
# HYDROSPACE 2023 Report: Summary and Recommendations


**HYDROSPACE 2023 Workshop**
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# HYDROSPACE 2023 Report: Summary and Recommendations

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# I. Introduction

The European Space Agency (ESA), in the context of the "Earth Observation Science for Society" Programme, GEWEX, and the Centre National d'Études Spatiales (CNES, the French Space Agency), organised a sequel joint event to HYDROSPACE 2021 and the Earth Observation for Water Cycle Science 2020 Conference (EO4Water2020). The 5th Space for Water Cycle and Hydrology Workshop, HYDROSPACE 2023, took place in Lisbon, Portugal, from November 27th to December 1st 2023.
HYDROSPACE 2023 was dedicated to evaluating the most recent advancements in utilizing Earth Observation (EO) data from satellites for water cycle science and hydrology, along with its practical applications. The conference aimed to explore the potential of both existing and forthcoming EO satellites, coupled with advanced modelling and innovative technologies. Additionally, it sought to address the primary challenges and opportunities in enhancing our current capacity to observe, comprehend, and forecast the water cycle, including its impacts and interactions with human activities and ecosystems. A key objective of the event was to contribute to shaping a collective scientific agenda within the community, which could inform future scientific endeavours undertaken by ESA and other space agencies, aimed at tackling the major scientific and societal challenges of our time.


*Figure 1: The HYDROSPACE-2023 group picture.*

The HYDROSPACE 2023 Workshop welcomed participation of EO scientists, water researchers and students, modelers, Earth system and climate scientists, representatives from industry and operational agencies, policy makers, representatives of local communities, and other stakeholders. Their collective expertise and insights were instrumental in fostering knowledge exchange and collaboration, with a shared goal of shaping the scientific agenda for advancing EO water research and future applications. Overall, the event attracted 270 registrations, from 45 countries, of which **207 participants** (Fig. 1) from **22 countries** (Fig. 2) could actually attend in Lisbon. We received **233 abstracts** from 34 countries (Fig. 3). The whole workshop was recorded and can be viewed online. Presentations and posters are also online at https://www.hydrospace2023.org/photo-gallery-and-presentations.

It was largely recommended that the next HYDROSPACE Workshop should be held in November 2025. HYDROSPACE is not a registered trademark, and any institution can organise or co-organise future events.

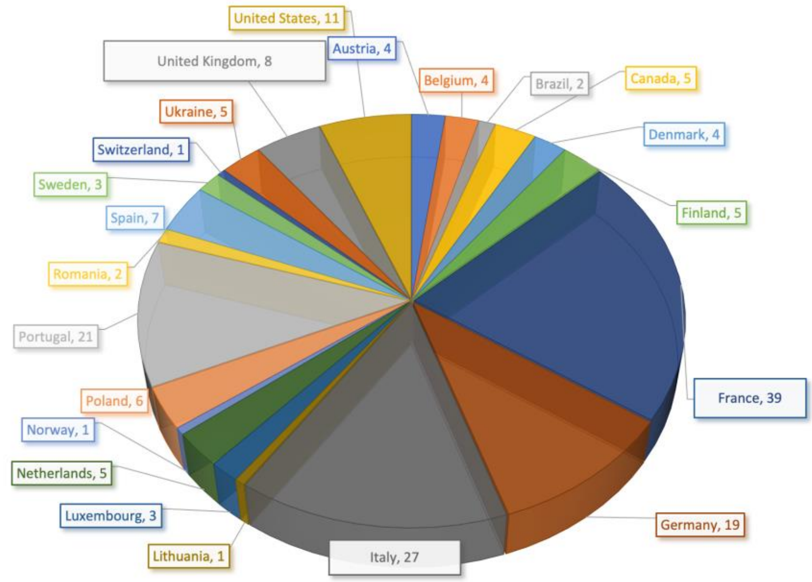


*Figure 2: Number of participants by countries. 270 persons from 45 countries registered to the event, of which 207 from 22 countries could actually attend.*

