CSQ-44

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models
3. How important are the anthropogenic influences on the water cycle and how accurate can we predict the anthropogenic influences on the water cycle?	A). Quantify **anthropogenic forcing of continental scale water availability**: extent to which the changing greenhouse effect modified the water cycle over different regions and continents	Observables: land cover changes (at seasonal to annual scale), changes in water levels in lakes and man-made reservoirs (at weekly to seasonal scale), as well as irrigated areas.	10-100km at seasonal and annual steps	Time series analysis of observation; Scenario simulations with coupled ESM models; Use of DTE for decision support
	B). Detect **water management influences:** extent to which water management practices and land use changes (e.g., deforestation) modified the water cycle on regional to global scales	Estimate the water used for irrigation by estimating the cumulative difference between evaporation and precipitation of an area.	1km at daily-weekly step	Time series analysis of precipitation and evaporation products; Comparison of observation products to reanalysis
	C). Quantify **variability and trends of water availability:** effects of water and land use and climate changes on the variability (including extremes) of the regional and continental water cycle	Irrigation water use by extracting groundwater by GRACE observations (depletion of groundwater levels for large regions).	10km at weekly – monthly step	Availability of management data and coupled water cycle modelling (incl. groundwater, SM, discharge and evaporation and precipitation)

Narrative: How important are the anthropogenic influences on the water cycle and how accurate can we predict the anthropogenic influences on the water cycle?

We need to develop observation and simulation technologies to quantify anthropogenic influences on the water cycle and to understand and predict the changes to Earth's water cycle due to anthropogenic influences.

The observation aspects for answering these questions can be achieved by observing the land cover changes (at seasonal to annual scale), changes in water levels in lakes and man-made reservoirs (at daily to weekly and seasonal scale), as well as irrigated areas. It is possible to estimate the water used for irrigation by estimating the cumulative difference between evaporation and precipitation of an area. If the region is irrigated by extracting groundwater, it has been demonstrated that GRACE observations can be linked to the depletion of groundwater levels for large regions (Rodell and Reager, 2023). Availability of management data and coupled modeling are other necessary means to fully resolve the above questions.

Progress towards solving these science questions of water cycle requires the generation and exploitation of improved data sets of precipitation, evaporation and transpiration, river discharge, soil moisture, snowpack, surface water bodies, groundwater, vegetation, land use change data, among other information. This can be synchronized with advances in Earth system modeling across scales to advance the development of an integrated analysis of the water and energy exchanges within and between the atmospheric and continental reservoirs. Advances in these aspects directly contribute to our ability in devising adaption strategies and to strengthen the resilience of our society to adverse impacts due to anthropogenic changes.

In summary, despite the many advances in the satellite observation of many water cycle related variables and parameters, major efforts are still needed to be able to close the water, energy and carbon cycles at different scales in space and time. In awaiting the availability of fluorescence as an observable from the ESA FLEX satellite, another geophysical variable (or loosely observable), **water potential in soils, plants and atmosphere**, appear to be extremely promising in lynch-pinning the water, energy and carbon processes on land. (The same process may also prove important in sequestration of CO_2 in oceans, though the description must be via algae mediated radiation-water-carbon photosynthesis processes). On such basis of state-of-the-art in describing, analyzing and modeling energy-water-carbon fluxes on land, the following can be summarized:

- Interpretation of SIF (sun-induced fluorescence) requires (and will advance) full spectrum understanding of water-energy-carbon (Soil-Water-Plant-Energy) interactions.
- Describing water potential gradients is one key step for explaining SIF-GPP (gross primary productivity) dynamics. ***(This is identified as a gap/hole in geophysical information)***
- SIF and microwave observation (of plant water content) (radiometry, scatterometry, SAR tomography) can potentially access water potential in soil and plants (Zhao, et al. 2023).
- Observation of the profile of water vapor concentration in the atmosphere from troposphere to stratosphere are highly desirable and may be achieved by means of combined vertical profiling (or via IASI type of sensing) and limb sounding.

