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

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1. Introduction

Stable water isotopes—HDO, H218O, and H216O—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.

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; Khairoutdinov and Randall, 2003] that incorporates heavy water isotopes, essentially by replicating the same transformation processes that the lighter isotope, H216O, is subject to, and which also includes fractionation [Blöossey et al., 2016].

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.

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].

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.

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:

\[
\frac{\partial R_E}{\partial t} = \frac{1}{h} \left( \frac{\partial}{\partial z} \left[ h \left( \frac{\partial}{\partial z} \left( \frac{\partial q}{\partial z} \right) \right) \right] - \frac{\partial q}{\partial z} \right) - \frac{\partial q}{\partial z} \frac{\partial q}{\partial z} - \frac{\partial q}{\partial z} \frac{\partial q}{\partial z}
\]

where \( h \) is the cold pool height, \( w_e \) the entrainment velocity, \( X \) is a heavy water isotope, and the superscript \( \text{ext} \) 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

Khairoutdinov, M. F. and D. A. Randall (2003), Journal of the Atmospheric Sciences, 60, 467–482.