Tellus (1977), *29*, 530–534

On the nature of persistent stratospheric clouds in the Antarctic

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(Manuscript received November 8, 1976; in final form January 26, 1977)

ABSTRACT

Thin, persistent very high clouds called "Stratospheric Cist" were reported at Maudheim base (71°03′S, 10°56′W) during the 1950–51 austral winters. The nature of these clouds, whether they are H_2O or dust, is of importance in the proposed sink for stratospheric moisture in the Antarctic winter.

Results are presented from analyses of unpublished daily cloud reports and daily upper air measurements from the Maudheim expedition. The results reveal strong evidence that the "Stratospheric Cist" were stratospheric ice clouds. Given this identification, an upper limit of 6–7 ppm can be assigned to the water vapor mixing ratio in the lower stratosphere for the 1950–51 Antarctic winters.

1. Introduction

Mother-of-pearl (nacreous) clouds lying in the stratosphere are reported, on the average, about 15 days per decade in the Northern Hemisphere (Stanford & Davis, 1974). Most of these sightings are over the Scandinavian area and are orographically induced, lasting typically for periods of the order of hours. Although fewer observers are present, it appears that such clouds also occur in significant numbers in high southern latitudes (Stanford & Davis, 1974).

In contrast to these short-lived, orographically related stratospheric clouds, cloud veils, apparently lying in the stratosphere and persisting an order of magnitude longer in time (of the order of days or weeks or more) were reported by the careful observations made during the Maudheim Antarctic expedition in 1950–51 (Liljequist, 1956). The Maudheim observers noted a class of long-lasting, thin, very high clouds which they termed "Stratospheric Cist."[1] Stratospheric cloud veils have sometimes also been reported in Scandinavian mother-of-pearl cloud situations, for example, Hesstvedt (1959). The Antarctic variety are apparently longer lasting due to more continuously cold stratospheric conditions.

These Antarctic cloud reports have been recently used as partial evidence for precipitation of water vapor in the stratosphere, in conjunction with a proposal that the winter Antarctic may be a sink for the removal of stratospheric water vapor (Stanford, 1973). There has been some concern, however, that the Maudheim observations may have referred to dust clouds (Volz, 1975). The exact nature of the clouds has importance in conjunction with the possible stratospheric water vapor sink in the Antarctic winter and thus bears closer scrutiny.

This paper presents the results of careful analyses of the original Maudheim radiosonde data, together with a comparison of the Maudheim cloud logs. The results reveal strong evidence that the majority of the observations identified as "Stratospheric Cist" actually were H_2O clouds lying in the lower stratosphere.

2. Observational data and analyses

Figs. 1 and 2 show the results of calculations of the saturation mixing ratio with respect to ice (the temperatures are generally colder than −70 °C) for the upper troposphere and lower stratosphere over

[1] The author is grateful to a referee who pointed out the existence of similar cloud reports made during the 1957–60 Antarctic expedition to Norway Station. Detailed examination of these previously unpublished reports will be the subject of a future investigation.

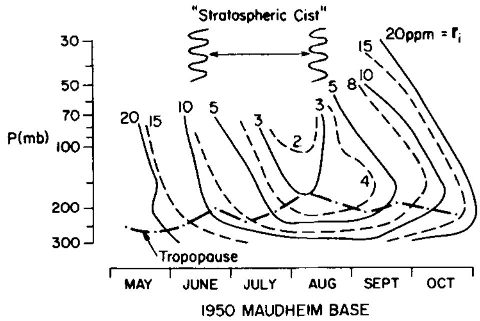

Fig. 1. Saturation mixing ratios of water vapor with respect to ice (in ppm, i.e. units of 10^{-6} g H_2O/g air) vs pressure for Maudheim base (70°03′S, 10°56′W) during the 1950 Antarctic winter. The curves extend up to the bursting level of the balloons. The temperature data used were half-monthly means. The position of the half-monthly mean tropopause is indicated. The approximate dates over which "Stratospheric Cist" were reported are also indicated.

