A new height for the summer mesopause – Antarctica, December 2007

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Abstract

Two VHF atmospheric radars operating in Antarctica during austral summer 2007/2008 found the Polar Mesosphere Summer Echo (PMSE) layer at 3-5 km higher altitude during the early season, compared to the late season, and to earlier seasons. Temperatures from the microwave limb sounder on the Aura satellite, show that the height of the cold summer mesopause was ~3 km higher than usual at the same time. The winter polar vortex over Antarctica did not break up until late December, so that eastward winds in the lower stratosphere were as strong as westward winds in the upper stratosphere during the early part of the austral summer. We find that a combination of limited gravity wave forcing from below in the same hemisphere and interhemisphere coupling between the winter stratosphere/mesosphere and the summer mesopause may explain the observations, and suggest a need for reappraisal of the formation mechanisms for the summer mesopause.

Index terms

3334 3349 3332

Introduction

The polar summer mesopause region, at about 80-90 km height, is much colder than anywhere else in the atmosphere. It is so cold that ice clouds form, despite the very low amounts of water vapour present. These noctilucent clouds (NLC, also known as polar mesospheric clouds, PMC) can be seen by eye from the ground and have been documented for more than 100 years [*Gadsden and Schröder*, 1989]. It has been suggested that NLC characteristics will be a sensitive indicator of increasing greenhouse gases in the atmosphere [*Thomas et al.,* 1989]. However, although some studies claim to have seen increasing NLC brightness [*DeLand et al*., 2007], others do not see a significant change in NLC occurrence and point out that there are aspects of NLC climatology which are still not well understood (particularly wave effects and the quasi-decadal cycle, *Kirkwood et al.,* [2008]). Hence, effects of increasing greenhouse gases may be difficult to resolve. On the other hand, there is a widespread view that at least the processes determining the height of the NLC layer are well understood.

The height of the mesopause, i.e. the temperature minimum between the mesosphere and thermosphere, has previously been reported by *von Zahn et al.*[1996] and *She and von Zahn* [1998] to lie at only two different levels worldwide. Using various techniques to measure temperature profiles, a higher level mesopause near 100 km altitude was found to prevail over most of the globe, while a distinct lower height, near 88 km, was found at mid- to high latitudes in the summer hemisphere. This two-level mesopause has been reproduced by modelling, including sensitivity tests, by *Berger and von Zahn* [1999]. The height of the 'normal' mesopause was found to be determined primarily by radiative and photochemical factors whereas the lower height and colder temperatures of the summer mesopause can be reproduced only by the inclusion in the model of (parameterized) gravity wave (GW) drag. There are however more recent reports from low-latitudes that the two-level concept may be inadequate [*Friedman and Chu*, 2007].

As the ice particles which form close to the mesopause become ionised, they also lead to very strong radar echoes known as Polar Mesosphere Summer Echoes (PMSE), which are readily detected by VHF radar. The height range of PMSE has been found to correspond well to the height range of water vapour saturation from just above to just below the summer polar mesopause [*Morris et al.,* 2007], while NLC generally lie below the mesopause, in the lower part of the PMSE layer [*von Zahn and Bremer*, 1999]. The heights of NLC and PMSE have also been reported to vary little from time to time and over the globe. For example, the centroid heights for NLC lie at 83 km at Andenes (69°N, *Fiedler et al.* [2005]), between 83 and 85 km at Spitzbergen (78° N, *Lübken et al.,* [2008]), between 83 and 85 km at Rothera (68°S) and between 84 and 87 km at South Pole [*Chu et al.,* 2003, 2006]. The height of maximum PMSE occurrence so far reported for the northern hemisphere (NH) lies at 85 km at Kiruna, Andenes and Svalbard (68°N , 69°N, 78°N, *Kirkwood et al.,* [2007], *Hoffmann et al,* [1999], *Lübken et al.,* [2004], respectively) at 86 km at Davis and at Wasa (69°S, 73°S, *Morris et al.,* [2007], *Kirkwood et al.,* [2007]) and at 85 km at Halley (76°S, *Jarvis et al.,* [2005]). Reports so far of PMSE and NLC heights show changes of ~1-2 km over the season (which lasts from about 1 month before mid-summer to 2 months after mid-summer), most often with an overall downward trend from early to late season [*Chu et al.,* 2003, 2006, *Morris et al*., 2007, *Lübken et al.,* 2008].

