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A seasonality of δD of water vapor (850–500 hPa) observed from space over Jeju Island, Korea

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ABSTRACT: We examined the seasonal variations of isotopic composition of water vapor in the lower troposphere (850–500 hPa) to relate those of precipitation and groundwater using satellite observations from the Aura Tropospheric Emission Spectrometer (TES) over the volcanic Island of Jeju, Korea. We ran an isotope-enabled general circulation model (IsoGSM) and calculated 120-hr reverse-calculated trajectories for air parcels corresponding to the TES observations to better understand the seasonal variations of δD of water vapor in the lower troposphere. δD of precipitation by previous studies and the model results show winter-enriched, while summer-enriched water vapor isotope is observed by the TES observations, which may require a validation campaign using *in-situ* measurements or continuous monitoring of water vapor isotopes around Jeju Island.

Key words: Jeju Island, isotope, water vapor, seasonality

1. INTRODUCTION

Stable water isotopic measurements have been widely used to study the hydrological cycles, particularly, processes related to water movement among different reservoirs, e.g., atmospheric moisture cycling, evaporation, transpiration, groundwater recharge, snowmelt infiltration, and runoff (Worden et al., 2007; Lee et al., 2009; Lee et al., 2010a; Lee et al., 2010b; Peng et al., 2010). In addition, isotopic compositions of meteoric water, either directly measured (precipitation, ice cores or snowpack) or indirectly inferred from datable materials (speleothems and tree rings), are among the most important paleo-proxies for past climate reconstruction (Posmentier et al., 2004). The isotopic compositions of meteoric water are correlated with climate variables, such as temperature, humidity, wind speed and precipitation amount. The empirical relationships between isotope ratio and climate variables are the fundamental bases for interpretation of paleo archives, such as ice cores and speleothems (Jo et al., 2010; Liu et al., 2011). However, the interpretation of isotopic variations in terms of climate change is often hampered by a lack of other related observations of the climate variables in both space and time.

To reconstruct the paleoclimate, isotope-enabled general circulation models (GCM) have been developed and applied to many scientific questions (Lee et al., 2007; Yoshimura et al., 2008; Yoshimura et al., 2010; Risi et al., 2012). To ensure the isotope-enabled GCMs, the GCM simulations should be compared with observed isotopic distributions of precipitation and water vapor. Water vapor is the most abundant greenhouse gas in the atmospheric hydrological cycle and the changing distribution of water in the atmosphere has been obvious and significant implications for water resources and climate variations (Lawrence et al., 2004). Recently, satellite observations of tropospheric water vapor and its isotopic composition have become available (Worden et al., 2007). These new measurements have the potential to add insight into characterizing the distribution of moist processes affecting the distribution of water vapor.

Jeju Island has both subtropical maritime climate and temperate climate and thus shows four distinct seasons with moderately hot summer and cold winter. Throughout the year, winds come from north to northeast resulting in a temperate condition of the northern Eurasian Continent in the winter, whereas winds originate from south to southeast resulting in a high temperature and humidity condition typical of the northern Pacific Ocean (Lee et al., 2007). Different air masses affect Jeju Island (cold and dry continental polar air masses vs. moist maritime tropical air masses), resulting in a unique seasonal variations in isotopic composition of water vapor. This provides us with a better understanding of where the moisture originated and history of the moisture. Therefore, the objective of this study would be to investigate a seasonality of water vapor isotope around Jeju Island, which has never been reported. This paper is organized as follow: section 2 introduces previous studies of stable water isotopes around Jeju Island, and in section 3, we

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will describe the Tropospheric Emission Spectrometer (TES) measurements and models used in this study. Seasonality of δD of liquid water and water vapor will be presented and discussed in section 4 and a summary and implications will follow in section 5.

2. BACKGROUND ON THE USE OF STABLE ISOTOPE IN JEJU ISLAND

2.1. Overview of Studies utilizing Stable Water Isotopes

A limited number of stable water isotopic studies have been conducted over the volcanic island of Jeju, South Korea, in which groundwater from precipitation is a major freshwater resource. Davis et al. (1970) first investigated the isotopic composition of groundwater with tritium data to provide the flow regimes of groundwater. They estimated the mean residence time of groundwater (ranges between 2 and 8.5 years) and also concluded that the "*altitude effect*" of precipitation is not observed in the isotopic composition of groundwater. After several decades of Davis et al. (1970), isotopic compositions of precipitation and groundwater have been investigated for several scientific purposes, such as groundwater salinizataion and nitrate contamination (Kim et al., 2003; Koh et al., 2005) and variations of precipitation isotopes and contribution of precipitation to groundwater over the volcanic island (KS Lee et al., 1999; S Lee et al., 1999; Lee et al., 2003).

