On the physics of stratospheric (nacreous) cloud formation

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ABSTRACT

The purpose of this note is to point out that conjectures that stratospheric lee waves might be able to produce the required additional cooling necessary for nacreous (mother-of-pearl) cloud formation in the lower stratosphere are in good agreement with recent experimental results obtained by Lilly and co-workers for mountain-induced lee waves. A recent conjecture of a very moist stratosphere to account for the formation of stratospheric clouds thus appears unnecessary.

Introduction

In two review articles, Hesstvedt (1969, 1959) has given a comprehensive survey of the climatology and possible physical mechanism for formation of nacreous (mother-of-pearl) clouds. In brief, these clouds are observed only rarely, at high latitudes, in the winter months, and occur at heights of 17–31 km with an average of around 23 km (i.e., in the stratosphere). Since the stratosphere is thought to be quite dry (water vapor mixing ratio of $\sim 3 \times 10^{-6}$ g H_2O/g air) from recent measurements [see, for example, Mastenbrook (1968, 1971)], unusually low temperatures are required for saturation with respect to ice. At the 50 mb level, for example, $T \leqslant -85°C$ is required for saturation with respect to ice with the above water-vapor mixing ratio. At 30 mb, $T \leqslant -88°C$ is required. Such low temperatures do not often occur in the lower stratosphere, although temperatures near $-70°C$ or $-80°C$ are known to occur on rare occasions at high latitudes in the winter months. Because nacreous clouds are often observed in conjunction with an advancing tropospheric polar cold front, it is reasoned that part of the cooling required occurs as adiabatic cooling in the lower stratosphere when the air at this level flows over the troposheric front.

The lenticular shape of nacreous clouds, similar to the lee-wave clouds formed in the troposphere on the down-wind side of mountains, suggests that additional cooling may occur as the stratospheric flow is lifted adiabatically over the crests of orographically-induced lee waves which extend into the stratosphere. The location of Norwegian mother-of-pearl cloud sightings, on the lee side of Norway's mountain chain (Hesstvedt, 1959) is also consistent with this suggestion. However, the amplitude of stratospheric lee waves and the magnitude of the cooling at their crests, compared with the temperature of the undisturbed atmosphere, were not available when Hesstvedt (1969) wrote his treatise. He had to assume that the needed cooling, on the order of 5–10°C, was reasonable for stratospheric lee-wave situations.

Recent studies

More recently, McIntosh (1972) has criticized this concept. Analyzing a nacreous cloud observation over Scotland on 10 January 1971, McIntosh found a most probable height of about 25 km for this cloud. He then estimated a frost point of $-91°C$ for 25 km, assuming a water-vapor mixing-ratio of 2×10^{-6} g/g. McIntosh found that such a low temperature, if it was attained by means of adiabatic cooling in a lee-wave situation, indicated a lee-wave lifting of 3 km or more. Since such a large amplitude for a stratospheric wave seemed hardly credible,

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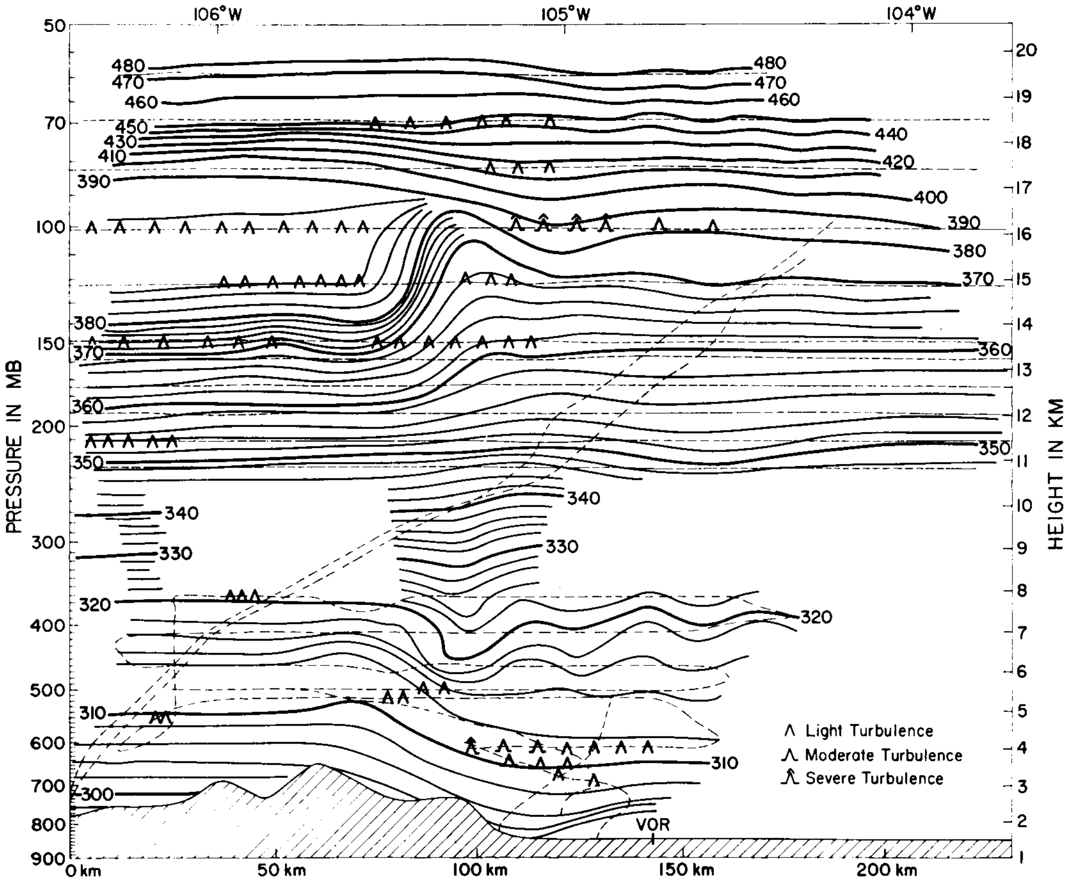

Fig. 1. Mountain-induced lee-wave structure of 17 February 1970 near the Colorado Rocky Mountains. The solid lines are lines of constant potential temperature. (Reprinted from Lilly (1971).)

