CSQ-42

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
1. To what extent can we predict the Earth's water cycle closure in space and time?	**A) Reservoirs:** Quantify the rate of expansion of the fast and slow reservoirs (atmospheric water vapor in the troposphere and stratosphere; storage on the land surfaces and in the oceans), its spatial character, its determinant factors and the extent of its predictability	1a)Fast reservoirs: atmospheric water vapor (WV), soil moisture (SM), vegetation water content (VWC), and surface water storage (SWS) (in lakes, man-made reservoirs and rivers); WV profile and its changes in response to temperature; Column WV from observations in microwave, infrared, optical, and UV spectrum. SM from passive microwave observations (SMOS and SMAP) and follow-on high resolution mission; VWC from coarse scale microwave observations (ASCAT,	1)WV: Changes from diurnal to daily and weekly time scale at hm to 10 km spatial resolution; Atmospheric WV profile (2m, 100m vertical resolution) SM & VWC: kilometer scale (e.g. 1 - 10 km) at daily to diurnal time steps - a future higher resolution L-band space mission is highly desirable;	WV: Atmospheric water vapor retrieval algorithms; inverse radiative transfer models; data assimilation; coupling the observation of humidity and temperature to generate a consistent dataset. SM & VWC: Retrievals algorithms (0^{th} order RT models); Combination with SAR and scatterometer data; GNSS and bistatic retrievals; use of auxiliary data by means of machine learning;	CC mitigation and adaptation policy Climate finance Green deal Water and food security Agriculture transition

		SMOS and SMAP) via vegetation optical depth; brightness temperature (e.g. SMOS and SMAP, and multi-frequencies in the upcoming CIMR), backscattering coefficient in C- (SAR and ASCAT) and L-band (e.g. ROSE-L); GNSS SWS: extent of surface water bodies and the changes in water levels (Optical and SAR sensors for surface water extent, radar altimetry and interferometry for water levels; SWOT for observation of rivers, lakes and inundation plains) 1b)Slow reservoirs: groundwater, snow, glaciers and ice caps, ice sheets and sea ice, and freeze and thaw and permafrost.	SWS: 10s of meters at daily to weekly time steps	in-situ data for validation from e.g. International Soil Moisture Network (ISMN) SWS: retrieval algorithms; change detection algorithms Groundwater, snow, glaciers and ice caps, ice sheets and sea ice: change detection	

		Groundwater: observations from mass change missions (GRACE and GRACE-FO); A new mission with much improved resolution in space and time will further advance the observations of terrestrial water storage. Optical, thermal and microwave observations for snow, glaciers and ice caps, ice sheets and sea ice, and permafrost.	10 ~100 km at weekly to monthly steps for groundwater; 10s of meters at weekly to monthly steps for snow, glaciers and ice caps; km~10 km at monthly to seasonal steps for ice sheets and sea ice; km~10km at diurnal to daily steps for freeze and thaw and (seasonally) permafrost;	using time series of observation data; retrievals algorithms	

		1c)Other relevant variables: sea level and sea surface salinity	10km for sea level and sea salinity;		
	B) Flux exchanges: Quantify fluxes of water between Earth's main reservoirs in space and time and their predictability (precipitation, evaporation, water vapor convergence and surface and groundwater discharges)	2) Observation of clouds and precipitation processes by CloudSat and EarthCARE on polar orbits (full global coverage of vertical profiles of clouds and light and solid precipitation) and Global Precipitation Measurement (GPM) for solid and liquid precipitation observations Observables for clouds and precipitation are optical properties in the optical and thermal spectrum and microwave brightness temperature and radar backscatters. New and novel observations, for example for marine stratocumulus, may	2) global precipitation dataset (e.g. the IMERG, half hourly and 0.1°x0.1° and aggregates at longer time scale). 10km clouds properties at hourly scale	Clouds and precipitation: retrieval algorithms based on radiative transfer; Bayesian retrievals; Machine learning algorithms; Validation by in-situ data collected by GPCC (global Precipitation Climatology Center)	

		be formulated due to their strong impact on radiation balances. Evaporation (and transpiration): observation of evaporation needs to cover the whole spectrum from optical to thermal range and the retrievals need to consider the involved essential physical and biochemical processes (coupling water, energy, and carbon cycles). Transfer of water through the soil, roots, stem and leaves can be quantified by measuring and simulating **water potential** and link the change of water potential to external forcings of radiation, precipitation and meteorology, the growth of above and below ground plant	Evaporation: hm ~km at diurnal (half hourly) steps for **water potential** as well as full spectrum observation (incl. fluorescence)	Opt/TIR based retrieval algorithms; ESM/DTE based retrievals with data assimilation of optical, TIR and MW observations; Validation with in-situ measurements by Eddy covariance methods (e.g. Fluxnet)	

