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The evolution of the dehydration in the Antarctic stratospheric vortex

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Abstract. In 1994 an intensive program of balloon-borne frost point measurements was performed at McMurdo, Antarctica. During this program a total of 19 frost point soundings was obtained between February 7 and October 5, which cover a wide range of undisturbed through strongly dehydrated situations. Together with several soundings from South Pole station between 1990 and 1994, they give a comprehensive picture of the general development of the dehydration in the Antarctic stratospheric vortex. The period of dehydration typically starts around the middle of June, and a rapid formation of large particles leads to a fast dehydration of the vortex. The evaporation of falling particles leads to rehydration layers, which have significantly higher water vapor concentrations than the undisturbed stratosphere. Through the formation of these rehydration layers in the early stages of the dehydration we can estimate a particle fall speed of 1/3 km/d and thus a mean particle size of 4 μm. Ice saturation was observed over McMurdo in only two cases and only well after the onset of the dehydration. From the inspection of synoptic maps it then follows that a small cold region inside the vortex seems to be sufficient to dehydrate the entire vortex. Above 20 km the dehydration is completed by the end of July. From the descent of the upper dehydration edge we can estimate a mean descent rate inside the vortex of 1.5 km/month. In McMurdo we observed occasional penetration of the vortex edge in cases where the vortex edge was close to McMurdo, however, these cases seem to have little effect on the bulk of the vortex. A sounding from November 3, 1990, at South Pole shows that the dehydration may persist into November and indicates that there is no significant transport into the vortex throughout winter and early spring.

1. Introduction

An important step in the development of the Antarctic "ozone hole" is the formation of polar stratospheric clouds (PSCs) during the austral winter. The formation of PSCs causes a reduction of water vapor in the lower stratospheric vortex. The first measurements of this dehydration by *Kelly et al.* [1989] during the airborne Antarctic ozone experiment (AAOE) in 1987 showed a reduction of water vapor from 3. to 4.5 parts per million by volume (ppmv) outside the vortex to values as low as 1.5 ppmv inside. Balloon-borne measurements of frost point temperature by *Rosen et al.* [1988, 1991] and *Hofmann et al.* [1991] showed that the dehydration can persist into October, well beyond the times of minimum temperatures in the lower stratosphere. There have been only few in situ measurements of water vapor in the Antarctic stratospheric vortex to date, and the onset and development of the dehydration have not been observed previously.

This paper presents data of balloon-borne frost point soundings at McMurdo during 1994 and at South Pole between 1990 and 1994. The data from McMurdo map out the period from February through October and show the different stages during the formation and completion of the dehydration. The data at South Pole were taken mainly during the austral spring, however, several winter profiles at South Pole complete the picture. This paper includes (1) a brief description of the instrument, (2) a characterization of the temperature development in the lower stratosphere observed over McMurdo, (3) the water vapor profiles prior to the time of dehydration in 1994 at McMurdo, (4) a determination of the beginning of the dehydration, (5) a detailed description of the dehydration mechanism, (6) a discussion of the importance of cold region processing during the period of active dehydration, and (7) a discussion of the period of sustained dehydration.

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2. Instrumentation

The balloon-borne frost point hygrometer similar to the one used in this study was originally developed by *Mastenbrook* [1968]. It has been used in its present configuration with only minor changes since 1980 [*Oltmans*, 1985]. In 1990 a digital interface to the Vaisala RS-80 radiosonde was added.

The instrument is based on a chilled mirror principle and measures the temperature of a mirror, which is controlled such that the mirror maintains a small and constant layer of frost coverage. Under these conditions the mirror temperature equals the frost point temperature of the air passing over the mirror.

Figure 1 shows a schematic diagram of the instrument. The mirror is connected to a cryogenic liquid, which has a temperature between 30 and 90°C below the frost point. A heater circuit heats the mirror against this cryogenic bath in order to maintain a constant temperature. The frost coverage on the mirror is detected by a phototransistor, which senses the light of a light-emitting diode (LED) reflected off the mirror surface. The

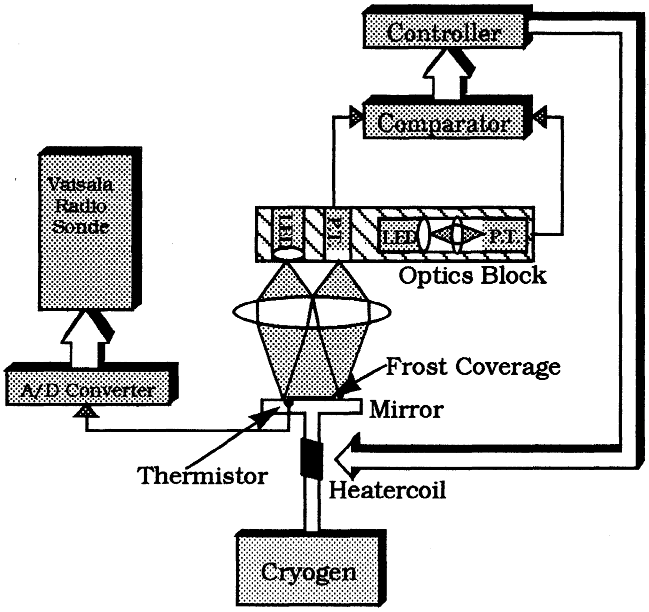

Figure 1. Schematic diagram of the frost point hygrometer

peak emission of the LED is at 940 nm. Any amount of frost reduces the output current of the phototransistor. This signal is used as the input of a controller circuit, which maintains the mirror temperature at the frost point.

