A Lagrangian investigation of water vapor isotopes in radiative-convective equilibrium

Giuseppe Torri (gtorri@hawaii.edu), University of Hawai'i at Mānoa

SCHOOL OF OCEAN AND EARTH SCIENCE AND TECHNOLOGY

1. Introduction

Stable water isotopes—HDO, $H_2{}^{18}O$, and $H_2{}^{16}O$—are **useful tools** that have been employed in the study of a wide variety of processes in the Earth's system.

Applications range from paleoclimatology to groundwater hydrology, to the study of atmospheric processes.

In order to interpret correctly the isotopic signal from rainfall or water vapor, a good understanding is needed of **how each atmospheric process can impact isotope fractionation**.

Models of varying degree of complexity have been used so far, but most either **oversimplify** or neglect some atmospheric processes which are known to be important.

While useful to obtain a first-order understanding, these models leave **many open questions**.

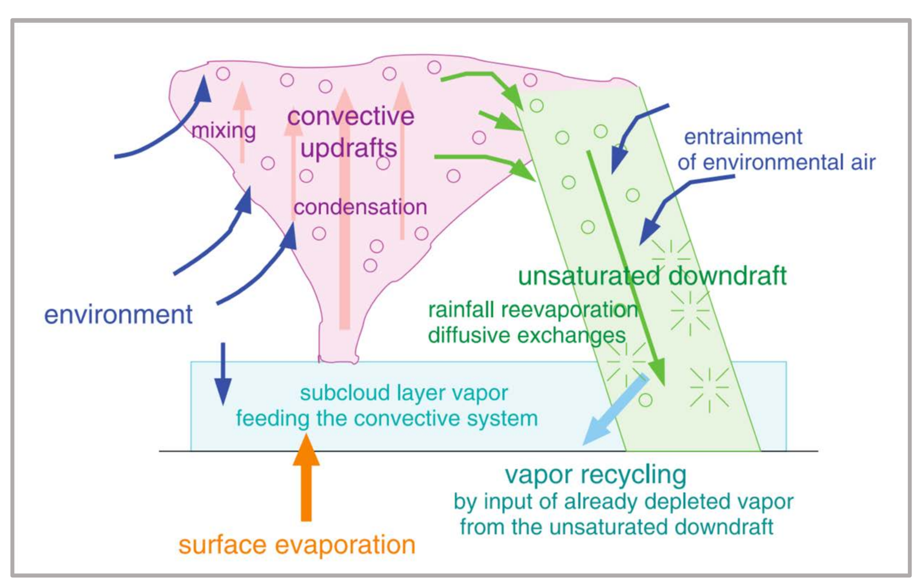


Figure 1: Conceptual model used in Risi et al. (2008) to determine the isotopic composition of water vapor and rainfall in radiative-convective equilibrium. The study uses a single-column model that does not explicitly resolve cold pools nor processes such as lateral entrainment in updrafts and downdrafts [from *Risi et al.* (2008)].

2. Research questions

The overarching goal of this work is the achievement of a deeper understanding of how atmospheric processes in deep convective systems affect the water vapor isotopic composition of the dynamical components of the systems.

The main questions that will be addressed can be summarized as:

- What controls the **water vapor isotopic composition** of the main dynamical components of deep convective systems (updrafts, downdrafts, cold pools)?
- How are these compositions affected by **mesoscale organization**?
- Why do the isotopic compositions change with **increasing precipitation rate**?

Answering these questions will help further our understanding of how **precipitating systems affect** water isotopes, which could **help improve the interpretation of** current and past records of stable water isotopes.

3. Methods

We address the questions using a **numerical approach**, through a combination of an isotope-enabled cloud resolving model (CRM) and a Lagrangian particle dispersion model (LPDM).

The CRM is a modified version (Iso-) of the System for Atmospheric Modeling [SAM; *Khairoutdninov and Randall*, 2003] that **incorporates heavy water isotopes**, essentially by replicating the same transformation processes that the lighter isotope, $H_2{}^{16}O$, is subject to, and which also includes fractionation [*Blossey et al.*, 2010].

The model is run with a horizontal resolution of **250 m** and a stretched vertical grid that goes from **500 m** in the upper troposphere to **31 m** in the boundary layer.

We choose to study systems in **radiative-convective equilibrium** over an **oceanic surface** as this is the simplest setting that contains all the necessary ingredients that characterize a deep convective system.