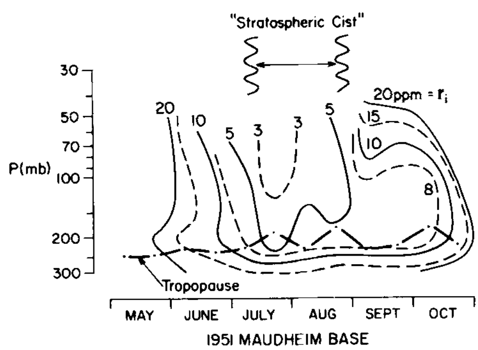

Fig. 2. Same as Fig. 1, but for the 1951 Antarctic winter at Maudheim.

Maudheim base (71°03′S, 10°56′W) during the austral winters of 1950 and 1951. The calculations follow the method described by Stanford (1973). Briefly, the saturation mixing ratios are calculated from

$$r_i(p,T) = \frac{0.622e_i(T)}{p - e_i(T)} \tag{1}$$

where p is pressure, T is radiosonde temperature, and $e_i(T)$ is the vapor pressure over ice (hexagonal) at temperature T given by List (1949). As discussed by Stanford (1974), the sizes and concentrations of stratospheric aerosols are such as to provide adequate condensation nuclei and to greatly reduce the effects of surface curvature in particle growth. In light of other experimental errors, we here take the sublimation vapor pressure to be that over a plane surface, as given by List (1949). The temperatures are from the half monthly means of radiosonde data given by Schumacher (1958). The position of the half-monthly mean tropopause is also indicated.

From the latter part of June until the middle of August, 1950, and from the middle of July through the end of August, 1951, observations of clouds called "Stratospheric Cist" were reported by the Maudheim observers, as indicated in Figs. 1 and 2. Quoting Liljequist (1956);

> "From about midwinter till beginning of October we often observed an extremely thin cloud-veil, which was probably situated in the lower stratosphere and seemed to cover the whole sky. We used to refer to this type of cloud as 'Stratospheric Cist'.
>
> "In 1950 we observed this cloud for the first time in the middle of June, but were not then clear as to its nature. The light conditions obtaining, with the sun about 5° below the horizon, gave the cloud-veil the appearance of an ordinary frontal cloud-system far to the north, though it never rose any higher in the sky, but remained the same day after day. The 'Stratospheric Cist' was then common till the middle of August, and thereafter less frequent. It was observed for the last time on October 7th.
>
> "In 1951 the 'Stratospheric Cist' was seen for the first time on July 6th. It was common in July and August, and was last seen on October 9th."

Further information about the "Stratospheric Cist" observations, together with three sound reasons for believing that these clouds actually did occur in the lower stratosphere, are given in Stanford (1973). Calculations of saturation mixing ratios based on the *daily* upper air temperatures and their comparison with the *daily* Maudheim cloud observations would be useful in determining the nature of the "Stratospheric Cist" clouds. However, the daily upper air observations from Maudheim have not been published previously. The daily upper air temperature vs pressure data have been made available to us by N. J. Schumacher, Det Norske Meteorologiske Institutt, Blindern. The daily reports of "Stratospheric Cist" from Maudheim also have not been published previously and were made available to us by Prof. G. H. Liljequist, University of Uppsala.

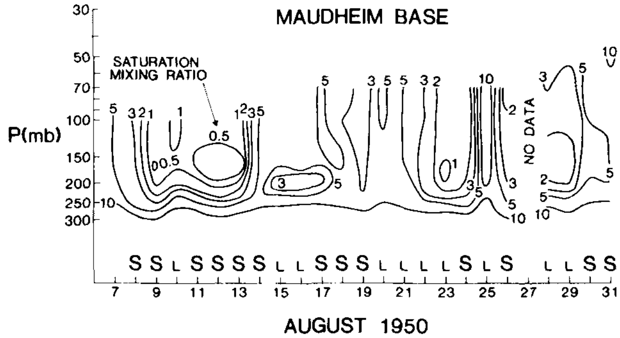

Fig. 3. Daily water vapor saturation mixing ratios (in ppm, i.e. units of 10^{-6} g H_2O/g air) with respect to ice over Maudheim base for August 7–31, 1950. The dates for which "Stratospheric Cist" were reported are indicated by "S" while "L" indicates days for which the records showed lower cloudiness that may have obscured observation of thin high clouds.

