Summertime Moisture Transport to the Southern South American Altiplano: Constraints from In Situ Measurements of Water Vapor Isotopic Composition

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ABSTRACT

Austral summer transport of water vapor to the southern South American Altiplano is investigated using in situ measurements of water vapor isotopic composition collected from 1 November 2012 to 10 February 2013 on the Chajnantor Plateau in the Chilean Andes. Onset of the wet season in December was associated with an increase in mixing ratios from an average of 1500 ppmv during the winter dry season to 5400 ppmv in early December. Water vapor isotopes $\delta D$ and $\delta^{18}O$ increased from dry season averages of $-235_{\text{ppm}}$ and $-31_{\text{ppm}}$, respectively, to wet season averages of $-142_{\text{ppm}}$ and $-17_{\text{ppm}}$, reaching as high as $-70_{\text{ppm}}$ and $-17_{\text{ppm}}$, respectively. The highest water vapor $\delta$ values were close to those measured in coastal settings, suggesting little condensation during transport to the site. About 5% of the wet season data have $\delta$ values that are lower than expected for Rayleigh distillation and are associated with high relative humidity (>75%), easterly winds, and periods of low outgoing longwave radiation over the Altiplano, consistent with moistening by deep convection. The remainder of the data have $\delta$ values that are greater than expected for Rayleigh distillation, up to 250 $\delta$ above the Rayleigh curve. These data are consistent with mixing between very dry air and moist air from the boundary layer. The data show intraseasonal variability coherently linked to the position of the Bolivian high, with moist air associated with a southward displacement in the Bolivian high. The humidity over the southern Altiplano during the wet season reflects a balance among advective drying, advective moistening with little condensation, and convective moistening.

1. Introduction

The Altiplano is a broad, 250-km-wide plateau in the Andes between 15° and 23°S with an average elevation of 3800 m. It represents an important boundary in the climate of South America between the hyperarid west coast and the much moister continental interior. The Altiplano itself is semi-arid, but experiences substantial moisture variability across a broad range of time scales controlled by continental to hemispheric-scale processes (Vuille 1999; Garreaud and Aceituno 2001; Garreaud 2000; Garreaud et al. 2003).

Most of the precipitation in the Altiplano falls between November and March, a period sometimes referred to as Altiplanoic winter, when an upper-level anticyclone, the Bolivian high, develops southeast of the central Andes and easterly flow transports moist air from the continental interior (Vuille 1999; Lenters and Cook 1997). During the rest of the year, westerly flow transports extremely dry air from the southeastern Pacific to the region.

An important question revolves around the processes that transport moist air to the southern South American Altiplano during the austral summer. Paleoclimate indicators show that the subtropical Andes were likely moister in the past, even sustaining glaciers at sites that are far too dry to support glaciers in the modern climate (Kull and Grosjean 2000; Ammann et al. 2001). The water vapor transport processes that supported the development of glaciers in the past, and how those processes may change as the climate warms in the future, are not well understood at present. Several studies have indicated an important role for deep convection associated with the South American monsoon in moistening the atmosphere over the tropical Andes (Vuille et al. 1998; Thompson et al. 2000), where glaciers have persisted in some places since the Last Glacial Maximum (21 ka). Samuels-Crow et al. (2014a) used remote sensing data of water vapor isotopic composition to show that December–February (DJF) water vapor transport
over the Andes north of about 19°S is linked with deep convection over the continental interior. Their study did not focus on the region south of 19°S, but their results suggest a much less prominent role for deep convection in moistening that part of the Andes and Altiplano, raising the question about the precise balance between the different processes that set the humidity over the southern South American Altiplano.

One issue that has hampered studies of water vapor over the Altiplano is a lack of high-resolution in situ measurements from this remote region. The aridity of the Altiplano makes it an ideal site for submillimeter astronomy, and the Chajnantor Plateau, on the southern edge of the Altiplano (Fig. 1), is home to several astronomical observatories that make detailed meteorological measurements in support of their astronomical work. Since 2012, we have been supplementing the routine meteorological measurements made at the Atacama Large Millimeter Array (ALMA) Observatory with measurements of atmospheric water vapor isotopic composition, which have been used in many studies to provide additional constraints on water vapor transport processes beyond what is recorded in routine meteorological measurements (Galewsky et al. 2007, 2011; Hurley et al. 2012; Noone 2012; Noone et al. 2011; Steen-Larsen et al. 2013, 2014).

The goal of this study is to use in situ measurements of water vapor isotopic composition along with standard meteorological measurements to explore the processes that control summertime water vapor transport over the South American Altiplano.

