

Dear Editor

In the final response, we summarise the comments from the referees together with our point-by-point answers and directly indicate how we changed the manuscript. At the end of the document, there is a marked-up version of the revised manuscript.

## Response to Anonymous Referee #1

Dear Referee, we thank you for your comment. In the following we split your comment in two parts (*italics*) and present our response.

*In the introduction it is said that is important to understand the dynamically variable Arctic atmosphere to be able to improve atmospheric models. I think the authors have to expand upon this. Why is the Arctic atmosphere important to study? Can there for example be a connection between the dynamics in the Arctic middle atmosphere and the increased melting of the Arctic ice? Why are SSW crucial events?*

During an SSW the state of the atmosphere is highly distorted with effects observed in both dynamics and composition over different latitudes and altitudes (e.g. Chau et al. (2012), Dörnbrack et al. (2012)). The relevance of SSWs for measurement - model and model - model intercomparison has been covered in a variety of publications (e.g. Salmi et al. (2011), Straub et al. (2012), Pedatella et al. (2014)).

Our paper describes a data set obtained during a campaign and presents scientific results for two selected events: the two SSWs and the strong amplitudes of the Q2DW. The analysis of the two SSWs is based on the work presented in Straub et al. (2012). Presenting the results for the two following SSWs observed with the same instrument from the same location is valuable. But we think that repeating the motivation in the current paper would not add new information. In order to include your comment, we add the citation of Salmi et al. (2011), Dörnbrack et al. (2012) and Pedatella et al. (2014) in the introduction.

*The descent rates of middle atmospheric air, after the observed SSWs, are dis-*

*cussed in the paper. I think the authors have to expand upon this as-well. For example, which is the normal descent of Arctic air in the wintertime due to the meridional circulation?*

We agree with the referee that normal wintertime descent of the Arctic air is interesting. In MIAWARA-C's ground-based water vapour time series we see effects of the autumn descent. In autumn, the mixing barrier related to the polar vortex just starts to build up and to affect the latitudinal water vapour distribution. Therefore, the air sampled over Sodankylä does not necessarily represent "vortex air" and estimating the autumn descent from our data set would need additional investigation. Such a study is beyond the scope of our current paper but could be interesting for future work.

## References

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Straub, C., Tschanz, B., Hocke, K., Kämpfer, N., and Smith, A. K.: Transport of mesospheric H<sub>2</sub>O during and after the stratospheric sudden warming of January 2010: observation and simulation, *Atmospheric Chemistry and Physics*, 12, 5413–5427, doi:10.5194/acp-12-5413-2012, 2012.

## Response to Anonymous Referee #2

Dear Referee, your helpful and detailed comments and suggestions are highly appreciated and we thank you for investing your time. In the following we answer your comments and indicate changes in the manuscript. We summarise the main points of your general comments in italics and present the response.

We agree with the referee, there have been many studies investigating SSWs. Nevertheless, we think that extending the investigation of SSWs using new data is valuable for both understanding and categorising SSWs and for demonstrating the possibilities of ground-based measurements. We are aware that our contribution to research related to SSWs in this paper is a report of observations and we basically repeated a combination of the analysis used in Straub et al. (2012) and Scheiben et al. (2014) for two consecutive events with a water vapour dataset obtained at the same location.

In order to emphasise the Q2DW, we switch the sections in the text to match the order in the title with Q2DW first and SSW second. In addition, we are going to underline the Q2DW results in the abstract and discussion.

### **Comments:**

*page 373, lines 12 13: This sentence sounds somehow strange. Substituting entering with the transport of this trace gas could help. Besides that I would argue this transport is not the main source. For the middle atmosphere as a whole it is more like a 50-50 thing with the water vapour production from CH<sub>4</sub> and H<sub>2</sub> providing*

*the other half.*

We agree and changed the sentence to:

There are two major sources of middle atmospheric water vapour. The first one is vertical transport through the tropical transition layer. ...

*page 373, line 14: I suggest to use the term freeze-drying instead of dry-freezing. It is simply more common.*

Done.

*page 373, line 20: The horizontal gradients are sustained by the vortex edge. Otherwise the descending air would mix with mid-latitude air.*

We added:

..., which are sustained by the vortex edge.

*page 374, line 8: It should be two days, ... instead of of two day, .... And so on.*

Done.

*page 374, lines 25 - 28 & page 375, lines 1 - 3: There is a lot of doubling in these two sentences, like this paper, ground-based or radiometer, which makes a bit confusing. In addition, the phrase illustrate the capability appears to be too shy for the potential of such observations.*

Changed page 374, lines 23 - 28 & page 375, lines 1-3 to:

Measurements of the state of the atmosphere are essential for increasing the understanding of the dynamically variable Arctic winter atmosphere and help to improve the quality of models. In addition to satellites, ground-based instruments are used to monitor the atmosphere. They offer the benefit of being relatively easy to maintain and of a long lifetime compared to satellite instruments. In this paper water vapour data obtained with a microwave radiometer at the Arctic station of the Finnish Meteorological Institute FMI in Sodankylä in Northern Finland is used to demonstrate the capability of ground-based measurements at one station to monitor variations caused by Q2DW and SSWs.

The ground-based Middle Atmospheric Water vapour RAdiometer for Campaigns (MIAWARA-C) measured in Sodankylä for 20 months from June 2011 to March 2013. ...

