GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO. 7, PAGES 795-798, APRIL 1, 1997

# Dehydration and sedimentation of ice particles in the Arctic stratospheric vortex

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**Abstract.** Balloon borne frost-point hygrometers and backscatter sondes were launched at Sodankylä, Finland in January and February of 1996. These instruments measure water vapor and the backscatter ratio of light due to polar stratospheric clouds in the Arctic stratospheric vortex. Here we report the results of a hygrometer sonde and a backscatter sonde launched within 3.5 hours of each other on January 22/23. Together these soundings show a strong loss of water vapor due to the formation of ice clouds as a result of record cold temperatures in the Arctic stratosphere. The separation of the upper edge of the layer showing water vapor loss and the upper edge of the PSC layer indicates sedimentation of the ice particle layer, possibly leading to a permanent dehydration in the upper part of the layer exhibiting water vapor loss.

## 1. Introduction

The formation of polar stratospheric clouds (PSCs) has been shown to be a major factor in the catastrophic ozone depletion over Antarctica through heterogeneous chemical reactions [*Solomon*, 1990]. These clouds may consist of water ice particles (type II) or a mixture of nitric acid, water and possibly sulfuric acid (type I PSCs). PSCs are observed also in the Arctic, but since the lower stratosphere is generally warmer in the Arctic than the Antarctic, Arctic PSCs are more sporadic. Type II PSCs are especially rare in the Arctic. Sedimentation of PSC particles leads to a partial removal of nitric acid (denitrification) and at least over Antarctica to a removal of water vapor (dehydration) as well. This removal causes a dramatic change in the chemical composition of the stratosphere. Dehydration is thus a strong indicator that the air has been processed by heterogeneous chemistry and that its composition is strongly perturbed.

Dehydration has been observed in the winter Antarctic stratospheric vortex [*Rosen et al.*, 1988, *Kelly et al.*, 1989, *Vömel et al.*, 1995], however, unambiguous dehydration has not been previously observed in the Arctic stratospheric vortex [*Ovarlez*, 1991, *Ovarlez and Ovarlez,* 1994, *Kelly et al.*, 1990]. Layers of lower than average water vapor content have been observed, but could not be attributed unequivocally to dehydration [*Fahey et al.*, 1990, *Ovarlez and Ovarlez*, 1995]. Measurements aboard the ER-2 in the Arctic vortex during the STRAT mission in February of 1996 have shown some indications for dehydration [E. Hintsa, personal communication, 1997], possibly as a result of the same cold event observed in measurements presented here. The lack of dehydration in the Arctic vortex is mainly due to the warmer temperatures compared to the Antarctic vortex. The Antarctic vortex is more stable and symmetric and it confines the air more strongly to the polar night region where diabatic cooling takes place during the winter. Consequently, temperatures below the ice frost-point temperature of the unperturbed vortex are reached before midwinter solstice [*Vömel et al.*, 1995]. Ice clouds are subsequently formed on large scales leading to severe dehydration, observed in all measurements after the austral winter since 1987. The Arctic vortex, however, is more often perturbed by waves propagating upward from the troposphere. It is much less symmetric and the air is more often exposed to sunlight, keeping it warmer than its Antarctic counterpart. Nevertheless, extreme cold temperatures can be reached in the Arctic vortex in exceptionally cold winters, which was the case in January and February of 1996 [*Naujokat and Pawson*, 1996], and in lee waves generated by mountains or in air rising over tropospheric weather systems, leading to the formation of ice PSCs. Nacreous clouds, which are one form of polar stratospheric ice clouds, are frequently observed over northern Scandinavia.

## 2. Observations

In January and February of 1996 vertical profiles of water vapor, PSCs, and ozone were measured at Sodankylä, Finland (67.4°N, 26.6°E). Water vapor was detected using balloon borne frost-point hygrometers [*Oltmans*, 1985] which measure the temperature at which the ambient water vapor is in equilibrium with a small ice layer. These instruments measure water vapor only and are insensitive to water in the condensed phase. PSCs were detected using balloon borne backscatter sondes [*Rosen and Kjome*, 1991], which measure the ratio (commonly referred to as backscatter ratio) between light reflected by aerosols, ice particles and air molecules, measured by the instrument, and light reflected by air molecules only. The latter depends only on the air density and is derived from pressure and temperature. Ozone was measured simultaneously using electrochemical concentration cells. Here we show the results of the frost-point sounding on January 23, 0:01 GMT and the backscatter sounding 3.5 hours earlier on January 22, 20:35 GMT. These are the first profiles obtained in the Arctic stratospheric vortex showing a severe loss of water vapor in a thick layer of ice PSCs (figure 1).