To avoid the problem of temperature drift of the photoelements, a second LED/phototransistor pair is used to determine the temperature drift of the sensing elements. This reference pair is in thermal contact with the sensing elements, and its optical path is direct, not across the mirror. The comparison of the sensing elements with the reference elements compensates the drift of the elements and allows an accurate determination of the frost coverage of the mirror.

The heating element is wound around the mirror stem and is driven by the controller. The gain of this controller is changed during the flight, with a lower setting in the troposphere, and a 15 to 20 times higher setting in the stratosphere. Owing to the high gain of the controller, the frost coverage of the mirror varies by less than 0.1%. The stability of the controller depends strongly on the amount of water vapor in the air. Because of the low stratospheric mixing ratios the formation of a frost layer takes much longer compared to tropospheric values, which are orders of magnitude higher. Therefore the sensitivity of the instrument has to be much higher in the stratosphere, and much smaller changes in the frost layer have to be detected in order to guarantee a proper response to changes in water vapor. However, the evaporation of the frost layer depends mainly on the mirror temperature and is fast in the stratosphere as well as in the troposphere. Therefore the maintenance of a constant frost layer is critical and highly dependent on the altitude and the individual instrument setting. In some cases this causes oscillations of the instrument in one extreme and the insensitivity of the instrument to water in the other extreme. Oscillations commonly occur right after launch in the lowest part of the ascent before the instrument reaches a stable control. Insensitivity and oscillations occur in a short altitude range past the change to the high-gain setting during the ascent. This behavior of the instrument is obvious in the profile and usually occurs during ascent only. Outgassing of water vapor from the balloon envelope and the instrument usually leads to contamination of the stratospheric data during ascent. The magnitude of this problem depends strongly on the solar heating of balloon and instrument and is less important in the dark Antarctic winter. On descent this problem is negligible, except for a very short time after the turn of the balloon. For this reason we rely on descent data only and use ascent data only in those cases where they are confirmed by descent data. To get a good vertical resolution during descent we use valved balloons in which the leakage rate of helium determines the descent velocity.

The accuracy of the instrument depends on several factors, such as thermistor calibration, stability of the controller, measurement error, and digitizing error. The temperature of the mirror is measured by a small bead thermistor, which is installed just below the mirror surface and is in excellent thermal contact with the mirror. The thermistor mounted in the mirror is individually calibrated in the laboratory down to -79°C to an accuracy of better than 0.05°C. Down to temperatures of -93°C, the fit to this calibration is accurate to within 0.2°C, based on a few calibration measurements done to these temperatures. A linear correction applied to this fit below -79°C gives results within 0.05°C over the entire range of measurements [*Layton*, 1961]. The resistance of the thermistor is then converted into a voltage, digitized, and transmitted via a radiosonde to the receiving station on the ground. The controller usually maintains the mirror temperature within 0.3°C, and the digitizing method creates an error between 0.1°C at 0°C and 0.02°C at -90°C. The self heating of the thermistor is less than 0.1°C. The radiosonde (Vaisala RS-80) also provides the pressure, temperature, and humidity information. The humidity obtained by a humidity sensitive capacitor is used for comparison purposes only.

The performance is slightly variable from instrument to instrument and depends on the quality of the photoelements and their matching, the mirror, the gain, and several other factors. Overall we estimate the accuracy of the measured frost point temperature to be better than 0.5°C, which translates to less than 10% in stratospheric water vapor mixing ratio.

3. Sounding Program

The frost point data presented in this paper were collected in 1994 over McMurdo and between 1990 and 1994 over South Pole. In both places we conducted ozone soundings as well, which will be discussed elsewhere. These soundings were also used to characterize the temperature of the lower stratosphere. The focus of this paper is on the McMurdo data, since for the first time the development of the dehydration was studied in detail. Nineteen soundings were launched from McMurdo between February 7 and October 5, 1994, of which 18 gave reliable data. Seven soundings between February 7 and June 13 map the development during the austral summer and fall, prior to dehydration, while 11 soundings between June 19 and October 5 show the development of the dehydration during the winter and early spring. The data from South Pole were mainly taken during the austral spring in the years 1990 to 1994. However, in 1993, soundings were successfully made during the winter as well.

4. Temperature Development

The dehydration of the lower stratosphere over Antarctica is a direct result of the extremely cold temperatures reached inside the vortex during the dark winter months. As the temperature reaches the saturation level, ice particles begin to form, which settle out of the stratosphere and thereby remove water from the vortex. The lowest water vapor mixing ratio should therefore be determined by the minimum temperature the air encountered,