Diurnal observations appear necessary to observe water potential at scales of half-hourly to hourly in time and kilometer to hectometer in space. ***(This is seen as an Observation gap that needs to be bridged to adequately characterize and describe the diurnal processes at the relevant scale where the processes take place).***

(Full text on Water Cycle)

I). Societal relevance of water cycle

Viewed from space, the most striking feature of our planet is the water. In liquid and frozen form, water covers 75% of the Earth's surface and in gas form it fills the sky with clouds. Water is practically everywhere on Earth, from inside the planet's crust to inside the cells of the human body (NASA). The water cycle describes where water is on Earth and how it moves. Water is stored in the ocean, in the atmosphere, on the land surface, and below the ground as a liquid, a solid, or a gas. Water moves between the places where it is stored, and at large scales, through watersheds, the atmosphere, and below the Earth's surface. Water moves at very small scales too. It is in humans, plants, and all other organisms. Human activities impact the water cycle, affecting where water is stored, how it moves, and how clean it is (USGS).

The impacts of climate change on humans occur primarily through changes in the water cycle and the cycling of water is intimately linked with energy exchanges among the atmosphere, ocean, and land (including biosphere) that determine the Earth's climate and cause much of natural climate variability. "Water is at the heart of both the causes and effects of climate change." (NRC, 1999). The cycling of water through the biological systems is mainly in the way of photosynthesis by which plants, algae and cyanobacteria use sunlight, water, and carbon dioxide to create oxygen and energy in the form of carbohydrate. Photosynthesis provides the oxygen, food and energy needed to maintain animal life on the present Earth system and powers 99 percent of Earth’s ecosystem. It is therefore through photosynthesis that Earth’s water, energy and carbon cycles are coupled in terms of forcings and feedbacks. Recent droughts and floods in Europe have highlighted the urgency in observing, simulating and predicting, and adapting to the changes in the water cycle.

A few examples of recent droughts and floods in Europe

During the summer of 2022, parts of Europe experienced drought conditions exacerbated by heat waves, which was suggested and confirmed to be Europe's worst drought in 500 years. The drought had serious consequences for hydropower generation and the cooling systems of nuclear power plants, as the drought reduced the amount of river water available for cooling. Agriculture in Europe was also negatively affected by the drought (wikipedia).

While the Netherlands is known for its water management infrastructure, the extreme droughts of 2018-2020 in the Netherlands still induced huge economic damages in agricultural production, disrupted river navigation and damaged buildings and unique nature. The drought-related damage in 2018 alone was estimated between 900 and 1,650 million Euro (Kramer et al., 2019) and as a result the minister of agriculture has established an action programme for climate adaptation in agriculture (LNV, 2020).

In July 2021, several European countries were affected by severe floods. Some were catastrophic, causing deaths and widespread damage. At least 243 people died in the floods, including 196 in Germany, 43 in Belgium, two in Romania, one in Italy and one in Austria. The floods are estimated to have cost up to 2.55 billion Euro in insured losses, with the total damage costs being much higher, at a minimum of €10 billion (wikipedia).

II). Science questions that are directly relevant to European policy making

The knowledge and capability in observing, analyzing and predicting water cycle changes are directly relevant to societal needs related to water use, prevention of damages by and adaptation to extremes manifested in floods, droughts and fires. In addition to ensuring water security for drinking water and industrial and environmental water use, water availability is most critical to food security because ca. 80 percent of freshwater resources are used in agricultural irrigation. Quantification of carbon sequestration capacity of land and oceans will also contribute to the Paris Agreement and EU Green Deal and Digital Europe Programme and provides scientific foundation for implementing other EU initiatives such as ‘carbon farming’ and ‘farm to fork’.

