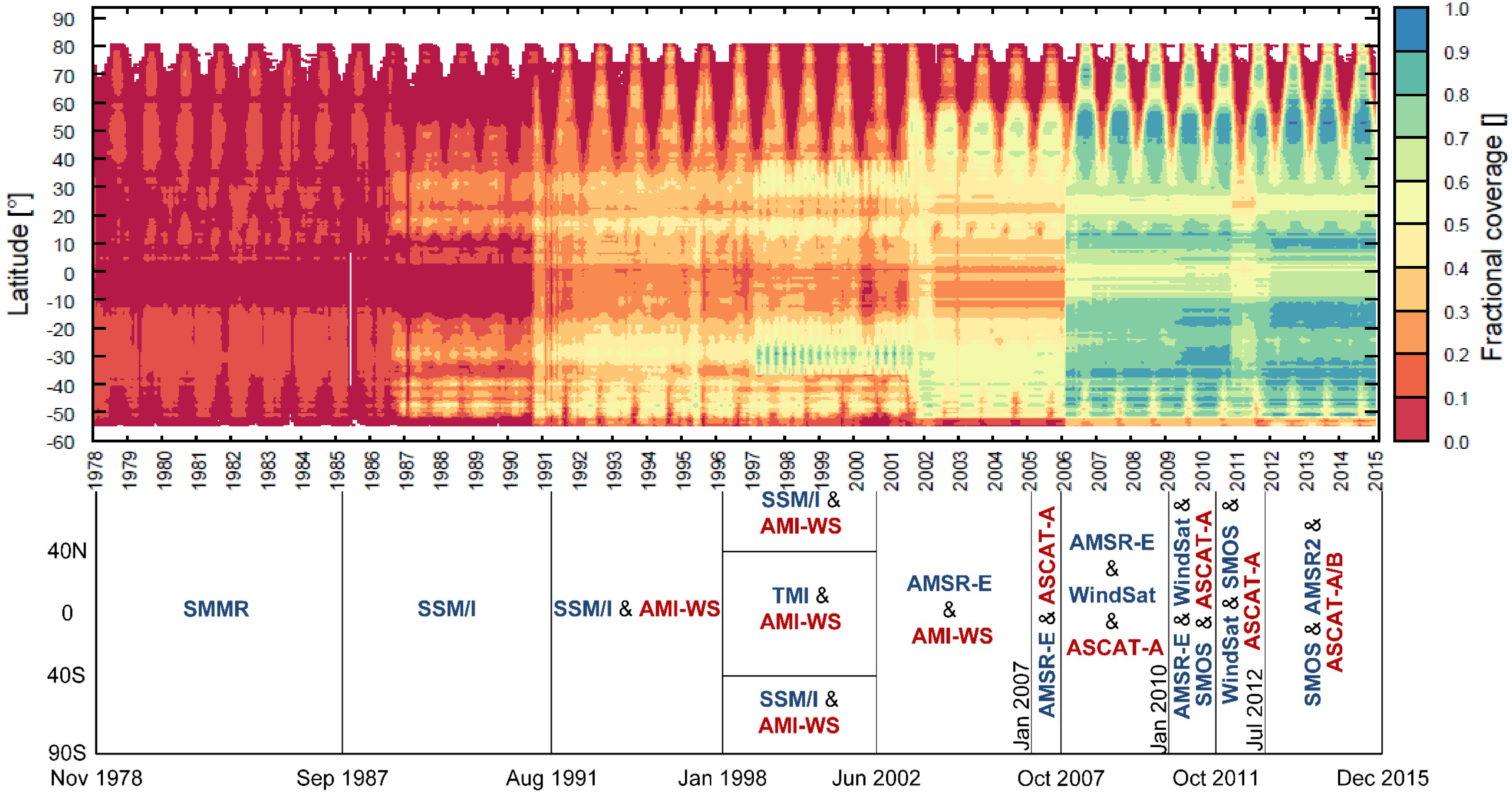
Increased data exchange is mutually beneficial

- *countries that provide data would in return receive improved warnings of water-related hazards*
- *thus resulting in positive socioeconomic impacts*

Global availability of real-time weather and hydrology data in June 2019.
(a) Locations (black dots) and the countries (blue) with surface-based meteorological https://oscar.wmo.int/surface/#/
(b) that publish their real-time river discharge data on their individual repositories without restrictions or cost. https://public.wmo.int/en/our-mandate/water/whos.

Lavers et at., 2019/EnvRes

observational gaps: some examples from satellites



Fraction of days per month with valid (i.e., unflagged) observations of ESA CCI SM v03.2 COMBINED for each latitude and time period.

Dorigo et al., RSE, 2017

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Lessons learned

- Long-term monitoring Earth's water cycle has made **great progress** in recent decades, but many observational gaps still need to be overcome.
- Satellites and in-situ observations **cannot comprehensively describe the water cycle** - neither alone nor together
- Even at coarse scales, **uncertainties** of many water cycle components are large.
- The **water budget cannot be accurately closed** if one of the components is not observed.
  - too short observation records or failing intercalibration of sensors over time.
  - long common baseline period, which is currently lacking for the ECVs that do provide trends based on scientific consensus
  - This becomes increasingly challenging at finer spatial and temporal scales.

