# nature

# The Living Record of Science

# 《自然》百年科学经典

英汉对照版（平装本）

## 第七卷（下）


总顾问：李政道（Tsung-Dao Lee）

英方主编：Sir John Maddox
Sir Philip Campbell

中方主编：路甬祥




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VII

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# Contents
# 目录

# Volume VII

# (1985-1992)

# Stratospheric Clouds and Ozone Depletion in the Arctic during January 1989

D. J. Hofmann *et al.*

## Editor's Note

**The prediction that human-made chlorofluorocarbons (CFCs) released into the atmosphere could destroy ozone in the stratosphere, exposing the Earth's surface to greater intensities of harmful ultraviolet rays, was verified by observations in the Antarctic in 1985. The atmospheric conditions are particularly conducive to ozone destruction there, owing to the cold and the isolation of air circulation in a vortex. The Arctic does not have such a steady vortex, but it was suspected that ozone depletion might nevertheless happen there—less extensively, but much closer to regions of dense population. Here atmospheric scientist David Hofmann and co-workers report the first confirmation of that, from observations made the previous winter. Arctic ozone depletion was regularly seen in subsequent years.**

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Stratospheric clouds, believed to be necessary for springtime polar ozone depletion to take place, were detected with balloon-borne sensors at Kiruna, Sweden during January 1989, the coldest January in the north polar stratosphere for at least 25 years. Comparison of the ozone profile in the region of the clouds with those obtained during the past three austral spring seasons at McMurdo Station in Antarctica suggests the beginning of ozone depletion at a height of 22–26 km.

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THE role of stratospheric clouds in springtime polar ozone depletion has been recognized in the Antarctic but not, so far, in the Arctic. Here we describe measurements made from two instrumented balloons in January 1989 with which we have been able to establish both the appearance of Arctic stratospheric clouds and the signature of the onset of ozone depletion at or around the altitude of these clouds.

The Arctic polar stratosphere during the winter of 1988–89 was unusually cold with no stratospheric sudden warmings until February[1]. The polar vortex was relatively stable throughout January, giving rise to conditions similar to those in the Antarctic winter stratosphere. The January average North Pole 30-hPa (~22-km altitude) height and temperature were the lowest ever measured. The average temperature at 30 hPa for January was as much as 12 °C below the 20-year mean over large areas of the polar region. Figure 1 shows the 30-hPa heights and temperatures on 23 and 24 January and on 30 and 31 January, periods covering the two balloon flights to be discussed here. Before 23 January, the vortex was centred near the North Pole. Intensification of the Aleutian high-pressure system began a shift of the vortex towards Scandinavia on 24 January which

# 1989年1月北极上空的平流层云与臭氧亏损

霍夫曼等

编者按

1985年南极的观测结果证实了释放到大气中的人为产生的氯氟烃（CFCs）破坏平流层中臭氧，使地球表面暴露于更强的有害紫外线辐射中的预测。由于寒冷和极涡中大气环流的隔离，那里的大气条件容易导致臭氧破坏。北极并不存在如此稳定的极涡，然而有人怀疑臭氧亏损仍可能发生在那里——范围更小，但更接近于人口密集的区域。本文中大气科学家戴维·霍夫曼和他的同事们通过前一个冬季的观测结果首次证实了北极臭氧亏损。在随后几年中，北极臭氧亏损定期出现。

平流层云被认为是春季极地臭氧亏损发生的必要条件，1989 年 1 月我们利用气球运载的探测仪探测了瑞典基律纳地区的平流层云，这个 1 月是至少 25 年来北极平流层最冷的 1 月份。对比南极地区麦克默多站上过去三年的春季臭氧廓线与云层所在区域的臭氧廓线，我们认为臭氧亏损的起点位于海拔 22~26 km 处。