S Lee et al. (1999) collected precipitation samples at different locations and altitudes over the island and showed the "*altitude effect*" of precipitation isotope, representing a removal of moisture from the original air mass from the ocean surface towards the mountain regions. They indicated that there are differences in the air masses contributing to precipitation above and below the boundary between the atmospheric boundary layer and the free troposphere by showing a discontinuity in the "*altitude effect*" around 1000 m above the sea level. Lee et al. (2003) examined the isotopic composition of precipitation over the northeastern Asia, including Jeju Island. They found that the isotopic composition of precipitation at Jeju Island is not dependent on temperature (the "*temperature effect*").

KS Lee et al. (1999) first correlated the isotopic composition of precipitation and groundwater, indicating that the whole year precipitation contributes to groundwater recharge. This implied that recharge occurs throughout the year and that evapotranspiration influences are minimal. Kim et al. (2003) showed that the saline water results from the mixing of groundwater with seawater using the relationship between oxygen vs. hydrogen isotopes. Koh et al. (2005) correlated precipitation and groundwater isotopes, indicating that groundwater is recharged by rainy season precipitation and is not experienced further evaporation, which is consistent with KS Lee et al. (1999). Lee et al. (2007) analyzed movement of soil water through unsaturated soil zone and estimated mean residence times for soil waters from precipitation and groundwater isotopes using two well-mixed models. They also concluded that deuterium excess (*d-excess,* $d = 8 \cdot \delta^{18}O - \delta D$) is a good tracer to evaluate recharge process.

2.2. Seasonality of Precipitation Isotopes

From the global perspective, eastern Asia reveals the most complex patterns of spatial and temporal distribution of stable isotopic composition of precipitation (Araguás-Araguás et al., 1998; Posmentier et al., 2004). At typical mid-latitude and high-latitude continental locations, seasons control temperature and water isotopes correlate with temperature ("*temperature effect*"). On the other hand, over the tropics, water isotopes correlate with amount of precipitation, so called the "*amount effect*". Seasonality of precipitation isotope was discussed by Araguás-Araguás et al. (1998), with emphasis on the China territory including Pohang, Korea, based on the Global Network of Isotopes in Precipitation (GNIP) database. Lee et al. (2003) related the isotopic composition of precipitation from the GNIP database to climate conditions in northeastern Asia with two-year period of precipitation isotopes at Jeju Island, Korea. Posmentier et al. (2004) examined the seasonality of precipitation isotope using the GNIP database and a two-dimensional isotope-enabled model.

In most mid-latitude, the isotopic compositions of precipitation ($\delta^{18}O$ or δD) are enriched in the summer and depleted in the winter. However, the previous studies observed that this isotopic seasonality is reversed in the coastal regions of the eastern Asia, for example, Pohang in Korea, while farther inland it returns to a summer-enriched/winter-depleted seasonal distribution. Araguás-Araguás et al. (1998) observed strong seasonal variations of deuterium excess values in precipitation caused by a complete reversal of atmospheric circulation over these areas and changing source of atmospheric moisture. Posmentier et al. (2004) discussed climatic factors that influence isotopic seasonality, either summer-enriched or the reverse. Using a two-dimensional model, they showed that one of the important mechanisms for the observed isotopic pattern in Asia could be interseasonal variations in vertical atmospheric stability.

Over Jeju Island, a distinct seasonality of isotopic composition of precipitation (δD, $\delta^{18}O$ and *d-excess*) has been observed in the previous studies (S Lee et al., 1999; Lee et al., 2003; Lee et al., 2007). S Lee et al. (1999) first documented the isotopic seasonality, assuming there are two types of regional air trajectories which bring to Jeju Island; the NNW trajectory from the land mass between November to March and the SSE trajectory from the Pacific Ocean between April and October. Lee et al. (2003) related the deuterium excess to different air masses affecting the island during different seasons (a cold-dry continental polar air mass in winter vs. a hot-humid maritime tropical air mass in summer).

3. THE TROPOSPHERIC EMISSION SPECTROMETER (TES) INSTRUMENT

With the advent of new technology in stable water isotopes, such as online reduction mass spectrometry, laser-induced spectroscopy, and spectrometer on-board satellite, it has been easier to analyze isotopic composition of liquid water and vapor. The isotopic composition of liquid water, such as groundwater and precipitation, has been measured by the previous work, but the isotopic composition of water vapor has never been observed over Jeju Island. Currently, the Tropospheric Emission Spectrometer (TES) on the Aura is the only measurement for water vapor isotope over Jeju Island.

The Tropospheric Emission Spectrometer (TES) on the EOS-Aura platform is a nadir viewing infrared Fourier transform spectrometer, which covers a spectral range between 650 cm^{-1} and 3050 cm^{-1} as discussed in Beer et al. (2006). The footprint of each nadir observations is approximately 5.3 km × 8.5 km. In the nadir view, TES data have been sensitive to the abundant tropospheric gas species including H_2O and HDO (Worden et al., 2004; Worden et al., 2006). Global surveys are the routine observations that TES conducts and made on approximately a "one day on, one day off (standard products)" cycle, which is an entire survey requires 16 orbits (around 26 hours) and TES rests to avoid mechanical wear and tear and extend the life of the instrument if no "Special Observations" are needed. The "off" periods are available for the "Special Observations". Both standard products and special observations are used in this study. The analysis presented here utilizes TES version 003 data (R10, http://tes.jpl.nasa.gov).

