

Dear Editor,

Dear Referee,

thank you very much for your further comments and suggestions. In the following we reply to your comments and try to clarify the remaining issues.

Best regards!

Yenny Gonzalez et al.

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**Editor Final Comment to the Author:**

Dear Yenny et al.

Many thanks for the additional revisions, which again helped to improve the readability of your papers. I am happy to accept your paper for publication in ACP, subject to one suggestion: I think it would be appropriate to thank the reviewers for their very constructive input and their help in presenting your excellent results in a better and clearer way.

With best regards,  
Heini

[Our reply:](#)

Dear Heini Wernli,

We agree with you that special thanks should be given to the referees. In order to do that we will add to the Acknowledgement Section the following sentence:

“We thank the editor and the three anonymous referees for their very constructive input and their help in improving the presentation of our results.”

Many thanks for your collaboration and for guiding the review process.

Yenny Gonzalez et al.

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**Referee comment:**

The authors have substantially improved their initial manuscript particularly with respect to the isotope measurements setup and calibration as well as the existing literature review and comparison of their data with other published data. I have a few important final comments, that should be taken into account for a better readability and also because they address inconsistencies or unclarities in the presentation:

Our reply:

Thank you very much for this feedback.

**Referee comment:**

1. In general: please use “ppmv” if the humidity data is in parts per million with respect to volume. This should be changed in the axes labels of the Figures as well as in the text.

Our reply:

Yes, we absolutely agree. This has been corrected in the final version.

**Referee comment:**

2. My previous major comment 4: I can follow the authors’ argumentation about the difficulty to average the data and agree to some extent with the necessity of showing 10 min averages. However, to me there is still a major problem of readability in the Figures. Furthermore, in my opinion there is a certain discrepancy between the time resolution of the meteorological analysis data underlying the trajectory calculation, the time resolution of the back-trajectories and the time resolution of the dD-H<sub>2</sub>O data pairs. To improve the readability of the Figures, I would suggest to divide Figures 2 and 3 each into 2 Figures and thus, enlarge the panels. For each station one Figure would show the diurnal and annual cycles and another Figure would show the time series. In the time series Figures the 10 min data could be shown in a shaded way (in light colours) in the background and 1-3 hourly averaged data lines could be overlaid (both for  $\delta^2\text{H}$  and H<sub>2</sub>O). The averaging time period should be chosen such that the time series can be followed by eye. Periods without data do not need to be shown proportionally to the full time range, a lot of information space is lost this way.

The time gap could be indicated with a double vertical line and an indication of the gap on the x-axis. Furthermore I think that the authors should argue explicitly in the paper (Section 2.2) for the need of using 10min data for their analysis in a similar (but slightly condensed) way as they do in their response to my major comment 4 (Review 1).

Our reply:

- Discrepancy between time resolutions:

Yes, there is a different time resolution of the analyses (6h), trajectory interpolation steps (1h), and the measurements (10min). This is in general a problem when comparing point measurements of the real atmosphere with model/analyses data: the point measurements well captures all the short-term and small scale variations of the atmosphere, whereas the model has a limited spatial and temporal resolution and can only capture the large scale and longer term variations. Averaging the point measurements over time is not trivial. H<sub>2</sub>O is rather log-normally distributed. So there will be a difference whether we calculate the mean or the median H<sub>2</sub>O during 3 hours. Furthermore, averaging

$\delta D$  is not trivial and the averaging method can affect the outcome of the isotopologue study (see our discussion in the first reply). So in summary: the averaging will affect the outcome of our study and we should avoid it where possible.

A model can hardly resolve variation within a few hours (the reanalysis data are 6 hourly). So to our understanding it is reasonable to treat all measurement made 3 hour before the model output and 3 hour after the model output as being equally representative for the scale that is simulated by the model. It is right that all these observations will represent different small scale situations. However, none of these small scale situations can be captured by the model. It does not really matter whether we use the observation that perfectly coincides in time with the model output or whether we use any other of the observations made with 3 hour.

- Problems in calculating averages for H<sub>2</sub>O and  $\delta D$ :

We will briefly summarize our reply given above and our reply to the first round of comments to the referee. Therefore, we will add the following explanation in an additional paragraph at the end of Section 2.2 of the manuscript:

“The leading errors are due to the calibration corrections, meaning that they are systematic errors for the period between two calibrations. Thus calculating 1 h or 3 h averages instead of 10 min averages will not significantly reduce these errors. Actually, the variations we see within 1 h are mostly real atmospheric variations (recall the high precision of the 10 min averages!). Calculating averages of these real atmospheric small scale variations is not trivial and might affect the H<sub>2</sub>O- $\delta D$  distribution: first, H<sub>2</sub>O is often log-normally distributed and it will make a difference whether we use the mean or the median H<sub>2</sub>O concentrations. Second, H<sub>2</sub>O- $\delta D$  pairs do not vary along a single straight line. If we just average all the  $\delta D$  and all the H<sub>2</sub>O values, the averaged H<sub>2</sub>O- $\delta D$  data point will be below the mixing line or the Rayleigh curve described by the individual data points. If we average the  $\delta D$  weighted by H<sub>2</sub>O we will lie close to the mixing line but we will not well capture the situation of a Rayleigh process. In order to avoid artefacts caused by data averaging, all the H<sub>2</sub>O- $\delta D$  distribution plots of our study are made with high resolution data (10 min averages).”

Furthermore, we will complement page 7, line 138 by writing:

“[...] instrument precision (for 10 min averages and at 15700 ppmv it is better than 0.2‰, see Aemisegger et al., 2012, Fig. 7a, and for very dry conditions within a few permil) as well as [...]”

- Figures 2+3:

As the referee suggested, we split Figures 2 and 3. However, we think that it is important to show a Figure with the time periods of observations at IZO and TDE. These time series plots should include the gaps (periods when there are no observations due to instrumental failure or extreme atmospheric conditions), so that the reader gets aware of periods where there are a lot of data (in summer) and where there are less data (at IZO in winter and at TDE in spring). We will modify Fig 2 as follows:

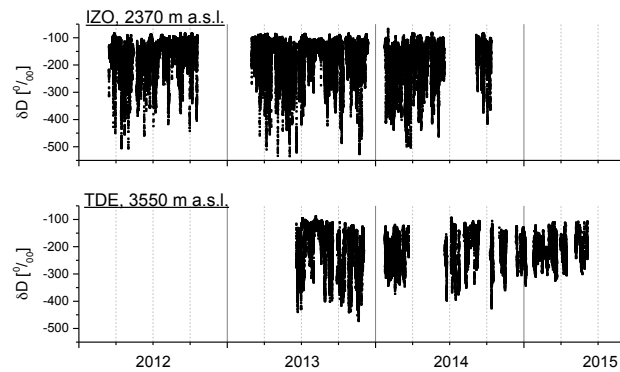


Fig. 2: Time periods covered by water isotopologue in-situ observations at IZO (upper panel) and TDE (lower panel). Shown are all 10 minute averages of  $\delta D$  measured at any time of the day.

We motivate this Figure in the last paragraph of Sect. 2.2 by the following paragraph:

“While during summer data have been registered almost continuously, the measurements have often been interrupted during winter. There are only a few measurement days in December and January (at IZO) and in January (at TDE).”

The intention of this Fig. 2 is not to show all the detailed variability in the data (this is not possible by a full time series plot).

In order to reveal the variability in the data we have Figure 3. In Figure 3 will now be exclusively dedicated to the annual cycles (mean values for each month) and the mean diurnal cycles (mean diurnal cycle for each month). This Figure 3 shows clearly the interesting detailed variations (which cannot be made visible in a figure like Fig. 2).

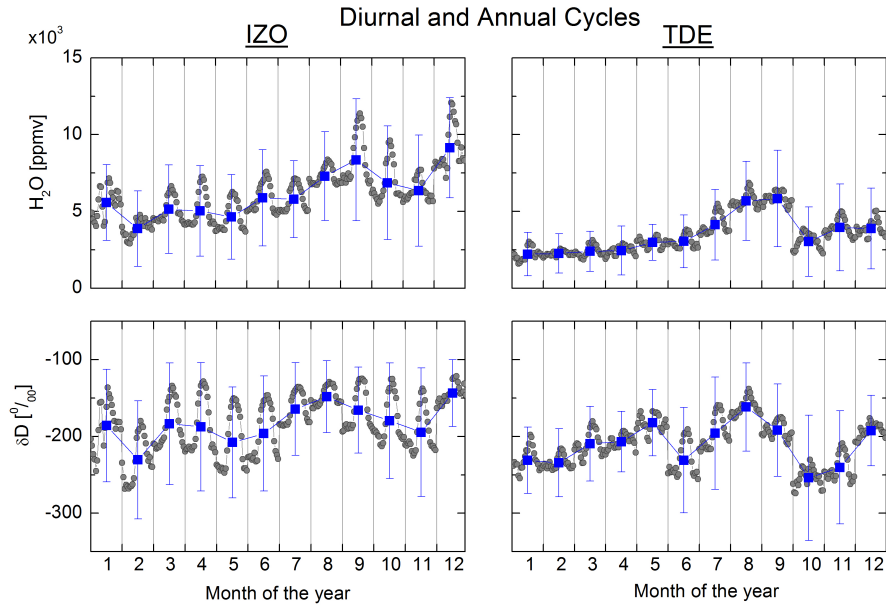


Fig. 3: The mean diurnal cycle and annual cycles of H<sub>2</sub>O and δD (left panels for IZO and right panels for TDE). Grey dots show the mean diurnal cycles for each month (mean value for each hour of the day) and the blue squares the annual cycle (mean and standard deviation of all observations that fall within an individual month).

**Referee comment:**

3. In Figures 2 and 3: I do not understand why the temporal data coverage of the H<sub>2</sub>O measurements (upper) panel and the \_2H measurements (lower) panel is not the same. Some data gaps in H<sub>2</sub>O do not exist in \_2H and vice-versa.

**Our reply:**

Yes, there was an error with the x-axis in the upper plots (not synchronized in time). In the new Fig. 2 we show the IZO and TDE data on the x-axis scale.

**Referee comment:**

4. In Figure 2: “time series of 1 h h”. Remove one “h”.

**Our reply:**

Yes, it has been corrected.

**Referee comment:**

5. Figure 4: there are too many points in these Figures to be able to distinguish the distribution of the data. Thus I suggest to either make an additional Figure with 4 panels of 2 dimensional density plots, or to provide an additional Figure with the PDFs of each variable (\_2H and H<sub>2</sub>O) at each station.

Our reply:

Yes, we agree. We provide an additional Figure in an additional Appendix: “Appendix B: Diurnal signals as seen in H<sub>2</sub>O-δD distribution density plots”.

In order to introduce this addition we added the following paragraph at the end of Section 3.1:

“

Appendix B complements this study of the diurnal signals in the H<sub>2</sub>O-δD distribution. Fig. A5 shows a two dimensional plot of the density of the H<sub>2</sub>O-δD pairs for “nighttime” and “daytime observations”.

“

The Text and Figure of the Appendix will be as follows:

“

APPENDIX: Diurnal signals as seen in H<sub>2</sub>O-δD distribution density plots

Figure 4 shows all the observed 10 min averaged H<sub>2</sub>O-δD data pairs, which is a large amount of data (about 75000 and 40000 data points at IZO and TDE, respectively). From Fig. 4 it becomes clear that the IZO daytime observations cover only a limited area in the H<sub>2</sub>O-δD distribution space. There is no single IZO daytime observation with δD below -345‰ (and almost no daytime observations with δD below -220‰ for H<sub>2</sub>O above 10000 ppmv). For TDE the situation is not clear from Fig. 4.

In order to give a statistical insight into the differences between the H<sub>2</sub>O-δD distributions during day and night we additionally calculate the density of the H<sub>2</sub>O-δD distributions for the daytime and nighttime data pairs. The respective distribution density plots are shown in Fig. A5 and clearly confirm that for IZO the daytime and nighttime H<sub>2</sub>O-δD distributions are significantly different. For TDE the day-night differences are less pronounced, but they become visible in the density plot (right panel of Fig. A5). For instance, at TDE the probability for δD being below -300‰ is significantly higher during night than during day (compare the areas marked by the thick black and orange lines).