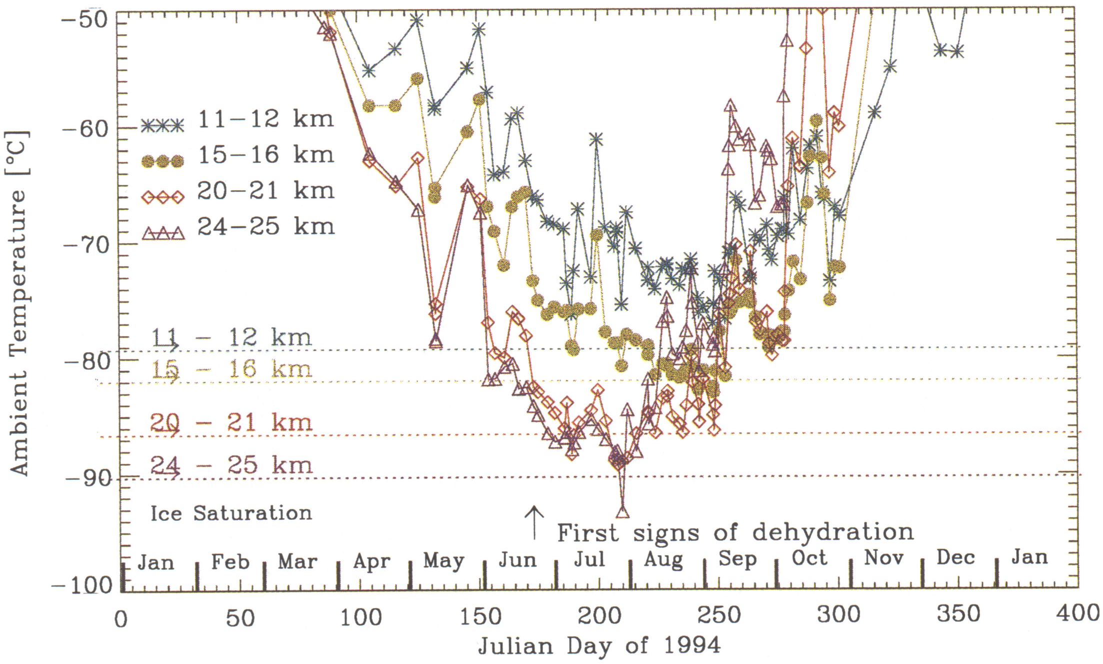

Plate 1. Ambient temperature measured over McMurdo at different levels. Note that the time when the minimum temperature is reached differs for these levels. In general, the minimum temperature is reached earlier at the higher levels. Also note that the ambient temperature at different levels reaches the frost point temperature well past the first observations of dehydration.

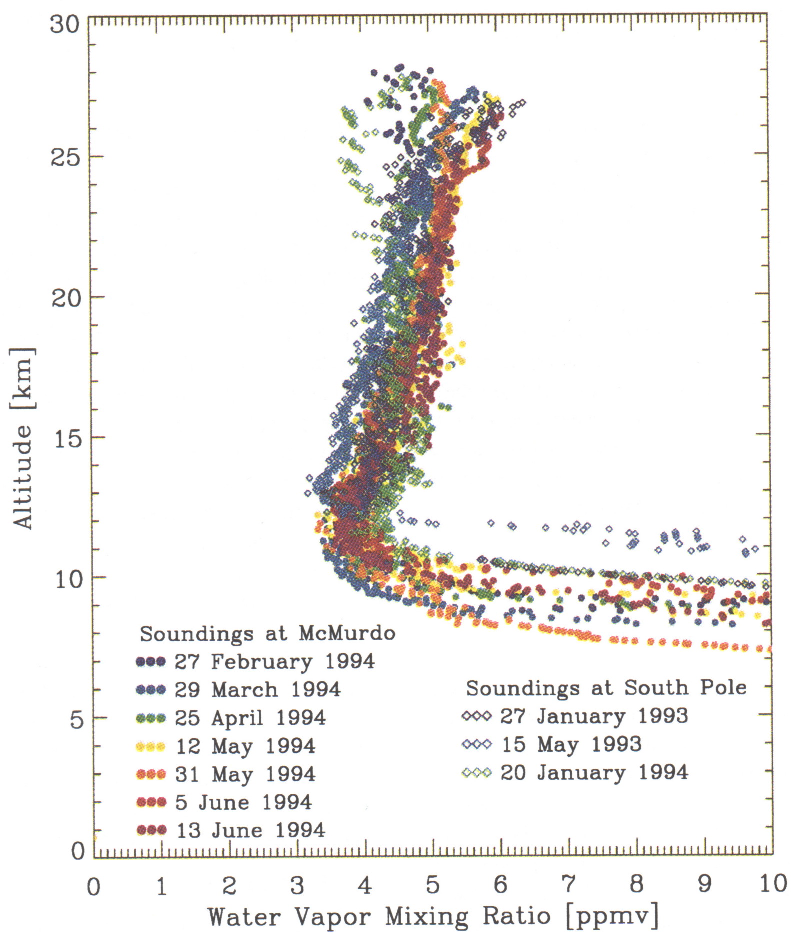

Plate 2. Water vapor profiles taken during the summer months at McMurdo in 1994 and at South Pole in 1993 and 1994.

