The occurrence of cirrus particles in the upper troposphere is more common than previously reported. The presence of cirrus seems to be the rule in tropical regions with clear conditions being the exception.

Particle size distributions for both thin and opaque cirrus are presented. Two different size distributions characterize ice particles in sub-visible cirrus. The most common has a peak distribution in the 1 to 10 micron region with a rapid decrease of larger particles. The second type contains ice crystals with diameters from 100 to 2000 microns which appear to have fallen from higher levels.
THE CIRRUS AND SUBVISIBLE CIRRUS BACKGROUND

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1. INTRODUCTION

The purpose of this paper is threefold:
(1) to describe the different types of cirrus,
(2) to show that the occurrence of cirrus clouds is much greater than previously reported, and
(3) to investigate the downward transport of water and aerosols by cirrus particles from the upper mid-latitude troposphere.

Over the past decade cirrus clouds have become more important as both we and our technology have become more sensitive to environmental factors. Hypersonic reentry vehicles experience erosion due to cirrus particles in the upper troposphere. Laser systems are adversely affected by cirrus clouds. Cirrus particles reduce the efficiency of laminar flow wings. Scattering of sunlight by cirrus also inhibits solar energy collectors.

In 1974 we realized that cirrus clouds caused significant erosion of reentry nose cones. Later we studied attenuation of laser beams used in high power weapon beam systems, and the role of cirrus clouds in generating cells or seeded clouds in storm systems.

During these studies we found subvisible cirrus particles in the upper troposphere (Barnes, 1980 a,b) and we documented the occurrence of both cirrus and subvisible cirrus particles (Valley, 1978a, b; Barnes, 1980). During these missions we found subvisible cirrus particles near the tropopause (Barnes, 1980a,b) and we documented the occurrence of both cirrus and subvisible cirrus particles (Valley, 1978a, b; Barnes, 1980). During these studies we found subvisible cirrus particles in the upper troposphere. Lady clouds are adversely affected by cirrus clouds. Cirrus particles reduce the efficiency of laminar flow wings. Scattering of sunlight by cirrus also inhibits solar energy collectors.

2. BACKGROUND

Our early work with the erosion of nose cones began at Wallops Island, Virginia (Plank, 1974a,b; Berthel, 1976). Initially high acceleration missiles were used. They reached maximum velocity before exiting from the top of the storm. The main meteorological interest was in the middle layers of the store with less interest in the cirrus at the top of or overlying the store. Since only winter-time large-scale storms were used, the C-130 aircraft could usually ascend into the cirrus.

Because ground launched missiles did not simulate reentry heating and ablation, a few missiles were boosted out of the atmosphere and then accelerated back into the atmosphere at hypersonic speeds (Plank, 1977b; Cunningham, 1977). These tests were far from satisfactory to us because the reentry test region was well off of the coast and at the extreme range of the weather radars (Cranefield, 1978).

Testing was then moved to the Kwajalein Missile Range (KMR) in the Marshall Islands. Minuteman ICBM boosters launched the reentry vehicles from Vandenberg AFB, CA. Weather data in the reentry corridor and along the reentry trajectories were obtained from instrumented aircraft and from the powerful tracking radar at KMR (Barnes, Nelson, and Metcalf, 1974).

Cirrus particles near the tropopause (at 16 or 17 km) became more significant because of the higher velocity of the reentry vehicles at these heights and the increased altitude. In fact the cirrus particles relative to the nose cones. Small particles do not survive passage through the shock wave, but large particles do strike the nose cone; they induce spallation and cause premature transition from laminar to turbulent flow. This change in the flight characteristics can cause the reentry vehicle to miss its target.

Our work in heavy weather was documented for the Wallops Island missions (Plank, 1974a,b; Barnes, 1976a,b) and for the KMR missions in clear, light and heavy weather (Barnes, Metcalf, and Nelson, 1974; Metcalf, Barnes, and Kraus, 1975a,b; Metcalf, Kraus and Barnes, 1975a,b; Barnes and Metcalf, 1975; Barnes, 1976; Oyer, Berthel and Izual, 1981).

A review of some of the KMR test missions conducted under clear weather conditions revealed some anomalies. A preliminary investigation suggested that these anomalies were due to cirrus clouds. These missions were conducted on moonless nights to enhance visual tracking of the nose cones as they glowed white hot after reentering the earth's atmosphere at about 90 km altitude. In fact the criterion for these missions was that nose cones were to be tracked optically from first glow until they reached the surface. Stars could be seen on these night reentries at Kwajalein. The stars can be seen through thin cirrus layers. This was dramatically demonstrated by photographs of some missions where the glowing nose cones lit up thin cirrus layers, temporarily obliterating the stars.