In the austral summer 2007/2008, two VHF radars were operating in Antarctica to observe PMSE. In December, the whole PMSE layer was found to lie up to 5 km higher than usual, with a rapid downward migration to usual heights in early January. Here we present those observations, and discuss their interpretation.

Observations

Figure 1 compares temperatures measured by the microwave limb sounder (MLS) on the Aura satellite with the PMSE observations for the 2007/2008 season made by the Davis radar (55 MHz, 69°S, 78°E), and the MARA radar at Wasa/Aboa (54.5 MHz, 73°S, 13°W). Detailed descriptions of the two radars can be found in *Morris et al.,* [2004] and *Kirkwood et al.,* [2007]. The MLS measurements are described in *Schwartz et al.,* [2008]. We have used MLS v.2.2 results with 1.8 km added to the MLS estimate of geopotential height (GPH) to account for suspected bias in the MLS value (0.45 km, *Schwartz et al.*, [2008]) and the difference between geopotential and geometric height (1.35 km), since the radars measure geometric height. Downward trends over the season are clear in all panels. The lower edge of the PMSE layer follows the 160 K contour through almost the whole season, the centre lies 2-3 km below the temperature minimum. Note that the FWHM of the MLS averaging kernels at mesopause heights is 14-16 km so that more detailed comparison with PMSE heights (resolution 150 m) is not meaningful.

Figure 2 (upper panel) compares seasonal PMSE height changes from the two Antarctic radars, with a 10-year record from the NH radar ESRAD in Kiruna, Sweden [*Kirkwood et al.* 2007]. The centroid heights for the layers have been computed using 1-day averaged signal-to-noise ratio (SNR), then smoothed by a 5-day running mean. Centroid height is a weighted mean height – we have used log(SNR) as the weighting factor (0 for SNR<1). Figure 2 (upper panel) clearly demonstrates the small height changes which are usually observed for the PMSE layer in the NH. In the southern hemisphere (SH), heights are more variable from year to year and over the season. The 2007/2008 austral summer stands out with the highest PMSE layer height in the early season and the biggest change between early and late season (3 km at Davis, 5 km at Wasa/Aboa). The seasons 2004/2005 and 2005/2006 show the lowest maximum heights with least change over the season (~1 km). 2006/2007 shows PMSE highest at the very beginning and in the middle of the season.

Discussion

Temperatures at the summer mesopause are generally considered to be driven far below radiatively determined values by dynamic effects. Predominantly eastward propagating GWs break in the upper stratosphere and mesosphere, depositing eastward momentum and causing deceleration of the westward zonal wind. The vertical gradient in the zonal wind must be balanced by a poleward decrease of temperature, hence the polar summer mesopause is driven towards low temperatures. In the zonal mean equilibrium case, balancing residual flows also arise, from the summer to the winter hemispheres at mesopause heights, and upward (downward) flows below in the summer (winter) polar region (e.g. *Andrews et al.,* [1987], ch.7). GWs with predominantly eastward momentum will reach the mesosphere only if westward winds are stronger than eastward winds at heights below the mesosphere, so that westward-travelling GWs are preferentially filtered out. In the NH, the seasonal change, from eastward stratospheric winds in winter, to the westward stratospheric winds of summer, occurs long before the start of the PMSE/NLC season (see Figure 2, lower panel, and *Kirkwood et al.*, [2008]), and affects all stratospheric heights more or less simultaneously. In this situation the preferential filtering of westward travelling GWs will be sure to happen. In the southern hemisphere (SH), the change from winter to summer wind direction in the mesosphere also occurs well before the NLC/PMSE season [*Dowdy et al.,* 2007], but in the stratosphere it occurs much later, in general several weeks after the start of the PMSE/NLC season (Figure 2, lower panel). At the time when SH PMSE start to be observed (typically late November), westward winds in the upper stratosphere/lower mesosphere are no stronger than the eastward winds still blowing in the lower stratosphere. So filtering of eastward and westward travelling GWs reaching the upper mesosphere will be rather symmetrical, and no net eastward momentum flux can be expected. Reduced GW forcing alone might be expected to lead to a warmer summer mesopause, but the observations (Fig. 1) show the coldest mesopause in the early season when the GW forcing is weakest. MLS temperature profiles over Wasa and Davis (not shown) also demonstrate that the mesopause between 1-21 December was 5-10 K colder in 2007 compared to 2005 and 2006. At the same time, MLS temperatures just below the mesopause (75-85 km) were 5-10 K higher in 2007, again suggesting less GW forcing at those heights than in previous seasons.