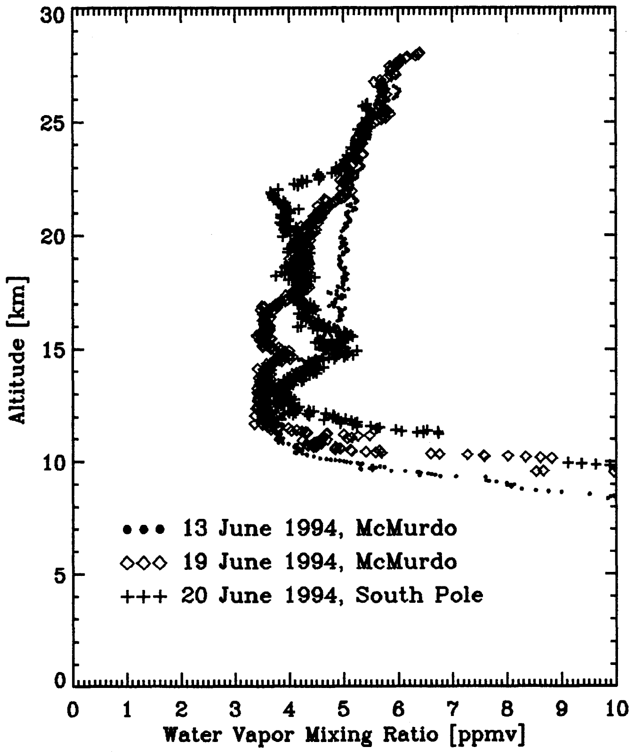

Figure 2. The onset of the dehydration marked by a very sudden decrease in water vapor, which was recorded at McMurdo (June 19) and South Pole (June 20). Since McMurdo was not well inside the vortex on June 13, we estimate that the dehydration began inside the vortex around the second week of June.

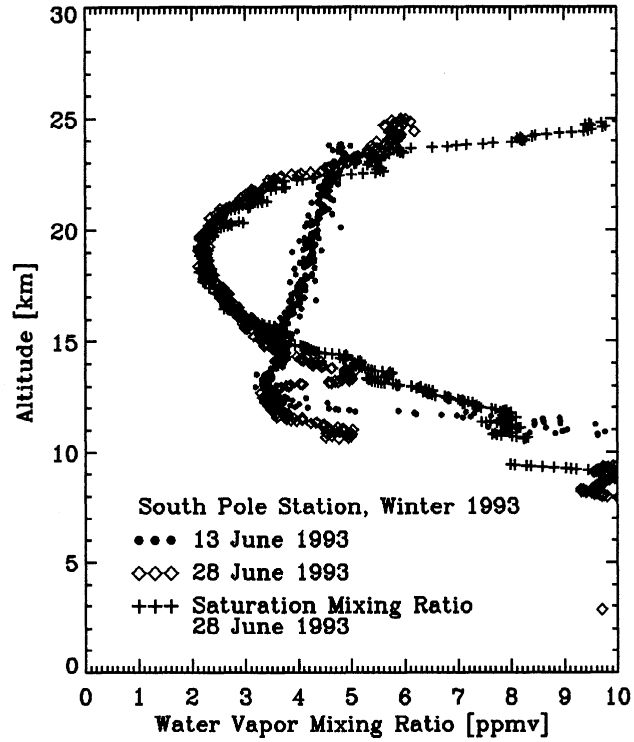

Figure 3. The falling ice particles evaporating as they reach lower and warmer altitudes and leaving a clear signature in the water vapor profile. The sounding on June 28, 1993, at South Pole shows saturation through most of the dehydration and rehydration regime. This shows that the dehydration in this case happens locally over South Pole.

assuming that all particles are removed from the stratosphere. The development of the dehydration should then approximately follow the temperature development of the vortex. Plate 1 shows the temperature at several levels over McMurdo. It is clear that the minimum temperature is reached earlier at the 24-km level, with a delay at the lower levels of up to 40 days. This was also found for the minimum temperature inside the vortex in the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis. For each level the saturation temperature with respect to ice is indicated, which was derived from the last undisturbed profile on June 13. The first clear occurrence of dehydration is also marked and shows that dehydration was observed at this altitude well before the temperature over McMurdo reached saturation with respect to ice.

5. Results

5.1. Predehydration

Between February 27 and June 13 we obtained seven profiles at McMurdo, which show overall very little change in vertical structure with time (Plate 2). They all have a minimum near the base of the stratosphere between 3.4 and 4.3 ppmv and generally increase to the top of the sounding at 27 to 28 km to a mixing ratio between 4.5 and 6.0 ppmv. Plate 2 includes profiles both for times when McMurdo was inside and outside the vortex, and thus for this period a distinction between the air inside and outside the vortex is virtually impossible. Three profiles from South Pole confirm this picture. There is some variability at 25 to 28 km, which may be an indication of poorer instrument performance close to ceiling altitude.

5.2. Beginning of Dehydration

The first profile which unambiguously shows signs of dehydration was obtained on June 19 over McMurdo (Figure 2). One day later, another profile from South Pole shows even stronger dehydration. The June 13 profile, however, is not representative of the end of the undisturbed stratosphere within the vortex, since the vortex center had moved away from McMurdo. A profile from June 5, which clearly was obtained inside the vortex, shows minor variations in the 15 km range, but these cannot be unambiguously linked to dehydration. However, this profile may indicate the very beginning of the dehydration. Our estimate for the time at which the coldest region within the vortex reached the frost point temperature therefore is the second week of June. It is of importance that by June 19 the temperature over McMurdo was still 5 to 15°C above ice saturation.

Lidar data up to June 19 (A. Adriani, personal communication, 1995) do not indicate the presence of ice particles over McMurdo. Therefore, by this date, particles that have formed have already settled out, removing water from the altitude region where a reduced water vapor mixing ratio was observed, before reaching McMurdo. We thus did not observe the very initial stage of particle formation and therefore have no information whether in this stage a certain degree of supersaturation is required or not.