Despite the advances in our knowledge about the Earth’s water cycle, it remains extremely challenging to accurately observe, explain, simulate and predict water availability and extremes (in the form of floods and droughts), such that our societies can adequately plan, construct, manage and adapt our infrastructure and management systems to ensure sufficient water availability (for domestic use, industrial use and irrigation and environmental use) and to prevent and reduce such adverse climate change impacts (storms and floods, droughts, and forest fires and heat waves). The figure below illustrates the challenges in simulating the occurrence of droughts by the state-of-the-art Earth System Models (ESMs).

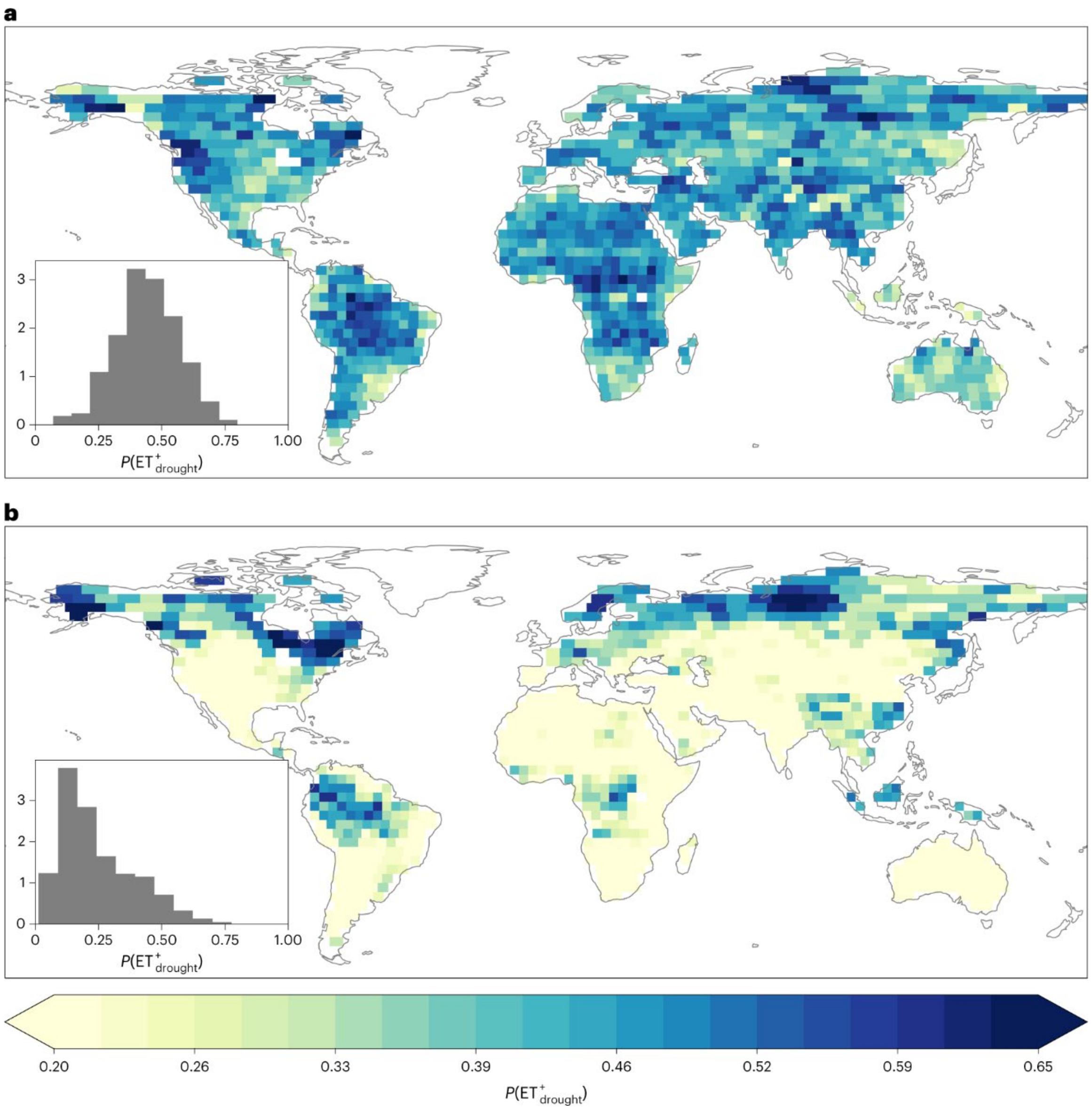

Figure 1. CIMP6 ESMs significantly underestimate the probability of drought-driven increases in ET. *a) Observed p(ET+$_{drought}$) during droughts between 2003 and 2020, b) p(ET+$_{drought}$) based on the CMIP6 ESM ensemble mean. Insets in a) and b) show probability density function (PDF) of each location's p(ET+$_{drought}$) across the globe (Zhao, et al., 2022).*

To this end, the major scientific questions that need to be answered according to the Global Energy and Water Exchanges Project of the World Climate Research Programme (GEWEX, 2021; Stephens, et al., 2023) are as follows:

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

2. What are the main coupling determinants between Earth's energy, water and carbon cycles and how accurately can we predict the forcings and feedbacks between the different components of the Earth system?

3. How important are the anthropogenic influences on the water cycle and how accurate can we predict the anthropogenic influences on the water cycle?

III). Water cycle closure

The water cycle (also known as the hydrological cycle) is a biogeochemical cycle that describes the continuous movements and changes of water on, above and below the surface of the Earth. The water cycle closure can be written for a given region as:

$$\delta = v + \frac{dC_A}{dt} + P - ET - R + WT + \frac{dC_T}{dt} \qquad (1)$$

$$\frac{dC_T}{dt} = \frac{\partial(SM+GW+SW+VWC+SWE+PI)}{\partial t} \qquad (2)$$