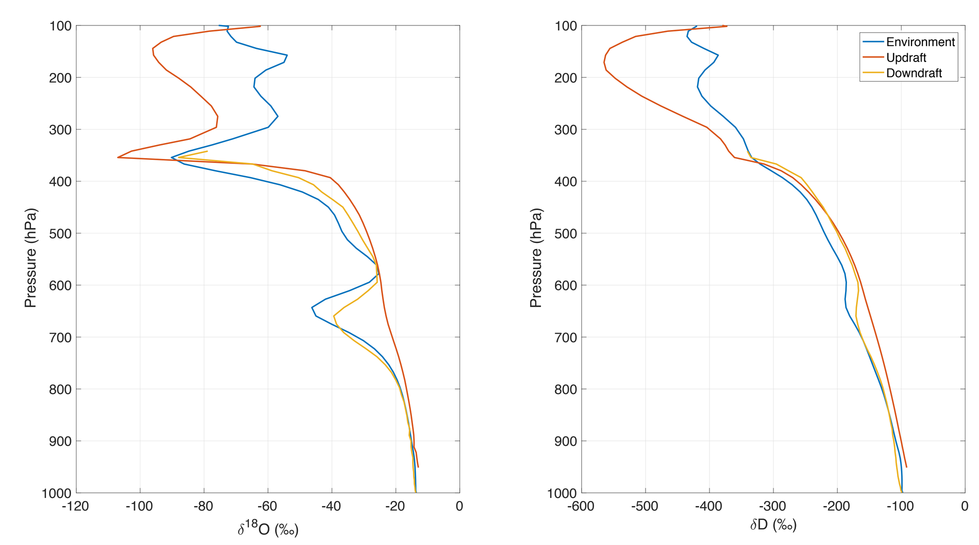


Figure 2: Vertical profiles of oxygen-18 (left) and deuterium abundances in water vapor (right) within updrafts (red), surface-reaching downdrafts (yellow), and the environment (blue).

The core region of cold pools are overall depleted, but show pockets that are relatively enriched in oxygen-18.

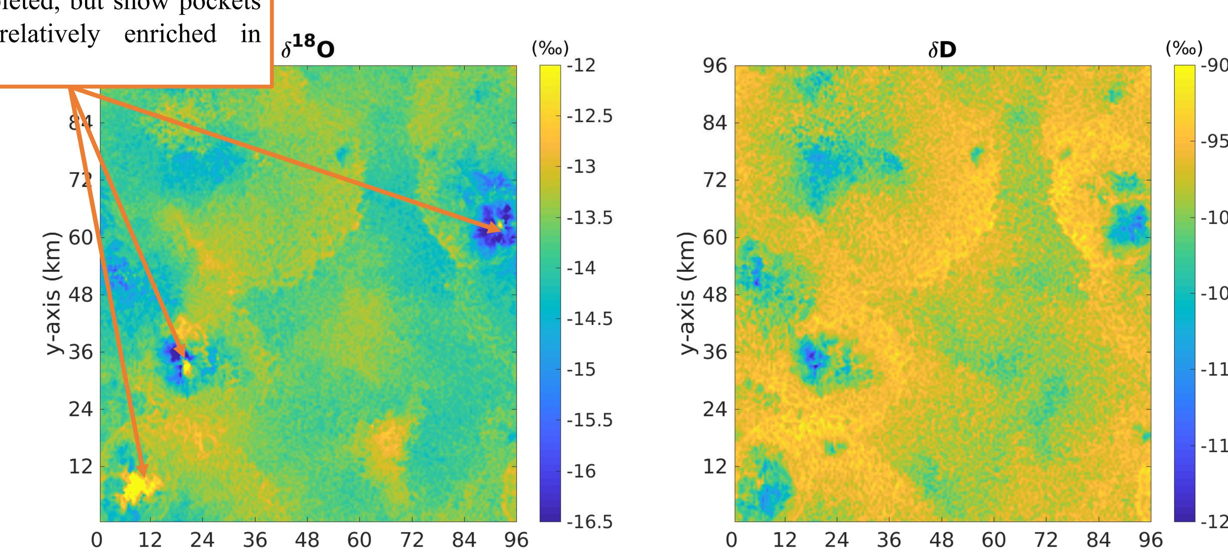
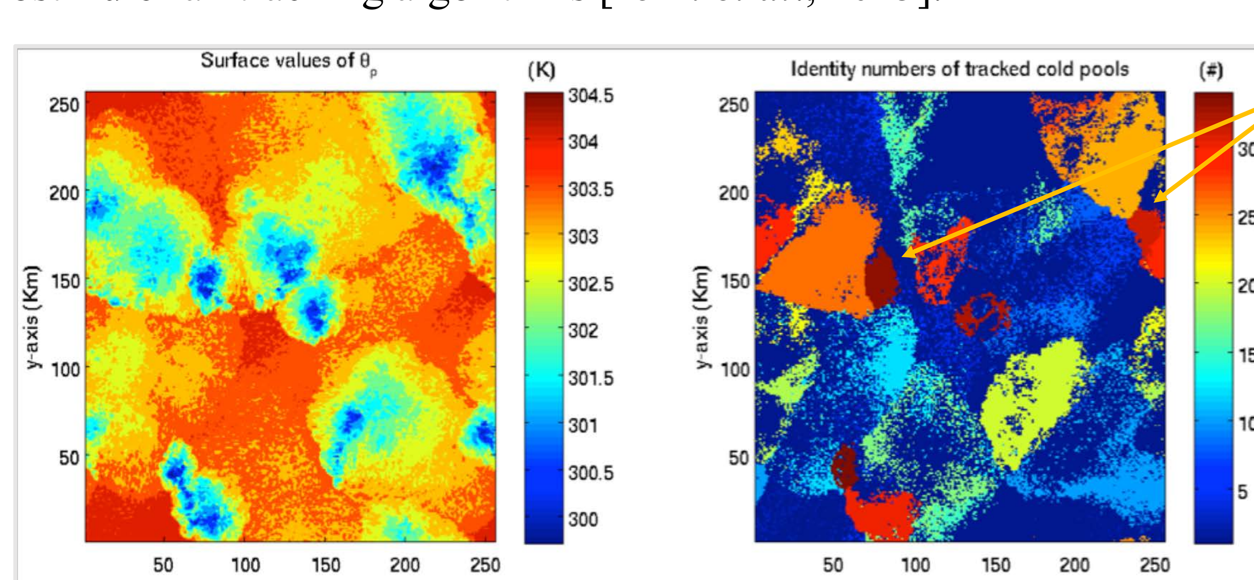