The water vapor profile (figure 1a) shows a dramatic loss in water vapor between 484 K and 558 K (21.5 km to 24.3 km), with a minimum value of 2.5 ppmv at 515 K (23.1 km). Values of this magnitude are typical for the dehydration period over Antarctica but have not previously been observed in the Arctic. The backscatter sonde (figure 1b), which measures the backscatter ratio in two channels at 490 nm and 940 nm, shows two PSC layers exhibiting

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Paper number 97GL00668.
0094-8534/97/97GL-00668$05.00

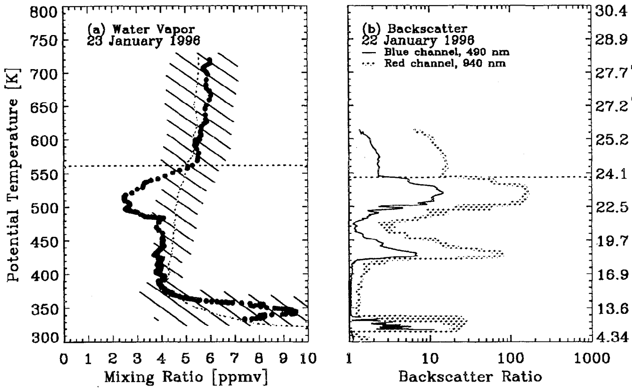


**Figure 1.** (a) Water vapor profile obtained over Sodankylä, Finland on January 23, 1996 showing a strong water vapor loss in the Arctic vortex. The hatched area represents the maximum and minimum of 9 soundings which have been obtained in the Arctic between 1989 and 1995. The thin line shows the mean of these profiles. (b) Backscatter profile obtained 3.5 hours prior to the frost-point sounding. This profile shows two extreme layers of ice PSCs, which are superimposed over a very broad PSC type I layer, extending up to the ceiling altitude of the sounding. The well defined upper edges (dashed lines) of the vapor depletion layer and the ice PSC layer are separated by about 300 m.

extremely high backscatter ratios between 430 K to 454 K (18.9 km to 19.9 km) and 487 K to 547 K (21.8 km to 24.0 km), with a peak value of 170 in the 940 nm channel. These two layers of high backscatter ratio are caused by ice PSCs and are superimposed on a very broad region of elevated backscatter ratio between about 414 K (17.5 km) and the ceiling altitude of the balloon at 613 K (26 km), which most likely consists of type I PSCs. Both soundings show an unusually high tropopause at 11.8 km. The total ozone column during this sounding was only 222 DU. The minimum temperature during the ascent of this sounding was -93.6°C at 517 K (23.5 km), the coldest temperature ever observed at Sodankylä. The water vapor depleted region is very close to saturation (figure 2a). The temperature profile of the backscatter sounding in the type I PSC region is well below the nitric acid trihydrate (NAT) temperature assuming a nitric acid mixing ratio of 1 ppbv and a water vapor mixing ratio of 4.5 ppmv [*Hanson and Mauersberger*, 1988]. The temperature profile in the upper part of the upper ice PSC layer is fairly similar to the profile obtained 3.5 hours later during the frost-point sounding. However, there is a significant difference between the two profiles in the lower part of this layer.

The ratio of the two backscatter ratios at 940 nm and 490 nm (color ratio) can be used to obtain an estimate for the size of the particles [*Rosen et al.*, 1993]. In the case of the upper ice PSC layer the color ratio shows values between 11 and 15 corresponding to particles larger than 1 to 2 μm in radius. Furthermore the particle size increases toward the lower parts of the ice PSC layer, which is an indication for settling of the particles. The backscatter ratio can also be used to obtain an estimate for the condensed mass contained in the observed cloud [*Rosen et al.*, 1993]. At the peak of the upper ice PSC layer the condensed mass is equivalent to about 2 ± 0.4 ppmv of water vapor, consistent with a measured water vapor minimum of 2.5 ppmv, corresponding to a loss in the gas phase of between 1.5 to 2.5 ppmv.