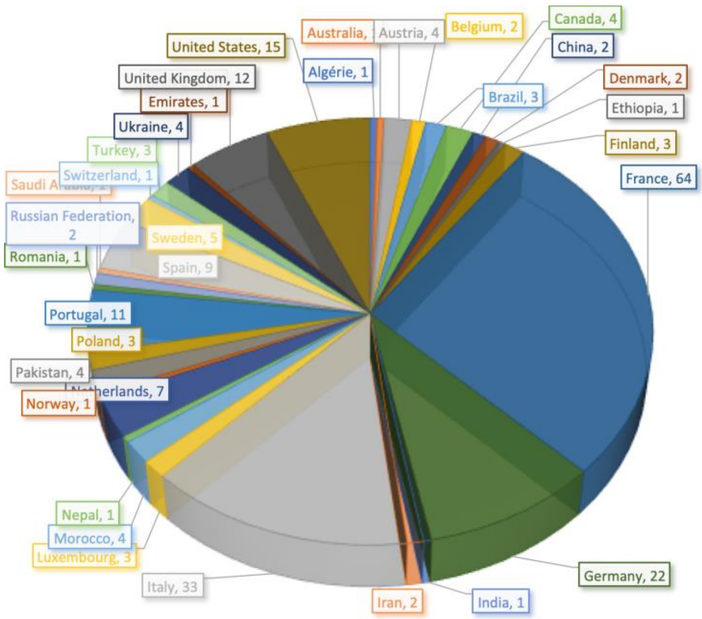


*Figure 3: Workshop Submissions. 233 abstracts were received from 34 countries*

# II. Workshop Key Themes

## 1. Advances in remote sensing methods, techniques, and products

*Co-chairs: Jiaming Chen, Luca Ciabatta, Jean Francois Crétaux, Jacopo Dari, Fernando Jaramillo, Kevin Larnier, Diego Miralles, Nuno Moreira, Karina Nielsen, Fabrice Papa; Nicolas Picot; Marco Restano, Angelica Tarpanelli, Elena Zakharova*

**1.1.** Advances in EO-base retrievals of hydrological surfaces and sub-surface variables: water bodies and water level elevations, river discharge, runoff, irrigation, evaporation, soil moisture, ground water variations, total water storage.

**1.2.** Advances in atmosphere satellite-based observations, rainfall, clouds, clouds-aerosol interactions, water vapour and water vapour isotopologues.

## 2. Advances in the use of EO for land surface and hydrological modelling

*Co-chairs: Simon Munier, Filipe Aires, Adrien Paris, Pierre-Olivier Malaterre, Rajat Bindlish, Gabrielle De Lannoy, Luca Brocca*

**2.1.** Advances in the use of EO to enhance hydrological modelling.

**2.2.** Hyper-resolution hydrology (towards continental scale high resolution hydrological modelling).

**2.3.** Advances in the use of EO for Land surface modelling and reanalysis.

## 3. Advances in science and process understanding

*Co-chairs: Benjamin Kitambo, Karim Douch, Cintia Bonanad, Sofia Ermida*

**3.1.** Advances in observing, understanding, and predicting the role of the water cycle in the Earth and climate system.

**3.2.** Observing and assessing the impact of human activities in the water cycle at global to local scales (water consumption, agriculture, industry, energy).

**3.3.** Understanding the carbon-water-energy nexus.

## 4. Water science for society

*Co-chairs: Christian Schwatke, Francesco Avanzi, Guy Schumann, Cédric David, Chiara Corbari, Simone Gabellani*

**4.1.** Advances in observation, characterisation, and prediction of hydro-climatic extremes (floods, droughts, heat waves) and its compound and cascade events.

**4.2.** Water resource management, climate adaptation and mitigation: a user perspective.

**4.3.** Capacity building, knowledge transfer and sustainable development.

### 5. Novel technologies and future missions: the future of water cycle research

*Co-chairs: Ilias Daras, John Reager, Yiljan Zeng, Wolfgang Wagner, Antara Dasgupta, Claude Duguay*

**5.1.** Water research and novel technologies. (e.g., AI, open science platforms, data intensive science, digital twins).

**5.2.** Future EO missions and coming observing capabilities for water and hydrology research and applications. Preparing for the coming Sentinel expansion and Next Generation missions, new meteorological missions, New Space, and national capabilities.