5.3. Dehydration Mechanism

As the ice particles settle out of one altitude region, they encounter regions of warmer temperature and begin to evaporate. This process rehydrates the stratosphere, increasing the water vapor mixing ratio to levels above the undisturbed profiles. This

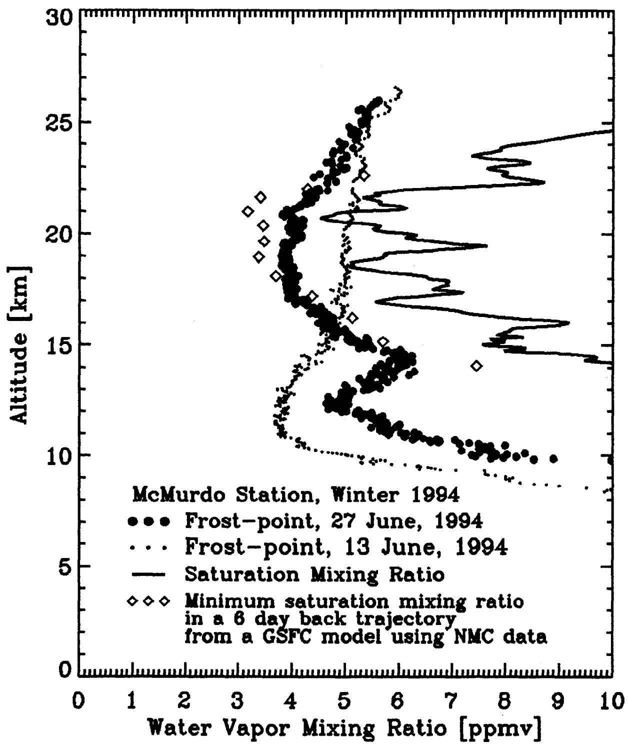

Figure 4. The signature of falling and evaporating ice particles observed on June 27, 1994, at McMurdo. However, the profile does not show saturation and therefore does not indicate the presence of particles. Backtrajectories, on the other hand, do show that during the last 6 days the air parcels were cold enough to explain the observed structure in the water vapor profile. This is an example of remote dehydration.

was seen in several profiles, and a good example of this mechanism was obtained at South Pole on June 28, 1993 (Figure 3). In this case the entire region between 15 and 23 km shows strong dehydration and the region between 12.5 and 15 km a strong enhancement in water vapor due to the evaporating particles. Furthermore, the entire region of dehydration almost to the peak of the rehydration layer is saturated with respect to ice, indicating the presence of particles over this range. In this case the process of dehydration is clearly a local event.

A sounding on June 27, 1994 at McMurdo shows the same features with a dehydration regime above a rehydration layer (Figure 4). This profile was taken 2 weeks after the last undisturbed profile was observed. If we take the date of this last undisturbed profile as the beginning of the dehydration, we obtain an estimate of 2 weeks for the time of processing for the June 27 profile. Taking from this profile an estimated falling distance of 5 km, we obtain an estimated falling speed of roughly 1/3 km/d. This estimate, of course, is crude, since the particle formation and evaporation process strongly change the size distribution of the particles and since we cannot determine the actual start of the dehydration to within less than a week. However, it is the first (though indirect) observation of the falling speed of the ice particles. From this falling speed we can also estimate a mean diameter of the particles [*Kasten*, 1968] at about 4 μm. This estimate gives a mean value for the particles having a significant fall speed. It is a lower limit estimate, because the estimated time does not consider the time for particle formation and evaporation and because the altitude range involved is likely to be larger than our estimated falling distance. It is likely that the particles, which transport the bulk of the mass, are slightly larger than our estimate.

This evaporation process may have important implications for the particle formation and chemistry of the lower altitudes, in which most of the rehydration seems to occur. Assuming that the denitrification is mainly facilitated through the incorporation of nitric acid trihyhrate (NAT) particles and nitric acid into ice particles [*Wofsy et al.*, 1990], nitric acid would be released with the evaporation of particles in the warmer layers. Some of the observed layers had temperatures of up to 5°C above ice saturation, in which NAT particles could evaporate to some extent. This will increase the undisturbed nitric acid concentration, along with the water vapor concentration, and thus may lead to increase in size and possibly freezing of liquid sulfuric acid aerosols through an increased uptake of nitric acid and water [*Beyer et al.*, 1994]. Also, since the conversion of $ClONO_2$ on the surface of aerosol particles is strongly depended on the amount of water present [*Hofmann and Oltmans*, 1992] this reaction will be accelerated inside the rehydration layers.

However, the rehydration layers are not permanent, since these layers continue to cool beyond the time when the higher layers passed their temperature minimum. Therefore these lower layers will eventually become dehydrated as well, and the temperature minimum will determine the level of dehydration; but because of the temporary increase of water vapor and possibly nitric acid in the rehydration layers, the process of initial particle formation in these layers may be significantly different than in the higher layers, which are dehydrated first.

