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Observations of vertically thick polar stratospheric clouds and record low temperature in the Arctic vortex

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Abstract. On 12 and 13 January 2001 backscatter sondes launched at Sodankylä, Finland (67° N, 27° E) detected an extraordinarily thick polar stratospheric cloud layer of more than 8 km vertical extent. On these days the polar vortex passed over northern Scandinavia. This provided synoptic-scale low stratospheric temperatures leading to the formation of both liquid and solid phase particles. Two days later, on 15 January 2001, a regular radiosonde measured record low temperature of 176.7 K at an altitude of 25.2 km at the vortex edge. High vertical resolution radiosonde profiles and meteorological analyses indicate strong mountain wave activity on this day. This provides further evidence that the coldest temperatures in the Arctic lower stratosphere occur as a consequence of mountain wave cooling under cold synoptic-scale background conditions.

Introduction

Cold temperatures trigger the activation of inert chlorine species at the surface of polar stratospheric cloud (PSC) particles by complex heterogeneous reactions [*Solomon*, 1999]. PSCs consist of water ice particles (PSC of type II), of solid nitric acid trihydrate ($HNO_3 \cdot 3\ H_2O$ - NAT; PSC of type Ia), or of liquid supercooled ternary solutions ($HNO_3/H_2SO_4/H_2O$ - STS; PSC of type Ib). For a given mixing ratio of water vapor and nitric acid, PSCs can exist if the local temperature falls below one of the threshold values $T_{\mathrm{NAT}} > T_{\mathrm{STS}} > T_{\mathrm{frost}}$ [*Hanson and Mauersberger*, 1988]. The actual formation process, however, is still a matter of debate [*Peter*, 1997; *WMO*, 1999]. The greater the region occupied by PSC particles the greater the probability of large-scale ozone reduction in spring. Indeed, low Arctic springtime ozone levels were observed during cold stratospheric winters [*Rex et al.*, 1997]. Low temperatures inside the vortex are related to weak planetary wave forcing [*Coy et al.*, 1997; *Newman and Nash*, 2000].

Here we report and discuss two exceptional observations in the wintertime Arctic stratosphere 2000/01 obtained by balloonborne measurements performed from Sodankylä, Finland (67° N, 27° E). First, backscatter sondes detected an extremely thick PSC layer inside the polar vortex on two consecutive days. Secondly, a regular radiosonde measured record low stratospheric temperature close to the edge of the polar vortex two days later.

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Observations

Balloonborne backscatter sondes were launched on 12 and 13 January 2001. These sondes measure aerosol backscatter at wavelengths $\lambda = 490$ and 940 nm with an average vertical resolution of 30 m [*Rosen and Kjome*, 1991]. The backscatter ratio R_λ is defined as the ratio of total (i. e. aerosol and molecular) to molecular backscatter. Pressure, temperature, ozone density, and tropospheric relative humidity are measured simultaneously. The instrument signal noise relevant for our measurements is of the order of 1%. The aerosol color index CI, defined by $(R_{940}-1)/(R_{490}-1)$, serves as a rough estimate for particle sizes and allows to distinguish between liquid (CI < 6) and solid (CI > 9) particles [*Larsen et al.*, 1997].

On both days a thick PSC layer was detected extending from about 18 to 26 km of altitude (Fig. 1). On 12 January, the backscatter ratios R_{940} and R_{490} fluctuated around 7 and 2, respectively. The color index was generally small (around 6). Between 18 and 23 km of altitude the temperature dropped slightly below T_{STS}. Thus, the cloud layer was mainly composed of liquid droplets, most likely a STS. On 13 January, the stratosphere above 20 km cooled down by about 4 K and a pronounced stratification developed (Fig. 1, bottom). The backscatter ratio R_λ for both λ increased dramatically in the cold layers (maximum values $R_{940} \approx 55$, 150, and more than 200 in altitudes of circa 21.5, 22.5, and 25.5 km were obtained). The values of R_{490} were generally smaller, but increased significantly in the three layers as well. CI-values greater than 9 were found in all of the cold layers, which indicate the presence of water ice particles. Furthermore, maximum R_λ-values correspond to regions with $T < T_{\mathrm{frost}}$.

