Response to Anonymous Referee #3

We appreciate the comprehensive, practical, and instructive comments of referee #3. They have helped us improving the paper. We are responding to the comments in the following way:

General In my opinion, the superb quality of the isotope dataset (with some question marks, see see discussion on humidity below) deserves a more in-depth analysis of the atmospheric conditions explaining the isotopic variations in the water vapor. For instance, with reliable ground observations and high resolution (space and time) ERA5 it is now possible to use higher-level temperatures (e.g. 850 hPa) to characterize air masses in the analysis, see below.

We did a more in-depth analysis in different aspects such as the examination of the water vapour origin, diurnal cycles in summer, and extreme *d* values (based on another referee's comment, in the revised manuscript, we use "*d*" instead of "d-excess"). Also, a higher-level temperature (850 hPa) from ERA5 (Hersbach et al., 2020) is evaluated and added to the text (revised manuscript, Subsubsection 3.2.1, line 256). Generally, we have substantially improved the manuscript based on the specific comments of this referee and of two other anonymous referees.

Fig. 1 is too empty: use it to indicate summer/winter surface pressure distribution, sea ice edges, surface topography, and grounding line.

We add different information to the figure such as surface topography, mean sea level pressure, Antarctic grounding line, and sea ice edge in austral summer and winter:

<u>Revised manuscript, Subsection 2.1, Figure 1:</u>

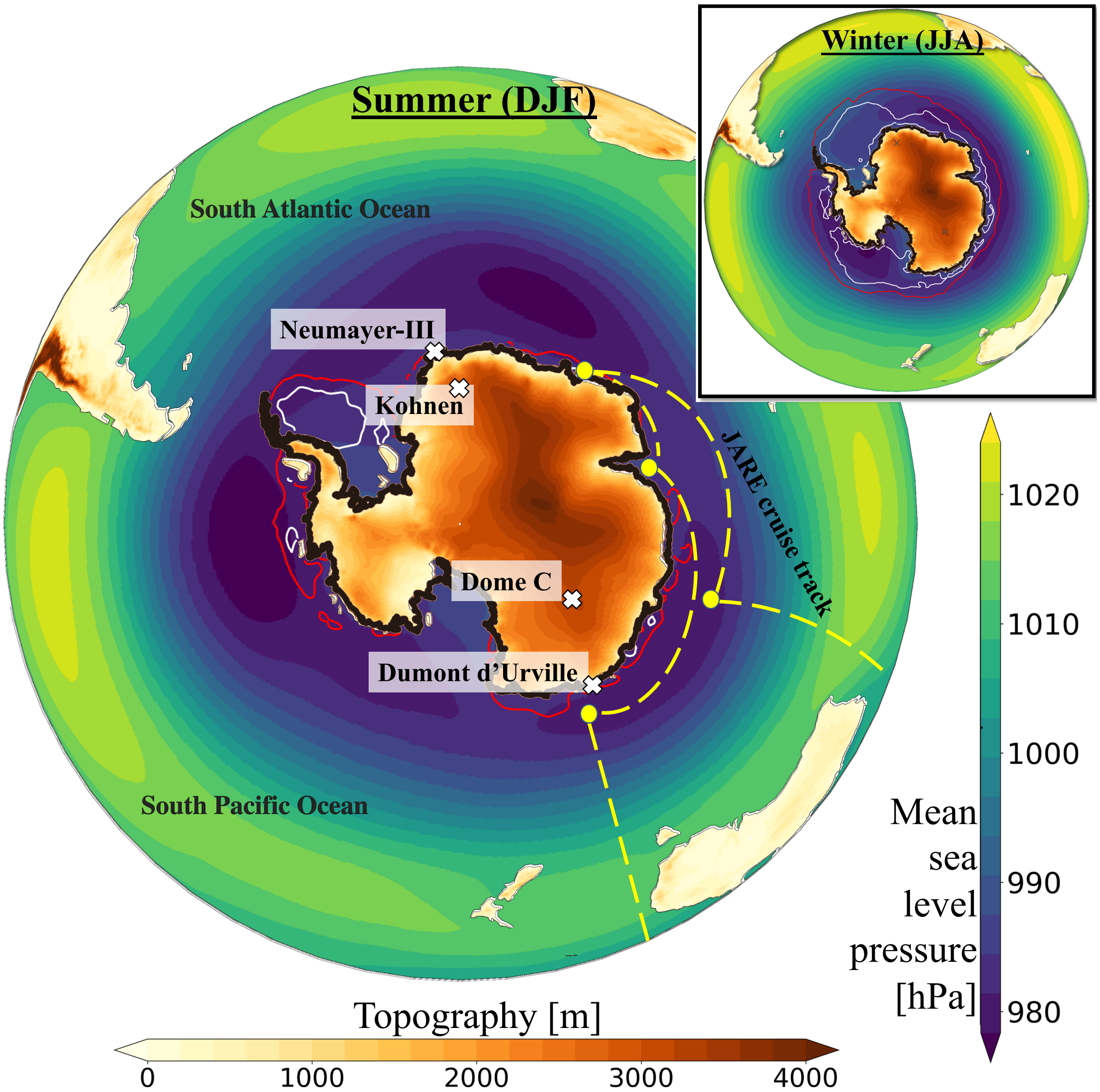

Figure 1. (Figure 1 in the revised manuscript). Map of Antarctica with topography [meter], mean sea level pressure [hPa], Antarctic grounding line (black line), and sea ice fraction [red line: fraction > 0.45, white line: fraction > 0.90] in austral summer (big map) and austral winter (small map), considering years of 2017 and 2018. The topography, mean sea level pressure and sea ice fraction are based on meteorological data from the European Centre for Medium-range Weather Forecasts (ECMWF) ERA5 reanalysis (Hersbach et al., 2020) and the Antarctic grounding line is based on Depoorter et al. (2013). The location of our study (Neumayer III) and other studies which provided continuous water vapour isotopic measurements in Antarctica (Ritter et al., 2016; Casado et al., 2016; Bréant et al., 2019) are shown in white colour and JARE cruise track related to Kurita et al. (2016) is shown in yellow colour.

Fig. 2: It would be interesting to plot RH separately in this figure as well. How do the moisture measurements of the Picarro instrument compare to those of the meteorological field? Ah, I now see this is reported later (l. 195). Please mention this earlier.

The relative humidity and its climatology are added to the figure (Figure 2). The comparison between the humidity measured by Picarro and the one measured by meteorologists at the station is brought up earlier (revised manuscript, Subsection 3.1, line 193).