Figure 3: Surface values of water vapor abundances of oxygen-18 (left) and deuterium (right) from a snapshot in the simulation.

The LPDM [*Nie and Kuang*, 2012; *Torri et al.*, 2015] is run **online with IsoSAM**. Particles are distributed uniformly in the horizontal directions and in the vertical pressure coordinate, which allows each Lagrangian particle to be interpreted as a parcel of air with a definite mass.

The positions of the Lagrangian particles are combined with the output from IsoSAM. This makes it possible to **associate physical properties**, such as temperature and mixing ratios of light and heavy water vapor isotopes, to each Lagrangian particle. These properties are **updated** every time step using tendencies computed by IsoSAM.

The LPDM can also be used to **track dynamical structures**, such as cold pools, more efficiently than most Eulerian tracking algorithms [*Torri et al.*, 2015].



The algorithm successfully recognized cold pools as distinct even when they collide with other cold pools. This is hard to achieve with Eulerian tracking algorithms.

Figure 4: Comparison between the surface values of density potential temperature diagnosed from a model simulation (left) and the identity numbers assigned by Lagrangian tracking to various cold pools (right).

4. Preliminary results – cold pools

We start by focusing on **cold pools**, arguably one of the least understood components of deep convective systems. We use Lagrangian tracking to **collect statistics** on the isotopic composition of cold pools observed in the simulation.

As hinted by Fig. 3, the results suggest that the interior of cold pools contains vapor that is very depleted in deuterium, but **less depleted in oxygen-18**.

This is likely due to the fact that the air feeding cold pools from greater altitudes **experiences more rain evaporation**, which alters its deuterium excess.