*page 378, lines 27 - 28 & page 379, lines 1 - 3: I think the water vapour development here is even more complex than described. If you look at the lowermost mesosphere there appears to be a brief influx of former vortex air above Sodankylä just after the central SSW date. Shortly afterwards water vapour volume mixing ratios jump up again before a second weaker influx of former vortex air occurs. This happens within roughly 10 to 14 days after the central date of the SSW. Just at the 3 ppmv or 4 ppmv isopleth higher up in the middle mesosphere you see the steady descent in the aftermath of the SSW. Can you elaborate on that a bit? In that regard I think there are some inconsistencies to the message conveyed by the sentence in lines 18 - 20 on page 379.*

We generally agree with your comment, the water vapour isopleths for VMR values around 5.5-6 ppmv show the behaviour as you describe in your comment: there seems to be an influx of former vortex air right after the central date. A confirmation can be found in the distance to the vortex edge. For the year 2013, there is a double peak in distance to the vortex edge in the mesosphere and upper stratosphere. Calculation of Lagrangian 5day backward trajectories based on ECMWF operational data confirms that there have been different phases: 1) Just before the central date low-latitude air has been transported to Sodankylä. 2) Around the central date the origin of the air arriving at Sodankylä is in polar regions. 3) Afterwards, there is a second influx of low-latitude air.

In the revised manuscript we discuss the influx of former vortex air supported by the distance to the vortex edge and its effects seen in water vapour mainly for the 5.5-6 ppmv isopleths. The steady descent is only observed for VMR larger than 5 ppmv. Additionally, we have changed the order of the paragraphs.

*page 379, lines 5 - 6: I would be a little bit more careful here. In the uppermost stratosphere the vortex air could already be dryer than non-vortex air. Some nice examples of this are shown in Nassar et al. (2005) and Lossow et al. (2009).*

You are right. The transition from vortex air being more humid to being dryer compared to non-vortex air is located at approximately 40-45 km and does not coincide with the stratopause. We changed the sentence to: The descent above polar regions results in horizontal gradients of water vapour at the vortex edge. Inside the vortex, stratospheric air below 40-45 km is more humid than outside

whereas the mesospheric vortex air is characterised as being dryer than non-vortex air.

*page 380, lines 14 - 16: Something is fishy with the second part of the sentence. Should it be something like this: ... and only at high latitudes the Q2DW has been observed near winter solstice?*

Yes, thank you.

*page 381, line 3: I would put here already a reference to Figure 6.*

Done.

*page 381, lines 11 & 12: There is certainly no amplitude peak at 2 days at 0.05 hPa in November. But there is one close by with a period of little less than 2 days that very likely can be attributed as Q2DW. The amplitude is just a little smaller than in the uppermost stratosphere. So, the message that there is no Q2DW in the upper mesosphere I would not support.*

We assume that you are talking about the local maximum in amplitude at 1.5 days with an amplitude of 0.2 ppmv. Even though the amplitude is comparable to the one observed on 1 hPa with 2 days, it is much less defined if compared to neighboring periods. We had a look on figures showing period against time for 1.5 days for different altitudes and we do not see a clear maximum. Therefore, we do consider the small local maximum to be clearly related to the Q2DW.

*page 381, lines 15 & 16: Here you could add a reference to Merkel et al. (2003) and Sonnemann et al. (2008).*

We included the two references. We especially thank you for pointing out Sonnemann et al. (2008), it would have been a pity if we missed to mention their ground-based microwave work.

*page 381, discussion of Figures 5 - 7: The figures are discussed to discern differences in the Q2DW in the mesosphere and stratosphere. I feel that this is a bit misleading. From Figure 4 I would make a separation between above and below 0.1 hPa, roughly.*

You are right. We follow your suggestion and separate between above and below



0.1 hPa instead of mesosphere and stratosphere.

*page 387, Figure 2 & page 388, Figure 3: I did bother a bit with the upper panel of these figures. I found that the overlaid distance to the vortex edge is covering up some details that I liked to look on. Could that be an idea to move the information to a separate panel?*

Thank you for your suggestion. We added a fourth panel to the figure.

### **Technical corrections:**

*page 377, line 21: cause should read course. This happens again on page 379, line 24.*

Done.

*page 380, line 15: hight should read high.*

Done.

## **References**

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## Signatures of the two day wave and sudden stratospheric warmings in Arctic water vapour observed by ground-based microwave radiometry

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**Abstract.** The ground-based microwave radiometer MIAWARA-C recorded the upper stratospheric and lower mesospheric water vapour distribution continuously from June 2011 to March 2013 above the Arctic station of Sodankylä, Finland (67.4° N, 26.6° E) without major interruptions and offers water vapour profiles with temporal resolution of one hour for average conditions. ~~Over the measurement period, the instrument monitored the changes in water vapour linked to two sudden stratospheric warmings in early 2012 and 2013. Based on the water vapour measurements, the descent rate in the vortex after the warmings is 364 for 2012 and 315 for 2013.~~ The water vapour time series of MIAWARA-C shows strong periodic variations in both summer and winter related to the quasi two day wave. ~~In the mesosphere Above 0.1 hPa~~ the amplitudes are strongest in summer. The stratospheric wintertime two day wave is pronounced for both winters ~~on altitudes below 0.1 hPa~~ and reaches a maximum amplitude of 0.8 ppmv in November 2011. ~~Over the measurement period, the instrument monitored the changes in water vapour linked to two sudden stratospheric warmings in early 2012 and 2013. Based on the water vapour measurements, the descent rate in the vortex after the warmings is 364 m d<sup>-1</sup> for 2012 and 315 m d<sup>-1</sup> for 2013.~~

### 1 Introduction

The Arctic atmosphere is highly variable. Over the year, it is affected by the extremes of solar radiation ranging from long daylight periods in summer to the complete lack of Sun light in winter. The absence of radiative heating in the stratosphere leads to strong eastward winds, the polar vortex, and

descent of air over the Arctic region in winter. As a consequence of the polar winter condition, the temperature of the stratosphere decreases allowing polar stratospheric clouds to form. These clouds play a major role in the heterogeneous catalytic destruction of ozone in spring. In addition to influencing the temperatures the polar vortex acts as a mixing barrier for trace gases. This mixing barrier can give rise to sharp gradients in trace gases such as nitrous oxide, ozone or water vapour.

