BAMS
Meeting Summary

How Stable Water Isotope Measurements and Modeling Can Help Bridge the Gap between Research on Weather and Climate Time Scales

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Hybrid workshop "Water Isotopes: From Weather to Climate"

What: 150 scientists from different fields of weather and climate research gathered online as well as at local hubs to discuss how water isotopes can contribute to address key open questions in atmospheric science across time scales.

When: 15–17 November 2021

Where: Online and with local hubs in Bergen, Zurich, Bremerhaven, and Tokyo

KEYWORDS: Precipitation; In situ atmospheric observations; Measurements; Surface observations; Climate models; Tracers

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Stable water isotopes have long been used in climate research. Ice cores, cave deposits, and sediment archives have revealed parts of the history of the climate system on long time scales. Over the last decades, new analytical methods have emphasized that stable water isotopes also contain strong signals on much shorter, meteorological time scales. Studies increasingly show that these signals contain valuable information about atmospheric processes and the water cycle on a range of time scales from a few seconds to millennia. Water isotopes are thus becoming a tool for gaining process understanding from measurements and for constraining numerical models on a continuity of scales, from weather to climate.

Variations in the stable water isotopes in water vapor and precipitation are a combined result of all phase changes and mixing processes along the life cycle of water vapor, from evaporation to precipitation. Thereby, the water isotope composition becomes a measurable quantity of different aspects of the global water cycle, such as, e.g., the turnover of latent heat and water vapor mixing processes along its atmospheric transport pathway. When added to studies focused on atmospheric dynamics or microphysics, for example, water isotopes provide valuable additional constraints that integrate over a sequence of processes, such as evaporation, mixing, and condensation.

However, there are several impediments to utilizing the potential of stable water isotopes for atmosphere and climate sciences. Most importantly, the subject of stable water isotopes and the required analytical methods are more common within geochemistry and are not usually part of the curriculum in atmospheric and climate science. Expert knowledge on this subject applied to atmospheric sciences is thus distributed over the globe within a fairly small community.

So far, this small community has relied on major geophysical conferences for exchanges between specialists and to demonstrate the use of stable water isotopes for specific problems in atmospheric and climate science. The ongoing pandemic may have especially affected such a small and distributed community. Without a chance to meet their peers, young scientists in particular have a hard time building their professional network. Building on a workshop organized by US CLIVAR in Boulder, Colorado, in 2019 (Bailey et al. 2021), we therefore organized a hybrid workshop with the aim to continue efforts toward establishing water isotopes as a common tool from weather to climate time scales and to establish contacts that last into a time beyond the pandemic.

Workshop format: Online hybrid, with local hubs

Scientific meetings in the times of the pandemic were difficult to plan, with constantly changing regulations, differing among countries, and with varying levels of travel restrictions. We therefore decided to organize the workshop in a hybrid format, with "local hubs" in Bergen, Norway; Zürich, Switzerland; Tokyo, Japan; and Bremerhaven, Germany. Participants could join in person at one of the local hubs, if regulations allowed, to enjoy a social component during the workshop. About half of the participants joined at local hubs, the other half online, from many different countries and time zones.

To facilitate global participation, the 3-day workshop took place between 1100 and 1700 UTC each day, leaving some time for other work during the workshop period. Still, the time window made for challenging working times in places like the U.S. West Coast and Australia. Oral Zoom sessions were therefore made available on YouTube the following day (https://www.youtube.com/channel/UCPzlhAl01axyCly9snXhcpQ/videos). The oral sessions were started by an intro and recap at the start of each day, followed by a topical keynote talk and several short talks. This was followed by discussion sessions. Assigned hosts led sessions on the same four topics on all three days, allowing participants to contribute to several topics. A conference website (https://watercycle.w.uib.no/workshop-water-isotopes-from-weather-to-climate-summary/) helped participants to navigate between the different digital sessions.

