Journal of Hydrology 547 (2017) 111–123

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

# An insight into the western Pacific wintertime moisture sources using dual water vapor isotopes

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ARTICLE INFO

*Article history:*
Received 2 August 2016
Received in revised form 9 November 2016
Accepted 25 January 2017
Available online 28 January 2017
This manuscript was handled by L. Charlet, Editor-in-Chief, with the assistance of Pedro J. Depetris, Associate Editor

*Keywords:*
d-excess
Source moisture
Box model
Humidity deficit
Water vapor

ABSTRACT

Continuous measurements of isotopic ratios in atmospheric water vapor in a western Pacific region (Taipei, Taiwan) in two winters (2011 and 2012) were made and analyzed to understand the moisture source characteristics. In wintertime, the so-called East Asian Monsoon dominates, largely affecting the climate and meteorology of this region. Being located in the subtropical region, Taipei provides an ideal opportunity for studying interactions between high latitude cold and dry continental air masses and low to mid-latitude warm and wet oceanic air. Indeed, the dual isotope function, d-excess shows the presence of two distinct moisture sources, contributing to the winter vapor isotope variability. Undoubtedly, the dominant moisture source is the high latitude continental cold air masses reaching Taipei with d-excess values of >20‰. Alongside, wet and warm air masses characterized by strong air-sea interaction from the surrounding oceans, possessing d-excess value of ~10‰ also play a role. The interactions of these two distinct air masses cause the d-excess values to change by as much as ~20‰ in a few days. Multiple regression analysis shows that source moisture composition and water vapor mixing ratio combined control over 60% of the observed variability. We developed a box model to show that both high and low d-excess events in the winter are primarily controlled by the humidity deficit over the ocean. The information obtained in this study could be used in interpreting the paleoclimate proxies within the East Asian region.



## 1. Introduction

The isotopic composition of water vapor in the atmosphere is an important source of information for quantifying processes controlling the hydrological cycle (Gat, 1996; Hartmann, 2002). Over the last several decades, water isotope measurements have focused on studying the liquid component, i.e., precipitation, surface water, groundwater, etc. (Rozanski et al., 1993; Gat, 1996; Clark and Fritz, 1997). Only a few measurements on atmospheric water vapor were made, as it required laborious manual techniques (Jacob and Sontag, 1991; Uemura et al., 2008). The use of infrared laser spectrometers (Kerstel et al., 1999; Baer et al., 2002) which employ wavelength-scanned cavity ring-down spectroscopy (WS-CRDS) for continuous high resolution measurement of water vapor in the atmosphere has simplified the isotope analysis and has been applied widely in recent years (Bailey et al., 2013; Laskar et al., 2014; Samuels-Crow et al., 2014; Klein et al., 2015; Delattre et al., 2015).

Combined measurements of $^{18}O/^{16}O$ and D/H isotopic ratios (denoted by $\delta^{18}O$ and $\delta D$) in precipitation led to the concept of a parameter known as d-excess which is relatively less sensitive to the rainout fractionation and is defined by d-excess = $\delta D - 8 \times \delta^{18}O$ (Dansgaard, 1964). It is considered to be a tracer of the humidity condition at the source region. Further interpretations of d-excess involve temperature variation at the source or shifts in the moisture origin (Vimeux et al., 2002; Masson-Delmotte et al., 2005). In addition, mixing of air masses along their trajectories (Hendricks et al., 2000; Sodemann et al., 2008) can modify d-excess values. It is known that when an air parcel travels over a continent, addition of vapors due to evapotranspiration and its removal by rainout processes can modify the isotope character-

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http://dx.doi.org/10.1016/j.jhydrol.2017.01.047
0022-1694/

istics of the moisture in the parcel and subsequently the rainwater from that parcel. For example, moisture recycling increases the d-excess (Froehlich et al., 2008) as witnessed for extreme events like tropical cyclones and typhoons (Laskar et al., 2014). In this work, we assess in detail the d-excess values of atmospheric water vapor over Taiwan to decipher the moisture sources and understand their variation in the winter season. This information potentially acts as an important constraint in modeling the regional isotope climatology (Yoshimura et al., 2008) dominated by the East Asian Monsoon systems. In addition, knowledge of the isotopic variability in modern hydrological cycle will enhance the understanding and provide meaningful insights for interpreting the East Asian Monsoon variability reconstructed from Paleo-archives like speleothems, which is still hotly debated (Liu et al., 2014; Maher and Thompson, 2012).

Taiwan is located in the western Pacific, and its weather is influenced strongly by two climate systems: winter and summer monsoons. The Tropic of Cancer runs through the middle of it and consequently it has a sub-tropical climate in the north while the south has tropical regime with high mountains. Despite its climatologically interesting location in the interface of Pacific Ocean and Asian mainland centered in the confluence of three distinct air masses (Peng et al., 2010), there is no GNIP (Global Network of Isotopes in Precipitation) station here and scant attention has been paid for the isotope hydrological study. Earlier research in this region was confined to precipitation samples or modeling (Peng et al., 2010, 2011). Recently, a comprehensive year around analysis of the water vapor isotope variability has been reported (Laskar et al., 2014). These authors showed a lack of seasonality in the vapor isotope data, owing to absence of equilibrium between the vapor and the liquid phases caused by tropical convective systems during the summer period. The vapor isotope variation in the winter period remains unexplored so far.