Which include the **Fluxes**, v is the atmospheric water vapor convergence (or divergence, i.e. net flux of water vapor to the said region, which may be estimated as $\frac{dC_A}{dx}$ for the selected time period); P is precipitation; ET is evaporation/transpiration; R is runoff/discharge; WT is human water transfer, and the **Storages**, C_A is the atmospheric water vapor content; C_T is the total terrestrial water storage which may include, SM - soil moisture; GW - Ground Water; SW - Surface Water; VWC - Vegetation Water Content; SWE - snow water equivalent and PI - permanent ice (glaciers; ice sheet; permafrost) (x is the space coordinate, and t is the time variable; the fluxes can be expressed in water depth in e.g. mm per unit time and the storages in water depth in mm; runoff and human water transfers are commonly expressed as volume per unit time, but can be converted to water depth by dividing the surface area of interest).

To close the water cycle is to minimize δ for any given region and time period (δ is zero when the water cycle is closed). Assuming that the water cycle closure is achieved for a given region on land, the atmospheric part of water budget can be written as

$$v + \frac{dC_A}{dt} = -P + ET \qquad (3)$$

Eq (3) indicates that the water vapor convergence (or divergence) and the changes in atmospheric water vapor content is balanced by precipitation out and evaporation into the atmosphere. Observation of the exchanges of water vapor in space ($v = \frac{dC_A}{dx}$) between the said region and its surroundings and water vapor changes in time within the region ($\frac{dC_A}{dt}$), as well as observation of precipitation (P) and evaporation (ET) will enable the closure of this part of the water cycle budget.

Similarly the terrestrial part of the water budget for a given region can be written as

$$\frac{dC_T}{dt} = -P + ET + R - WT \tag{4}$$

Which says that the changes in the total terrestrial water storage in time is balanced by the difference between the fluxes of precipitation, evaporation, discharge and human water transfer. However it is important to remember that human water transfer can significantly influence the amount of evaporation in arid and semi-arid regions where precipitation is usually very limited. Human water transfer may take place between regions (water diversion from one region to another) or by changes in storages (extraction of groundwater). This is usually to satisfy water needs for irrigation and other water uses. As a consequence, the different storage terms are also impacted (e.g. soil moisture, ground water and surface water), and these changes may also influence the precipitation through water (vapor) recirculation (i.e. the evaporated water vapor is condensed and falls back to the same region as precipitation).