<u>Revised manuscript, Subsection 3.1, Figure 2:</u>

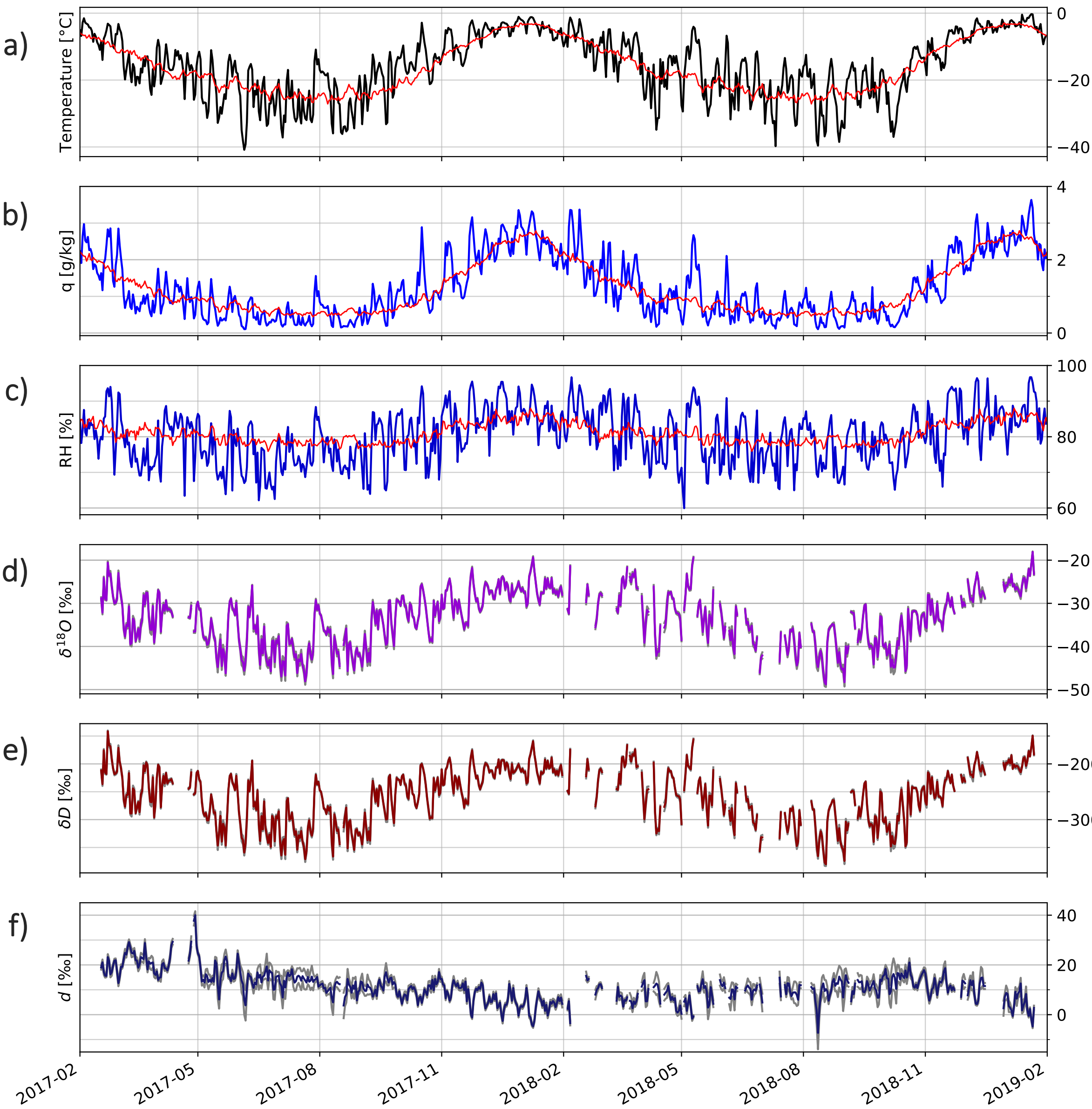

Figure 2. (Figure 2 in the revised manuscript). Daily averaged observations at Neumayer Station from February 2017 to January 2019. Downward: a) 2-m temperature [°C]; b) specific humidity [g kg^{-1}]; c) relative humidity [%]; d) δ^{18}O [‰]; e) δD [‰]; f) d [‰]. To have a better comparison, the climatology (multi-year daily average temperature, specific humidity, and relative humidity over the 38-year period from 1981 to 2018) is shown with a red line in meteorological observations. The determined uncertainties of the Picarro instrumental data (see text) are plotted as gray lines.

Table 1 can be moved to an appendix.

Corrected as requested (revised manuscript, Appendix B, Table B1).

Fig. 4: In Fig. 3 you show a large difference between q measured at the Picarro inlet and the meteorological field (from T and RH measured at 2 m), and suggest this may be caused by strong near-surface inversions in moisture. Yet, here you continue to directly compare isotope values with temperatures from that same field. Please elaborate somewhat on why you think that does not pose a problem during variable inversion conditions.
l. 195-200: The correlation is high, but a) there is still considerable scatter and b) the slope is off by 50%. These are important differences. These differences can be discussed in somewhat more detail, e.g. are these high values at all possible given the outside temperatures measured at~20 m above the surface, or would this imply over saturation? You could also select non-inversion conditions (cloudy, strong winds) to check your assumptions on the inversions.

We have analysed the different q values now in more detail and expanded the corresponding text in the revised manuscript as follows:

Revised manuscript, Subsection 3.1, line 193:

We compare the specific humidity measured by the Picarro instrument with the specific humidity values measured routinely as part of the meteorological observations at Neumayer Station (Schmithüsen et al., 2019). The relationship between these two series of humidity measurements is $q_{(Picarro)} = 1.5q_{(meteorology)}+0.08$ (N = 12198, hourly values between 17 February 2017 and 22 January 2019, r = 0.97, standard error of the estimate = 0.0022 $g.kg^{-1}$; revised manuscript, Fig. 3). The rather high slope between both humidity measurements and also a number of unusual high and low Picarro humidity values motivated us to analyse the difference between both humidity data sets in more detail.
The inlet of the Picarro instrument is situated approx. 17.5 m above the surface level of the station. As the station is placed on a small artificial hill, this surface level is approx. 7.6 m higher than the surface level of the meteorological mast placed 50 meters besides the station building. Thus, the total height difference between the Picarro inlet and the height of the meteorological humidity measurements is approx. 22 m. In principle, higher humidity values at the Picarro inlet could be explained by a humidity inversion layer above the surface, which could remove near-surface moisture at the meteorological mast position by hoar frost formation. However, temperature differences between a 2-meter temperature sensor at the meteorological mast and temperatures measured on the roof of the station do not exceed 2 °C during our measurement period. No strong temperature inversions are found for the days with extreme Picarro humidity measurements.
To test if contamination by exhaust gases could be another reason for the data mismatch, the wind direction was analysed for those hourly Picarro humidity values which are much higher than the corresponding humidity values measured by the meteorological station. Most of the outliers coincide with a wind direction from the south (and a few from east), which excludes the possibility that a contamination by exhaust gases is the reason for the unusually high Picarro humidity values.
Picarro humidity measurements have been compared with independent humidity observations for a few studies, so far. Aemisegger et al. (2012) calibrated and controlled the humidity of their Picarro instrument by a dew point generator and showed a linear relationship between

Picarro measurements and the humidity measured by the calibration system with a slope of 1.27 and an uncertainty of 100-400 ppm (0.06-0.24 $g.kg^{-1}$). Tremoy et al. (2011) reported that the slope between humidity measured by a meteorological sensor and humidity measured by a Picarro instrument can change from 0.81 to 1.47 depending on site conditions. Bonne et al. (2014) also showed a non-linear response of their Picarro instrument compared with the humidity measured by a meteorological sensor. Based on their data, the ratio between Picarro humidity and sensor humidity values changed from 1 to 1.87, depending on the amount of humidity. Compared to the results of these studies, we rate the calculated ratio of our Picarro humidity measurements versus the humidity data from the meteorological mast ($q_{(Picarro)}/q_{(meteorology)}$ = 1.5) as unobstructive.
As in previous studies (e.g., Bonne et al., 2014) we will use the Picarro humidity data for the calculation of the humidity response functions required for the calibration of the isotope measurements. All analyses regarding the relationships between water vapour isotopes and local climate variables, on the other hand, are based on the humidity and corresponding temperature data measured at the meteorological mast.