Guidelines for improvement

Agenda

By assessing the capability of available ground and Earth observations of water cycle ECVs, we

1. provide the **most-recent observation based assessment** of the water cycle and global water storages,
2. **discuss gaps** in existing observation systems,
3. **formulate guidelines** for future water cycle observation strategies.

capability demands and outlook of water cycle fluxes and storage

- Relevant in situ observations lag of spatial and temporal coverage and required data sharing capabilities.
- Many expert groups working on different water cycle components.
- Aim: Earth observation enables a comprehensive and more consistent assessment of the hydrological cycle as a whole; inconsistencies are reduced.

Dorigo et al. (2021/BAMS)

Table 3. Summary capability demands and outlook of water cycle storages.

Storage	Observational needs: In situ	Observational needs: EO	Observational outlook: In situ	Observational outlook: EO	Other (methodological developments, reanalysis, etc.)
Oceans	Enhance the Argo array of profiling floats including full-depth Argo to estimate the contribution of deep-ocean warming and salinity changes	Ensure the continuity of satellite altimetry beyond 2030; ensure the continuity of satellite gravimetry and surface salinity missions	Establishment of a fully global, top-to-bottom, dynamically complete, and multidisciplinary Argo program	Constellation of satellite altimetry for sea level and satellite radiometry for sea surface salinity; the CIMR mission concept can provide continuity for satellite salinity measurements	A suite of ocean reanalysis products that assimilate various in situ and EO measurements for ocean ECVs; in the future Argo will integrate seamlessly with satellite and with other in situ elements
Terrestrial open water (lakes, artificial reservoirs, wetlands)	Determine the exact quantity of water from lakes and wetlands that contribute to global closure of the water cycle; more precise and more frequent updates of hypsometry curves needed	Ensure the continuity of high-resolution satellite altimetry beyond 2030		SWOT mission for characterization or water table depth of smaller lakes; Sentinel-1 and Sentinel-2 satellites will greatly complement existing series of Landsat images used for hypsometry curves	Focus on a set of representative lakes that most objectively reflect the climatic signal
Atmospheric water vapor	More in situ measurements are needed over oceans and in the Southern Hemisphere	Improved satellite-based measurements to measure water vapor over land during cloudy conditions, in the lower troposphere and the boundary layer; dedicated mission for moisture convergence monitoring	Increased number of frost point hygrometer launch sites as part of the GRUAN network	CrIS and ATMS instruments for JPSS-3 and JPSS-4; IASI-NG, METImage, MWI, and MWS on EPS-SG, AMSR-3 on GOSAT-GW	Reanalysis models must be improved to maintain water mass balance
Groundwater	Maintain and extend in situ national groundwater level monitoring networks to close observational gaps (particularly in the Global South) and promote data sharing among countries	Higher spatial resolution to monitor smaller aquifers; long-term observing system	Establishment of new national groundwater monitoring programs	Next-generation global gravity satellite missions with increased spatial resolution planned	Improved modeling and downscaling of groundwater variations using machine learning
Soil moisture	Expand capabilities to underrepresented regions (e.g., Africa, southern America) and climates that are currently poorly covered (e.g., monsoon, tropic, polar); clever, dense network design to bridge scale gaps	Continuation of dedicated L-band soil moisture missions; improved spatial resolution	Establishment of fiducial reference networks (ESA, Copernicus)	CIMR L band, Tandem-L, ROSE-L, HydroTerra for diurnal variability, high-resolution products from downscaling and SAR satellites	Better retrievals and models for dense vegetation and organic soils
Glaciers	Additional multitemporal glacier inventories every ~20 years; better spatial coverage of glacier thickness measurements; at least one long-term mass-balance monitoring program in every larger mountain range providing glaciological variability at seasonal to annual time resolution	Close geodetic gaps in regions where glaciers dominate runoff during warm/dry seasons, e.g., in the tropical Andes and in Central Asia, and in the heavily glacierized regions dominating the glacier contribution to sea level rise, i.e., Alaska, Arctic Canada, Russian Arctic, Greenland and Antarctica	Maintain and expand worldwide in-situ network with a focus on long-term monitoring programs.	Spaceborne altimetry (*ICESat-2*); increasing availability of large-scale high-resolution DEMs; unlock national archives of aerial surveys and photogrammetric processing of early optical satellite data	Exploit reconstructions from topographic maps and geomorphological evidence
Ice sheets and ice shelves	International coordinated observation flight campaigns to cover the "missing areas" along major outlet glaciers, particularly in East Antarctica; Surface traverse campaigns for improving firn models and englacial hydrology, especially in Greenland with its increasing seasonal melt zones	Continuation and effective combination of various existing satellite programs, e.g., *ICESat-2*, CryoSat, and future ESA Crystal missions	Campaigns in Greenland and Antarctica for satellite validation; need to close observational gap with unknown outlet glacier thickness in East Antarctica	ESA Crystal mission, Copernicus CMIR, Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL), and ROSE-L	Need of more diverse atmosphere reanalysis products, e.g., snow densities, firn compactions, snow drift and surface conditions, to narrow down ice sheet mass change models