Thanks to its relatively long chemical lifetime in the order of months in the stratosphere and weeks in the mesosphere (Brasseur et al., 1999), water vapour can be used as a tracer for dynamical events in the middle atmosphere wherever there are horizontal or vertical gradients in the water vapour distribution. The global mean circulation leads to horizontal water vapour gradients from polar to mid-latitudinal middle atmosphere. Therefore, monitoring water vapour in polar regions is valuable for monitoring dynamics and events such as sudden stratospheric warmings (SSWs). For recent studies using water vapour as a tracer see e.g. Lossow et al. (2009), Lee et al. (2011), Straub et al. (2012), Scheiben et al. (2012). Ground-based microwave radiometry is the only method capable of obtaining middle atmospheric water vapour time series with temporal resolution in the order of an hour and therefore well suited for the investigation of dynamical effects in polar regions. The instruments measure reliably and can easily be maintained.

~~The main source~~ ~~There are two major sources~~ of middle atmospheric water vapour ~~is entering~~. ~~The first one is vertical transport~~ through the tropical transition layer. The lower stratosphere is extremely dry because of the cold tropopause temperatures in the tropics resulting in ~~dry-freezing freeze-drying~~. The second source of middle at-

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65 mospheric water vapour is the oxidation of methane lead-  
ing to a positive vertical gradient in volume mixing ratio  
(VMR) throughout the stratosphere. The increasing photo- 120  
dissociation with altitude results in a negative gradient in the  
mesosphere.

70 The latitudinal distribution of water vapour in the middle  
atmosphere is mainly determined by the large scale resid- 125  
ual circulation. Above the winter polar region dry meso-  
spheric air descends inducing horizontal gradients in the wa-  
ter vapour VMR. ~~This horizontal gradient makes, which~~  
~~are sustained by the vortex edge. These horizontal gradients~~  
75 ~~make~~ water vapour a valuable tracer for short term trans- 130  
port in the winter hemisphere, e.g. in the course of SSW.  
Above the summer polar region, upwelling of relatively hu-  
mid stratospheric air results in high water vapour VMR in the  
mesosphere.

80 Sudden stratospheric warmings are events occurring in the 135  
winter hemisphere and are characterised by a fast and strong  
increase of stratospheric temperature and simultaneous cool-  
ing of the mesosphere in the polar region. In the course of  
SSWs the polar circulation is strongly distorted from normal  
85 winter conditions with stratospheric zonal winds reversing to 140  
westward and the temperature increases from 60° N towards  
the pole. Studies of recent SSWs revealed transport processes  
and effects on tracers (Coy et al., 2009; Funke et al., 2010;  
Manney et al., 2009; Straub et al., 2012; Scheiben et al.,  
90 2012). The change in the wind field results in weakened or 145  
dissolved high-latitude transport barriers and leads to trans-  
port and mixing of air masses from lower latitudes to polar  
regions.

95 Uneven in-situ heating of the atmosphere and the asym- 150  
metric distribution of land can excite planetary waves. Nu-  
merous studies identified the most prominent periods of  
these waves to be approximately two ~~daydays~~, five ~~daydays~~,  
ten ~~day days~~ and sixteen ~~daydays~~. The most prominent plan-  
etary wave component in the mesosphere is the quasi-two day  
100 wave (Q2DW) with amplitudes larger than 10 K in temper- 155  
ature and wind amplitudes of several tens of  $\text{m s}^{-1}$  in the  
mid- to low-latitude summer mesosphere (Tunbridge et al.,  
2011; Wu et al., 1993). The QT2W can interact with at-  
mospheric tides and influence the variability of polar meso-  
spheric clouds (Merkel et al., 2009; Kulikov, 2007). Most  
105 observational studies of the Q2DW focus on the summer- 160  
time Q2DW with the largest amplitudes coming from west-  
ward propagating zonal wave numbers W2, W3 and W4 (e.g.  
Limpasuvan et al., 2000). In addition to analysis of dynami-  
cal variables, Limpasuvan and Wu (2003) analysed the sum-  
110 mertime Q2DW in mesospheric water vapour measured by 165  
UARS MLS and found amplitudes of up to 0.35 ppmv near  
the mesopause.

115 Recent studies discussed a strong Q2DW activity around 170  
winter solstice at high latitudes (Nozawa et al., 2003; Sand-  
ford et al., 2008; Tunbridge and Mitchell, 2009) related to  
an eastward propagating E2 wave using wind measurements  
from meteor radars and geopotential height from Aura MLS.

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~~Understanding-~~

~~Measurements of the state of the atmosphere are essential~~  
~~for increasing the understanding of the dynamically vari-~~  
~~able Arctic winter atmosphere is important for improving~~  
~~models and help to improve the quality of models.~~  
~~Examples of recent studies using SSW events for comparing~~  
~~models and measurements are given in Salmi et al. (2011),~~  
~~Dörnbrack et al. (2012) and Pedatella et al. (2014).~~ In addition  
to satellites, ground-based instruments are used to monitor  
the state of the atmosphere. They offer the benefit of being  
relatively easy to maintain and of a long lifetime compared  
to satellite instruments. In this paper data obtained by ground-  
based microwave radiometry water vapour data obtained with  
a microwave radiometer at the Arctic station of the Finnish  
Meteorological Institute FMI in Sodankylä in Northern Finland  
is used to illustrate demonstrate the capability of ground-based  
measurements of water vapour obtained at one station to  
monitor variations caused by Q2DW and SSWs.