For the whole earth system the water cycle is closed (meaning the total amount of water on Earth is conserved)

$$\frac{dC_A}{dt} + P - ET + \frac{dC_T}{dt} = 0 \tag{5}$$

or

$$\frac{dC_A}{dt} + \frac{dC_T}{dt} = ET - P \tag{6}$$

which says the change in the total storage in the atmosphere, ocean and land in time is equivalent to the difference in evaporation (and transpiration) and precipitation in the whole Earth system.

From an observational point of view, we can now directly observe the changes in storage ($\frac{dC_A}{dt} + \frac{dC_T}{dt}$) by GRACE and GRACE-FO missions, the precipitation (P) by the GPM and other microwave and optical missions, while the observations of evaporation (ET) can only be achieved via indirect retrievals that relay on other geophysical variables (radiation, albedo, land surface temperature and other vegetation properties, as well as meteorological variables). It is important to realize that the different observation technologies have very different spatial and temporal coverage and the resolved water cycle closure can only be assessed at the lowest spatiotemporal resolution. This is currently determined as 3° x 3° in space (ca. 300km by 300km at equator) and bi-monthly time intervals, determined by the characteristics of the GRACE and GRACE-FO missions. Downscaling techniques (data assimilation, or in a Digital Twin Earth framework) can then be used to downscale the water cycle components to higher spatiotemporal resolutions. It is also important to recognize that evaporation (and transpiration) is the variable that links the water cycle to the energy cycle over water and unvegetated surfaces, and it links the water cycle, energy cycle and carbon cycle over vegetated lands. By observing the water levels in rivers, we may estimate the discharges (R) by linking the water level and rivers cross sections to discharges (via so-called rating curves that convert water levels to water flow volumes). Altimeters and interferometers on missions like Sentinel-3 and SWOT shall help to improve the estimation of discharges. The more challenging component to observe is the human water transfer (WT), diversion of water from reservoirs and lakes may be estimated by altimeters, while the extraction of groundwater may be estimated as a consequence of changes in storage by GRACE and GRACE-FO missions. Next we shall discuss in more detail each of the science challenges.

IV). Geophysical variables, observables and observation methods

1. 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.

2. What are the main coupling determinants between Earth's energy, water and carbon cycles and how accurately can we predict the forcings and feedbacks between the different components of the Earth system?

We need to be able to quantify the inter-relationships between Earth's energy, water and carbon cycles in order to advance our understanding of the Earth system and our ability to predict it across scales. More specific science questions can be formulated as follows.
1). **Forcing-feedback understanding**: What are the main climate forcings and feedbacks formed by energy, water and carbon exchanges?

2). **ABL process representation**: To what extent are the properties of the atmospheric boundary layer (ABL) defined by sensible and latent energy and water exchanges at the Earth's surface versus within the atmosphere (i.e., horizontal advection and upper troposphere - lower stratosphere (UTLS) exchanges)?

3). **Understanding circulation controls:** To what extent are exchanges between water, energy and carbon determined by the large-scale circulations of the atmosphere and oceans?

4). **Land-atmosphere interactions**: What are the role of land surface-atmospheric interactions in the water, energy and carbon budgets across spatiotemporal scales?

The coupling of the energy and water cycles with the carbon cycle need to be pursued by including the observation and description of photosynthesis as a major component of the whole system, such that we can better close the water budget over land, provide improved information for water availability and quality for decision making for water, energy and food security and for initializing and assessing climate predictions across multiple time scales and at the relevant adaptation scales (e.g. political and administrative regions). Detecting and attributing past changes in the water cycle due to either changing greenhouse gasses or land and water use changes will be essential to advance our prediction capability and tools for devising adaptation alternatives to these changes. The importance of describing photosynthesis in a coupled dynamic water-energy-carbon system is illustrated in the following figures.

