The Relationship Between Composite Cirrus Morphology and Large-Scale Meteorology Derived from 94-GHz Cloud Radar Data

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Introduction

While it is generally recognized that clouds play an important role in the climate system, many fundamental cloud properties have not been extensively observed. Clouds can be described on multiple spatial and temporal scales. At the largest scales, the patterns of cloud systems denote synoptic scale motions. These patterns are, however, strongly modulated by mesoscale atmospheric motions and individual cloud elements exist and are maintained by turbulence coupled to cloud microphysical processes. It is the microphysical characteristics of clouds that have been most extensively studied, largely by the use of instrumented aircraft. This is particularly true in recent years with the First International Satellite Cloud Climatology Project Regional Experiment (FIRE), International Cirrus Experiment (ICE), and EUCREX field campaigns. While thoroughly understanding the microphysical mechanisms important to the smallest spatial and temporal scales is critical, recent field experiments have not adequately quantified the macroscopic characteristics of clouds or their variability. Beyond this, the relationship of both the microphysical and macrophysical cloud characteristics to the meso-synoptic atmospheric state is still largely undetermined from data. For example, there exists very little published literature simultaneously documenting the occurrence of multiple cloud layers, cloud base height, cloud top height, and internal cloud structure. This is not surprising since all conventional cloud observational methodologies are restricted to some degree by the natural variability of cloud occurrence coupled with the limitations of the observing systems.

A cloud observational methodology that bypasses many of the difficulties of conventional techniques is the utilization of surface-based short wavelength radars (Kropfli et al. 1995). These remote sensing systems operating typically in the Ka and W bands are able to sense multiple optically thick cloud layers and collect data continuously. For this study, we use the Penn State University (PSU) 94-GHz (3-mm wavelength) Doppler radar (Clothiaux et al. 1995; Peters et al. this volume). The PSU radar was operated in a vertically pointing mode from early October through mid-December 1994 with a primary goal of characterizing continental stratocumulus clouds (Albrecht et al. this volume). However, incidental to the data collection effort was the generation of an extensive observational record of cirrus cloud properties. We will concentrate on the cirrus data in this paper. The data consists of equivalent radar reflectivity (Ze) with approximately 12-second temporal and 75-meter vertical resolution. The data have been cloud screened using the masking technique described by Clothiaux et al. (1995).

While knowledge of the microphysical and optical characteristics of cirrus has increased substantially in recent years, fundamental uncertainties concerning the temporal and spatial variability of these upper tropospheric ice-phase clouds still remain. These uncertainties were recognized by Winker and Vaughn (1993) (WV) and Uttal et al. (1995) (UT) who presented cloud climatologies derived from surface-based remote sensing systems. The dataset considered here is somewhat more statistically robust than either WV or UT since the PSU radar is not limited by lower cloud layers as in the WV lidar study and the PSU radar operated unattended for many hours and collected data continuously for many days unlike UT. Also, in order to place the radar time series within a larger-scale context, meteorological profiles derived from the Rapid Update Cycle (RUC) model were collected operationally from the National Meteorological Center (NMC). The RUC model is a data assimilating mesoscale model that ingests asynoptic observations and is reinitialized every three hours. The model output used here consists of consecutive initialization, 1- and 2-hour forecasts.

Results

Cirrus layers in the radar reflectivity profiles are defined loosely as those layers that have a cloud-base temperature colder than -20ºC. It should be noted that this definition of cirrus excludes cirrus-capped deep cloud layers such as nimbo- and altostratus clouds. Also, cirrus generated by deep convection are conspicuously absent from this dataset. All cirrus layers considered are associated with midlatitude dynamical events such as jet streams and elevated frontal surfaces.

During the approximately 2 months of data collection, nearly 1000 hours of radar data were acquired and cirrus cloud layers, as defined here, were observed 24% of the time. However, no clear trend of cirrus occurrence is noted in the radar dataset as a function of time of day. Multiple cirrus cloud layers occurred 7% of the time. While the occurrence of cirrus with lower cloud layers occurred very often, the exact frequency of occurrence has not been tabulated as of this writing.

Table 1 presents several fundamental cloud layer quantities, their variance, and ranges. One must consider, when viewing these values, that the reflectivity of a certain fraction of cirrus is below the minimum detectable signal of the radar. WV, for instance, report cirrus mean layer heights from their lidar case study at 10-12 km and layer thickness between 0.86 and 0.94 km. The WV results are higher and thinner respectively than those reported here although the WV results may be biased toward optically thin cirrus. The results reported in Table 1 do tend to agree closely with the compilation of Dowling and Radke (1990) who report average cirrus cloud top altitude of 9-10 km, cirrus layer thickness of 1.5 km, and typical cloud center altitudes of 9 km.