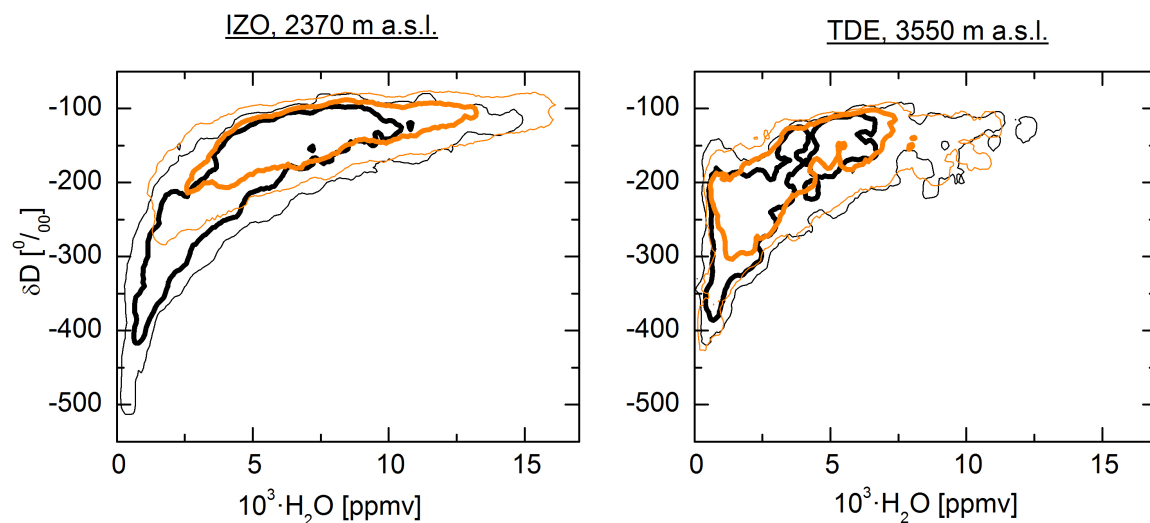


Fig A5: H<sub>2</sub>O-δD distributions as obtained for the “nighttime observations” (10 min averages made between midnight and 1 hour after sunrise, black contour lines) and the “daytime observations” (10 min

averages made between 3 and 10 hours after sunrise, orange contour lines). The thin and thick lines mark areas that include 95% and 66% of all the data. The plot shows the density distributions of the data points from Fig. 4.”

**Referee comment:**

6. Figure A5 replace “Km” by “km” to avoid confusion with the unit Kelvin.

Our reply:

The notation has been corrected in Figures 5, 6, A5 and A6.

**Referee comment:**

7. The Rayleigh and mixing lines in Figure 5 and 6 are orange and black respectively. In Figures 8 and 9 these two colours are inverted. This should be made consistent or otherwise explained in the legends of Figures 8 and 9.

Our reply:

Yes, we agree. The lines has been coloured consistently now.

**Referee comment:**

8. In my opinion Figure 10 is too busy. Could the two panels be organised vertically and the Figures be enlarged? Additionally, could a thick and a thin solid line be used, I find the dashed lines make the Figure difficult to read.

Our reply:

Yes, we enlarged the figures and substituted the dashed line by a thin solid line.

**Referee comment:**

9. p. 2, L. 18: add “the” different pathways.

Our reply:

Done.

**Referee comment:**

10. p. 3, L. 40-42: “is strongly affected by the mixing of air masses which humidity properties...” I do not understand this sentence, reformulate.

Our reply:

Line 41 has been changed to: “[...] by the mixing of airmasses, whose humidity properties are defined by their [...]”

**Referee comment:**

11. p. 4, L. 62: replace “resumes” by “summarises”.

[Our reply:](#)

Done.

**Referee comment:**

12. p. 5, L. 105: replace “pmm” by “ppmv”.

[Our reply:](#)

We apologize for this mistake. We used now “ppmv” everywhere.

**Referee comment:**

13. p. 6, L. 137: “based on additive” this is not very clear, reformulate, do you mean “based on additive errors”?

[Our reply:](#)

We have removed “, based on additive, ” since it is clear from the context that we account for all the different and independent contributions when calculating the total error.

**Referee comment:**

14. p. 8, L. 164: “of 1 resolution”, this is not clear, reformulate

[Our reply:](#)

It is “of 1 h resolution”. It has been corrected.

**Referee comment:**

15. p. 8, L.174: “transports the climb of gases” this is not a proper scientific formulation.

[Our reply:](#)

We have removed “climb of” so that it will read as: “[...] transports the gases [...]”

**Referee comment:**

16. p. 15, L. 368-369: I do not understand what this sentence means, reformulate.

[Our reply:](#)

The sentence has been corrected to: “[] also showed that higher – latitude airmasses are more humid than expected []”

**Referee comment:**



17. p. 15, L. 372 and p. 16, L.413: “evaporation from a rather warm ocean” I cannot follow this argument, ocean evaporation would not lead to  $\delta D$  in a range of  $-300\text{‰}$  to  $-200\text{‰}$ .

Our reply:

The two Rayleigh lines as shown in the paper are calculated for initialization with  $\delta D=-80\text{‰}$ ,  $RH=80\%$  and two different SST:  $18^\circ\text{C}$  and  $25^\circ\text{C}$ . For a SST of  $30^\circ\text{C}$  the Rayleigh line would further move to higher humidity values: it starts with  $\delta D=-80\text{‰}$  but with very high humidity (30000 ppmv). Rayleigh condensation will then lead to a  $\delta D$  below  $-250\text{‰}$  at a humidity of about 10000 ppmv.

**Referee comment:**

18. p. 16, L. 399: “For such study”, reformulate.

Our reply:

We will change to: “In this paper we perform such kind of study and therefore combine the isotopologue data [...]”

**Referee comment:**

19. p. 16, L.412: “indicates to rain re-evaporation” remove to.

Our reply:

Done.

**Referee comment:**

20. p. 20, L. 511: “in of slope’, reformulated.

Our reply:

We removed “of”, so that it will read as: “[...] the uncertainty in slope (a) of [...]”

Additional modifications:

In addition we make the following corrections, which we think can further improve the clarity of the manuscript:

- a) Line 105/106: We will replace the sentence: “Thus, the subtropical [...]” by:
- b) “Thus, the in-situ  $\text{H}_2\text{O}-\delta D$  measurements made at the different subtropical free tropospheric stations register data that are within the same order of magnitude.”
- c) Line 141: replace “low depleted” by “strong depleted”
- d) Line 142: replace “dD” by “ $\delta D$ ”
- e) Line 143: modify as: “[...] 500 ppmv,  $<4\text{‰}$  at 4500 ppmv and even smaller for higher humidity.”

# Detecting moisture transport pathways to the subtropical North Atlantic free troposphere using paired H<sub>2</sub>O- $\delta$ D in situ measurements

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## Abstract

We present two years of in-situ measurements of water vapour ( $\text{H}_2\text{O}$ ) and its isotopologue ratio ( $\delta\text{D}$ , the standardized ratio between  $\text{H}_2^{16}\text{O}$  and  $\text{HD}^{16}\text{O}$ ) made at two remote mountain sites on Tenerife Island in the subtropical North Atlantic. We show that the data – if measured during nighttime – are well representative for the lower/middle free troposphere. We use the measured  $\text{H}_2\text{O}$ - $\delta\text{D}$  pairs, together with dust measurements and back-trajectory modelling for analysing the moisture pathways to this region. We can identify four principally different transport pathways. The airmass transport from high altitudes and high latitudes shows two different scenarios. The first scenario brings dry airmasses to the stations, as the result of condensation events occurring at low temperatures. The second scenario brings humid airmasses to the stations, due to cross isentropic mixing with lower level and more humid air during transport since last condensation. The third pathway is transport from lower latitudes and lower altitudes, whereby we can identify rain re-evaporation as an occasional source of moisture. The fourth pathway is linked to the African continent, where during summer dry convection processes over the Sahara very effectively inject humidity from the boundary layer to higher altitudes. This so-called Saharan Air Layer (SAL) is then advected westward over the Atlantic and contributes to moisten the free troposphere. We demonstrate that the different pathways leave distinct fingerprints on the measured  $\text{H}_2\text{O}$ - $\delta\text{D}$  pairs.

## 1 Introduction

In the subtropical free troposphere, in the region of the descending branch of the Hadley cell, the humidity is not conserved along the mean subsidence (Pierrehumbert, 1998). Instead, this dry air is often moistened (Galewsky and Hurley, 2010; Couhert et al., 2010; Risi et al., 2012). The few studies based on atmospheric modelling points the turbulent transport of water vapour from the surface upward as the dominant moistening process balancing the drying in the subtropical free troposphere (Couhert et al., 2010; Risi et al., 2012). Additional

processes, such as evaporation of condensate and isentropic eddy transport of moist air from the tropics, are suggested to also contribute to moisten this region (Galewsky and Hurley, 2010, and references therein); but the sources and dynamics involved in this moistening are still unclear.

5 Several studies indicate that water vapour isotopologue observations are very promising for investigating the different moisture pathways in this region. Such observations can be used to distinguish between the different mechanisms associated to the moistening (e.g., Galewsky and Hurley, 2010; Noone et al., 2011; Tremoy et al., 2012; Samuels-Crow et al., 2014; Bailey et al., 2013, 2015; Dyroff et al., 2015; Steen-Larsen et al., 2015; Schneider et al., 2015). Stations located in the subtropical free troposphere are key emplacements for studying the synoptical scale humid transport in the subtropics. Studies based on water vapour isotope observations in the Pacific Subtropical free troposphere, highlight the relevance of moisture exchange between the boundary layer and the free troposphere due to shallow convection at local scale (Bailey et al., 2013). In addition, subtropical moisture is strongly affected by the mixing of air masses ~~which humidity properties~~, whose humidity properties are defined by their condensation and evaporation history on regional scale (Noone et al., 2011). In the North Atlantic, studies based on in-situ water vapour isotopologue measurements have been focused on the moisture sources influencing the marine boundary layer (Benetti et al., 2014; Steen-Larsen et al., 2014, 2015). However, studies in relation to transport pathways of moisture in the subtropical North Atlantic free troposphere including long-term measurements of water vapour isotopologues have not been reported yet. In contrast to the Pacific, the atmosphere over the subtropical North Atlantic is regularly affected by dust outbreaks (from the Sahara desert), and consequently, the scheme of moisture exchange of the Pacific subtropical region can not fully describe that occurring in the Subtropical North Atlantic. In order to fill this gap, we present and discuss the first multi-year observational in situ data set of free tropospheric water vapour isotopologues in the subtropical North Atlantic region.

In the following we express the isotopologues  $\text{H}_2^{16}\text{O}$  and  $\text{HD}^{16}\text{O}$  as  $\text{H}_2\text{O}$  and  $\text{HDO}$ . The  $\delta$ -notation expresses the per mil difference of the stable isotope ratio of a water sample

( $R = \text{HDO}/\text{H}_2\text{O}$ ) from that of the isotope ratio of Vienna Standard Mean Ocean Water, i.e.,  $\delta\text{D} = 1000 \times (R/R_{\text{VSMOW}} - 1)$  ( $R_{\text{VSMOW}} = 3.1152 \times 10^{-4}$ , Craig, 1961; Coplen, 2011).

In Sect. 2 of this paper we present the measurement sites and discuss the methodology of our study. In Sect. 3 we document that our nighttime measurements are representative for the subtropical North Atlantic lower free troposphere. We use backward trajectories and dust measurements as tracers for detecting the main meteorological processes. Then, we document that these processes leave unique fingerprints in the  $\text{H}_2\text{O}$ - $\delta\text{D}$  distribution. Section 4 ~~resumes~~ summarises the work.

## 2 Methodology

### 2.1 Measurement site

As study area we use Tenerife (Canary Islands, Spain;  $28.3^\circ \text{N}$ ,  $16.5^\circ \text{W}$ ). At this island, two high mountain sites are run by the Izaña Atmospheric Research Centre. IZO is a mountain top station located at 2367 m a.s.l., whereas TDE is a small measurement site located at the volcanic cone at 3550 m a.s.l. In the context of the project MUSICA (MUlti-platform remote Sensing of Isotopologues for investigating the Cycle of Atmospheric water), we installed two Picarro instruments at IZO and TDE stations. These instruments provide continuous isotopologues data for altitudes above 2000 m which are unique for the subtropical North Atlantic.

A schematic depiction of the locations of IZO and TDE and the meteorological processes affecting the measurement sites are shown in Fig. 1. In the subtropical North Atlantic region, the atmospheric stability is determined by the combination of two synoptic processes that well define the Marine Boundary Layer (MBL) and the Free Troposphere (FT). In the MBL, a quasi-permanent North-northeast (NNE) trade wind blows ( $< 1000$  m a.s.l., Palmén and Newton, 1969). In the FT, the descendent branch of the Hadley cell around  $30^\circ \text{N}$  results in a North-west (NW) subsidence regime (Galewsky et al., 2005; Cuevas et al., 2013). This subsidence is frequently alternated in summer with South-east (SE) Saharan dust

outbreaks (Chiapello et al., 1999). Episodes of airmass transport from South-west (SW) direction are also occasionally observed.