Section 3.2.1: Melting and the resulting cutoff of surface temperature at 0 °C is probably less relevant to explain the limited day-to-day variability in 2 m temperature during summer, because melting at Neumayer is mostly a daytime feature, i.e. seldomly lasts a full day, and therefore has less impact on daily mean temperature. A more probable explanation is that because of the absorption of solar radiation the surface radiation deficit becomes small or absent in summer, preventing the formation of strong near-surface temperature inversions in the daily mean. It is the regular formation (clear skies, weak winds) and destruction (cloudy skies, strong winds) of these inversions that explain the large interdiurnal temperature variability in the non-summer seasons.

We thank the referee for this alternative explanation. We fully agree with these arguments and changed the text accordingly:

Revised manuscript, Subsubsection 3.2.1, line 265:

Daily temperature and $\delta^{18}O$ values in summer are less fluctuating than in the other three seasons (revised manuscript, Fig. 4). This might be explained by a weaker temperature inversion, lower sea ice variability, and stronger sublimation and snowmelt in summer.

Hudson and Brandt (2005) showed that the temperature inversion strength variations in winter are one reason for the large day-to-day variability of 2-meter temperature in Antarctica. In winter, clouds can be much warmer than the surface, which leads to a strong temperature inversion. However, changes in wind speed and direction might change the cloud cover and thereby weaken or destroy the inversion layer, in short time. Due to these processes, stronger temperature inversions can lead to higher temperature variability in winter.

As sea ice can strongly limit the heat flux between a relatively warm ocean and the atmosphere, sea ice coverage variations close to Antarctica's coastal stations can primarily affect the near-surface temperature at the stations (Turner et al., 2020). Decreasing sea ice variability close to the Neumayer Station in summer compared to other seasons, which is true for most other coastal stations in Antarctica, may also lower the temperature variability.

Another reason for the reduced temperature variations in summer can be a stronger heat loss, which prevents temperatures above zero. At Neumayer Station, the largest sources of heat loss in summer are sublimation and snow melting (Jakobs et al., 2019). The sublimation is primarily temperature-controlled and is only significant at Neumayer station in summer. About 19 % of the annual snowfall at this location is removed by sublimation (Van den Broeke et al., 2010). The second source of heat loss at the station is snow melting. In summertime, when the air temperature can rise above 0°C, the surface snow will reach its melting point and start to melt. For the melting process, the incoming radiative energy is partly used for latent heat uptake, keeping the near-surface temperature close to the melting point.

These three phenomena might explain the detected cut-off at 0°C of the 2-m temperature (Fig. 4). They could also partly explain the lower correlation coefficient between the 2-m temperature and δ^{18}O in summer, as upper air temperatures most likely control the latter.

