Reports

Temperature Measurements in Noctilucent Clouds

Abstract. *Results of ten rocket soundings conducted from Kronogard, Sweden, and Barrow, Alaska, during the summers of 1963 through 1965 indicate that a temperature of 150°K or less is a necessary but not sufficient condition for the existence of noctilucent clouds. Water vapor appears to be a critical ingredient in the occurrence of these clouds.*

Noctilucent clouds have been a subject of interest for many years because of the great heights above the earth at which they occur. These clouds have generally been observed at altitudes ranging from 78 to 90 km, the majority of observations indicating a cloud height of about 83 km (*1*). They have been sighted only at high latitudes and most frequently during the 4- to 6-week period following the summer solstice (*2*). Noctilucent clouds are visible only during the time that the sun is below the observer's horizon, and they are directly illuminated by sunlight against a darkened sky background. High latitudes provide favorable geometry for observation of the clouds for considerably longer periods each day than middle or low latitudes do, but the fact that clouds exist only at high latitudes and only during summer can be explained in terms of the temperature structure of the mesosphere at these latitudes.

We employed the rocket-borne acoustic grenade technique (*3*) to provide measured profiles of atmospheric temperature, pressure, density, and wind to an altitude of 95 km. A total of ten grenade soundings were carried out from Kronogard, Sweden (66°N), and Barrow, Alaska (71°N), during the summers of 1963 through 1965 to determine the relation between the mesospheric temperature structure and the occurrence of noctilucent clouds. The soundings in Sweden were conducted under a cooperative program between NASA and the Swedish Space Committee, and the results of those soundings have been published (*4*).

Results of the Barrow soundings (August 1965) are given in Fig. 1a. These profiles display remarkable uniformity, with temperature variations generally on the order of 3° to 4°K from profile to profile throughout the mesosphere. The mesopause temperatures ranged from 132° to 140°K, and the steep uniform lapse rate, which is typical of the high-latitude summer mesosphere, was observed in all the soundings. An error analysis has been performed on these data, and the errors associated with the temperatures mentioned above are 1° to 3°K. We initiated this series of four soundings during a display of noctilucent clouds and completed it almost 48 hours later, during the confirmed absence of the clouds. Noctilucent clouds cannot be detected during daylight, but the two daylight soundings were intended to observe possible daytime variations.

Very little change in the temperature structure can be seen between soundings made in the presence and absence of noctilucent clouds (*5*). It is not surprising that there is almost no diurnal temperature variation, because the upper atmosphere at Barrow is exposed to almost continuous sunlight during early August (the solar elevation angle at 50 km, for example, varies only from 30 deg at noon to 6 deg at midnight). The same situation is evident in Fig. 1b, which shows results of the noctilucent cloud sounding and the control from Barrow, with a similar pair of soundings made almost 72 hours apart at Kronogard. The first sounding at each site was conducted during a display of noctilucent clouds, and the second served as a control sounding, having been carried out in confirmed absence of the clouds. At Barrow, the minimum temperature of the profile made in the presence of clouds was 139°K, which is 3°K warmer than the mesopause temperature of the control sounding. At Kronogard, however, the minimum temperature of the profile made during the cloud display was 130°K, or 18°K colder than the mesopause temperature of the control.

The profile of the average temperature for the five soundings conducted during displays of noctilucent clouds and the average profile for the three soundings conducted during the confirmed absence of these clouds do not differ by more than 5°K at any point between 45 and 90 km. The warm stratopause, the steep uniform lapse rate, and the extremely cold mesopause are essentially identical for both profiles. Also evident for the five soundings conducted during displays of noctilucent clouds are mesopause temperatures that varied from 130° to 147°K. Correspondingly, for soundings conducted in the absence of clouds, the mesopause temperatures ranged from 129° to 149°K. Thus the coldest temperatures did not necessarily produce noctilucent clouds, but the clouds were always accompanied by mesopause temperatures less than 150°K.