3.1. δD of Water Vapor from TES Analysis

For the analysis shown here, we selected TES HDO/H_2O observations in which the retrieval degrees of freedom of the HDO component of the profile retrieval is higher than 0.5 (Worden et al., 2006). This criterion ensures that the estimate of profile of HDO/H_2O ratio is sufficiently sensitive to the true distribution of HDO/H_2O and that there is significant error reduction in the estimate of the HDO/H_2O ratio relative to the assumed *a priori* uncertainty (Worden et al., 2004; Worden et al., 2006; Brown et al., 2008; Lee et al., 2011). The sensitivity decreases with latitude through its dependence on temperature and water amount (Worden et al., 2010). There is a bias in the HDO/H_2O ratio of approximately 6% (Worden et al., 2006), assumed to be related to the spectroscopic line strengths of HDO or both HDO and H_2O combined. This bias must be corrected for in order to better compare the TES isotope data to the moisture process models shown in this work. Lee et al. (2011) discussed this correction in detail. Worden et al. (2011) first compared TES HDO/H_2O profiles to *in-situ* HDO/H_2O measurements at the Mauna Loa observatory to better characterize a bias in the TES HDO data. As such, we restrict our analysis to lower troposphere or free troposphere (850–500 hPa) mean values (Lee et al., 2011).

The HDO/H_2O ratios were expressed in the δ notation as a part of thousand difference relative to Vienna Standard Mean Ocean Water (VSMOW) following by the definition

$$\delta D = \left[\frac{(HDO/H_2O)_{obs} - (HDO/H_2O)_{VSMOW}}{(HDO/H_2O)_{VSMOW}}\right] \times 1000 \quad (1)$$

where HDO and H_2O are proportional to the number of molecules of each species. The ratio ($(HDO/H_2O)_{VSMOW}$) is 311.52×10^{-6} by volume. The TES data used in this work come from December 2004 to August 2008.

A composite map (a rectangle: 32°–34°N, 124°–129°E) of water vapor amount (Fig. 1a) and its δD (Fig. 1b) from December 2004 through August 2008 is given in Figure 1. Instantaneous satellite retrievals are aggregated into 1° latitude ×1° longitude regions. It should be noted that the annual mean of water vapor amount and its δD during this period is 2.3 ± 0.2 (1σ) g/kg and –185.2 ± 3.9 (1σ) ‰, respectively.

3.2. Models

3.2.1. HYSPLIT model

Trajectory analysis was used to determine transport routes of air masses. Back trajectories were calculated using the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory, http://ready.arl.noaa.gov/HYSPLIT.php) model from the NOAA Air Resources Laboratory, which is a complete system for computing simple air parcel trajectories to complete dispersion and deposition simulations with archived meteorological data provided from NCEP/NCAR Reanalysis data. This model provides insight into the history of the air masses that were sampled in our study and has been used in other similar studies that related air parcel trajectories with the isotopic composition of precipitation (KS Lee et al., 1999; Ersek et al., 2010). The model computes the advection of a single particle, or simply its trajectory. Furthermore, the model does not calculate any isotopic fractionation or include a convective mixing parameterization, such as would be needed to explicitly simulate the isotopic changes associated with condensation and evaporation associated with moist convection (Strong et al., 2007). Each trajectory was initiated at 3,000 meters above ground level to capture mean heights of the 850 and 500 hPa levels over the study region.

3.2.2. IsoGSM model

Yoshimura et al. (2008) produced a multi-decadal and globally three-dimensional stable water isotope data (IsoGSM, Isotopic Global Spectral Model, http://www.ccsr.u-tokyo.ac.jp/~kei) set by introducing isotopic fractionation process into the Scripps Experimental Climate Prediction Center (EPCP) global spectral model and applying spectral nudging toward the meteorology captured by the National Centers for Envi-