A virtual poster session took place each day, using the online tool gather.town. Participants could wander between online rooms, look at posters, and join a group video chat with the poster presenter and workshop participants. While for some participants this was their first-ever poster session, many others remarked that the online format was astonishingly similar to an in-person event. To maximize feedback and interaction for young scientists, we tasked voluntary participants to send comments and questions to specific presentations after the workshop (the organizers prepared a list with presenters and commenters before the start of the workshop). In a survey after the workshop, participants confirmed that the overall format was perceived as a good compromise, remarking it even had enabled broader international participation than would have been possible with an exclusively physical workshop. Furthermore, in comparison to traditional meetings, this format strongly reduced costs and CO_2 emissions related to travel.

Progress in observational and modeling activities

The workshop provided an impressive snapshot of the rapidly enhancing observational capabilities that contribute to moving the field from observation-limited to observation-driven science. Modeling activities also continue to expand and develop, with isotope implementations becoming available for a range of models, creating new opportunities for addressing scientific questions by combining measurements and models.

Innovative experimental techniques. One of the largest game-changers for the field has been the advent of laser spectrometry in the last decade, enabling in situ measurements of water vapor isotopes at weather time scales. As shown in several presentations, the installation of laser spectrometric instruments on the ground, ships, aircrafts, or unmanned aerial vehicles have provided valuable data from different regions of the world, from high to low latitudes, including vertical profiles through the troposphere or near the surface. These novel observations reveal the complexity of processes that control the variability of isotope signals. In addition, novel remote sensing techniques including satellite and surface-based observations have shed light on vapor phase isotope variability over various layers of the troposphere. While the interpretation of these observations remains challenging and is limited by the sparsity of in situ measurements for ground-truthing, their combination with model simulations using adequate observation operators is promising for understanding and validating moist processes in the mid- to upper troposphere in model simulations.

New observations of isotopes in all three phases of water provide insight into how the Earth's water cycle operates. Cloud-free and near-surface regions have become fairly accessible by drones and field-going in situ laboratories for extreme conditions, providing much-needed profile information. Even though monthly ground-based precipitation isotope measurements have a long tradition (since the 1960s), high-time-resolution measurements that could provide cloud-related information are relatively rare and mostly based on manual sampling. Water isotopes in clouds (vapor and hydrometeors), however, are still rare and challenging to obtain. Impressive progress has been made recently with aircraft-based isotope observations. While sampling the liquid and ice phase of clouds still is a challenge, promising new techniques based on phase-separating inlets for in situ measurements start to emerge.

Advances in modeling capabilities. Impressive progress has been made in high-resolution (kilometer-scale) modeling of water isotopes in both idealized and realistic configurations [see Bailey et al. (2022) for an overview of existing isotope-enabled models]. This allows the simulation of isotope fields in unprecedented detail, for example, of (sub-)tropical mesoscale cloud clusters. Several presentations have shown how to exploit these simulations for detailed process studies, such as the impact of convective processes on vapor isotope composition in the upper troposphere. These studies identify processes that have become observable only with the most recent progress in measurement systems, thereby motivating and guiding future observational strategies.

The signals on the integrated moist history of an air parcel contained in water isotopes on weather time scales suggests their usefulness for data assimilation studies (e.g., Toride et al. 2021). Advances in the assimilation of isotopic observations provide another interesting avenue for combining new observations with models. Although the added value of assimilating real isotopic observations in an operational context still needs to be quantified and better understood, these activities offer a unique opportunity to strengthen the connection between the water isotope and meteorological communities.

Showcases of water isotopes in specific research topics

The key value of isotope research in atmospheric science is the powerful observational anchor they provide for constraining processes that are not directly measurable by traditional measurements. However, the communication gap between the isotopic and non-isotopic communities was highlighted as a major challenge at the US CLIVAR workshop in Boulder. We provide three specific examples on how water isotopes have added value to a specific research topic, in part taken from a collection of recent literature in the field assembled by workshop participants (https://watercycle.w.uib.no/files/2021/11/Literature_references_Stable_Isotopes_Workshop_2021.pdf).