Becker and Fritts [2006] have proposed an additional dynamic forcing contributing to the formation of the summer mesopause, namely extension of the meridional circulation from the winter to the summer hemisphere at mesopause heights. They used modelling to show that this can lead to an additional deceleration of the zonal wind in the summer hemisphere. Further experimental support for the possibility of interhemispheric control has been found in terms of a statistical relationship between NLC properties and stratospheric temperatures in opposite hemispheres [*Karlsson et al.,* 2007].

Since the change to winter circulation in the NH usually occurs in August/September, long before the start of the SH NLC/PMSE season (Figure 2, lower panel and *Dowdy et al.,* [2007]), forcing from the NH might be expected to be the dominant mechanism in the early SH season. We can also note that the onset of summer in the stratosphere in the SH 2007/2008 season (i.e. the reversal of the zonal wind) was later than average, after the solstice, in late December, likely favouring the interhemispheric coupling mechanism. However, this late onset was not unique – a similar late onset occurred in 1999/2000 and in 2006/2007 the onset was only slightly earlier. Slightly higher NLC altitudes at South Pole were reported in 1999/2000 compared to 2000/2001 [*Chu et al.,* 2003] but the height of the PMSE layer in 2006/2007 did not reach as high as in 2007/2008 (*Fig 2, upper panel).* So although the late change to summer circulation in the stratosphere might be part of the explanation, something more may be needed to explain the high PMSE heights in the early 2007/2008 season, compared to 2006/2007.

Becker and Fritts [2006] used a model with explicit GWs to study the factors affecting the NH PMSE season in 2002. They found that increased Rossby wave activity in the SH (winter) stratosphere led to a lower height for the GW driven branch of the residual circulation in the same hemisphere. This circulation pattern carried over to the NH (summer) where it corresponds to an eastward zonal acceleration at the same height. Reversing this argument, we might expect to find this circulation at higher altitude than usual in the winter hemisphere (NH) in December 2007 if there is reduced Rossby wave activity there. Inspection of stratospheric diagnostics (http://code916.gsfc.nasa.gov./Data_services/met/ann_data.html) indeed indicates unusually low levels of Rossby wave activity (low levels of northward momentum flux at 45–75°N) in the lower stratosphere (100 hPa) at the end of November and the beginning of December. In addition, temperatures in the upper part (10 hPa and above) of the northern polar vortex in December 2007 were among the lowest recorded since 1978, a further indication of low Rossby wave activity.

To estimate the state of the residual (meridional) circulation at mesopause heights in the NH we use winds measured by the meteor radar in Kiruna, Sweden (69°N, 20°E) [*Mitchell et al.,* 2002]. A comparison of the winds between the 2007/2008 season (solid line) and previous seasons is shown in Figure 3. The lower panel represents a measure of the level of planetary wave activity. Here we can see that late 2007 stands out as a year with very little planetary wave disturbances, as found in the NH stratospheric data. However, two other years show similarly low disturbance levels, late 2001 and late 2006. Figure 3 (upper panel) shows 25-day averaged meridional winds in the upper part of the mesopause region. Between 10 and 40 days before solstice, the wind in late 2007 was systematically slightly poleward. Similar winds were seen in late 2006 and even stronger poleward winds in late 2001. (The meridional wind between 80 – 90 km in late 2007 was slightly equatorward, and not significantly different to previous years). The poleward wind above 90 km fits qualitatively with the concept of interhemispheric coupling – a poleward meridional wind at 92-99 km in the NH could lead to an equatorward wind and eastward forcing at the same altitude in the SH.

