



**HAL**  
open science

## Special Issue on Earth's Changing Water and Energy Cycle

Benoit Meyssignac, Sonia Seneviratne, Remy Roca, Graeme L Stephens, Michael Rast

► **To cite this version:**

Benoit Meyssignac, Sonia Seneviratne, Remy Roca, Graeme L Stephens, Michael Rast. Special Issue on Earth's Changing Water and Energy Cycle. *Surveys in Geophysics*, 2024, 45 (6), pp.1715-1720. <10.1007/s10712-024-09873-5>. <hal-04891238>

**HAL Id: hal-04891238**

**<https://hal.science/hal-04891238v1>**

Submitted on 16 Jan 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization



## Special Issue on Earth's Changing Water and Energy Cycle

**Benoit Meyssignac<sup>1</sup> · Sonia Seneviratne<sup>2</sup> · Remy Roca<sup>1</sup> · Graeme L. Stephens<sup>3</sup> · Michael Rast<sup>4</sup>**

Published online: 18 December 2024

© The Author(s), under exclusive licence to Springer Nature B.V. 2024

Atmospheric radiative processes are a fundamental component of the Earth's dynamic global water–energy cycle; they also determine both the Earth's climate and changes to the climate. Climate itself is driven by the delicate balance between solar radiative heating and long-wave radiative cooling. Local radiative imbalances set into motion the vast circulation patterns of the atmosphere and oceans, shaping our terrestrial environment and biosphere. Any shifts in climate stem from adjustments to the radiative steady state between incoming short wave and outgoing long-wave radiation, whether due to increased concentrations of greenhouse gases or aerosols, or to changes in properties of the Earth's surface.

Central to the problem of predicting climate sensitivity to radiative changes, along with associated regional climate changes, are numerous feedback mechanisms. Particularly important are those mechanisms involving the coupling between the hydrological cycle and radiative processes such as cloud feedback and water vapour feedback, or feedback from changes in the land water and energy balance. Clouds and particularly convective processes in the atmosphere play a critical role in modulating the radiation budget. Convection within the atmosphere drives the vertical transport of heat and moisture, creating complex feedback loops that influence cloud formation and the radiative balance. Convection also results in precipitation and associated latent heat release to the atmosphere, both of which are important for the forcing of the larger scale circulation. This dual role of deep convective clouds makes them one of the most significant, yet least understood, variables in the

---

✉ Benoit Meyssignac  
benoit.meyssignac@univ-tlse3.fr

Sonia Seneviratne  
sonia.seneviratne@env.ethz.ch

Remy Roca  
remy.roca@cnr.fr

Graeme L. Stephens  
graeme.l.stephens@nasa.gov

Michael Rast  
michael.rast@issibern.ch

<sup>1</sup> LEGOS (CNES/CNRS/IRD/UT3), Université de Toulouse, 31400 Toulouse, France

<sup>2</sup> Institute for Atmospheric and Climate Science, ETH Zurich, 8092 Zurich, Switzerland

<sup>3</sup> Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

<sup>4</sup> International Space Science Institute (ISSI), 3012 Bern, Switzerland

global energy cycle. The intricate relationship between cloud properties, convective processes and atmospheric circulation is particularly crucial for predicting climate response to changes in radiative forcing, making the study of clouds indispensable for understanding shifts in Earth's energy budget. Changes in the water cycle also have a direct relevance for human society impacts, related to the availability of freshwater on land.

Achieving a quantitative understanding of the feedback responses to radiative changes necessitates a foundation of precise, comprehensive and globally consistent observations of the water–energy cycle of the Earth (in the atmosphere, as well as on land and in the ocean). This includes observations of the key water and energy fluxes, along with observations of clouds, in particular those that are convection driven.

Satellite observations, with their global coverage and short revisit times, constitute the primary way to gather these comprehensive and precise measurements that shape our current climate. From 26 to 29 September 2022, a Workshop, held at the International Space Science Institute (ISSI) in Bern, Switzerland, provided a collaborative platform to tackle the observational challenges anticipated in the coming decade. With a focus on improving our knowledge of the global water–energy cycle, particularly through satellite observations, the sessions combined structured presentations with open discussions, facilitating a comprehensive exchange of information amongst the participants. Through this process, they evaluated the current state of emerging themes in the Earth's water–energy cycle, covering areas such as Earth's energy imbalance, energy and water fluxes, meridional heat transport and the role of convection and clouds in the water–energy cycle. The Workshop also stimulated discussions on how satellite data and in situ observations, together with numerical simulations of the atmosphere, can help to improve our understanding of the different processes that influence the Earth's water–energy cycle on varying time scales.