In Fig. 2a, the temperature profiles of the two backscatter sondes are shown together with a sequence of high vertical resolution radiosonde profiles in the period from 11 to 17 January. Temperatures below the frost point were measured during each sonde launch between 13 and 14 January. We further point out that in the shown period, a remarkable rise and fall of the tropopause with a maximum to minimum difference of about 4 km occurred. During this event the tropopause reached its maximum of about 13 km on 13 January at 18 UT. This value is more than 3 km larger than the long-term average tropopause level in January at Sodankylä.

On 15 January 2001, a series of five radiosonde launches enabled the observation of large-amplitude stratospheric temperature fluctuations. The vertical temperature profiles are characterised by a nearly uniform tropopause level

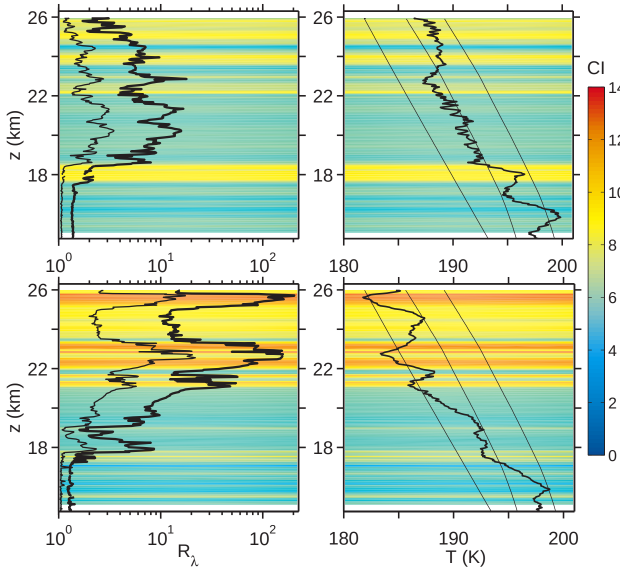

Figure 1. Left: Vertical profiles of backscatter ratio R_λ on 12 January 2001 at 17:40 UT (top) and 13 January 2001 at 17:52 UT (bottom) measured by balloonborne backscatter sondes. Thick solid lines mark $\lambda = 940$ nm, thin lines $\lambda = 490$ nm. Right: Corresponding temperature profiles. The threshold temperatures $T_{\text{frost}} < T_{\text{STS}} < T_{\text{NAT}}$ are indicated by straight solid lines. They are calculated assuming volume mixing ratios of 5 ppm for water vapour and a LIMS profile at 68° N for HNO_3 [*Carslaw et al.*, 1994]. The aerosol color index CI = $(R_{940} - 1)/(R_{490} - 1)$ is shown as colorshading in the background of each plot.

and a marked inversion above the tropopause (Fig. 2a). However, the rising top of this inversion and the gradually growing stratospheric temperature fluctuations mark the stratospheric wave event. The largest temperature fluctuations on this day occurred at 12 UT. In this sounding, three stratospheric inversions of about +4 K/km (this corresponds to a Brunt-Väisälä frequency of $N \approx 2.6 \cdot 10^{-2}$ s^{-1}; $N = \sqrt{g/\Theta\, \mathrm{d}\Theta/\mathrm{dz}}$, where Θ is the potential temperature) alternate with layers where the temperature drops more than 23 K within 4 km ($N \approx 1.4 \cdot 10^{-2}$ s^{-1}). Below the highest inversion the sonde measured a record low temperature of 176.7 K at an altitude of 25.2 km (this is the coldest temperature in the 42 years database of regular radiosoundings at Sodankylä). During the night and the following day the wave amplitude diminished and the tropopause descended.

The amplification of the large-amplitude stratospheric temperature fluctuations went along with a steady increase of the near-surface wind speed and the wind speed maximum near the tropopause (Fig. 2b). There, maximum values of 50 - 55 m/s were attained on 14 to 15 January almost simultaneously with the stratospheric wave event. In the stratosphere, a wave structured vertical profile of the horizontal wind speed gradually developed in a similar way as for the temperature.