		biomass, and the extraction of water by the growing roots. The direct observables are soil moisture, vegetation water content and near surface atmospheric water content. Discharges: Observation of surface water discharges by the SWOT mission (surface water levels and the slopes of water elevation in large rivers) by its Ka-band SAR interferometry; No currently obvious viable means for observation of groundwater discharges (from one river basin to another, or from river basins to ocean) but analysis of GRACE and GRACE-FO data and higher resolution	Discharges: 10~100m horizontal, ~cm vertical and quasi instantaneous in time	In-situ measurements (collected by GRDC-Global Runoff Data Center); Retrieval algorithms; Model simulations	

		observation may reveal future potential of such observation.			
	C). Extremes in precipitation and floods: Quantify the changes in local rainfall and its extremes under climate change across the regions of the world and the associated flood extremes (frequency, extent and severity)	Regional climate systems and local topographical and land use features dependent precipitation extremes (intensity-duration- frequency) Flood extent and frequency and severity of floods (return period);	Measure precipitation intensity at mm water depth per half hour (currently at 3-hourly) and its duration of different occurrence; Mapping post flood extents by high resolution optical and SAR sensors (hm~km at daily-weekly steps);	GPM-IMERG data series for global scale applications; integration of other observation techniques (e.g. geostationary observations and microwave links from commercial telecommunications, for local precipitation extremes; validation by dedicated in-situ observation (ground radar and microwave links) Embedding a hydrological model in an ESM for prediction of precipitation extremes and floods at the same time; Integrating real time space observation of	

			Estimation of frequency and severity of floods using precipitation (extremes) in a hydrological model.	these events into an ESM by means of data assimilation and machine learning for a true DTE	

Narrative: To what extent can we predict the Earth's water cycle closure in space and time?

In order to determine the extent to which Earth's water cycle can be predicted, observation and modeling capabilities are needed to be able to quantify the reservoirs (where is the water on Earth?), the fluxes (how it moves?) and extremes (what are the largest magnitudes and when and where do they occur?).

Quantitative progress need to be made in terms of the following specific questions:
1). **Reservoirs:** What is the rate of expansion of the fast and slow reservoirs (in the atmosphere, on the land surfaces and in the oceans), what is its spatial character, what factors determine this and to what extent are these changes predictable?

The fast reservoirs include atmospheric water vapor, soil moisture, surface water (in lakes, man-made reservoirs and rivers), and vegetation water content in terms of changes from diurnal to daily and weekly time scale; other reservoirs that may be considered the slow changing ones include groundwater, snow, glaciers and ice caps, ice sheets and sea ice, and permafrost. The impacts of changes in these slow reservoirs on water cycle dynamics usually manifest at a longer time scale from weekly to seasonal and multiannual scales. Other relevant water cycle related geophysical variables are sea level and sea surface salinity.

The geophysical variables of interest in the atmosphere are the distribution of atmospheric water vapor in the troposphere and stratosphere and its changes in space and time in response to atmospheric temperature (profile). Column water vapor products have been generated from observations in microwave, infrared, optical, and UV spectrum. Accurate observation of the profile of atmospheric relative humidity (from land and ocean surface up to lower stratosphere) may be achieved by coupling the observation of humidity and temperature to generate a consistent dataset. Datasets on atmospheric temperature and humidity profiles have been identified as a critical issue for more than 30 years (WMO, 2012).

On the land surface, soil moisture, groundwater, surface water (in lakes, reservoirs and rivers), and vegetation water (water storage in biosphere, e.g. vegetation water content and their diurnal and seasonal changes) are the needed geophysical variables.

The observations of soil moisture have made major advances by the proven capability of passive microwave observations provided by SMOS and SMAP missions. Although other observation have also been used to retrieve soil moisture (e.g. combined with SAR and scatterometer data, e.g. Bauer-Marschallinger, 2018; and the use of auxiliary data by means of machine learning, e.g. Han et al., 2023), coarse scale microwave observations (ASCAT, SMOS and SMAP) also provide relevant estimates of vegetation water content (in terms of vegetation optical depth, e.g. Frappart et al., 2020).