~~This paper presents the water vapour distribution above~~  
~~Sodankylä measured by the The~~ ground-based Middle  
Atmospheric Water vapour RAdiometer for Campaigns  
(MIAWARA-C) measured in Sodankylä for 20 months from  
June 2011 to March 2013. The high temporal resolution of  
the order of one hour above one location can only be ob-  
tained by ground-based microwave radiometry. In addition,  
microwave radiometry is the only remote sensing technique  
capable of monitoring water vapour in the middle atmo-  
sphere from the ground (Kämpfer et al., 2012). Analysing  
the dominant periods in the water vapour variations on each  
altitude level, a strong Q2DW is identified and discussed.  
The wintertime Q2DW observed with MIAWARA-C is the  
first observation using ground based microwave radiometry.  
The water vapour evolution was recorded without major in-  
terruptions and shows the effects on water vapour during  
two autumn descents, one spring ascent and two SSWs. In  
both winters, there has been a SSW. The 2012 and the 2013  
SSWs are compared to the 2010 event which has been moni-  
tored by MIAWARA-C from the same location and is dis-  
cussed in detail in Straub et al. (2012). Straub et al. (2012)  
found a descent rate after the SSW of  $350 \pm 40 \text{ m d}^{-1}$  by  
fitting the 5.2 ppmv isopleth. By using backward trajectory  
calculations, the observed increase in water vapour VMR  
between 0.1 and 0.03 hPa could be attributed to meridional  
advection of subtropical air and mesospheric upwelling in  
the course of the SSW. ~~Analysing the dominant periods~~  
~~in the variations on each altitude level, a strong Q2DW is~~  
~~identified and discussed. The wintertime Q2DW observed~~  
~~with MIAWARA-C is the first observation using ground~~  
~~based microwave radiometry.~~

After describing the instrument, the measured water  
vapour time series is presented. The measured water vapour  
data is spectrally analysed and signatures of the summertime  
and wintertime Q2DW are discussed. Additionally, the two  
SSWs of 2012 and 2013 are discussed complementing

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the measured water vapour profiles with temperature data from Aura MLS and ECMWF model data. ~~Additionally, the measured water vapour data is spectrally analysed and signatures of the Q2DW are discussed.~~

**2 MIAWARA-C**

MIAWARA-C is a compact microwave radiometer designed for campaigns to measure middle-atmospheric water vapour profiles. It is controlled remotely and operated continuously under all weather conditions except rain. The pressure broadened emission line of water vapour at 22.235 GHz is measured with a heterodyne receiver and spectrally analysed with a fast Fourier transform spectrometer and a spectral resolution of 30.5 kHz and a usable spectral bandwidth of 400 MHz. A detailed description of the instrument is presented in Straub et al. (2010). With the ARTS/Qpack software package a water vapour profile is retrieved from the measured spectrum (Buehler et al., 2005; Eriksson et al., 2011) by the so called optional estimation technique (Rodgers, 2000). The retrieval version v1.1 used in this paper is described and validated in Tschanz et al. (2013).

For MIAWARA-C the reliable altitude range of the retrieval v1.1 is defined as the region where the area of the averaging kernel (AoA) is larger than 0.8. This definition results in a sensitive altitude range from 4 hPa (37 km) to 0.017 hPa (75 km). Beyond these limits the instrument is still sensitive, however the contribution from the a priori profile increases and the quality of the assignment to altitude levels decreases. The full width at half maximum of the averaging kernels is a measure for the vertical resolution of the water vapour profiles and is approximately 12 km in the reliable altitude range. The measured and calibrated spectra are integrated prior to the retrieval in order to increase the signal to noise ratio. For v1.1 the spectra are integrated until they reach a fixed noise level which results in a constant altitude range and in a varying integration time. The number of retrieved profiles per day is mainly determined by the tropospheric conditions and is presented in Tschanz et al. (2013) for both the 2010 and the 2011–2013 campaigns in Sodankylä. On 60% of all measurement days during the 2011–2013 campaign 10 or more profiles per day can be retrieved from MIAWARA-C's measured spectra.

**3 Campaign overview**

MIAWARA-C monitored middle-atmospheric water vapour above Sodankylä over 20 months without major data gaps from 13 June 2011 until 7 March 2013. There are only 3 measurement gaps of more than 24 h over the whole measurement period. The interruptions are mainly caused by rain. With a constant noise level in brightness temperature of 0.0141 K, a total of 8823 profiles could be retrieved.

An overview of the time series is presented in Fig. 1. The measurements of MIAWARA-C started in boreal summer with upwelling of humid stratospheric air into the mesosphere resulting in high water vapour vmr in the mesosphere. In September, the global circulation starts to turn to winter conditions with descent of dry mesospheric air shifting the water vapour maximum down to 10 hPa which is around MIAWARA-C's lower altitude limit. As a result of the descent, the polar mesosphere is extremely dry.

The data set obtained by MIAWARA-C is ideally suited to investigate the temporal variability in water vapour caused by periodic phenomena on short time scales or effects of events such as SSWs. Investigation of the quasi 16 day wave in mesospheric water vapour during the boreal winter 2011/12 based on data from MIAWARA-C has already been presented in Scheiben et al. (2014). This paper focuses on the effect of SSWs and the Q2DW.

In MIAWARA-C's time series the effects of two SSWs on water vapour are clearly visible, the first one taking place in January 2012 and the second one in January 2013. The central dates of the SSWs defined as the occurrence of the maximum zonal mean temperature at 1 hPa and 60° N are marked as black dashed lines in Fig. 1. A detailed discussion of the influence of SSWs on middle atmospheric water vapour and the 2010 event as observed by MIAWARA-C are presented in Straub et al. (2012) and Scheiben et al. (2012). In the **cause course** of a SSW, the eastward winds in the stratosphere are reversed to westward and humid mid-latitude or subtropical air is transported into the Arctic region. MIAWARA-C observes this humid air as a sharp increase in water vapour from 2 to 0.1 hPa. After both SSWs, the circulation returns to normal winter conditions and the descent over the Arctic restarts, which can be seen as down-welling of water vapour in the time series. Details of the effects of the SSWs are discussed in Sect. 3.2.