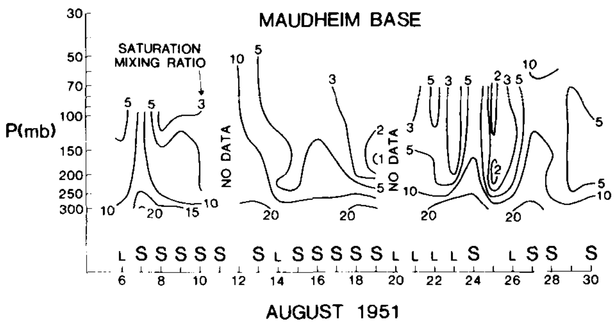

Fig. 4. Similar to Fig. 3, but for August 6–30, 1951.

Calculations of the daily saturation mixing ratios with respect to ice were performed for Maudheim base. Contours of constant saturation mixing ratios with respect to ice are shown in Figs. 3 and 4. Fig. 3 shows the period August 7–31, 1950, and reveals extremely low values of the saturation mixing ratio, due to the very cold conditions in the lower stratosphere during mid-winter. If the stratospheric water vapor content in 1950 was similar to the generally accepted current value of ~2.5 ppm, it is clear from Fig. 3 that large depths of the lower stratosphere over Maudheim must have been highly supersaturated. Stratospheric clouds almost certainly had to have been present during this time. Fig. 3 also shows the days (denoted by "S") on which "Stratospheric Cist" were reported. ("L" denotes days for which the records showed lower cloudiness that likely precluded observation of high clouds.)

Fig. 4 shows a similar winter period for 1951. Again "Stratospheric Cist" were reported rather uniformly throughout this period when the cold stratospheric temperatures reduced the saturation mixing ratios to very low values, typically a few ppm.

3. Discussion

3.1. *Evidence for H_2O clouds*

The data presented in Figs. 3 and 4 argue convincingly that the Maudheim "Stratospheric Cist" were stratospheric H_2O clouds. Due to the extremely low temperatures involved ($\lesssim -70\,°C$), they were likely ice clouds. Due to the excellent agreement between the reports of "Stratospheric Cist" and the occurrences of H_2O (ice) saturation mixing ratios sufficiently low to produce precipitation in the lower stratosphere, the evidence is strong that the "Stratospheric Cist" were indeed stratospheric H_2O (ice) clouds, rather than dust.

3.2. *Estimate of stratospheric moisture in 1950–51*

If the Maudheim "Stratospheric Cist" observations refer to ice clouds in the stratosphere, then careful analyses of the observational records and upper air temperature data may be utilized to yield an estimate of the maximum value of stratospheric moisture for the period. For example, Fig. 5 shows a time section of saturation mixing ratio (r_i) over the period July 7–12, 1951. The dates on which "Stratospheric Cist" were reported are also indicated. Notice that three reports occurred on days with $r_i \gtrsim 5$ ppm (July 7, 9 and 11) while none were reported (Liljequist, 1976) on days with $R_i \gtrsim 10$ ppm (July, 8, 10, 12). One must be careful to note that the radiosonde data for this period are absent (due to balloon failure) at altitudes above 70 mb. Thus the r_i values at 30–50 mb could have been less than 5 ppm for those days on which "Stratospheric Cist" were reported. The maximum mixing ratios were evidently somewhere between 5 and 10 ppm, and could possibly have been below 5 ppm.

