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Using Budget Analysis to Compare Water Isotope Simulations with the Goal of Enhancing Extreme Weather Forecasts

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Water isotopes offer insights into the Earth's water cycle, including unique perspectives on processes related to extreme weather events like atmospheric rivers. Atmospheric rivers are principal conduits for meridional transport of heat and moisture through the subtropics and mid-latitudes. However, uncertainty persists in how they source moisture and how this organization might change in the future persists. We examine these extreme events from using water isotope-enabled Atmospheric General Circulation Models. Nevertheless, the modeled water isotope can diverge from the predicted outcomes where non-equilibrium fractionation and kinetic effects, which are largely parameterized in the models, occur. Therefore, to investigate extreme hydrological events and quantify the model uncertainties, a comprehensive water isotope budget analysis is essential, incorporating a surface-atmosphere integrated approach.

In a recent study, a process-based decomposition analysis was introduced, capturing the 6hourly changes, or tendencies, in atmospheric oxygen isotope values [1]: (Equation 1)

This method not only provided the first global estimation of atmospheric fractionation rates but also was employed to investigate how different parts of the water cycle impact isotope values (Figure 1). Here, we examine the water cycles in the present-day period to highlight changes in fractionation processes. Our analysis spans different atmospheric regions, using models including GISS-E2.1, IsoGSM-LR/HR, MIROC5-iso, and ECHAM6-wiso, forced by reanalyses MERRA-2, ERA5, JRA-55, and NCEP-R2.

By integrating the isotope budget method with consideration of vapor source distribution in the moisture convergence system [2], we will discuss how each fractionation process enriches or depletes atmospheric water isotope values. Additionally, we anticipate that perturbed parameterizations related to cloud physics and convection processes will be more effectively constrained through model-data isotope comparisons, thereby enhancing the predictability of extreme hydrological events in models. We hope that, with the sensitive response of water isotopes in mid- to high latitudes, isotope modeling research in the future might be helpful in addressing the globally increasing threat of hydrological events, such as atmospheric rivers and extratropical cyclones.

[1] Bong et al. (2024), *Journal of Geophysical Research: Atmospheres*, 129. https://doi.org/10.1029/2023JD038719

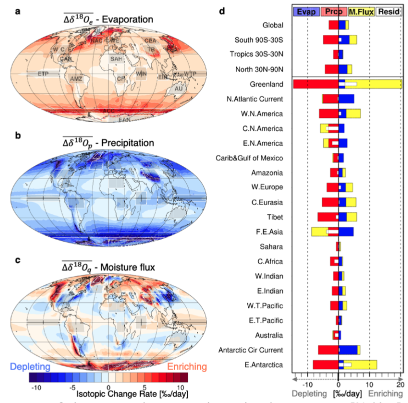
[2] LeGrande et al. (2024), *Geophysical Research Letters*, In Press: Just how river-like are atmospheric rivers?

Equation 1

$$\frac{\delta^{18}O_{t+\Delta t} - \delta^{18}O_t}{\Delta t} = \Delta\delta^{18}O_t = \Delta\delta^{18}O_{e_t} + \Delta\delta^{18}O_{p_t} + \Delta\delta^{18}O_{q_t}\ [‰/s]$$

Here, $\Delta\delta^{18}O_e$, $\Delta\delta^{18}O_p$, and $\Delta\delta^{18}O_q$ represent rates of isotopic changes due to evaporation, precipitation, and horizontal moisture flux, respectively.

Figure 1



Global time means of decomposed oxygen isotopic change rates [‰/day] in the model ensemble. **a** Evaporation role is enriching the atmosphere by supplying heavy water, while **b** precipitation is depleting the atmosphere. **c** horizontal moisture flux is making a balance between fractionations of evaporation and precipitation. Regional isotope mass budget analysis considering **a-c** is **d**, and the white bar ($\Delta\delta w$) is a residual of considering all isotopic processes ($\Delta\delta w_e + \Delta\delta w_p + \Delta\delta w_q$). Note that the global residual accounts for approximately 1.1% when considering all three processes, signifying the conservation of water isotope mass.