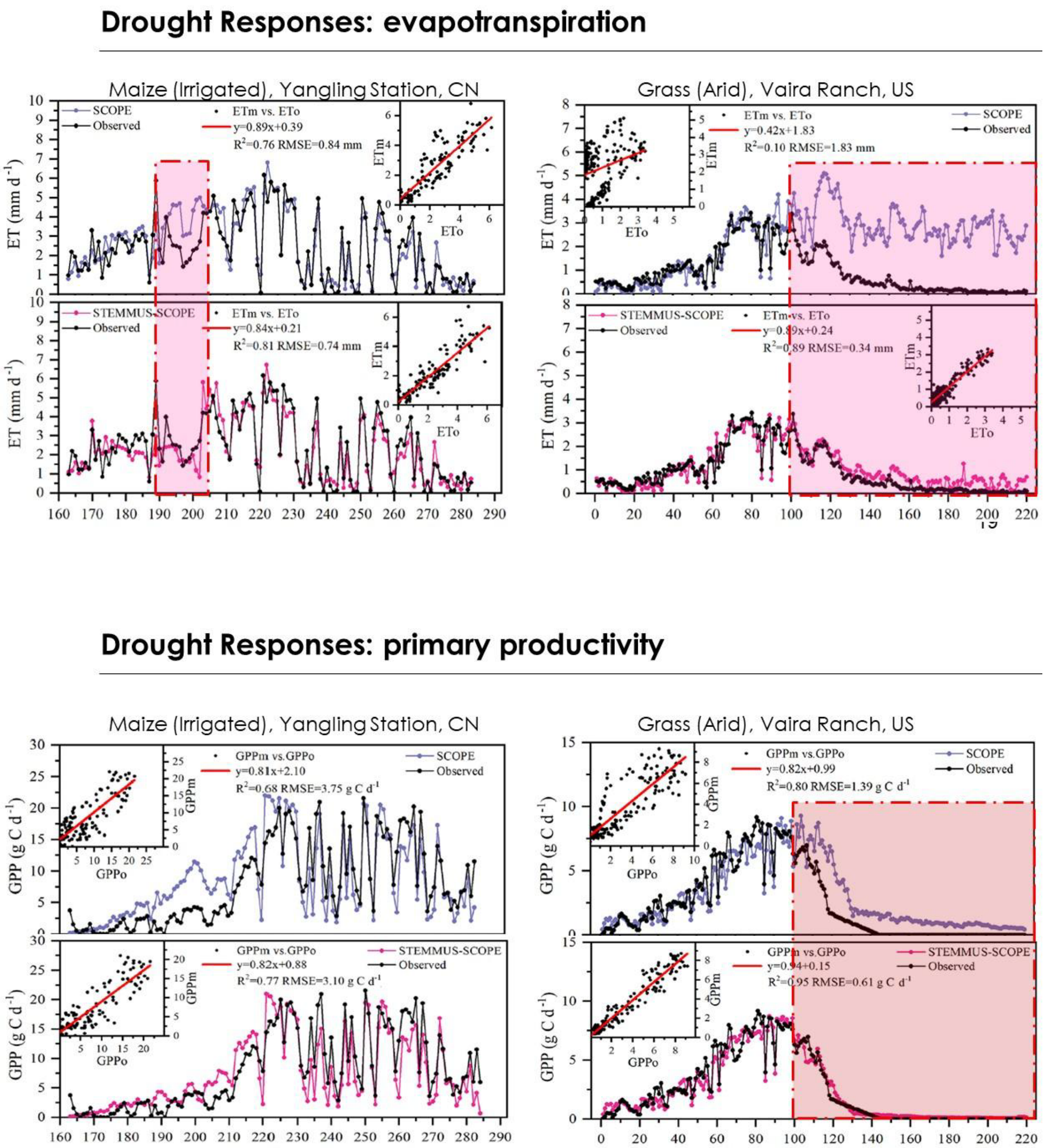

Figure 2. Simulations of drought responses in evaporation and transpiration (termed together as evapotranspiration, ET) and sequestration of carbon dioxide fluxes (gross primary productivity, GPP) of two sites: *one irrigated maize and another grassland in arid climate by two modelling systems (Wang et al., 2021).*