在南极地区，平流层云在春季臭氧亏损中的作用已经得到公认，但到目前为止，它在北极地区的作用仍尚未明确。本文中我们介绍了 1989 年 1 月利用载有仪器的气球进行的观测，以此得以确定北极平流层云的出现及其对应海拔高度处臭氧亏损出现的信号。

1988~1989 年冬季，北极平流层异常寒冷，直到 2 月都没有出现平流层爆发性增温现象[1]。整个 1 月极涡相对稳定，从而形成了与南极冬季平流层相似的条件。1989 年 1 月北极 30 hPa 处（海拔约 22 km）平均高度和平均温度均是有史以来测到的最低值。北极大部分地区 1 月 30 hPa 处平均温度比 20 年的平均值低了 12℃。图 1 所示为 1 月 23 日、24 日和 1 月 30 日、31 日 30 hPa 处的高度和温度值，本文所讨论的两个气球探测航次正是在这两个时期内进行。1 月 23 日之前，极涡中心位于北极附近。阿留申高压系统的增强使得极涡从 1 月 24 日开始向斯堪的纳维亚移动，并

was eventually followed by a major stratospheric warming on about 10 February (K. Labitzke, personal communication). Before the major warming, however, temperatures as low as −92 °C were observed on 1 February at 30 hPa over southern Scandinavia. Temperatures below −85 °C in the 20–25-km region were responsible for the frequent displays of nacreous or "mother of pearl" clouds (stratospheric water-ice crystals) observed at Kiruna, Sweden (68° N, 20° E).