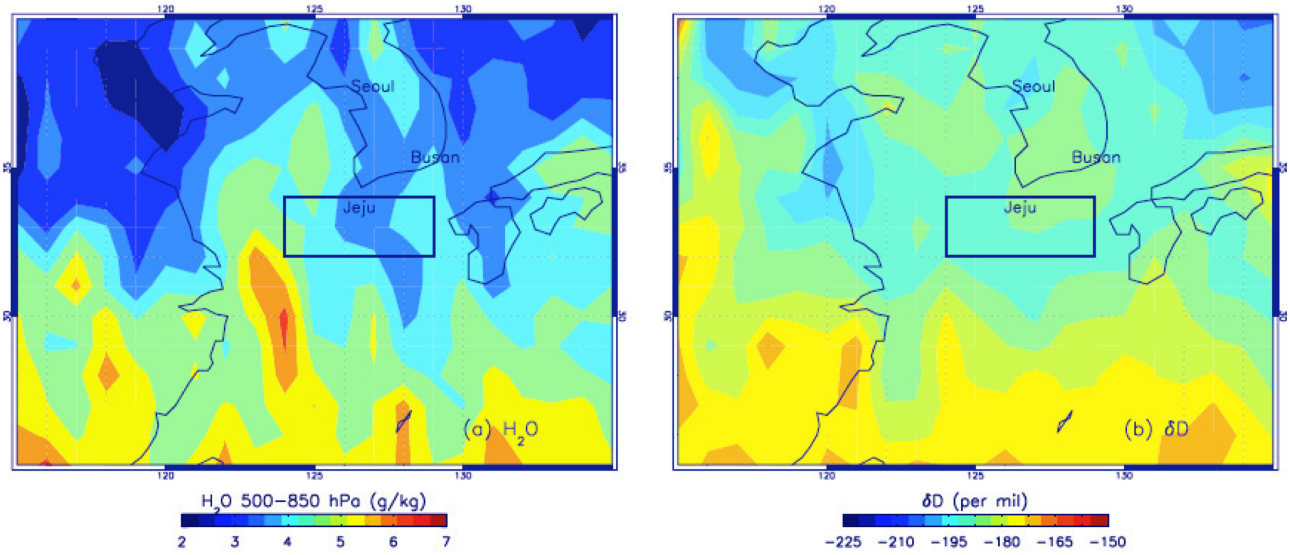

Fig. 1. Maps of composite annual mean of water vapor amount (a) and its isotopic composition (b) for December 2004–August 2008, indicating the region selected for study.

ronmental Prediction (NCEP) Reanalysis. We did not consider TES vertical sensitivity in this work (Lee et al., 2011). Unlike the global model calculations forced only by sea surface temperature, this model constrains large-scale atmospheric circulation to that of observation, and therefore the simulated isotopic fields are reasonably accurate over the entire globe for daily to inter-annual time scale (Yoshimura et al., 2008). This model is useful in providing information in regions where *in-situ* isotope observations are not available, which are required for a variety of biogeochemical, hydrological and paleoclimate studies (Yoshimura et al., 2010).

In this work, we present the model results as an example of how an isotope-enabled general circulation model produces precipitation, water vapor and their isotopic composition around Jeju Island. There are some limitations of this study. First, we do not consider vertical sensitivity regarding averaging kernels of the satellite retrieval algorithms of the TES data because the purpose of this study is not to compare water vapor and its isotopic composition between the TES measurements and model results (Lee et al., 2011; Yoshimura et al., 2011). The procedure of application of TES operator to model results is detailed in Yoshimura et al. (2011). Second, we will not discuss the physics of the model used in this study because it is beyond the scope of this study. As Yoshimura et al. (2011) suggested, discrepancies between the model and satellite observations could be corrected when performing data assimilation.

4. RESULTS AND DISCUSSION

4.1. Variations of Water Vapor Amount and Its δD

In this section, we explore distributions of the isotopic composition of water vapor as compared to a theoretical Rayleigh distillation processes and mixing models to elucidate the moist processes and sources. In Figure 2, TES vapor isotope (δD) from observations is plotted as a function of specific humidity (g/kg) to show the history of evaporation and condensation processes and to infer the water vapor transport characteristics (Worden et al., 2007; Brown et al., 2008; Lee et al., 2011). The lower line (orange dotted) in each figure shows a model of Rayleigh condensation, or what we would expect for an air parcel originating from the local ocean at the mean local ocean temperature followed by condensation in the lower troposphere and upper planetary boundary layer. The Rayleigh distillation model describes isotopic depletion as vapor is lost to precipitation (Worden et al., 2007). The top line (orange solid) shows a mixing model in which dry depleted air is mixed in with vapor continuously evaporated from the nearby ocean. The analytical form for both models is also explained in the supplemental material of Worden et al. (2007).