The local moisture exchange between the MBL and the FT is limited by a Temperature Inversion Layer. In the surroundings of the island, the top of the MBL, which is frequently located just below the temperature inversion layer, is characterized by a stratocumulus layer formed by condensation of water vapour onto the pre-existing particles (Rodríguez et al., 2009). This layer creates a quasi-continuous foggy and rainy regime between 800 and 2000 m a.s.l., that is more pronounced on the northern part of the island. The effectiveness of this layer in separating the MBL from the FT is reflected in the relative humidity (RH) profile. In the FT, the RH is typically around 20 %; while it is normally above 60 % in the MBL (Cuevas et al., 2013). Vertical mixing between MBL and FT air is observed during daylight due to the upslope flow regime (taking place at very local scale).

## 2.2 Measurements of water vapour isotopologues

Two commercial cavity ring-down spectrometers (Picarro model L2120-I) have been used for water vapour isotopologues monitoring at the two mountain sites at Tenerife. At IZO, measurements started in March 2012, and at TDE in July 2013. ~~Time series of and  $\delta D$  (around 2 of~~ The data sets consist of about 75,000 (at IZO) and 40,000 (at TDE), 10 min average) averages. Time series of  $\delta D$  measurements at IZO and TDE stations are shown in ~~Figs. ?? and ?? (left column), respectively~~ Fig. 2. The measurement gaps are due to instrument failure and maintenance ~~or extreme weather conditions. While during summer data have been registered almost continuously, the measurements have often been interrupted during winter. There are only a few measurement days in December and January (at IZO) and in January (at TDE).~~

At IZO,  $H_2O$  data between 200 to 16000 ppmv and  $\delta D$  between -500 to -90‰ were recorded. At TDE,  $H_2O$  ranged between 250 and 12000 ppmv, and  $\delta D$  ranged between -430 to -100‰. At Mauna Loa free troposphere station, Noone et al. (2011) reported  $\delta D$  values between -100‰ to -400‰ and humidities between 500 to 15000 ppmv. On the Chilean hyperarid Chajnantor Plateau, Samuels-Crow et al. (2014) recorded  $H_2O$ - $\delta D$  pairs ranging

from 95 ppmv and -465 ‰ to 12500 ppmv and - 45 ‰. Thus, the subtropical free troposphere stations show in-situ H<sub>2</sub>O-δD pairs measurements made at the different subtropical free tropospheric stations registered data that are within the same order of magnitude.

At IZO, the sampling inlet is installed 4 m above the roof of a 6-floor building at a height of 30 m above ground (2397 m a.s.l.). It consists of stainless steel tube of 18 m that goes from the terrace of the tower, through the service channel to the Picarro laboratory. A vacuum pump generates an inflow of 2810 lpm (standard conditions) throughout the sampling line, which has an inner diameter of 80 mm. The manifold has an inner diameter of 80 mm and a length of 250 mm. The instrument takes the air sample using stainless steel tube with an inner diameter of 4 mm, which go from the manifold to the inlet of the analyzer (1.6 m). An additional pump with an inflow of 5 lpm is connected in serie at the inlet of the instrument. The residence time of the air inside the tubing is approximately 8 seconds.

At TDE, the inlet is also 4 m above the roof at a height of 6 m above the ground (3556 m a.s.l.). The sampling line is connected to a manifold with an inner diameter of 60 mm and a total length of 5 m where the air is pumped at 20 lpm. The air then flow to the instrument throughout stainless steel tubes with an inner diameter of 4 mm (3.3 m). At TDE, an additional pump with an inflow of 5 lpm is also connected in serie at the inlet of the instrument. The residence time of the air is approximately 44 seconds.

No heated tubing was implemented at any of the stations. Only for 7.6 % and the 4.6 % of the data at IZO and TDE stations the relative humidity values have been above 90 %. In these conditions, the outside temperature at IZO ranges between -6 and 15° C, whereas at TDE varies between 6 and 11° C. Since the tubing in the buildings is kept around 21° C, condensation events in the inlet lines can be excluded.

For calibration purposes we used two liquid working standards of composition  $\delta D_{S1} = -142.2 \pm 0.7\text{‰}$  and  $\delta D_{S2} = -245.3 \pm 0.7\text{‰}$ . The working standards were prepared from a mixture of ground water from Karlsruhe (Germany) and a melted Antarctic snow (S1), and the pure melted Antarctic snow (S2). The isotopologue composition of these standards was measured by Le Laboratoire des Sciences du Climat et de l'Environnement (LSCE-CEA, France) and referenced to the VSMOW2/SLAP2 scale (IAEA, 2009). For routine measure-

ments we need a significant amount of liquid standards (1 liter/year and instrument). Of our two standards large amounts are available and we can perform continuous calibrations during long measurement periods.

The instruments are calibrated every 8-12h by using liquid standards injected with Picarro's Standard Delivery Module (SDM). The error estimation, ~~based on additive,~~ accounts for instrument precision (for 10 min averages and at 15700 ppmv it is better than 0.2%, see, Aemisegger et al., 2012, Fig. 1) well as errors due to the following corrections: a) uncertainty of the standards (0.7% for both), b) humidity dependence (from 0.3% for 10000 ppmv, up to 8.0% at 200ppm ppmv), c) extrapolation of VSMOW2-SLAP2 scale outside the range of calibration (for humid air: < 2.0%; up to 5% for low-strong depleted, i.e. generally dry air), d) calibration (1% for the whole humidity range).

The absolute uncertainties in  $\delta D$ - $\delta D$  are then < 15% at 500 and ppmv, < 4% at 4500 ppmv and even smaller for higher humidity. More detailed information about the calibration procedure, stability and uncertainty estimations of the two instruments is given in Appendix A.

The leading errors are due to the calibration corrections, meaning that they are systematic errors for the period between two calibrations. Thus, calculating 1 h or 3 h averages instead of 10 min averages will not significantly reduce these errors. Actually, the variations we see within 1 h are mostly real atmospheric variations (recall the high precision of the 10 min averages). Calculating averages of these real atmospheric small scale variations is not trivial and might affect the  $H_2O$ - $\delta D$  distribution: first,  $H_2O$  is often log-normally distributed and it will make a difference whether we use the mean or the median  $H_2O$  concentrations. Second,  $H_2O$ - $\delta D$  pairs do not vary along a single straight line. By averaging the  $\delta D$  and the  $H_2O$  values, the averaged  $H_2O$ - $\delta D$  data point will be below the mixing line or the Rayleigh curve described by the individual data points. If we average the  $\delta D$  weighted by  $H_2O$ , the pairs will lie close to the mixing line but we will not well capture the situation of a Rayleigh process. In order to avoid artefacts caused by data averaging,



all the  $\text{H}_2\text{O}-\delta\text{D}$  distribution plots of our study are made with high resolution data (10 min averages).

### 2.3 Measurements of dust

Long-term measurements of aerosol at Izaña includes chemical composition, dust concentrations and size distribution. The methodology and quality control of aerosol in situ techniques are described in Rodríguez et al. (2012). In Izaña, bulk mass concentrations of aerosols is clearly dominated by desert Saharan dust (Basart et al., 2009; Rodríguez et al., 2011). We used records of dust at Izaña to detect the arrival of North African air (Rodríguez et al., 2012).

Unfortunately, in situ dust measurements are not available at TDE. In order to distinguish between clean and dust laden conditions at this station we use the AERONET columnar-integrated aerosol optical depth (AOD) level 2.0 obtained at a wavelength of 500 nm at IZO (<http://aeronet.gsfc.nasa.gov>). See more details of calibration procedures, data acquisition and processing in Holben et al. (1998).

### 2.4 Back-trajectories

Transport pathways of moisture are analysed by integrating the Global Data Assimilation System archive information (GDAS1, NCEP) in the Hybrid Single Particle Lagrangian Integrated Trajectory model HYSPLIT 4.0. The GDAS1 is available each 6 h, and the post-processing converts the data to  $1^\circ \times 1^\circ$  latitude–longitude grids and from sigma levels to the 23 pressure levels between 1000 and 20 hPa (Rolph et al., 2014). HYSPLIT performs a linear interpolation between the times of the available input data (6 h) for calculating 5 day back-trajectories of 1 h resolution (Draxler and Rolph, 2003). The trajectories are released at the height above sea level of the stations. The vertical component of the back-trajectories was computed using the vertical model velocity. The end points of the trajectories were set at Tenerife ( $28.3^\circ \text{ N}$ ,  $16.5^\circ \text{ W}$ ) at the elevations of the IZO and TDE stations.

### 3 Results

#### 3.1 The effect of the local diurnal upslope flow

The airflow regime at IZO is driven by the occurrence of upward transport of humid air during daylight and downward transport of dry FT air at night. The upward transport is caused by the combination of the thermally driven growth of the MBL volume and the buoyant airflows caused by the heating of the air located just above the terrain (Rodríguez et al., 2009). This upslope flow transports the ~~climb-of~~ gases emitted at lower parts of the island, which is captured in the marked daily cycle of gases and particles measured at IZO (e.g., Rodríguez et al., 2009). The highest concentrations of pollutants is observed in the early afternoon.

~~The right columns in Figs. ?? and ?? show~~ Fig. 3 shows the monthly mean daily cycle of  $\text{H}_2\text{O}$  and  $\delta\text{D}$  at IZO and TDE stations, respectively (grey dots). The annual mean and standard deviation of  $\text{H}_2\text{O}$  and  $\delta\text{D}$  at both stations is also shown in blue dots. There is a marked daily cycle in the  $\text{H}_2\text{O}$  and  $\delta\text{D}$  data of the IZO station (left column in Fig. ??3) and a weaker one at the TDE station (right column in Fig. ??3). At IZO, the diurnal cycle of  $\text{H}_2\text{O}$  and  $\delta\text{D}$  is more pronounced than the annual cycle. At TDE, the  $\text{H}_2\text{O}$  annual cycle is stronger than the diurnal cycle. However, at TDE,  $\delta\text{D}$  data also show a diurnal cycle with an amplitude similar to the amplitude of the annual cycle.

The distribution of the 10 min  $\text{H}_2\text{O}$ - $\delta\text{D}$  pairs collected at IZO and TDE stations are shown in Fig. 4. The whole data set (10 min average) is presented in grey dots; black dots ~~show~~ represent the data collected at night during nighttime (from midnight to 1-h after sunrise) ~~and orange crosses show~~. Orange crosses represent the data collected during daylight (from 3 to 10-h after the sunrise, when the upslope breeze is active).

At IZO, the lowest  $\delta\text{D}$  values are measured at nighttime (~~left column in~~ Fig. 4). During daylight, we observe less depletion. The  $\text{H}_2\text{O}$ - $\delta\text{D}$  pairs measured at IZO during daylight are assembled in the upper side of the  $\text{H}_2\text{O}$ - $\delta\text{D}$  distribution ( $\delta\text{D} = -146 \pm 39\%$ , orange crosses, left column in Fig. 4). At midday, the increase of humidity is associated to a mean isotopic composition of  $\delta\text{D} = -131 \pm 35\%$ . This value is similar to the one measured close to the ocean by Dyroff et al. (2015). The  $\delta\text{D}$  mean value of these in-flight measurements measured

around the top of the MBL, 600–900 m a.s.l. in front of Tenerife coast was  $-124 \pm 43\%$ . Thus, the shifting of the  $\text{H}_2\text{O}-\delta\text{D}$  pairs to the upper side of the distribution is the result of the mixing of dry FT air with water evaporated from the surrounding ocean and exported by turbulent mixing at the top of the MBL. This result is in agreement with the one found by Noone et al. (2011) in Mauna Loa (Hawaii).

At TDE, the difference between the daylight and nighttime  $\text{H}_2\text{O}-\delta\text{D}$  distribution is not as clear as at IZO (right column in Fig. 4). The weaker diurnal effect at TDE station is due to its location. TDE is located at a higher altitude on a rather sharp peak (Pico del Teide). There it is less exposed to the slope breezes, and consequently, the influence of the MBL-FT air mixing is weaker.

At IZO, gases and particles measured at nighttime well represent FT conditions (Gómez-Peláez et al., 2006; Rodríguez et al., 2009, 2012; Cuevas et al., 2013). To examine the variability of the  $\text{H}_2\text{O}-\delta\text{D}$  pairs in the subtropical North Atlantic FT, and in order to avoid the possible local MBL-FT mixing, only the  $\text{H}_2\text{O}-\delta\text{D}$  pairs measured at nighttime at IZO and TDE will be considered in the following study.