The modeling system SCOPE describes the canopy radiative transfer (including sun-induced fluorescence), energy balance and photosynthesis but ignores the water and heat transport in the soil and roots system (instead an average soil moisture is prescribed), while the STEMMUS-SCOPE system describes the coupled processes both in the canopy and rooting systems. Under non-water stressed conditions, both modeling systems can reasonably simulate the exchanges of energy, water and carbon between land and the atmosphere. However when the plants suffer drought stress (highlighted areas in both figures), SCOPE grossly overestimated the water fluxes and the carbon fluxes, while STEMMUS-SCOPE achieved a much better fidelity compared to the observed fluxes. The major advances in the STEMMUS-SCOPE system are to describe the transfer of water through the soil, roots, stem and leaves through the concept of **water potential** and link the change of water potential to external forcings of radiation, precipitation and meteorology on the one hand and the growth of above and below ground plant biomass (in shoots and roots) and the extraction of water by the growing roots on the other. As such this dynamic system can be viewed as a digital twin that represents both the structure and function of the real water-soil-plant system and mimics the actual forcings and feedbacks. The STEMMUS-SCOPE also simulates and thus links satellite observables in the visible, infrared, and thermal spectrum (reflectance, leaf and soil temperatures and sun-induced fluorescence) to water-energy-carbon processes above- and below-ground and can be used to perform Observation System Simulation Experiments (OSSEs). The concept of digital twins is currently also pursued by WCRP in its new lighthouse activities and by the EU in the Destination Earth initiative (DestinE). These initiatives provide ample opportunities for integrating new EO observables into existing infrastructure for their best use in resolving the scientific questions related to water cycle identified in this note. They would also contribute to and be taken up by the CGMS-IESWG initiative (Coordination Group of Meteorological Satellites - the International Earth Surface Working Group) which aims to gather requirements specific to surface observations to enhance understanding and ability to monitor the components of the Earth system including land, vegetation, snow, ice, and coastal and open waters. It may be reasonably expected that the new capability demonstrated in Figure 2 can help improve the simulation capabilities of the CIMP6 ESMs as shown in Figure 1.

3. How important are the anthropogenic influences on the water cycle and how accurate can we predict the anthropogenic influences on the water cycle?

We need to develop observation and simulation technologies to quantify anthropogenic influences on the water cycle and to understand and predict the changes to Earth's water cycle due to anthropogenic influences. Specific questions need to be answered.

1). **Anthropogenic forcing of continental scale water availability**: To what extent has the changing greenhouse effect modified the water cycle over different regions and continents?

2). **Water management influences:** To what extent do water management practices and land use changes (e.g., deforestation) modify the water cycle on regional to global scales?

3). **Variability and trends of water availability:** How do water and land use and climate changes affect the variability (including extremes) of the regional and continental water cycle?

The observation aspects for answering these questions can be achieved by observing the land cover changes (at seasonal to annual scale), changes in water levels in lakes and man-made reservoirs (at daily to weekly and seasonal scale), as well as irrigated areas. It is possible to estimate the water used for irrigation by estimating the cumulative difference between evaporation and precipitation of an area. If the region is irrigated by extracting groundwater, it has been demonstrated that GRACE observations can be linked to the depletion of groundwater levels for large regions (Rodell and Reager, 2023). Availability of management data and coupled modeling are other necessary means to fully resolve the above questions.

Progress towards solving these science questions of water cycle requires the generation and exploitation of improved data sets of precipitation, evaporation and transpiration, river discharge, soil moisture, snowpack, surface water bodies, groundwater, vegetation, land use change data, among other information. This can be synchronized with advances in Earth system modeling across scales to advance the development of an integrated analysis of the water and energy exchanges within and between the atmospheric and continental reservoirs. Advances in these aspects directly contribute to our ability in devising adaption strategies and to strengthen the resilience of our society to adverse impacts due to anthropogenic changes.

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