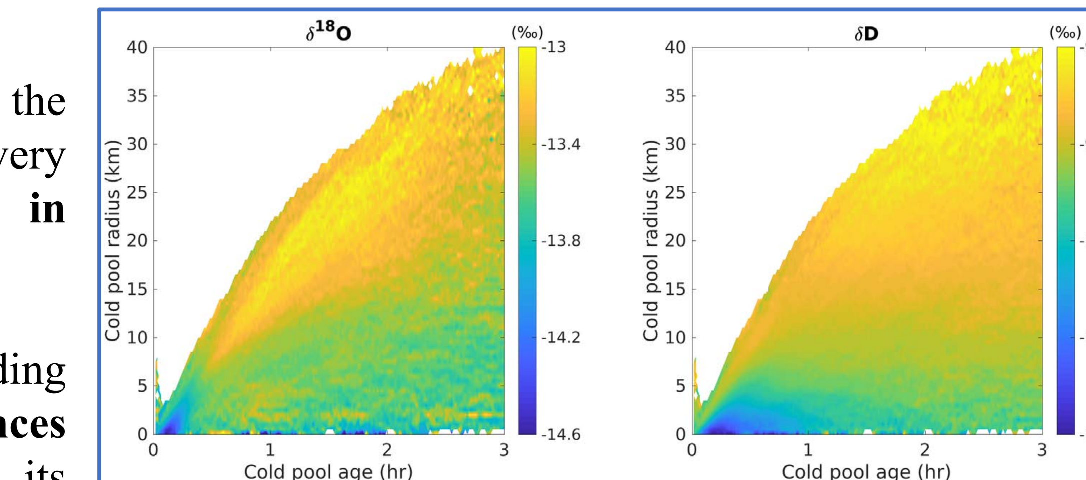


Figure 5: Water vapor abundances of oxygen-18 (left) and deuterium (right) averaged over all tracked cold pools as a function of cold pool age and radius.

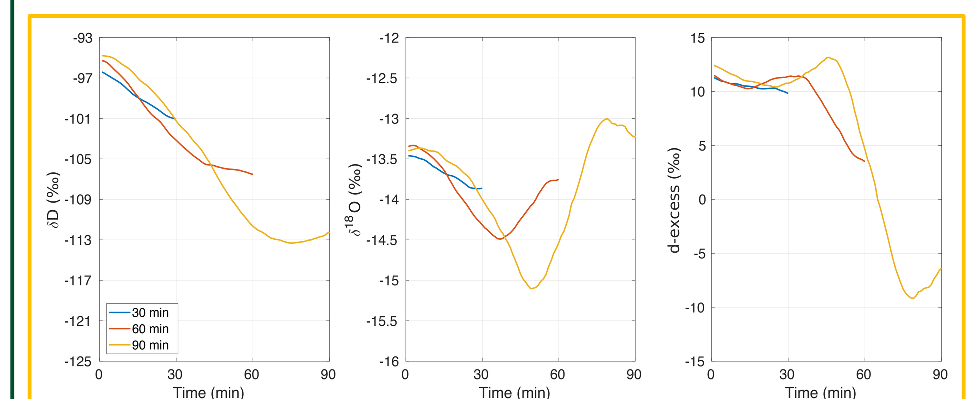


Figure 6: Surface values of deuterium abundance (left), oxygen-18 abundance (center), and deuterium excess (right) for downdrafts that last 30 (blue), 60 (red), or 90 (yellow) minutes.