On August 7, 1951 (see Fig. 4), "Stratospheric Cist" were reported with $r_i \sim 10$ ppm at the highest level reached by the balloon, 90 mb. However, this value, 10 ppm, is probably indecisive in establishing an upper limit to stratospheric moisture, since a straightforward, smoothly connecting 5 ppm contour from August 6 and 8 appears to require passing through August 10 at high altitudes.

August 12 and 13, 1951, in Fig. 4 appear to provide a clear case: no stratospheric clouds were reported on August 12, with $r_{min} \sim 10$ ppm, while August 13, with $r_{min} \sim 5$ ppm, did occasion a "Stratospheric Cist" report.

A search of the 1950 and 1951 cloud reports and results of the daily r_i calculations reveals the number of cases of "Stratospheric Cist" reported as a function of the minimum values of r which would produce saturation with respect to ice (Table 1).

Table 1 suggests that the mixing ratio of water vapor in the Antarctic winter lower stratosphere was not greater than about 6–7 ppm. This 1950–51 value is larger than the generally accepted present value of stratospheric moisture, ~2.5 ppm. Errors in radiosonde temperatures are not likely to account for all the difference, since an error of even ±2 °C would account for less than 1 ppm error in saturation mixing ratio under these conditions (Stanford, 1973).

One possible explanation of this result is that the stratosphere was more moist a quarter of a century ago. A second possibility is that of "piling up" of moisture due to the fallout of frozen moisture from higher up. This could be consistent with the water

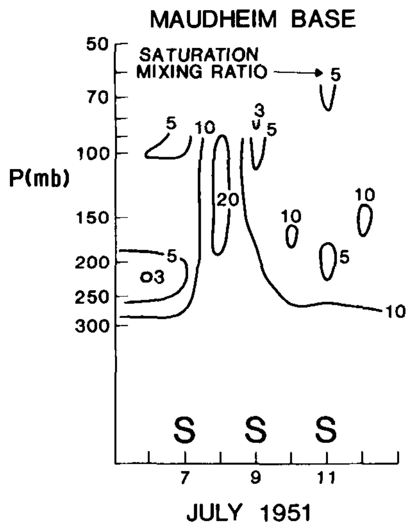

Fig. 5. Similar to Fig. 3, but for the period July 7–12, 1951.

Table 1. *N = Number of days on which "Stratospheric Cist" were reported at Maudheim.* r_{min} = *minimum stratospheric water vapor mixing ratio which would produce saturation with respect to ice, in ppm, i.e. units of* 10^{-6} *g* H_2O*/g air*

r_{min} (ppm)	N
<1	6
1–1.9	6
2–2.9	9
3–3.9	10
4–4.9	11
5–5.9	8
6–6.9	9*
7–7.9	1
8–8.9	0
9–9.9	0
10–10.9	1†
11–11.9	2‡
12–12.9	0
≥13 ppm	0

* Includes one case of "possibly Stratospheric Cist" with lowest r_i of 3 ppm located at 230 mb.

† A case of "probable Stratospheric Cist" where r_i = 10 ppm at 90 mb and likely smaller at lower pressures.

‡ Both cases were listed as only "possible" Stratospheric Cist.

vapor sink mechanism proposed by Stanford (1973). Since the fallout speed decreases with increasing atmospheric density, the precipitation fallout from the higher layers may temporarily accumulate in the lowest layer of the stratosphere.

A third possible (and perhaps the most likely) explanation relates to the low maximum altitudes reached by the radiosondes in the Antarctic winter. Data were not generally available in the 30–50 mb region, where normal mother-of-pearl clouds occur in the Northern Hemisphere stratosphere. Thus, the upper limit of 6–7 ppm for the mixing ratio values might have been smaller if radiosonde data for the 30–50 mb region had been available.