[Appendix B complements this study of the diurnal signals in the  \$\text{H}\_2\text{O}-\delta\text{D}\$  distribution. Fig. A5 shows a two dimensional plot of the density of the  \$\text{H}\_2\text{O}-\delta\text{D}\$  pairs for “nighttime” and “daytime observations”.](#)

## 3.2 The Saharan Air Layer and the moisture in the subtropical North Atlantic FT

The meteorological pattern of the subtropical North Atlantic region is characterized by a constant transport of Atlantic airmasses that alternates with Saharan dust events, especially in summer. Previous works carried out in this region show that these two regimes can easily be distinguished by their dust content. At IZO, dust concentrations under background clean conditions are lower than  $2 \mu\text{g m}^{-3}$  (Rodríguez et al., 2009); whereas during Saharan events, dust concentrations above  $25 \mu\text{g m}^{-3}$  are usually observed (Rodríguez et al., 2015). The Izaña AOD levels for background conditions are usually lower than 0.05 (García et al., 2012), and frequently above 0.10 during dust events (Basart et al., 2009; García et al., 2012).

The left column in Figs. 5 and 6 show the distribution of 5 day back-trajectories for non-dust and dust laden conditions at IZO and TDE stations, respectively. We considered that an air mass experiences condensation when RH along the trajectory to the station exceeds the limit of 80 % during a 3 h time interval (James et al., 2004; Sodemann et al., 2008). If this occurs, we set this point as initial point of the back-trajectory. If no condensation was observed along the 5 days path, the back-trajectory was fully drawn. Clean dust-free air masses originate from the FT over the Atlantic (first row in Figs. 5 and 6). Dust laden air masses are originated in North Africa close to the surface (dust > 25  $\mu\text{g m}^{-3}$ , AOD > 0.1, second row in Figs. 5 and 6).

The right column in Figs. 5 and 6 show the 10 min average  $\text{H}_2\text{O}$ - $\delta\text{D}$  pairs measured under non-dust (green dots) and dust laden conditions (red dots) at IZO and TDE stations, respectively. The whole  $\text{H}_2\text{O}$ - $\delta\text{D}$  distribution (grey dots) is quite well confined within two theoretical curves. The theoretical line on the low  $\delta\text{D}$  value side of the distribution represents the evolution of an air mass that has experienced Rayleigh distillation, a gradual dehydration in which all condensate is immediately removed from the vapour phase (initial conditions: RH = 80 % and SST = 25 °C, orange line). The Rayleigh process starts when saturation is reached (dew point). The equations and coefficients for saturation over water conditions were taken from Johnson et al. (2001). For the theoretical mixing we assume moistening by evaporation from the ocean surface and drying by middle/upper tropospheric air (initial conditions of air mass 1:  $\text{H}_2\text{O} = 18000 \text{ ppm}$ ,  $\text{H}_2\text{O} = 18000 \text{ ppmv}$ ,  $\delta\text{D} = -84\text{‰}$ ; air mass 2:  $\text{H}_2\text{O} = 400 \text{ ppm}$ ,  $\text{H}_2\text{O} = 400 \text{ ppmv}$ ,  $\delta\text{D} = -600\text{‰}$ , black solid line). The calculation of this mixing line is based on the simplified solution of the diffusion mixing model shown by Noone et al. (2011, eq. 6). These two theoretical lines (Rayleigh and mixing) mostly cover the set of  $\text{H}_2\text{O}$ - $\delta\text{D}$  measured during this study.

The  $\text{H}_2\text{O}$ - $\delta\text{D}$  pairs associated to clearly non-dust conditions represent 55 % of the data collected at IZO, and 51 % of the data collected at the TDE. The origin of the North Atlantic air masses reaching IZO and TDE stations covers a wide area (0–60° N, 45° W–20° E), and also a wide range of altitudes (0–10 km; left column in Figs. 5 and 6). A wide  $\text{H}_2\text{O}$ - $\delta\text{D}$  distribution is measured under the arrival of dust-free air masses (green dots in right column

in Figs. 5 and 6). This distribution illustrates the effect of non-Rayleigh processes affecting  $\text{H}_2\text{O}$  and  $\delta\text{D}$ , such as air mass mixing and different  $\text{H}_2\text{O}$ - $\delta\text{D}$ -relations (Rayleigh-curves) of air masses from different source regions (Brown et al., 2013). At both stations, nighttime  $\text{H}_2\text{O}$ - $\delta\text{D}$  pairs below a minimum Rayleigh curve for air masses with subtropical origin (initial  $\text{H}_2\text{O} = 27000 \text{ ppm}$ ,  $\delta\text{D} = -71\%$ ) cannot be explained by condensation or mixing. Therefore, this occasional super-Rayleigh observations indicate additional fractionation related to either intracloud or subcloud processes or postcondensational exchange (Brown et al., 2013, and references therein). These observations will be discussed later.

Saharan dust conditions ( $\text{dust} > 25 \mu\text{g m}^{-3}$ ) were observed in 20 % of IZO and 19 % of TDE of the whole recorded data. At IZO summer data represent 74 % of the Saharan dust measurements, and 70 % of TDE measurements. The  $\text{H}_2\text{O}$ - $\delta\text{D}$  pairs collected under dust laden conditions were confined in the upper part of the distribution (red dots in Figs. 5 and 6). During these events, relatively enriched and moist  $\text{H}_2\text{O}$ - $\delta\text{D}$  pairs were measured. Mean values for IZO were  $-133 \pm 35\%$  for IZO and  $7000 \pm 3000 \text{ ppmv}$ ; and for TDE  $-152 \pm 44\%$  and  $5000 \pm 2000 \text{ ppmv}$ , respectively. The  $\text{H}_2\text{O}$ - $\delta\text{D}$  distribution under dust laden events is well limited by theoretical lines that simulate the mixing between BL and FT air. The dashed black line drawn in Figs. 5 and 6, represents the mixing between the following air masses: air mass (1)  $\text{H}_2\text{O} = 16000 \text{ ppm}$ ,  $\delta\text{D} = -93\%$  and air mass (2)  $\text{H}_2\text{O} = 400 \text{ ppm}$ ,  $\delta\text{D} = -600\%$ . This mixing line was determined as best fit of the border of the data of dust laden air.

Episodes of moderate dust content ( $2 < \text{dust} < 25 \mu\text{g m}^{-3}$ ,  $0.02 < \text{AOD} < 0.1$ ) are related to air masses that have travelled westward from the African continent towards the Atlantic Ocean and then return eastward laden with remaining dust where they are measured at IZO. These events are the mixing product of clean North Atlantic and Saharan dust laden air masses. As consequence, they do not show a unique fingerprint on the  $\text{H}_2\text{O}$ - $\delta\text{D}$  distribution, and they are not shown here.

Dust-laden Saharan air masses contribute to moisten the dry subtropical North Atlantic FT. The information of the  $\text{H}_2\text{O}$ - $\delta\text{D}$  pairs measured under these conditions indicate typical dehydration/mixing process also observed over the ocean. The transport of dust starts

over the Sahara desert, where dust storms are driven by local thermal low pressure systems at the surface. In summer, the shift northward of the north-east trade winds and the Inter-Tropical Convergence Zone (ITCZ) in combination with a convective boundary layer prompts the strong injection of dust at high altitudes (Guirado et al., 2014; Rodríguez et al., 2015). The dust is then exported westward at subtropical latitudes (20–30° N) within the Saharan Air Layer (SAL), a stratum of warm dust laden air, normally located between an altitude of 1 to 5 km with a maximum dust load at an altitude between 2 and 3 km (e.g., Prospero et al., 2002; Rodríguez et al., 2011; Andrey et al., 2013; Rodríguez et al., 2015). Previous works indicate that the moisture content of the SAL during summer has its origin on evaporation of the warmer Mediterranean Sea, which is then driven by the trade winds over North Africa, mixed in the Sahara desert with dust and then transported into the SAL to the subtropical North Atlantic FT (Millán et al., 1997, 2004; Rodríguez et al., 2011). Risi et al. (2010) showed column vapor  $\delta D$  summer mean from satellite observations and atmospheric models varying between -100‰ and -160‰ for the region covering the Mediterranean Sea and the Sahara desert (period 2003–2005). These mean values are in agreement with our dataset.

### 3.3 Classification of North Atlantic airmasses as a function of the last condensation temperature

In this section, we focus on the moisture transport pathways over the North Atlantic. For this purpose, we only work with airmasses corresponding to clean conditions (not linked to SAL) and we use the theory of the last condensation (LC) point. According to this theory, the mixing ratio is determined by the specific humidity at the point of LC, in case it is not affected by subsequent mixing (Galewsky et al., 2005, and references therein).

We use GDAS1 data and HYSPLIT back-trajectories to derive information about the LC point and mixing after LC and then relate this information to our H<sub>2</sub>O- $\delta D$  observations. The LC point is identified at the area where RH exceeds 80 % during a 3 h time interval (James et al., 2004; Sodemann et al., 2008). We use the corresponding 3 h averages of

temperature and specific humidity at this LC point (in the following referred to as  $T_{LC}$  and  $H_2O_{LC}$ ) for classifying the airmasses.

We create three main different data groups:  $T_{LC} < 250$  K,  $250$  K  $< T_{LC} < 270$  K, and  $T_{LC} > 270$  K. The temperatures  $T_{LC} = 250$  K and  $T_{LC} = 270$  K correspond to humidities of approximately 1700 and 8000 ppmv, respectively. The exact values of the temperatures that define the three temperature groups are more or less arbitrary. Important is here not the absolute value. What is important is that we distinguish airmasses according to their temperatures at the last condensation point. We group all airmasses for low  $T_{LC}$  (last condensation at low temperatures, i.e. dry at the last condensation point). and for high  $T_{LC}$ , i.e. last condensation at high temperatures and accordingly humid airmasses. Furthermore, we create a group that lies in between.

The top panels of Fig. 7 (left for IZO and right for TDE) show that  $T_{LC}$  is a good proxy for the locations of the LC point, since the data groups automatically with respect to the location and humidity of the last condensation point. The coldest saturation temperatures (220–250 K, blue colour) typically corresponds to air transported from the upper extra-tropical troposphere ( $> 40^\circ$  N,  $< 450$  hPa). These airmasses represent 32 and 43 % of the airmasses reaching IZO and TDE station, respectively. Airmasses experiencing LC at warmer temperatures (250–270 K) usually originate between 20 and  $50^\circ$  N at 400–600 hPa (grey colour in Fig. 7). They represent 48 and 42 % of the airmasses reaching IZO and TDE, respectively. Warmest LC temperatures (270–290 K) usually originate between 0 and  $40^\circ$  N and pressure levels above 600 hPa (red colour in Fig. 7). They represent 20 and 14 % of the airmasses reaching IZO and TDE, respectively.

We use the logarithmic difference between the humidity given by GDAS1/HYSPLIT at the station ( $H_2O_{t=0}$ ) and the humidity at the LC point ( $H_2O_{LC}$ ), in order to analyse if the air mass experienced variations on the moist content during the transport from the LC point to the stations ( $\log[H_2O_{t=0}] - \log[H_2O_{LC}]$ , hereafter  $\Delta H_2O$ ). We postulate that the airmasses with  $\Delta H_2O$  within the  $\pm 0.1$  bin do conserve the properties of the LC point during their transport to IZO and TDE. Negative  $\Delta H_2O$  indicates that the airmasses mix with drier airmasses during the transport to the stations (we exclude situations of rainout by requiring that RH

never reaches 80 % before the LC point). Positive  $\Delta H_2O$  indicates that the airmasses get moister. The bottom panels of Fig. 7 shows the normalized distribution of  $\Delta H_2O$  for the three  $T_{LC}$  groups (blue, black, and red coloured lines, respectively). Left panel for IZO and right panel for TDE.

At IZO the humidity concentrations since the LC point are best conserved for  $T_{LC} > 250$  K (red and grey line). At TDE we observe a relatively clear moistening for  $T_{LC} < 270$  K (grey and blue line) and generally a drying for airmasses with  $T_{LC} > 270$  K (red line). The total contribution of airmasses with  $\Delta H_2O < -0.1$  (i.e. drying since LC) is 19 % at IZO and 43 % at TDE, revealing that drying by mixing with dry air is more frequently observed at IZO. For  $T_{LC} > 270$  K, i.e. for air that has been rather humid at the LC point the drying by mixing with subsiding dry air is very clearly observed at TDE (red line, bottom right panel of Fig. 7). The total contribution of airmasses with  $\Delta H_2O > +0.1$  (i.e. moistening since LC) is 46 % at IZO and 29 % at TDE. This moistening is most pronounced for air with the LC point in the upper troposphere of the extra-tropics ( $T_{LC} < 250$  K) and it becomes in particularly evident at IZO (blue line, bottom left panel of Fig. 7). This moistening process is more important at IZO than at TDE, due to IZO's location at a lower altitude, which is directly affected by turbulent mixing from the marine boundary layer.