The height of the summer mesopause depends both on this interhemispheric forcing and other factors (photo-chemical heating, same-hemisphere wave forcing). It will move in height with the inter-hemispheric forcing only if this term dominates. However, we note that the maximum pre-solstice poleward wind in the NH, 20 days before solstice, corresponds to the highest altitude for the SH PMSE layer. Similar arguments should apply to late 2006 and 2001. There are no SH measurements of PMSE or NLC heights in late 2001 to compare with, however as we see in Fig. 2, PMSE height in late 2006 was slightly higher compared to earlier years, although not as high as in late 2007. On the other hand, the measurements in Figure 3 are from a single location and may not be representative for the whole hemisphere. In practice, considerable modelling effort, including all contributing factors, will be needed to check whether interhemispheric coupling can indeed cause the observed variability of SH mesopause height.

Summary

Two VHF atmospheric radars were operating in Antarctica, at Wasa/Aboa (73°S, 13°W) and at Davis (69°S, 78°E) in the austral summer 2007/2008. Both radars observed the PMSE layer at 3-5 km altitude higher during late November, December and early January, than for the remainder of the season. Temperature measurements from MLS on the Aura satellite show that the mesopause over Antarctica was located ~3 km higher in the early season, compared to the later season. The winter polar vortex over Antarctica did not break up until late December, so that eastward winds in the lower stratosphere were as strong as the westward winds in the upper stratosphere during the early part of the PMSE season. This means that the usual explanation of the formation of the cold summer mesopause by breaking GWs, filtered by predominantly westward winds in the stratosphere cannot apply. We consider instead the possible role of inter-hemispherical coupling from NH residual circulation (as proposed by *Becker and Fritts* [2006]). We find evidence for lower than average levels of planetary wave activity and a stronger meridional jet in the NH between 92 and 99 km in early December 2007. This supports the possibility of forcing at mesopause heights from the winter hemisphere at higher altitudes than usual.

We find that the year-to-year and seasonal variations of PMSE height are much greater in the SH than in the NH. The observations indicate that middle-atmosphere conditions in both the same hemisphere and in the opposite hemisphere may contribute to this.

The concept of only two mesopause levels worldwide, determined respectively by radiative/chemical processes and by GW propagation from below [*Berger and von Zahn*, 1999], needs to be revised. For SH summer, models must be developed to show also a third, intermediate and variable level, which is not seen every year. Our observations support the possibility that the SH early summer mesopause forms through forcing from the winter hemisphere, at times when the GW forcing from below is ineffective.

We further note that existing models using only parameterized GW forcing (LIMA, *Lübken and Berger*, [2007]), fail to correctly reproduce the start date of the PMSE/NLC season. PMSE (and NLC) are systematically observed at much earlier dates (1-3 weeks) than predicted by the model, in both hemispheres. It seems that the interhemispheric coupling mechanism proposed by *Becker and Fritts* [2006], may offer a solution to both problems.