The calculations of r_i here assumed the hexagonal phase of ice (I_h). Cubic ice (I_c) occurs at low temperatures, although the onset temperature is in considerable question, perhaps being near or below −100 °C, below the temperatures of interest here. However, even if I_c occurs, the difference in latent heat of sublimation between I_h and I_c is given by various workers as from zero to 8.8 kJ/kg, small compared with that for I_h, 2838 kJ/kg. (See P. V. Hobbs, *Ice Physics*, Clarendon Press, Oxford, 1974, Chapter 1.) Calculation then shows that r_i will be changed by less than about 5%, which is less than the estimates of other errors involved here (of order 10%). Thus the question of the exact crystallographic form of the ice at these Antarctic stratospheric temperatures is not crucial to the ideas presented in this paper.

4. Summary

Careful analyses of cloud observations and upper air measurements at Maudheim base (71°03′ S, 10°56′ W) during the austral winters of 1950 and 1951 reveal that the "Stratospheric Cist" clouds reported were most probably ice clouds lying in the lower stratosphere. Given this identification, an upper limit of about 6–7 ppm can be assigned to the mixing ratio for lower stratospheric moisture during the 1950–51 Antarctic winters.

5. Acknowledgements

We are grateful to Professor G. H. Liljequist, University of Uppsala, for providing an extensive translation of the original Maudheim cloud logs. N. J. Schumacher, Det Norske Meteorologiske Institutt, Blindern, also kindly provided daily radiosonde temperature vs pressure data from Maudheim. It is a tribute to the Maudheim team that their observations are still providing valuable research data over a quarter of a century later.

The assistance of Vigfus Asgeirsson and Kathy Harper in data analysis is appreciated. Partial support of this work under National Science Foundation Grant GA-31776 is also appreciated.

REFERENCES

Hesstvedt, E. 1959. Mother of pearl clouds in Norway. *Geofysiske Publikasjoner 20*, 1–29.

Liljequist, G. H. 1956. Halo-phenomena and ice-crystals. *Norwegian-British-Swedish Antarctic Expedition, 1949–52: Scientific Results*, Vol. II, Part 2A, Norsk Polarinstitutt, Oslo.

Liljequist, G. H. 1976. Private communication.

List, R. J. 1949. *Smithsonian meteorological tables*. Smithsonian Institution, Washington, D.C.

Schumacher, N. J. 1958. Temperature, height and humidity. *Norwegian-British-Swedish Antarctic Expedition, 1949–52: Scientific Results*, Vol. I, Part 1, Norsk Polarinstitutt, Oslo.

Stanford, J. L. 1973. Possible sink for stratospheric water vapor at the winter antarctic pole. *J. Atmos. Sci. 30*, 1431–1436.

Stanford, J. L. 1974. Stratospheric water-vapor upper limits inferred from upper-air observations: Part I. Northern Hemisphere. *Bull. Am. Met. Soc. 55*, 194–212.

Stanford, J. L. & Davis, J. S. 1974. A century of stratospheric cloud reports: 1870–1972. *Bull. Am. Met. Soc. 55*, 213–219.

Volz, F. E. 1975. Implications of antarctic clear-sky striations. *Antarctic J. 10*, 228–9.

О ПРИРОДЕ УСТОЙЧИВЫХ СТРАТОСФЕРНЫХ ОБЛАКОВ В АНТАРКТИКЕ

В течение южных зим 1950–1951 годов на базе Модхайм (71°03′S, 10°55′W) наблюдались устойчивые очень высокие облака, называемые "стратосферная гробница". Природа этих облаков — состоят ли они из воды или пыли — важна для предлагавшегося стока стратосферной влаги антарктической зимой. Представлены результаты анализа неопубликованных данных ежедневных наблюдений облаков и аэрологических измерений в экспедиции Модхайм. Эти разультаты ясно свидетельствуют в пользу того, что "стратосферные гробницы" были ледяными облаками. Если это так, то верхний пеедел в $(6–7)\cdot 10^{-6}$ может быть приписан отношению смеси водяного пара в нижней стратосфере для антарктических зим 1950–1951 гг.