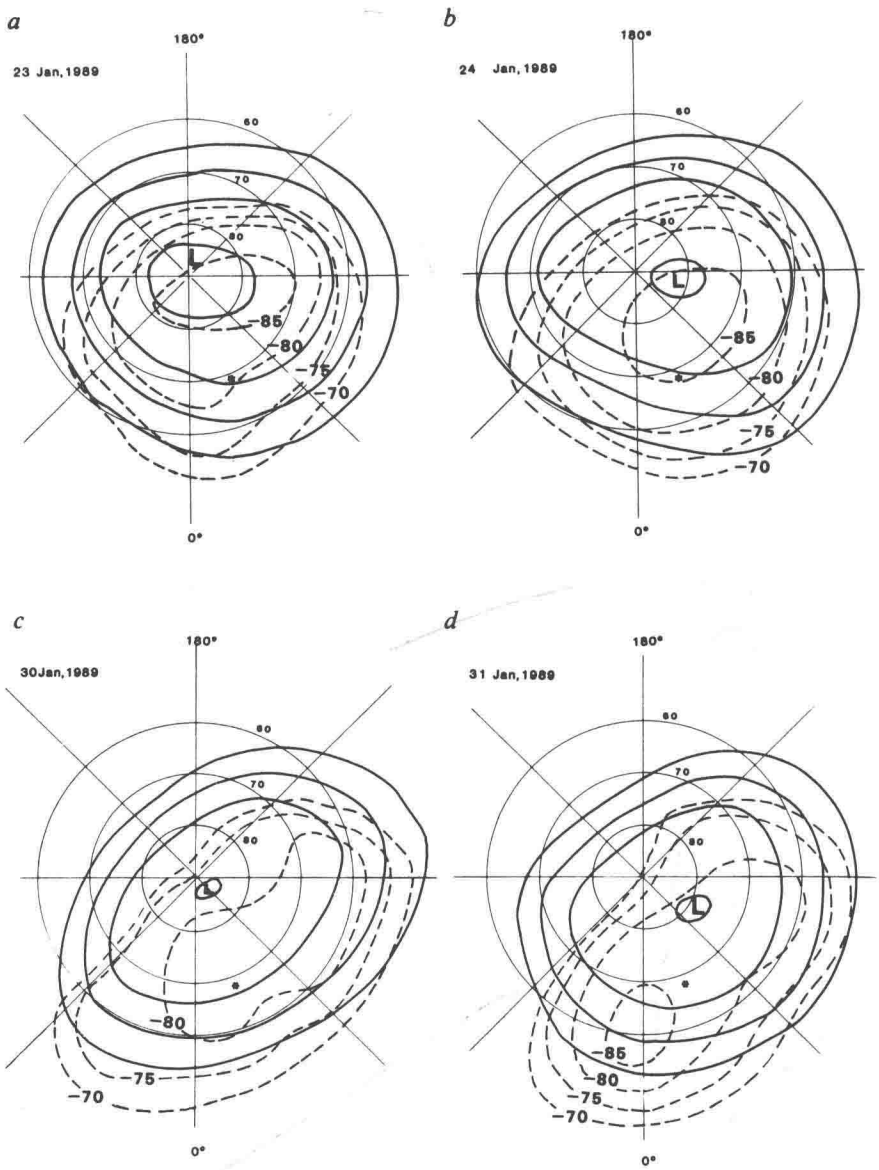


Fig. 1. Temperature (dashed) and height (full) contours at 30 hPa in the Arctic for 00:00 GMT on 23 January (*a*), 24 (*b*), 30 (*c*) and 31 (*d*), 1989, from the Berlin analysis (K. Labitzke, personal communication). The height contour of the north polar low is 21.5 km and the contour interval is 0.5 km. Temperatures are in °C. The location of Kiruna is marked by a star. Balloon flights at Kiruna occurred from 14:30 to 17:30 GMT, 23 January, and 11:30 to 14:30 GMT, 30 January.

最终导致平流层从 2 月 10 日左右开始明显变暖（拉比茨克，个人交流）。不过在明显变暖之前，2 月 1 日在斯堪的纳维亚南部上空 30 hPa 处测到的温度仍低达 –92℃。海拔 20~25 km 处的温度低于 –85℃，因此，瑞典基律纳（68° N，20° E）观测到贝母云或“珠母”云（平流层水 – 冰晶）频繁出现。