More specifically, the objectives of the Workshop were:

1. To review our current understanding of the Earth's water–energy cycle and its variability, from seasonal to multi-decadal time scales, and to characterise the roles played by clouds and atmospheric convection
2. To review the available observing systems that provide information on the Earth's water–energy fluxes, and to identify primary gaps and uncertainties in them
3. To assess the ability of model-data syntheses to estimate variations in the Earth's water–energy fluxes and of global atmosphere–ocean-coupled models in estimating and projecting the Earth's energy budget.

The objectives outlined above led to a systematic assessment of current estimates of the Earth's water and energy fluxes on pentadal to decadal time scales, derived from satellite observations and atmosphere–ocean reanalyses. Simulations from global coupled atmosphere–ocean models over the past decades were also evaluated against observational data from the first decade of the twenty-first century. Many discussions focused on the role of clouds in the energy cycle, with a focus on tropical clouds and their response to surface warming patterns, which, in turn, can influence global warming. Central to this analysis was the relationship between tropical clouds—both high and low clouds—and tropical deep convection. Other articles published here addressed observed trends in the land and ocean water cycle. Thus, the Workshop produced a collection of scientific articles in this Special Issue of *Surveys in Geophysics* offering a comprehensive overview of its key themes, ranging from insights into various physical processes to challenges in observation and modelling.

One fundamental issue in understanding the current global water–energy cycle variability is to determine the actual Earth Energy Imbalance (EEI) that drives the long-term global warming observed over the past decades. The article by Hakuba et al. (2024) examines the trends and variability in EEI derived from the observed Top Of the Atmosphere (TOA) radiation budget obtained by NASA’s Clouds and the Earth’s Radiant Energy System (CERES) project and from planetary heat inventories based on 21 ocean heat content datasets. This comprehensive comparison assesses variability and accuracy across datasets, revealing a trend in the EEI over the past two decades that doubled the EEI. It also shows the influence of data sources and sampling methods on EEI estimates, contributing to an improved estimate of the EEI uncertainty and an improved understanding of the discrepancies between different estimates. This paper also examines zonal trends in TOA radiative fluxes and identifies the impact of potential future data gaps on EEI trend estimates. The article of Loeb et al. (2024) analyses the causes for the trend in EEI. It shows that the rise in EEI stems primarily from a large increase in Absorbed Solar Radiation (ASR), only partially offset by an increase in Outgoing Longwave Radiation (OLR). Despite differences in ASR and OLR trends during specific periods (the climate “hiatus”, and El Niño phases), the EEI trends remained steady, indicating a persistent accelerated climate warming that is most worrying.

The excess of energy entering the climate system at the TOA in response to the EEI is mostly stored in the ocean but also in the atmosphere, in land and in the cryosphere. The sum of the heat stored in all compartments of the climate system should agree with the time integral of the EEI over any time scale and give information on where the excess of heat is redistributed in the climate system. However, achieving such a balanced budget with observations has been challenging because of sparse observations, in particular in the ocean at depth and at high latitudes under sea ice. Johnson et al. (2024) for the first time achieve a balance, on seasonal time scales, integrating the ocean heat content down to the deepest observed mixed layer only. By encompassing the portion of the ocean where energy is exchanged with the atmosphere on seasonal time scales, they show that the ocean dominates global seasonal energy storage, peaking in April. Smaller contributions from land and atmosphere, which peak later in the year, partially offset ocean heat storage, aligning with net global TOA energy fluxes over the seasonal cycle. This is promising for a better closure of the energy budget at interannual and longer time scales.

While the energy balance at the TOA determines the overall heat uptake in the climate system, the energy balance at the Earth’s surface and in the atmosphere governs the thermal changes in our environments. It further defines the radiative energy that drives the sensible fluxes and the evaporative fluxes and, with them, the global water cycle. Accurate knowledge of these energy fluxes is critical for understanding the water–energy cycle.

Wild and Bosilovich (2024) investigate how well the atmospheric reanalyses represent the global surface and atmospheric energy balances. They identify significant inconsistencies, particularly in latent heat flux and the global water cycle, challenging reanalyses’ reliability as reference datasets for the global mean surface and atmospheric energy fluxes. One of the reasons for these inconsistencies is that surface and TOA fluxes in reanalysis come from short-term model forecasts. These are only poorly constrained by observations. Surface fluxes can alternatively be inferred from an atmospheric energy budget approach using CERES observations at the TOA and estimating the divergence of atmospheric energy transport from reanalysis fields such as winds, temperature and others, which are strongly constrained by numerous observations via data assimilation. Mayer et al. (2024) adopt such an approach to derive the surface energy budget at global and regional scales. The inferred net surface energy

fluxes exhibit reduced global and large-scale biases compared to surface flux estimates derived from reanalyses' output or from data based on remote sensing and models. This approach, which improves understanding of how the TOA net radiation is redistributed through improved estimates of the divergent atmospheric energy transports, provides critical insights into regional patterns of ocean heat uptake.