Figure 8 shows the  $H_2O$ - $\delta D$  distribution as measured at IZO for the different  $T_{LC}$  groups. The  $H_2O$ - $\delta D$  data pairs correspond to 10 min averages measured within  $\pm 3$  h of the air mass arrival time of the trajectory. For each  $T_{LC}$  group, the  $H_2O$ - $\delta D$  data points have been colour-coded as a function of  $\Delta H_2O$ . The green colour highlights those data associated to  $\Delta H_2O$  within  $\pm 0.1$ , thus, conserving water vapour concentrations since LC. The dark grey marks data with  $\Delta H_2O$  out of the  $\pm 0.1$  range. Figure 9 shows the same for TDE station.

For the cold LC temperatures ( $T_{LC} < 250$  K) and at TDE we typically observe dry air ( $H_2O < 3000$  ppmv, see left panels in Fig. 9). For IZO we also observe dry air if there has been no mixing since LC ( $\Delta H_2O \pm 0.1$ , green dots, upper left panel in Fig. 8). However, this is only the case for about 14 % of all the airmasses that have their LC at these low temperatures. This extratropical subsiding dry air has already been reported in other subtropical free troposphere stations in the Pacific such as Chajnantor Plateau (in Chile, Samuels-



Crow et al., 2014) and Mauna Loa station (in Hawaii, eg., Noone et al., 2011; Bailey et al., 2015). Generally at IZO the humidity is not conserved since LC if  $T_{LC}$  is low. In most cases these airmasses are mixed with humid air during their transport. This mixing can then be observed in the measured  $H_2O$ - $\delta D$  pairs. If there is a lot of mixing ( $H_2O > 8000$  ppmv) the vapour is clearly enriched in HDO, which is consistent with moistening by mixing with humid air (dark grey dots in the bottom left panel of Fig. 8). At the Pacific subtropical FT Mauna Loa station, Bailey et al. (2015) also showed that higher-latitude airmasses are more humid than expected, and attributed this to local mixing processes.

For the warmest LC temperature group ( $T_{LC} > 270$  K, right panels in Fig. 8) we observe occasionally  $H_2O$ - $\delta D$  pairs below the exemplary Rayleigh distribution, which can be explained by evaporation from a rather warm Ocean or by re-evaporation of falling rain droplets. Under these conditions the subtropical North Atlantic free troposphere is particularly humid. These tropical airmasses moving northeast towards the Canaries, moistening the atmosphere, are also observed in the subtropical Pacific (in Mauna Loa station, Bailey et al., 2015). In some occasions, mixing with air from higher atmospheric levels can also dry these airmasses. The distribution of  $H_2O$ - $\delta D$  pairs describing this mixing lie above the exemplary Rayleigh line (dark grey dots in bottom right panels of Figs. 8 and 9).

For airmasses linked to intermediate  $T_{LC}$  (above 250 and below 270 K; central column in Figs. 8 and 9) we observe a mix of the different processes discussed above.

It is important to keep in mind that the meteorological parameters upwind of the stations as deduced by HYSPLIT/GDAS1 are the result of a dispersion model and analysis fields, each with an uncertainty. It is likely that our analyses are affected by these uncertainties. See more details in Appendix BC. Nevertheless, we are able to demonstrate a clear relation between the HYSPLIT/GDAS1 data and the measured  $H_2O$ - $\delta D$  pairs which a posteriori justifies our approach. Our simplified analysis suggests that the distribution of the moisture in the subtropical North Atlantic FT is controlled by the temperature at last condensation and subsequent mixing of airmasses. Thus, these results are in agreement with the idealized advection-condensation model proposed by Galewsky and Hurlay (2010).

## 4 Summary and conclusions

We report continuous measurements of water vapour isotopologues made at two mountain observatories (IZO at 2370 m and TDE at 3550 m a.s.l.) on the Island of Tenerife. We assume that the measurements made in the second half of the night are only very weakly affected by the local circulation on the island, and are well representative for the FT. This assumption is consistent to previous studies of trace gases made on the island's mountain and it is also consistent to the wide distribution of the H<sub>2</sub>O- $\delta$ D pairs corresponding to the nighttime observations. Thus, our measurements generate a unique continuous water vapour isotopologue data record for the lower/middle FT and can be used for studying free tropospheric water pathways. ~~For such study we~~ In this paper we perform such a kind of study and therefore combine the isotopologue data with back-trajectory calculations and dust measurements.

The distribution of water vapour isotopologues collected during dust-free North Atlantic conditions show a wide variability. This variability has been analysed in the context of the last condensation point. The results show that the lowest  $\delta$ D values registered at IZO are found in relation to airmasses that have experienced condensation at lower temperatures at higher latitudes and altitudes over the North Atlantic Ocean ( $T_{LC} < 250$  K,  $> 40^\circ$  N,  $< 400$  hPa). The condensation at low temperatures is responsible for the dryness of the subtropical North Atlantic FT. These airmasses seem to frequently experience mixing with more humid airmasses during the transport to the subtropical region. Moistening during subsidence was detected by analysing GDAS1/HYSPLIT data and identified in the measured H<sub>2</sub>O- $\delta$ D distribution. Humid airmasses are also detected when the last condensation takes place close to the surface at lower latitudes not far away from the Canaries ( $> 270$  K,  $> 600$  hPa), whereby the observed H<sub>2</sub>O- $\delta$ D distribution indicates ~~to~~ rain re-evaporation or evaporation over a warm Ocean as moisture source (increased depletion with respect to Rayleigh).

For dust episodes, rather humid and enriched vapour is detected at the stations, indicating a strong injection of boundary layer air into the FT. These dust laden airmasses, product

of a strong convection over the Sahara desert, reach the Canaries without having experienced significant condensation, and are found as an influential contribution for moisture in this region. We show that the measurements of water vapour isotopologues at regions located to the West of the African continent provide new insights into the influence of the African continent on the moisture budget of the FT of the subtropical Northern Atlantic.

5 In summary, our results indicate that, four different moisture transport pathways have to be considered in order to understand the subtropical North Atlantic moisture budget. While the dominant dryness of the region is determined by the mean subsidence of dry air from high altitudes of the extra-tropics (pathway 1), there are three main processes that moisten the FT over the Atlantic: horizontal mixing over the Atlantic with air from the Sa-  
10 haran Air Layer (pathway 2), transport of air from low altitudes ( $P > 600$  hPa) and latitudes (whereby humidity occasionally originates from rain-evaporation, pathway 3), and vertical mixing close to the Canaries (pathway 4).

Figure 10 gives an overview on the  $\text{H}_2\text{O}-\delta\text{D}$  distributions as observed when one of the four different pathways is clearly prevailing. It depicts the areas with highest density of the observed  $\text{H}_2\text{O}-\delta\text{D}$  pairs. Pathway 2 is dominating when there is high aerosol load (dust  $> 25 \mu\text{g m}^{-3}$  or AOD  $> 0.1$ , red contour lines). The other pathways are dominating for low aerosol load (dust  $< 2 \mu\text{g m}^{-3}$  or AOD  $< 0.02$ ) and when  $T_{\text{LC}}$  and  $\Delta\text{H}_2\text{O}$  are situated within specific ranges. Pathway 1 is prevailing for  $T_{\text{LC}} < 250$  K and  $\Delta\text{H}_2\text{O}$  within  $\pm 0.1$  (grey contour lines). Pathway 3 is prevailing for  $T_{\text{LC}} > 270$  K and  $\Delta\text{H}_2\text{O}$  within  $\pm 0.1$  (green  
20 contour lines). Finally pathway 4 is dominating for  $T_{\text{LC}} < 250$  K and  $\Delta\text{H}_2\text{O} > 1.0$  (blue contour lines). This pathway is mainly limited to altitudes below 3000 m a.s.l., and it is more frequently observed at IZO than at TDE. In the range of high humidity, pathways 2 and 4 are difficult to distinguish, because both pathways are mixing between dry and humid air-masses. The use of aerosol measurements allows distinguishing these two situations and  
25 also give new insights into the properties of the air masses over the Sahara desert and their subsequent advection over the Atlantic Ocean.

The summary as shown in Fig. 10 reveals that the  $\text{H}_2\text{O}-\delta\text{D}$  pairs measured in the subtropical North Atlantic FT well reflect the dominating moisture transport pathways to this

atmospheric region. A continued long-term monitoring of water vapour isotopologue ratios would offer a unique possibility for investigating the importance of the different mechanisms responsible for the expected moistening of the subtropical North Atlantic FT in response to climate change.

## Appendix A: Calibration procedure of Picarro instruments

### A1 Mixing ratio calibration

Measurements of absolute humidity obtained from the meteorological sensors have been used for correcting Picarro's humidity measurements. The meteorological stations are located close to respective Picarro inlets. The temperature and relative humidity of these stations have been used for calculating the water vapour pressure ( $e = e_{\text{sat}} \cdot \text{RH}/100$ ). The saturation vapour pressure is calculated from the Magnus–Tetens formula ( $e_{\text{sat}} = 6.1094 \cdot \exp^{(17.625 \cdot T)/(243.04 + T)}$ , WMO, 2008).

Figure A1 shows 1 h resolution of simultaneous measurements of humidity from the meteorological station and the Picarro at IZO and TDE stations, respectively. The slope ( $S$ ), intercept ( $i$ ) and coefficient of determination ( $r^2$ ) of the linear fit at each station are shown. The linear fit obtained at each station is applied for correcting the Picarro humidity measurements.

### A2 Isotopic calibrations with the SDM system

Calibration measurements are carried out every 8–12 h by sequentially measuring the two working standards at three different water vapour mixing ratios of around 6000, 12000 and 18000 ppmv using a Picarro Standard Delivery Module (SDM). Therein, a micro-liter volume of liquid working standard is injected into a heated oven where it evaporates completely without fractionation. It is subsequently diluted into a flow of dry synthetic air. The amount of liquid working standard can be adjusted in a certain range, and together with the flow rate of synthetic air determine the humidity of the calibration gas mixture produced. This calibration

gas mixture is then measured by the Picarro spectrometer for 20 min at each humidity level. A 6 min time interval is discarded between ambient and calibration measurements, as well as between different humidity levels and working standards. This allows for appropriate isotope and humidity exchange in the measurement cell of the Picarro spectrometer. The calibration procedure thus takes slightly over 2 h.

5 The calibration frequency, as well as the calibration humidity levels have been modified slightly during the course of our measurements depending on demands during certain campaign periods. At TDE, the air flow is controlled by an electronic mass flow controller, while at IZO, the flow is controlled by a rotameter. The reduced precision of this second device is translated in a larger variability of the calibration humidity at IZO in comparison to TDE  
10 (Fig. A2).

In order to apply the calibration gas measurements to our ambient measurements, we first filter out calibration measurements where any of the syringes of the SDM was clogged. We then analyse the humidity dependence of the measured raw isotope ratios during calibration using the three recorded humidity levels. If a humidity dependence significantly  
15 larger than the precision of the calibration measurements was found, we would have to apply a correction function. This was not the case for our calibration measurements. Figure A3 shows an example measurement of humidity dependence of  $\delta D$  at IZO and TDE stations, respectively. An uncalibrated working standard was used in a bubbler to saturate synthetic air with water vapour. This air was then diluted into a variable flow of synthetic air  
20 to produce a gas mixture of variable humidity. The data are averaged for 1 min, and the error bars denote the 1-sigma-standard deviation of the  $\delta D$  measurements. For low humidity measurements, where the instrument is most susceptible to a humidity dependence of  $\delta D$ , the dependence remains within the scatter of the data (1-sigma standard deviation). Please also be aware that we use a Picarro L-2120i model. The Picarro models L-21xxi have significantly less dependency on humidity concentrations than the Picarro models L-11xxi (e.g.,  
25 Aemisegger et al., 2012).

The stability of the humidity dependence for SDM calibrations along the whole study period is shown in the left column of Fig. A2. We analyse the differences obtained from

the regular calibrations made below and above 15000 ppmv. No significant differences are observed along the humidity range covered with the SDM, being the  $3\sigma$  below 0.8‰ at IZO (1.8‰ at TDE) (instrumental precision  $<0.5\text{‰}$ ).

