We greatly appreciate the variety of helpful comments from the reviewer. The page and line numbers refer to the reviewed manuscript, not the re-revised manuscript.

On the other hand I found some details of their analysis mysterious and complicated (e.g. sometimes using medians and sometimes means) and as a non-specialist in analysis of this sort of data analysis I worry whether these complications make the extract signal more or less certain.

The reviewer is correct that some additional explanation is needed for why means and medians are both used. For Fig. 1 of the manuscript, the explanation is provided at p7L8, but the explanation should be tied to the figure(s) for which it is relevant. Actually, the explanation is relevant for Figs. 1, 2, 4, and 5, all of which extend well up into the southern high-latitude stratosphere. The dehydration in the lower stratosphere during winter could be expected to lead to larger random relative error in retrieved water vapour VMR, but it appears that the MAESTRO measurements are also biased low at this altitude/season for an unknown reason. The reviewer is correct that the extracted monthly water vapour signal time series is less certain for MAESTRO at southern high latitudes in the lower stratosphere (relative to ACE-FTS). This paper is focussed on the upper troposphere and any “analysis” of the response to either annular mode uses medians.

We now write at p7L6:

Monthly time series are created at northern and southern high latitudes using occultation profiles in the 60-90°N and 60-90°S latitude bands, respectively.

The following is now moved immediately after Fig. 1 is first mentioned in the text:

At southern high latitudes, monthly means are preferred for Fig. 1 and for the illustrated time series (Fig. 2) instead of medians which, for MAESTRO, have a dry bias in the widely dehydrated winter lower stratosphere. However, systematic and seasonally-dependent biases cancel out given the sensor-specific deseasonalization as discussed at the end of this section, so only medians are used in the regression analyses (Sect 2.5).

We have rewritten the sentence at p7L22:

A month is included in the climatology and anomaly dataset at any altitude where ≥20 observations exist for that given month and altitude.

To justify the use of medians in the regression, we now write at p11L11:

The use of medians is preferable for detecting the AAO response in the troposphere since this measure of central tendency is less susceptible to remaining outliers in the individual retrieved profiles and because smaller standard errors for the AAO fitting coefficient are obtained.

The proposed connection between the annular modes and observed UTLS water vapour concentrations is interesting (the authors make the simple practical point that taking account of this connection might potentially improve trend estimates) and it is of course natural to consider possible mechanisms, of which the authors identify three — (i) variations in temperature changing saturation mixing ratios and therefore water vapour concentrations, (ii) effects of meridional transport and (iii) effects of tropopause variation.

The authors seem to rule out (iii), without providing any explicit evidence to support that. (They report that there is no significant correlation between high-latitude tropopause height or pressure and the annular modes — but do not provide any evidence or cite other any other publications on this topic.) They show some evidence for (ii) — though it is a little difficult to assess this because all quantitative information in the paper comes in the form of fractional change.

There are two pieces of evidence for mechanism (iii) mentioned in the reviewed manuscript:

1) the small correlation coefficients between tropopause pressure (or height) and the local annular mode, and
2) the dropoff in the response of water vapour and saturation VMR to the local annular mode with increasing altitude (p16L21). This is illustrated in Figs. 8-9 of the manuscript.

We now refer to Figs. 8-9 at the end of p16L21.

An example of tropopause height anomaly and the AAO time series is provided below in Fig. 1. Note the huge negative AO events in 2010 and 2013 and the lack of a signal in tropopause height at those times. We feel it is not worth including such a figure in the paper.

Fractional change is easier to understand, particularly for water vapour in the troposphere where the vertical gradient and seasonal variation are huge. Fractional change is also preferable for the regression analysis: even after deseasonalization, the interannual variability of UTWV would be skewed toward summer (more humid) months using (absolute) VMR anomalies. Relative anomalies allow each season to be weighted “equally” during the regression.

A review of the literature on mechanism (iii) is presented below as this point is repeated by the reviewer in their detailed comments. This review of the literature provides support that mechanism (iii) is correctly ruled out.

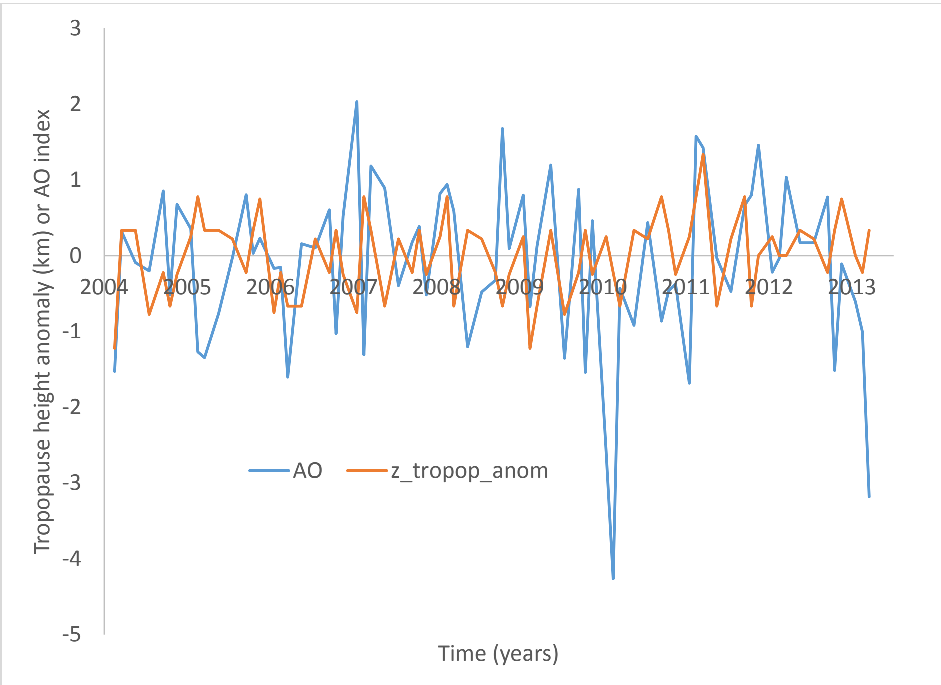

Figure 1. Correlation between AO and tropopause height anomaly at northern high latitudes (R=-0.009).

To what extent is the magnitude of water vapour variations accounted for by the magnitude of variations in saturation mixing ratio? They argue for some role for (i), but this is based on the view (in my view incorrect) that Eulerian mean meridional circulation is an indication of meridional water vapour transport.

The reviewer is incorrect that we infer some role for mechanism (i) above based on use of the Eulerian mean meridional circulation. The reviewer likely meant mechanism (ii). The role for mechanism (i) is determined from the difference in observed responses for water vapour and saturation VMR. For example, had we seen that the response of saturation VMR to the local annular mode is as large as the observed response of water vapour to the local annular mode, we would have concluded that, mechanism (i), which is a simple mechanism, can explain the response of observed UTWV, however this is not clearly the case, considering all altitudes in both hemispheres. We address mechanism (ii) in response to the next comment.

To clarify, the sentence at p15L24 now reads:

Below 9 km, the response of saturation VMR tends to be weaker than the response by deseasonalized water vapour observed by the ACE instruments, implying that the temperature mechanism cannot fully explain the strong observed response of water vapour to the AAO at southern high latitudes.

In summary, this paper identifies a scientifically interesting connection, but the assessment and discussion of possible mechanisms is weak (or even flawed) at present. In my view this assessment and discussion needs to be clarified and strengthened, and in addition several other parts of the text need to be clarified (see detailed comments below), if the paper is to be suitable for publication.

We discuss mechanisms (i)-(iii) more thoroughly in the revised manuscript thanks to the reviewer's guidance. There is added discussion regarding mechanisms (i) in response to the previous comment. The discussion has been strengthened with regard to the tropopause mechanism as can be seen in response to a detail comment by the reviewer below.

We have mechanism (ii) as a possible mechanism because

a) the meridional circulation changes in the right direction (i.e. more poleward or less equatorward) as a response to the annular mode and
b) because of the meridional gradients in water vapour (i.e. much more water vapour at mid-latitudes).
c) Boer et al. (2001) have already shown that the mean meridional flux of moisture correlates with the annular modes in the high-latitude upper troposphere with the correct sign.

The reviewer is correct that the Eulerian mean meridional circulation is not an ideal proxy of meridional water vapour transport. It is an oversimplification of the actual (Lagrangian) meridional transport of water vapour, particularly when the meridional transport is accompanied by adiabatic ascent and especially for air with high relative humidity. However the reviewer's earlier statement is 'black' and 'white' (i.e. correct or "incorrect" indicator of meridional water vapour transport).

In the high-latitude upper troposphere, the air is generally of low relative humidity (see Tables 1-2 below), thus condensation and local evaporation are of reduced importance. The exception is in autumn in both high latitude regions where monthly median RH is 60% below 8 km. Also, Fig. 7 of Thompson and Wallace (2000) shows that the meridional transport is accompanied by increased tendency for downward transport at all latitudes poleward of 60° in either hemisphere during the negative phase of the local annular mode, which reduces the likelihood of condensation.

If the meridional transport mechanism were completely "flawed", there would be no expected response by water vapour to the annular mode resulting from this mechanism. But, as a matter of fact, this mechanism should apply so long as one condition is met: RH is <<100%. (If air is nearly saturated, the water vapour content can solidify as it ascends adiabatically. Where there is adiabatic descent associated with the poleward transport, saturated air (RH=100%) containing ice crystals can sublimate upon adiabatic descent and thus the meridional transport mechanism would raise water vapour VMR at high latitudes during the negative phase of the annular mode as we propose.) Certainly, adiabatic ascent of 1 km in altitude during poleward transport can lead to condensation of fairly dry air. However, condensed phase water is short-lived in the upper troposphere because of quick evaporation. This is reflected by the fact that ~1% of the mass of water is in the condensed phase (Jakobson and Vihma, 2010 and reference therein). Thus, even in the case of RH approaching 100% in ascending air, cirrus clouds will tend to entirely evaporate before the ice particles can become large enough to fall out (Prospero et al., 1983), given the dry surrounding air. Furthermore, if the ice crystals contained most of the upper tropospheric water and mostly fell out before evaporating, the residence time of water in the upper troposphere would not be weeks (Ehhalt, 1973, Grewe and Stenke, 2008), much longer than that of clouds (hours to, at most, days, Sherwood, 1999). It should be noted that condensation does not change the position of water versus latitude or altitude. Only fallout (e.g. precipitation) either removes water entirely from the atmosphere or lowers the altitude if vaporization of the precipitation occurs at a lower altitude. When the data is examined on a monthly timescale, the poleward meridional transport anomaly during negative annular mode events can increase water vapour in the high latitude upper troposphere regardless of whether a fast condensation/evaporation cycle occasionally occurs in the transported air. Furthermore, the most active period for the northern annular mode is in winter when relatively humidity throughout the northern high-latitude upper troposphere is typically <50%. Similarly at southern high latitudes, the period with the highest RH (March-April) falls within the February-April period that is least active in terms of the southern annular mode (Fig. 2 below), thus condensation during poleward isentropic transport is expected to be less likely. In summary, the meridional transport mechanism has some merit to explain the observed UTWV response to the annular modes in spite of the condensation that may be entailed because of adiabatic ascent. Besides these physical reasons, there is fairly strong support for an increase in poleward upper tropospheric moisture flux at high latitudes via the meridional mean circulation during the negative phase of the annular modes in Fig. 6 of Boer et al., 2001, particularly for the southern hemisphere.

	Jan	Feb	Mar	May	Jul	Sep	Oct	Nov
5.5	0.335617	0.462469	0.38858	0.451742	0.300384	**0.553609**	**0.571373**	0.340632
6.5	0.283264	0.405649	0.29817	0.459975	0.278343	**0.539661**	**0.605771**	0.285934
7.5	0.312263	0.382111	0.275328	0.330195	0.23801	**0.516496**	**0.636739**	0.290052
8.5	0.272733	0.284577	0.189989	0.206088	0.234673	0.48554	0.432782	0.240061
9.5	0.249756	0.193447	0.123872	0.160169	0.171938	0.276875	0.205811	0.167602
10.5	0.167219	0.111737	0.072695	0.085588	0.112302	0.126958	0.064448	0.085188
11.5	0.09266	0.070041	0.046764	0.031768	0.048221	0.044892	0.030172	0.044921
12.5	0.061291	0.052781	0.040223	0.015955	0.016347	0.020894	0.019038	0.030688
13.5	0.052826	0.04782	0.037186	0.012174	0.010023	0.017143	0.01894	0.029114

Table 1 – MAESTRO median relative humidity monthly climatology at northern high latitudes. Attention is drawn to values with RH>50% using **bold** font.

	Jan	Mar	Apr	May	Jul	Aug	Sep	Nov
5.5	0.310024	**0.626803**	**0.507172**	0.213319	0.219246	0.276444	0.291133	0.419851
6.5	0.263378	**0.540145**	**0.579326**	0.187391	0.260762	0.287748	0.225472	0.391969
7.5	0.228613	0.435262	**0.617069**	0.2073	0.248503	0.314471	0.261696	0.315829
8.5	0.156192	0.285326	0.361675	0.167558	0.266384	0.341194	0.26456	0.286568
9.5	0.072464	0.118378	0.144259	0.122986	0.322713	0.397068	0.269495	0.199539
10.5	0.029431	0.044948	0.0555	0.062195	0.285494	0.406514	0.235269	0.138362
11.5	0.014229	0.022363	0.029256	0.037983	0.206186	0.315443	0.217465	0.077029
12.5	0.008628	0.014608	0.020678	0.02835	0.162493	0.238863	0.177464	0.047755
13.5	0.007154	0.012039	0.019473	0.025059	0.135857	0.275199	0.328633	0.030085
14.5	0.005526	0.011337	0.019085	0.026622	0.134767	0.326208	0.411309	0.021036

Table 2 – same as Table 1 but for southern high latitudes

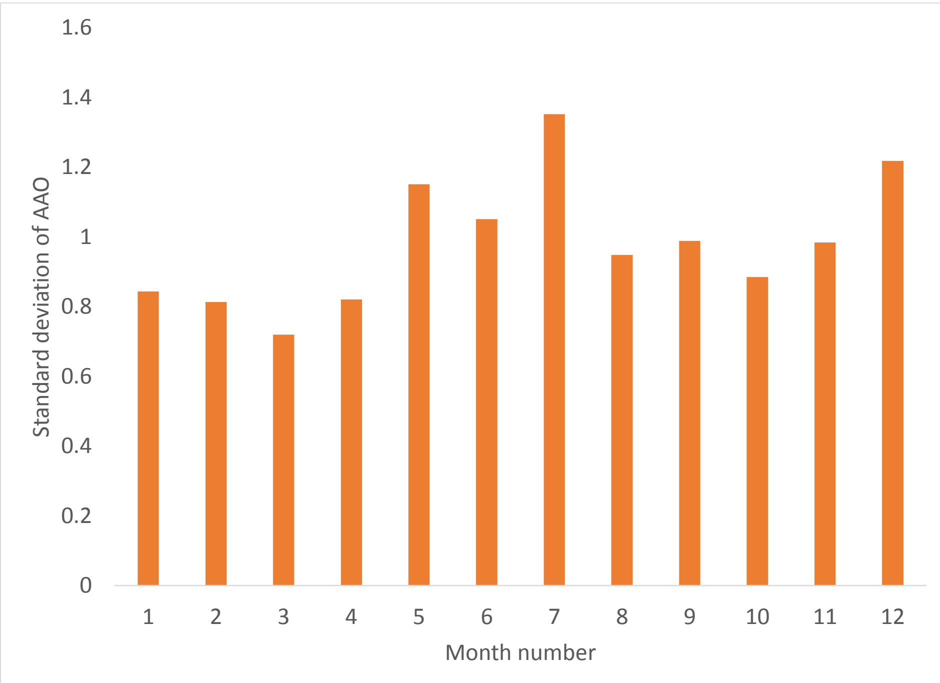

Figure 2. Monthly standard deviation of the AAO index (1979-present).