In the present work, our aim is to investigate the variability in water vapor isotope composition during winter (November to March) which is a quiescent period devoid of any extreme weather events, affected primarily by northeastern winter monsoon. The idea is that the influence of distinct air masses and rapid changes in the physical conditions associated with these air masses (Peng et al., 2010) would reflect in the intra-seasonal isotopic variability. The data would help to understand the role of the controlling factors like source conditions, land surface temperature, and vapor transport processes in the western Pacific (Jouzel et al., 1982; Vimeux et al., 2002; Masson-Delmotte et al., 2005). Furthermore, quantification of the influences of these controlling factors using the multiple regression method is also presented, so as to aid in better understanding and modeling the monsoon systems at intra-seasonal scales, especially at the interface of continental landmasses and oceans. Finally, we modeled the d-excess variability of individual events using a simple box model (Gat, 1996; Gat et al., 2003) to understand the changes and interactions during the moisture transport prior to its arrival in Taipei.

## 2. Materials and methods

$\delta^{18}O$ and $\delta D$ values in water vapor along with its concentration were determined round the clock in Taipei. The measurements between 1st November 2011 and 10th January 2012 were carried out in Hsin-Tein, while the measurements between 11th January 2012 and 31st March 2012 were done on the rooftop of the Department of Atmospheric Science, National Taiwan University (NTU). The NTU site is located approximately 6 km north of Hsin-Tein. Sampling for the winter of 2012 (November 2012 to March 2013) was done on the roof of Department of Geography in the same campus. The measurements were done using a WS-CRDS (L2120-I, Picarro, USA) system. The entry part consists of a Teflon tube (diameter 6 mm) through which air was sucked into the inlet of the WS-CRDS using a membrane pump. All isotopic ratios are reported in $\delta$-notation (in ‰) relative to V-SMOW (Vienna Standard Mean Ocean Water) with analytical uncertainty of 0.1‰ in $\delta^{18}O$ and 0.8‰ in $\delta D$ values (for details see Laskar et al., 2014) and an uncertainty of ~100 ppmv in concentration.

The operation of WS-CRDS was automatized such that sets of data were collected and stored every ~2 s. Later, the whole data array (time and isotopologue values) was averaged at one-hour intervals for analysis and interpretation. The dataset was also used to get a synoptic view of the cumulative processes occurring at weekly/monthly time scales within the winter season. The weather parameters for the study location during the sampling period were acquired at hourly and daily scales from the nearest meteorology station of Central Weather Bureau (CWB), Taiwan. Statistical analysis using a simple *t*-test method was carried out to check the significance of the best fit linear regressions obtained for various correlations discussed below. In addition multiple regression analysis was performed to identify the dominant controlling factors for the observed variability in the d-excess. The model regression and its significance test were checked using R statistical package.

## 3. Results and discussion

Studies on Taiwan precipitation have shown that the isotope composition in different seasons is primarily influenced by interactions among diverse moisture sources (Peng et al., 2010). It was established that three distinct moisture sources participate in the precipitation over Taiwan, with the winter season characterized by a source having a mean $\delta^{18}O$ value of −3.2‰ and a mean d-excess value of ~24‰. The major moisture source for this precipitation is the vapor entering the region from the northeast of the island, originating mostly from the Asian continent (named as Polar Continental component in Peng et al., 2010). In summer, the contribution of moistures from the equatorial Pacific and the tropical maritime zones is apparent, with $\delta^{18}O \approx -6$‰ and d-excess ≈ 10‰. However, in addition to such established seasonal cycle, there exists significant intra-seasonal variability, with amplitudes comparable to the seasonal cycle (Laskar et al., 2014; Figs. 1 and 2). In order to understand the modes of the winter vapor variability and the cause(s) of the intra-seasonal oscillations, we investigated the variability of water vapor isotopologues at hourly time scale.

### 3.1. Hourly variability of vapor and its isotopic composition

The hourly water vapor concentration for the winter of 2011 ranged from ~9000 to 34,000 ppmv, while that for the year 2012 was from ~8000 to 34,000 ppmv. The onset of winter in the year 2011 showed a steep change (~27,000–18,000 ppmv, Fig. 1A) compared to that in 2012 (~23,000–19,000 ppmv in mid-winter, Fig. 2A). Rapid changes in dual isotopes of the vapor characterized the onset of winter (Figs. 1B, C and 2B, C). Despite large variability in water vapor isotopes occurring during the onset of winter, no noticeable change in the mean $\delta^{18}O$ value was observed for the period prior to and after the onset. On average, the late winter (March) mean $\delta^{18}O$ value was $-12.8 \pm 1.3$‰ in 2012 and $-12.9 \pm 1.2$‰ in 2013, as compared to the values of $-14.5 \pm 2.3$‰ and $-14.8 \pm 1.8$‰ in November. During the 2 week winter onset period (marked in Figs. 1 and 2), a progressive depletion in $\delta^{18}O$ values was observed with a sub-weekly variation >10‰ (Figs. 1B and 2B). The overall vapor $\delta^{18}O$ distributions indicated by the range and the mean $\delta^{18}O$ values for the two winters were similar (Figs. 1B and 2B). The $\delta D$ values for the winter of 2011 ranged from −61.8 to −190.1‰, while the winter of 2012 exhibited a