## 3. Results and Discussion

A high pressure system located over northern Scandinavia caused unusually strong lifting of the observed air mass prior to the arrival over northern Finland. This rising motion caused record cold temperatures in the stratosphere. A more detailed analysis of this cooling event was done using isentropic trajectory calculations on European Centre for Medium Range Weather Forecasting (ECMWF) initialized analysis fields [*Knudsen et al.*, 1996]. Trajectories were calculated on isentropic surfaces, both backwards in time (10 days) and forward (6 days), with starting points at Sodankylä at 0:00 GMT January 23, 1996 (figure 3). The trajectories at 430 K and 505 K correspond best to the observed ice PSC layers. All trajectories show a considerable upward movement and corresponding cooling prior to the arrival at Sodankylä. The maximum lifting and cooling was reached a few hours before the arrival. After passing over Sodankylä, the trajectories returned more gradually to the initial conditions. The trajectory calculations exhibit a warm bias compared to the measured temperature profiles at Sodankylä and thus the calculated temperatures are shifted to match the temperatures measured in the frost-point sounding. Although this adjustment increases the uncertainty in the temperature along the trajectory, it does not, in this case, strongly affect the time estimate when ice saturation was reached. The shaded areas in figure 3 mark the time when the temperature shows saturation for 4.5 ppmv of water. For the center of the upper ice PSC layer at 505 K, this occurs between roughly 16 hours prior to arrival at Sodankylä and 8 hours after passing. Thus the total lifetime of the ice particles within this air mass is roughly 24 hours.

The upper ice PSC layer observed in the backscatter sounding coincides mostly with the vapor depletion layer. However, in the upper part of this region, there is a noticeable misalignment between the well defined top of the vapor depletion layer and the well defined top of the ice PSC layer. The PSC layer seems to be shifted downward with respect to the vapor depletion layer. The temperature profiles (figure 2a) are quite similar within the misalignment region. The ozone profiles (figure 2b) also show a slight misalignment, however, here the ozone profile during the later frost-point sounding appears to be at a slightly lower altitude with respect to the ozone profile during the earlier backscatter sounding. This slight downward shift would indicate some small descent of the air mass between the two soundings. Therefore, vertical

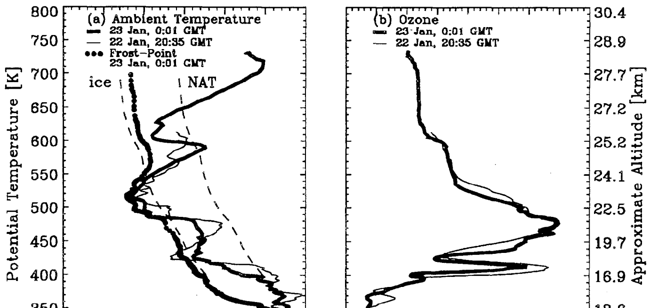


**Figure 2.** (a) Temperature profiles obtained during the frost-point sounding (descent) and the backscatter sounding. The dashed lines indicate the frost-point temperatures for 4.5 ppmv of water vapor (ice) and for 1 ppbv of nitric acid and 4.5 ppmv of water vapor (NAT). The measured frost-point temperature is shown as dotted line.The region of vapor depletion is close to ice saturation. Most of the entire region above about 415 K shows temperatures below the NAT temperature. (b) Ozone profiles obtained during these two soundings, indicating a slight vertical descent between the backscatter and the frost-point sounding.

