Earth and Planetary Science Letters 481 (2018) 387–394

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Importance of depth and intensity of convection on the isotopic composition of water vapor as seen from IASI and TES δD observations

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A R T I C L E   I N F O

Article history:
Received 27 November 2016
Received in revised form 16 October 2017
Accepted 24 October 2017
Available online 8 November 2017
Editor: H. Stoll

Keywords:
stable water isotopes
water vapor isotopologues
convection
water cycle
convective mixing
infrared remote sensing

A B S T R A C T

We use tropical observations of the water vapor isotopic composition, derived from IASI and TES spaceborne measurements, to show that the isotopic composition of water vapor in the free troposphere is sensitive to both the depth and the intensity of convection. We find that for any given precipitation intensity, vapor associated with deep convection is isotopically depleted relative to vapor associated with shallow convection. The intensity of precipitation also plays a role as for any given depth of convection, the relative enrichment of water vapor decreases as the intensity of precipitation increases. Shallow convection, via the uplifting of enriched boundary layer air into the free troposphere and the convective detrainment, enriches the free troposphere. In contrast, deep convection is associated with processes that deplete the water vapor in the free troposphere, such as rain re-evaporation. The results of this study allow for a better identification of the parameters controlling the isotopic composition of the free troposphere and indicate that the isotopic composition of water vapor can be used to evaluate the relative contributions of shallow and deep convection in global models.

1. Introduction

The water isotopologues ($H_2{}^{16}O$, $H_2{}^{18}O$ and HDO for the main ones) are useful tracers of the hydrological cycle as they fractionate during the phase changes of water, and have therefore been used for many purposes from paleoclimate reconstructions (*e.g.* Hoffmann et al., 2003; Vimeux et al., 2009; Tierney et al., 2010) to the evaluation of past and modern climate simulations (*e.g.* Hoffmann et al., 1998; Jouzel et al., 2000; Yoshimura et al., 2011). Since the last decade, observations of the δD ($\delta D = 1000 \times \left(\frac{HDO/H_2O}{VSMOW} - 1\right)$) in the vapor from satellite allow to study the isotopic variations in the vapor phase at a large scale (*e.g.* Worden et al., 2007; Frankenberg et al., 2009) and proved to be particularly beneficial for investigating the hydrological processes (*e.g.* Risi et al., 2012; He et al., 2015; Galewsky et al., 2016). The interpretation of the isotopic composition of water vapor is however not straightforward and questions remain about the processes controlling the isotopic composition of water vapor and the precipitations.

In particular, the role of tropical convection on the isotopic composition of rainfall has been widely discussed in the literature. Dansgaard (1964) first documented an anti-correlation between the isotopic composition of the precipitation and the precipitation intensity. This "amount effect" has also been observed in near-surface water vapor (Lawrence et al., 2004) downwind of organized convection, with more rainfall resulting in more depleted water vapor. From the first distributions of δD in the tropical free troposphere, Worden et al. (2007) also suggested the role of the intensity of convection in depleting the water vapor. Later on, however, observational studies suggested a relationship between the depletion of the vapor and the degree of organization of the convection (Kurita et al., 2011; Berkelhammer et al., 2012). Similar relations have also been shown from observations in the precipitation (*e.g.* Lekshmy et al., 2014; Aggarwal et al., 2016) suggesting the interest of such observations to constrain the representation of convective and stratiform rain in model (Aggarwal et al., 2016).

While most recent studies point out a primary depleting mechanism associated with the depth/stratiform fraction of convection, the relative effects of depth and intensity of convection have not been discussed. However intensity and depth of convection are strongly tied together as more intense convection is generally asso-

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https://doi.org/10.1016/j.epsl.2017.10.048
0012-821X/

ciated with more deep/organized convection. Additionally, theoretical interpretations of the mechanism responsible of the depletion differ (*e.g.* Lee et al., 2007; Risi et al., 2008; Kurita, 2013; Moore et al., 2014), highlighting a need to refine the controls on the isotopic composition of water. We test the following hypothesis: both the depth and the strength of convection affect the relative distribution of the isotopic composition of water vapor in the free troposphere. To test this hypothesis, we compare diabatic heating rate profiles obtained from the Tropical Rainfall Measuring Mission (TRMM) (Shige et al., 2007), against remotely sensed observations of free tropospheric δD derived from thermal infrared (IR) radiances measured from two remote sounders: TES (Tropospheric Emission Spectrometer) onboard the NASA Aura and IASI (Infrared Atmospheric Sounding Interferometer) onboard MetOp satellite. As the isotopic composition of precipitation is rather a consequence of the isotopic composition of water vapor and, as we expect the isotopic composition of precipitation to vary in concert with the isotopic composition of vapor in the lower troposphere (*e.g.* Kurita et al., 2011; Conroy et al., 2016) an understanding of the parameters controlling the isotopic composition of water vapor might offer insight into the amount effect. Moreover, assessing the sensitivity of δD estimates obtained from TES and IASI to the different depth/intensities of convection is also useful to define their potential role to evaluate the representation of convection in climate models. The different ways of simulating the proportion of shallow and deep convection in climate models have indeed been recognized as a major issue in assessing a precise climate sensitivity (Sherwood et al., 2014).