2. Background

a. Stable isotopic composition of water vapor

The relative abundance of stable isotopologues such as H$_2^{18}$O, H$_2^{16}$O, and HDO is controlled by a variety of processes and records the history of evaporation, condensation, and mixing in a given air parcel (Noone 2012). Isotopic measurements are reported relative to Standard Mean Ocean Water (SMOW) in parts per thousand (‰) using δ notation, where for the HDO/H$_2$O ratio,

$$\delta = \left( \frac{\text{HDO}}{\text{H}_2\text{O}} \right) \text{SMOW} - 1 \times 1000, \quad (1)$$

where $R_{\text{SMOW}}$ is the HDO/H$_2$O ratio in Standard Mean Ocean Water.

The starting point for most analyses of water vapor isotopic composition is the Rayleigh distillation model (thick solid line in Fig. 2), an idealization in which condensate is removed immediately from an ascending air parcel. The equation describing this process is

$$\frac{d\ln R}{d\ln q} = \frac{\alpha(T) - 1}{\alpha(T)} \frac{d\ln q}{d\ln q}, \quad (2)$$

where $R = \text{HDO/H}_2\text{O}$ is the isotope mixing ratio for HDO or another heavy isotopologue, $q$ is the mixing ratio, and $T$ is the temperature. Under equilibrium conditions, the condensate will be enriched in heavy isotopes by an amount given by the temperature-dependent equilibrium fractionation factor $\alpha$:

$$R_{\text{condensate}} = \alpha R_{\text{vapor}}. \quad (3)$$
For analysis in $q$–$\delta$ space, the most relevant atmospheric parameters for the Rayleigh curve are the initial isotopic composition of the water vapor and the temperature and pressure at the lifting condensation level (LCL). The reference Rayleigh distillation curve used here is based on an initial water vapor $\delta D$ of $-100\%$, which is in the range of $\delta$ values in marine boundary layer air reported by several studies (Gat et al. 2003; Uemura et al. 2008; Steen-Larsen et al. 2014); temperature at the LCL of 288 K; and pressure at the LCL of 885 hPa. The main results presented below do not vary significantly over a range of meteorologically plausible parameters.

If mixing occurs between two air parcels that have followed the same Rayleigh curve, the resulting parcel will be less depleted in heavy isotopes than would be expected from a parcel at the same mixing ratio subject to Rayleigh distillation alone (Galewsky and Hurley 2010). Regardless of whether or not two air parcels have been subjected to the same Rayleigh distillation process, the mixing ratio $q$ of the mixed parcel is the weighted average of the mixing ratio of the two parcels:

$$q_{\text{mix}} = f(H_2O)_1 + (1 - f)(H_2O)_2,$$

where $f$ is the mixing fraction. The $\delta$ value of the mixed parcel is not a simple weighted fraction of the two parcels, though, because the resulting ratio of heavy to light isotopic abundance $R_{\text{mix}}$ is given by

$$R_{\text{mix}} = \frac{f(HDO)_1 + (1 - f)(HDO)_2}{f(H_2O)_1 + (1 - f)(H_2O)_2}.$$

A mixing line that connects the moist and dry endpoints of the Rayleigh curve is shown by the thick dashed line in Fig. 2. Mixing can occur between any number of air masses, and those air masses need not lie along the Rayleigh curve (Galewsky and Hurley 2010), so the entire region between the Rayleigh curve and the dashed mixing line is thus accessible via mixing.

An analysis of the mixing line in Fig. 2 illustrates some of the important processes that we will see in the following sections. As a moist air parcel mixes with a dry air parcel, the dry air parcel primarily acts to lower the mixing ratio of the moist air mass but does not change its isotopic composition simply because there is so little water vapor in the dry parcel. Only after the mixing fraction of the dry air mass exceeds 90% does the isotopic composition begin to drop toward the values of the dry air mass. This implies that moderate advective drying can nearly preserve the isotopic composition of the moist air parcels and simply moves them to the left on a $q$–$\delta$ plot of the kind shown in Fig. 2.

Moist convection can generate water vapor with $\delta$ values below the Rayleigh curve at a given mixing ratio, a process that has been linked to the so-called isotope amount effect (Bony et al. 2008). This occurs through a variety of processes, including reevaporation of hydrometeors, recycling of isotopically depleted water vapor in the subcloud layer, and moisture convergence (Risi et al. 2008; Noone 2012; Moore et al. 2014). Samuels-Crow et al. (2014a) quantified the difference between the measured and $\delta$ values and the Rayleigh curve at a given mixing ratio to propose a simple diagnostic for detecting the influence of convection in measurements of water vapor isotopic composition, a slightly modified version of which we will use below.