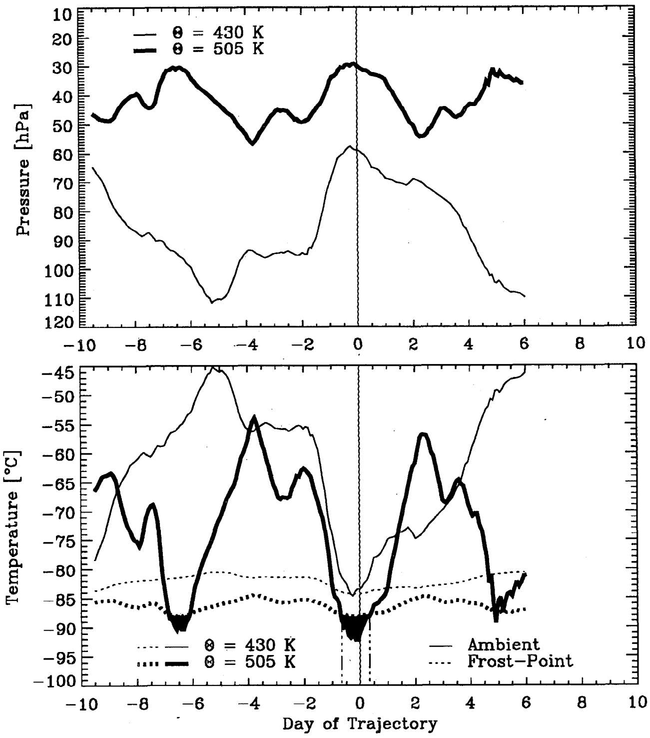


**Figure 3.** History and development of the air observed at two selected levels from back and forward trajectory calculations. Day = 0 marks the time of the frost-point sounding. The trajectory at 505 K is at the peak of the upper ice PSC layer, whereas the trajectory at 430 K is at the peak of the lower ice PSC layer. (a) Pressure development. (b) Development of ambient temperature (solid lines) and frost-point temperature for 5 ppmv (dashed lines). The shaded areas mark the time the temperature is below ice saturation.

motion of the streamlines in the time between the two soundings does not seem to explain the misalignment between the PSC layer and the vapor depletion layer, because the earlier detected PSC layer was found to be lower than the later detected vapor depletion layer. The vapor depletion layer is close to saturation and, thus, evaporation of the ice particles is unlikely, suggesting that this misalignment may have been caused by the settling of the ice particles over this distance. The difference between the upper edge of the vapor depletion layer and the upper edge of the ice PSC layer is roughly 16 K or 300 m (figure 1). Assuming sedimentation as the only cause for this separation, a time of 16 hours for sedimentation over this distance, and neglecting the initial particle formation process, we obtain a particle fall speed of 0.5 cm/sec. Further assuming spherical ice particles, this fall speed then corresponds to a particle radius of about 5 μm [*Kasten*, 1968]. This size estimate is consistent with the estimate obtained from the backscatter color ratio and very similar to an estimate of the particle size from the fall speed observed over Antarctica [*Vömel et al.*, 1995]. However, the estimate presented here is slightly better, since the strong cooling event allowed us to determine the time when ice saturation was reached with better accuracy and since the particles are still present at the time of the observation.

The region between 484 K and roughly 496 K (21.5 km to 22.3 km), which is the lowest part of the vapor depletion region, shows an interesting difference between the two soundings. In this part of the profiles, the temperature during the backscatter sounding is above the ice frost-point for 4.5 ppmv of water and thus too warm for ice particle formation. The lower backscatter ratio further implies that in this region type I PSCs are more likely than ice PSCs. The temperature during the frost-point sounding, however, is substantially colder and we do observe a loss in water vapor, suggesting that we observed the initial stage of the ice cloud formation within this layer. This region shows saturation in the lowest part, but in no case did we see indications for supersaturation, indicating that ice PSCs form readily at ice saturation possibly through nucleation on the preexisting type I PSC particles.

Since only in the upper part of the vapor depletion layer the ice particles are removed by settling, most of the vapor depletion layer will likely be rehydrated when the air moves out of the cold region and warms up as indicated by the trajectory analysis. Therefore, sustained dehydration will only occur in the region where the particles have fallen out. The trajectory analysis indicates that the air in the vapor depletion layer stayed below ice saturation for 4.5 ppmv of water vapor for about another 8 hours. Assuming the same fall speed, the particles will fall another 150 m, which will remove them from a layer of about 450 m at the top of the vapor depleted region. Thus from the total height of the vapor depletion layer of 2.8 km only a layer of 450 m may show sustained dehydration after all ice particles have evaporated. The observed water vapor mixing ratio 450 m below the upper edge of the vapor depletion region is 3.2 ppmv and thus the sustained dehydration is unlikely to be less than this value. Particle evaporation within this time may further lessen the effect of the dehydration event. However, if the ice particles are coated with NAT [*Peter et al.*, 1994], evaporation may be delayed and the layer of sustained dehydration thicker than our estimate.