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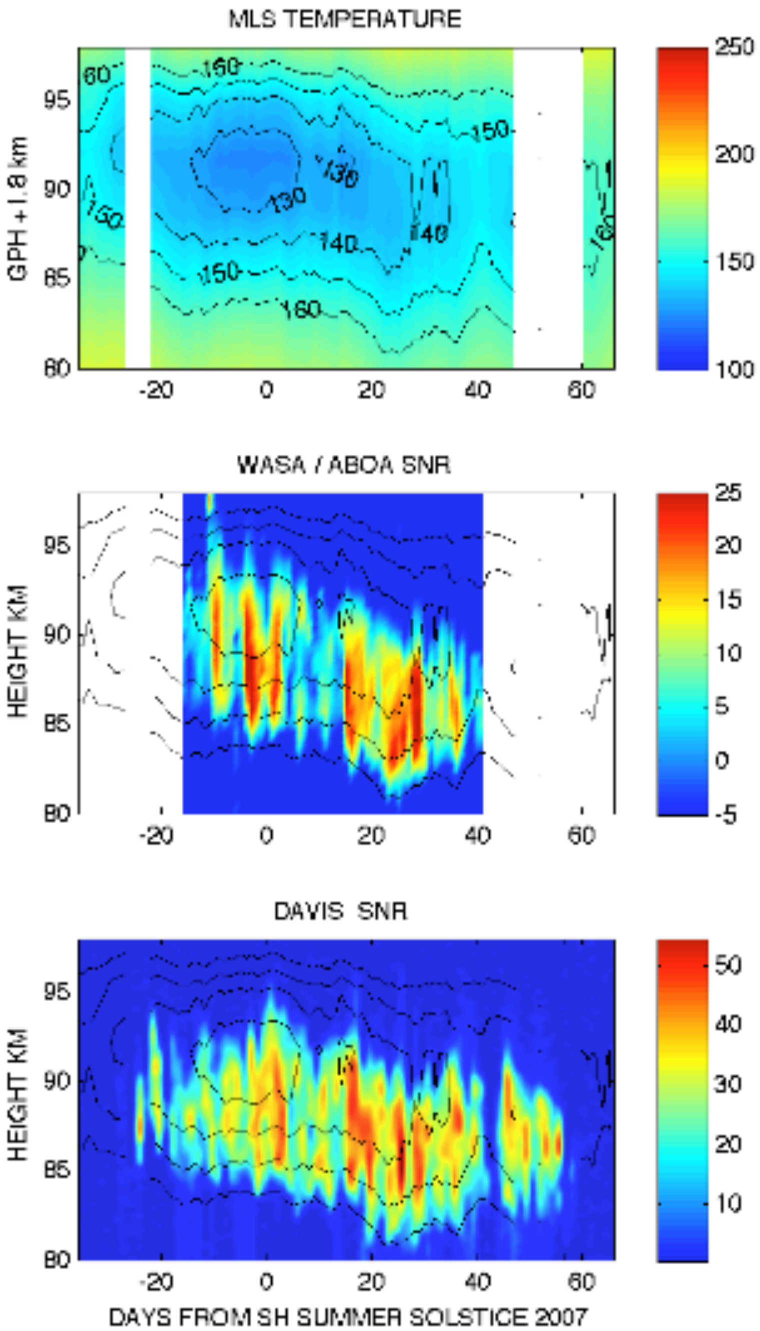

Figure 1. Top panel: Zonal mean temperatures from Aura-MLS averaged over latitudes 70-75 ° S. Middle panel: PMSE SNR (dB) measured at Wasa/Aboa. Lower panel: PMSE SNR (dB) measured at Davis. MLS temperature contours are reproduced on all 3 panels.