In order to show how water vapor amount and its δD vary with different seasons, Figure 2 illustrates the relationship between water vapor and its isotopic composition observed from different seasons. Distributions of water vapor and its isotopic composition are examined over Jeju Island, Korea (32°–34°N, 124°–129°E) between 2004 and 2008. Most of the observations are reasonably constrained by the theoretical curves for Rayleigh condensation from moisture originating over an oceanic source, with initial δD value of –79‰ (orange dotted line) and the curve representing mixing of air parcels (orange solid line). The Rayleigh distillation lines originate from air parcels with saturation specific humidity values based on oceanic surface temperatures observed by TES. Table 1 summarizes the mean values of

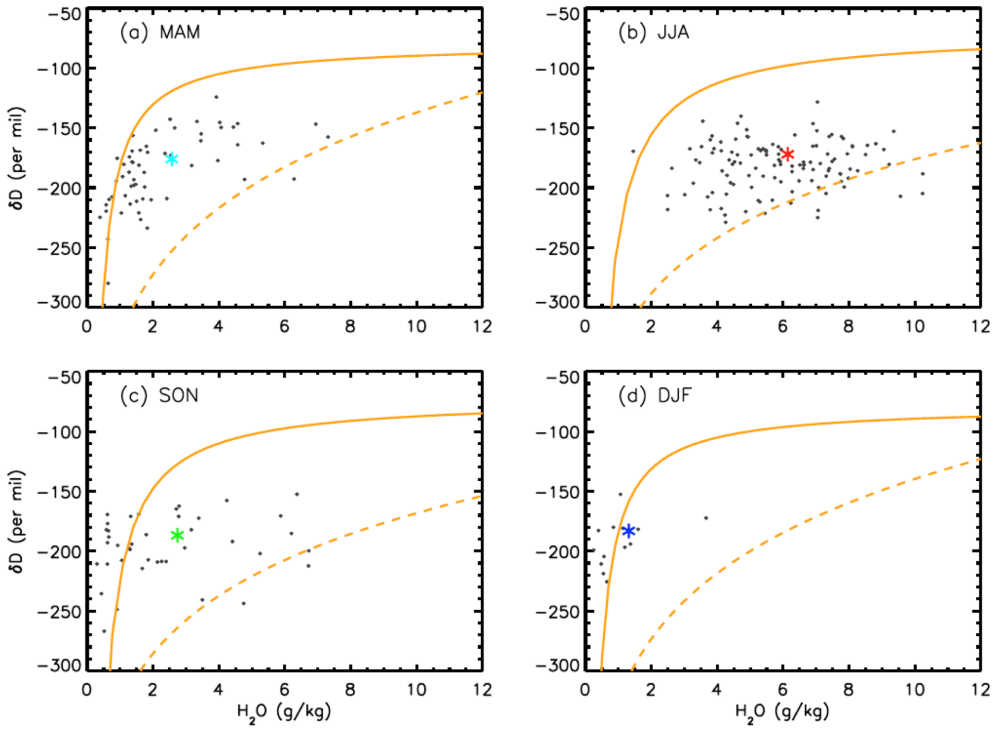

Fig. 2. Bivariate plots of water vapor versus its isotopic composition over the region (charcoal dots). The symbols '*' represent mean values of water vapor and its isotope. Solid evaporation line depicts turbulent mixing of water vapor from the saturated layer at the ocean surface into a drier air parcel aloft. A Rayleigh distillation model (dotted) describes isotopic depletion as vapor is lost to precipitation. The TES data used in this Figure come from December 2004 to August 2008. (a) March, April and May (MAM, cyan) (b) June, July and August (JJA, red) (c) September, October and November (SON, green) (d) December, January and February (DJF, blue).

Table 1. The mean, standard error of the mean for TES water vapor measurements and δD for each season between 2005 and 2008 over Jeju Island, Korea

Season	H_2O (g/kg) (mean ± standard error)	δD (‰) (mean ± standard error)
MAM (March to May)	2.3 ± 0.2	–185.2 ± 3.9
JJA (June to August)	5.9 ± 0.2	–181.2 ± 1.8
SON (September to November)	2.5 ± 0.3	–195.9 ± 4.1
DJF (December to February)	1.1 ± 0.2	–192.3 ± 5.6

All mean δD values are mass-weighted.

water vapor amount and its isotopic composition ('*' represents mean value of water vapor and its isotope in Fig. 2).

The observations constrained by the two curves show several characteristics (Fig. 2 and Table 1). Figure 2 shows that the evaporation curves more closely describe the dry air parcels (Figs. 2a, c and d) while the Rayleigh condensation curves more closely describe the moist air parcels (Fig. 2b). Some observations are not described accurately by the Rayleigh description of evaporation from the oceanic source followed by condensation. Specifically, Figure 2b shows moist points are more depleted than the Rayleigh curve. A similar feature, called the 'amount effect', is found statistically in monthly or longer scales precipitation in regions of intense rainfall and may be attributed to a reversal of the depletion of the isotopic composition of the parent condensing vapor caused by the return of water to the cloud by evaporation. Mechanisms of the amount effect have been quantitatively detailed in Lee et al. (2008) and Risi et al. (2008). The dry season observations are, in particular, during DJF (Fig. 2d), located in the marine evaporation lines. During DJF (Fig. 2d), the distribution (850–500 hPa) is relatively drier (1.1 g/kg) and more isotopically depleted than that of JJA (Fig. 2b). The fact that the isotopic composition of water vapor during DJF is more depleted than that of JJA is not consistent with the previous results of precipitation isotopes (Lee et al., 2003).