There are two schools of thought concerning the composition of noctilucent cloud particles. One theory assumes the presence of sufficient water vapor at the mesopause to form ice particles by a process of saturation and condensation (*6*). The other does not accept the presence of water vapor and

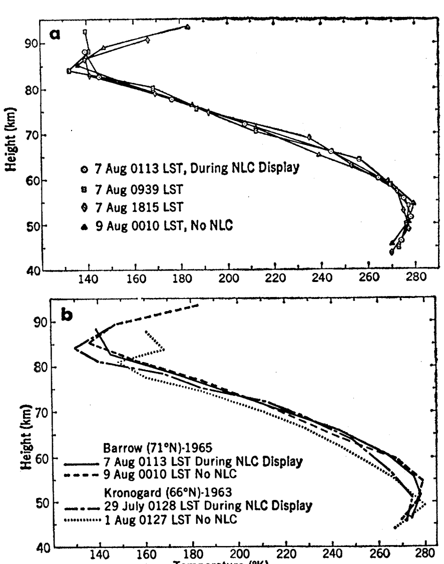

Fig. 1. (a) Temperature profiles above Barrow, Alaska (71°N), during August 1965. (b) Temperature profiles above Kronogard, Sweden (66°N), and Barrow during the summers of 1963 and 1965, respectively. Note that the Barrow mesopause was colder in the absence of noctilucent clouds than during the cloud display, but the reverse was observed at Kronogard. *LST*, local standard time; *NLC*, noctilucent cloud.

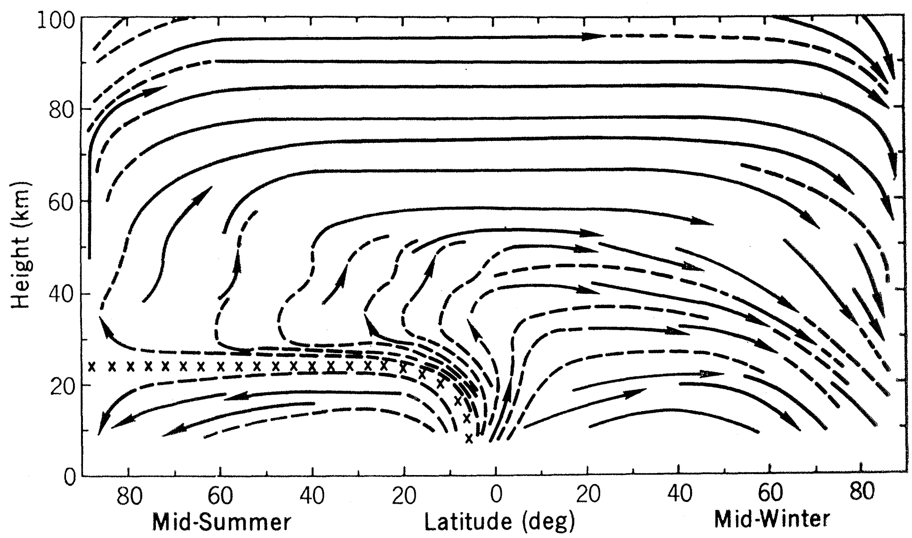

Fig. 2. Meridional circulation. [after Hesstvedt]

ice, but explains the noctilucent clouds in terms of the light-scattering properties of the dust alone (*7*), which is believed to originate from the vaporization of incoming meteors or from the surface of the earth. Sampling experiments (*8*) have been conducted to resolve the question of the composition of cloud particles, and traces of a volatile substance believed to be ice were found surrounding many of the larger particles obtained from a noctilucent cloud.

We believe, in view of the temperature data reported above, that the occurrence of noctilucent clouds depends largely on the amount of water vapor present at the mesopause, if one assumes that the optical geometry, the dust nuclei, and a cold mesopause exist, although, in fact, these conditions may vary considerably in both space and time. Khvostikov has postulated that "Noctilucent clouds appear in the atmosphere at the place and the time where and when the temperature of the air turns out to be low enough" (*9*). However, the results shown in Fig. 1b indicate that a given low temperature alone is not sufficient to produce noctilucent clouds, unless, we believe, the low temperature occurs in conjunction with sufficient water vapor. Thus the water vapor content of the high atmosphere must be considered.

Seasonal variations of the mesopause temperature not only produce sufficiently cold conditions for the formation of noctilucent clouds, but also provide a circulation consistent with the transport of water vapor to the mesopause at high latitudes in summer. Nordberg and Stroud (*10*) reported the high-latitude summertime mesopause to be almost 80°K colder than the wintertime mesopause, and our results confirm this finding. These seasonal variations of temperature are not consistent with considerations of radiation alone, since, at high latitudes, the summer mesosphere is heated almost 24 hours a day and the winter mesophere is dark almost 24 hours a day. Leovy (*11*) demonstrated that a meridional circulation superimposed on an atmosphere in radiative equilibrium produced good qualitative agreement with observed seasonal variations of temperature. This meridional circulation caused ascending motion at the summer pole and descending motion at the winter pole, thereby transferring heat from the radiatively heated upper atmosphere of summer to the heat-deficient upper atmosphere of winter.