In defence of the meridional flux mechanism, we now write at p15L15:

Boer et al. (2001) have already demonstrated that the response of mean meridional flux of UTWV to the annular modes using climate model simulations. However, poleward isentropic transport may involve ascent which may lead to condensation when RH reaches 100%. If sufficient water vapour condenses, precipitation may occur, which would lower the local VMR of water vapour. But evaporation and condensation play a minor role in the polar tropospheric water budget (Boer et al., 2001), with water vapour representing 99% of the total water content (Jakobson and Vihma, 2010, and reference therein). There are many additional, related arguments in favour of the Eulerian mean meridional circulation as a plausible mechanism to account for the response of high-latitude UTWV to the annular modes. Firstly, the high-latitude upper troposphere has low RH (<50%) with the exception of autumn (e.g. March-April in the southern hemisphere). Secondly, in this autumnal period of higher RH (e.g. 60% below 8 km), the annular mode activity is low for either hemisphere and conversely, the active period for either annular mode falls in a season of low RH. Thirdly, the vertical component of the meridional circulation tends to shift downward during the negative phase of the local annular mode in either hemisphere (Fig. 7 of Thompson and Wallace, 2000), thereby reducing the likelihood of condensation. Fourth, ice crystals formed during poleward ascending motion will tend to return to the vapour phase before precipitating, given the dry, surrounding air (e.g.

Prospero et al., 1983). Finally, precipitation may evaporate before descending into the lower troposphere given the vertical gradient in ambient temperature. These five additional arguments suggest that the meridional flux mechanism could be effective in transporting water vapour to the high-latitude upper troposphere on a monthly timescale during the negative phase of the annular mode. Boer et al. (2001) showed that there is an increased poleward upper tropospheric moisture flux via the meridional mean circulation at high latitudes during the negative phase of the annular mode in either hemisphere. According to analysis of Boer et al. (2001), the mean meridional flow mechanism appears to be of greater relative importance in the high-latitude upper troposphere in the southern hemisphere. The effectiveness of the mean meridional flux mechanism in increasing UTWV VMR during negative AAO periods is amplified by the large latitudinal gradients in UTWV between southern mid and high latitudes.

There is also additional assessment and discussion of the tropopause mechanism (see reply to final detailed comment below) and eddy moisture flux has been considered as a possible mechanism. In the re-revised manuscript, we now write at p15L13:

However, Boer et al. (2001) clearly show for both hemispheres that annular-mode-related moisture fluxes via eddies are too small (relative to the mean meridional flux) and of the wrong sign to explain the poleward transport of moisture in the high-latitude upper troposphere. However, only the meridional eddy flux term was considered, whereas Del Genio et al. (1994) point out that large scale eddies transport moisture upward as well as poleward.

Since Boer et al. relied on climate model simulations and only used half of the calendar months (November to April), we essentially verified their Fig. 6 using a 20-year period of ERA Interim data (1995-2004, Dee et al., 2011) and all seasons. We find both a weak relationship between eddy moisture flux and the AO (Fig. 3 below) and a response that is of the wrong sign to explain the ACE-observed UTWV response (Fig. 4 below). Both findings are consistent with Boer et al. (2001) and so, we have simply referred to the work of Boer et al. (2001) in the discussion of the eddy moisture flux mechanism. Our eddy moisture flux regression analysis was limited to pressures $\leq$250 hPa (i.e. below the tropopause) as the eddy moisture flux derived from the ERA Interim data only remains coherent in the troposphere. In the stratosphere, as expected, the eddy moisture flux is extremely small, even when taking account of the reduced water vapour VMRs.

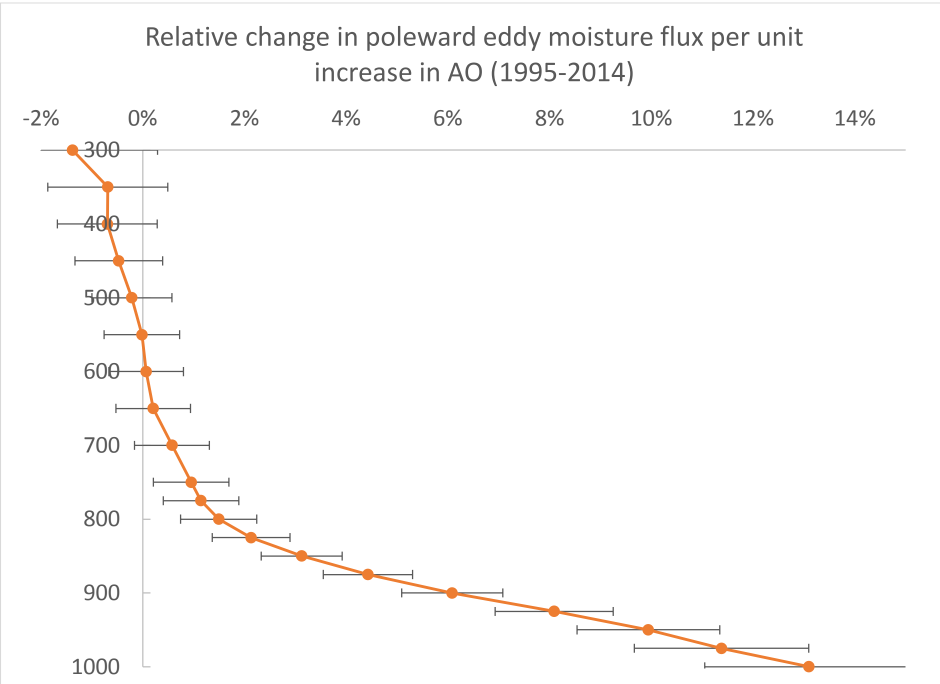

Figure 3. Response and its uncertainty (±1 standard error) of the meridional component of the eddy moisture flux to the AO (1995-2004) at 60.5°N.

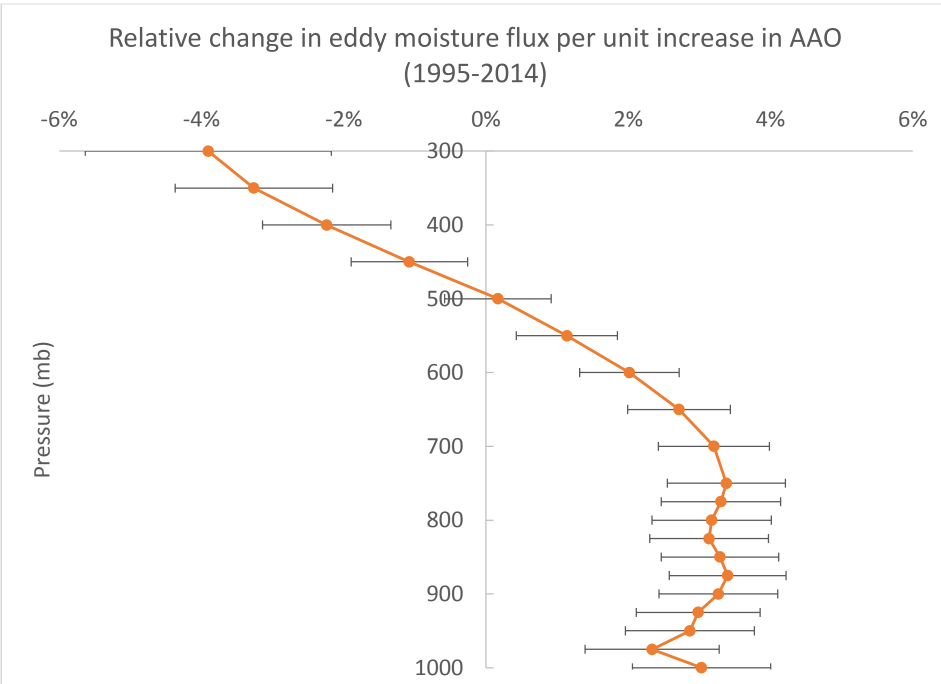

Figure 4. Response and its uncertainty (±1 standard error) of the meridional component of the eddy moisture flux to the AO (1995-2004) at 60.5°N. In the southern hemisphere, negative values indicate a poleward flux during the positive phase.

Note that there are other minor changes throughout this sub-section on proposed mechanisms.

Detailed comments follow:

p3 l10: 'In the middle stratosphere' — I wasn't sure why you qualified by 'middle'. It would be more logical to emphasise the 'stratospheric overworld' — i.e. the part of the stratosphere that does not connect to the troposphere along isentropic surfaces (see e.g. Holton et al 1995) since it is this part of the stratosphere where water vapour concentrations will be controlled by entry at the tropical cold point and by methane oxidation. In the 'lowermost stratosphere' on the other hand, as you note, there is the possibility of rapid exchange with the troposphere along isentropic surface which means that water vapour concentrations are not set by the tropical cold point (e.g. see Dessler et al 1995 JGR).

We have changed "middle stratosphere" to "stratospheric 'overworld' (Dessler et al., 1995)".

p3 l23-30: It would be helpful to refer to the specific figure (actually Figure 7) in Thompson and Wallace (2000) that shows this signature in the mean meridional flow. But note that what is shown in that Figure is the Eulerian mean meridional circulation — and this is certainly not the whole story regarding the transport of trace species — see e.g. Plumb and Mahlman (1986 J. Atmos. Sci.). So if you want to associate a particular phase of the annular mode with transport of a trace species (in this part of the paper you are ignoring condensation/evaporation effects) then you need to justify carefully why the Eulerian mean circulation should be relevant.

The Eulerian mean meridional circulation has been justified above as a plausible mechanism for the meridional transport of UTWV at high latitudes. We now write at p3L27 and elsewhere in the re-revised manuscript:

(Fig. 7 of Thompson and Wallace, 2000)

p6 l24: Why do you use median rather than mean temperatures?

The quality control procedure involved in the GEM temperature analyses is not perfect. Eliminating the very infrequent outliers is possible for completely unrealistic analysis temperatures of <100 K but it is possible that the temperature analysis will only be in error by a plausible difference (-10 K). The use of the median greatly reduces the impact of imperfect quality control.

We made no change to the manuscript based on this comment since means are never used for temperatures, so the earlier comment by the reviewer about ‘mysterious’ switching between means and medians only applies to water vapour.

Also if you are trying to calculate a monthly mean tropopause height then wouldn’t it make more sense to calculate tropopause heights on the basis of, say, daily data and then average those calculated heights?

It might make more sense in a thought experiment, but not in reality. As a practical example, we examined the temperature profiles (N=110) in September 2006 at southern high latitudes as sampled by ACE. Note that because of the unusual temperature profile in the tropopause region September at southern high latitudes, unconventional tropopause definitions are required. The monthly average and median of the individual tropopause heights are 11.8 and 11.5 km, respectively. The climatological average tropopause for all Septembers, using the tropopause definition in Sect. 2.3, is a more reasonable 9.94 km ± 1.24 km (±1 standard deviation), and the tropopause for September 2006 is 9.5 km. Using the mean or median of the individual tropopause heights can produce a higher monthly tropopause in September in the Antarctic partly because the distribution of tropopause heights is positively skewed (Fig. 5 below). While it makes some sense that colder tropopauses would be located at higher altitudes (Fig. 6 below), the relationship is quite strong and the temperatures of the highest tropopauses are more indicative of the Antarctic lower stratosphere (T < 187 K). Thus, the monthly tropopause height (for September at southern high-latitudes) obtained by averaging individual tropopause heights suffers because a considerable fraction of the individual tropopause heights are likely biased high (e.g. truly in the lower stratosphere). Similar to using the low temperatures to indicate lower stratospheric air, one can examine the VMRs of gases, with ozone being the best discriminator between clearly tropospheric (O_3 VMR < 100 ppb) and clearly stratospheric (O_3 VMR > 150 ppb) air. For the individual profile with a lapse rate tropopause height of 16.5 km (Fig. 3 below), O_3 VMR is > 150 ppb at all heights in the 10.5-15.5 km range, heights which are all supposedly tropospheric with a conventional lapse rate tropopause definition, yet the O_3 VMR clearly indicates stratospheric air.

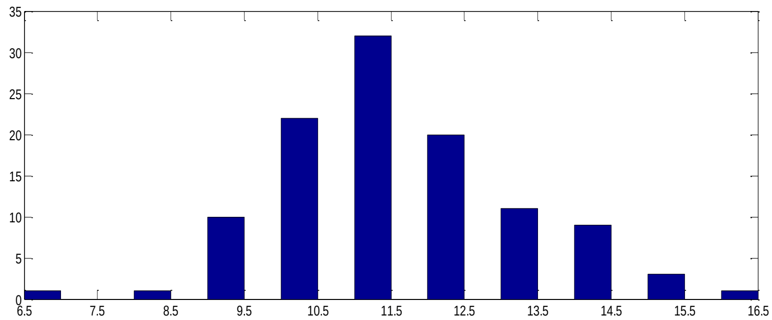

Figure 5. Histogram of tropopause heights in September 2006 at southern high latitudes. Vertical bars are in 1 km increments from 6.5 to 16.5 km.

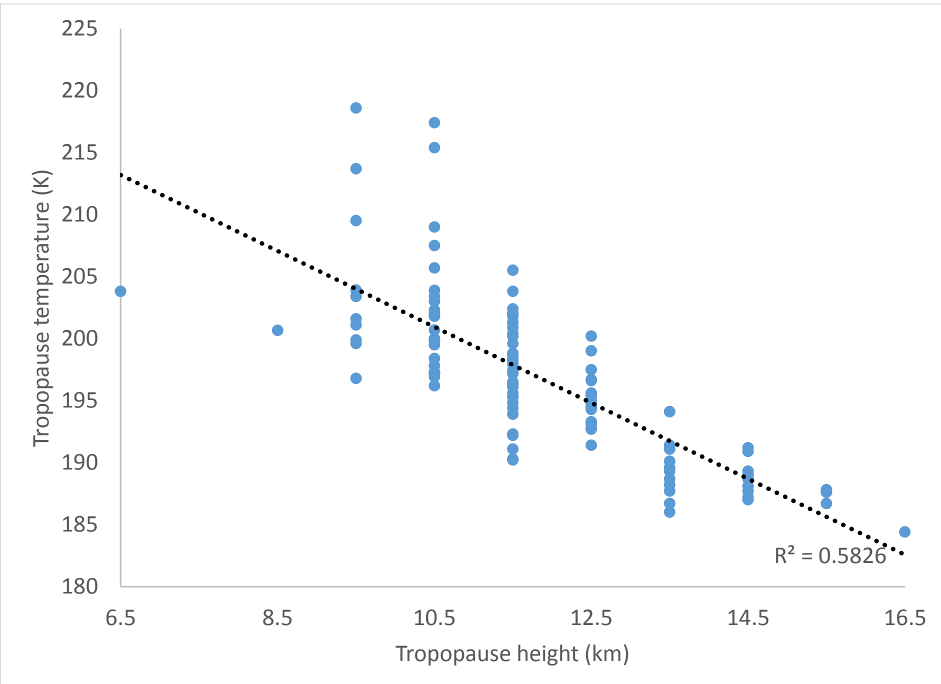

Figure 6. Relationship between tropopause height and tropopause pressure in September 2006 at southern high latitudes, plus a linear fit to these data (N=110).

We add the second sentence at p6L29 to explain why a different definition is required. The first sentence is added in response to another comment below:

Use of monthly median or mean profiles give tropopauses that tend to be too high in September. The same problem is manifested when using a monthly average of tropopause heights determined from individual profiles.

p6 l27-29: Please clarify the definitions of the 'thermal tropopause' and the 'lapse-rate tropopause' — are they different?

The reviewer has identified that there was some confusion about the meaning of "thermal tropopause". The reviewer's question has prompted the rewording of these lines more clearly as follows:

For the northern hemisphere, the monthly tropopause height is defined as the height above 5 km that is the lower of the lowest local minimum or the lowest height at which the lapse rate is <2 K/km in monthly median temperatures from the Global Environmental Multiscale (GEM) regional assimilation system (Laroche et al., 1999). In the southern hemisphere, due to the winter lower stratosphere being colder than the tropopause region, the definition is the same except that the lapse rate and lowest local minimum are determined using the monthly maximum temperature profile.

Note that we removed the use of “thermal tropopause” and in doing so there should be no confusion with the concept of “lapse rate tropopause”.

Also you have different tropopause definitions for NH and SH — using median temperatures for the former and maximum temperatures for the latter. If this is important — and I suppose that it is — then more explanation is needed. You say ‘the lapse rate tropopause concept has been used previously’ — I would have assumed that the lapse rate tropopause concept is the standard one (i.e. the ‘WMO definition’) used by almost all meteorologists — which makes me think that if you need to justify use of this it must actually be non-standard and therefore requires more explanation.

The explanation is similar to two earlier responses regarding:

1) the difference between using mean and median temperatures.