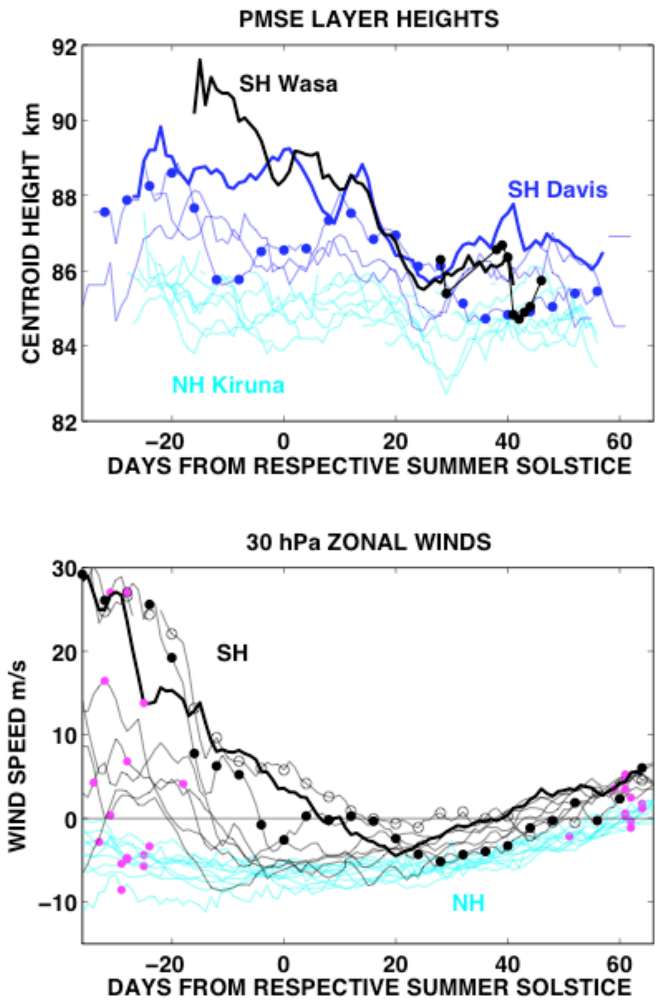

Figure 2. Comparison between NH (cyan) and SH (black/blue). *Upper panel:* Centroid heights for PMSE layers. Thick black line: Wasa/Aboa Dec 2007-Jan 2008 ; Thin black line with black circles: Wasa/Aboa Jan/Feb 2007. Cyan: Kiruna (1997, 1998 and 2000-2007). Thick blue lines: Davis 2007/2008. Thin blue lines: Davis 2004/2005, 2005/2006, and 2006/2007 (2006/2007 marked with blue circles).

Lower panel: Zonal mean zonal winds at 30 hPa, 60° N (cyan) and 60° S (black). Only years when the start and end of the PMSE or NLC season are known are plotted. Thick black line marks Austral winter 2007/2008, open circles 1999/2000, filled circles 2006/2007. Magenta dots mark the start and end of the PMSE season. (NH: PMSE from ESRAD, Kiruna, SH: 1999-2001, HF PMSE from *Hosokawa et al.,* [2005]; 2002, PMC from *Karlsson et al.,* [2007], since 2003 from Davis VHF radar). Winds from NCEP (http://code916.gsfc.nasa.gov./Data_services/met/ann_data.html)

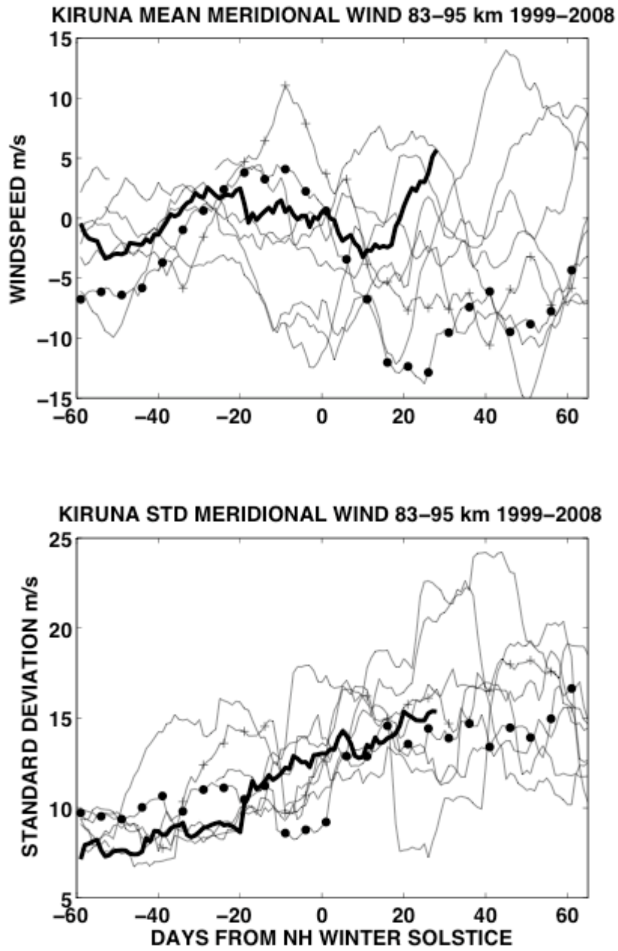

Figure 3. Characteristics of meridional winds in the upper mesosphere from the meteor radar in Kiruna, Sweden (NH winter), for the winter seasons Nov. 1999- Feb. 2008. Thick black line shows winter 2007/2008 , + 2001/2002, o 2006/2007. Upper panel shows running mean (for the 25 days before the date plotted) meridional wind at heights 83-95 km winter. Lower panel shows standard deviation of daily mean winds, over the 83-95 km height interval, for 25-day intervals preceding the date plotted.