5.4. Remote Dehydration

As pointed out earlier, we did not observe saturation over McMurdo until well after the beginning of the dehydration and then only in two soundings and not over an extended period of time. The profile on June 27, 1994, at McMurdo clearly shows that the entire dehydration and rehydration region is not saturated, which makes the presence of ice particles unlikely. We can therefore not explain the observed water vapor profile by local dehydration. However, this dehydration could have happened somewhere else, before the air reached McMurdo. From backtrajectory calculations we can determine the coldest temperature encountered along the trajectory, which in this case was 6 days earlier. If we assume that every particle that formed was removed, then the minimum temperature along the trajectory should determine the level of dehydration within the air parcel. This calculation gives a remarkably good agreement of the minimum saturation mixing ratio along these trajectories and the observed water vapor mixing ratio (Figure 4). Therefore it is clear that a cold region within the vortex, which covers only a part of the area of the vortex, is sufficient to dehydrate large portions of the vortex and that large-scale saturation is not required to explain large-scale dehydration. From our frost point soundings and synoptic temperature maps we could determine an upper limit for the area, which could produce the observed dehydration. This area usually covers less than 10-25% of the total vortex area and is possibly much smaller if the dehydration is very rapid. Since McMurdo is usually not near the vortex center or the coldest region within the vortex, observations of deep layers of saturation are usually rare.

Although the Arctic stratosphere is usually significantly warmer than the Antarctic stratosphere, this cold region processing may lead to more frequent and deeper dehydration in the Arctic stratosphere than has been assumed so far. However, in situ observations by *Ovarlez* [1991, 1994] and our group (unpublished) have not shown evidence of significant dehydration over the Arctic.

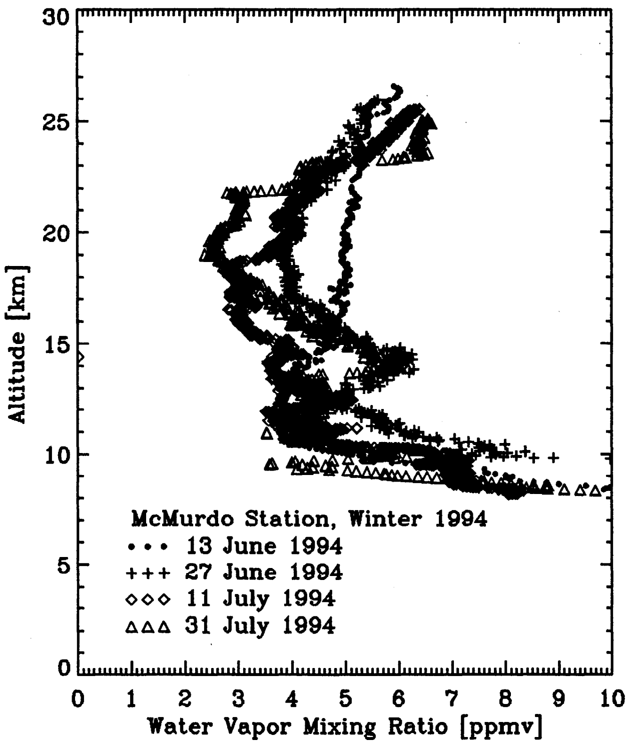

Figure 5. The frequent occurrence of rehydration layers marking the ongoing drying of the vortex. Note that the profile on July 31 exhibits much higher water vapor between 12 and 18 km. This reflects the motion of the vortex and the fact that the drying of the vortex is not homogeneous.

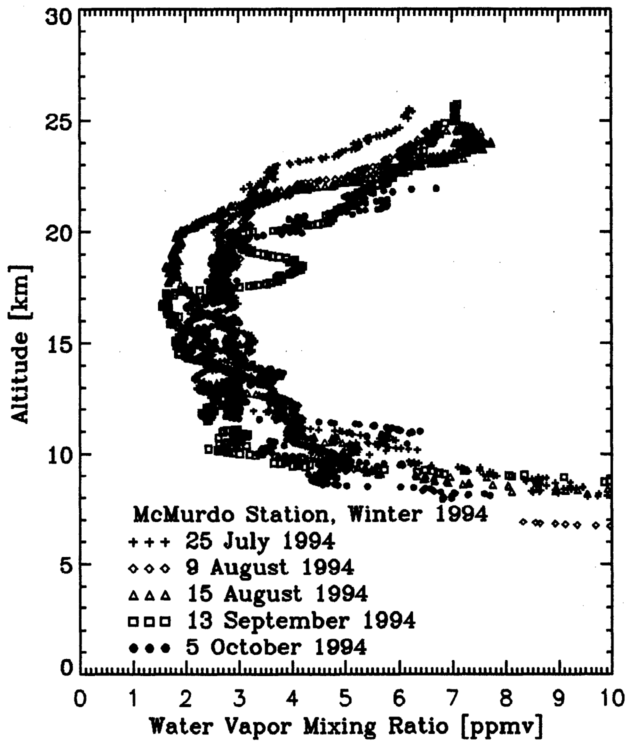

Figure 6. The water vapor profiles which do not change dramatically after the minimum temperature is passed. This period of sustained dehydration begins, depending on altitude, between late July and late August. Note two instances of highly enhanced water vapor on September 13 between 17.5 and 19.5 km and on October 5 between 10.5 and 11.5 as well as between 9 and 10 km. This increase in water vapor is a result of the proximity of the vortex edge.