2) how to best determine monthly tropopause heights

The use of monthly maximum temperatures is slightly risky because of rare, erroneous outliers in the GEM analysis, so median temperatures are generally preferable, including northern high latitudes. But at southern high latitudes in winter, the use of the monthly median temperature clearly fails, similarly to the averaging of individual tropopause heights. For example, the tropopause using monthly median temperatures in September 2006 at southern high latitudes is >14 km.

When defining the tropopause at high latitudes, the goal was to select a statistic (or two, if necessary) which would not locate the tropopause in September at southern high latitudes at 16 km for example, when we know from the local monthly ozone vertical profile and secondly from the latitudinal variation of tropopause height, that this is clearly stratospheric. We also thought there would be greater objection to using the ozone profile to define the tropopause in a region where ozone depletion occurs in the lower stratosphere. We thought enough justification was given for the selection of different statistics, but rereading Sect 2.3, we agree with the reviewer that more justification is needed. The mean suffers from the same problem as the median for SH: the monthly mean tropopause in September 2011 and 2012 is 13.5 km (and we note that the monthly mean temperature at 13.5 km is colder than all earlier Septembers). For comparison, using the monthly maximum temperature profile to define the monthly tropopause, values of 12.5 and 10.5 km are obtained in September 2011 and 2012, respectively, which are more reasonable given ACE-FTS O_3 VMR exceeds 150 ppb at 10.5 km (but not below) in both of those Septembers.

The ‘WMO definition’ of the lapse rate tropopause is used. What is unconventional and unintuitive is that this definition is applied to the monthly temperature profile, which means the temperature profile is a statistical quantity (median in NH, maximum in SH).

As mentioned above, two sentences have been added to the re-revised manuscript at p6L29.

p7 l7-10: Again to me this use of medians for some purposes and means for others seems mysterious. If medians don't work for the SH then why not use means for both NH and SH?

We share the reviewer's distaste for mystery in science papers. This question has been addressed in our response to the general comment (above). In both hemispheres, medians "do work" for the purpose of analyzing the response of high latitude water vapour to the local annular mode in both the upper troposphere and lower stratosphere. Means are simply used to present a less biased picture of stratospheric water vapour (from MAESTRO) in Figures 1, 2, and 4 and so that the stratospheric seasonal cycle is more realistic in Fig. 5 of the paper.

p7 l13: You say 'Because ACE instruments sample southern high latitudes in only eight of twelve calendar months' — but then you seem to imply that this is true in the NH as well (without saying it directly).

We thank the reviewer for spotting this. We have reworded this:

ACE instruments sample each high latitude region in only eight of twelve calendar months. November, January, March-May and July-September represent spring, summer, autumn and winter, respectively, when a seasonal timescale is used in the southern hemisphere. In the north (…)

p7 l29 + Figure 1 caption: Why use 'bias' when this often has a specific technical meaning? For example in a subsequent sentence you say ACE-FTS has a high bias of 10% — which in this case (Hegglin et al 2013) means difference from a multi-instrument mean. It would be clearer to simply say 'relative difference between MAESTRO and ACE-FTS' when that is what you mean, both in the text and in the caption and indeed in the figure annotation.

We agree with the reviewer. We now write at p7L29:

Figure 1 illustrates the relative difference between MAESTRO and ACE-FTS water vapour climatologies at both high latitude bands.

The x-axis title of Fig. 1 has now been changed from "Bias" to "Relative difference".

p8 l4: 'Accounting for an upper troposphere +10% wet bias in ACE-FTS, MAESTRO and ACE-FTS agree …' — I found this confusing — do you mean 'If we accept that ACE-FTS has a positive bias then the two agree'? Wouldn't it be clearer to say that the two agree (by some criterion) apart from at levels where ACE-FTS has an acknowledged positive bias.

In the revised manuscript, we write:

Except below 8 km where a slight wet bias for ACE-FTS is likely, MAESTRO and ACE-FTS agree within ±20% at all heights up to 17.5 km (in 1 km steps) in both hemispheres at high latitudes.

p8 l7: The ordering of the Figures seems odd — you mention Figure 4 and Figure 3 here, but Figure 2 has not yet been mentioned. In any case subtracting information in Figure 4 from that in Figure 3 would not make any sense because Figure 3 is for NH and Figure 4 is SH climatology.

We thank the reviewer for spotting this incorrect numbering of Fig. 2. To address both issues raised here by the reviewer, we now insert the following sentence before the sentence at p8L7:

The monthly water vapour VMR time series are shown for the southern and northern hemisphere in Figs. 2 and 3, respectively.

Personally I would find it clearer if the missing months (4 per year) were explicitly displayed in Figures 2 and 3 as 'empty' bands rather than somehow stretching 8 months to cover a year.

The captions for Figs. 2-3 declare the number of calendar months used. We had already attempted the modification to these figures suggested by the reviewer using white 'empty' bands and it becomes much more difficult to see the annual cycle in water vapour at the tropopause. Given that:

1) the same eight calendar months are plotted for every year,
2) there is not a two month gap between any of these eight calendar months, and
3) 'empty' bands are used when one of these eight calendar months are unpopulated in a given year,

we feel/hope that this is acceptable.

p9 l2: Since you have previously given Larson et al (2005) as a reference for the AO I assume that their definition is the same as that of Thompson and Wallace (2000)?

Larson et al. clearly state that the "AO index used (…) is based on the methodology of Thompson and Wallace (2000)."

No change is required since the reviewed manuscript already stated at p9L4 that "the AO index is calculated following the method of Thompson and Wallace (2000)."

p9 l3-7: To me this (e.g. including annular mode index for trend uncertainty if it improves uncertainty without increasing bias) all sounds a bit complicated. I'm not convinced I (or any reader) could repeat this calculation from the details given here.

At p9L4, we now have simplified the following methodological statement, which has no effect on the results discussed in Sect. 4.1:

"When examining trend uncertainty reduction (Sect. 4.1), the regression uses a linear trend, plus a constant; the annular mode index term is included for trend determination if it improves the trend uncertainty."

We have verified that the AO and AAO basis functions do not show a trend of their own (significant at the 2σ level) over the period of available ACE records data. Periods are shown in Figs. 2-3 for MAESTRO. We do not believe that the description of the trend calculation is missing any details.

p10 l3: 'The southern high-latitude time series has slightly less water in the UTLS in late winter than at northern high-latitudes … due to the colder air temperatures.' — this is pretty difficult to make out from your figures — not least because months are not shown (and which months are omitted is not clear from the Figures —- as noted previously).

The plotting of the eight months as a continuous time series has been discussed in response to a previous comment. Late winter is available in both hemispheres (September for SH, and March for NH). The sentence has been deleted because the figures are not in the same units. Fig. 2 shows means while Fig. 3 shows medians. This is the reason why it is difficult to detect any difference, as the reviewer correctly points out. The documented interhemispheric difference was noted in an apples-to-apples comparison of monthly medians (not shown), but we prefer to leave Figs. 2-3 as they are. There are no other sentences in the manuscript which compare these two figures.

p10 l10-15: There seems to be a strong implication here that upper tropospheric water vapour is explained by LOCAL temperatures — i.e. little role for effects of remote temperature variation being communicated by transport. Is that what you intend? Have other authors commented on this and indeed have there been previous modelling studies investigating this point?

The reviewer is correct that there is a role for temperature variation in the lower troposphere both at high and lower latitudes, which would be communicated by deep convection (or Hadley cell circulation at low latitudes) to the upper troposphere. The role of remote temperature variations is not necessarily minor, but the local temperature cycle appears sufficient to explain the seasonality of water vapour throughout the upper troposphere. To be frank, nothing is implied in Sect 3.1. This is an inference by the reviewer. Our statements for both hemispheres in Sect. 3.1 were carefully worded to not rule out the role of remote temperature variations. As an example of a previous paper on this topic, Sioris et al. (2010) used summer and winter temperatures from a seasonal sub-arctic climatology and incorrectly claimed that the difference in UTWV in the 60-70°N band between Jan-Feb. (mid-winter) and July (mid-summer) could not be explained by local temperatures. The source of error was due to a mismatch: seasonal temperatures were used but the water vapour was measured close to the peak of the season. In the first sentence of Sect. 4 of the manuscript reviewed by the referee, we wrote “driven by the seasonality of the local temperature”. In the revised manuscript, we modify this to:

Polar regions have a strong seasonal cycle in UTWV, which is consistent with the seasonality of the local temperature.

Chen et al. (1999) have one sentence that states that the spatial distribution of extratropical water vapour VMR at 316 mb has a similar seasonal variation to that at 215 mbar (the latter pressure level is mostly in the stratosphere at high latitudes). They state that “the extratropical upper tropospheric (specific) humidity has highest values in summer because of more water vapor transported from low latitudes and higher summer temperature.” It is clear that they are referring to high latitudes as well as mid latitudes with this statement. They do not attempt to quantify whether local temperature variation can entirely explain the seasonal cycle as we have done.

Thus the second sentence of Sect. 4 becomes:

The importance of the seasonal cycle in local temperature on UTWV seasonality at high latitudes has been stated previously (Chen et al., 1999).

More importantly, the modelling study by Del Genio et al. (1994) discusses the cause of the seasonality and this study is cited by others seeking to explain the seasonality. This study clearly states that seasonal differences in the transport of humidity from low latitudes via both small-scale moist convection and the large-scale mean meridional circulation is minor. Del Genio et al. (1994) discuss how large scale eddies transport humidity upwards at high latitudes into the upper troposphere and account for the seasonality at high latitudes. Thus transport from below is a likely candidate, while transport from lower latitudes is fairly ineffective. The third sentence of Sect. 4 becomes:

On the basis of general circulation model simulations, Del Genio et al. (1994) demonstrated that small-scale moist convection and the mean meridional circulation have a minor role in the seasonal cycle of polar UTWV.

Zahn et al. (2014) comment that water vapour is:

a) not controlled by local temperature field in the extratropical upper troposphere and lowermost stratosphere (UT/LMS).
b) determined by the coldest temperature the air parcel experienced along its pathway to the UT/LMS.

It appears however that these authors have lumped the UT and LMS together when, in this case, they should not have for two reasons:

1) If extratropical air ascends vertically from the surface to the UT, the coldest point it experiences is likely to be the "local temperature" of the UT. (In other words, the statements by Zahn et al. are potentially contradictory for the UT, but reasonable for the LMS.)
2) The statement (b) accounts for freeze-drying of air, but not for moistening which can occur as clouds vaporize in ambient air with low RH. Their comment seems appropriate for the stratosphere where clouds are rare.

We decided not to reference this paper as their comments appear to pertain to the LMS.

p10 l18-19: You refer first to 'weak seasonal variations in the lower stratosphere' and then to 'The large seasonal cycle amplitude … in the lower stratosphere' — I'm confused.

This is a simple mistake by the reviewer. The first statement refers to observed water vapour VMR and the second refers to saturation VMR. These sentences are important to understanding why the annular modes would have little influence on lower stratospheric water vapour when operating via the temperature mechanism.

p11 l1-2: 'the seasonal variation in water vapour concentration' would be clearer.

We thank the reviewer for spotting this. The sentence is revised as follows:

“sufficient to explain the seasonal variation of water vapour VMR…”

p11 l11-13: ‘The use of medians is preferable … where the water vapour mixing ratios are not normally distributed’ — why should normally distributed or not determine whether medians are preferable?

The reviewer is correct to question this statement. The sentence is deleted. The revised text was presented in response to the first general comment (above).

p12 l12: This discussion of the radiative impact of AAO-related water vapour variations would seem better to me in the final Discussion section of the paper rather than here in the middle of the description of the variations themselves.

We thank the reviewer for this suggestion. This paragraph becomes Sect. 4.1 in the revised manuscript. Subsequent sections and the references to those sections have been renumbered.

p15 l13-14: As noted previously, referring to the signature identified by Thompson and Wallace (2000) in the Eulerian mean meridional circulation is not a convincing argument for there to be a corresponding signature in meridional transport of water vapour.

This point is addressed by our response to the related general comment.

p15 l24: ‘this response’ — do you mean ‘the response in the saturation VMR’?

Yes. The sentence was rewritten (and is included above in response to a general comment).

p16 l6: ‘this isolated region’ — which isolated region?

This has been revised as follows:

The effectiveness of the meridional flux mechanism during negative AAO periods is amplified by the large latitudinal gradients in water vapour between southern mid and high latitudes.

p16 l18-21: You assert that there is no strong correlation between high-latitude tropopause height or pressure and the annular modes but present no explicit evidence, nor do you cite any other papers on this topic. A bit more concrete supporting evidence is needed.

As stated before, concrete evidence such as Fig. 1 (above) exists, but such a figure is not worthy of inclusion in the publication in our opinion. The two time series show no visible correlation and the correlation coefficient bears that out. There could be four such figures: one for tropopause height and one for tropopause pressure in each hemisphere. We disagree with the reviewer: four correlation coefficients with magnitude <0.1 is explicit evidence.

We find a response of tropopause height anomaly (zonal 60-90°N) to the AO of -4 ± 59 m (±1 standard error) per unit change in AO. The response of tropopause pressure anomaly to the AO is -0.7 ± 2.3 hPa (±1 standard error) per unit change in AO. Both are so insignificant that we will not dwell on the opposite directions of our height and pressure-based responses of tropopause anomaly to AO.

Hess and Lamarque (2007) show that the tropopause pressure variation attributable to the AO is insignificant through most of the 60-70°N band (except for Siberia). Our average sampled latitude for occultations extending down to an altitude of 10.5 km is 71°N in our 60-90°N 'high latitude' band. The latitude of 71°N, according to Hess and Lamarque is on the border of the region with 90% confidence of a tropopause change attributable to AO. Further north, there is a clear relationship: the tropopause pressure decreases (i.e. the tropopause rises) with increasing AO.

Cai and Ren (2007) show that the increase in pressure (i.e. decrease in height) of the 300 K surface (approximately the high latitude tropopause) from the positive phase to the negative phase of a NAM event is ~14 hPa. This is a small fraction of the overall range of monthly tropopause pressures of 107 hPa, based on our GEM tropopause pressure in our study. Cai and Ren (2007) cite an earlier study by Ambaum and Hoskins (2002) whose Fig. 3b shows that the tropopause height response to the North Atlantic Oscillation (NAO) largely cancels out zonally over the 60-90°N band because of opposite responses over Iceland and northern Siberia, but there is a slight increase in tropopause height as NAO increases over this band. The NAO and the AO are highly correlated (r>0.95) so their result (based on a regression) should hold for AO as well. Ambaum and Hoskins (2002) limited their analysis to December to February, when the northern annular mode is most active. Thus, the weak response in tropopause height to the NAO would be expected to weaken further if the entire year was considered. The peak response of the tropopause height of +350 m per unit change of the NAO index covers <10% of the total area of the high-latitude region and yet is smaller than the standard deviation of tropopause height anomalies of 530 km we find. The sign of their NAO fitting coefficient would not serve as a mechanism to explain increases of UTWV during the negative phase of the local annular mode.

The analysis of Highwood et al. (2000) find a similar rising of the tropopause with increasing AO index.

Añel et al. (2006) correlated annual changes in the tropopause height to annual variations in the NAM indices of Baldwin and Dunkerton at 700 hPa and 50 hPa. They find correlations of either sign at a number of high-latitude Eurasian stations but always with a magnitude <0.7. This paper is not cited in our re-revised manuscript since the studied geographic area is too limited and some concern about the quality of the paper (see correlation coefficient of -55 for first station in their Table 1).

We now write at p16L23:

According to several studies (e.g. Cai and Ren, 2007; Ambaum and Hoskins, 2002; Highwood et al., 2000; Hess and Lamarque, 2007), the high-latitude tropopause tends to rise during the positive phase of the AO. The response of the tropopause is of the wrong sign to explain increases of UTWV during negative phase of the AO.

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Upper tropospheric water vapour variability at high latitudes – Part 1: Influence of the annular modes

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Abstract

Seasonal and monthly zonal medians of water vapour in the upper troposphere and lower stratosphere (UTLS) are calculated for both Atmospheric Chemistry Experiment (ACE) instruments for the northern and southern high-latitude regions (60-90°N and 60-90°S). Chosen for the purpose of observing high-latitude processes, the ACE orbit provides sampling of both regions in eight of 12 months of the year, with coverage in all seasons. The ACE water vapour sensors, namely MAESTRO (Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation) and the Fourier Transform Spectrometer (ACE-FTS) are currently the only satellite instruments that can probe from the lower stratosphere down to the mid-troposphere to study the vertical profile of the response of UTLS water vapour to the annular modes.