Addressing the clouds–circulation conundrum with water isotopes in the trades. The recent participation of several European and American water isotope research teams in the international field campaign EUREC4A (Elucidating the Role of Clouds–Circulation Coupling in Climate; Bony et al. 2017) has allowed multiplatform measurements (Bailey et al. 2022) and modeling studies (Blossey et al. 2021) at an unprecedented level of detail within and around shallow trade wind cumulus clouds. These clouds are ubiquitous over the tropical oceans and represent a key uncertainty factor in climate sensitivity estimates (Bony et al. 2017).

The formation of trade wind cumulus clouds depends on the interplay between many physical processes at different scales. The large-scale circulation modulates vertical profiles of humidity and temperature by differential advection, thereby modulating the strength of vertical mixing of water vapor between the boundary layer and the free troposphere for which water isotopes are an observational constraint (Risi et al. 2019; Hu et al. 2022). The balance between convective drying of the boundary layer by in-mixing of dry air from the free troposphere and turbulent moistening by ocean and rainfall evaporation is a central element in the process chain of shallow cumulus cloud formation and determines the isotope signal of the subcloud layer (Galewsky et al. 2022). Cold pools driven by precipitation evaporation has been shown to trigger new convective cells at their edge and is associated with distinct so-called moist patches representing positive water vapor anomalies at their edges (Torri 2021). Diagnosing the origin of the moisture in these moist patches has been an important challenge in the last years and water isotopes are now used to provide valuable observational answers to identify the key moistening factor of cold pool air parcels. Investigating the distinct isotope signatures associated with the different boundary layer moistening and drying processes (Risi et al. 2021) provides important insights into their relation to the macroscale cloud properties under different large-scale flow configurations (Aemisegger et al. 2021).

A weather system-based approach to water isotope research in atmospheric science. The large variability in isotope signals measured and simulated at the mesoscale has opened the door for weather-system-based studies. These studies range from the tropics, where the precipitation or vapor isotope signals associated with tropical cyclones has been studied (Sánchez-Murillo et al. 2019; de Vries et al. 2022), to studies of the subtropical heat low for the variability in subtropical free tropospheric humidity, seen through the lens of water isotopes (Lacour et al. 2017; Dahinden et al. 2021). Several authors have investigated isotope signals associated with midlatitude cyclones (Thurnherr et al. 2021) and deciphered moisture source information from other influences during intense precipitation from land-falling atmospheric rivers (Weng et al. 2021). When extending into polar regions, atmospheric rivers contribute to the mass and radiation balances of the Arctic and Antarctica. Marine cold-air outbreaks in these regions provide local and intense water cycles on a mesoscale, with unique opportunities for in situ observations of evaporation and precipitation. Such weather-system-based studies have allowed us to link water isotope signals to both large-scale atmospheric drivers and subgrid-scale processes, thereby providing valuable opportunities for model evaluation and data assimilation.

Toward a new era for the contribution of water isotopes to paleoclimate. Historically, the major contributions of water isotope studies to climate research have been in the area of paleoclimate. In particular, water isotope records in polar regions have allowed quantitative reconstructions of past polar temperatures. However, uncertainties in the interpretation of paleoclimate isotope records have persisted for decades, particularly in tropical regions. The uncertainties concern the mechanisms controlling the isotopic composition of rainfall, the isotopic modifications from rainfall to proxies (e.g., speleothems), and the spatial representativeness of local records in a context where paleoclimate records are sparse.

Several recent advances allow us to hope for progress in the near future. First, paleoclimate modeling capabilities have improved dramatically, with more and more fully coupled isotope-enabled models, the recent development of isotope-enabled Earth system models, and the development of isotope-enabled transient simulations (He et al. 2021). Second, advances in data assimilation now allow paleoclimate data to be assimilated into paleoclimate simulations (Tierney et al. 2020; Okazaki et al. 2021). The use of isotopic records in data assimilation is made more powerful by advances in proxy system forward-modeling approaches (Okazaki and Yoshimura 2019) and by the recent development of isotopic data compilations (e.g., Comas-Bru et al. 2020).

Overall, it was striking to see how much the communication gap between isotope specialists and nonspecialists has narrowed in these three showcases. Detailed water isotope process studies use the same models, configurations, diagnostic tools, and concepts as current studies without involvement of water isotopes. Such a convergence of tools is an important asset that enables further growth of the research field.