Subsequently we determine a linear regression function of the two working standards S1 and S2 measured during calibration (Fig. A4). This function is of the form  $\delta D_{VSMOW} = a + b \times \delta D_{measured}$ , and it takes the uncertainty of the isotopic composition of the working standards as well as the precision of the calibration measurements into account. We determine a calibration function for every calibration measurement described above (1 to 2 per day). We apply this function to the ambient measurements in order to transfer these measurements onto the VSMOW2/SLAP2 scale. The uncertainty in this linearity is about  $\pm 2\text{‰}$  (determined with standards between  $+15\text{‰}$  and  $-428\text{‰}$ , (see Fig. 2 of Aemisegger et al., 2012). Since our working standards cover 100‰, the uncertainty in the slope (a) of the aforementioned calibration function is  $2\text{‰}/100\text{‰}$ .

Each day, the data are calibrated with the resulting combination of the calibration at 3 different humidity points (no humidity dependence was found) and a linear fit between the responses of the 2 standards. The right column of this Figure shows the time series of the SDM calibrations carried out at IZO and TDE stations (gaps are due to instrumentation's repairs). No temporal drifts are observed in the different time series indicating that both Picarro instruments are very stable and consistent over time.

For the total uncertainty estimation we consider the instrumental precision as well as uncertainty components: a) uncertainty of the standards (0.7‰ for both dry and humid air), b) humidity dependence (from 0.3‰ for 10000 ppmv, up to 8.0‰ at 200 ppmv), c) extrapolation of VSMOW2-SLAP2 scale outside the range of calibration (for humid air:  $<2.0\text{‰}$ ; up to 5‰ for strong depleted air), d) calibration (1‰ for the whole humidity range). The absolute uncertainties in  $\delta D$  are then  $<14.7\text{‰}$  for strong depleted air at 500 ppmv and  $<4\text{‰}$  at 4500 ppmv.

## Appendix B: Discussion of the representativeness of the used $T_{LC}$ and $\Delta$ Diurnal signals as seen in $H_2O$ parameters- $\delta D$ distribution density plots

Figure 4 shows all the observed 10 min averaged  $H_2O$ - $\delta D$  data pairs, which is a large amount of data (about 75,000 and 40,000 data points at IZO and TDE, respectively). From Fig. 4 it becomes clear that the IZO daytime observations cover only a limited area in the  $H_2O$ - $\delta D$  distribution space. There is no single IZO daytime observation with  $\delta D$  below -345 ‰ (and almost no daytime observations with  $\delta D$  below -220 ‰ for  $H_2O$  above 10000 ppmv). For TDE the situation is not clear from Fig. 4.

In order to give a statistical insight into the differences between the  $H_2O$ - $\delta D$  distributions during day and night, we additionally calculate the density of the  $H_2O$ - $\delta D$  distributions for the daytime and nighttime data pairs. The respective distribution plots are shown in Fig. A5 and clearly confirm that for IZO the daytime and nighttime  $H_2O$ - $\delta D$  distributions are significantly different. For TDE the day-night differences are less pronounced, but they become visible in the density plot (right panel of Fig. A5). For instance, at TDE the probability for  $\delta D$  being below -300 ‰ is significantly higher during night than during day (compare the areas marked by the thick black and orange lines).

## Appendix C: Discussion of the representativeness of the used $T_{LC}$ and $\Delta H_2O$ parameters

There are two different reasons for a not perfect representativeness: First, there is an uncertainty in the trajectories, which is the larger the longer the trajectory. Second, the model does not well resolve the fine structured topography of Tenerife, which might affect the flow of air masses and already the height attribution of the trajectories might be incorrect.

In our case, the trajectories are released at the height above sea level of the stations. We tested the uncertainty we could have in the representativeness of our backward trajectories by looking also in the backward trajectories released 500 m above and 500 m below. The data set describes those days in which last condensation has been observed along the

25 pathways at the three altitudes (only during the nighttime period, 0 and 6 UTC), and we calculate for all trajectories the parameters  $T_{LC}$  and  $\Delta H_2O = \log(H_2O_{t=0}) - \log(H_2O_{LC})$ .

The test is made for the TDE station and we correlate the parameters as obtained at 3500 m (altitude of the site), with the parameters as obtained at 4000 m (blue stars in Fig. A6 and A7) and 3000 m (red stars). The green line represents the diagonal (3500 m). The uncertainty test was carried out with 3 years of back-trajectories (2012-2014). The Pearson's coefficients obtained for  $T_{LC}$  and  $\Delta H_2O$  (for each of the three  $T_{LC}$  categories) are shown in the figures.

5 The scatter in the plots documents the uncertainty in the representativeness of the  $T_{LC}$  and  $\Delta H_2O$  as used in our study. However, we think that this scatter is a conservative uncertainty estimation. The reason is that we work with nighttime data (midnight – one hour after sunrise). During that time the atmosphere above the island is rather stable and local effects (not resolved by the model) should by far be less important than during daytime. That is we think that the air mass recorded during nighttime the stations IZO and TDE corresponds to air traveling over the ocean around the island at very similar altitudes and the scatter for altitude differences of as large as  $\pm 500$  m likely overestimates the actual uncertainty.

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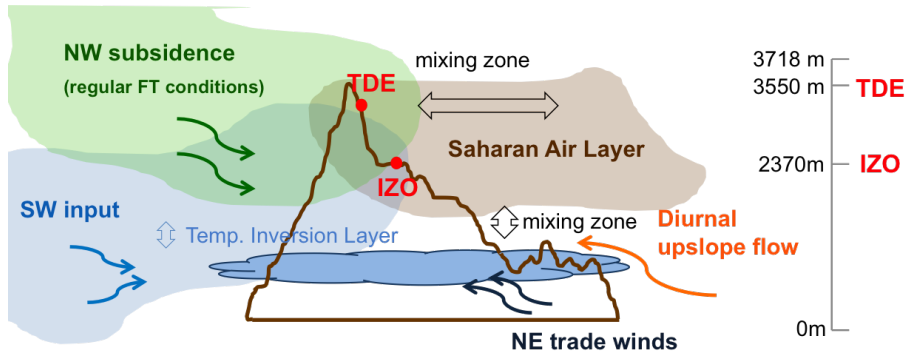
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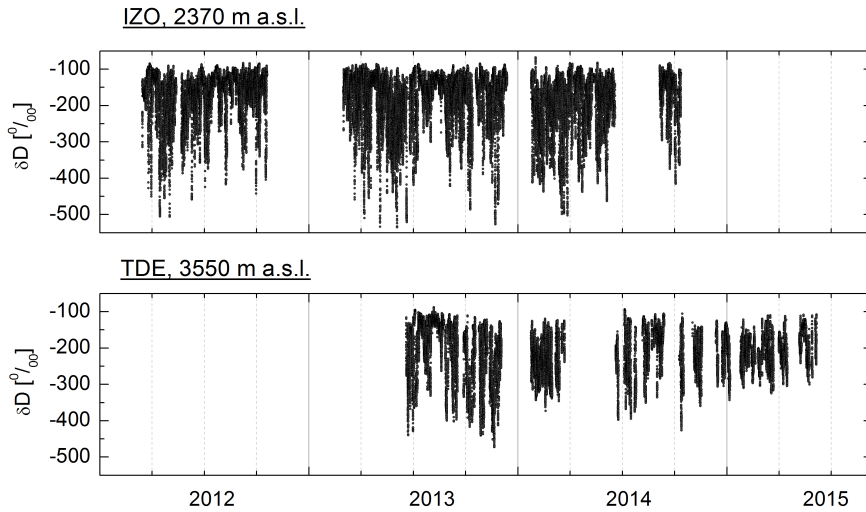
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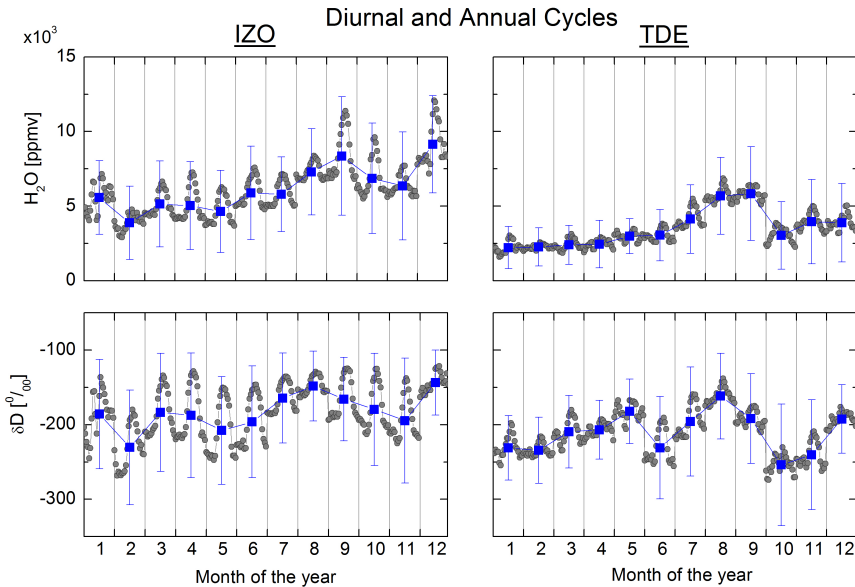
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**Figure 1.** Schematic depiction of the processes influencing the water vapour balance over Tenerife Island in the subtropical North Atlantic. A temperature inversion layer separates the Marine Boundary Layer (MBL) and the Free Troposphere (FT). In the MBL, NE trade winds blow, while in the FT, the regular NW subsidence regime is alternated in summer with Saharan dust outbreaks. At the island, the upslope winds prompt that MBL air reaches the low FT during daylight. IZO and TDE stations are represented as red dots.



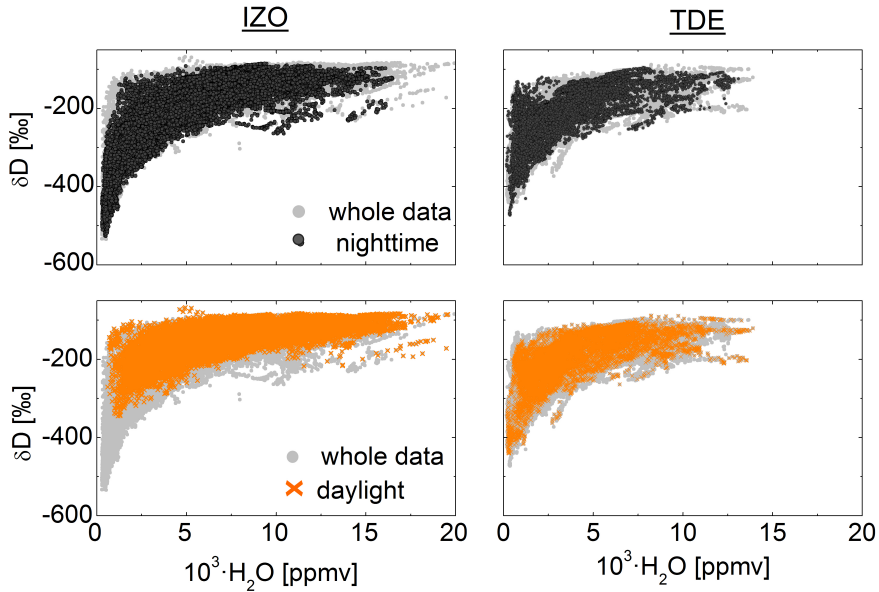
**Figure 2.** Left: time-series of 1h Time periods covered by water isotopologue in-situ observations at IZO (upper panel) and TDE (lower panel). Shown are all 10 min averages of  $\delta D$  measured at IZO-station. Black dots represent any time of the data collected from midnight to 1 after sunrise (nighttime) day. Orange crosses represent the data collected during daylight.