In addition to the two reversals to winter conditions and the two SSWs, MIAWARA-C observed the change from winter to summer circulation in 2012.

**3.1 Signatures of the quasi two day wave**

[Comment: used to be section 3.2](#)

Ground-based microwave instruments for water vapour such as MIAWARA-C can achieve a high temporal resolution in the order of hours and offer the possibility to investigate short term variations in the amount of the trace gas. The median of the integration time over the whole measurement period from June 2011 to March 2013 is below one hour allowing the investigation of periodic structures in water vapour in an ideal way. Spectral decomposition of MIAWARA-C's time series showed dominant variations with periods of approximately 16, 10, 5 and 2 days. A detailed analysis of the evolution and regional differences of the quasi 16 day wave for winter 2011/12 has already been presented in Scheiben

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et al. (2014) using ground-based microwave data of trace gases including the data obtained with MIAWARA-C. In this study we concentrate on the investigation of the Q2DW. At mid-latitudes, the Q2DW is most pronounced in the summer mesosphere and only at ~~high latitudes~~ high latitudes the Q2DW ~~near the winter solstice~~ has been observed ~~near~~ winter solstice (Nozawa et al., 2003; Sandford et al., 2008; Tunbridge and Mitchell, 2009).

For the spectral decomposition a wavelet-like approach is chosen as described in Studer et al. (2012). We successfully applied this method to other middle atmospheric trace gas studies (e.g. Hocke et al., 2013; Scheiben et al., 2014). The wavelet-like analysis has the advantage of capturing variations with non-persistent phase. The data on each retrieval pressure level are treated as a separate time series. A digital non-recursive, zero-phase finite impulse response filter is applied using a Hamming window with a length of three times the center period. We define the amplitude of the wave as peak-to-peak of the filtered signal.

The 2 day amplitude analysis of our data set is presented in Fig. 2. Generally, the Q2DW activity is stronger in the mesosphere above 0.1 hPa than below and varies strongly with time with slightly higher values in late summer and autumn. July 2012 shows a strong and persisting Q2DW above 0.1 hPa. As an example of the 2 day amplitude in the mesosphere, the results on 0.05 hPa are shown in detail in Fig. 4 and 5. Below 0.1 hPa the amplitude is higher in winter than in summer and coincides with the presence of the polar vortex over Sodankylä from November to April. The strongest Q2DW effects are observed in November 2011; the activity is strongly increased reaching values of up to 0.8 ppmv from 0.8 to 0.1 hPa corresponding to a relative amplitude of 10–15 %.

A periodogram for the two periods with enhanced Q2DW activity is presented in Fig. 3 for ~~a mesospheric and a stratospheric altitude level~~ two altitude levels, one above and one below 0.1 hPa. The amplitude shown is a mean value from 1 to 30 November 2011 and from 27 June to 24 July respectively ~~resulting in lower values~~. In November 2011, the 2 day wave is only observed on 1 hPa but not in the mesosphere on 0.05 hPa. On the other hand the example of a summer Q2DW for July 2012 shows ~~activity in the mesosphere but none in the stratosphere~~ enhanced activity above 0.1 hPa but none on the lower stratospheric level. In addition to 2 day activities, variations with periods from 14 to 18 days are visible on both altitude levels. In July 2012 on 0.05 hPa in the mesosphere, a relatively strong variation with a period of approximately 5 days is observed. In middle to high latitudes the summertime quasi 5-day variation has been identified as being predominantly a planetary normal mode (1,1) of Rossby waves (Merkel et al., 2003; Sonnemann et al., 2008). Sonnemann et al. (2008) have observed and analysed the quasi 5-day variations in a mesospheric water vapour

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data set obtained with a ground-based 22 GHz microwave radiometer.

An illustration of the Q2DW for the two periods showing both filtered time series and measurement is given in Figs. 4 and 5. In order to enhance the visibility of the periodic 2 day structure in the measurements, the filtered ~~signal~~ signals with periods of 5, 10 and 16 days are subtracted from the interpolated measurement. The mean of the measurement is added to the filtered signal. The close agreement of measurement and Q2DW signal on 1 hPa shown in Fig. 4 suggests the conclusion that the Q2DW activity in November 2011 attributes for most of the remaining variation. The mesosphere does not show a strong correlation between measurement and filtered signal. For the summertime Q2DW, which is illustrated in Fig. 5, the remaining variations in the measured data agree well with the filtered signal in the mesosphere but not in the stratosphere.

### 3.2 Signatures of 2012 and 2013 SSWs in water vapour

Comment: used to be section 3.1

MIAWARA-C has monitored the water vapour evolution above Sodankylä during three SSWs in 2010, 2012 and 2013. The 2010 event is discussed thoroughly in Straub et al. (2012). ~~The and the~~ discussion of the observed water vapour variations related to the ~~2012 and 2013 events~~ following SSWs follows Straub et al. (2012). An overview of the 2012 and 2013 events is illustrated in Figs. 6 and 7 with water vapour measured by MIAWARA-C, zonal mean temperature from Aura MLS v2.2 at 80° N and operational ECMWF zonal mean zonal wind at 60° N. The central date of the SSWs, which we define as the maximum zonal mean temperature at 1 hPa and 60° N, is 16 January for 2012 and 9 January for 2013.