Remaining challenges and the way forward

From the daily discussion rounds during the workshop, focused on the topics of observations, modeling, data access and storage, and communication; workshop presentations; and follow-up conversations, we have distilled several key points that summarize the state of the discussion and emphasize remaining challenges and opportunities to move the field forward.

Observation needs and challenges.

- The measurement of vertical isotopic profiles and of different water phases within and outside of clouds with reliable statistics and fast-response instruments appear crucial to test several hypotheses regarding the interaction of convective and microphysical processes, using research aircraft, ultralight airplanes, and drones.
- Observations of the second-order parameter *d*-excess as a process indicator are still limited and are poorly simulated by models, even more so for the second-order parameter ^{17}O-excess. Nonetheless, there is value in further developing observational coverage and capabilities in both regards. For improvements in modeling, an important step will be to narrow down the uncertainty in the nonequilibrium fractionation factor and its dependency on boundary layer stability and wind speed. Advances in this respect are to be expected from contributions at the workshop.
- Precipitation measurements are still the backbone and gold standard for isotope-enabled climate model validation. This points to a large relevance of gathering such observations on a denser spatial grid and for providing easier means to access such data. In addition, precipitation measurements with daily to subdaily time evolution are valuable for studies of weather events and processes. The community could contribute more to extend existing archives, such as the Global Network of Isotopes in Precipitation (GNIP) at the International Atomic Energy Agency (IAEA), both in terms of coverage and data types.

Water isotope modeling on weather and climate scales.

- There was a consensus that up-to-date intercomparison exercises for water isotope–enabled models would be timely and highly useful. Such an exercise, termed Stable Water Isotope Intercomparison Group phase 3 (SWING3), should have subdaily outputs for the past decade to help interpret field campaign observations and apply different model diagnostics. Furthermore, high-resolution simulations in idealized radiative–convective equilibrium, as in the Radiative–Convective Equilibrium Model Intercomparison Project (RCEMIP) exercise (Wing et al. 2018), could provide a nearly inexhaustible source of process studies and of opportunities for single-column model evaluation.
- Paleoclimate simulations with the same model versions as for the present climate, as in the Paleoclimate Modelling Intercomparison Project phase 4 (PMIP4) exercise (Kageyama et al. 2018), would be very useful to link the processes controlling the water isotope composition for the present and at paleoclimate time scales. This would help guide strategies to exploit present-day measurements to infer the mechanisms driving isotopic records at the paleoclimate time scales. Furthermore, water isotopes will serve as useful observational constraints for evaluating fully coupled Earth system models. The implementation of isotope physics in land surface and ocean schemes provides new opportunities for studying interactions between the Earth's surface and the atmosphere at climate time scales through the lens of water isotopes.
- Since model codes often evolve rapidly and without adapting isotope-specific formulations, maintaining water isotope model code is challenging. Implementation efforts run

the danger of not being part of continuous model development and rather attached to a specific version. Convincing arguments for the value of water isotope enabled models are important to ensure long-term efforts to keep and maintain water isotope code within model-code archives (the “trunk”).

Communication challenges.

- As was highlighted in several discussions, bridging the gap between water isotope and non-isotope communities, and to a wider audience, remains a major challenge. However, such efforts are necessary to make the value of water isotopes accessible for other atmospheric science communities and to ensure the maintenance of water isotope model code.
- Many ideas emerged, such as aggregating outreach resources and creating a collection of “water isotope success stories” to show examples of where water isotope information has contributed to solving scientific questions. Another suggestion was to create a buddy system between water isotope specialists and nonspecialists, for example, during the Observations for Model Intercomparisons Project (obs4MIP) for a systematic use of water isotopes in model evaluation. Model and data archiving and documentation for ease of availability are crucial requirements in such efforts.
- Water isotopes show large signals on weather time scales. The information contained herein has potential, both for enhancing our process understanding and to be used in data assimilation. If the community continues to demonstrate the value of water isotopes by combined measurement and model activities, it will strengthen arguments for the value of dense, continuous in situ measurement networks and satellite observations, and for further intensifying science on the continuity from weather to climate time scales.

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