2. Datasets and methods

2.1. Data

In this study we use retrieved H_2O and δD profiles from IASI measured radiances (Lacour et al., 2012) which are sensitive to variations of δD in the free troposphere and for which the error is estimated and validated against ground-based FTIR and TES retrievals to approximately 38‰ on a single measurement basis (Lacour et al., 2015). We use the retrieved values of δD and H_2O at 4.5 km, where the maximum of sensitivity lies (typical averaging kernels describing the vertical sensitivity of the retrieval are shown in supplemental material). Only cloud free scenes are used. While one of the advantages of IASI is to provide numerous measurements a day, currently there are no computational facilities capable of processing this number of recorded spectra. We thus focus on two limited datasets: one representative of the whole tropics (25°S to 25°N) for April 2013 and another one above the maritime continent (65°E–155°E–15°S–10°N) for the year 2010. To check the robustness of our finding, we also use TES retrieved profiles of δD and H_2O (Worden et al., 2012) above the maritime continent as nearly co-located TES and IASI datasets were available for this region. To evaluate the vertical distribution of diabatic heating rate, we use the monthly latent heating product (3H25 Version 7) obtained from TRMM Precipitation Radar (PR) measurement with the Spectral Latent Heating (SHL) retrieval method (Shige et al., 2007). We also use the monthly stratiform fractions available from the monthly 3H31 product (version 7).

Latent heating profiles are directly related to the presence of precipitating clouds and the height of maximum heating can be attributed to different depths of convection. Shallow convection is recognized when the latent heating profile peaks in the lower troposphere (between 2 and 4 km), deeper convection is characterized with maximum heating between 4 and 7 km and convection associated to stratiform clouds is identifiable when latent heating profiles peak in the upper troposphere (Schumacher et al., 2015). Non or weakly precipitating clouds can not be detect in TRMM PR measurements because of a lack of sensitivity of the instrument to light rain. Surface precipitation rates are used to characterize the intensity (also refereed as strength) of convection.

IASI estimates at 4.5 km have been gridded on TRMM monthly product (0.5° × 0.5°). On average there are about 50 observations (N) of δD available per grid cell per month, which resulting in an improved precision of approximately a factor 7 relative to an individual measurement. IASI can provide δD estimates almost everywhere on the globe with a time of revisit of 12 hours on condition that the scene is cloud free as IASI measurements are opaque to the atmosphere below thick clouds. TRMM PR measurements are made everywhere where it rains with a time of revisit of 2–3 days. These differences are likely to induce a sampling bias. Nevertheless, it assumed that at the monthly time scale, the mean signal observed by the two instruments is representative of the average situation.

2.2. Method

Variations in δD are to first order tied to those in specific humidity according to a Rayleigh model as:

$$\delta D_{rl} = (\alpha - 1)\ln\frac{q}{q_0} + \delta_0, \tag{1}$$

with q_0 and δ_0 the specific humidity and the isotopic composition of the water vapor source, and α the coefficient of fractionation. To a second order, for a given source, deviations from a Rayleigh curve are the signature of particular processes that act to enrich or deplete the vapor. To quantify these enriching or depleting effect we compute the deviation from a reference Rayleigh as: $D_{rl} = \delta D - \delta D_{rl}$. We assume a constant water vapor source to compute the reference Rayleigh model as the average specific humidity at 2 m above ocean surface ($q_0 = 25$ mmol/mol) for the tropics. This model constitutes an idealized framework where the isotopic composition of the convective updraft defined here characterize quiescent conditions. In reality, the initial composition of the updraft can be modified by many processes, including rain reevaporation, and then feed the convective updraft. Nevertheless we assume that at the monthly scale, the used Rayleigh model constitutes a lower limit of possible δD–q at equilibrium. The uncertainty resulting from the use of a constant water source and the confidence in the absolute values of our retrieval are discussed in further details in supplemental material.

Additionally, we provide the temporal correlation ($r_{\delta-q}$) between $log(q)$ and δD to further characterize the δD–q relationship. We take advantage of IASI bi-daily sampling to compute correlation coefficients between the temporal variations of $\log(q)$ and δD (N varies between 50 and 62). The correlation coefficients are tested for the hypothesis of no correlation and only p-values lower than 0.01 are kept.

In this study we define the amount effect as the sensitivity of δD to precipitation rates, and argue that it can be identified in the vapor as well as in precipitation when the isotopic composition of vapor is analyzed as a function of precipitation rates.

3. Observed relationships between the isotopic composition of water vapor and the depth and strength of convection

3.1. Isotopic signature of convection's depth along a longitudinal section

Fig. 1 introduces the basis of our rationale and the metrics used for this study. It shows a longitudinal section of the latent heating profiles (averaged between 5°S and 5°N) obtained from TRMM PR through the Indian to the Pacific oceans for April 2013. The corresponding longitudinal sections of D_{rl} and the $r_{\delta-q}$ from IASI together with the precipitation rates are also shown. The section