The 2012 event shows two maxima in temperature at 1 hPa with the second one coinciding with the wind reversal. Trajectory analysis of the origin of the air above Sodankylä shows that both maxima coincide with transport from mid-latitude air (not shown here). The effects on water vapour can be seen for both temperature maxima as an increase between 1 and ~~0.4~~ 0.03 hPa caused by the transport of humid mid-latitude air into the polar region. The evolution of 80° N zonal mean temperature for 2012 is similar to 2010 (see Straub et al., 2012): at 1 hPa the temperature increases by 20 and 30 K for 2010 and 2012 respectively whereas there is an increase of 50 K in 2013. The 2013 event is characterized by extremely low temperatures of less than 200 K at approximately 3 hPa ~~approximately~~ one month after the SSW. The wind reversal of 2013 reaches low stratospheric altitudes and persists in the lower stratosphere for more than two months.

The ~~measured local water vapour time series shown in Figs. 6 and 7 shows for both the 2012 and the 2013 event a sharp increase in water vapour in the altitude range from 1~~



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to 0.03 hPa. After the 2012 event the water vapour descends steadily for two months and shows a similar behaviour as the 2010 SSW. Even though the 2013 event is pronounced in zonal mean temperature and wind, the effect on the local water vapour measurements are more complex. Coinciding with the wind reversal and the stratospheric warming, there is the increase in water vapour but the steady descent is only observed on the upper altitudes; the 5 isopleth (yellow colour) descends continuously whereas the 6 isopleth (red colour) shows a sharp descent at the time of the end of the wind reversal.

The zonal mean water vapour distribution is determined by the general circulation. In the stratosphere, vortex air descends above polar regions results in horizontal gradients of water vapour at the vortex edge. Inside the vortex, stratospheric air below 40–45 km is more humid than the air outside whereas the mesospheric vortex air is characterised as being dryer than non-vortex air (Nassar et al., 2005; Lossov et al., 2009). As discussed in Scheiben et al. (2012), potential vorticity might be used as a tracer for vortex air in the lower stratosphere but does not correlate with the observed tracer distributions in the upper stratosphere and lower mesosphere. Therefore, we apply the distance to the vortex method described in Scheiben et al. (2012) as an indicator for vortex air. Negative distance to the vortex edge implies that the vortex is located above the station.

The water vapour measurements for the 2012 and the 2013 SSWs overlaid by contours of as well as the distance to the vortex edge above Sodankylä are shown in Figs. 6 and 7. Before the warmings the vortex is mainly centred at the pole resulting in a constant distance to the vortex edge for all altitudes above Sodankylä. In late December 2012–2011 the vortex starts to be disturbed which can be seen by a change in the distance to the vortex edge. The change in the distance to the vortex edge coincides with a first short wind reversal in the mesosphere and a temperature increase and decrease in the stratosphere and mesosphere respectively (Fig. 6). In the course of the SSW mid- to low-latitude air enters the polar region as the vortex is disturbed. The air above Sodankylä is of low latitude origin which can be seen as an increase in water vapour. The period after the SSW 2013 shows a steady recovery to winter conditions, on all altitudes above Sodankylä air of the reforming polar vortex and the steady descent of the humid air is observed. For 2012 the situation is similar in general but descent is interrupted in late February there. There is non-vortex air above Sodankylä resulting in a short increase of water vapour from 1 to 0.02 hPa. During this increase the vortex edge is located above Sodankylä.

The measured local water vapour time series shown in Figs. 6 and 7 shows for both the 2012 and the 2013 event a sharp increase in water vapour in the altitude range from 1 to 0.03 hPa. After the 2012 event the water vapour descends for two months and shows a similar behaviour as the

2010 SSW except for the short period when non-vortex air passes over Sodankylä. Even though the 2013 event is more pronounced in zonal mean temperature and wind, the effects on the local water vapour measurements are more complex. Coinciding with the wind reversal and the stratospheric warming, there is the increase in water vapour but the steady descent is only observed on the upper altitudes; water vapour isopleths of values smaller than 5 ppmv (green and blue colour) descend continuously whereas the 5–6 ppmv isopleths (orange and red colour) show a sharp and short descent right after the central date of the SSW. This descent can be explained by former vortex air passing over Sodankylä after the central date and is consistent with a double peak structure in the distance to the vortex edge.

MIAWARA-C has observed three warmings at Sodankylä. After the warmings normal polar winter conditions are reforming and the humid air which has entered in the course of the event is descending with the mean residual circulation. Following Straub et al. (2012), the descent rate of the air above Sodankylä after the SSWs is determined by linearly fitting the 5.2 ppmv isopleth. For 2012 the time period from 16 January to 18 February is considered for the fit and 9 January to 17 February for 2013. The resulting descent rates of  $364 \text{ m d}^{-1}$  for 2012 and  $315 \text{ m d}^{-1}$  for 2013 are comparable to  $350 \text{ m d}^{-1}$  determined for the 2010 warming (Straub et al., 2012).