Discussion

Fig. 3 explains the temporal evolution of the stratospheric and tropospheric flow by meteorological analyses

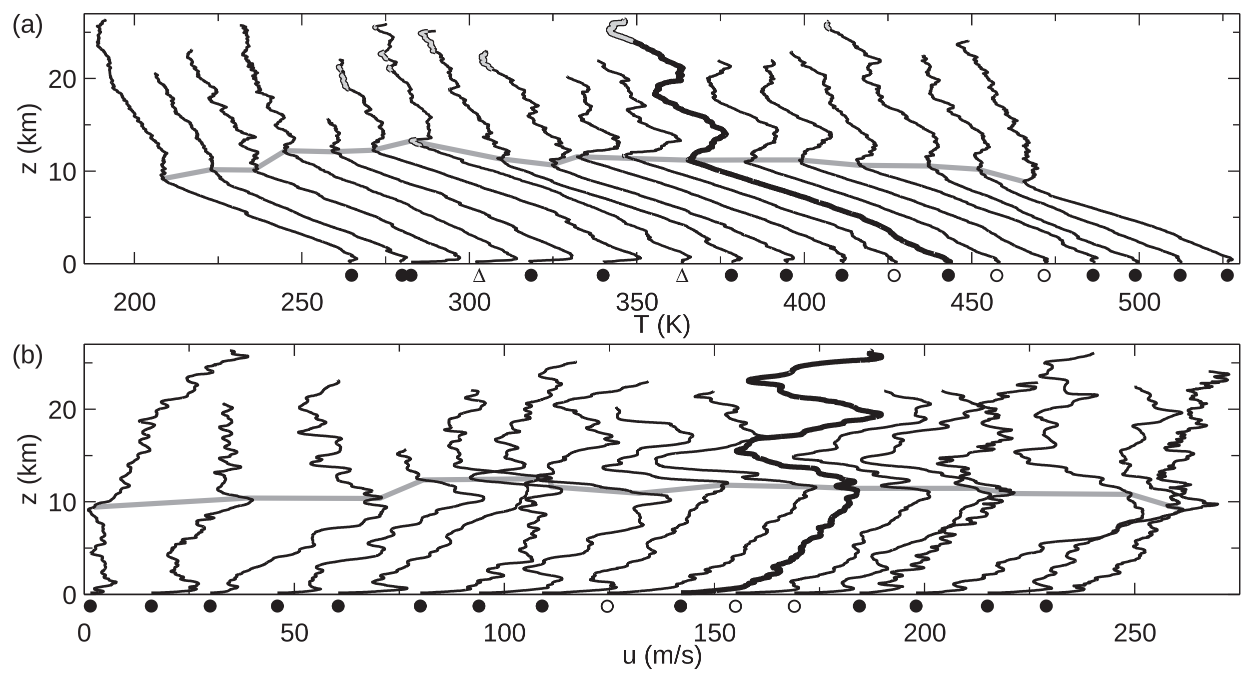

Figure 2. High vertical resolution profiles of temperature (a) and horizontal wind speed (b) measured by radiosondes launched at Sodankylä between 11 January 2001 at 12 UT and 17 January 2001 at 12 UT. Regular 12 hourly soundings are marked by full circles. Additional soundings (open circles) were launched on 15 January 2001 at 06 UT, 15 UT, and 18 UT (from left to right). The temperature profiles shown in Fig. 1 are marked by triangles. Consecutive profiles are shifted each by (a) 15 K and (b) 15 m/s. The thick profile marks the January 15 launch at 12 UT. Gray segments indicate layers with temperatures below T_{frost}, which is computed as in Fig. 1. The grey horizontal thick lines show the tropopause height.

during the considered period. In the troposphere, the track of an intensifying cyclone north of Greenland got deflected by a stable anticyclone (blocking high) extending from the Atlantic Ocean to central Europe (Fig. 3, bottom). The evolving counterrotating vortices caused a stormy westerly flow past the Scandinavian mountain ridge after 13 January 2001. Furthermore, in the stratosphere, the polar vortex passed over northern Scandinavia in the period shown (Fig. 3, top and middle). This advection of cold stratospheric air masses increased the temperature difference between middle troposphere and lower stratosphere. Large values of this temperature difference are related to a high tropopause if tropospheric and stratospheric temperature gradients do not change essentially [*Zängl and Hoinka*, 2001]. Here, the temperature difference between the 5 and 15 km levels increased from 33 to 58 K (first and sixth profile in Fig. 2a) between 11 and 13 January. This and the extending anticyclone can explain the unusual high and cold tropopause on the latter date. Accordingly, minimum temperatures (Fig. 1, right) and a low value of integrated total ozone (25% below the mean for January, not shown) were measured above Sodankylä on this day. A closer investigation of the ozone reduction in the considered period will be published elsewhere.