The seasonal variations in the water amount (g/kg, a) and its isotopic composition (δD, b) over Jeju Island are presented in Figure 3. The island has the maximum amount of water vapor in July, which is consistent with the observed precipitation amount pattern in the previous studies (S Lee et al., 1999; Lee et al., 2003). As we mentioned earlier, in

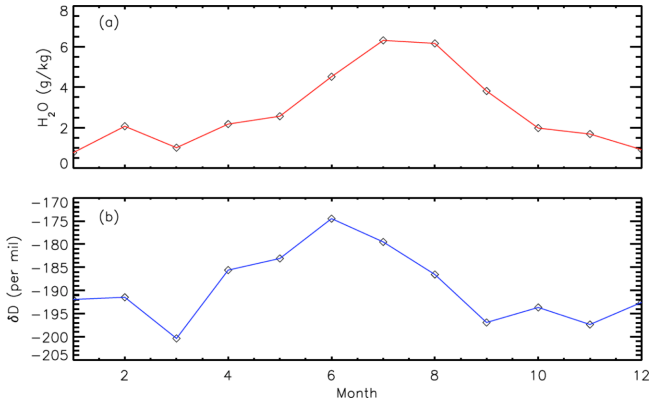

Fig. 3. Monthly average of water vapor amount (a) and its isotopic composition (b).

contrast, the isotopic composition of water vapor is more enriched in summer and more depleted in winter. The isotopic composition of water vapor over the island shows the maximum δD in June (summer-enriched), which looks completely opposite to precipitation isotopes (winter-enriched), which has been never discussed in the previous studies. We will discuss this following section.

4.2. Seasonality of Isotopic Composition of Water Vapor

To help interpret the variability of water vapor and its isotopic composition presented in Figure 3 and Table 1, 120-hr-reverse-calculated trajectories for air parcels at selected times were performed using the NOAA HYSPLIT model (R. R. Draxler and G. D. Rolph, Hybrid Single-Particle Lagrangian Integrated Trajectory model, 2003). Each trajectory corresponds to each TES point observed in Figure 2. This trajectory analysis is a first attempt with the isotopic composition of water vapor over Jeju Island. Lee et al. (2003) explained a seasonality of *d-excess* from precipitation values using a trajectory analysis. During periods of high δD (JJA) in Figure 4b, trajectories show advection from the South China Sea and the North Pacific. As shown in Figure 4d, however, trajectories of air mass during DJF (low δD) show advection from the west, suggesting the Yellow Sea and China as the primary source of water vapor. Water vapor evaporated from a warm body of water should have higher isotopic composition than vapor from relatively cold bodies of water. Advection or mixing with water vapor evaporated from ocean is the primary cause of variability of isotopic composition of water vapor in the troposphere (Strong et al., 2007; Worden et al., 2007).

To discuss the summer-enriched seasonality of water vapor isotope (δD) in contrast to winter-enriched precipitation isotope, we simulate the isotope-enabled GCM (IsoGSM) to better understand distribution of water vapor isotopologues because there is no *in-situ* observations of water vapor isotope over Jeju Island. Figure 5 presents the time series of monthly mean precipitation rate (Fig. 5a) and its isotopic composition (Fig. 5b, $\delta D_{precipitation}$) and water vapor amount (Fig. 5c, specific humidity) and its isotopic composition (Fig. 5d, δD_{vapor}) between 850 and 500 hPa from the simulated values by the IsoGSM. The model shows a good agreement in patterns of precipitation rate, its isotopic composition (winter-enriched) and water vapor amount with the previous studies (S Lee et al., 1999; Lee et al., 2003). How-