The evaluation of global satellite soil moisture products primarily relies on in-situ data from contributing networks coordinated and quality controlled by the International Soil Moisture Network (ISMN) (Dorigo et al., 2023).

The observables relevant to soil moisture are brightness temperature in L-band (e.g. SMOS and SMAP, and multi-frequencies in the upcoming CIMR), backscattering coefficient in C-and (SAR and ASCAT) and L-band (e.g. ROSE-L). Next advances can be expected by generating higher resolutions data products at the resolution of kilometer scale (e.g. 1 - 10 km) at daily to diurnal time steps. Given the proven capabilities of passive microwave observation at L-band by SMAP and SMOS, a future higher resolution L-band space mission would be highly desirable.

For groundwater, observations from mass change missions like GRACE and GRACE-FO (Rodell and Reager, 2023) have made the most impact in detection of groundwater depletions. A new mission with this technology but much improved resolution in space and time will further advance the observations of terrestrial water storage.

For monitoring surface water storages, the extent of surface water bodies and the changes in water levels need to be determined. Optical and SAR sensors can effectively measure the surface water extent, while radar altimetry and interferometry have successfully measured water levels. The recent launch of the Surface Water and Ocean Topography (SWOT) mission is expected to make major advances in observation of rivers, lakes and inundation plains.

The observation of snow, glaciers and ice caps, ice sheets and sea ice, and permafrost have been conducted by using optical and SAR and passive microwave sensors. A variety of challenges exist in observing each of these geophysical variables. Advances in sensing technology, e.g. those of SMOS and SMAP capabilities but with higher resolution in space can be expected to help generate the much needed datasets.

2). **Flux exchanges**: To what extent are the fluxes of water between Earth's main reservoirs changing and to what extent in space and time scale can these changes be predicted?

The flux exchanges between the different reservoirs on Earth can be characterized by precipitation, evaporation, water vapor convergence and surface and groundwater discharges. The observation of precipitation is often considered together with the observation of clouds because of the tight links between clouds and the precipitation processes. CloudSat and EarthCARE on polar orbits provide full global coverage of vertical profiles of clouds and light and solid precipitation, while the Global Precipitation Measurement (GPM) mission have been providing solid and liquid precipitation observations that have enabled to generate consistent global precipitation dataset (e.g. the IMERG, half hourly and 0.1°x0.1° and aggregates at longer time scale). The observables for clouds and precipitation are optical properties in the optical and thermal spectrum and microwave brightness temperature and radar backscatters. New and novel observations, for example for marine stratocumulus, may be formulated due to their strong impact on radiation balances.

The observation of evaporation (including transpiration which is technically the water transpired by plants from soil to the atmosphere) has been approached so far by semi-empirical approaches, largely because it has been difficult to observe near surface water vapor gradients from space which are needed to quantify evaporation (such as done by in-situ observation using eddy covariance and Bowen ratio methods). However because evaporation couples water cycle and energy cycle over water surfaces and water, energy and carbon cycles over vegetated surfaces, major progress can be made in quantifying water cycles by achieving better observation of evaporation. Due to the aforementioned coupling, the observation of evaporation needs to cover the whole spectrum from optical to thermal range and the retrievals need to consider the involved essential physical and biochemical processes.

For observation of surface water discharges, the SWOT mission is expected to make major advances, thanks to its ability to observe surface water levels and therefore the slopes of water elevation (which can be translated to flow rates) in large rivers by its Ka-band SAR interferometry technology. There is currently no viable means for observation of groundwater discharges (from one river basin to another, or from river basins to ocean), however analysis of GRACE and GRACE-FO data and higher resolution observation may reveal future potential of such observation.

3). **Extremes in precipitation and floods:** How will local rainfall and its extremes change under climate change across the regions of the world? And what are the associated flood extremes (frequency, extent and severity)?

Precipitation extremes are determined by both regional climate systems and local topographical and land use features. While the GPM-IMERG data series are the state-of-the-art for global scale applications, integration of other observation techniques (e.g. geostationary observations and microwave links from commercial telecommunications, see e.g. Kumah et al., 2022) may provide the much needed local information for observing the precipitation extremes. While the flood extent may be observed post floods by high resolution optical and SAR sensors, the frequency and severity of floods must be estimated using precipitation (extremes) in a hydrological model. The embedding of a hydrological model in an Earth System Model can enable the prediction of precipitation extremes and floods at the same time. When real time space observation of these events can be integrated into such an ESM by means of data assimilation and machine learning enabled by High Performance Computing, a true Digital Twin Earth can be created for these tasks.

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