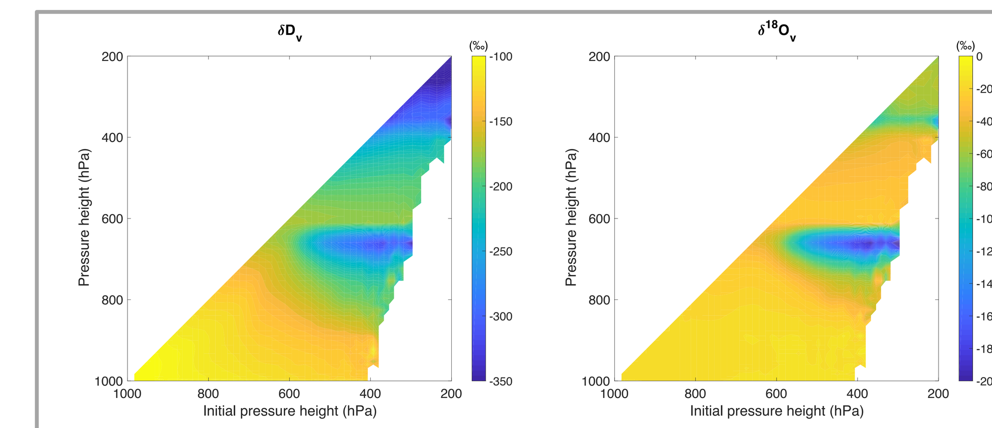
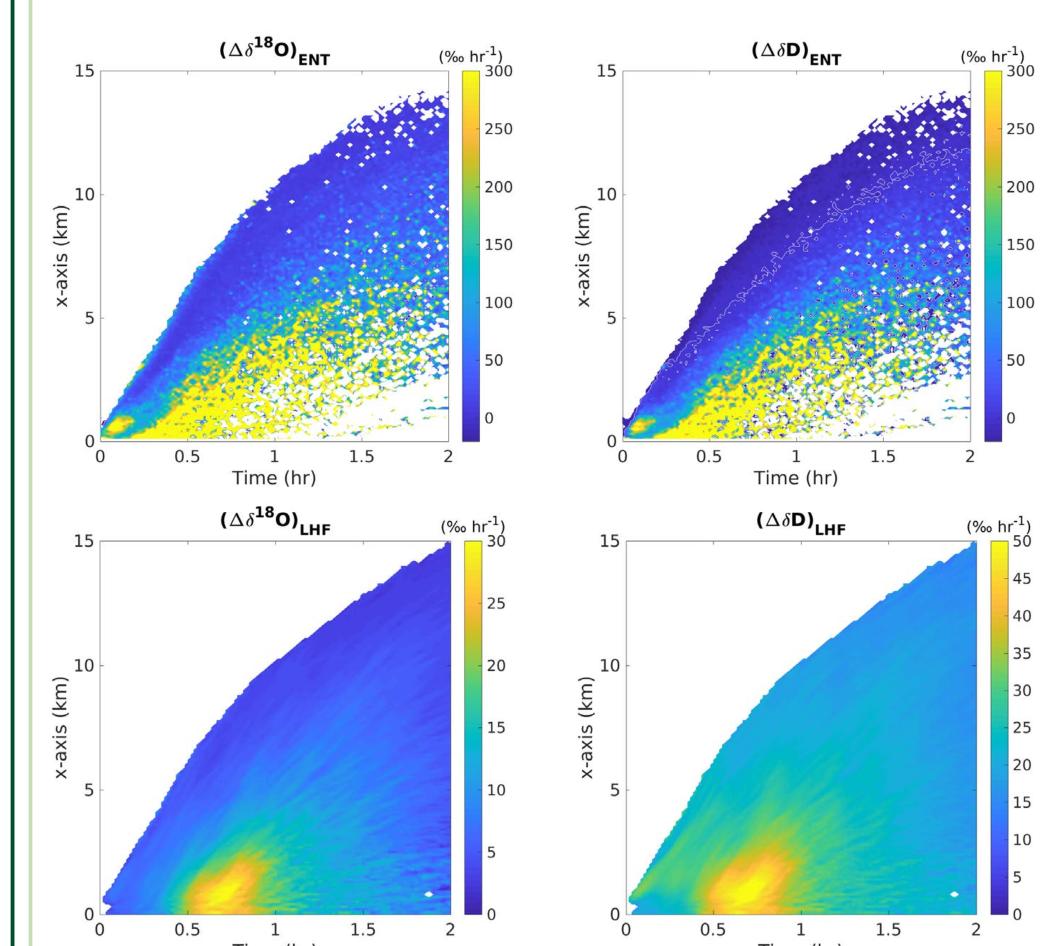


Figure 7: Abundances of deuterium (left) and oxygen-18 (right) for water vapor in downdrafts having different initial heights.

Figure 8: Rate of change of abundances of oxygen-18 (left) and deuterium (right) due to gust front entrainment (top) and surface latent heat fluxes (bottom) for cold pools shown as a function of cold pool age and radius.



How do **surface latent heat fluxes** and **gust front entrainment** influence the isotopic composition of a cold pool?

Modeling cold pools using **shallow water equations**, [*Ross et al.*, 2004] one can show that:

$$\frac{1}{R_X}\frac{\partial R_X}{\partial t} = \left[\frac{1}{q_X}\left(\frac{\partial q_X}{\partial t}\right)_{LHF} - \frac{1}{q}\left(\frac{\partial q}{\partial t}\right)_{LHF}\right] + \frac{w_e}{h}\left[\frac{q_X^{ent}}{q_X} - \frac{q^{ent}}{q}\right]$$

where h is the cold pool height, w_e the entrainment velocity, X is a heavy water isotope, and the superscript ent indicates entrained values.

With the aid of the Lagrangian tracking, we can compute each term and assess the importance of different processes at various stages of the cold pool life cycle.

5. Summary (so far)

We begin the study of stable water vapor isotopes by focusing on **cold pools**.

Air originating at great altitudes can inject vapor with **negative d-excess** values in the cold pool.

Entrainment appears to have an overall **stronger influence** than surface fluxes; the two are comparable near cold pool edges.

6. Bibliography

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