Meteorological records often showed cirrus overcast at sunrise and sunset. Further investigations led us to conclude that there is a thin, persistent overcast of cirrus in the tropics most of the time.

Later we provided cirrus particle size distributions and densities to the Advanced Radiation Technology project of the Air Force Weapons Laboratory. These data were inputs to models of the propagation and attenuation of high energy laser weapon systems. Flight reports present the data and results from a number of C-130 flights which were conducted in New Mexico and adjoining states. Most of the data were taken in thin or opaque cirrus, but some subvisible cirrus data were obtained. These data were needed for studies of the effectiveness of high energy laser ballistic defense systems mounted in patrol aircraft. The aircraft would cruise below the cirrus and hence the laser beam would penetrate the cirrus to reach its target. Our research flights were conducted in the New Mexico area to provide climatological data for scheduled testing of the Airborne Laser Laboratory, the system's test bed.
Data obtained for these Air Force programs were used by NASA and Department of Energy (Derr, 1980) to study the effects of cirrus clouds in reducing the effectiveness of solar collectors located at ground level.

Another application has been to a future aircraft which would operate in the upper troposphere (Maistro, Feldman and Davis, 1981). This aircraft would use a laminar flow wing which would increase lift by approximately 30%. The laminar flow is held onto the wing by sucking air in through fine slits on top of the wing. The concept has been tested and flown (Hall, 1964), but the increase in lift is lost when the wing is in cloud. Test data showed occasional loss of lift when not in cloud; possibly caused by sub-visible cirrus.

The occurrence of cirrus clouds above other clouds and the seeding of lower cloud decks by large crystals (Bergeron, 1950) is important in understanding the process of high tropospheric systems and the production of precipitation. For two winter seasons we provided high cover in cirrus clouds for the investigations of storms near Seattle under the CYCLES program (Herzegh and Hobbs, 1981).

Cirrus particles may cause damage to the tiles on returning Space Shuttle flights. NASA calculations indicate that particles larger than 1 micron (1000 microns) in diameter could damage the tiles.

We will attempt to define cirrus clouds and particles they occur in the non-urban troposphere and to show how they contribute to the downward flux of both water vapor and aerosols.

3. THIN AND OPAQUE CIRRUS

We will now look at those cirrus clouds which are not visible. This is not a very precise definition, but it will do for now.

Cirrus clouds are generally found in that part of the troposphere where the temperature is less then -25°C. How do particles move to or from these levels? The most dramatic way is by convective clouds such as thunderstorms. Liquid/ice water content values can exceed 3 gm/m3 in intense storms found during summer, but concentrations at cirrus levels are usually .01 gm/m3 or less. At mid-latitudes most cirrus is associated with cyclonic storms, the jet stream, or upper level troughs. The earth receives its maximum heating from solar radiation in the tropics and the induced convective storms play a major role in the general circulation of the earth's atmosphere. These tropical convective storms transport the water vapor from the boundary layer right up to, and in some cases beyond, the tropopause. This source of high tropospheric water vapor has been illustrated by time lapse movies from a French meteorological satellite which senses radiation at the water vapor absorption wavelength. These movies show tongues of water vapor surging poleward from the tropics.

At Kwajalein the frequency of severe convective storms which contain lightning or which penetrated the tropopause (as determined by radar) was small. Both visual and IMS observations indicated that cirrus was present almost all of the time at Kwajalein. Unfortunately, the airborne hygrometer did not work in the cold temperatures in the high tropical troposphere so that no measures of the relative humidity or water vapor content were obtained. The Lear 36 was limited to 14 km and on almost every daylight flight we could see the thin cirrus above it. The cirrus seen above the aircraft was quickly named "cirrus evanes" or "cirrus above us".

This thin layer on almost every flight was usually seen from the surface at sunrise and sunset. I began to wonder if this thin cirrus layer persisted throughout the day and, if so, was it possible to see it at other times. The TDQ-11 radar (Paulsen, Petrocchi and Mclean, 1970) operating at a wavelength of 5 cm was designed to detect cloud. Using the one at KMR, we were not able to detect this thin cirrus unless it was also obvious visually. Indeed, the human eye turned out to be a better detector since it could pick out these thicker streaks of cirrus which were not over the radar.