# III. Objectives of HYDROSPACE 2023

The objectives of the HYDROSPACE 2023 Workshop were the following:

- Reviewing the latest advances and results in the use of EO technology to monitor and characterise the different components of the water cycle (terrestrial hydrology, groundwater, atmosphere, oceans, mountain ranges and glaciers), hydrological processes and its interactions with human activities and ecosystems.
- Reviewing the progress in understanding the water cycle as well as its variability and sensitivity to climate change including hydro-climatic extremes with related compound and cascade events.
- Reviewing the progress of novel EO-based high-resolution data, methods, and approaches for modelling the water cycle at basin scales targeting spatial and temporal scales compatible with decision making.
- Exploring the status of future EO missions under preparation by space agencies and industry and latest advances in novel EO technologies, future mission concepts and new mission ideas for water cycle research and hydrology.
- Exploring opportunities offered by the effective integration of latest EO data, AI, advanced models, information technology and communication, cloud computing and high-performance computing capabilities for developing Digital Twins, fostering open science, and developing novel applications serving policies and society.
- Fostering networking and collaborative research in water sciences, bringing together different expertise, data and resources in a synergistic manner ensuring that the final result may be bigger than the sum of the parts.
- Identifying the major scientific challenges, observation gaps and research needs for the coming years and advancing towards the definition of major scientific priorities in water cycle research that may drive scientific activities of ESA and other partners in the coming years.

# IV. Main Recommendations from the Workshop

The workshop participants were tasked with incorporating their personal perspectives on the future directions of research and development in their respective fields, along with key recommendations for space agencies, into their presentation materials. These recommendations were then compiled and summarized by the session chairs, and subsequently presented during a dedicated session at the end of the workshop. The objective was to converge toward a set of noteworthy recommendations that would feed reflections on the future of EO for water cycle and hydrology sciences. The whole set of recommendations that emerged from the discussions has been further merged and homogenised for a better legibility. They are classified below in six items:

- community needs, in terms of access to data and future satellites
- synergies between missions and priority EO data processing
- hydrological variables
- process understanding and modelling
- operational applications and benefits for society
- other

## • Community needs in terms of:

- **Access to EO data and circulation of new products**
    - **EO data from the private sector** can be a good complement to the publicly available data from space agencies. We need to work on this complementarity and access to their data should be facilitated by **fostering more collaborations with owner companies**.
    - Collecting various processed EO data for specific areas can be a tedious work. There is an across-the-board request for a **centralized platform where data are stored and easily downloadable** (e.g. Google Earth Engine).
- **future satellites and in situ data**
    - **High frequency revisiting altimetric observations are still needed** (e.g. SMASH Constellation of small satellites) to complement high spatial coverage (SWOT).
    - **Enhanced and sustained monitoring of mass change observations** from space (e.g. NGGM and MAGIC) are needed to support water management applications and offer solutions to tackle the global water crisis.
    - It is of utmost importance to **maintain in situ networks** (e.g. stream gauges) and expand others (evapotranspiration, soil moisture)
    - **Citizen science** (e.g. use of personal weather station) can be a great source of data and should be developed with dedicated programmes.

## • Synergies between missions and priority EO data processing

- It will be very fruitful to exploit SWOT data to retrospectively **increase the amount of hydrological information retrievable from S1-2-3-6** images and altimetry data.
- **FF-SAR and UF-SAR processing** shall be better investigated: retracking strategy, **waveform classification** (eventually with **AI**) and platforms/tools to generalise its use shall be developed (e.g. ESA Altimetry Virtual Lab).

- ## Hydrological variables
  - Results intercomparison requires working with the same state of the art and up-to-date **hydrological (geo-)references**: vectors of river networks, watershed delineation, water mask for river width, land cover etc. (e.g. SWORD). Developing such a common benchmark, maintaining and enriching it has become a necessity.
  - **Consistency and quantification of EO data quality is very important** for operational applications and services as it informs the decision-making with the level of confidence one can give to the data. An **assigned confidence level to EO products** is thus required, especially when data assimilation and ML techniques are involved in the process of the data. A dedicated endeavour should be undertaken in this direction.
  - **Precipitation is still poorly covered and suffer from high uncertainties** despite its importance in the continental water cycle. Interactions with the meteorology community can help improving precipitation products.
  - Promote the study of the **water cycle with a climate perspective**, by developing **long time series**, e.g. a “water cycle” ECV.
  - GCOS hydrosphere **ECVs** such as **Terrestrial Water Storage** and **Groundwater** need to be dedicatedly monitored with enhanced spatial and temporal resolution and accuracy.