5.5. Active Dehydration

The dehydration process is active as long as the minimum temperature has not been reached. This leads to the dehydration/rehydration signature in the water vapor profiles, which was clearly observed over McMurdo through the end of July (Figure 5). This coincides roughly with the time of the coldest temperature in the upper dehydration region. By this time we also observed the minimum mixing ratio in this altitude region. The lower levels still continue to dehydrate as the temperature in these lower levels continues to drop. Rehydration layers in the 10 to 11 km region were observed through August 15, which was the end of the intensive observation period. The rehydration layer was no longer observed in the September 13 sounding at McMurdo.

On July 25, 1994, the profile over McMurdo shows strong dehydration, with no rehydration layer remaining, whereas the profile from July 31 again clearly shows a rehydration layer. On July 25 the cold center of the vortex was much closer to McMurdo compared with July 31, which shows that the dehydration does not happen homogeneously, but rather from the interior of the vortex outward. Therefore, during the active period of dehydration, the level of dehydration observed also depends on the location within the vortex.

5.6. Sustained Dehydration

As the minimum temperature is passed, the active dehydration ends and the water vapor remains unchanged unless water vapor is added from outside the vortex. Despite a few characteristic features the profiles obtained between early August and early October show a remarkable similarity (Figure 6). The dehydration regime extends roughly from 12 to 20 km. In this

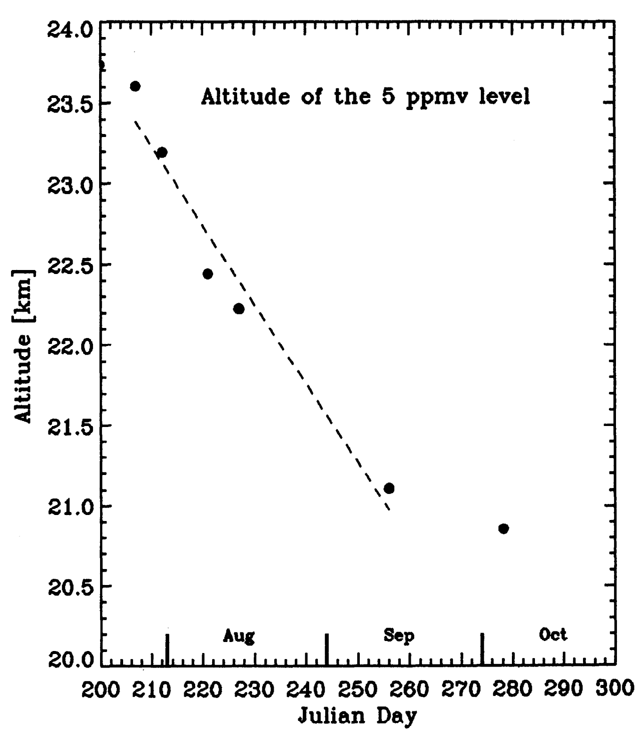

Figure 7. The upper edge of the dehydration region, where the 5 ppmv level has a well-defined altitude, which is plotted against time. From the descent of this level we can infer a mean descent rate of 1.5 km/month between late July and early October.

time period, water vapor, again, is a conservative tracer and we can clearly distinguish air outside the vortex from air inside the vortex.

Between 19 and 20 km we did not see an increase in water vapor between late July and early October, which shows the strong isolation of the vortex in this altitude region. Through late winter and early spring, however, we observed a strong increase in water vapor in altitudes of the upper dehydration regime and above (21 km and above), which we attribute to vertical descent (Figure 7). This vertical descent does not penetrate deep into the dehydration regime. Between 22 and 23 km, dehydration is observed between late June and early August and the water vapor concentration continues to increase after this as a result of the descent. From the descent of this upper dehydration edge we can estimate a mean descent rate of 1.5 km/month for August, about 2.2 km/month for late July and less than 1.0 km/month for September. These values are substantially lower than those given by *Russell et al.* [1993] and are a further indication for the strong confinement of the vortex. At 20 km the dehydration persists throughout the last sounding on October 5, 1994, showing that the effective descent does not reach that far down. Furthermore, there is no indication for horizontal transport into the vortex in the 20-km region.

The minimum temperature in the region from 11 to 15 km is reached around late August. We have only two soundings after this time at McMurdo on September 13 and October 5, but there are several soundings from previous years at South Pole. None of the South Pole soundings shows a significant increase in water vapor in this altitude region. The latest of these soundings, from November 3, 1990, still shows 2.5 ppmv of water between 12.5 and 15 km. This clearly indicates that in the lower altitudes of the dehydration regime the bulk of the vortex is also well isolated and that there is no significant transport into the vortex. However, the sounding on October 5, 1994, at McMurdo shows signs of rehydration layers at 11 and 9.5 km, with a peak value of 6 ppmv, which is clearly higher than typical predehydration values. This demonstrates the penetration of the vortex edge and subsequent processing in the lower parts of the vortex close to the vortex edge.

The sounding from September 13, 1994, at McMurdo (Figure 8) shows the signature of air from outside the vortex between 17.5 and 19.5 km. This may again indicate transport across the vortex boundary. However, we do not see any signs of subsequent processing in the form of rehydration below, and therefore this may just reflect the fact that the vortex boundary is not a vertical cylinder. Clearly, on this day the vortex edge was close to McMurdo, and so we do not believe that this observation affected the bulk of the vortex. Furthermore, we found a significant difference between the ascent and descent profile in this region, which was not due to contamination and which may reflect a sharp gradient typical for the vortex boundary.