By blocking out the sun with the corner of a building or other object, and looking at the region near the sun, structure in the thin cirrus could be identified. Unfortunately, the structural variations in the concentration of sea salt spray in the boundary layer could also be seen at the same time. With a little training it became easy to separate the low level variations moved rapidly with the west motion typical of the trade winds while the thicker cirrus moved at slower relative motion and generally to the east or northeast, depending on the upper level winds.

Detection of this thin cirrus at night was more difficult. Even when full, the moon was not bright enough to use this technique, but by looking in the vicinity of the moon a thin cirrus layer sometimes could be detected. Through experience we learned to differentiate between the thin cirrus due to the boundary layer and the cirrus caused by cirrus. If the cirrus was thick enough it could be seen by moonlight.

When very thin cirrus occurred on a moonless night, observation of faint stars could have been used. However, this requires a familiarity with the stars in this region.

We found that thin cirrus was present almost all the time at Kwajalein. We also observed thin cirrus over the United States when the official observers were reporting no cirrus. This higher frequency of cirrus might have an effect on available solar energy as calculated by Derr (1980).

Let us return to the question of generation of cirrus. Some particles are generated in convective storms and are lifted to cirrus levels. If the particles are heavy enough, they will settle out under gravitational action. If small (under 20 microns) they will be kept at these levels by Brownian motion and small scale turbulence.

The in-situ formation of cirrus particles from water vapor at these levels could begin either by deposition on hygroscopic aerosols, by spontaneous nucleation, or by other means. The possible mechanism of formation will not be dis-
discussed here. We will provide data on the occurrence of cirrus particles. If there is a sufficient supply of water vapor to form cirrus, the initial size distribution seems to evolve with a peak in the distribution curve in the 1 to 10 \( \mu \text{m} \) region with a logarithmic decrease in the concentration with increasing size. As more particles form, the peak increases in both size and in number count. Figures 1 and 2 show typical distributions in light, opaque cirrus. For in-situ, isolated thin cirrus layers, the height of the maximum concentration is generally about 1 km below the tropopause (McLean, 1957).

If enough particles form, larger particles (in excess of 1000 \( \mu \text{m} \)) appear, and aggregation begins, causing a rapid increase of the larger particles at the expense of the middle size particles as Lo and Passarelli (1981, 1982) saw, during advecting spiral descents flown by our C-130.

Figure 3 shows a typical distribution from more dense cirrus clouds. These distributions are generally associated with widespread storm situations where there is a large supply of water vapor and upward vertical motion to carry the water vapor to the cirrus levels. Because the winds are generally faster at higher levels than at lower levels, the cirrus shields both from thunderstorms and cyclonic storm systems move out in front of the storms while continuing to generate over the storms.

Sub-visible cirrus consists of cirrus particles in the atmosphere which are not dense enough to be seen. This immediately presents a problem since the same aggregation of particles may be seen at some times, but not at others. An example of thin cirrus overcasts at sunrise and sunset at Kwajalein which were not detected at night or at mid-day has been cited.

Sub-visible cirrus consists of two distinct types which may exist simultaneously. The first type is the most common and consists of about \( 10^3 \) to \( 10^5 \) particles per cubic meter, a peak near 2 \( \mu \text{m} \) and with no particles larger than 100 \( \mu \text{m} \). Figure 4 shows an example of an exponential fall off of particles with increasing size. Our data indicates that 70% of our flights in clear air at cirrus altitudes contain this type of background distribution. Indeed it is unusual when we are
At cirrus altitudes and detect nothing with the PMS ASSP scatter-probe (Barnes, 1980b).

The other type of sub-visible cirrus consists of individual large crystals, 100 to over 2000 microns in diameter, with a density of less than one particle per cubic meter. One flight showed an average of one particle every eight cubic meters. Figure 5 shows data from a flight where both types of sub-visible cirrus were present. These data were taken with a PMS ASSP and modified PMS 2-D Precipitation Probe (Kuehlerberg, 1970), and the existence of the larger particles was visually verified using a snow stick (Barnes, 1980b).

These large particles fall due to gravity, and in arctic regions where they may reach the ground before melting they create what are known as "diamond dust" snowfalls. Larger crystal are frequently seen to fall from higher clouds; cirrus unicus, mare's tails, is an example where the concentration is large enough to be seen. Both our observations at mid-latitudes (Barnes, 1980b) and observations by Hogan (1975) and Ohake, Jayawena, and Sakurai (1978) in arctic regions provide examples where these large particles appear in clear air with no visible clouds above.