Table 1. Cirrus layer statistics compiled from October to mid-December at State College, PA using the PSU 94 GHz radar.

	Mean	SDV	Range
Base Ht.	8.1	1.2	5.5-10.5
Top Ht.	9.5	1.3	6-11.3
Thickness	1.25	1.07	.75-4.5
Mid Ht.	8.8	1.1	5.5-11

Temperature-reflectivity distribution was compiled from all cirrus observations in the Fall 94 dataset. As expected, based on water vapor availability arguments, the colder volumes tend to have lower reflectivities (as low as the minimum detectable signal of the radar) and likely contain significantly less ice water than the warmer layers. These warmer, more highly reflective cirrus layers, however, occur much less often in this dataset.

The majority of cirrus-filled range gates (>80%) occurred at temperatures between -35 and -48ºC and had reflectivities between -26 and -33 DbZe. The typical cirrus had ice water contents between 2 mg m^{-3} and 0.6 mg m^{-3} . The interpretation of the frequency peak near -40ºC is not entirely clear at this time. One possible explanation is that homogeneous nucleation of ice crystals occur in water saturated updrafts. These crystals then grow as they are lofted to colder temperatures and eventually descend through the ice saturated layers where they continue to grow. It is at this point that these hydrometeors contribute significantly to the radar reflectivity. Apparently, at temperatures warmer than -35°C, sublimation as well as ice growth appears to be equally likely. We draw this conclusion from the widening frequency distribution at these warmer temperatures and also from the plot of cirrus layer integrated reflectivity as a function of layer mean temperature shown in Figure 1. Along the solid line superimposed on Figure 1, reflectivity increases with increasing temperature indicating crystal growth while along the superimposed dashed line, reflectivity decreases with warming temperatures. We conclude that this reflectivity decrease

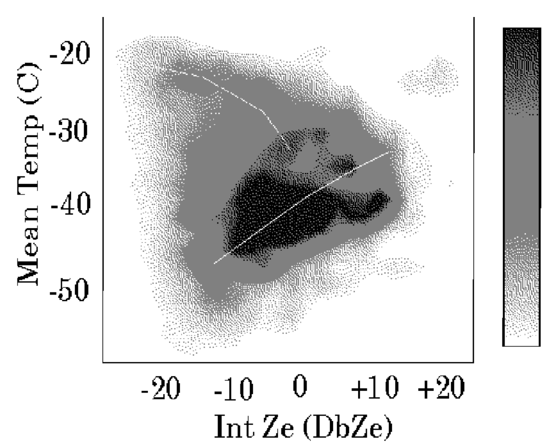

Figure 1. Cirrus layer integrated reflectivity as a function of layer-mean temperature is shown. The solid line is meant to denote that part of the distribution that shows increasing reflectivity with layer-mean temperature while the dashed denotes sublimating cirrus fall streaks.

with warming temperatures occurs when sublimating cirrus fallstreaks pass over the radar. More detailed case study analyses are required to further explain these statistical features in the radar dataset.

Summary and Future Work

An extensive cloud radar dataset was collected during a 2-month period in the Fall of 1994 on the campus of Penn State University. The advantages of short wavelength radars for cloud studies are clearly evident in this and other companion papers presented in this issue. We have combined the radar dataset with hourly mesoscale model output so that the observations could be placed within a meteorological context. The fundamental cirrus cloud statistics discussed above confirm the findings of previous authors who used more conventional forms of cloud observation. Cirrus tend to occur in layers above approximately 8 km, and typically extend to heights between and 9 and 10 km. Cirrus clouds tend to be geometrically thin—typically less than 1.5 km—and often have thicknesses much less than 1 km. The majority of cirrus observations recorded during this period occurred at temperatures between -35ºC and -45ºC and had reflectivities between -26 and -33 DbZe. The integrated reflectivities of these cirrus layers ranged between -10 and +5 DbZe. Evidence was presented for a direct relationship between layer temperature and radar reflectivity; however, at temperatures above -35ºC a significant number of cirrus layers appeared to be sumblimating.

Analysis of this dataset is only in its initial phase. We intend to examine the statistical relationships of these fundamental cirrus characteristics with the large-scale meteorology in which the clouds existed. Establishing these types of relationships is important for parameterizing cirrus clouds in large scale models. Beyond this, we will consider the perturbation imposed by the cirrus on the surface radiation budget and seek to connect this information to the meteorological forcing of the larger-scale atmosphere.

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