#### 4 Conclusions

Observational data of middle atmospheric water vapour obtained at the Arctic research station in Sodankylä has been presented. The focus has been put on discussing the water vapour time series measured by the ground-based microwave radiometer MIAWARA-C. This instrument has monitored the water vapour evolution above Sodankylä from June 2011 to March 2013 without major measurement gaps. The temporal resolution of the retrieved profiles is approximately one hour for average conditions. The high temporal resolution of the data set allows the investigation of short term variations in this key atmospheric constituent. The data set of MIAWARA-C is used to investigate variations with periods close to two days related to the Q2DW. A wavelet like analysis showed a varying activity in the mesosphere with generally higher amplitudes in the Arctic summer. Additionally, there is an enhanced activity in 2 day oscillation for both 2012 and 2013 winters below 0.1 hPa reaching a maximum value of 0.8 ppmv in November 2011. In addition to the strong Q2DW activity, there was a SSW in both winters affecting the measured water vapour profiles. Around the zonal mean wind reversal there is a sharp increase in water vapour caused by transport of humid mid- to low-latitude air into polar regions from 1 to 0.06 hPa. After the SSW the circulation returns to normal winter conditions and the air descends over the Arctic region. The descent rates after the

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SSWs are  $364 \text{ m d}^{-1}$  for 2012 and  $315 \text{ m d}^{-1}$  for 2013, for  
 2010 Straub et al. (2012) found  $350 \text{ m d}^{-1}$ . In 2012 the de-  
 scent was interrupted by a short increase in water vapour in  
 late February which can be explained by the polar air moving  
 away from Sodankylä and the measurement of air originating  
 from lower latitudes. Ground-based microwave radiometry  
 of middle atmospheric water vapour thus is an excellent tool  
 to investigate periodic structures and transport events.

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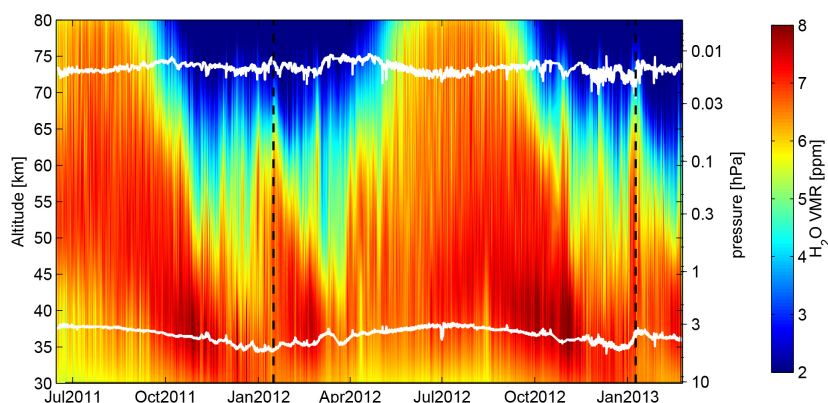
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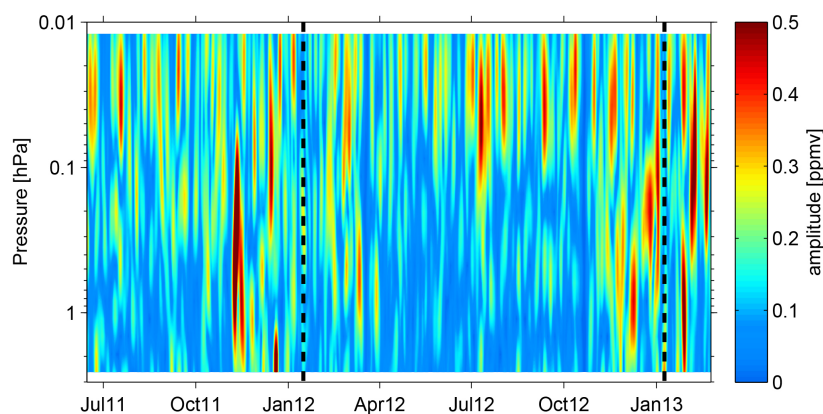
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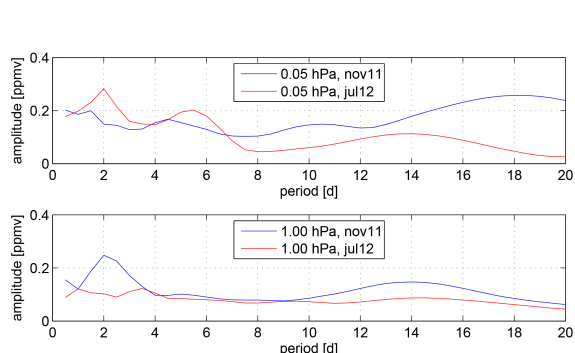
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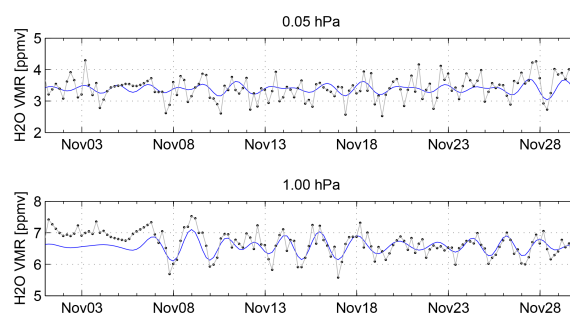
**Figure 1.** Overview of the water vapour time series measured by MIAWARA-C. The two black dashed lines mark the central dates of the two SSWs. The reliable altitude range is indicated by white lines ( $AoA > 0.8$ ).



**Figure 2.** Amplitude of the 2 day activity in MIAWARA-C's water vapour time series. The two black dashed lines mark the central dates of the two SSWs.



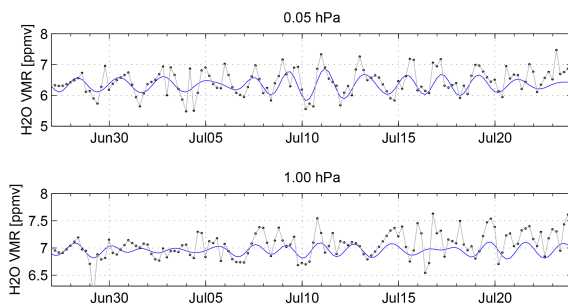
**Figure 3.** Mean amplitude of different periods obtained by filtering the water vapour time series on two altitude levels (top: 0.05 hPa, bottom: 1 hPa) for 1 to 30 November 2011 (blue) and 27 June to 24 July 2012 (red).