Of course, all of these processes can interact, and we will see that mixing between convectively depleted air and very dry upper-tropospheric air can potentially mask the presence of convectively depleted air masses by shifting those measurements to the left on a $q$–$\delta$ plot so that they lie above the Rayleigh curve. This balance between convective moistening and advective drying will prove to be important in understanding the hydrologic cycle in the southern South American Altiplano.

Several studies have investigated water vapor isotopic composition in the marine boundary layer, which represents an upper bound on the water vapor isotopic composition. Some of the highest $\delta$ values have been reported from the Mediterranean, with $\delta D$ as high as $-70\%$ and $\delta^{18}O$ as high as $-12\%$ (Gat et al. 2003). Uemura et al. (2008) presented a transect of marine boundary layer water vapor from the Southern Ocean (as far south as 66°S) to about 30°S. Their $\delta D$ values ranged from a low of $-174\%$ to a high of $-98\%$, and $\delta^{18}O$ values that ranged from $-25\%$ to $-12\%$. Steen-Larsen et al. (2014) measured marine boundary layer water vapor isotopic composition in Bermuda (32°N) for over a year and found average $\delta D$ values of $-80\%$ and average $\delta^{18}O$ values of $-11.81\%$.

In the free troposphere, water vapor isotopic composition varies substantially, with $\delta D$ reaching as low as $-540\%$ and $\delta^{18}O$ as low as $-65\%$, in the middle troposphere (Galewsky et al. 2011) and $\delta D$ averaging $-650\%$ in the upper troposphere (Sayres et al. 2010).

The deuterium excess parameter ($d$) is defined as $d = \delta D - 8\delta^{18}O$ and has been extensively studied with precipitation (Gat 1996), but somewhat less so with water vapor. In the free troposphere, the $d$ increases with altitude, especially at pressures below 400 hPa (Blossey et al. 2010; Bony et al. 2008). Samuels-Crow et al. (2014b) analyzed the water vapor $d$ in the dataset we have collected on the Chajnantor Plateau, which is the same dataset used here. They showed that the mean $d$ on the Chajnantor Plateau during the August
b. The Chajnantor Plateau

The ALMA Observatory (Wootten and Thompson 2009) is located on the Chajnantor Plateau at an altitude of 5 km and is one of the driest sites on Earth’s surface, outside of Antarctica, with median precipitable water vapor (PWV) of 1.2 mm (Giovanelli and Darling 2001). There are strong seasonal variations in PWV, averaging less than 1 mm between March and December and frequently exceeding 10 mm during the summertime months. There is a modest diurnal cycle in PWV, which is highest in the late afternoon, with a rapid decrease after sunset. Giovanelli and Darling (2001) showed that the diurnal cycle of PWV lags the insolation cycle by about 4 h with an amplitude of about 20% around the median PWV values.

Galewsky et al. (2011) presented the first water vapor isotopic measurements from the site and showed that dry air from the upper tropical troposphere (UTT) reaches the surface at Chajnantor, with mixing ratios as low as 215 ppmv and water vapor δD values as low as −540‰ values that are consistent with aircraft measurements from the upper troposphere (Sayres et al. 2010). They further showed that this dry UTT air mixes with moister air from the middle and lower troposphere to set the wintertime humidity over the southern South American Altiplano.

Several paleoclimate studies have suggested that the region around Chajnantor was intermittently wetter from the Last Glacial Maximum to the early Holocene (Ammann et al. 2001; Bobst et al. 2001; Betancourt et al. 2000; Geyh et al. 1999) but the processes associated with this moistening are not well understood. While the present study is focused on a relatively short period in the modern climate record, it is hoped that an improved understanding of the modern processes may help to improve our understanding of the processes that controlled these past periods of moistening.

3. Methods

Mixing ratio and isotopic composition were measured using a Picarro L2130 analyzer. This system uses new spectroscopic techniques that yield significantly improved precision and less drift in measurements of δ values than earlier Picarro, Inc., analyzers such as the L1115 and L1102 models. At 2500 ppmv, the 1σ precision of the instrument based on external standards is better than 0.5‰ for δD and 0.1‰ for δ18O when averaged for 100 s. Two secondary standards were injected an average of three times per month into a vaporizer operated at 140°C prior to delivery to the instrument to monitor instrument drift, and the measurements presented here were corrected for the minimal drift encountered. The analyzer was housed at the ALMA Observatory’s central weather station, which is a heated hut situated at 5-km altitude near the central cluster of the observatory. Outside air was introduced into the analyzer from a Teflon line mounted on the roof of the weather station, about 5 m above the ground surface. The line was unheated, but condensation in the line is not an issue at the very low relative humidity on the Chajnantor Plateau. Measurements were made every 30 s and the results presented here are 5- and 30-min averages.