These observations clearly show that in extreme cases conditions similar to the Antarctic stratospheric vortex can be found in the Arctic and ice PSC formation and the associated dehydration may also occur there. The similarity of the size of the ice particles causing Arctic and Antarctic dehydration indicates that once ice saturation is reached and sustained sufficiently long, the speed of dehydration is comparable in both polar regions. In the Antarctic stratospheric vortex the cold temperatures causing widespread and severe dehydration are reached in every winter and are long lasting. In the Arctic, on the other hand, dehydration is, so far, limited to episodic events. The extent to which these events may change the water vapor distribution depends on their size, lifetime and frequency. A colder stratosphere resulting from the buildup of greenhouse gases and increases in the water vapor content of the stratosphere [*Oltmans and Hofmann*, 1995] may lead to more frequent occurrences of ice PSCs and more frequent and stronger dehydration.

ECMWF analyses show that the cold event observed on January 23 had a cross section of about 1000 km perpendicular to the flow, a length of about 2500 km and a lifetime of about 17 days. Thus a small cold region processed air flowing through it for about this time. Using typical wind speeds in this altitude range a 450 m thick sustained dehydration layer could have been created over an area of around half of the total vortex area. This is a crude estimate, but indicates that a small cold region within the vortex may process a large fraction of the vortex if the lifetime of the cold region is sufficiently long. An increase in the cross section of the cold region will increase the processed area, and an increase in the length of the cold region will increase the height of the sustained dehydration layer, since it will give the particles more time to settle before reevaporating. Most of the coldest events in the Arctic lower stratosphere are connected with the generation of mountain lee waves or dynamical forcing by tropospheric weather systems. During a cold winter, an increase in the number of such events would likely increase the horizontal extent of the processed area.

## 4. Summary and Conclusions

In situ observations of water vapor and backscatter ratio in the Arctic winter lower stratosphere have shown, for the first time, severe water vapor loss in the presence of type II PSCs. The formation of these water ice PSCs and the subsequent dehydration occurred in a region of strong adiabatic cooling which was caused by a high pressure system over northern Scandinavia. The upper edges of the ice PSC layer and the water vapor loss layer were separated vertically which indicates settling of the ice particles. The results of a trajectory analysis showed that ice saturation had been reached 16 hours before the observation which led to an estimate for the fall speed of 0.5 cm/sec. This is very similar to an estimate obtained in the Antarctic polar vortex. The fall speed estimate corresponds to a particle radius of about 5 $\mu$m which is consistent with the particle size indicated by the calculated color ratio of the measured backscatter ratios. The observed backscatter ratio maximum of 170 at 940 nm implies a mass in the condensed phase equivalent to roughly 2 ppmv of water vapor, consistent with the observed water vapor minimum of 2.5 ppmv, corresponding to a loss in the gas phase of 1.5 to 2.5 ppmv.

The trajectory analysis indicates that the temperature of the air mass stayed below the ice frost-point for another 8 hours after the measurement. This implies that the settling of the ice particles continued for a total of 24 hours, leading to sustained dehydration in a depth of about 450 m at the top of the cold layer with a minimum water vapor mixing ratio between 3.2 to 3.5 ppmv. The lower parts of the observed cold layer were most likely rehydrated by evaporation of the ice particles after passing through the cold region. According to meteorological analyses, the cold region persisted for about 17 days and had a considerable horizontal extent. If the air masses going through cold region were contained in the polar vortex, it is possible that this sustained dehydration would in the end have characterized up to half of the entire vortex area.

**Acknowledgments.** This work was partially supported by the NSF office of polar programs. One of us (HV) was supported by a NASA Global Change Fellowship. We are grateful to Bjørn Knudsen of the Danish Meteorological Institute (DMI) for the use of the trajectory model and to ECMWF for the use of their numerical analysis. We are also indebted to Terry Deshler and Börje Sjöholm for a last minute rescue effort. Thanks also to Eric Hintsa for a preprint of his paper and an anonymous reviewer for helpful comments.

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(Received November 6, 1996; revised January 22, 1997; accepted February 7, 1997)