The Arctic oscillation (AO), also known as the northern annular mode (NAM), explains 64% ($r=-0.80$) of the monthly variability in water vapour at northern high-latitudes observed by ACE-MAESTRO between 5 and 7 km using only winter months (January to March, 2004-2013). Using a seasonal timestep and all seasons, 45% of the variability is explained by the AO at 6.5±0.5 km, similar to the 46% value obtained for southern high latitudes at 7.5±0.5 km explained by the Antarctic oscillation or southern annular mode (SAM). A large negative AO event in March 2013 produced the largest relative water vapour anomaly at 5.5 km (+70%) over the ACE record. A similarly large event in the 2010 boreal winter, which was the largest negative AO event in the record (1950-2015), led to >50% increases in water vapour observed by MAESTRO and ACE-FTS at 7.5 km.

1 Introduction

Water vapour is the most important greenhouse gas in the atmosphere (Lacis et al., 2010) playing an important role in climate change by magnifying changes in radiative forcing by longer-lived greenhouse gases through the water vapour feedback (Dessler and Sherwood, 2009). A variety of observations have shown that, at near-global scales, specific humidity in the troposphere has been increasing along with atmospheric temperatures in a manner consistent with that predicted by the Clausius-Clapeyron equation – approximately 7%/K (Hartmann et al., 2013). Long-term increases in water vapour are expected in the troposphere due to long-term increases in temperature and the resulting exponential increase in saturation vapour pressure (Soden and Held, 2006). ~~In the middle stratosphere,~~In the stratospheric 'overworld' (Dessler et al., 1995), long-term changes in water vapour may result from changes in the temperature of the tropical tropopause 'coldpoint' that controls the dehydration of tropospheric air as it enters the stratosphere (Brewer, 1949) and from changes in its stratospheric source gas, namely methane (Oman et al., 2008). Water vapour in the extratropical lowermost stratosphere may be additionally influenced by changes in isentropic transport from the subtropics (Dessler et al., 2013). Additionally, absorption by atmospheric water vapour of radiation at terahertz and radio frequencies is a serious impediment for radio astronomy and for long-distance communications (Suen et al., 2014). The vertical distribution of water vapour is relevant for all of the effects mentioned.

In order to understand and attribute long term changes, internal modes of variability, particularly those with longer periods, should be considered simultaneously. In the extratropics, the annular modes explain more of the month-to-month and year-to-year variance of the atmospheric flow than any other climatic phenomenon (Thompson and Wallace, 2000; http://www.atmos.colostate.edu/ao/introduction.html). The northern and southern annular modes (NAM, SAM), also known as the Arctic oscillation (AO) and Antarctic oscillation (AAO) respectively, produce a strong zonal flow at mid-latitudes during their positive phase with an equatorward meridional flow near 60° latitude, and weaker zonal flow during the negative phase accompanied by an increased tendency for poleward flow ~~during the negative phase (~~(Fig. 7 of Thompson and Wallace, 2000~~). In the high-latitude upper troposphere, where water vapour enhancements due to evaporation at the surface are minor relative to the lower troposphere, it is~~

~~the negative phase of the annular modes that is expected to increase water vapour by increased transport from more humid lower latitudes.~~, Fig. 6 of Boer et al., 2001). Devasthale et al. (2012) used the Atmospheric Infrared Sounder (AIRS) on the Aqua satellite to study the longitudinal and vertical structure of water vapour in the 67-82°N band and interpreted the observed structure by separating the observations according to the phases of the Arctic oscillation. ~~To our knowledge, no one has studied the~~The impact of the Arctic and Antarctic oscillation on upper tropospheric water vapour (UTWV~~).~~) has been studied by Boer et al. (2001) using a climate model with atmospheric and oceanic coupling and using the reanalysis data from the National Centers for Environmental Prediction.

The AO exhibits the largest variability during the cold season (Thompson and Wallace, 2000). Groves and Francis (2002) related TOVS (TIROS Operational Vertical Sounder) precipitable water vapour net fluxes across 70°N in winter to the phase of the AO. Li et al. (2014) showed that the longwave radiative forcing anomaly due to NAM-related variability of cold season water vapour for the 2006 to 2011 period at northern high latitudes is small (~-0.2 W/m^2).

Here, the relationship between water vapour in the upper troposphere and lower stratosphere (UTLS) at northern and southern high-latitudes (60-90°N and 60-90°N) and their respective annular modes is studied using observations from satellite-based limb profilers. A particular focus is the height dependence of the relationship: does it extend up to or above the tropopause?

2 Method

2.1 Satellite observations

SCISAT was launched in 2003 carrying a suite of solar occultation instruments to carry out the mission named the Atmospheric Chemistry Experiment (ACE) (Bernath et al., 2005). The ACE instruments measuring water vapour are Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation (MAESTRO, McElroy et al., 2007) and the Fourier Transform Spectrometer (FTS, Bernath et al., 2005). The ACE datasets begin in February 2004. The measurements provide a unique combination of high vertical resolution and the ability to measure the water vapour profile from the mid-troposphere to the lower stratosphere where the volume mixing ratio (VMR) is <10 ppm (parts per million), below the lower detection limit of the nadir-sounding AIRS (Gettelman et al., 2004). HIRS (High-Resolution Infrared Radiation Sounder) is the nadir sounder used in the last two Intergovernmental Panel on Climate Change (IPCC) assessments (e.g. Hartmann et al., 2013) for long-term trend studies of upper tropospheric humidity (Soden et al., 2005; Shi and Bates, 2011). However, the trend analysis of the HIRS dataset is confined to the region 60°N to 60°S (Bates and Jackson, 2001). The Tropospheric Emission Spectrometer (TES) should also be mentioned, but in polar regions at pressures < 400 mb, the vertical resolution of TES is 11.6 km (Worden et al., 2004). IASI (Infrared Atmospheric Sounding Interferometer) water vapour retrievals have coarse poor vertical resolution in the polar upper troposphere and the upper altitude limit of the retrieval only approaches the tropopause (Herbin et al., 2009; Wiegele et al., 2014). Other current limb sounders include the sub-millimetre radiometer on Odin which can only measure in the upper troposphere in the tropics (Rydberg et al., 2009) and the Microwave Limb Sounder on Aura which can only probe down to 316 mb (~8 km) (Su et al., 2006). The fact that MAESTRO and ACE-FTS are on the same platform is extremely valuable for comparing the month-to-month variations of atmospheric constituents observed by both instruments.

The MAESTRO water vapour retrieval method follows the one used previously (Sioris et al., 2010). Data are available at https://databace.scisat.ca/level2/mae_water/ after user registration. Some of the main algorithm changes are described here. The maximum allowable optical depth in the water vapour fitting window (926.0-969.7 nm) is reduced from 7.63 to 6.7. This reduces the number of noisy spectra but also possibly increases susceptibility to a dry bias at the lowest altitudes. Also, MODTRAN 5.2 (Berk, 2013 and references therein) is now used for forward modelling. The water vapour absorption line intensities are mostly from Brown et al. (2002) and have uncertainties of 2-5%, an improvement relative to the previous version (Sioris et al., 2010) which used MODTRAN 4 (relying on the HITRAN 1996 spectroscopic database). Water vapour profiles are retrieved from all available MAESTRO optical depth spectra (version 3.12, spanning 2004 to 2013) from the ongoing ACE mission. For version 3.12 optical depth spectra, the tangent height registration relies on matching simulated O_2 slant columns obtained from air density profiles, based on temperature and pressure retrieved from ACE-FTS (Boone et al., 2013), with slant columns observed by MAESTRO using the O_2 *A* band. MAESTRO water vapour mixing ratios that are more than twice as large as all other mixing ratios at any altitude in the same month were examined in detail and filtered if related to a measurement problem. Significant outliers are not numerous and no recursion is necessary. No other filtering is necessary. ACE-FTS gridded version 3.5 data are used in the study. The FTS retrieval is described by Boone et al. (2013). ACE-FTS water vapour with retrieval uncertainty of >100% are filtered as well as data points that are significantly negative (i.e. magnitude of mixing ratio is greater than retrieval uncertainty). Polar Ozone and Aerosol Measurement III (POAM III) water vapour measurements are also used to compare the observed seasonal cycle. Only version 4 data (Lumpe et al., 2006) with a flag of 0 are used.

2.2 Retrieval uncertainties and validation

POAM III has been validated down to 8 km or ~300 mb (Nedoluha et al., 2002; Lumpe et al., 2006) and this is used as the POAM III lower altitude limit in this work. Previous comparisons between MAESTRO and ACE-FTS have been favourable (Sioris et al., 2010, Carleer et al., 2008). ACE-FTS water vapour has been used in the validation of other instruments (e.g. Lambert et al., 2007) and in the Stratospheric Processes And their Role in Climate (SPARC) Data Initiative (Hegglin et al., 2013). Waymark et al. (2013) compared version 3 ACE-FTS water vapour data with the previous well-validated version 2.2 (e.g. Carleer et al., 2008) and found 2% differences over a large altitude range. Since the MAESTRO tangent height registration has improved substantially since the previous publication (Sioris et al., 2010), the current version of MAESTRO water vapour profiles has been validated in a global sense versus ACE-FTS in the companion paper (Sioris et al., 2015).

Beside the validation results, it is also valuable to look at retrieval uncertainties to understand the expected data quality. Based on an analysis of one year of southern high-latitude data, the MAESTRO water vapour retrieval relative uncertainty is found to be best at the lowest retrieval altitude of 5 km and is typically ~30% for a 0.4 km thick layer. The smallest retrieval relative uncertainty of 2% for ACE-FTS occurs typically at 8.5 km (considering 5.5 to 19.5 km) and rapidly deteriorates below 7 km to 15% based on northern high-latitude data (2004-2013) on a 1 km altitude grid.

2.3 Tropopause definitions

For the northern hemisphere, the monthly tropopause height is defined ~~by~~as the height above 5 km that is the lower of the ~~thermal tropopause~~lowest local minimum or the lowest height at which the lapse rate is <2 K/km in monthly median temperatures from the Global Environmental Multiscale (GEM) regional assimilation system (Laroche et al., 1999). In the southern hemisphere, due to the ~~extreme cold in the~~ winter lower stratosphere~~,~~ being colder than the tropopause region, the definition is ~~defined as~~ the ~~lower of the thermal tropopause or the lowest height at which~~same except that the lapse rate ~~is 2 K/km in~~ and lowest local minimum are determined using the monthly maximum ~~temperatures~~temperature profile. Use of monthly median or mean profiles give tropopauses that tend to be too high in September. The same problem is manifested when using a monthly average of tropopause heights determined from ~~the GEM assimilation system~~individual profiles. The lapse rate tropopause concept has been used previously for the extratropics (e.g. Randel et al., 2012). With ~~this~~the chosen definition, the climatological tropopause at southern high latitudes is at 10.5 km for the winter half of the year (May-October) and at 9.5 km in the summer half (November to April).

2.4 Anomalies

To arrive at water vapour anomalies, there are three steps: creation of the time series (e.g. monthly or seasonal), compilation of the climatology, and deseasonalization. ~~To create monthly medians for~~Monthly time series are created at northern and southern high latitudes~~,~~ using occultation profiles in the 60-90°N and 60-90°S latitude ~~band are selected. At southern high latitudes (60-90°S), monthly means are preferred particularly for MAESTRO instead of medians to avoid a low bias in the widely dehydrated winter lower stratosphere~~bands, respectively. The sampling provided by the ACE orbit as a function of latitude and month is illustrated by Randel et al. (2012). The consequence of the non-uniform latitudinal sampling as a function of month for the purpose of this study is discussed in Sect. 2.5. This sampling pattern repeats annually. ~~Because~~ ACE instruments sample ~~southern~~each high ~~latitudes~~latitude region in only eight of twelve calendar months~~,~~. November, January, March-May and July-September represent spring, summer, autumn and winter, respectively, when a seasonal timescale is used~~.~~ in the southern hemisphere. In the north, climatological values are obtained for all calendar months except April, June, August, and December. The seasonal anomalies use the following groupings at northern high latitudes: winter consists of January and February, spring includes March and May, summer is composed of July and September and the fall is represented by October and November.

Vertically, the binning is done in 1.0 km intervals centered between 5.5 km and 22.5 km (above 23 km, the MAESTRO water vapour absorption signal tends to be below the lower detection limit). ~~The monthly mean at a given altitude bin~~A month is included in the climatology and anomaly dataset ~~if there are~~at any altitude where ≥20 observations ~~per~~exist for that given month and altitude. A single MAESTRO profile can supply more than one observation per altitude bin since the water vapour retrieval is done on the tangent height (TH) grid, which is as fine as 0.4 km at the lowest TH of 5 km and as the angle widens between line-of-sight and the orbital track. The same process is followed with ACE-FTS and POAM III data to generate monthly median and mean time series.

The monthly climatology, used to deseasonalize the time series, is generated by averaging the monthly medians and means over the available years. Figure 1 illustrates the ~~bias~~relative difference between MAESTRO and ACE-FTS water vapour climatologies at both high latitude bands. At southern high latitudes, monthly means are preferred for Fig. 1 and for the illustrated time series (Fig. 2) instead of medians which, for MAESTRO, have a dry bias in the widely dehydrated winter lower stratosphere. However, systematic and seasonally-dependent biases cancel out given the sensor-specific deseasonalization as discussed at the end of this section, so only medians are used in the regression analyses (Sect 2.5). An ACE-FTS high bias of ~10% has been observed for the extratropical upper troposphere (40-80°N and 40-80°S, near 300 hPa) (Hegglin et al., 2013). While inconclusive, a general wet bias between 5 and 8 km is also suggested by lidar comparisons in the extratropics (Carleer et al., 2008; Moss et al., 2013). ~~Accounting for an upper tropospheric +10%~~Except below 8 km where a slight wet bias ~~in~~for ACE-FTS is likely, MAESTRO and ACE-FTS agree within ±20% at all heights ~~(5.5-~~up to 17.5 km~~,~~ (in 1 km steps) in both hemispheres at high latitudes.

The monthly water vapour VMR time series are shown for the southern and northern hemisphere in Figs. 2 and 3, respectively. At each height, the monthly climatology (e.g., Fig. 4) is subtracted from the time series (e.g., Fig. ~~3~~2) to give the absolute deseasonalized anomaly. Dividing the monthly absolute anomaly by the monthly climatology gives the relative anomaly. Note that July and August 2011 were omitted from the MAESTRO southern high latitude climatology at 6.5-9.5 km due to a ~50% enhancement at these altitudes due to the Puyehue volcanic eruption (Sioris et al., 2015). The same process is followed to generate anomalies of temperature, relative humidity (RH), tropopause pressure, and tropopause height. The anomalies of relative humidity with respect to ice are based on pressure and temperature from the GEM assimilation system and an accurate saturation vapour pressure formulation (Murray, 1967). The latitude sampling anomaly is generated by calculating the average sampled latitude for each high-latitude band and then the mission-averaged latitude in each high-latitude band is subtracted.

Note that, because conclusions below about the importance of the annular modes are reached based on water vapour anomalies and the fact the deseasonalization is sensor-specific (i.e. the time series observed by each instrument is deseasonalized using its own climatology), ~~overall~~constant biases and seasonally-dependent biases are actually inconsequential. Relevant biases are discussed in Sect. 2.5.

2.5 Regression analysis

We use a multiple linear regression analysis to determine the contribution of the appropriate annular mode to the variability in deseasonalized water vapour at high latitudes as a function of altitude. The set of available basis functions include a linear trend, the monthly AAO (Mo, 2000) and AO (Larson et al., 2005) indices (http://www.cpc.noaa.gov/products/precip/CWlink/) and ~~a~~the latitude sampling anomaly time series. This basis function is included to illustrate that sampling biases are minor even on a monthly time scale (using only the eight months which sample each high-latitude region). Note that the AO index is calculated following the method of Thompson and Wallace (2000).

When determining the response of water vapour to the AO, the AO index plus a constant are used, and the linear trend is included if it is significant at the 1 standard error (σ) level. When examining trend uncertainty reduction (Sect. 4.~~1~~2), the regression uses a linear trend, plus a constant; the annular mode index term is included for trend determination if it improves the trend uncertainty~~ without biasing the trend at the 1σ level.~~. Median water vapour anomalies are used in the analysis in both hemispheres since they respond with smaller uncertainty to the local annular mode than anomalies based on monthly means.