The two secondary standards [NM-3 and Antarctic snow (ANT)] were calibrated to international standards at the University of New Mexico and were chosen because they span a broad range of isotopic composition (δDNM-3 = −97‰, δ18ONM-3 = −13.1‰, δDNM-3 = −388‰, and δ18OANT = −49.7‰). Standard values did not vary systematically during the study period.

The Picarro analyzer has a systematic bias in δ values at mixing ratios below 1000 ppmv. Prior to deployment, this concentration bias was quantified at Picarro, following methods described by Galewsky et al. (2011) and Johnson et al. (2011). The 1σ uncertainty in 5-min averages of measurements increased at lower mixing ratio, but values of 0.4‰, 0.1‰, and 0.5‰, for δD, δ18O, and d, respectively, at a mixing ratio of 2570 ppmv were found. The concentration bias correction was based on the linear relationship between δ values and the inverse of the mixing ratio (1/q) determined during this experiment using the technique described in Johnson et al. (2011). These biases are not a significant issue during the moist season, when mixing ratios usually exceed 5000 ppmv. The Picarro analyzer has a moist bias of up to 23% in mixing ratio measurements (K. Dennis 2014, personal
communication) that was only recently brought to our attention by the vendor after they compared the results of the isotope analyzer with a dedicated mixing ratio analyzer. They have subsequently updated the spectroscopy in current analyzers to correct for this problem.

We took advantage of automated weather stations mounted on the roof of ALMA Observatory’s array operations site (approximately 440 m north of the central weather station) to quantify the mixing ratio at the site. The two automated weather stations are equipped with Vaisala instruments that measure pressure, temperature, and relative humidity at subsecond intervals with low errors. We calculated the water vapor mixing ratio and matched the 5- and 30-min averages to our 5- and 30-min averages of δD and δ18O. Uncertainties in mixing ratio measurements were approximately 4% of the calculated mixing ratio during the driest times and 2% of the calculated mixing ratio on days with the moistest conditions. Calculated mixing ratios were approximately 21% lower than reported by the Picarro analyzer, which is consistent with the known biases in the instrument.

The 5-m wind data were obtained from the Atacama Pathfinder Experiment (APEX), which is another observatory located on the Chajnantor Plateau, at the same elevation and about 2 km from the central weather station.

Owing to the kinetic effects associated with the sublimation of snow, persistent snow cover can impact measurements of water vapor isotopic composition, and even though several astronomical observatories on the Chajnantor Plateau collect routine surface meteorological data, none collect surface snowfall or snowpack data. Satellite estimates of snow cover can provide some constraints, however, and Fig. 3 shows daily snow cover averaged over the Chajnantor Plateau derived from the MODIS instrument on the Terra satellite. The satellite data show that the most persistent period of snow cover across the Chajnantor Plateau occurred from 7 to 15 February 2013, with a shorter period of extensive snow cover on 22 January. Outside of these periods, snow cover on the Chajnantor Plateau was negligible and therefore unlikely to affect the isotopic measurements presented below.

The Chajnantor Plateau is extremely remote and, despite the excellent infrastructure of the ALMA Observatory, is a challenging site for continuous operation of any instrumentation. The snowfall event in mid-February of 2013 generated a power surge that temporarily damaged the University of New Mexico (UNM)’s Picarro water vapor analyzer, so we are only able to present reliable isotopic data from 1 August 2012 through 10 February 2013.

4. Results

Figure 4 shows the 30-min-averaged data from the water vapor isotopic analyzer for the 1 November 2012–10 February 2013 time period and provides a useful overview of the dataset during austral summer. November was representative of the dry season and is included here for context. During November 2012, as during the rest of the dry season, surface mixing ratios averaged 1500 ppmv (0.93 g kg⁻¹) and regularly dropped below 500 ppmv (0.31 g kg⁻¹), with a pronounced diurnal cycle in the water vapor isotopic composition. Nighttime minima were associated with subsidence of dry air from the upper troposphere, and δD values...
reached as low as \(-450\) and \(\delta^{18}O\) values reached as low as \(-67\%\). The \(d\) during November ranged from \(0\) to \(112\%\), and had a prominent diurnal cycle, with the daily maxima in \(d\) occurring during the nighttime minima in mixing ratio, consistent with the results of Samuels-Crow et al. (2014b).