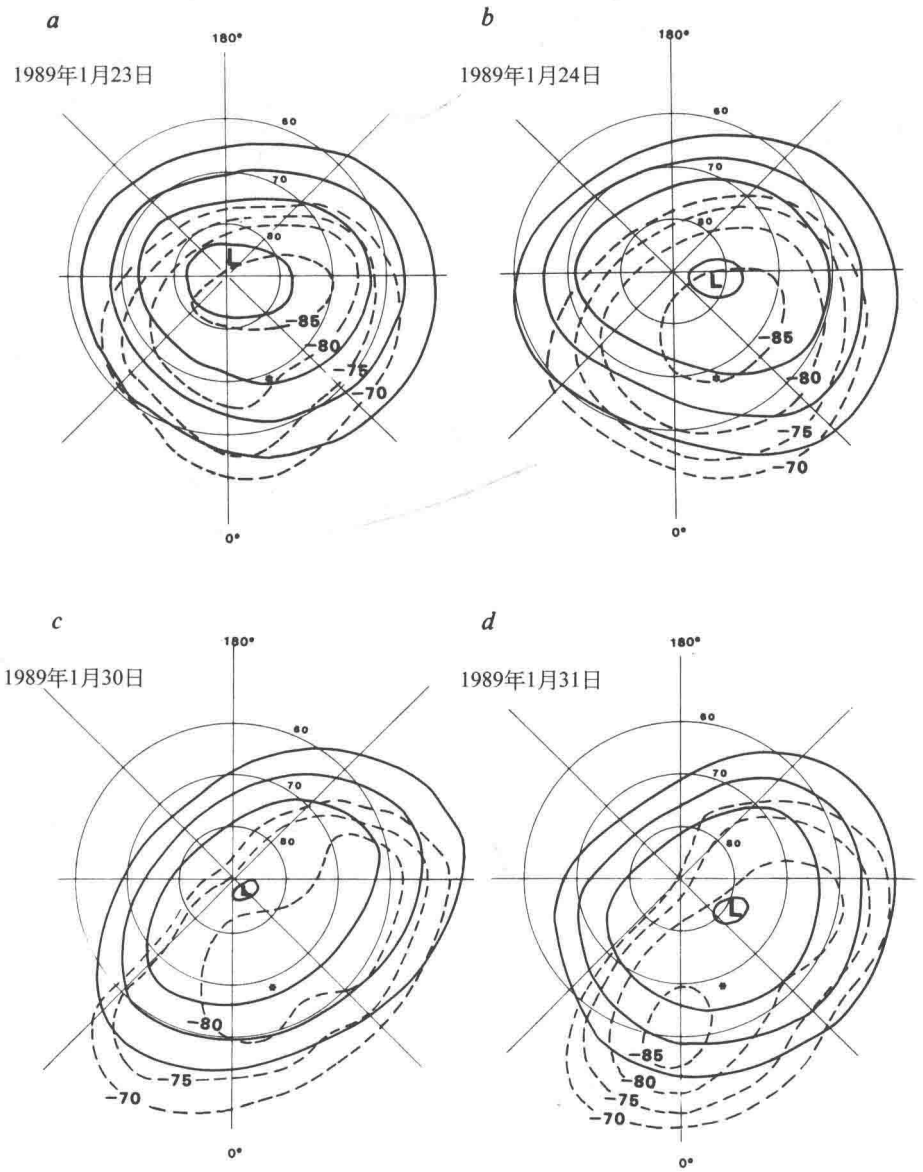


图 1. 由柏林分析得到的 1989 年 1 月 23 日（*a*）、24 日（*b*）、30 日（*c*）、31 日（*d*）00:00 GMT（译者注：格林尼治标准时间）北极地区 30 hPa 处的温度（虚线）和高度（实线）等值线（拉比茨克，个人交流）。北极的最低等高线为 21.5 km，等值线间隔为 0.5 km。温度的单位为℃。基律纳的位置以星号标出。在基律纳，气球飞行的时间分别为 1 月 23 日 14:30~17:30 GMT 和 1 月 30 日 11:30~14:30 GMT。

Stratospheric clouds are thought to be important in converting hydrochloric acid and chlorine nitrate into active chlorine and in stratospheric denitrification through the condensation of $HNO_3$ vapour, thus removing odd nitrogen from the gas phase which would otherwise prevent the destruction of ozone by the active chlorine[2]. The observation of extensive stratospheric clouds in the Arctic in January 1989 is therefore important in assessing ozone depletion under perhaps the most favourable conditions for this to occur since at least 1957. Before 1957 there was insufficient chlorine in the stratosphere to cause ozone depletion even with extensive clouds.

At a pressure of 30 hPa and for a typical stratospheric water-vapour mixing ratio of 5 p.p.m.v., a temperature of ~ −87.5 °C is required to condense the vapour and form ice clouds (the "frost point" temperature). However, studies of the nitric acid trihydrate (NAT) solid in the laboratory[3] indicate that this crystalline phase will form at a temperature of −80 °C (10 parts per $10^9$ by volume (p.p.b.v.) $HNO_3$) to −81 °C (5 p.p.b.v. $HNO_3$) for 5 p.p.m.v. water vapour at 30 hPa. A predominant NAT composition of Antarctic stratospheric clouds was proposed earlier from theoretical considerations[4,5] and has been identified in *in situ* measurements in Antarctica[6]. Thus, it appears that extensive NAT clouds and more local nacreous (water-ice) clouds should have formed in the Arctic stratosphere above ~20 km during January 1989. Because sunlight is also required to destroy ozone, the question of Arctic ozone depletion hinges on the amount of time that the air, which has been heterogeneously processed by stratospheric clouds, has spent in sunlight. As the Arctic polar vortex generally breaks down before sufficient sunlight reaches the near-polar regions, the most probable location for the detection of ozone depletion in the Arctic is near the Arctic circle during unusually cold years. For example, Kiruna experienced ~8 hours of sunlight per day on 23 January at 21 km where temperatures as low as −86.7 °C were observed. Owing to the effects of the Aleutian high, the vortex and the coldest regions are generally displaced towards Scandinavia (see Fig. 1) so that locations such as Kiruna are quite favourable. Here we report observations of polar stratospheric clouds and ozone during balloon flights on 23 and 30 January at Esrange, near Kiruna.