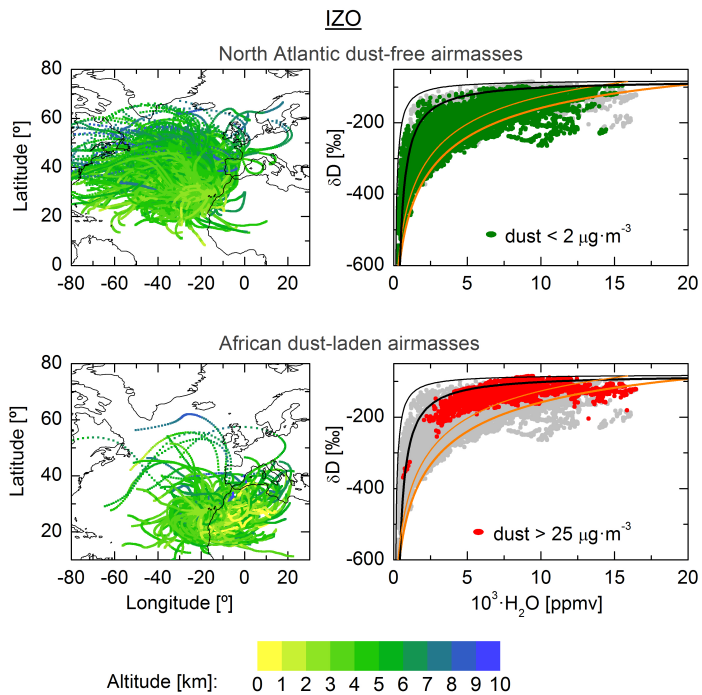
**Figure 3.** The mean diurnal cycle and annual cycles of  $\text{H}_2\text{O}$ - $\delta\text{D}$  (from 3 to 10 after sunrise left panels for IZO and right panels for TDE). Right: Grey dots show the mean diurnal cycle of and  $\delta\text{D}$  observed cycles for each month (mean value for each hour of the year. Blue dots show day) and the blue squares the annual cycle (mean and standard deviation) of the data set all observations that fall within an individual month).



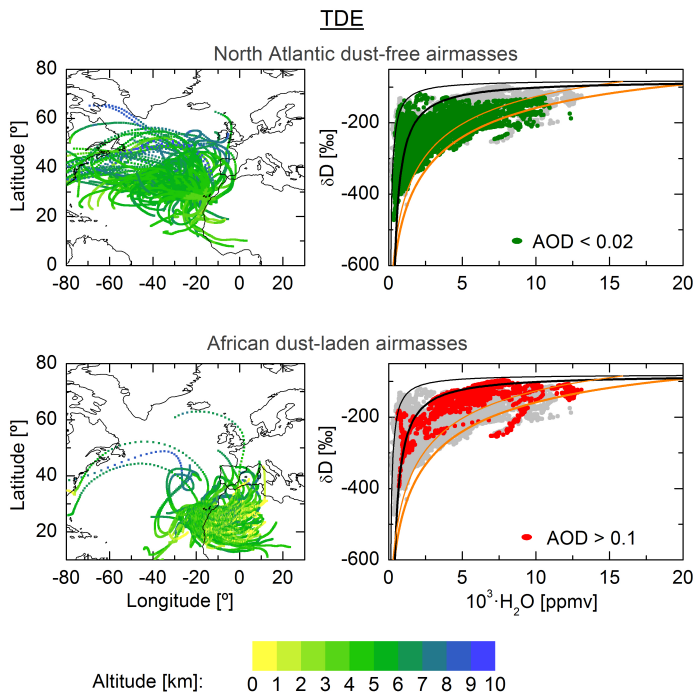
Same as Fig. ?? for data collected at TDE station:



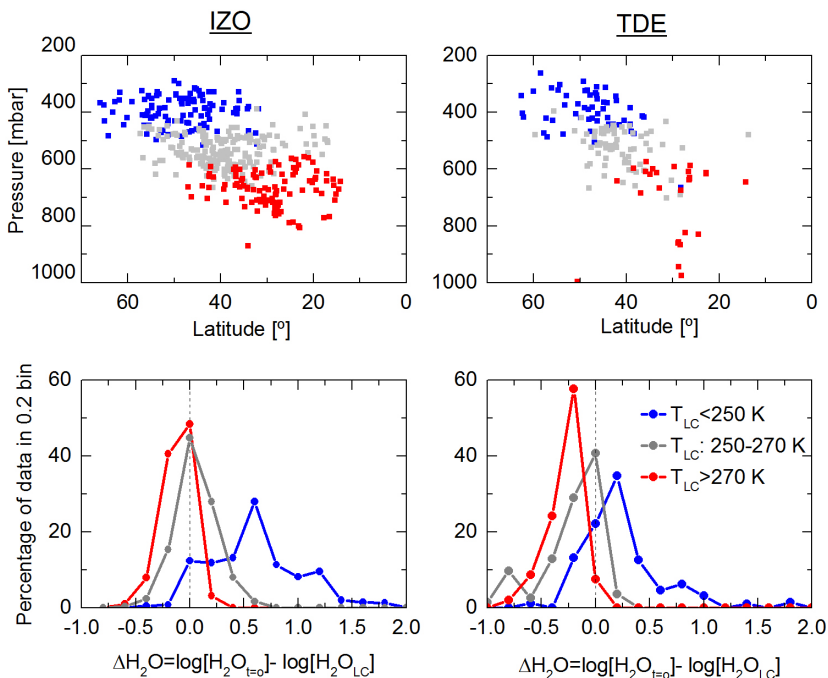
**Figure 4.** Distribution of the  $\text{H}_2\text{O}$ - $\delta\text{D}$  pairs (10 min averages) at IZO (left) and TDE (right) stations. Grey dots show all data for the individual stations. Black dots represent the data collected during nighttime (from midnight to 1 h after sunrise). Orange crosses represent the data collected during daylight (from 3 to 10 h after the sunrise). The whole data set is presented in grey dots.



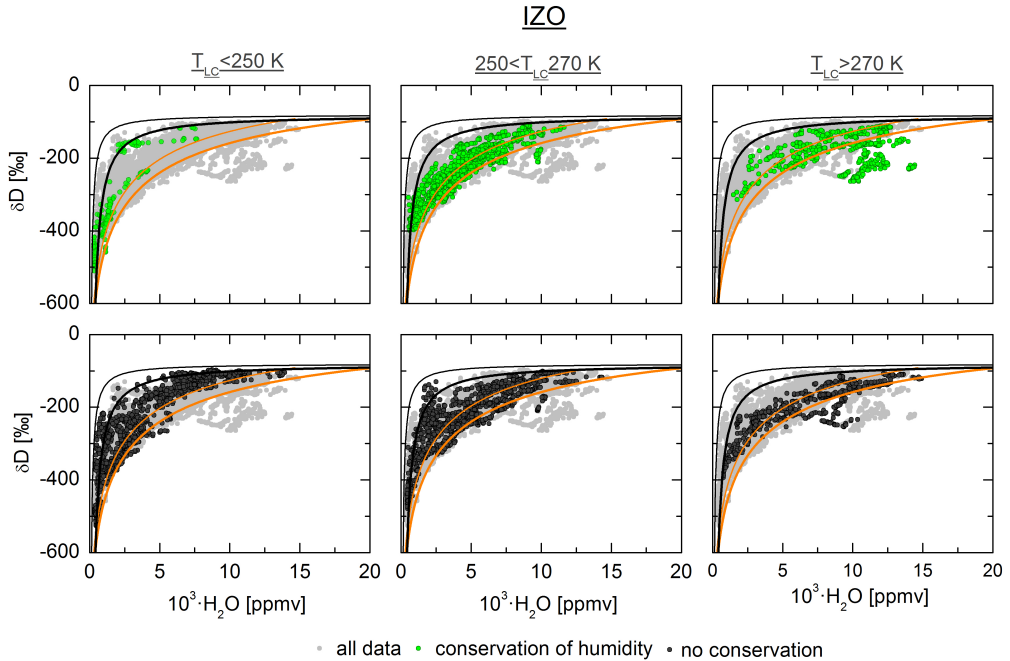
**Figure 5.** Airmasses reaching IZO station as a function of the dust load. First row shows non-dust conditions, second row, dust laden conditions. The colour-bar indicates the altitude (km) of these airmasses in each grid. The left column shows the trajectories. The right column shows the  $\text{H}_2\text{O}$ - $\delta\text{D}$  distribution (pairs are presented on 10 min average): all data (grey dots), data measured under non-dust conditions (green dots) and data for dust laden conditions (red dots). Orange lines represent the evolution of an airmass that has experienced Rayleigh distillation for  $\text{RH} = 80\%$  and  $\text{SST} = 18^\circ\text{C}$  (thin line) and  $\text{SST} = 25^\circ\text{C}$  (thick line), respectively. These temperatures cover the annual mean sea surface temperatures around the Canaries. The black thin line represents the mixing between a moist airmass (initial conditions:  $\text{H}_2\text{O} = 18000$  ppmv,  $\delta\text{D} = -84\%$ ) and a dry airmass (initial conditions:  $\text{H}_2\text{O} = 400$  ppmv,  $\delta\text{D} = -600\%$ ). The black thick line represents another mixing process (initial conditions for moist end member:  $\text{H}_2\text{O} = 16000$  ppmv,  $\delta\text{D} = -93\%$ ; initial conditions for dry end member:  $\text{H}_2\text{O} = 400$  ppmv,  $\delta\text{D} = -600\%$ ).



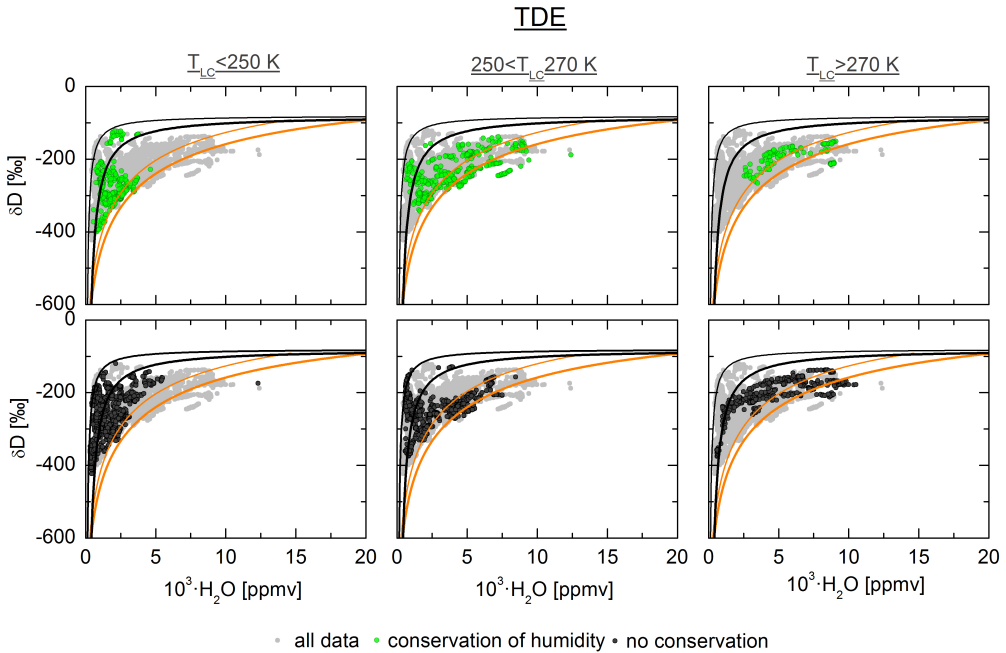
**Figure 6.** Same as Fig. 5 for the data collected at TDE station.



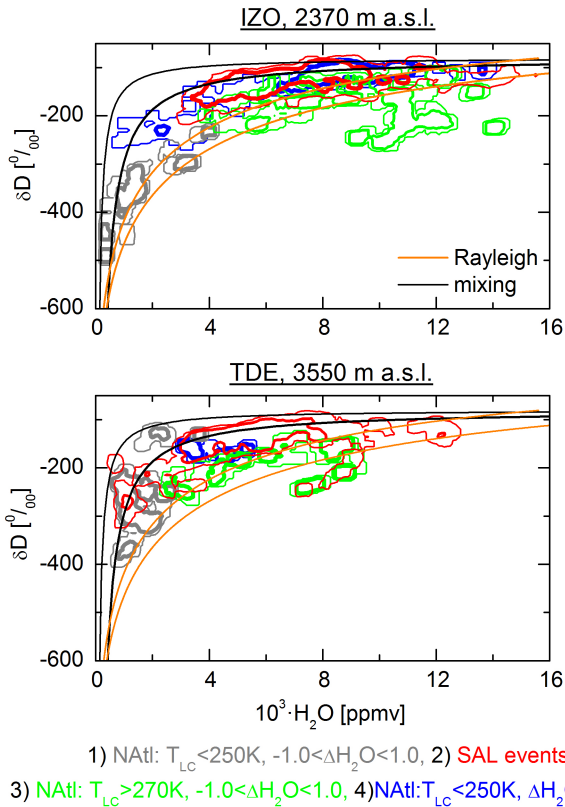
**Figure 7.** Trajectory-based analysis of the last condensation (LC) point for non SAL conditions. Upper panels: location (pressure-latitude) of LC point. Bottom panels: Histograms for  $\Delta H_2O = \log[H_2O_{t=0}] - \log[H_2O_{LC}]$ . The different colours correspond to different  $T_{LC}$  groups:  $T_{LC} < 250$  K (blue line),  $250 \text{ K} < T_{LC} < 270$  K (grey line) and  $T_{LC} > 270$  K (red line).