Hesstvedt (see *12*) used a similar meridional circulation proposed earlier by Murgatroyd and Singleton to explain the presence of water vapor in the upper atmosphere. This model is also consistent with the observed variations of temperature. As can be seen in Fig. 2, Hesstvedt's model shows that the source of water vapor is the tropical troposphere and that water vapor enters the stratosphere through the gap in the tropopause (*13*). From this relatively narrow latitudinal band near the equator, air rises to an altitude of 25 km, moves meridionally toward the summer pole, and then ascends rapidly at high latitudes. Poleward of 60 deg latitude in the summer hemisphere, air at 80 km is seen to originate from the equatorial troposphere. Such a model qualitatively explains the mechanism both for transporting water vapor to the summer mesopause and for transferring heat from the summer mesosphere to the winter mesosphere, thereby accounting for the observed sea-

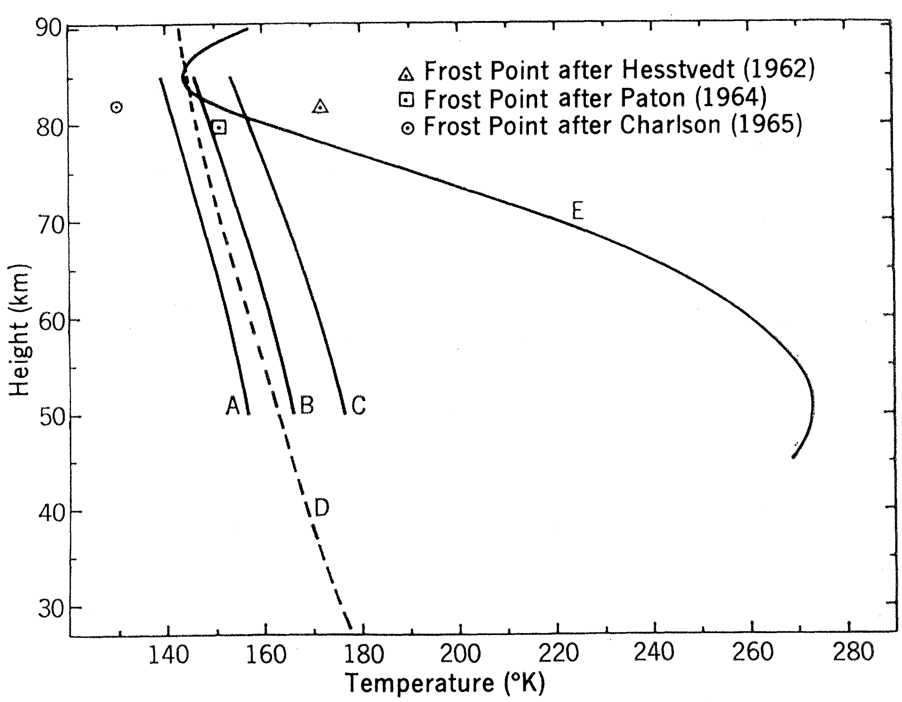

Fig. 3. Comparison of estimates of frost points by several authors, with the average temperature profile for the five soundings conducted during displays of noctilucent clouds. *A*, Frost point for $r = 10^{-3}$ g kg^{-1}; *B*, frost point for $r = 10^{-2}$ g kg^{-1}; *C*, frost point for $r = 10^{-1}$ g kg^{-1}; *D*, extrapolation from measured frost points at 28 to 30 km [after Badinov *et al.* (1966)]; and *E*, average temperature profile for five soundings made during displays of noctilucent clouds, 1963 to 1965.

sonal variations in the temperature structure.