## Cloud Particle Measurements

The data were obtained with University of Wyoming balloon-borne particle counters as used on many occasions in Antarctica[7]. The optical counter has an air-sample flow rate of ~200 $cm^3\ s^{-1}$, capable of resolving low concentrations (~$10^{-3}$ $cm^{-3}$) as associated with ice-crystal formation. The instrument measured in seven size ranges, radius $r \geq 0.20$, 0.25, 0.30, 1.0, 2.0, 3.0 and 5.0 μm, for spherical particles or slightly non-spherical particles of equivalent volume. A condensation-nuclei detector sensitive to particles with $r \geq 0.01$ μm was added for the second flight on 30 January to obtain the total aerosol concentration profile and to determine the fraction of condensation sites taking part in cloud-particle growth.

Figure 2 shows the temperature and $r \geq 0.20$ μm aerosol profiles measured during balloon ascent for the two flights. For the flight of 23 January, temperatures were $< -80$ °C between

一般认为，平流层云在盐酸和硝酸氯转化为活性氯以及平流层脱氮过程中均发挥着重要作用。在脱氮过程中，平流层云通过 $HNO_3$ 蒸气凝结，进而从气相中脱去奇氮加速了活性氯对臭氧的破坏[2]。因此，1989 年 1 月对北极大范围的平流层云做的观测对于评估此次臭氧亏损有着重要意义，这次臭氧亏损事件是自至少 1957 年以来最有利条件下的产物。1957 年以前，平流层中虽然有大量云层，但其中的氯含量并不足以引起臭氧亏损。

当气压为 30 hPa、平流层中的水汽混合比为 5 ppmv 这一典型值时，要使水汽凝结形成冰晶云，温度需达到 –87.5℃ 左右（“霜点”温度）。然而，对固态三水合硝酸（NAT）的实验室研究[3] 表明，在 30 hPa、水汽混合比为 5 ppmv 时该结晶相的形成温度为 –80℃（$HNO_3$ 为 10 ppbv，ppbv：按体积计算的十亿分之一）到 –81℃（$HNO_3$ 为 5 ppbv）。理论研究[4,5] 很早就推断南极平流层云中的主要成分为 NAT，并且已在南极就地测量中得到证实[6]。因此，1989 年 1 月期间，似乎会有大量 NAT 云和更多的局部贝母云（水–冰晶）应该会在北极地区 20 km 以上的平流层中形成。由于破坏臭氧还需要阳光的参与，因此，北极地区臭氧亏损的问题取决于平流层云非均相过程产生的空气接受光照的时间长短。由于北极极涡通常在足够的阳光照射到极地附近之前就已消亡，因此探测北极臭氧亏损的最佳位置是在异常寒冷年份的北极圈附近。例如，基律纳在 1 月 23 日每天接受约 8 小时光照，其上空 21 km 处所观测到的温度低达 –86.7℃。由于阿留申高压的影响，极涡及最冷地区通常会向斯堪的纳维亚移动（见图 1），因此，像基律纳这样的位置是非常有利的观测地点。本文中，我们将报道 1 月 23 日和 30 日在基律纳附近的雅斯兰吉航天中心进行的气球飞行对北极平流层云和臭氧的观测。