Meysignac et al. (2024) use the inferred surface fluxes from Mayer et al. (2024), combined with ocean heat content estimates based on satellite and in situ observations in an ocean energy budget approach, to derive the meridional heat transport in the ocean. They compare their estimate of the ocean meridional heat transport with that obtained from an array of floating instruments and instruments at depth in the North Atlantic region (The RAPID and OSNAP arrays). They find a strong alignment between the ocean energy budget estimate and the in situ estimate, showing that at basin scale the atmospheric and ocean energy budgets, combined with CERES TOA measurements and ocean heat content estimates, provide a robust method for evaluating the meridional ocean heat transport.

On a regional scale as well, but over land, Rodell et al. (2024) analyse the sharp decline in global terrestrial water storage derived from measurements made by the GRACE satellites from 2014 to 2023. They show the likely link to extreme droughts over the five continents initiated by two successive El Niño events in 2014–2016 time frame, which were followed by persistent low terrestrial water storage and a lack of recovery. It is likely that climate-driven evapotranspiration changes contributed to this observed decline in terrestrial water storage.

Three papers revisit the long-standing question of the role of tropical “hot towers” in driving the large-scale circulation of the tropical atmosphere, using atmospheric energy budget analyses informed by modern observational tools (Stephens et al. 2024; Pilewskie et al. 2024; Derras-Chouk and Luo 2024). These studies validate the scale of the original convective mass flux estimates proposed by Riehl and Malkus more than 40 years ago, which suggested the presence of approximately 2000 such hot towers, each around 5 km wide, active at any given time to sustain the Hadley–Walker circulation in the mean. Unlike the diagnostic approach of the original study, these works adopt a mechanistic perspective, focusing on identifying, characterising and summing convective towers. The use of combined active and passive satellite observations emerges as a critical element when constructing the energy budget from this mechanistic angle. With this bottom-up approach, the mass flux appears to be driven by fewer, but more intense, towers than originally diagnosed. However, methodological diversity in identifying the towers continues to contribute to uncertainty in the energy budget closure. This uncertainty is expected to diminish when the results from recent or upcoming satellite missions, such as EarthCARE, INCUS, and AOS/C2OMODO, become available.

Beyond the specific role of hot towers, Stephens et al. (2024) leverage interannual variability to explore the interconnectedness of deep convection, large-scale circulation and EEI. Their work further elucidates the pathways through which deep convection influences cloud feedback, primarily through its coupling with large-scale circulation. Notably, this study highlights the importance of the “pattern effect”, a critical yet under-appreciated component of current understanding.

Taking a regional and climate trend perspective, with a focus on the tropical Atlantic Ocean and Africa, Roca et al. (2024) investigate trends in convective organisation over the last 40 years using a unique METEOSAT dataset and advanced tracking algorithms. Their findings reveal a linear trend over the past 30 years, favouring smaller, but longer-lived, deep convective systems.

Finally, Stubenrauch et al. (2024) synthesise key lessons from the nearly two-decade-long Global Energy and Water EXchanges (GEWEX) Cloud Assessment effort, which produced a unified cloud database through extensive international collaboration. This study underscores the importance of long project timelines and robust international coordination for ambitious initiatives of this scale. The methodological framework developed by the Cloud Assessment team has since been adopted as the standard for other GEWEX-Data and Analysis Panel (GDAP) assessment exercises, such as the recent precipitation assessment.

All these studies and discussions underscore the significant progress that has been made in understanding the Earth's water–energy cycle and its mean state. Through comprehensive observations and advanced modelling, we now have a clearer picture of how radiative processes, atmospheric convection and large-scale circulation shape the current climate system. However, the challenge ahead lies in unravelling how this mean state evolves in a warming climate, particularly as the Earth's water–energy cycle is intricately linked to the spatial patterns of surface warming. This adds complexity, as the response of convection, clouds and circulation to these warming patterns remains highly uncertain. Addressing these uncertainties requires continued advancements in satellite missions, improved observational datasets and enhanced numerical simulations. Together, these tools will enable a more robust understanding of how the Earth's water–energy cycle adjusts to a rapidly changing climate, at the same time providing critical insights for future climate projections.