Table 3. *Continued.*

Storage	Observational needs: In situ	Observational needs: EO	Observational outlook: In situ	Observational outlook: EO	Other (methodological developments, reanalysis, etc.)
Permafrost	The main difficulty for assessing permafrost distribution, ice content and mass changes is that permafrost is not visible at the surface	Still no reliable remote sensing technique for detecting permafrost; need for a surface subsidence product	Spatial observational gaps have to be filled	Tentatives are in progress within the ESA/CCI project	Most urgent need is a sustainable and reliable funding of monitoring networks and the database infrastructure, ensuring long-term availability of observational data
Snow	Expand ground-based observation networks	Continuation of satellite programs		CIMR is expected to provide SWE at improved accuracy and resolution; SAR based approaches (e.g., Sentinel-1) for mapping snow mass and SWE in mountain areas	Fusing observations from active and passive sensors or combining them with independent reference data

Table 4. Summary capability demands and outlook of water cycle fluxes.

Flux	Observational needs: In situ	Observational needs: EO	Observational outlook: In situ	Observational outlook: EO	Other methodological developments, reanalysis, etc.
Ocean evaporation	Near-surface observations with focus on air temperature and humidity	Improved satellite retrieval algorithms for near-surface ECVs with focus on air temperature and humidity	Explore the use of air–sea observations from new autonomous platforms such as saildrones and wave gliders; sustained and expand existing surface buoy network	Continuity of microwave imager programs via, e.g., EUMETSAT (EPS-SG) and JAXA (GOSAT-GW) and NOAA JPSS (ATMS)	Improvement of the model constraint of the ocean *E–P* estimates and the model–data synthesis capability of EO to the ocean water cycle; reconcile large spread in atmospheric reanalysis models and satellite gridded products
Land evaporation	Novel means to measure interception loss over multiple ecosystems	Missions dedicated to measuring evaporation to improve water budget closure over tropical, semiarid and high-latitude areas	Use of data from new in situ networks such as SAPFLUXNET (http://sapfluxnet.creaf.cat) in combination with eddy-covariance data	New types of EO (such as solar induced chlorophyll fluorescence) and new platforms (such as CubeSats and UAVs)	
Ocean precipitation		Retrieval skills need to be improved, to address intermittent nature and high spatial and temporal variability of precipitation		Continuity of microwave imager and sounder programs via, e.g., EUMETSAT (EPS-SG), JAXA (GOSAT-GW) and NOAA (JPSS); NASA-JAXA PMM; improved snow retrieval capabilities with ICI (EUMETSAT, EPS-SG), largely improved temporal sampling with the TROPICS mission (NASA); new microwave imager mission CIMR (ESA)	Integration of multiple sensors and deriving reanalysis products will address the high spatial and temporal variability
Land precipitation	Improve timeliness to contribute precipitation data to GPCC	Improved consistent long-term datasets		Same as for ocean precipitation	Integration of multiple sensors (in situ, remote sensing) and techniques (rain gauges, meteorological radars, soil moisture)
River discharge	Improve timeliness to contribute data to GTN-R; long-term, regular measurements of upstream river discharge on finer spatial scale	Increase numbers of virtual stations from altimetry	In situ observations are globally under thread due to reduced field observation capabilities and priorities	SWOT for measuring rivers wider than 100 m; SWOT assimilation into models to derive first globally consistent information on river discharge	Data integration and assimilation methods will be used to provide information on river discharge based on different sensors and observation techniques

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Outlook

Technical

- **SWOT** is expected to revolutionize continental water cycle observability
  - by allowing the global characterization of lake and river discharge dynamics in regions with sparse ground monitoring or restrictive data sharing policies.
- EU-Copernicus program (and others) has defined several **High Priority Candidate missions**
  - e.g. CIMR, CRISTAL, and ROSE-L have particular relevance for improved characterization of various water cycle components (including snow, ice sheets and shelves, glaciers, and soil moisture).
- **Artificial intelligence and machine learning** should become routinely applied
  - for reduction of retrieval errors and uncertainties of upcoming and existing missions.

Organisational

- **WMO unified data policy** can help to improve data exchange of operational hydrological obs.
- Extension of the WMO Global Basic Observation System (**GBON**) to **hydrology variables**
  - + **sustainable funding mechanism** (e.g. SOFF) are required to maintain and expand observation, in particular in data-scare regions.

Final remarks

Continuation of measurements, sustainable operation of EO and in situ networks are essential. **Long records are key.**

No matter how sophisticated the satellites or observing systems are, **observation errors** in the individual products **will always be present and lead to inconsistencies between ECVs**.

An advanced closure of the water cycle **requires enhanced model-data synthesis capabilities**, particularly at regional to local scales.
Data exchange capacities (interoperability) have to be improved.

More exchange between hydrological, climate and satellite research communities is essential.
Observe water cycle components in conjunction with the energy and carbon cycles.

This **should be adopted and implemented by high level organizations**,

meeting the SDGs and other international water-related agendas (WMO, UNESCO, FAO, etc)

Thank you for your interest

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