The types of biases that could affect the analysis of water vapour variability are due to:

1) interannual variation in latitudinal sampling~~ non-uniformity (Toohey et al., 2013), ~~, and
2) interannual biases in retrieved water vapour profiles.

Regarding the non-uniform sampling of latitudes by the ACE orbit mentioned in Sect. 2.4, the correlation between monthly time series of average sampled latitude in the northern high-latitude region and the Arctic oscillation index is 0.19 and similarly the correlation between the monthly time series of average sampled latitude in the southern high-latitude region and the Antarctic oscillation index is 0.12. Given these very low correlations, ACE's latitudinal sampling should have a negligible impact on any conclusion about the response of the observed water vapour anomaly to the annular modes, although this is tested below using the latitude sampling anomaly as a basis function. Toohey et al. (2013) estimated monthly mean sampling biases in the UTLS to be ≤10% for the category of instruments that includes ACE-FTS (and MAESTRO). The interannual biases are also < 10% given that Sect. 3.2 below shows that approximately half of the southern high-latitude water vapour seasonal anomaly (typically ±10% in amplitude) can be explained by interannual variability in the Antarctic oscillation (i.e. real dynamical variability, not artificial instrument-related variability). Also, there are no known issues with either MAESTRO or ACE-FTS specific to a certain year. Furthermore, the self-calibrating nature of solar occultation, combined with the wavelength stability of spectrometers (relative to filter photometers) minimize interannual bias for MAESTRO and ACE-FTS. For example, any variation in the optical (or quantum) efficiency of the instrument does not need to be calibrated as it does with an instrument measuring nadir radiance.

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3 Results

The MAESTRO water vapour record (Fig. 2) at southern high latitudes is similar to the records of contemporary limb sounders as shown in Fig. 13 of Hegglin et al. (2013). ~~The southern high-latitude time series has slightly less water in the UTLS in late winter than at northern high-latitudes (Fig. 3) due to the colder air temperatures.~~

3.1 Seasonal cycle

The dehydration in September that extends downward into the upper troposphere at southern high-latitudes (Fig. 4) is clearly observed by MAESTRO annually (Fig. 2).

The variability in the UTWV at southern high latitudes on a monthly timescale is dominated by the seasonal cycle. The observed seasonal variation is a factor of ~5 at 8.5 km (Fig. 5). The seasonal cycle in water vapour is consistent with the ratio of maximum to minimum saturation vapour mixing ratio at 8.5 km of 4.6 (±1 standard deviation: 3.9-5.3), obtained for a typical year, namely 2010, using analysis temperatures and pressures from the GEM assimilation system, sampled at ACE measurement locations for January and August, the months corresponding to the maximum and minimum water vapour in ACE-FTS and POAM III data at 8.5 km, respectively. The approximate equality between the seasonal cycle amplitudes of observed and saturation VMR in the troposphere implies a much weaker seasonal cycle in RH. The strong seasonal cycle in UTWV is in stark contrast to weak (30%) seasonal variations in lower stratospheric (13.5 km) monthly means, according to MAESTRO observations. The large seasonal cycle amplitude in saturation vapour mixing ratio in the lower stratosphere is largely due to the extremely cold temperatures in September.

The stronger seasonal cycle at northern high-latitudes (e.g. at 5.5 km, Fig. 6) is partly due to the non-uniform latitudinal sampling differences in the months of maximum and minimum water vapour VMR, particularly in the southern hemisphere. The northern hemisphere seasonal cycle amplitude vertical profile (Fig. 6) is thus a truer reflection of the amplitude of the seasonal cycle at ~~~70°N.~~high latitudes. Figures 5 and 6 illustrate that the seasonal cycle amplitude of observed water vapour VMR in the lower stratosphere departs from the seasonal cycle amplitude of the ~~saturated~~saturation vapour VMR due to the isolation of this overlying atmospheric region from large sources of water vapour. According to GEM temperature analyses, the amplitude of the seasonal cycle in temperature is 18 K with a sharp peak in mid-summer (e.g. July) and generally sufficient to explain the seasonal variation of water vapour VMR and its vertical dependence in the upper troposphere (Fig. 6).

In spite of the large tropospheric seasonality at high latitudes, it is possible to deseasonalize the water vapour records from the ACE instruments and investigate the remaining sources of temporal variability, as shown next.

3.2 Antarctic oscillation

At 8.5 km, where the largest anti-correlations exist between MAESTRO water vapour at 8.5 km and the AAO index, it is observed that the relative standard error on the AAO fitting coefficient is reduced when the regression is performed using a seasonal ~~timestep~~timescale rather than a monthly ~~timestep~~timescale. Thus, in Fig. 7, the MAESTRO and ACE-FTS seasonal median relative anomaly for 8.5±0.5 km and 7.5±0.5 km, respectively, are presented. The use of medians is preferable for detecting the ~~AAO~~annular mode response in the troposphere ~~where the water vapour mixing ratios are not normally distributed. The monthly medians are also~~in both hemispheres since this measure of central tendency is less susceptible to remaining outliers in the individual retrieved profiles and because smaller standard errors for the AAO fitting coefficient are obtained. The large positive anomaly in 2011 is due to the most explosive eruption of a volcano in the last 24 years, namely Puyehue, and will be discussed in the companion paper (Sioris et al., 2015).

~~1.1~~ At 8.5 km, where the response of water vapour to AAO has the smallest relative uncertainty for both ACE-FTS and MAESTRO, the response ranges between +23% and -18% for individual seasons and the standard deviation of the AAO response time series is 10% (2004-2012). The anomalies in the upper troposphere are highly correlated with each other (e.g. R = 0.79 for MAESTRO absolute anomalies at 8.5 versus 9.5 km on a monthly timescale). In the stratosphere (altitude $\geq$ 10 km), the response of MAESTRO water vapour to AAO is weak (not significant). Figure 8 illustrates the vertical profile of the AAO response. There is a strong vertical correlation between the water vapour responses to the AAO observed by the two instruments and the responses are statistically significant (up to the 4σ level for ACE-FTS at 7.5 km) in the 5.5-8.5 km for both instruments indicating that the AAO affects water vapour throughout the upper troposphere at southern high latitudes. The MAESTRO and ACE-FTS AAO fitting coefficients are not different from 0 at the 1σ level at 10.5 and 11.5 km, respectively. Slight differences between the ACE instruments may relate to differences in their respective fields of view (FOV). MAESTRO's FOV is 1 km in the vertical direction, whereas ACE-FTS, because of its 3.7 km circular field of view at a tangent point 10 km above the ground, will see some contribution from the troposphere even when the FOV is centered 1.5 km above the tropopause. Given that the ACE-FTS field of view is circular, the full-width at half-maximum of the FOV is 3.2 km. Due to vertical oversampling of the FOV, the vertical resolution of the water vapour products from each ACE instrument is finer than the height of the FOV (see also Sioris et al, 2010). Nevertheless, differences in vertical resolution between the ACE instruments will lead to a slight difference in terms of the peak altitude of the anti-correlation between the water vapour anomaly and AAO. The

Formatted: Heading 2, Line spacing: single, Outline numbered + Level: 2 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Tab after: 1.02 cm + Indent at: 1.02 cm impact of non-uniform latitudinal sampling is deferred to Sect. 3.3. The response profile of saturation volume mixing ratio to the AAO is also shown and is discussed in Sect. 4.~~2.~~3.

~~As stated in Sect. 1, the AO is most active in the winter when the surface is coldest. Therefore less infrared (IR) radiation is emitted and trapped by AO-related increases in atmospheric water vapour. Over Antarctica, the AAO instead shows strength in late spring (Thompson and Wallace, 2000) at a time when there is increased IR radiation emitted by the surface, possibly making AAO-related water vapour changes more likely to lead to increases in temperature at the surface and to reduce outgoing longwave flux at the top of the atmosphere (TOA). The impact of AAO-induced variability of upper tropospheric water vapour on surface climate and outgoing longwave flux at the top of the atmosphere is assessed for November 2009 and November 2010, two months when the AAO was of opposite phase (see Appendix A for details of the method). The cooling rate differences at the surface between these negative and positive phases of the AAO are trivial (< 0.07K) in late spring (November). The outgoing longwave flux is reduced by 0.7 W/m^2 in November 2009 relative to November 2010 due solely to AAO-related upper tropospheric changes in water vapour. Scaling this change to the typical AAO fluctuation in all seasons (1979-2014), variations of 0.2 W/m^2 in the outgoing longwave flux at the TOA are found, which are equal to the magnitude Li et al. (2014) found for the AO-related IR flux changes at TOA due to water vapour for the Arctic cold season. Note that Li et al. (2014) found the AO-related water vapour changes to be much smaller than AO-related cloud changes.~~

3.3 Arctic oscillation

Figure 9 shows the altitude dependence of observed water vapour response to the Arctic oscillation using all eight months that sample the northern high-latitude region. There is a coherent and statistically significant response (up to the 4σ level for MAESTRO) to the AO observed by both instruments, with a general decrease through the upper troposphere and a vanishing response in the vicinity of the tropopause. Above 12 km, the response to the AO is insignificant at the 1σ level. The magnitude of the response to the AO is also similar to the magnitude of the response of UTWV at southern high latitudes to the Antarctic oscillation.

The spatiotemporal sampling of ACE (Bernath et al., 2005) is quite non-uniform on monthly time scales whereas on seasonal timescales the spatial coverage of the entire high-latitude region becomes more complete. When the latitudinal sampling anomaly is used as a basis function in fitting monthly water vapour anomaly time series, it is generally not a significant term in either hemisphere. Fig. 9 shows that the inclusion of this term does not change the response to the AO, reinforcing the same finding for the response to the AAO (Fig. 8). Clearly, water vapour at high-latitudes is responding with high fidelity to the local annular mode.

Using the MAESTRO water vapour anomalies, a seasonal timestep and all seasons, 45% of the variability is explained at 6.5±0.5 km, similar to the fraction obtained for southern high latitudes.

The most active season for the AO is from January to March based on monthly standard deviations of the AO index in the period from 1950 to 2015. This three month period was used by Thompson and Wallace (2000). Figure 10 shows a water vapour anomaly time series for an altitude of 6.5 km, composed only of January, February and March (2004-2013). The wintertime anti-correlation between the ACE-FTS water vapour anomaly and the AO index peaks at 6.5 km with R = -0.57. MAESTRO shows a much stronger anti-correlation of R = -0.80 at 6.5 and 5.5 km. A large negative AO event in March 2013 produced the largest relative water vapour anomaly at 5.5 km (+70%) over the MAESTRO record. March 2013 was not available below 8 km for ACE-FTS but at 8.5 and 9.5 km, ACE-FTS and MAESTRO both show the largest positive anomalies for any March in either northern high-latitude data record (+32 and +35% at 8.5 km and +16 and +27% at 9.5 km for MAESTRO and ACE-FTS, respectively) and a vanishing enhancement at 10.5 km (above the monthly mean tropopause). A similarly large event in winter 2010, which was the largest negative AO event in the record (1950-2015), led to >50% and 30% increases in northern high-latitude water vapour observed at 7.5 km in January and February 2010, respectively, with agreement between MAESTRO and ACE-FTS. January 2010 has the largest anomaly at 7.5 km in any month (considering all seasons) of the northern high-latitude data records of MAESTRO and ACE-FTS. Steinbrecht et al. (2011) used a multiple linear regression analysis to demonstrate a significant increase in total column ozone (+8 Dobson units) in the winter of 2010 that was attributed to the same historically strong negative phase of the Arctic oscillation.

4 Discussion and conclusions

Polar regions have a strong seasonal cycle in UTWV, which is consistent with the seasonality of the local temperature. The importance of the seasonal cycle in local temperature on UTWV seasonality at high latitudes has been stated previously (Chen et al., 1999). On the basis of general circulation model simulations, Del Genio et al. (1994) demonstrated that small-scale moist convection and the mean meridional circulation have a minor role in the seasonal cycle of polar UTWV, and that the primary mechanism is eddy moisture fluxes.

In the Arctic upper troposphere, condensation and precipitation play a minor role in governing the water vapour abundance on monthly timescales. Near the Arctic tropopause (250-350 mb), cloud fractions are <35% (Treffeisen et al., 2007) and MAESTRO monthly median relative humidity at 9.5 km is < 40% in all 63 months in which this instrument has observed the northern high-latitude region. However, dynamical variability via the annular modes has been shown here to strongly affect UTWV at high latitudes. Apart from the seasonal cycle, the Antarctic oscillation is a dominant mode of variability in upper tropospheric (~8 km) water vapour at southern high latitudes on a seasonal timescale and the Arctic oscillation explains most of the variability at wintertime UTWV in northern high latitudes.

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4.1 Radiative impact

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As stated in Sect. 1, the AO is most active in the winter when the surface is coldest. Therefore less infrared (IR) radiation is emitted and trapped by AO-related increases in atmospheric water vapour. Over Antarctica, the AAO instead shows strength in late spring (Thompson and Wallace, 2000) at a time when there is increased IR radiation emitted by the surface, possibly making AAO-related water vapour changes more likely to lead to increases in temperature at the surface and to reduce outgoing longwave flux at the top of the atmosphere (TOA). The impact of AAO-induced variability of upper tropospheric water vapour on surface climate and outgoing longwave flux at the top of the atmosphere is assessed for November 2009 and November 2010, two months when the AAO was of opposite phase (see Appendix A for details of the method). The cooling rate differences at the surface between these negative and positive phases of the AAO are trivial (< 0.07K) in late spring (November). The outgoing longwave flux is reduced by 0.7 W/m^2 in November 2009 relative to November 2010 due solely to AAO-related upper tropospheric changes in water vapour. Scaling this change to the typical AAO fluctuation in all seasons (1979-2014), variations of 0.2 W/m^2 are estimated in the outgoing longwave flux at the TOA, which are equal to the magnitude Li et al. (2014) found for the AO-related IR flux changes at TOA due to water vapour for the Arctic cold season. Note that Li et al. (2014) found the AO-related water vapour changes to be much smaller than AO-related cloud changes.

~~41 Discussion and conclusions~~

~~Polar regions have a strong seasonal cycle in UTWV, driven by the seasonality of the local temperature. In the Arctic upper troposphere, condensation and precipitation play a minor role in governing the water vapour abundance on monthly timescales. Near the Arctic tropopause (250-350 mb), cloud fractions are <35% (Treffeisen et al., 2007) and MAESTRO monthly median relative humidity at 9.5 km is < 40% in all 63 months in which this instrument has observed the northern high-latitude region. However, dynamical variability via the annular modes has been shown here to strongly affect UTWV at high latitudes. Apart from the seasonal cycle, the Antarctic oscillation is a dominant mode of variability in upper tropospheric (~8 km) water vapour at southern high latitudes on a seasonal timescale and the Arctic oscillation explains most of the variability at wintertime UTWV in northern high latitudes.~~

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~~4.1~~4.2 Impact of fitting annular mode indices on decadal trends

In the most recent IPCC report, Hartmann et al. (2013) review the literature on trends in UTWV observed from satellite instruments. Only one such publication is cited, namely Shi and Bates (2011). This work uses HIRS data between 85°N and 85°S, but only trends at low latitudes (30°N-30°S) are discussed. While long-term trends in polar UTWV require continued measurements and investigation, including the AO index in the trend analysis improves trend uncertainties below 12 km over the MAESTRO record (e.g. by 16% at 6.5 km) and reduces a statistically insignificant (1σ) but consistent, positive bias in the decadal trend (2004-2013) that is found when the AO is excluded from the regression model. This bias stems from the two large negative events in the winters of 2010 and 2013 which lie near the end of the data record. The trend uncertainty reduction is 22% upon inclusion of the Antarctic Oscillation Index into regression modelling of the linear trend in water vapour at 8.5 km at southern high-latitudes, again with no significant impact on the linear trend itself.

~~4.2~~4.3 Proposed mechanisms

The amplitude of the response by water vapour to annular mode oscillations does not change significantly (1σ) whether UTWV is binned versus altitude or geopotential altitude in either hemisphere at high latitudes, indicating the insensitivity to the choice of vertical coordinate. This is important to note that as the correlation of other atmospheric variables with the annular modes is explored in this section.

There is some observational evidence for two mechanisms that could explain how UTWV at high latitudes responds to the annular modes. The first is through annular-mode-related air temperature fluctuations~~,~~ (Thompson and Wallace, 2000), which impact UTWV by changing the saturation vapour mixing ratio. For changes in saturation vapour mixing ratio to have an impact, there needs to be an available supply of upper tropospheric water vapour.