As Guest Editors we are very grateful to the ISSI staff for organizing and holding this Workshop, to all reviewers of the articles presented here, to Prof Michael Rycroft, Co-Editor-in-Chief, for his oversight of this Special Issue, and to the staff of Springer Nature for all their efforts.

## References

- Derras-Chouk A, Luo ZJ (2024) A geostationary satellite-based approach to estimate convective mass flux and revisit the hot tower hypothesis. *Surv Geophys*. <https://doi.org/10.1007/s10712-024-09856-6>
- Hakuba MZ, Fourest S, Boyer T, Meyssignac B, Carton JA, Forget G, Cheng L, Giglio D, Johnson GC, Kato S, Killick RE, Kolodziejczyk N, Kuusela M, Landerer F, Llovel W, Locarnini R, Loeb N, Lyman JM, Mishonov A, Pilewskie P, Reagan J, Storto A, Sukianto T, von Schuckmann K (2024) Trends and variability in Earth's energy imbalance and ocean heat uptake since 2005. *Surv Geophys*. <https://doi.org/10.1007/s10712-024-09849-5>
- Johnson GC, Landerer FW, Loeb NG, Lyman JM, Mayer M, Swann ALS, Zhang J (2024) Closure of Earth's global seasonal cycle of energy storage. *Surv Geophys*. <https://doi.org/10.1007/s10712-023-09797-6>
- Loeb NG, Ham S-H, Allan RP, Thorsen TJ, Meyssignac B, Kato S, Johnson GC, Lyman JM (2024) Observational assessment of changes in Earth's energy imbalance since 2000. *Surv Geophys*. <https://doi.org/10.1007/s10712-024-09838-8>
- Mayer M, Kato S, Bosilovich M, Bechtold P, Mayer J, Schröder M, Behrangi A, Wild M, Kobayashi S, Li Z, L'Ecuyer T (2024) Assessment of atmospheric and surface energy budgets using observation-based data products. *Surv Geophys*. <https://doi.org/10.1007/s10712-024-09827-x>
- Meyssignac B, Fourest S, Mayer M, Johnson GC, Calafat FM, Ablain M, Boyer T, Cheng L, Desbruyères D, Forget G, Giglio D, Kuusela M, Locarnini R, Lyman JM, Llovel W, Mishonov A, Reagan J, Rousseau V, Benveniste J (2024) North Atlantic heat transport convergence derived from a regional energy budget using different ocean heat content estimates. *Surv Geophys*. <https://doi.org/10.1007/s10712-024-09865-5>
- Pilewskie J, Stephens G, Takahashi H, L'Ecuyer T (2024) A multi-satellite perspective on “hot tower” characteristics in the equatorial trough zone. *Surv Geophys*. <https://doi.org/10.1007/s10712-024-09868-2>

- Roca R, Fiolleau T, John VO, Schulz J (2024) METEOSAT long-term observations reveal changes in convective organization over tropical Africa and Atlantic Ocean. *Surv Geophys*. <https://doi.org/10.1007/s10712-024-09862-8>
- Rodell M, Barnoud A, Robertson FR, Allan R, Bellas-Manley A, Bosilovich MG, Chambers D, Landerer F, Loomis B, Steven Nerem R, O'Neill MM, Wiese D, Seneviratne SI (2024) An abrupt decline in global terrestrial water storage and its relationship with sea level change. *Surv Geophys*. <https://doi.org/10.1007/s10712-024-09860-w>
- Stephens GL, Shiro KA, Hakuba MZ, Takahashi H, Pilewskie J, Andrews T, Stubenrauch CJ, Wu L (2024) Tropical deep convection, cloud feedbacks and climate sensitivity. *Surv Geophys*. <https://doi.org/10.1007/s10712-024-09831-1>
- Stubenrauch CJ, Kinne S, Mandorli G, Rossow WB, Winker DM, Ackerman SA, Chepfer H, Di Girolamo L, Garnier A, Heidinger A, Karlsson K-G, Meyer K, Minnis P, Platnick S, Stengel M, Sun-Mack S, Veglio P, Walther A, Cai X, Young AH, Zhao G (2024) Lessons learned from the updated GEWEX Cloud Assessment database. *Surv Geophys*. <https://doi.org/10.1007/s10712-024-09824-0>
- Wild M, Bosilovich MG (2024) The global energy balance as represented in atmospheric reanalyses. *Surv Geophys*. <https://doi.org/10.1007/s10712-024-09861-9>

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.