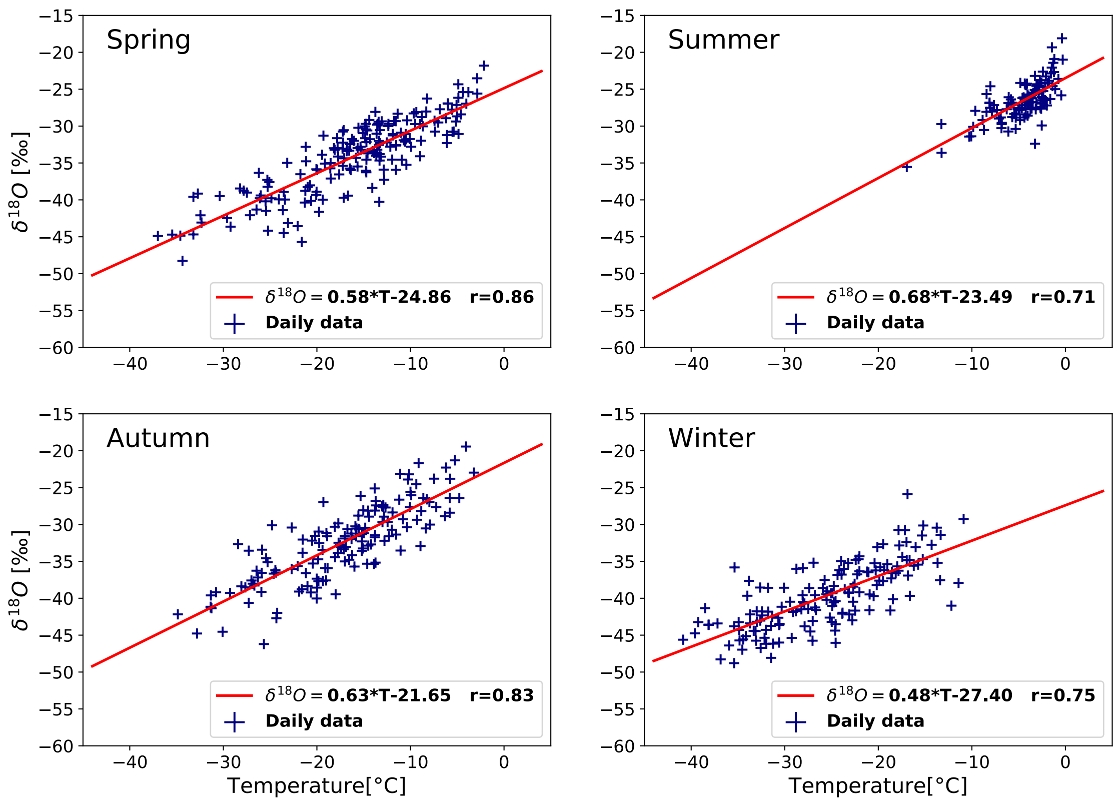

Figure 3. (Figure 4 in the revised manuscript). δ^{18}O [‰] vs. temperature [°C]. Four plots show daily average temperature–δ^{18}O values for different seasons of the year. For each season, a best fitted line, using the least-squares approach, for δ^{18}O vs. temperature is plotted as a red line and corresponding correlation coefficients are calculated.

Fig. 5 and Section 3.2.2: In an environment with unlimited evaporation/sublimation potential such as Neumayer, with near-continuous surface cooling outside of summer, the near-surface air will always be close to saturation (this is what you show in Fig.9). Repeating the correlation of water isotopes with humidity, as you did in Fig. 4 with temperature, is therefore not so useful.

We agree on this point. Based on another referee's comment we have removed Fig. 5 and Fig. 9 from the revised manuscript, merged the related text, and explain now the link between specific humidity and atmospheric temperature by the dominance of the Clausius–Clapeyron relation:

<u>Revised manuscript, Subsubsection 3.2.1, line 286:</u>

At Neumayer Station, the specific humidity is highly correlated with temperature (Jakobs et al., 2019), as expected from the general Clausius-Clapeyron relation between both quantities. As a consequence, the $\delta^{18}O$ values of water vapour at Neumayer Station are strongly correlated not only to temperature, but also to specific humidity ($r = 0.85$).

Section 3.2.3: have you tried correlations with relative humidity?

We analysed the correlation coefficient for relative humidity, but have not found a high correlation (around -0.35 for relative humidity-*d* and 0.75 for relative humidity-$\delta^{18}O$).
The correlation coefficient for relative humidity and $\delta^{18}O$ in different seasons are close (spring: $r = 0.73$, summer: $r = 0.57$, autumn: $r = 0.69$, and winter: $r = 0.65$). There are anti-correlations between the relative humidity and *d* for spring ($r = -0.43$), summer ($r = -0.59$), and autumn ($r = -0.19$). For winter, there is no correlation between the relative humidity and *d* ($r = 0.04$). These findings are added to the revised manuscript:

<u>Revised manuscript, Subsubsection 3.2.2, line 292:</u>

temperature and $\delta^{18}O$. The correlation coefficient for relative humidity and $\delta^{18}O$ in different seasons are similar (spring: $r = 0.73$, summer: $r = 0.57$, autumn: $r = 0.69$, and winter: $r = 0.65$).

<u>Revised manuscript, Subsubsection 3.2.2, line 300:</u>

This pattern can be detected also for temperature-*d*, specific humidity-*d*, and relative humidity-*d* relations. There is a negative correlation coefficient between temperature and *d* for spring, $r = -0.41$, summer, $r = -0.60$, and autumn, $r = -0.14$, but in winter a weak positive correlation, $r = 0.22$, is noticed. There are anti-correlations between the specific humidity (relative humidity) values and *d* for spring, $r = -0.50$ ($r = -0.43$), summer, $r = -0.71$ ($r = -0.59$), and autumn, $r = -0.24$ ($r = -0.19$), which are slightly stronger than the ones between temperature and *d*. For winter, there is a weak positive correlation between the specific humidity (relative humidity) and *d*, r = 0.13, (r = 0.04).

Fig. 6: please include the sea ice edge. The difference in latitudinal fetch and absolute uptake appears to be a combination of sea ice extent (sea ice preventing evaporation) and the semi-annual oscillation, the twice-annual expansion/contraction of the circumpolar pressure trough which determines the latitudinal fetch. The absolute temperature also plays an important role, with evaporation/sublimation being reduced at low temperatures (winter).

We thank the reviewer for this very helpful explanation. We have added the sea ice edge to our analyses (revised manuscript, Subsection 3.3, Figure 5) and this clarifies why in some areas close to the station we do not detect any evaporation:

<u>Revised manuscript, Subsection 3.3, line 310:</u>

Moisture uptake coming to Neumayer Station depends on different factors such as sea ice extent, the Southern Hemisphere semi-annual oscillation (SAO), and absolute temperature. As Fig. 5 shows, the sea ice prevents evaporation from the ocean. In the areas with ice coverage more than 90 %, the moisture uptake is minor. The SAO is the main phenomenon that affects surface pressure changes at the middle and high latitudes of the Southern Hemisphere (Schwerdtfeger, 1967). It means the twice-yearly contraction and compression of the pressure belt surrounding Antarctica as a result of the different heat capacities of the Antarctic continent and the ocean. The SAO leads to a clear half-yearly pressure wave in surface pressure at high latitudes and modifies the atmospheric circulation and temperature cycles (Van Den Broeke, 1998).