The second mechanism is through changes to the mean meridional flux itself (e.g. Boer et al., 2001, Devasthale et al., 2012; Thompson and Wallace, 2000), given the latitudinal gradient in water vapour between high and mid-latitudes at all upper tropospheric heights. Boer et al. (2001) have already demonstrated that the response of mean meridional flux of UTWV to the annular modes using climate model simulations. Poleward isentropic transport may involve ascent which may lead to condensation when RH reaches 100%. If sufficient water vapour condenses, precipitation may occur, which would lower the local VMR of water vapour. But evaporation and condensation play a minor role in the polar tropospheric water budget (Boer et al., 2001), with water vapour representing 99% of the total water content (Jakobson and Vihma, 2010, and reference therein). There are many additional, related arguments in favour of the Eulerian mean meridional circulation as a plausible mechanism to account for the response of high-latitude UTWV to the annular modes. Firstly, the high-latitude upper troposphere has low RH (<50%) with the exception of autumn (e.g. March-April in the southern hemisphere). Secondly, in this autumnal period of higher RH (e.g. 60% below 8 km), the annular mode activity is low for either hemisphere and conversely, the active period for either annular mode falls in a season of low RH. Thirdly, the vertical component of the meridional circulation tends to shift downward during the negative phase of the local annular mode in either hemisphere (Fig. 7 of Thompson and Wallace, 2000), thereby reducing the likelihood of condensation. Fourth, ice crystals formed during poleward ascending motion will tend to return to the vapour phase before precipitating, given the dry, surrounding air (e.g. Prospero et al., 1983). Finally, precipitation may evaporate before descending into the lower troposphere given the vertical gradient in ambient temperature. These five additional arguments suggest that the meridional flux mechanism could be effective in transporting water vapour to the high-latitude upper troposphere on a monthly timescale during the negative phase of the annular mode. Boer et al. (2001) showed that there is an increased poleward upper tropospheric moisture flux via the meridional mean circulation at high latitudes during the negative phase of the annular mode in either hemisphere. According to analysis of Boer et al. (2001), the mean meridional flow mechanism appears to be of greater relative importance in the high-latitude upper troposphere in the southern hemisphere. The effectiveness of the mean meridional flux mechanism in increasing UTWV VMR during negative AAO periods is amplified by the large latitudinal gradients in UTWV between southern mid and high latitudes. Note that these two mechanisms are not correlated spatially with each other to a high degree. This has been verified using the latitude and altitude dependence of their responses to the annular modes (Thompson and Wallace, 2000). The two mechanisms are complementary in that they both increase UTWV at high latitudes during the negative phase of the local annular mode.

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There are other mechanisms that are considered such as tropopause variations (discussed below) and meridional eddy moisture fluxes (Boer et al., 2001). As mentioned above, eddies are primarily responsible for the seasonal cycle of UTWV (Del Genio et al., 1994). However, Boer et al. (2001) clearly show for both hemispheres that annular-mode-related moisture fluxes via eddies are small (relative to the mean meridional flux) and of the wrong sign to explain the poleward transport of moisture in the high-latitude upper troposphere. However, only the meridional eddy flux term was considered, whereas Del Genio et al. (1994) point out that large scale eddies transport moisture upward as well as poleward.

We see no evidence in either high-latitude region of a fourth mechanism whereby the UTWV anomalies are simply explained by annular-mode-driven tropopause variations: the correlation between tropopause height or tropopause pressure anomalies and the relevant annular mode is not significant in either high-latitude region ($-0.1 < R < 0.1$). This is not surprising given that the magnitude of responses of water vapour and saturation vapour VMR to the annular modes diminish with increasing height toward the tropopause (Figs. 8-9). According to several studies (e.g. Cai and Ren, 2007; Ambaum and Hoskins, 2002; Highwood et al., 2000), the high-latitude tropopause tends to rise during the positive phase of the AO. Therefore, the response of the tropopause to the AO is of the wrong sign to explain increases of UTWV during the negative phase of the AO.

We proceed in this discussion considering only the first two mechanisms since they are supported by previous studies. The response profile of saturation vapour VMR relative anomalies (from analyses of the GEM assimilation system) to the AAO (Fig. 8) is studied in order to isolate and gain insight into the ~~relative~~ contribution of the ~~two~~first proposed ~~mechanisms. The ability to distinguish between the two mechanisms using saturation VMR anomalies requires that the mechanisms are not correlated spatially with each other to a high degree.~~ mechanism.~~This has been verified using the latitude and altitude dependence of their responses to the annular modes (Thompson and Wallace, 2000). The two mechanisms are complementary in that they both increase UTWV at high latitudes during the negative phase of the local annular mode.~~

Below 9 km, ~~this~~the response of saturation vapour VMR tends to be weaker than the response by deseasonalized water vapour observed by the ACE instruments, implying that the temperature mechanism cannot fully explain the strong observed response of water vapour to the AAO at southern high latitudes~~.~~ (Fig. 8). Near the tropopause (9.5-10.5 km), the response of saturation vapour VMR to the AAO becomes effectively zero (within 1σ), but the response of observed water vapour to the AAO is also decreasing considerably relative to lower altitudes. The response of water vapour to the AAO differs significantly between MAESTRO and ACE-FTS except at 5.5 and 6.5 km, making it generally difficult to unequivocally determine the ~~relative~~ contribution of the ~~two~~first proposed ~~mechanisms~~mechanism. Nevertheless, there is an obvious need for a mechanism in addition to the temperature-related one to explain the observed response of water vapour in the southern high ~~latitudes~~ latitude upper troposphere. ~~The effectiveness of~~This is consistent with the correlation between the annular mode and mean meridional moisture flux ~~mechanism during negative AAO periods is amplified by the large latitudinal gradients~~, particularly in ~~water vapour between this isolated region and~~ the southern ~~mid-latitudes.~~ hemisphere (Boer et al., 2001).

At northern high latitudes~~,~~ (Fig. 9), saturation vapour VMR responds to the AO in a similar fashion to its response to the AAO at southern high latitudes~~ (Figs. ~~.~~8-9).~~ The response of saturation vapour VMR to the AO at northern high latitudes tends to be smaller in magnitude than the response by water vapour inferred from ACE observations, but the difference is not statistically significant at all altitudes compared to the ACE-FTS water vapour response. The water vapour anomalies from the two ACE instruments show a decreasing response to the AO with increasing altitude at northern high latitudes, but generally differ in the magnitude of the response, as is the case as well at southern high~~-~~ latitudes. Thus, no general conclusion can be unequivocally drawn about the ~~relative contribution~~sufficiency of the ~~two~~first proposed ~~mechanisms~~mechanism in the northern high~~-~~ latitude upper troposphere.

~~We see no evidence~~The relative contributions by the different mechanisms involved in ~~either high-latitude region of a third mechanism whereby the UTWV anomalies are simply explained by annular-mode-driven tropopause variations:~~ the ~~correlation between tropopause height or tropopause pressure anomalies and the relevant annular mode is not significant in either high-latitude region (-0.1 <R<0.1). This is not surprising given that the magnitude of~~ ~~responses~~response of water vapour ~~and saturation VMR~~ to the annular modes ~~diminish with increasing height toward the tropopause.~~

remain uncertain partly due to significant intersensor differences (Figs. 8-9). Longer datasets and further analysis would be helpful to understand the contribution by ~~each~~the proposed ~~mechanism~~mechanisms.

Appendix A: Cooling rate differences

Cooling rate vertical profiles are calculated using MODTRAN5.2 (e.g. Bernstein et al., 1996) assuming an Antarctic surface altitude of 2.5 km, subarctic summer temperature profile, free tropospheric aerosol extinction (visibility of 50 km) and two water vapour cases:

(1) using MAESTRO climatological median water vapour between 6.5 and 9.5 km increased by the vertically-resolved water vapour response to AAO determined by multiple linear regression (with AAO and constant as the only predictors) for November 2009, when the AAO was in its negative phase (index of -1.92).

(2) same as (1), except for November 2010, when AAO index was +1.52 (positive phase).

Acknowledgements

The availability of the NOAA annular modes indices is appreciated. The ACE mission is supported primarily by the Canadian Space Agency. POAM III data were obtained from the NASA Langley Research Center Atmospheric Science Data Center. CES acknowledges Kaley Walker (University of Toronto) for her role in including MAESTRO in the Water Vapour Assessment (WAVAS) 2, organized by SPARC (Stratosphere-Troposphere Processes and their Role in Climate). CES is grateful to Frédéric Laliberté (Environment Canada) for a helpful discussion on separating the contributions by the two mechanisms proposed in Sect. 4.~~2~~3.

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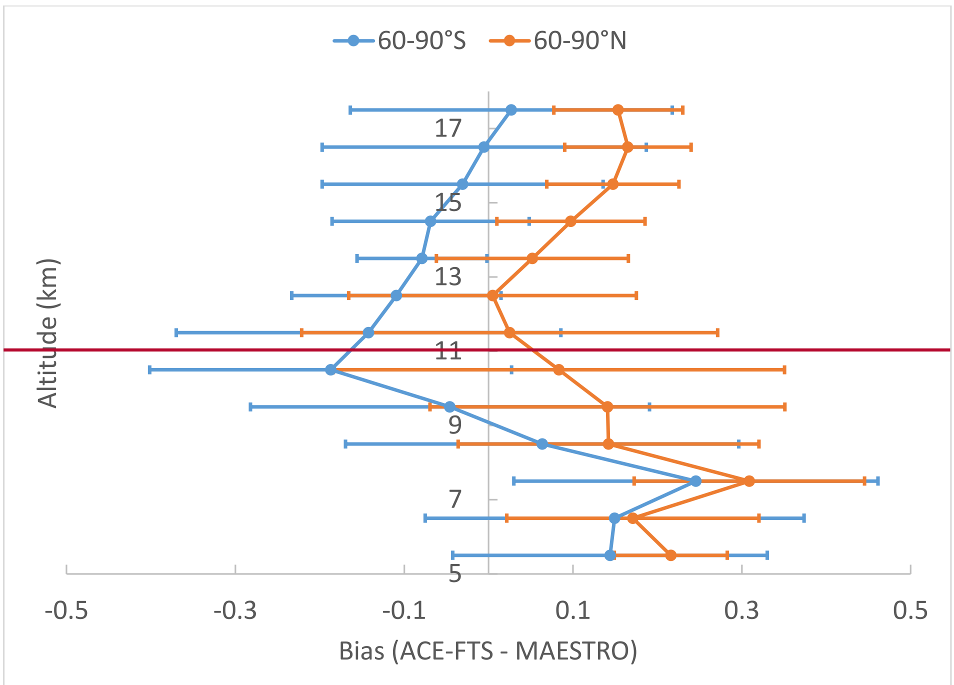


60-90°S
60-90°N
Altitude (km)
17
15
13
11
9
7
5
-0.5
-0.3
-0.1
0.1
0.3
0.5
Bias (ACE-FTS - MAESTRO)

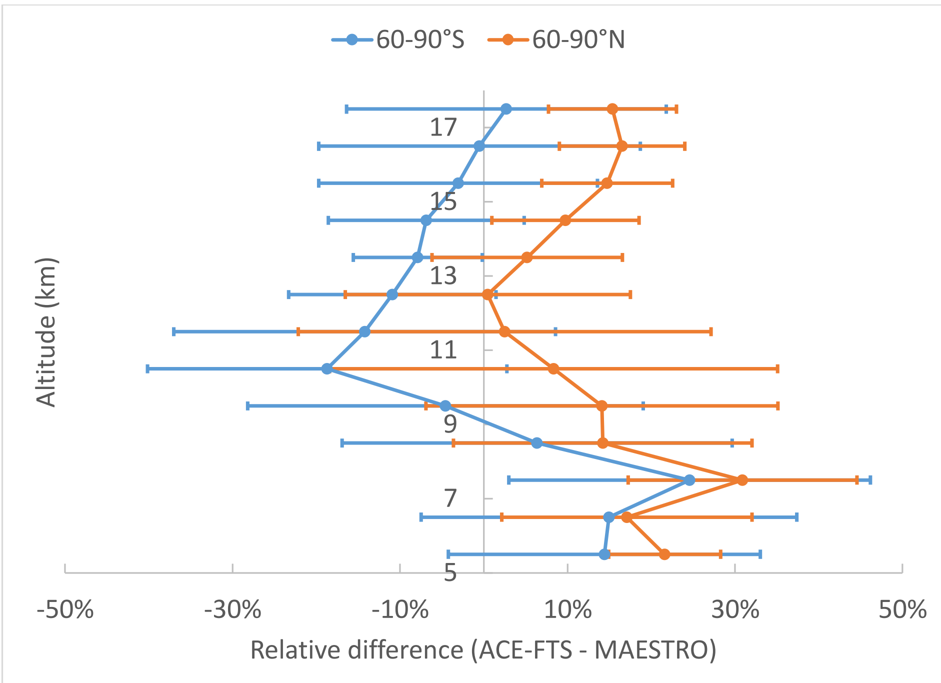


Figure 1. (orange) Relative differences between ACE-FTS and MAESTRO climatological medians averaged over the eight months sampling the northern high-latitude region and their standard deviation; (blue) relative differences between ACE-FTS and MAESTRO climatological means averaged over the eight months sampling the southern high-latitude region and their standard deviation. The horizontal bars show the standard deviation of the differences between the two climatologies over the eight available months. To account for vertical resolution differences, the MAESTRO climatology was vertically smoothed with a 3 km boxcar.

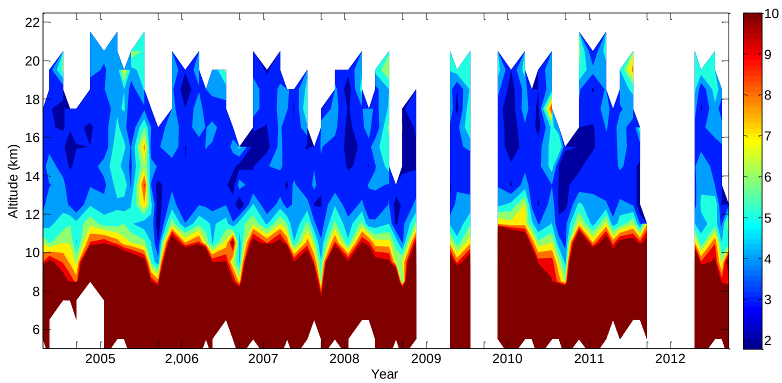


Figure 2. Time series of the MAESTRO monthly mean water vapour volume mixing ratio (VMR) versus altitude (5.5-22.5 km) at southern high latitudes (60-90°S) with a linear colour scale (ppm), emphasizing the stratospheric variability. Unlabelled ticks along the bottom correspond to September. The time series is composed using the eight months in which ACE samples the southern high latitudes (see Sect. 2.4).