McIntosh was forced to postulate another explanation involving a larger water-vapor mixing ratio (by over an order of magnitude of that reported by Mastenbrook) for the stratosphere.

Recently, Lilly and his colleagues (Lilly, 1971; Lilly et al., 1971) have shed considerable light on the complex nature of orographic lee-wave structures. In particular, their work reveals that unusually large wave amplitudes and temperature fluctuations can occur in standing lee-waves induced in the lower stratosphere. Fig. 1 shows data obtained on 17 February 1970 over the Rocky Mountains in Colorado. The constant potential temperature lines (solid lines) are thought to be reasonably good tracers of the stratospheric air motions and reveal a particularly large amplitude lee-wave near 150–100 mb. The wave amplitude is seen to be ~ 2.5 km at this point. Further details are found in Lilly (1971).

Fig. 2 shows the temperature obtained from the aircraft flight shown as a dashed line at about 102 mb altitude in Fig. 1. The data were obtained from Lilly et al. (1971). It can be seen from Fig. 2 (or calculated from Fig. 1) that the coldest portion of the lower atmosphere reached -81°C (at time 7:44), as the aircraft penetrated the peak of the large amplitude wave near 100 mb altitude. This represents an adiabatic cooling of about -8°C from the "undisturbed" stratosphere at the same altitude, and occurring in a horizontal distance of only about 20 km. This value of cooling in a stratospheric lee-wave situation is in good agreement with that postu-

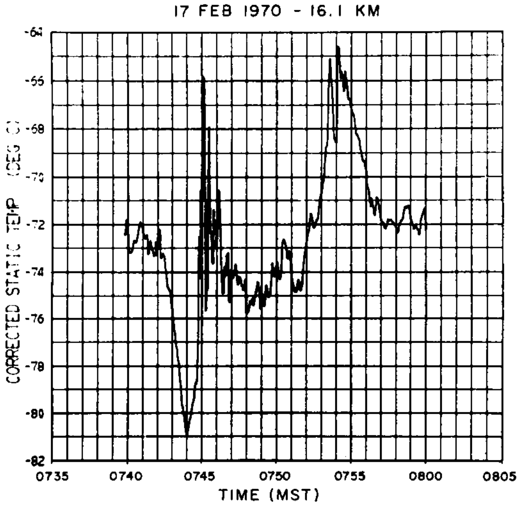

Fig. 2. Temperature measurement by aircraft flight-level shown as dashed line at 102 mb in Fig. 1. (Reprinted from Lilly et al. (1971).)

lated by Hesstvedt (5 to 10°C) as necessary to account for the formation of stratospheric clouds.

The lee-wave situation depicted in Fig. 1 is not unique. Indeed, such situations are thought to occur fairly frequently over the Rocky Mountains. Given the correct environmental wind situation, i.e. strong horizontal winds extending far up into the stratosphere and more or less perpendicular to the mountain chain (as is commonly observed in mother-of-pearl cloud situations), it is quite reasonable to expect the lee-wave crests to occur at even higher altitudes than those of Fig. 1. If the latter were to occur in conjunction with an already cold (~ -80°C) stratosphere such as sometimes occurs over northern Europe in winter, it would appear quite reasonable to expect to find, on such occasions, the extraordinarily low stratospheric temperatures needed for the formation of nacreous clouds in a relatively dry stratosphere.

It is interesting to note that Fig. 1 reveals little significant structure in the altitude range from about 8 to 14 km. On this occasion, the atmosphere exhibited a "double tropopause" in the undisturbed region west of the mountains, the lowest tropopause occurring at an altitude of about 13 km. The crest of the largest lee-wave occurs between 16 and 17 km altitude, well above this "undisturbed" tropopause level. That is, large lee-wave crests are not observed in the lowest stratospheric and highest tropospheric regions. Whether this feature of lee-wave structure is peculiar to this one day or is more generally representative is not known. The lack of significant structure in the 8–14 km altitude range is incompletely understood at this time. If it should turn out that this is a fairly common occurrence in lee-wave situations, this would provide a plausible explanation for the puzzling fact that nacreous clouds are not usually observed in the lowest few kilometers of the high-latitude stratosphere, but rather at the higher altitudes of 17–31 km.

Conclusions

Recently observed stratospheric lee-wave amplitudes appear to be sufficient to account for the additional cooling needed to form stratospheric clouds in a fairly dry stratosphere. The postulate of an unusually moist stratosphere to account for the formation of nacreous clouds appears unnecessary.

Acknowledgement

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О ФИЗИКЕ ОБРАЗОВАНИЯ (ПЕРЛАМУТРОВЫХ) ОБЛАКОВ В СТРАТОСФЕРЕ

Цель этой заметки указать, что концепции, предполагающие, что орографические волны в стратосфере могут приводить к требуемому дополнительному охлаждению, нуж'ому для образования перламутровых облаков в ниж ней стратосфере, находятся в хорошем согласии с недавними экспериментальными результатами, полученными Лилли и его сотрудниками для волн, возбуждаемых за горами. Поэтому недавнее представление об очень влажной стратосфере, необходимое для объяснения стратосферных облаков, представляется таким образом ненужным.