Beginning on 1 December 2012, the mixing ratios and water vapor \(\delta\) values all substantially increased during the onset of the wet season on the Chajnantor Plateau. This season was characterized by 2–3-week-long periods of mixing ratios in excess of 5000 ppmv (3.1 g kg\(^{-1}\)) and the highest water vapor \(\delta\) values in the dataset. The mixing ratio averaged 5400 ppmv (3.4 g kg\(^{-1}\)) between 1 December 2012 and 10 February 2013, with \(\delta D\) and \(\delta^{18}O\) values averaging above \(-150\) and \(-25\%\), respectively, and reaching as high as \(-70\) and \(-12\%\), respectively. Ten percent of the \(\delta D\) and \(\delta^{18}O\) measurements were above \(-123\) and \(-17\%\), respectively. The variability in \(d\) was substantially reduced during the wet season, only ranging between \(10\) and \(20\%\). There were some brief periods during which the water vapor \(\delta\) values were up to \(100\%\) lower than expected for a Rayleigh distillation process: \((\delta D_{\text{w}} - \delta D_{\text{r}}) < 0\). These points are highlighted in red in Fig. 4 and constitute about 5% of the data.

The moist periods were interspersed with 2–3-week periods of drier conditions with water vapor isotopic measurements similar to those from the dry season. This intraseasonal variability was closely linked to the position of the Bolivian high. Figure 5 shows the daily averaged NCEP–NCAR reanalysis 200-hPa geopotential height for selected dates from the 2012/13 wet season. As expected, the Bolivian high tended to be centered well north of the Chajnantor Plateau during dry periods (Figs. 5a,c) and tended to be centered nearly on top of the site during wet periods (Figs. 5b,d).
The relationships between surface wind direction, mixing ratio, and water vapor isotopic composition provide some essential context for understanding this intraseasonal variability. There was diurnal variability in the wind direction (not shown), and daytime heating of the surface apparently induces a circulation that generates winds from the west-southwest in both the dry and wet seasons. During the dry season (shown for November 2012; Figs. 6a,b), there were two clusters of wind directions. The driest, most isotopically depleted air was transported from the north-northwest, with slightly moister and more isotopically enriched air transported from the west-southwest.

During the initial part of the wet season (December 2012; Figs. 6c–e), the moistest and most isotopically enriched air was transported from the east, with a west-southwesterly component that transported slightly drier, but still relatively enriched water vapor to the site. Water vapor with anomalously low $\delta$ values \([\delta D_{v} - \delta D_{r} < 0]\) was primarily transported from the east-northeast (Fig. 6e).

The period of 1–15 January 2013 was associated with an extended episode of anomalously low water vapor $\delta$ values. Figures 6f–h shows three distinct peaks in wind direction, with the anomalously low $\delta$ values mostly linked with easterly transport, but with some transport from the west-southwest. The driest and most isotopically depleted air during this time was transported from the northwest.

The moist period during February 2013 (Figs. 6i,j) was primarily associated with easterly transport of very moist (mixing ratio $\geq 5000 \text{ ppmv}$), very enriched ($\delta D \geq -120^\circ_{oo}$) air and a west-southwest component that transported air with similar qualities. During this period, only two of the $\delta$ value measurements were lower than Rayleigh distillation.

While the time series data provide an essential starting point for analyzing the summertime humidity on the Chajnantor Plateau, a more detailed understanding of the processes that govern water vapor transport can be obtained by analyzing the joint distribution of mixing ratio and water vapor isotopic composition. Figure 7 shows the joint distribution of mixing ratio and water vapor $\delta D$ values for the dry season (1 September–30 November 2012; Fig. 7a) and the wet season (1 December 2012–10 February 2013; Fig. 7b).

During both periods, the data cluster fairly tightly around a single mixing line and most of the data lie well above the Rayleigh curve, which is generally diagnostic for mixing. During the wet season, the highest $\delta D$ values were around $-70^\circ_{oo}$. These are remarkably high $\delta$ values to be encountered in the high Andes, similar to values measured at many coastal sites, suggesting almost no condensation between the coast and...
the Chajnantor Plateau, and their relatively low mixing ratio indicates mixing with very dry air had lowered the mixing ratio while leaving the isotopic composition largely unaffected. While most of the data lie above the Rayleigh curve and are thus consistent with mixing between air masses, 5% of the wet season data lie below the Rayleigh curve, while an additional 5% lies within 25\% of the Rayleigh curve. The data below the Rayleigh curve are consistent with a convective influence that will be explored in more detail below.

We can gain a bit more insight into the data by looking at shorter periods, which are shown in Fig. 8. The December and January periods are quite similar, with most of the data falling cleanly on a mixing curve well above the Rayleigh curve, but with some points lying below the Rayleigh curve and others very near the Rayleigh curve. A period in early February (Fig. 8c) had the highest water vapor \( \delta \) values of the entire period and were approximately 200\% above the Rayleigh curve. In pure Rayleigh distillation, these high water vapor \( \delta \) values would be encountered at mixing ratios in excess of 25 000 ppmv (15 g kg\(^{-1}\)). In our data, these values were encountered at mixing ratios ranging from 3000 to 10 000 ppmv, indicating substantial mixing with very dry air. As described earlier, when mixing occurs between very moist and very dry air parcels, the isotopic composition is overwhelmingly controlled by the moist air mass even as the mixing ratio drops owing to the very dry air. Thus, even during the relatively moist summertime, the data from the Chajnantor Plateau require significant mixing of very dry air from the upper troposphere. For example, assuming that the moist end member of a two-component mixing solution has a mixing ratio of 25 000 ppmv and that the dry end member has a mixing ratio of 500 ppmv, then at 10 000 ppmv, the dry end member is contributing over 60\% of the air.