**Figure 8.**  $\text{H}_2\text{O}$ - $\delta\text{D}$  distribution (10 min data within  $\pm 3$  h of the arrival time of the airmass) measured at IZO station and analysed with regard to the LC point. The data set has been grouped in 3 groups corresponding to different condensation temperatures:  $T_{LC} < 250 \text{ K}$ ,  $250 \text{ K} < T_{LC} < 270 \text{ K}$  and  $T_{LC} > 270 \text{ K}$ . The  $\text{H}_2\text{O}$ - $\delta\text{D}$  pairs measured for reduced mixing since LC ( $\Delta\text{H}_2\text{O} \pm 0.1$ ) are presented in green. Pairs measured for increased mixing since LC ( $\Delta\text{H}_2\text{O}$  outside  $\pm 0.1$ ) are presented in dark grey. Rayleigh and mixing curves are plotted as in Figs. 5 and 6.

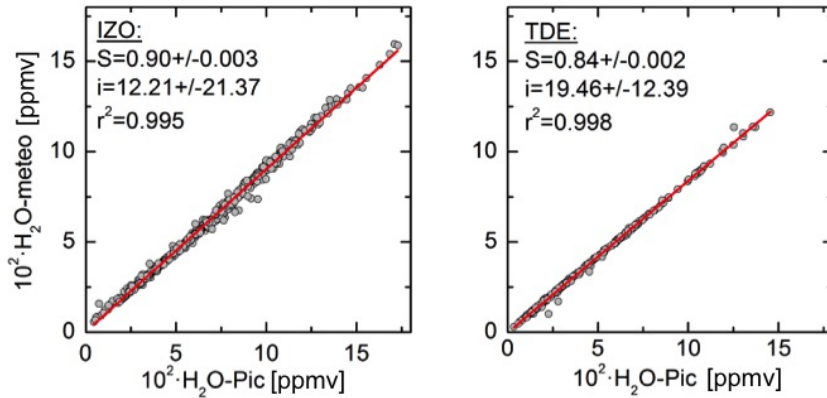


**Figure 9.** Same as Fig. 8 for the data collected at TDE station.

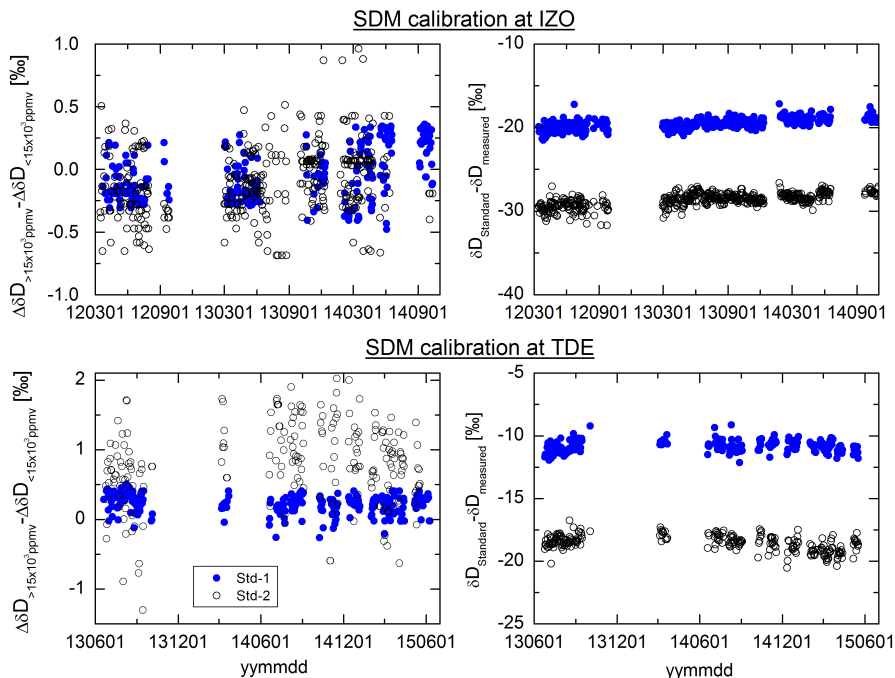


**Figure 10.**  $H_2O$ - $\delta D$  distributions as obtained for the four different moisture pathways that determine the free troposphere moisture budget in the surroundings of Tenerife (Left panel for IZO and right panel for TDE). Depicted are contour lines indicating the areas of the highest data point density. The thin dashed and thick solid lines mark the areas that include 95 and 66 % of all data, respectively. The different colour of the contour lines mark the different pathways (1–4) as given in the legend. Rayleigh and mixing curves are plotted as in Figs. 5, 6, 8 and 9.

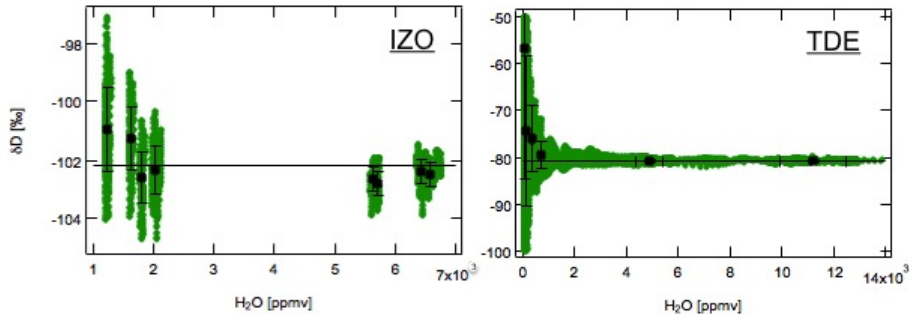




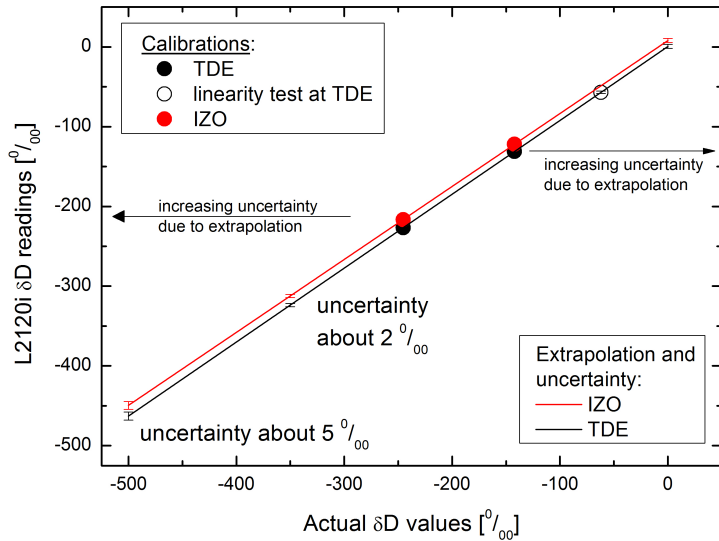
**Figure A1.** Grey dots show the 1 h humidity data pairs of the Picarro and the meteorological at IZO and TDE. Red lines indicate the linear fit of the distribution.  $S$  = slope,  $i$  = intercept,  $r^2$  = coefficient of determination.



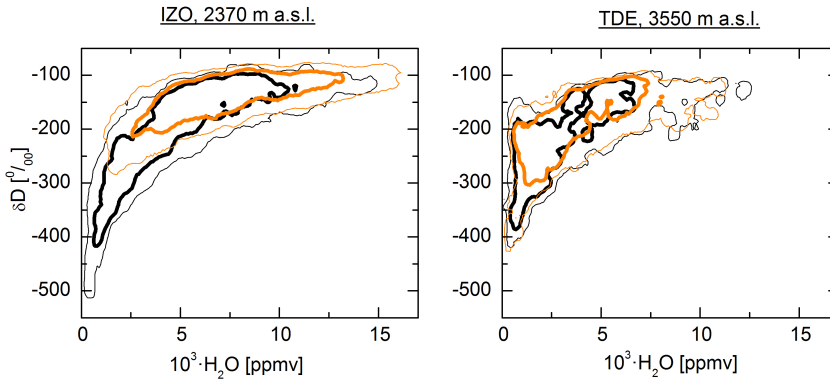
**Figure A2.** Difference between the measured  $\delta D$  and that from the two liquid standards used for calibrating the instruments at IZO (first row) and TDE stations (second row). The left column depicts the dependence of this difference to the humidity during calibration. The right column shows the evolution of the difference with the time for all humidity levels.



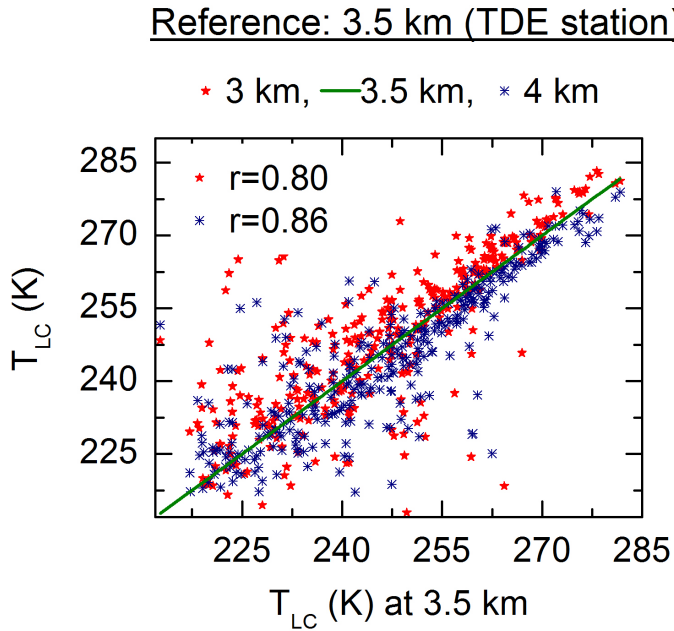
**Figure A3.** Measured humidity dependence of  $\delta D$  determined by measuring water vapor produced in a bubbler dilution system at IZO (left) and TDE (right) stations, respectively. Data shown are 1 min averages. The error bars indicate the  $1\sigma$  standard deviation of the  $\delta D$  measurements, within which the average  $\delta D$  of each humidity bin (black symbols) are identical to the average of all data.



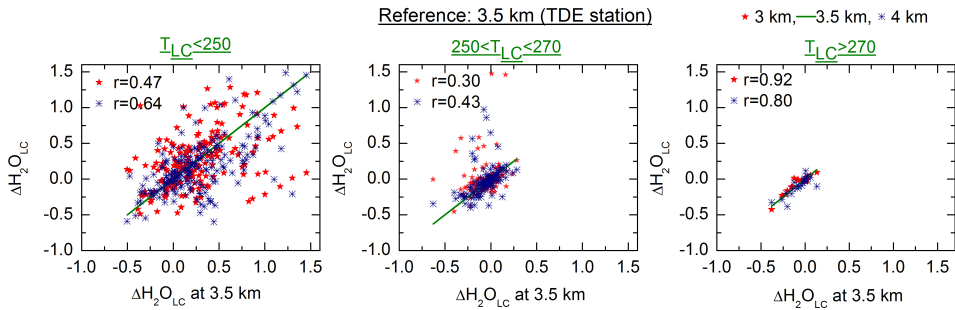
**Figure A4.** Schematic graph showing the use of two isotope working standards S1 and S2 with known  $\delta D_{VSMOW}$ . When the two standards are measured by an instrument one obtains  $\delta D_{measured}$ . A linear regression of the form  $y = a + bx$  can be used to transfer  $\delta D_{measured}$  onto the VSMOW scale. Note that uncertainties in  $x$  and  $y$  are considered.



**Figure A5.**  $H_2O$ - $\delta D$  distributions as obtained for the “nighttime observations” (10 min averages made between midnight and 1 h after sunrise, black contour lines) and the “daytime observations” (10 min averages made between 3 and 10 h after sunrise, orange contour lines). The thin and thick lines mark areas that include 95 % and 66 % of all the data. The plot shows the density distributions of the data points from Fig. 4.



**Figure A6.** A 3-year (2012-2014) analysis of the uncertainty in the vertical resolution of the model using TDE as reference station. The correlation between  $T_{LC}$  at 3500 m with 3000 and 4000 m respectively, is shown.



**Figure A7.** A 3-year (2012-2014) analysis of the uncertainty in the vertical resolution of the model using TDE as reference station. The correlation between  $\Delta H_2O = \log[H_2O'_{t=0}] - \log[H_2O_{LC}]$  at 3500 m with 3000 and 4000 m respectively, is shown.