If we take the mean of all profiles (Figure 9) during the period of sustained dehydration from McMurdo and compare those with the mean profile from South Pole, we observe no significant difference between these mean profiles. This indicates that the interior of the vortex is well mixed. A slightly higher mixing ratio at South Pole between 8 and 11 km could indicate the increase of upper tropospheric water vapor as a result of the evaporation of particles falling into the troposphere. However, this difference is statistically significant on a 90% level only

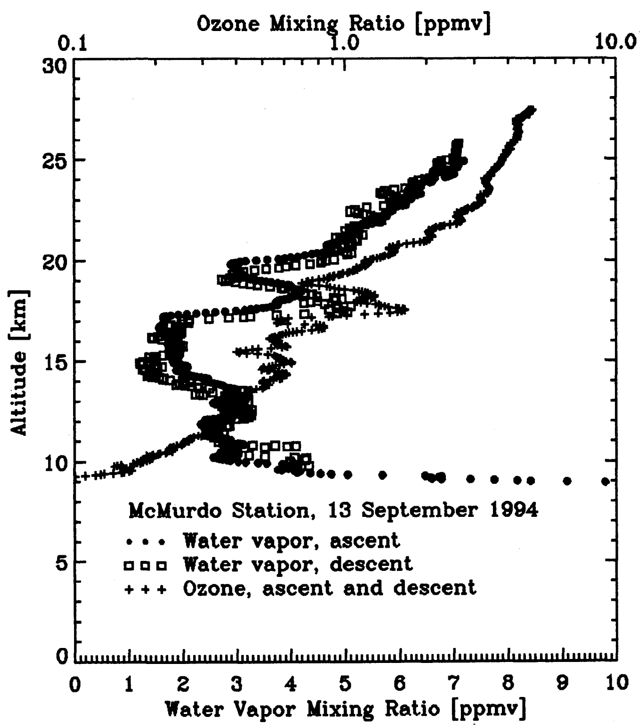

Figure 8. The layer of increased water vapor on September 13 between 17.5 and 19.5 km also reflected in the ozone profile. Interestingly, there is a shift in these two peaks during ascent but not during descent.

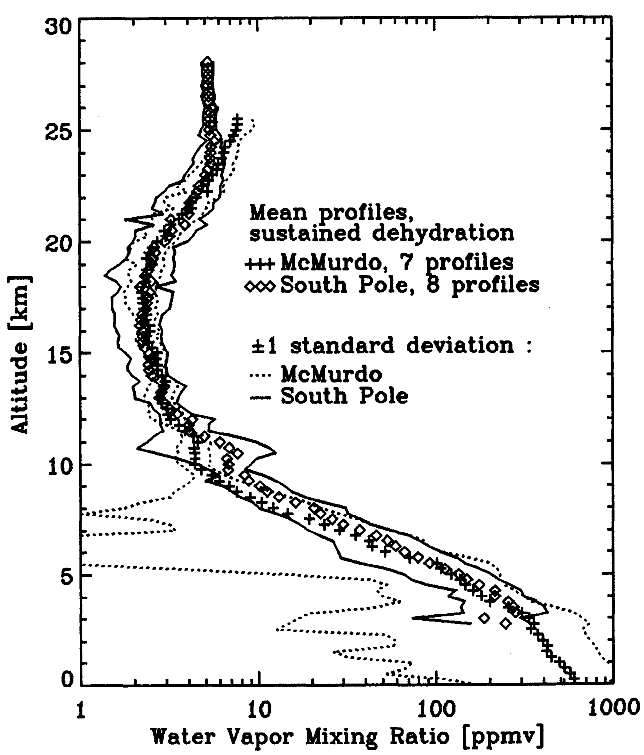

Figure 9. The mean profiles for South Pole and McMurdo during the period of sustained dehydration showing no significant difference, except for two regions between 8 and 11 km and above 24 km. In the lower regime the data at South Pole show increased water vapor, which may be a result of the ice particles falling into the troposphere. The difference above 24 km may reflect contamination of the data, despite great care taken during the measurements.

between 9 and 10 km. The difference between McMurdo and South Pole above 24 km may be due to contamination by outgassing near the top of the profile, despite great care taken during the measurements. Contamination, however, is not a factor for the difference at the lower altitude.

6. Summary

Beginning in about the second week of June, the coldest regions of the Antarctic stratospheric vortex reach frost point temperatures. This leads to rapid formation of particles, which have a significant fall speed, and therefore to rapid dehydration around the middle of June. During this early dehydration we observed layers of increased water vapor due to the evaporation of falling ice particles. These rehydration layers are a strong signal of the ongoing drying of the vortex. From the development of these rehydration layers in the first weeks of dehydration we can estimate the mean particle size at about 4 µm. The rehydration layers are a transient stage, which may have an important impact on the chemistry in these layers. They vanish as these layers are dehydrated by the continuing cooling of the vortex. Observations of strong dehydration, with a frequent lack of saturation at McMurdo, combined with synoptic maps show that a small cold region within the vortex is sufficient for large-scale dehydration. At 20 km we have seen no indication for any vortex penetration, either through vertical or horizontal transport. From the descent of the upper dehydration edge we can determine a mean descent rate of about 1.5 km/month. Below 15 km we have seen indication for occasional vortex penetration. However, this seemed to have little or no effect on the bulk of the vortex. Therefore the bulk of the vortex appears to be well isolated from its environment throughout the usual ozone hole season.

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