If we take a world-wide density of type 1 particles at one every 8 cubic meters (Barnes, 1980b), an average diameter of 0.5 μm/cm³, fall speed of 1 m/s and a fall distance of 2 km (Braham and Spyers-Durand, 1967; Hall and Pruppacher, 1976), then for each square meter, one particle reaches the bottom each 4 seconds. The amount of mass crossing a square meter every 8 seconds is:

\[ 4 \times 10^{-6} \text{ kg} = 2.6 \times 10^{-7} \text{g} = 2.6 \times 10^{-9} \text{g/cm}^3 \]

The surface of the earth is 4 × 10^12 m², and the total flux is 2.6 × 10^7 g/s = 1.33 × 10^6 kg s⁻¹. This gives the world annual rainfall as 396,000 km²/yr or 4.96 × 10^9 kg/yr, which shows that, on a world-wide basis, this downward flux of large cirrus particles is an infinitesimal contribution to the hydrological cycle.

If we calculate the depth of type 2 snowfall in arctic regions with a constant flux of 200 μm, we get 4 × (200 μm) / 1.1 × 10^5 m s⁻¹ = 1.6 μm.

This does not agree with observations of diamond dust snowfalls in arctic regions where accumulations of 1 cm/year are observed. Such observations indicate a 10^3 to 10^4 increase in concentration to around 10^2 to 10^3 particles/cm³. Concentrations of 200 μm and larger particles usually produce opaque cirrus. The reduction of visibility in opaque cirrus may be due to the larger number of type 1 ice particles in the 1 to 10 μm range usually found in opaque clouds along with the ice crystals over 200 μm in diameter.

A 10^4 increase in the number of particles would give 16 cm/year thus accounting for a large part of the annual precipitation in arctic regions. In subarctic climates these particles melt and evaporate before reaching the ground.
Cirrus particles falling from above into supercooled clouds act as seeders, converting the supercooled drops to ice which then grow rapidly leading to precipitation (Bergeron, 1950). This trigger mechanism is important in the precipitation processes in mid-latitudes, but it is doubtful that concentrations of type 2 sub-visible cirrus of one or two particles/cm^3 can seed the lower clouds. Heavier concentrations of type 2 cirrus have been observed by X band radar (Paulsen, Petrenko, and McLean, 1970). These appear similar to visual cirrus unicus and seem to emanate from generating cells. Using a TPG-11, Hobbs, et al. (1961) observed such a seeding and an enhancement of precipitation falling from the supercooled cloud although the precipitation was not recorded on the ground.

6. DOWNWARD TRANSPORT OF AEROSOLS BY CIRRUS

The gravitational settling of the type 2 particles is a source of downward transport of aerosols. Temperatures at the upper levels are colder, so more ice nuclei (IN) are activated. In the presence of sufficient water vapor, ice crystals grow rapidly and begin to fall. The particles carry the IN to lower levels and also sweep up other aerosols as they descend. If we assume that the type 2 crystals form on IN with diameters of 100 μm and density of 2 g/cm^3, then the downward flux would be about 10^5 kg/yr. Each crystal would sweep up 10^7 aerosols, so the scavenging process would be the more important factor in the downward aerosol transport.

7. SUMMARY

Observations of cirrus in the tropics and at mid-latitudes have shown that the occurrence of cirrus ice particles in the atmosphere is more prevalent than reported by ground observers.

Sub-visible cirrus observed from aircraft consist of two types. Type 1 is the background of small ice crystals with a peak in the size distribution at about 1 μm and a rapid exponential decrease for larger size particles. Type 1 is found at cirrus levels on most flights. The second type of sub-visible cirrus consists of large ice crystals with diameters greater than 100 μm, some being larger than 2000 μm. Type 2 crystals fall through the atmosphere and may or may not be found in conjunction with type 1 sub-visible cirrus.

opaque and thick cirrus clouds usually have a peak in the size distribution between 10 and 20 μm with an exponential decrease at larger sizes.

The downward flux of water and aerosols by subvisible type 2 cirrus is insignificant except in arctic regions where diamond dust snowfalls occur. Concentrations of type 2 cirrus falling from generating cells in large scale storm systems play a significant role in triggering precipitation in lower level, supercooled clouds.

REFERENCES


The occurrence of cirrus particles in the upper troposphere is more common than previously reported. The presence of cirrus seems to be the rule in tropical regions with clear conditions being the exception.

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