- ## process understanding and modelling
  - Water cycle studies would benefit from **broadening the scope to the energy and carbon cycle**.
  - There is a need to improve the closure of the water budget towards sub-basin scales and improve estimates of the water cycle components and their interaction.
  - **AI/ML is still underexplored in hydrology**. The necessity of physical interpretability of ML-based models must be further explored. We need more **collaboration between hydrologists and the computer science community** to ensure that state-of-the-art models are used.
  - The **quantification of Human impact on the water cycle and its short/long term consequences** still needs to be more investigated.
  - There is a need to increase the dialog with other Earth science communities:
    - interdisciplinary work: ocean, atmosphere and climate communities would benefit from satellite-derived hydrologic data.
    - In particular, the use of collocated land hydrology and atmospheric observations can yield fruitful results.

- In general, we have noted **few contributions in the field of process understanding** during the workshop. We need to put more emphasize on it and show how EO data help uncovering complex hydrological processes. The following suggestions have been made to increase the contribution in this area:
  - **Inviting more hydrologists with no EO background** to extend current activities based on EO data and develop new topics of research
  - fostering research focusing on the global hydrology of specific regions rather than focusing on the determination of one hydrological quantity globally.

- **Operational applications and benefits for society**
  - As a good practice, we should **involve more the stakeholders and end-users** during the early stage of research projects for a real co-construction of the final results.
  - Make sure to tackle the lack of funds for research in the Global South and understand where there is a need to better understand/quantify/forecast water resources
  - **Reliable (i.e. low false alarm rate) high-resolution maps with short latency** are needed to decide if and which action have to be taken locally (e.g. flood or drought events).
  - In general, **high-resolution data sets are required for most applications benefiting directly to stakeholders** (irrigation water management, snow cover etc.)
  - The use of EO-based drought indices needs to be discussed and clarified.

- **Other:**
  - Next Hydrospace workshop should include a training day on currently topical for early career scientists.

# V. Summaries from Opening Session Keynotes

Given the abundance of outstanding presentations at the workshop, we can only highlight a select few. However, as mentioned in the introduction, the slides, posters and the replay of the whole workshop can be downloaded from and viewed at:
https://www.hydrospace2023.org/photo-gallery-and-presentations
Overall, a significant part of the workshop was dedicated to the recently launched Surface Water and Ocean Topography (SWOT) mission (https://swot.jpl.nasa.gov/), jointly developed by the National Aeronautics and Space Administration (NASA) and

Centre National d'Études Spatiales (CNES) with contributions from the Canadian and UK Space Agencies. Numerous presentations focused on this wide-swath altimetry mission and showcased exciting new results and potential applications of the forthcoming data, which should become widely available in 2024. The expectations of SWOT seem clearly to be met, if not surpassed. Among the diverse range of keynote topics including flood management, surface water storage, hydrogeodesy, results from the Italian Research Council, Research Institute for Hydrogeological Protection (CNR-IRPI) team showed notable progresses in the development of a “hydrological digital twin”. More traditional research areas such as soil moisture estimation from space using the Soil Moisture Ocean Salinity (SMOS) and Soil Moisture-Active Passive (SMAP) missions were also presented, including a new low-cost L-band radiometer that could be a follow-up to instruments on missions such as SMAP. Sentinel-3 and Sentinel-6MF water level data as well as total water storage using Gravity Recovery and Climate Experiment (GRACE) were also subjects of many presentations. The opening keynote presentations are summarised in this section.

## Keynote 1: Towards a Digital Twin for the Water and Energy Cycle over Land

L. Brocca (CNR-IRPI, Italy), S. Gabellani, L. Alfieri, F. Avanzi, F. Delogu (CIMA Foundation, Italy), W. Wagner, M. Vreugdenhil (TU Wien, Austria), D. Miralles (UGent, Belgium), K. Nielsen (DTU, Denmark), F. Aires (ESTELLUS, France), D. Dalmonech and A. Collalti (CNR-ISAFOM, Italy), P. Quintana-Segui (OBSEBRE, Spain), S. Mantovani (MEEO, Italy), G. De Lannoy (KULeuven, Belgium), R. Orth (MaxPlanck, Germany), L. Samaniego, O. Rakovec (UFZ, Germany), J. Brombacher (eLEAF, The Netherlands), G. Camps-Valls (IPL, Spain), I. Trigo (IPMA, Portugal), S. Camici, A. Tarpanelli, C. Massari, L. Ciabatta, S. Barbetta, S. Modanesi, P. Filippucci, H. Mosaffa (CNR-IRPI, Italy), J. Dari (UNIPG, Italy)