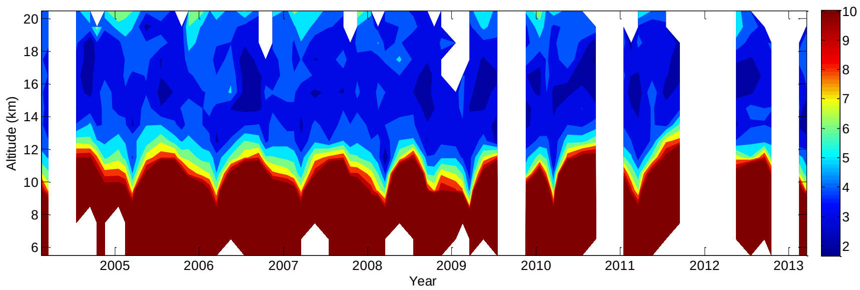
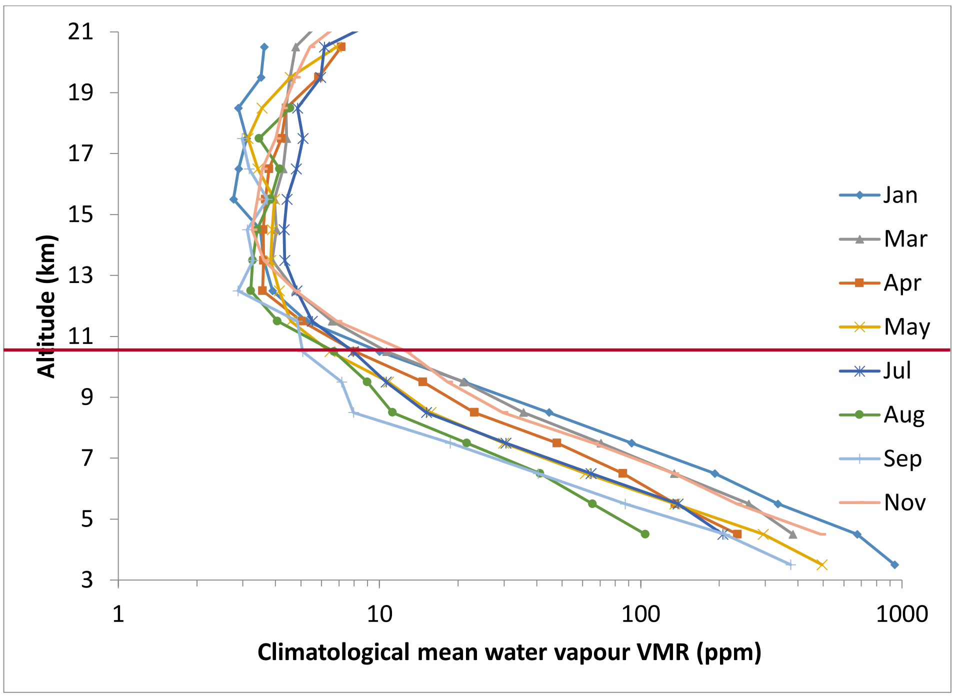
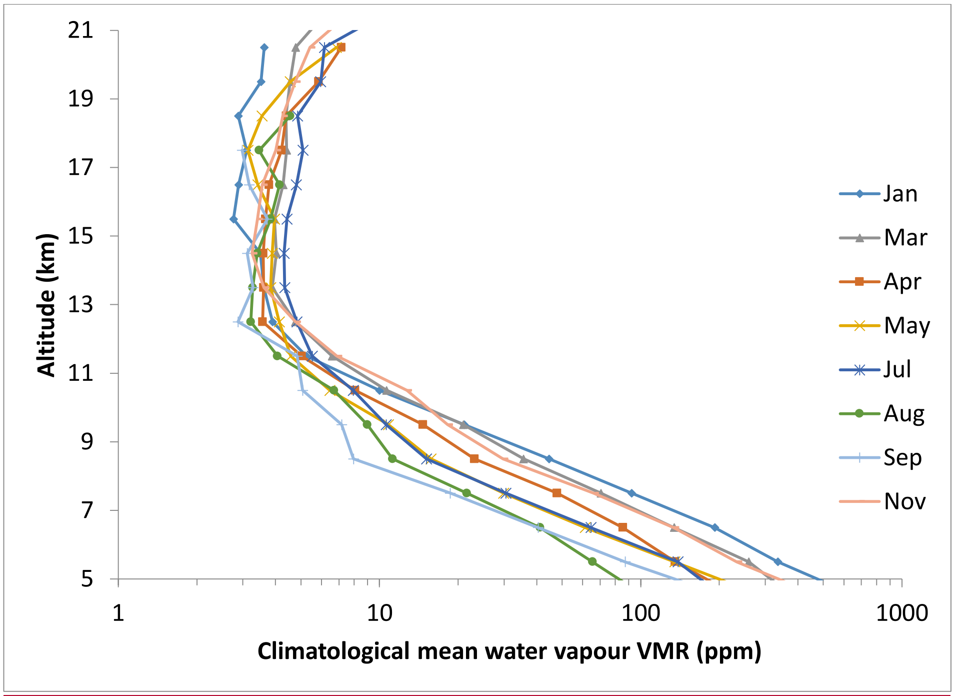


Figure 3. Time series of the MAESTRO monthly median water vapour volume mixing ratio (VMR) versus altitude (km) at northern high latitudes (60-90°N). The time series is composed using the eight months in which ACE samples the northern high latitudes (see Sect. 2.4).

1



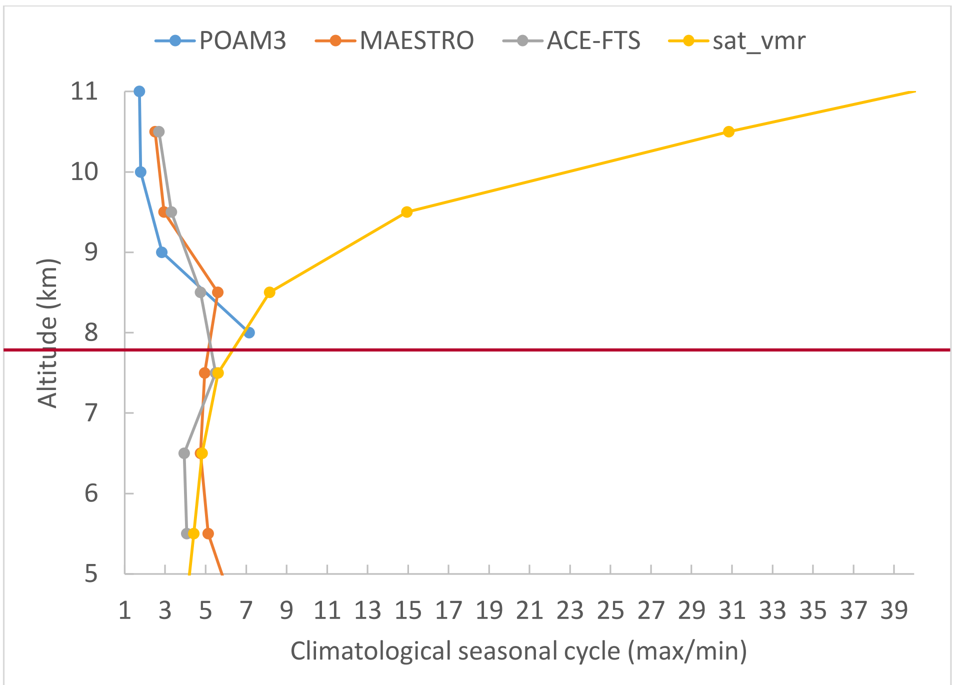
Altitude (km)
21
19
17
15
13
11
9
7
5
3
1
10
100
1000
Climatological mean water vapour VMR (ppm)
Jan
Mar
Apr
May
Jul
Aug
Sep
Nov



1

2 Figure 4. MAESTRO mean climatology (2004-2012) of the vertical distribution of water vapour
3 volume mixing ratio in the Antarctic (60-90°S) UT/LS for months with sufficient sampling of
4 the region. A logarithmic scale is used for the x-axis.

1



POAM3
MAESTRO
ACE-FTS
sat_vmr
Altitude (km)
11
10
9
8
7
6
5
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39
Climatological seasonal cycle (max/min)

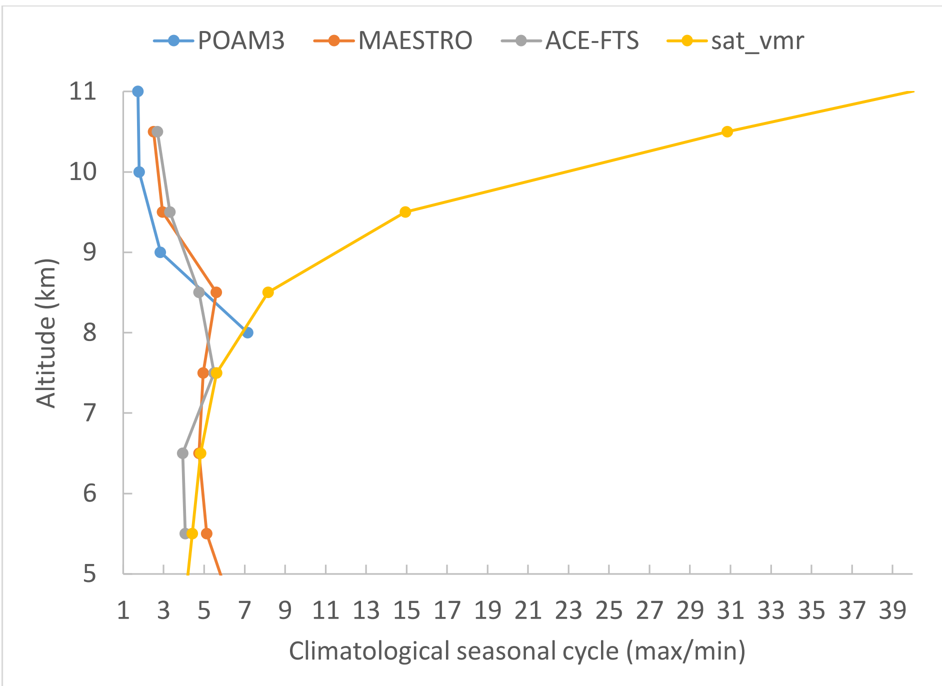
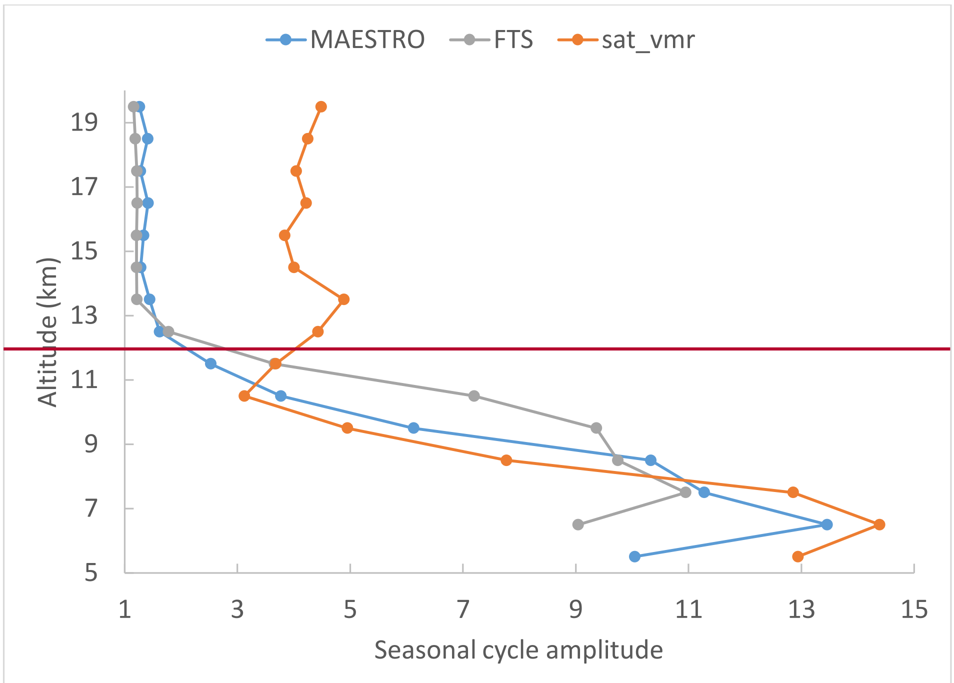


Figure 5. Vertical profile of the seasonal cycle amplitude of Antarctic water vapour observed by three instruments. The amplitude is calculated by taking the ratio of climatological monthly means at maximum (January or December) and minimum (August or September). Note that POAM III has a different orbit that tends to sample consistently at higher latitudes (Nedoluha et al., 2002) and thus tends to have stronger seasonality at 8 km (driven by the larger temperature range). The saturation vapour pressure climatology is obtained using GEM analysis temperatures sampled at ACE measurement locations.


MAESTRO
FTS
sat_vmr
Altitude (km)
19
17
15
13
11
9
7
5
1
3
5
7
9
11
13
15
Seasonal cycle amplitude

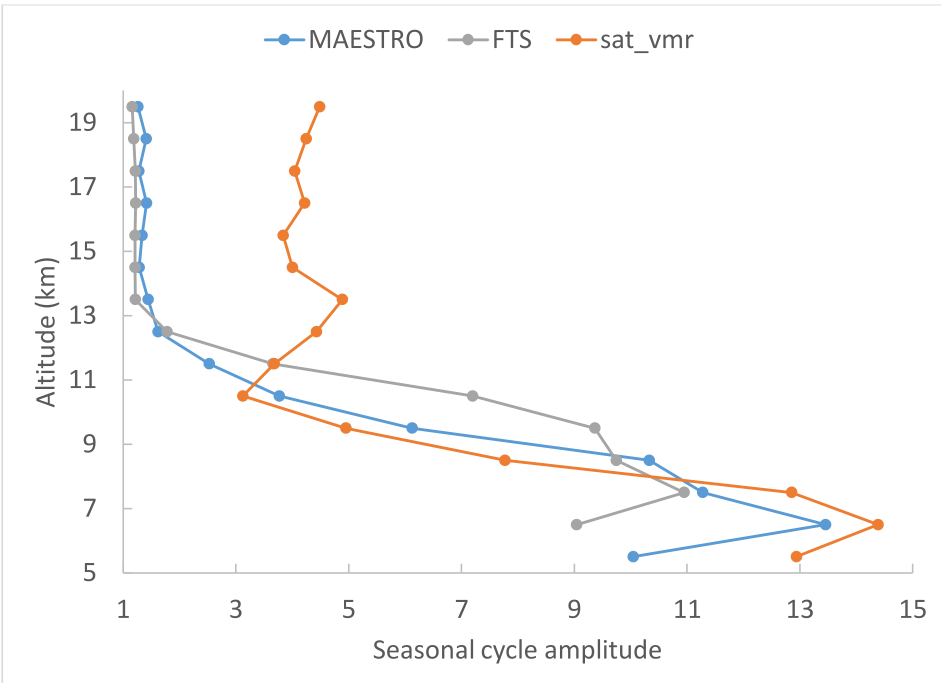
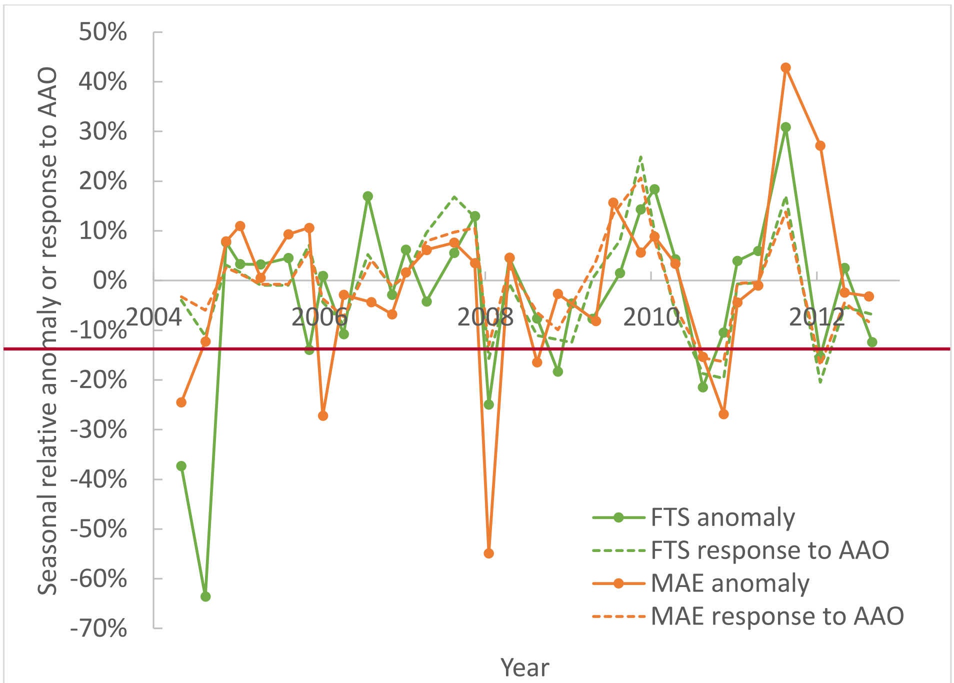


Figure 6. Analogous to Fig. 5 but for northern high latitudes. Profiles are presented at their respective native vertical resolutions.