One mechanism for generating the anomalously low water vapor \( \delta \) values in December and January is through recycling of water vapor in deep convection, so it is worth exploring the potential for deep convection in setting the water vapor isotopic composition in the present dataset. Outgoing long wave radiation values below 240 W m\(^{-2}\) have been associated with deep convection in the South American monsoon (Kousky 1988) and with so-called super-Rayleigh conditions where the water vapor isotopic composition is lower than predicted by the Rayleigh model (Samuels-Crow et al. 2014a). The period from 9 through 12 January 2013 was one of the few multiday periods with such low water vapor \( \delta \) values. Maps of Atmospheric Infrared Sounder

![Fig. 6. The 5-min averages of APEX wind direction and (top) mixing ratio and (middle) water vapor \( \delta \)D values, and (bottom) the direction of transport for conditions where \((\delta D_n - \delta D_r) < 0\).](image-url)
(AIRS)-derived OLR (Fig. 9) support the interpretation for deep convection as an influence on anomalously low δ values. During November 2012 (Fig. 9a), which was at the end of the dry season, the OLR over the Chajnantor Plateau was above 300 W m\(^{-2}\), and there were only isolated patches of low OLR over South America. On 9 December (Fig. 9b), there was a broad region of low OLR over the northern part of the continent, associated

**Fig. 7.** Joint distribution of mixing ratio and water vapor δD values for (a) September–November 2012 and (b) December 2012–10 February 2013. Contours indicate frequency of occurrence in percent, the outermost contour is 0.1%, and the contour interval is 0.1%. The Rayleigh distillation curve is shown by the thick solid line and the representative mixing curve by the thick dashed line.

**Fig. 8.** The 5-min averages of mixing ratio and water vapor δD for (a)–(c) the time periods indicated. The thick solid line represents the Rayleigh distillation and the gray dashed curve indicates a representative mixing curve. The δD value for the moist end members in (a) and (b) was −90\(^\circ\) at q = 13 000 ppmv, but the February mixing curve required an initial δD value of −80\(^\circ\) at q = 13 000 ppmv.
with the South American monsoon, but the Chajnantor Plateau is just south of this region of low OLR, and indeed there were only spotty occurrences of anomalously low water vapor $\delta D$ during this time. On 10 January, which was the only full day in the dataset with anomalously low water vapor $\delta D$, the region of low OLR spread over the southern South American Altiplano, including the Chajnantor Plateau. During the moist period on 5 February (Fig. 9d), the region of low OLR extended eastward from the Chajnantor Plateau, but the isotopic values did not indicate a significant role for deep convection in delivering moisture during this time.

The results presented thus far suggest that there should be a coherent link between the relative humidity and the deviation of the water vapor isotopic composition from the Rayleigh curve. We have shown that $(\delta D_v - \delta D_r) < 0$ is associated with deep convection, which likely arises from subcloud evaporation of hydrometeors and recycling of isotopically depleted water vapor. To the extent that convection acts to moisten the atmosphere, the preservation of negative values of $\delta D_v - \delta D_r$ should be associated with high relative humidity. Conversely, mixing of convectively moistened air with very dry upper-tropospheric air should act to lower the relative humidity and potentially move the water vapor $\delta$ values above the Rayleigh curve. Thus, the average value of $\delta D_v - \delta D_r$ reflects the balance between convective moistening and advective drying.

Figure 10 shows the relationship between $\delta D_v - \delta D_r$ and relative humidity for some key periods in the dataset. In November (Fig. 10a), the very dry conditions
were associated with very high values of $\delta D_v - \delta D_r$, which is consistent with strong advective drying. For the wet season, the average RH for data points with $(\delta D_v - \delta D_r) < 0$ was 75%, while the average RH for data points with $(\delta D_v - \delta D_r) > 0$ was 40%. The periods during December and January (Figs. 10b,c) showed a clear inverse relationship between $\delta D_v - \delta D_r$ and RH. The highest values of RH were associated with the lowest values of $\delta D_v - \delta D_r$, suggesting convective moistening nearly undiluted by dry air. In January, several data points at high RH had $\delta D_v - \delta D_r$ values that were positive but small (less than 20‰), suggesting the potential for a modest degree of drying of air parcels that were otherwise moistened by convection.