<u>Revised manuscript, Subsection 3.3, Figure 5:</u>

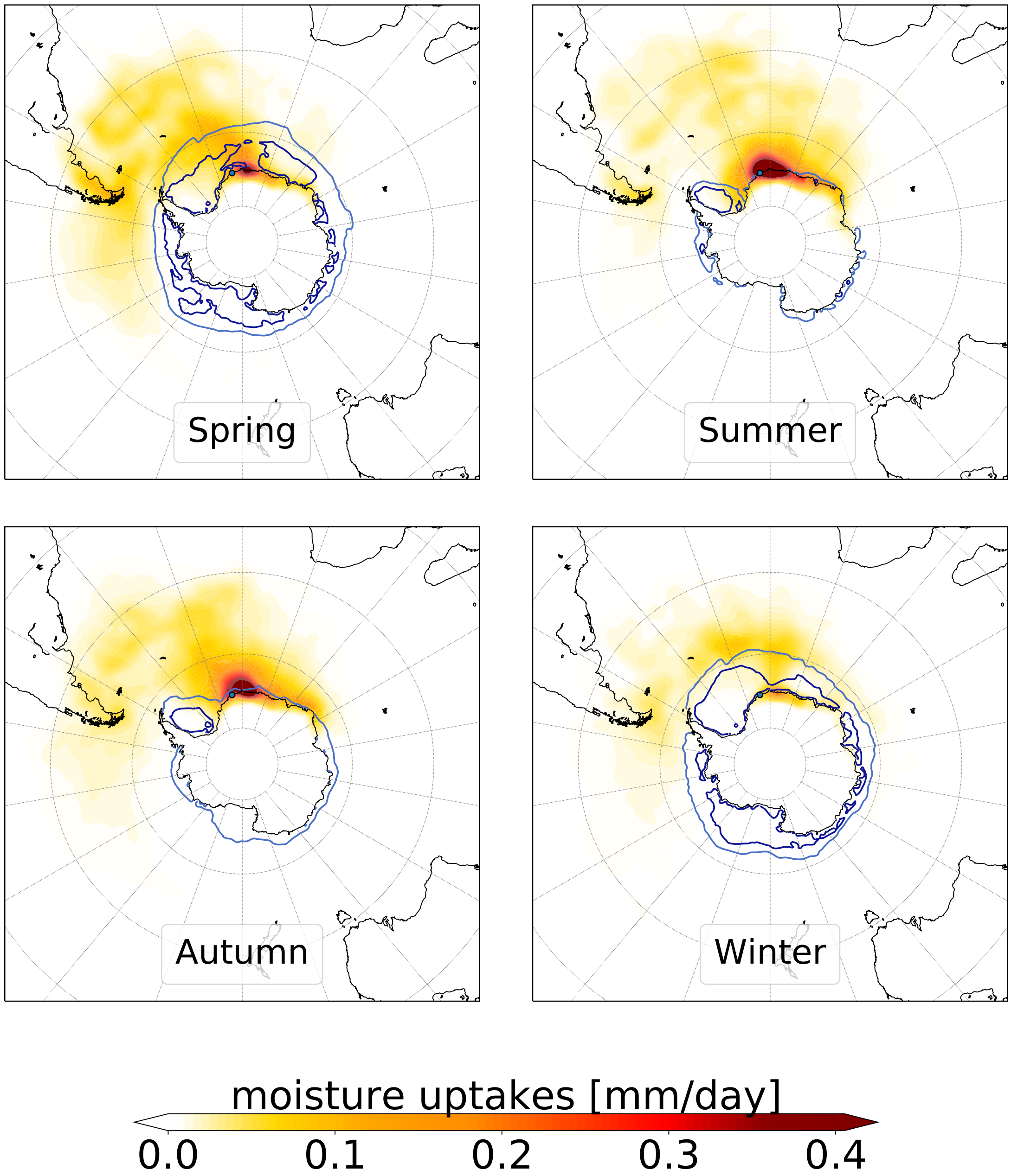

*Figure 4. (Figure 5 in the revised manuscript). Simulated mean moisture uptake occurring within the boundary layer [*mm day^{-1}*] in the pathway to Neumayer Station during last 10 days modelled by FLEXPART using ECMWF, ERA5 dataset (Hersbach et al., 2020), for spring (SON), summer (DJF), autumn (MMA), and winter (JJA), considering the year of 2017 and 2018. The mean sea ice edge based on ERA5 reanalysis (Hersbach et al., 2020) for ice coverage more than 45% and 90% is shown with light blue and dark blue lines.*

Fig. 8: This figure shows surface pressure reduced to sea level, and is therefore inaccurate over topography. Values over the continent should be masked.