As suggested by the ECMWF analyses in Fig. 3, the polar vortex passed over northern Scandinavia in a period of only 5 days (top), accompanied by a significant synoptic-scale stratospheric temperature decrease between 11 and 13 January (middle). Thus, the PSCs observed by the backscatter sondes were synoptically generated inside the polar vortex.

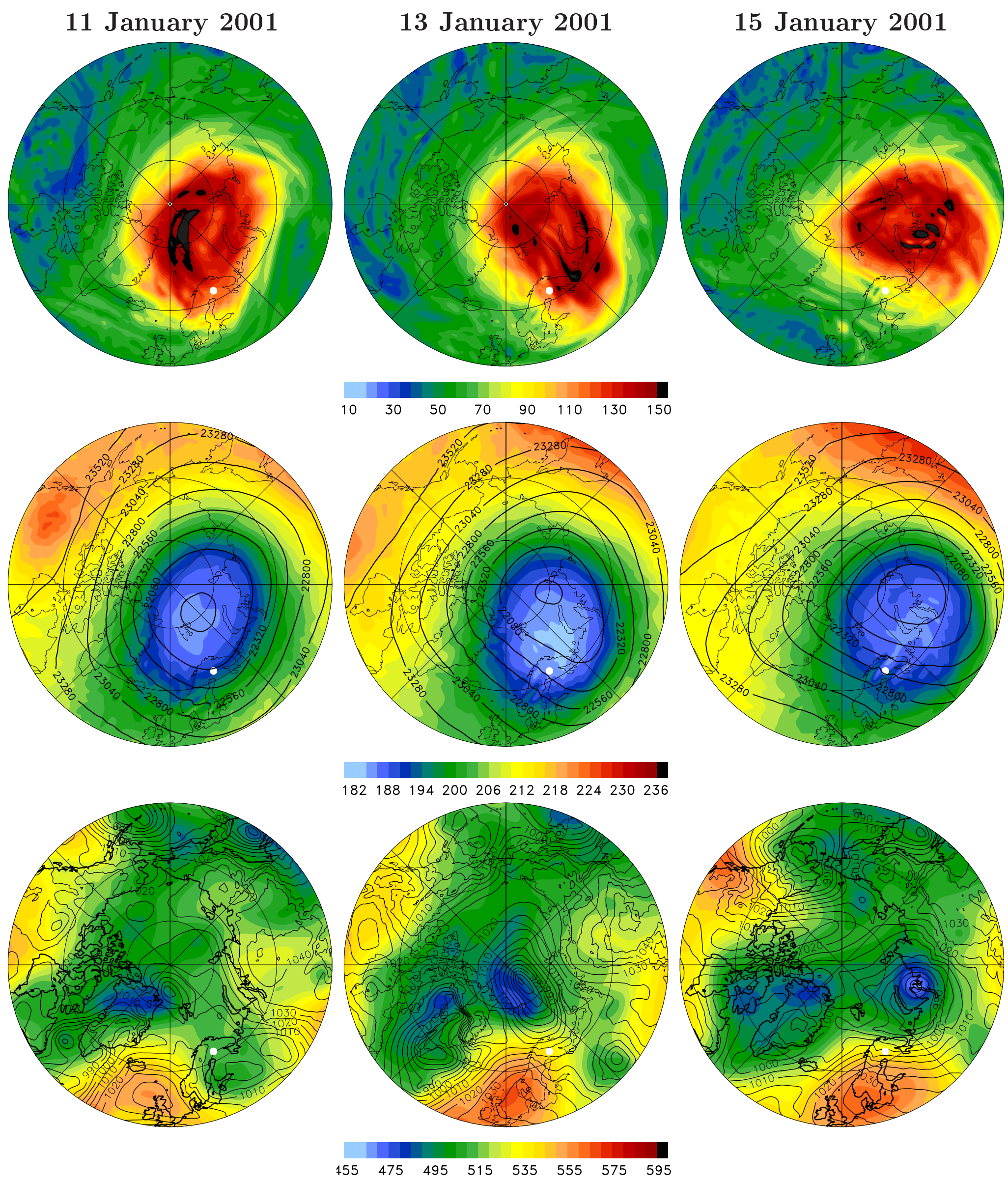

Figure 3. Tropospheric and stratospheric ECMWF analyses in polar stereographic projection on 11, 13, and 15 January 2001 at 12 UT. Top: Potential vorticity (10^{-6} K m^2 kg s^{-1}) at the 550 K isentropic surface. Middle: Temperature (K) and geopotential height (m) at the 30 hPa surface. Bottom: Mean sea level pressure (hPa, black lines) and geopotential height at 500 hPa (decameter, color shading). Latitude circles at 80° N and 60° N are plotted. The white spots mark the position of Sodankylä, Finland.

Furthermore, the amplification of the backscattered signal is consistent with the decreasing temperature (increasing potential vorticity) above Sodankylä due to the passing vortex.

The observed depth of the cold layer can be explained by the quick and undisturbed evolution of the polar vortex prior to the cold event. In the winter 2000/01 the polar vortex developed in a short, three week period starting in late December. The vortex spun up quickly without significant perturbations due to planetary waves. The zonally averaged meridional heat flux (`http://www.ncep.noaa.gov`) was low and correlated strongly with minimum temperatures inside the vortex prior to the PSC observations. Thus, an unusual deep and cold layer could develop. The considered period remained the coldest event of the winter 2000/01 above Sodankylä.

Optical in situ measurements can be used to estimate the chemical composition of cloud particles [*Larsen et al.*, 2000]. The detected synoptic-scale PSCs are interpreted as mainly composed of STS droplets. Thin NAT layers are identified within the ternary PSC. Close to the inner edge of the polar vortex thick layers of water ice particles were determined in the bulk of the PSC.