1



Seasonal relative anomaly or response to AAO
50%
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
-50%
-60%
-70%
2004
2006
2008
2010
2012
Year
FTS anomaly
FTS response to AAO
MAE anomaly
MAE response to AAO

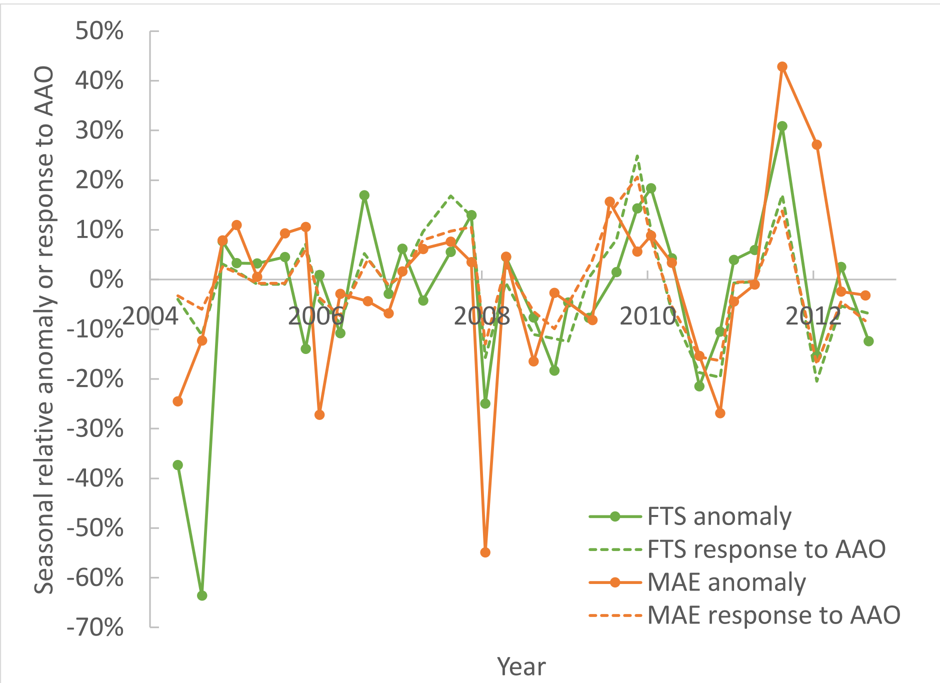
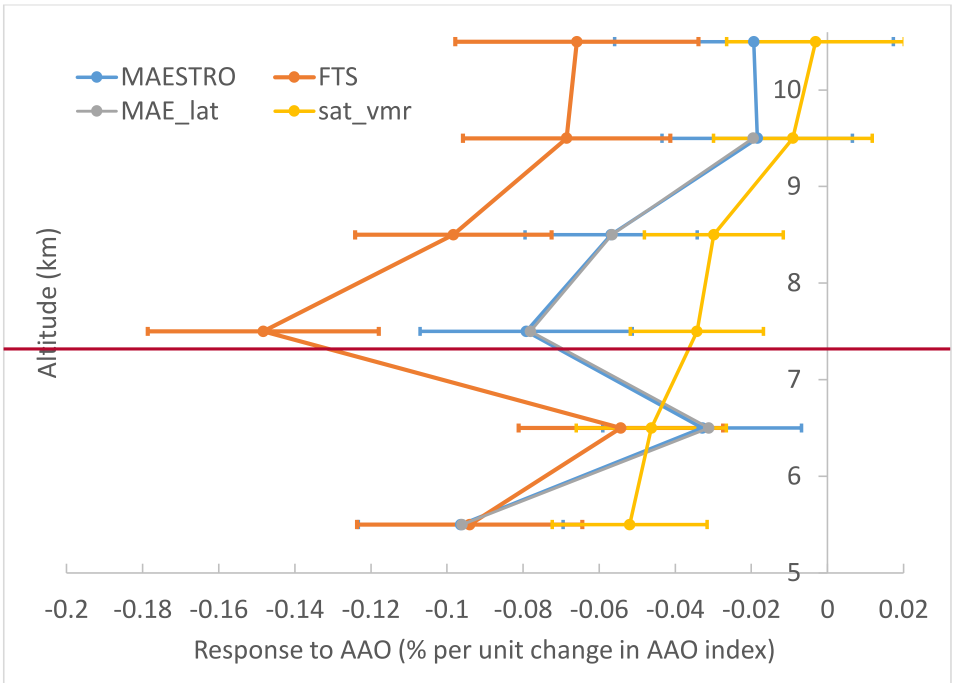


Figure 7. Seasonal median water vapour anomaly time series from MAESTRO (8.5 km) and ACE-FTS (7.5 km) in the Antarctic troposphere and the response of each to AAO determined by linear regression. Seasons with missing data are removed to avoid discontinuities. The markers on the response curves indicate the sampled seasons.


MAESTRO
FTS
MAE_lat
sat_vmr
Altitude (km)
5
6
7
8
9
10
-0.2
-0.18
-0.16
-0.14
-0.12
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
Response to AAO (% per unit change in AAO index)

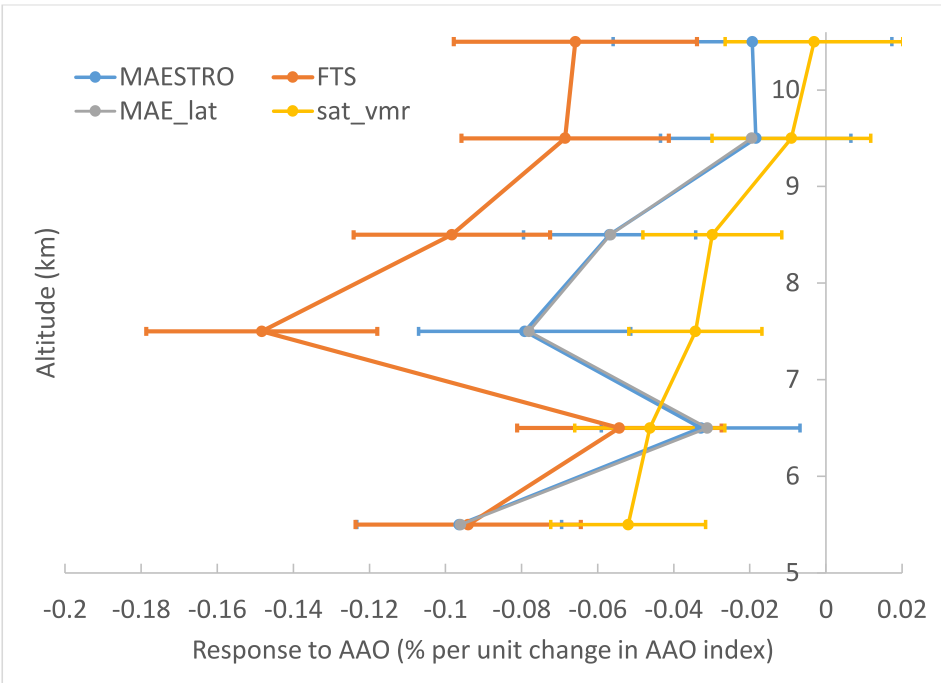
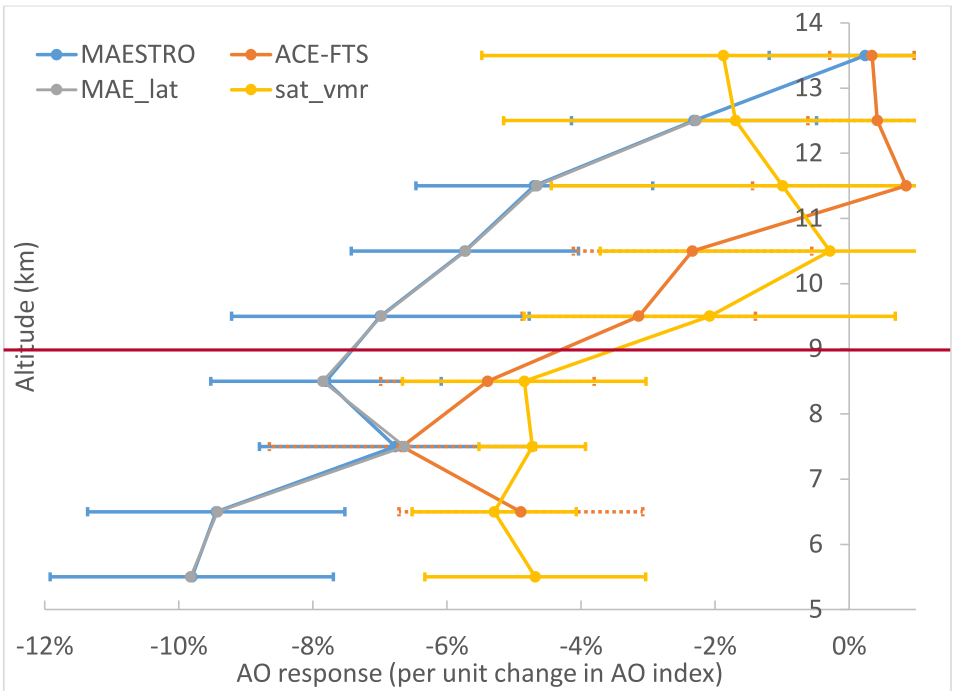


Figure 8. Vertical profile of response to AAO, using southern high latitude water vapour relative anomalies based on monthly medians (2004-2012). Horizontal bars are ±1σ, obtained by linear regression (including a trend term and/or a Puyehue proxy term depending on whether each is significant at the 1σ level). The "MAE_lat" profile shows the MAESTRO water vapour response to AAO upon including a basis function to account for the non-uniform latitudinal sampling. The 'sat_vmr' profile is obtained from a simple linear regression of saturation vapour VMR relative anomalies onto AAO.

1



MAESTRO
ACE-FTS
MAE_lat
sat_vmr
Altitude (km)
14
13
12
11
10
9
8
7
6
5
-12%
-10%
-8%
-6%
-4%
-2%
0%
AO response (per unit change in AO index)

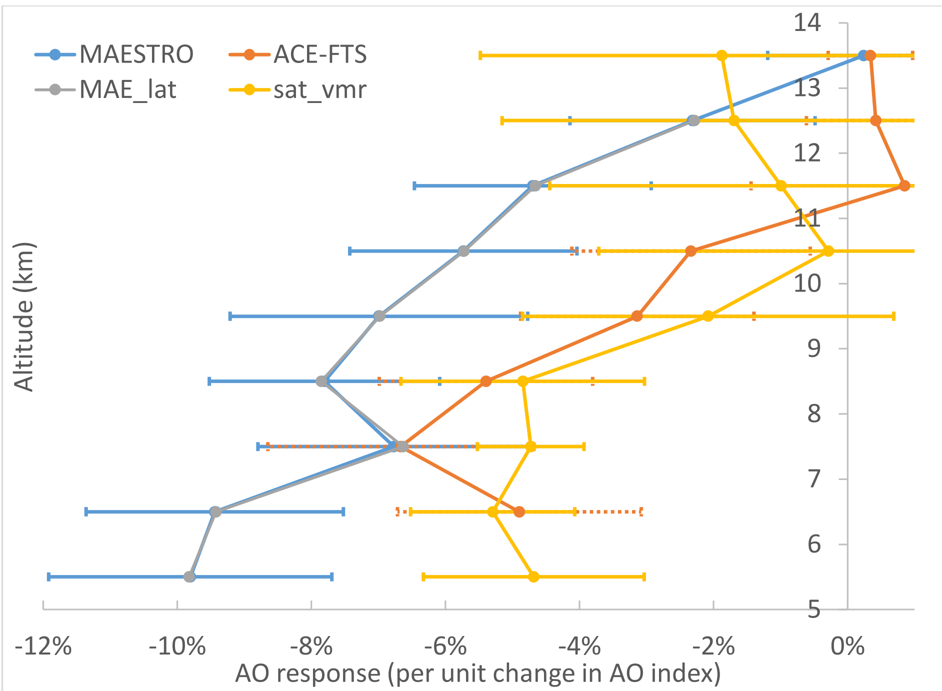
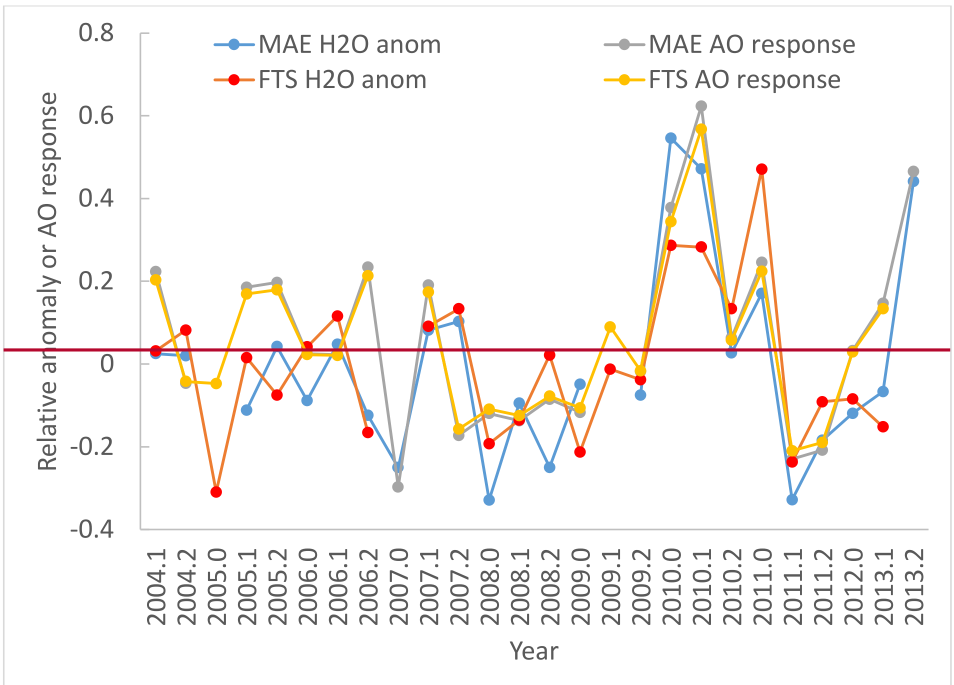


Figure 9. Analogous to Fig. 8, but for northern high latitudes water vapour in response to the Arctic oscillation. Error bars display ±1 standard error of the fitting coefficient for the AO index obtained by linear regression. At 5.5 km, the response of ACE-FTS is not shown since it has a standard error of >100% and the sample size decreases significantly.

1


MAE H2O anom
MAE AO response
FTS H2O anom
FTS AO response
Relative anomaly or AO response
0.8
0.6
0.4
0.2
0
-0.2
-0.4
2004.1
2004.2
2005.0
2005.1
2005.2
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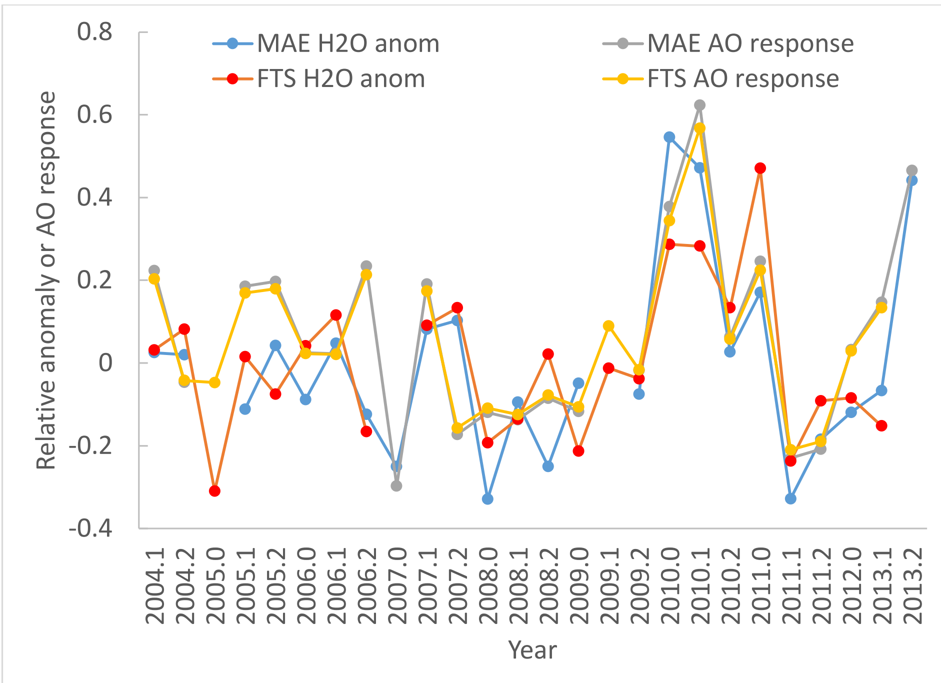

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2 Figure 10. Time series of water vapour relative anomalies observed by ACE-MAESTRO
3 ("MAE") and ACE-FTS at 6.5±0.5 km in winter months (January-March). Slight differences in
4 sampling exist between the two instruments due to the requirement for >20 observations per
5 month per altitude bin.