The slope of the $(\delta D_v - \delta D_r)$–RH relationship in February 2013 (Fig. 10d) was much shallower than the periods in December or January, with $\delta D_v - \delta D_r$. Recall that this was the period with the highest water vapor $\delta$ values in the entire dataset. The moderately high $\delta D_v - \delta D_r$ values along with high $\delta D$ values are suggestive of a period of advective moistening and moderate advective drying.

There was no statistically significant difference between the wet season $d$ values associated with $(\delta D_v - \delta D_r) < 0$ (which averaged 18.6‰) and the $d$ values with $(\delta D_v - \delta D_r) > 0$ (which averaged 17.8‰) at comparable mixing ratios. While the isotope amount effect has been well studied in single isotopologues, its influence on the $d$ has not received as much attention. In their numerical modeling study, Moore et al. (2014) indicated that the amount effect influenced $\delta D$ and $\delta^{18}O$ more or less proportionally, which suggests that the $d$ may not be

Fig. 10. Relationships between $\delta D_v - \delta D_r$ and surface measurements of relative humidity for selected time periods.
5. Discussion

On the other hand, Bony et al. (2008) presented observations and models of the isotope amount effect that showed a small increase in $d$ with precipitation rate, about $0.4 \text{ mm}^{-1} \text{ day}$, but they reported a fairly high degree of dispersion around the mean values. In the present dataset, the $d$ measurements do not provide a means for identifying the influence of upstream convection, but it is a small dataset and the subject warrants more scrutiny as the data volume and quality increase.

The record presented here is relatively brief, spanning only part of one wet season, so we must of course be cautious in expanding our interpretation to longer time scales, but several processes that influence the humidity over the southern South American Altiplano are evident. The observations from the Chajnantor Plateau show that the summertime humidity over the southern South American Altiplano is controlled by a balance between advective drying and, potentially, two different moistening mechanisms, one that is associated with little condensation, which we provisionally refer to as advective moistening, and another component that can be more confidently linked to deep convection, which we refer to as convective moistening. While a precise knowledge of this balance in the modern climate requires more data, which we are currently collecting, we can say that changes in this balance will change the humidity over the southern South American Altiplano and may help to explain the paleoclimate records of past moistening in the region.

In their global isentropic analysis of subtropical humidity, Couhert et al. (2010) identified a similar balance. They showed that the dominant drying mechanism in the subtropics is radiatively driven cross-isentropic subsidence of dry air that may be partially offset by moistening associated with the cross-isentropic transport of water vapor in convection. This cross-isentropic component is especially prominent over the core of the South American monsoon, well to the northeast of the Chajnantor Plateau, but as we saw above, relatively small changes in the position of the Bolivian high can shift convection to the south.

Couhert et al. (2010) also showed a prominent northwest–southeast-oriented streak in the isentropic eddy flux of water vapor over South America that they linked to so-called atmospheric rivers (e.g., Newell et al. 1992), which are related to filamentary intrusions of extratropical cyclones into low latitudes that export water vapor from the tropics. The precise mechanism by which these structures may transport water vapor to the Chajnantor Plateau requires more study, but the study of Zhu and Newell (1998) provides some clues. They partitioned water vapor fluxes into two components: a river flux that is filamentary in structure and exceeds certain limits related to mean fluxes at a given latitude and a background flux they refer to as the broad flux. They showed a northwest–southeast filament of “river” water vapor transport flux along the eastern side of the Altiplano in January and a “broad” flux that also transports water vapor from the northwest to the southeast, but with a modest component of transport that is nearly orthogonal to the Andes. While such a mechanism has not definitively been linked to water vapor transport over the Altiplano, it may provide a framework for interpreting isentropic eddy fluxes of moist air into the region.

Our results are broadly consistent with the results of Falvey and Garreaud (2005), who showed that horizontal advection of water vapor could explain the summertime mixing ratio over the Altiplano north of the Chajnantor Plateau. Their result was somewhat different from that of Garreaud (1999), who used numerical simulations to link moisture transport to the upslope flows along the eastern Altiplano, which were enhanced by the downward flux of easterly momentum. Our analysis shows that the diurnal cycle over this part of the Altiplano tends to favor transport from the west rather than from the east, suggesting that diurnal flows are not responsible for significant moisture transport to the site.