At Sodankylä, backscatter ratio profiles often exhibit a pronounced layering of increased R_λ like that of Fig. 1. On January 13 this feature can be explained by small-amplitude gravity waves (less than 4 K) excited by the jet stream. Later on, between 14 and 16 January, large-amplitude stratospheric temperature fluctuations (Fig. 2a) were caused by the nearly uniform flow over the Scandinavian mountain ridge (see geopotential heights in Fig. 3, bottom). Since the flow was stationary for more than 12 hours, inertia gravity waves could propagate into the stratosphere and caused vertically displaced isentropes at stratospheric levels far downstream of the mountains (see also [*Dörnbrack et al.*, 1999]). Visual observations at Sodankylä confirm the existence of wave-like PSCs on 15 and 16 January.

The stratospheric wave activity can be quantified by calculating the potential energy density $E_{\rm pot} = 0.5 \cdot g^2/N^2 \cdot \overline{(T'/T_0)^2}$ from stratospheric temperature fluctuations T'. These T' are the deviations from a mean background profile T_0 determined by fitting a quadratic polynomial to the temperature profile in a 7 km altitude range starting 4 km above the tropopause. The overbar indicates the average over this range. Generally, the stratospheric wave activity increased significantly during the polar vortex passage (Fig. 2). The highest energy density of $E_{\rm pot} \approx 20$ J/kg is obtained for 15 January 12 UT, where the record low temperature was measured. This value is more than ten times larger than the climatological January average of $E_{\rm pot}$ at Sodankylä.

Summary and Conclusions

We reported on two exceptional balloonborne stratospheric observations in the Arctic winter 2000/01. First, backscatter sondes detected an extraordinary 8 km thick PSC layer inside the polar vortex above northern Finland. At Sodankylä, PSCs between 15 and 27 km of altitude have been observed during last decade, but in only one case the detected PSC thickness was similar to that of the present case [*Vömel et al.*, 1997]. Secondly, the evolution of tropospheric weather systems enabled the excitation of inertia gravity waves at the Scandinavian mountain ridge. These mountain waves caused significant stratospheric temperature anomalies far downstream of their source. There a regular radiosonde measured record low temperature of 176.7 K at the polar vortex edge.

In the relatively warm Arctic stratospheric winter 2000/01, the polar vortex was stable for only three weeks. The overall fraction of possible PSC area inside the vortex was not greater than in the past winters. However, vertically thick PSCs were detected inside the polar vortex in mid-January 2001.

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