The figure is removed because one of other referees asked for it. But, in the revised manuscript (Subsection 2.1, Figure 1), the summer and winter views of this figure are shown as requested in the comments above (Figure 1).

Section 4.1.1: Temperature at Neumayer is mainly controlled by season (determining the free atmosphere, or 'background' temperature) and surface cooling (determining the negative departure of the near-surface temperature from this background temperature). Eliminating the latter by e.g. selecting the 850 hPa temperature over Neumayer from balloon soundings/ERA5 could facilitate the interpretation of water isotope values in terms of air-masses and large-scale circulation.

We added the ERA5 850hPa temperature (Hersbach et al., 2020) to our analyses. However, we find that the correlation coefficient between the 850hPa temperature and $\delta^{18}O$ (0.67) is lower than the one between the 2m temperature and $\delta^{18}O$ (0.89). The correlation coefficient is also lower if we look at the different seasons:

Season	T_{850hPa}- $\delta^{18}O$ correlation coefficient	T_{2m}- $\delta^{18}O$ correlation coefficient
Spring	0.60	0.86
Summer	0.21	0.71
Autumn	0.52	0.83
Winter	0.43	0.75

For this reason, we decided to continue working with the 2 m temperature in our manuscript, but now also report the lower correlation with the 850hPa temperature:

Revised manuscript, Subsubsection 3.2.1, line 256:

To look at the effect of temperature on isotopic compositions in term of air-masses and large-scale circulation, we examine a higher-level temperature (850 hPa), using ECMWF, ERA5 dataset (Hersbach et al., 2020). The average 850 hPa temperature for the year of 2017 and 2018 is -14.45°C, which is about 1°C warmer than the observed 2-meter average temperature. Daily values of the 850 hPa temperature vary between -31.09°C and -2.97°C, showing a smaller amplitude compared to the 2-meter temperature values at Neumayer Station. For the observational period, the correlation coefficient between the 850 hPa temperature and $\delta^{18}O$ (r = 0.68) is less than the one between the 2-meter temperature and $\delta^{18}O$ (r = 0.89). We can see this characteristic also in a seasonal view. The correlation coefficient for the 850 hPa temperature and $\delta^{18}O$ (the observed 2-meter temperature and $\delta^{18}O$) for different seasons is calculated: spring: r = 0.60 (r = 0.86); summer: r = 0.21 (r = 0.71); autumn: r = 0.52 (r = 0.83); and winter: r = 0.43 (r = 0.75).

Minor/textual l.100: "−16.10◦C (±1.05◦C).". What does the uncertainty indicate here? Given measurement uncertainty, suggest removing one digit, i.e. -16.1 °C

The uncertainty indicates the 1-sigma standard deviation of annual mean temperatures from the long-term mean, calculated for the period 1981-2018 (now explained in the revised manuscript, Subsection 2.1, line 111). The other correction is done as requested:

Revised manuscript, Subsection 2.1, line 108:

The mean annual temperature at Neumayer Station (since 1981) is −16.1 ± 1.1°C (the uncertainty indicates the 1-sigma standard deviation of annual mean temperatures from the long-term mean, calculated for the period 1981-2018).

l.*108: One standard deviation appears rather inclusive. Why was this value selected?*

We used the method defined by Klöwer et al. (2014) (which is referenced in the manuscript). They explain that “The threshold of one standard deviation, which leads to a selection of about 16% of all days as warm (cold) events, is chosen not too high to get a large sample of warm (cold) days.”

l.*115: "For the largest time of the year" -> "For most of the year"*

Corrected as suggested.

Revised manuscript, Subsection 2.3, line 125:

For most of the year, wind at Neumayer Station blows from easterly, southerly, or south-westerly directions.

124: "Cover the whole range..." but the numbers provided fall outside of that range?

Explained in the revised manuscript:

Subsection 2.3, line 131:

The calibration system at Neumayer Station was modified based on the isotopic composition of water vapour at Neumayer Station and used 3 different isotopic water standards (liquid), with $\delta^{18}O$ values of -6.07±0.1 ‰ (around -17 ‰ in water vapour), -25.33±0.1‰ (around -36‰ in water vapour), and -43.80±0.1‰ (around -54 ‰ in water vapour). Water standards with water vapour $\delta^{18}O$ values of around -54 ‰, -36 ‰, and -17 ‰, cover the whole isotopic measurements range in water vapour at Neumayer Station.

and

Revised manuscript, Appendix A, line 597:

The calibration system at Neumayer Station was also modified based on the isotopic composition of water vapour at Neumayer Station and used 3 different isotopic water standards (liquid), with $\delta^{18}O$ values of -6.07 ± 0.1 ‰ (around -17 ‰ in water vapour), -25.33 ± 0.1 ‰ (around -36 ‰ in water vapour), and -43.80 ± 0.1 ‰ (around -54 ‰ in water vapour). δD values of the standards (water liquid) are -43.73 ± 1.5 ‰, -195.21 ± 1.5 ‰, and -344.57 ± 1.5 ‰. One of the isotope standards ($\delta^{18}O = -25.33$ ‰) is used for quality control in not one but two of the four bubblers. Every year in January, a sample of each standard is taken and transferred to a laboratory in AWI Bremerhaven and was measured in order to know the isotopic composition. In this study, no change in the isotopic compositions of the standards has been detected. Water standards with water vapour $\delta^{18}O$ values of around -54 ‰, -36 ‰, and -17 ‰, cover the whole isotopic measurements range in water vapour at Neumayer Station.

l.138: Relative humidity (RH) is commonly expressed as %, not ppm. Moreover, the latter concentration suggests that you are talking about specific humidity (q). Later on you use 'absolute humidity'. Please clarify and provide these numbers (RH and q) for the presented ppm thresholds as well.

In the revised manuscript, we clarified our wording of different forms of humidity. Now, we distinguish between water concentration given in ppm, specific humidity given in $g.kg^{-1}$, and relative humidity given in %, in the whole text.
We provided specific humidity values for the presented water concentration thresholds in the revised manuscript. But the thresholds cannot be precisely given for relative humidity, since it can be different numbers for the thresholds, depending on the temperature:

Revised manuscript, Subsection 2.3, line 148:

The range of water concentration defined for the Picarro analyser is 1000 to 50000 ppm (parts per million expressed by volume/volume), which equals specific humidity values in the range of 0.62 to 31.10 $g\,kg^{-1}$). At Neumayer Station, water concentration easily reaches values below

1000 ppm in the austral winter. For water concentrations lower than 2000 ppm (specific humidity of 1.24 $g\ kg^{-1}$), the analyser shows systematic errors with biases of more than 1 ‰ for $\delta^{18}O$ (Casado et al., 2016).

l.182: "Humidity": absolute or specific humidity? l.189: "humidity amount..."Check throughout, please.

As we mentioned above, we clarified all wording related to humidity with respect to water concentration, specific humidity and relative humidity.

l.222: Only the summer slope differs significantly.

We agree and removed the sentence related to the highest and lowest slope in the revised manuscript.

l.262: Check the value of the standard deviation, that appears too large.

Here we considered the mean value of measurements and the standard deviation is 1-sigma standard deviation of calculating mean value considering hourly averages for all days. We explain it in the revised manuscript, and also consider the daily value instead of the hourly value:

<u>Revised manuscript, Subsection 3.4, line 324:</u>

The origin of the air masses measured at Neumayer Station depends directly on the local wind, which is characterized by relatively high wind speeds, with an annual mean value of 8.7 $m\ s^{-1}$ during the measurement period (with a standard deviation of 5.67 $m\ s^{-1}$, considering daily values of all days).

l. *302: 10.56 -> 10.6, see also l. 305.*

Corrected as requested:

<u>Revised manuscript, Subsubsection 4.1.2, line 405:</u>

We find that for 64 % of the days (22 out of 36 days) with the wind coming from east and wind speed above the daily average easterly wind of 10.6 $m\,s^{-1}$, the measured $\delta^{18}O$ values are higher than the predicted $\delta^{18}O$ value. This indicates that even for days, when no strong temperature changes can be observed, strong winds from east coincide with more enriched $\delta^{18}O$ values in water vapour at Neumayer Station. On the opposite, for 76 % of the days with katabatic winds and a wind speed higher than the daily averaged southerly wind of 4.6 $m\,s^{-1}$ (12 out of 17 days), measured $\delta^{18}O$ values are lower than the predicted $\delta^{18}O$ values.

l.309: warm/cold temperature -> high/low temperature

Corrected as requested (warm/cold event instead of warm/cold temperature):

Revised manuscript, Subsubsection 4.1.2, line 387:

During the observation period, on 86 % of all days that involve warm events at Neumayer Station, the wind came from east.

l. *324: neither -> either*

Removed from the revised manuscript.

Section 4.4: suggest changing the title into: Comparison to other sites

Corrected as requested:

Revised manuscript, Subsection 4.3, line 432:

4.3 Comparison to other sites

l.366: 'opposite' please rephrase

Corrected as requested:

Revised manuscript, Subsubsection 4.3.1, line 440:

Most comparable to our measurements is a recent study by Bréant et al. (2019), who have reported water isotopes in vapour from the Dumont d'Urville station in Adélie Land, which is also located at the Antarctic coast (Fig. 1).

Section 4.4.1: Mention that an extensive ice shelf is absent in the case of DDU, and that the station is situated on an island several km away from the coast.

Mentioned as requested:

<u>Revised manuscript, Subsubsection 4.3.1, line 442:</u>

During summer, most of the island is free of ice and snow and sea ice is rare (König-Langlo et al., 1998). The average temperature at the Dumont d'Urville station during

We thank referee #3 for his/her detailed comments and suggestions on our manuscript. We hope that we have dealt with all comments in an adequate manner and that the revised manuscript now qualifies for publication in The Cryosphere.

References

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