There is no more reason to believe that water vapor is homogeneously distributed in the high-latitude mesosphere than to believe that such a situation exists in the troposphere. The meridional circulation shown in Fig. 2 represents the average motion in the stratosphere and mesosphere, but this circulation is subject to frequent and dynamic changes, and, therefore, any assumptions of steady-state flow or homogeneous composition are unrealistic. Thus the low temperatures at the mesopause may not produce noctilucent clouds if there is insufficient water vapor available. Questions of the amount of water vapor available and the magnitude of the vertical velocity necessary to transport water vapor to the mesopause must remain unanswered for the present, since no *in situ* measurements have been made to confirm or to refute the estimates and extrapolations that have been published. Figure 3 shows that Hesstvedt estimated the mixing ratio at the mesopause to be 1 g kg^{-1}, which corresponds to a frost point of 172°K at 82 km (*14*). Hesstvedt later revised this value downward to the order of 10^{-2} g kg^{-1} (*12*), which is in reasonable agreement with Paton's estimate (*15*) of 6×10^{-3} g kg^{-1} (6×10^{-3} g kg^{-1} corresponds to a frost point of 150°K at 80 km). Charlson used our mesopause temperature measured at Kronogard (130°K) as a conservative approximation to develop a steady-state model for noctilucent clouds (*16*). Thus, estimates of the content of water vapor at the mesopause have grown smaller as the estimates and observations of mesopause temperatures have become lower.

Figure 3 also shows a comparison of the frost points for various mixing ratios and a curve which has been extrapolated from measurements at altitudes reached by balloon-borne instrumentation, with the average temperature profile for the five soundings made during displays of noctilucent clouds. Curves *A*, *B*, and *C* were computed for constant mixing ratios with the use of the pressure profile derived from the average of 15 measured temperature profiles at high latitudes in summer. Curve *A* gives the frost points for a mixing ratio of 10^{-3} g kg^{-1}, curve *B* for 10^{-2} g kg^{-1}, and curve *C* for 10^{-1} g kg^{-1}. Badinov *et al.* (*17*) have extrapolated values for frost points from measurements made by various techniques at balloon altitudes of 28 to 30 km, and these are given by curve *D*. These values are based on a mixing ratio measured in the stratosphere which they believe stabilizes with height to a value on the order of 10^{-3} g kg^{-1}. The average temperature profile for the five soundings of noctilucent clouds is given by curve *E* in Fig. 3. The mesopause temperature of 143°K corresponds to a saturation mixing ratio of approximately 1.3×10^{-3} g kg^{-1}. It must be remembered, however, that this is an average value of the mixing ratio and that both cooler and warmer temperatures, corresponding to lower and higher saturation mixing ratios, have been measured during the cloud displays.

Since no significant difference in the observed temperature was noted between the soundings conducted in the presence of noctilucent clouds and those conducted in the absence of the clouds, we conclude that a mesopause temperature of less than 150°K is a necessary but not sufficient condition for the existence of noctilucent clouds. Variability of the content of water vapor at the mesopause is also believed to be a key factor in the occurrence of these clouds. In view of the circulation that is implied by the seasonal differences in temperature in the mesosphere, we believe that small amounts of water vapor are transported by this circulation into the mesosphere during the summer at high latitudes. It is at these latitudes that saturation or supersaturation occurs in the narrow layer at the mesopause where these extremely cold temperatures are observed. We believe further that dust particles, probably originating from incoming meteors, serve as sublimation nuclei in this saturated region and grow to sufficient size to scatter sunlight, thus producing noctilucent clouds.

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Wake Collapse in a Stratified Fluid

Abstract. *A two-dimensional model is used to obtain quantitative data on characteristics of turbulently mixed wakes of bodies submerged in stratified fluids (more dense below than above). The time between turbulent mixing and maximum expansion of the wake before vertical collapse starts is 0.44* T, *where* T *is the local Väisälä-Brunt period. Time after mixing for maximum rate of horizontal spreading is about 2.0* T. *The average Väisälä-Brunt period for the oceans and atmosphere is discussed. It is predicted that the wake collapse phenomenon is not unusual in these environments. The characteristic time for the most active phase of vertical wake collapse should be between a few minutes to several tens of minutes. Qualitative observations of aircraft vapor trails tend to confirm that the phenomenon does occur at full scale.*

Bodies such as a model submarine traveling in a tank filled with water having homogeneous density, or an aircraft flying in air of uniform density, leave behind turbulent wakes that are due to mixing in the boundary layer and mixing by the propellers or jet engines. These turbulent wakes expand to have an irregular conical shape. Frequently, exhaust trails of jet aircraft illustrate this type of turbulent mixed wake when taking off.

The oceans and the atmosphere seldom are of homogeneous density (iso-