Abstract

Climate change profoundly affects the global water, energy, and carbon cycle, increasing the likelihood and severity of extreme events. Better decision-support systems are essential to accurately predict and monitor environmental disasters and optimally manage water and environmental resources. A Digital Twin (DT) of the water and energy cycle over land would offer ground-breaking solutions for monitoring and simulation. Yet, it requires high-resolution (1 km, 1 hour-day) satellite Earth Observation (EO) data, fully integrated with advanced and spatially distributed modeling systems. Building a high-resolution DT over land is challenging due to: (i) the impact of human interventions on land processes through, e.g., irrigation, reservoir management, water diversion, land use and land cover changes, (ii) the need for actual high-resolution (1 km, 1 hour-day) input (e.g., precipitation, evaporation) and ancillary (e.g., soil texture, vegetation) data for characterizing the complexity of the system (for several variables, e.g., soil moisture and evaporation, ground data are scarce), and (iii) the complexity of integrating EO and modeling in a seamless, parsimonious and consistent manner for large-scale applications at high-resolution.

A DT is a virtual replica of a real-world system composed of three main elements: observations, model simulations, and user interventions. On this basis, the overall objectives of a DT for the water and energy cycle are:

1. Developing high-resolution EO-based products over the whole of Europe and targeted regions in Africa, integrated with in situ observations, for the different components of the water and energy cycle. An error characterization of the EO-based products will also be carried out.
2. Integrating high-resolution EO-based products and advanced modelling for developing: (a) use cases in cooperation with dedicated stakeholders, and (b) science cases.
3. Developing an ad-hoc web platform to make the use and science cases available to the public, not only for data visualization and exploration but also for direct interaction with simulations and results.

The presentation will show first results toward the development of a DT for the water and energy cycle, as developed in the ESA DTE Hydrology project, with applications in the Mediterranean basin for flood and landslide risk mitigation, and for water resources management.

## Keynote 2: Enabling Climate Resilient Flood Management in South Sudan Using Earth Observation Data

Élia Cantoni-Gómez(1), Beatriz Revilla-Romero(1), Edoardo Borgomeo(2), Carlos Domenech(1), Antonio Rodriguez Serrano(2), Lukas Loescher(2), Clément Albergel(3)
(1)GMV, Tres Cantos, Spain, (2)World Bank, United States, (3)ESA-ECSAT, Didcot, UK

Abstract
Working in collaboration with the World Bank, the European Space Agency (ESA) Global Development Assistance (GDA) Climate Resilience Consortium, through GMV, is using Sentinel-1 high-resolution Synthetic Aperture Radar (SAR) imagery for flood monitoring in South Sudan. More specifically, Sentinel-1 imagery is used to monitor flood extension and frequency to identify the most flood prone areas. Then, detailed flood hazard maps are generated based on factors such as flood frequency, flood extent, or a combined flood hazard index. The resulting Earth Observation (EO)-based maps provide key information on the extent, frequency, and persistence of recent flooding seasons (2017-2022). This detailed flood hazard information can raise awareness of flood risk among local institutions and communities. For such purpose, EO data is consolidating its role in helping reduce flood risk to citizens' lives and livelihoods, as ground data is very sparse across many countries. By combining EO-based flood hazard maps with exposure datasets such as for population, building or crops, we provide additional country-wide information on the potential impacts of recent floods. The service covers the entire country of South Sudan and enables the creation of a flood hazard and exposure index, allowing the World Bank team to detect flooding hotspots and prioritize investment accordingly. These efforts will help the government develop detailed flood risk management plans.
ESA's GDA Programme is a global partnership implemented with key International Financial Institutions (IFIs) – World Bank and Asian Development Bank - to mainstream the use of Earth Observation (EO) into development operations.