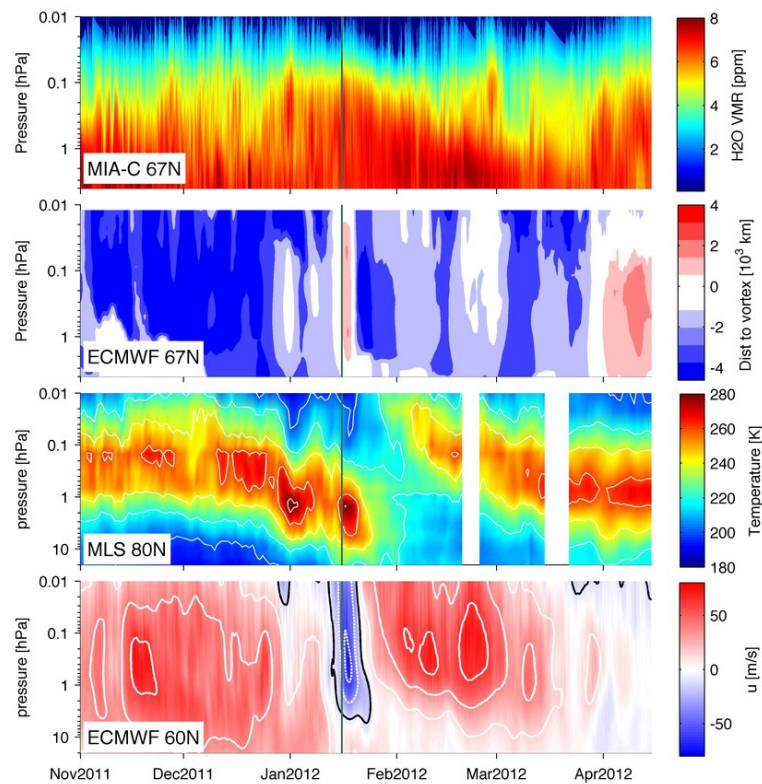
**Figure 4.** Measured water vapour data (black dots and grey lines) and filtered Q2DW signal (blue lines) for 0.05 and 1 hPa for November 2011. The mean value over the time period has been added to the filtered signal and contributions with periods of 5, 10 and 16 days have been subtracted from the measurement. In winter, the Q2DW is strong at 1 hPa and accounts for most observed variations with periods shorter than 5 days.

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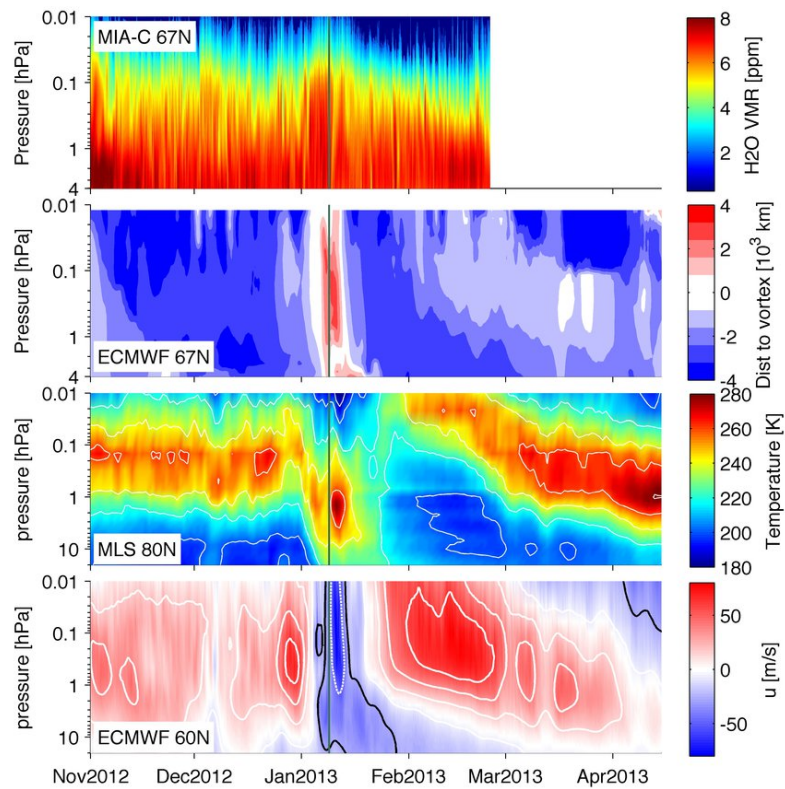
**Figure 5.** Measured water vapour data (black dots and grey lines) and filtered Q2DW signal (blue lines) for 0.05 and 1 hPa for July 2012. The mean value over the time period has been added to the filtered signal and contributions with periods of 5, 10 and 16 days have been subtracted from the measurement. In summer, the Q2DW is strong at 0.05 hPa but cannot explain the observed variations with periods shorter than 5 days on 1 hPa.



**Figure 6.** SSW 2012, the vertical green line marks the central date of the SSW (16 January 2012). First panel: water vapour measured by MIAWARA-C. Second panel: distance to the vortex edge (negative distance: polar vortex above Sodankylä, positive distance: non-vortex air above Sodankylä). Third panel: zonal mean temperature at 80° N from Aura MLS. Bottom: zonal mean zonal wind at 60° N from ECMWF operational analyses.

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**Figure 7.** SSW 2013, the vertical green line marks the central date of the SSW (9 January 2013). First panel: water vapour measured by MIAWARA-C. Second panel: distance to the vortex edge (negative distance: polar vortex above Sodankylä, positive distance: non-vortex air above Sodankylä). Third panel: zonal mean temperature at 80° N from Aura MLS. Bottom: zonal mean zonal wind at 60° N from ECMWF operational analyses.