Our results from the Chajnantor Plateau strike a significant contrast with studies from farther north in the Andes. Several studies have indicated that intense upstream convection is required to explain the isotopic composition of precipitation in the tropical Andes. The study of Samuels-Crow et al. (2014a) showed a boundary at a latitude of approximately 20°S between regions to the north where the water vapor isotopic composition was substantially influenced by upstream convection and regions to the south that are largely uninfluenced by upstream convection. They identified this region through a similar diagnostic to that used here and showed that in the Andes north of 20°S, satellite water vapor $\delta D$ values from 500hPa were up to 36‰ lower than predicted by the Rayleigh paradigm. They merged these observation with back-trajectory calculations to suggest that deep convection controls the water vapor isotopic composition over the tropical Andes. Over the subtropical Andes south of about 20°S, including over the Chajnantor Plateau, they showed that satellite water vapor $\delta$ values were 50‰–130‰ higher than predicted by Rayleigh distillation, consistent with our results, which showed an average value for $\delta D_e - \delta D_r$ of 81‰ during the wet season.
The diagnostic used here is fairly simple and depends critically on the initial water vapor isotopic composition used in the Rayleigh calculation. For an initial composition of $-100\%_\text{oo}$ about 5% of the dataset falls below the Rayleigh curve. If the starting $\delta$ value is raised to $-70\%_\text{oo}$ about 10% of the dataset falls below the Rayleigh curve. While only a very small percentage of the dataset falls below the Rayleigh curve, it is harder to estimate how much convective influence may be masked by mixing with dry air, which would act to move otherwise “overdepleted” parcels above the Rayleigh curve. In any case, convective moistening is less of an influence in the region around the Chajnantor Plateau than to the north of about 20°S.

This boundary in convective influence is very nearly coincident with the boundary between the glaciated Andes to the north and the presently unglaciated Andes to the south. Interpretations of tropical ice cores from Peru and Bolivia suggest that upstream changes in convection over the Amazon basin play a central role in controlling the isotopic composition of glacial ice (Hoffmann et al. 2003; Vuille and Werner 2005). The Chajnantor Plateau is currently unglaciated, but the site contains abundant striations and moraines that are unequivocally representative of past glaciation (Ammann et al. 2001), and there are several paleoclimatic records that indicate past moistening (Ammann et al. 2001; Bobst et al. 2001; Betancourt et al. 2000; Geyh et al. 1999). While the precise degree of moistening required to match the suite of paleoclimatic records is not well constrained, the current results provide a couple of different plausible mechanisms for bringing more water vapor to the southern South American Altiplano. One possibility involves a southern expansion or shift in cross-isentropic transport, potentially linked with a southern shift in the Bolivian high and associated links with convection, and the other associated with an increase in isentropic transport of water vapor associated with atmospheric rivers. Reliable proxy records of the isotopic composition of precipitation are difficult to obtain in the arid Andes (Quade et al. 2007), so analysis of such processes in general circulation model (GCM) simulations of the Last Glacial Maximum or late glacial periods would thus likely prove to be profitable.

6. Conclusions

The goal of this study was to use in situ measurements of water vapor isotopic composition and supporting meteorological data between 1 November 2012 and 10 February 2013 to improve our understanding of the processes governing summertime transport of water vapor to the southern South American Altiplano. Overall, the summertime humidity over the southern South American Altiplano reflects a balance between advective drying, advective moistening, and convective moistening. We found that the 2012/13 wet season on this part of the southern South American Altiplano was characterized by substantially higher mixing ratios and water vapor $\delta$ values than was the rest of the year. The water vapor $\delta D$ and $\delta^{18}O$ values averaged $-142\%_\text{oo}$ and $-20\%_\text{oo}$, respectively, when the mixing ratio exceeded 5000 ppmv, and reached as high as $-70\%_\text{oo}$ and $-17\%_\text{oo}$, respectively, similar to measurements from subtropical coastal regions. Even though the mixing ratios during this period were higher than during the rest of the year, they were substantially lower than expected for the undiluted transport of coastal air to the site; instead, these moist air parcels were mixed with very dry air from the middle and upper troposphere. Such dry air parcels lower the mixing ratio but do not substantially affect the isotopic composition. About 5% of the wet season measurements have $\delta$ values that are lower than predicted by a simple Rayleigh distillation model, indicating a restricted role for deep convection in moistening the southern South American Altiplano, an interpretation supported by satellite OLR data, and in marked contrast to similar studies from farther north in the tropical Andes. Those data that preserve the anomalously low $\delta$ values are associated with high relative humidity, suggesting limited advective drying. Summertime deuterium excess measurements from the site do not appear to be influenced by upstream convection, a result that is consistent with a proportional influence of convective moistening on the two isotopologues of water. Finally, data from the site exhibit intraseasonal variability that can be coherently linked to the position of the Bolivian high. Periods when moist, isotopically enriched air reaches the Chajnantor Plateau are associated with a southern displacement of the Bolivian high.

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