# Keynote 3: Toward a global long-term spatio-temporal variations of surface water storage anomaly from space from 1992 to 2015

Benjamin Kitambo(1)(2)(3), Fabrice Papa(1)(4), Adrien Paris(1)(5), Sly Wongchuig(1), Sylvain Biancamaria(1), Frederic Frappart(6), Ayan Santos Fleischmann(7), Romulo Jucá Oliveira(1), Laetitia Gal(1)(5), Pr. Raphael Tshimanga(2), Stephane Calmant(1)

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Abstract

The estimation of surface water storage (SWS) and its variations in space and time is crucial to understand the role of continental water in the regional and global water cycle. Surprisingly, the knowledge about its spatio-temporal variability and link with climate is still poorly understood at the global scale, despite the recent efforts devoted to characterization SWS in few large river basins. This lack of knowledge prevents the better understanding of the role of SWS dynamics into the hydrological and biogeochemical cycles of several river basins. Therefore, there is a fundamental need for the quantification of SWS globally.

Here we present our current effort that aims to estimate globally the long-term spatio-temporal variations from 1992 to 2015, based on satellite-derived observations. The method based on the hypsometric curve approach consists of the combination of surface water extent (in this case, from the Global Inundation Extent from Multi-Satellite GIEMS-2) dataset with topographic data from global Digital Elevation Models (DEMs), namely Forest And Buildings removed Copernicus DEM (FABDEM). As a primary result over the South American and African continents, SWS variations at monthly time step from 1992 to 2015 have been estimated and show a strong seasonal and interannual variability. The SWS-based annual mean amplitude was compared with previous estimates from multi-satellite observations over Amazon (~901 km$^3$), Orinoco (~264 km$^3$), Congo (~101 km$^3$), and Chad (~52 km$^3$) basins and showed an overall fair agreement, although there is still some ongoing work to be carried out. For the Congo basin, SWS is strongly impacted by local and regional climate [e.g., El Niño Southern Oscillation (ENSO)]. This new SWS long-term dataset at the continental scale is therefore a breakthrough as it can now be used as a baseline for future related datasets in several basins and importantly, a new source of information that opens new opportunities for hydrological and multidisciplinary sciences, including data assimilation, land–ocean exchanges and water management. Moreover, this global dataset will be a benchmark of the Surface Water and Ocean Topography (SWOT) products in playing a key role in its evaluation and validation.

# Keynote 4: Hydrogeodesy for addressing key hydrological questions and water resource sustainability

Fernando Jaramillo(1), Hossein Hashemi(2), Chao Wang(9), José Andrés Posada-Marín(20), Zahra Kalantari(3), Lan Wang-Erlandsson(22), Vili Virkki(28), Martin Maranon(1), Chunqiao Song(30), Hilary Martens(7), Fabrice Papa(5), Yoshihide Wada(4), Shimon Wdowinski(11), Jessica Fayne(6), Rodrigo Abarca del Rio(8), Jida Wang(12), W.R. Berghuijs(10), Tilo Schöne(13), Xander Huggins(14), Frédéric Frappart(17), Jay Famiglietti(15), Giuliano Di Baldassarre(16), Angelica Tarpanelli(18), Christopher Spence(19), Jean-François Cretaux(5), Kristian Rubiano(21), Michele-Lee Moore(22), George Allen(24), Etienne Fluet-Chouinard(23), Juan F. Salazar(20), Saeid Aminjafari(1), Clara Hubinger(1), Fangfang Yao(25), Luciana Fenoglio(26), Ayan Fleischmann(27), Tamlin Pavelsky(29), Marc Simard(33), Félix Girard(31), Simon Munier(34), Daniel M. Moreira(32), Abigail Robinson(1), Matti Kummu(28), Sebastian Palomino(11)
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Abstract
Increasing climatic and anthropogenic pressures are changing the world's water resources and hydrological processes at unprecedented rates. These pressures require ongoing evaluation of changes in the Earth's system and the water cycle. The current and rapid changes call for an urgent, global-scale, holistic assessment from both ground and space. We can address many open questions
about the evolving state of Earth's water cycle and climate through the emerging field of hydrogeodesy: the science that measures the Earth's solid and aquatic surfaces to