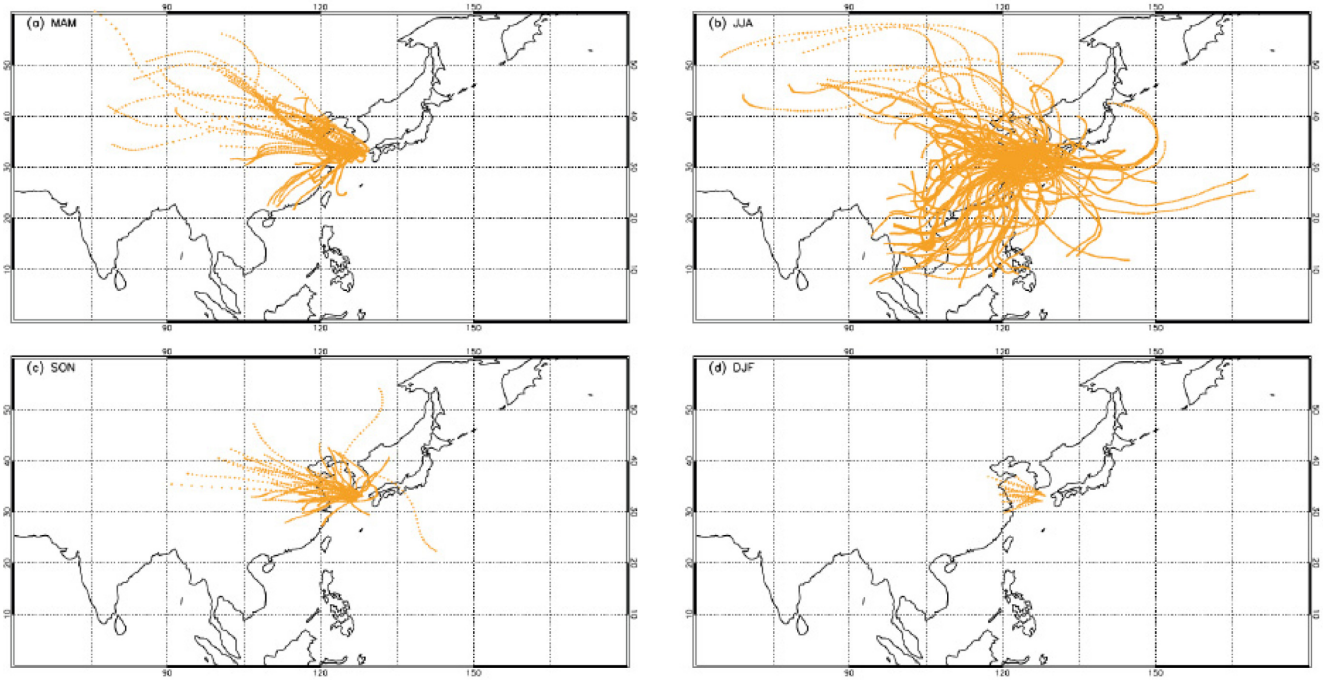

Fig. 4. Trajectory analysis of each season corresponding to TES observations (a) MAM, (b) JJA, (c) SON and (d) DJF.