## 云粒子测量

本文所用数据均由怀俄明大学气球运载的粒子计数器采集，该类计数器已在南极被使用过多次[7]。光学计数器的空气采样流速约为 200 $cm^3 \cdot s^{-1}$，足以分辨出冰晶形成时的低浓度值（约 $10^{-3}$ $cm^{-3}$）。该设备测量了 7 个尺寸范围：粒径 $r \geq 0.20$ μm、0.25 μm、0.30 μm、1.0 μm、2.0 μm、3.0 μm 和 5.0 μm 的球形粒子或等效体积的略呈非球形的粒子。在 1 月 30 日进行的第二次飞行中增加了凝结核探测器，它可以探测到粒径 $r \geq 0.01$ μm 的粒子，以获取总气溶胶浓度廓线，并确定云粒子生长过程中凝结核所占的比例。

图 2 给出了两次飞行中气球上升期间获得的温度及 $r \geq 0.20$ μm 的气溶胶廓线。1 月 23 日探测到，海拔 18.5~27 km 的温度低于 –80℃，20.2~21.3 km 温度低于 –85℃，

altitudes of 18.5 and 27 km and below −85 °C between 20.2 and 21.3 km, and reached −85 °C briefly several times between 23 and 25 km. Because the balloons encountered very low temperatures, the rise rate was generally kept low (1–2 m $s^{-1}$) with occasional short periods of float before ballasting. This may have resulted in inadequate ventilation of the temperature sensor and could account for some of the unusual temperature increases observed above ~20 km. This would not affect the particle counter or ozone sensors because they are aspirated by pumps. Some of the temperature structure seen during both flights may be related to orographic waves originating from the mountain ranges west of Kiruna which appeared to be responsible for the generation of nacreous clouds during the measurement period. Westerly wind speeds in the stratosphere were very high (in excess of 50 m $s^{-1}$) and a minimum temperature during the balloon ascent on 23 January of −86.7 °C was reached in the cold layer between 20 and 21 km. The second flight, on 30 January, did not experience such low temperatures, with a minimum of −82.7 °C at ~25 km.

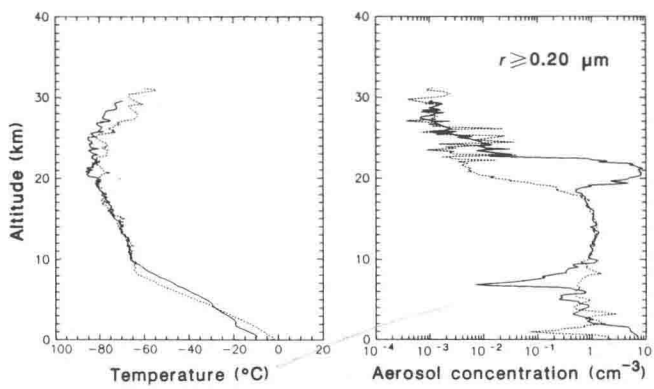


Fig. 2. Temperature and aerosol ($r \geq 0.20$ μm) profiles measured during balloon ascent at Kiruna, Sweden on 23 January (full lines) and 30 January (dashed lines) 1989.

The aerosol profiles in Fig. 2 indicate a normal sulphate layer between ~10 and 18 km with concentrations similar to those observed in Antarctica in September 1988[8]. These aerosols represent the global background sulphuric acid layer, there having been no major volcanic eruptions since EI Chichón in 1982 which increased the atmospheric sulphate concentration by nearly an order of magnitude[9]. In the cold layer at 19–22 km on 23 January we see a large increase in $r \geq 0.20$ μm particles, reaching a concentration of 8 $cm^{-3}$ or more than 50% of the concentration of condensation nuclei in this region. The condensation-nuclei or total-aerosol profile was measured on the second flight and is reasonably constant in the absence of homogeneous nucleation of new particles. The particle enhancement on 23 January actually extends uniformly at lower concentrations to at least 26 km.

The large particles ($r \geq 1.0$ μm) were also enhanced but only to the extent of ~1 in $10^4$ of the available condensation nuclei. Very few particles having radii >2 μm and no large ice crystals ($r \geq 5$ μm) were observed in the layer. Thus it appears that pure water did not