understand changes in water's availability, distribution, movement, and properties. Hydrogeodesy encompasses various geodetic technologies, including Altimetry, Interferometric Synthetic Aperture Radar (InSAR), Mass Gravimetry (e.g., the Gravity Recovery and Climate Experiment (GRACE) and GRACE-Follow On (GRACE-FO), Global Navigation Satellite Systems (GNSS) and GNSS Interferometric Reflectometry (GNSS-IR). During the last thirty years, these technologies have been used successfully to quantify changes in surface and groundwater resources from the local to the global scale. Comprehensive scientific reviews of these technologies already exist in the literature, highlighting each technology's limitations, requirements, and applications to track water. Yet, how the use of these technologies has recently evolved, and the role they play within current hydrological and sustainability frameworks remains to our knowledge unaddressed. Here, we first perform a meta-analysis of approximately 3,000 articles dealing with hydrogeodetic technologies to understand the range and trends of their application. Second, we discuss the potential hydrogeodetic technologies to transform our understanding of water sciences and climate under the umbrella of key hydrological and sustainability frameworks such as the Sustainable Development Goals of Agenda 2030, the Planetary Boundaries framework guiding towards a safe operating space for humanity, and the 21 Unresolved Questions of the International Association of Hydrological Sciences (IAHS). We find a marked and growing increase in publications of these technologies, with more studies combining several to increase the understanding of hydrological systems. Yet, we argue that hydrogeodesy can still be expanded to fill specific knowledge gaps in the hydrological community and guarantee a safe operating space for humans in terms of water resources. These geodetic technologies have reached a level of maturity that warrants their role in supporting key global water issues, including evaluating the impact of humans on water resources, sustainable consumption of water resources, and the resilience of these socio-hydrologic systems to change. The recently launched Surface Water and Ocean Topography (SWOT) mission and the upcoming NASA-ISRO Synthetic Aperture Radar (NISAR), and the European Space Agency's HydroGNSS are some of these instruments that offer the greatest hydrogeodetic potential to monitor the Earth's freshwater resources and their sustainability.

## Keynote 5: Conjugate Biophysical Regulation of Stomatal and Aerodynamic Conductances Determines Terrestrial Evaporation Response to Land Surface Temperature Variability

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Abstract

The evaporation regime of terrestrial ecosystems is influenced by land surface temperature (LST), which is modulated by conjugate effects of radiative warming, surface energy balance fluxes, biophysical conductances, soil moisture variability, and vegetation cover. Using the surface energy balance (SEB) principle, scientists have long

sought to capture the evaporation variability from satellite LST where ga and sensible heat flux is the central focus, while evaporation is estimated as a residual component of SEB. Surprisingly, the role of gcs has been largely overlooked until now due to the overriding emphasis on eliminating the uncertainties of the aerodynamic approach. Both ga and gcs play a significant role in controlling evaporation in the complex arid and semiarid ecosystems where evaporation is tightly coupled with soil water content. Therefore, integrating the roles of these conductances using the SEB principle is a crucial step towards comprehending evaporation responses to LST variations, understanding the biophysical principles governing ecosystem water use, and advancing the monitoring of evaporation through thermal remote sensing observations.
To test the SEB theory, we first explored the conductances of heat and water flux using eddy covariance observations across semiarid ecosystems in California. This analysis revealed novel and unique hysteretic patterns showing that the evaporation response to LST variability is a result of the control of gcs on evaporation in tandem with ga, soil water availability, and atmospheric aridity. The degree of hysteresis seemed to depend on varying levels of aridity. To test the reproducibility of this behavior in the thermal remote sensing model, we employed the analytical Surface Temperature Initiated Closure (STIC) model. In STIC, both the conductances are estimated analytically based on SEB principle, and the analytical expressions of both the conductances are derived from radiation, temperature, humidity, LST, and fractional vegetation cover. As a result, it does not include any semiempirical function of surface roughness and atmospheric stability for estimating aerodynamic conductance. By pairing Landsat LST with Sentinel-2 multispectral observations and meteorological forecasts, we inspected the ability of STIC to reproduce the effects of the dual conductances in shaping up the evaporation responses to LST variability for a range of soil and atmospheric aridity at the spatial scale. While the synergy of meteorological forecasts and thermal remote sensing observations allowed the visualization and verification of the dual conductances from space, repeating the spatial scale experiment at different times of the year reaffirmed how the interplay between energy and water supply-demand limitations influenced the conductance feedback on evaporation. The analysis offers an alternative approach of combining biological and physical explanations to investigate the highly complex evaporation variability from space. This integrated perspective lays the groundwork for future thermal remote sensing satellite missions.