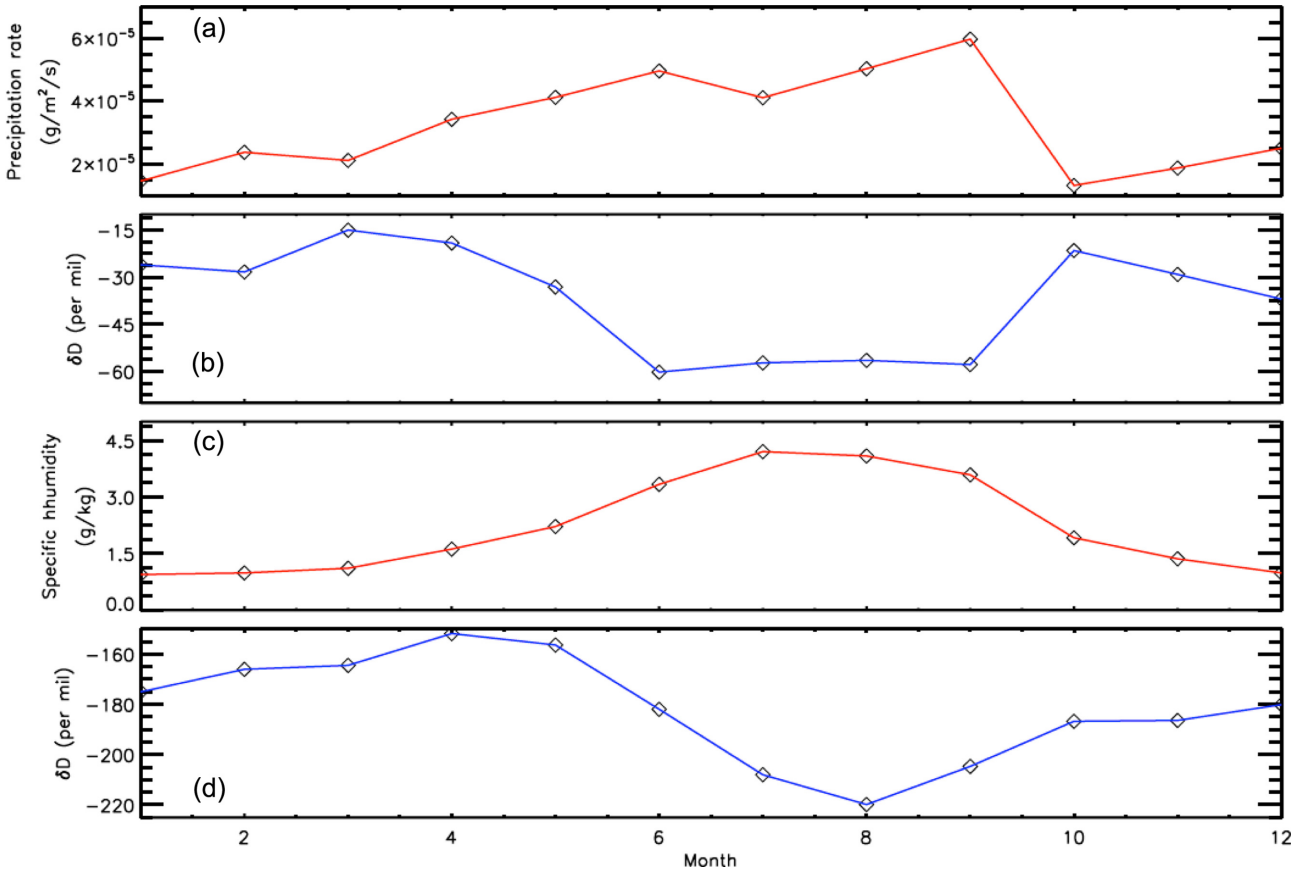

Fig. 5. Monthly mean from the simulated model results. (a) precipitation rate, (b) isotopic composition of precipitation, (c) specific humidity and (d) isotopic composition of water vapor between 850 and 500 hPa.

ever, the simulated isotopic composition of water vapor (winter-enriched) is not consistent with what we observed using TES data (summer-enriched).

Posmentier et al. (2004) identified climate factors that potentially contribute to seasonal variations in isotopic composition of precipitation. Climate factors, temperature, vertical stability, inland boundary of marine air masses, precipitation amount, intertropical convergence, polar front, marine-terrestrial evaporation ratio, condensation to liquid versus ice and relative humidity, influence the seasonal distribution of the isotopic composition of precipitation. Some of these climate factors cause isotopically summer-enriched precipitation, while others cause the reverse effect. The isotopic composition of water vapor can be also affected by the climate factors, but these processes would result in different isotopic compositions of precipitation and water vapor. Lee et al. (2011) showed the moist processes forming a certain type of clouds that make isotopically depleted tropospheric water vapor and enriched surface precipitation in the same regions.

The reverse isotopic seasonality of water vapor between 850 and 500 hPa (summer-enriched) can be expected if (1) the source of moisture for the summer and winter of the location is roughly the same because air transported vertically by warm convection will be enriched relative to its surroundings and the air mass at the source has similar properties, such as saturation and the isotopic composition, but the actual seasonal climate dynamics do not follow these simple assumptions and the air mass trajectories does not support this assumptions, (2) the shorter trajectory of moisture from the intertropical convergence, migrated north in the summer (approximately latitude of 45°N) causes higher isotopic composition of water vapor, (3) dry air subsides owing to the typical anticyclonic circulation in the winter, resulting in HDO-depleted air masses and (4) the TES instrument preferentially samples clear-sky conditions because remotely sensed δD has its own sensitivity and is subject to sampling biases related to the presence of clouds (Lee et al., 2011). The clear-sky air parcels are relatively dry and enriched in heavy isotope compared to those of cloudy observations over tropics and subtropics.

We hope that this finding would provide a motivation or stimulus for the community to discuss further and to observe and model isotopic composition of water vapor and its connections to the water cycle, climate dynamics and reconstruction of past climate.

5. SUMMARY AND FUTURE STUDY

In this study, we investigated a seasonality of water vapor and its isotopic composition using measurements from the Aura TES instrument over Jeju Island, Korea. To better understand the seasonal variations of isotopic composition of water vapor in the lower troposphere (850–500 hPa), we ran an isotope-enabled general circulation model (IsoGSM) and performed 120-hr reverse-calculated trajectories for air parcels using HYSPLIT corresponding to the TES observations. The isotopic composition of precipitation (δD) by the previous studies and model results show winter-enriched, while summer-enriched water vapor isotope is observed by the TES observations. During periods of high δD (JJA), trajectories show advection from the South China Sea and the North Pacific. Trajectories of air mass during DJF (low δD) show advection from the west, suggesting the Yellow Sea and China as the primary source of water vapor. The model shows a good agreement in patterns of precipitation rate, its isotopic composition (winter-enriched) and water vapor amount with the previous studies. However, the simulated isotopic composition of water vapor (winter-enriched) is not consistent with what we observed using TES data (summer-enriched).

This reverse seasonality needs to be confirmed and validated by a field experiment to make measurements of liquid water and water vapor isotopes in order to provide new data set for the processes that control the humidity of Jeju Island and the interpretation of paleoproxies (Jo et al., 2010; Johnson et al., 2011; Worden et al., 2011). Continuous endeavor toward better characterization of temporal variability of isotopic composition of liquid water and water vapor with more observations and atmospheric general circulation model studies are essential for a better understanding of the key mechanisms controlling the past and current water cycle and climate around the study area. We plan to measure the isotopic composition of water vapor at various altitudes over Jeju Island using both laser-induced spectroscopy and *in-situ* flask measurement (Johnson et al., 2011).

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