## Keynote 6: Update on SWOT: Transformative data from revolutionary technology, and implications for hydrology and water intelligence

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Abstract
A new satellite mission for oceanography and hydrology science called Surface Water and Ocean Topography (SWOT) was developed jointly by the U.S. National Aeronautics and Space Administration and France's Centre National d'Etudes Spatiales and

launched on December 16, 2022. Using state-of-the-art "radar interferometry" technology to measure the elevation of water, SWOT will observe major lakes, rivers and wetlands while detecting ocean features with unprecedented resolution and spatial coverage. SWOT data is poised to provide critical information that is needed to assess water resources on land, track regional sea level changes, monitor coastal processes, and observe small-scale ocean currents and eddies.

SWOT will revolutionize hydrology in several areas including surface water storage and discharge in rivers by providing a global baseline set of observations for millions of water bodies. SWOT will provide the very first comprehensive view of Earth's surface water from space and will allow scientists to determine changing volumes of fresh water across the globe. These measurements are key to understanding surface water availability and in preparing for important water-related hazards such as floods and droughts. SWOT will contribute to a fundamental understanding of the terrestrial branch of the global water cycle.

SWOT will also significantly advance oceanography by detecting ocean features with 10 times better resolution than present technologies. The higher resolution will reveal small-scale ocean features that contribute to the ocean-atmosphere exchange of heat and carbon. These are major components in global climate change and will improve the understanding of the ocean environment including motion of life-sustaining nutrients and harmful pollutants. SWOT data will be used to improve ocean circulation forecasts, benefiting ship and offshore commercial operations, along with coastal planning activities such as flood prediction and sea level rise.

SWOT is expected to achieve 1 cm precision at 1 km x 1 km pixels over the ocean and 10 cm precision over 1Km land areas. Other mission payloads include a conventional dual-frequency altimeter for calibration to large-scale ocean topography, a water-vapor radiometer for correcting range delay caused by water vapor over the ocean, and precision orbit determination package (GPS, DORIS, and laser retroreflector).

The purpose of this paper is to present the SWOT mission status, including post-launch experiences, preliminary results from the mission, and SWOT’s capability for supporting downstream applications.

# VI. Feedback from participants

**The following points were fed back by participants:**

- The sessions were not topical and there was a mix of many different parameters in each session block. Much of the work is variable-oriented (and even single variable-oriented at times) and participants expected topical rather than themed sessions.
- The connection between the various water cycle storages, the fluxes between them has to go beyond a budget approach (static) and needs to be consistent from local to global. Excited to see the increased role of altimetry in that!
- Discussions were very prolific, so more time would have been beneficial.
- Excellent progress shown and rich unfolding of the discussions.

- More time for discussing posters is needed.
- Need to attract an even more global audience.
- The showcase of the launch of the Water Cycle Science Cluster at ESA-ESRIN was much appreciated.
- This was a very interesting workshop with much progress since the previous one and this kind of workshop focusing on one thematic objective is of great interest.
- Brilliant and very active science community, including newcomers and development of applications.
- Observations of key hydro variables did a lot of progress, but with remaining challenges. This includes climate data records and near real time observations. This needs to lead to modelling and forecasting.
- Complementarity between satellites (including ‘NewSpace’, but not to be opposed to the ‘OldSpace’), in situ data (drone and others) and models have been demonstrated and needs to be pursued.
- Massive data processing is becoming a reality but is used often blindly.
- Assimilation techniques / Digital Twin becomes a reality with many different models and approaches, making possible to move from R&D to operational services as done for Ocean and Atmosphere. But real applications showcase remain to be developed / demonstrated.
- The lack of some key spatial observations: high frequency revisit time and other new sensors proposal are becoming vital.
- Calibration / Validation is also vital and needs to be reinforced.
- International collaborations are of key importance, not only among EU countries, obviously.
- Research agencies are funding many activities, but budgets remain an issue for many teams, and we need to better prepare our future (students, school, PhD, Post-Docs, early career scientists)
- The loss of 23 countries out of the potential 45 is partially due to non-granted visas and partially due to lack of funding: A couple of handfuls of travel grants reserved for Early Career Scientists in developing countries should be sponsored systematically for such focused workshops.
- A training should be organised at the 6th HYDROSPACE Workshop, with training material made available in advance on the workshop website.
- Keep on doing the video recording and publishing the replay on the workshop website.
- Appreciated to have slides and posters on the workshop website.
- Lovely hosted social dinner: thanks to all the sponsors.
- Excellent organisation! Thanks to Lorenza and Francesca from the ESA-ESRIN Conference Bureau.
- The next HYDROSPACE Workshop should be held no later than November 2025.


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