The Composite Characteristics of Cirrus Clouds: Bulk Properties Revealed by One Year of Continuous Cloud Radar Data

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ABSTRACT

The properties of midlatitude cirrus clouds are examined using one year of continuous vertically pointing millimeter-wave cloud radar data collected at the Atmospheric Radiation Measurement Program Southern Great Plains site in Oklahoma. The goal of this analysis is to present the cloud characteristics in a manner that will aid in the evaluation and improvement of cirrus parameterizations in large-scale models. Using a temperature- and radar reflectivity-based definition of cirrus, the occurrence frequency of cirrus, the vertical location and thickness of cirrus layers, and other fundamental statistics are examined. Also the bulk microphysical properties of optically thin cirrus layers that occur in isolation from other cloud layers are examined. During 1997, it is found that cirrus were present 22% of the time, had a mean layer thickness of 2.0 km, and were most likely to occur in the 8.5–10-km height range. On average, the cirrus clouds tended to be found in layers in which the synoptic-scale vertical motion was weakly ascending. The mean synoptic-scale vertical motion in the upper troposphere as derived from Rapid Update Cycle model output was $10.2 \text{ cm s}^{-1}$. However, a significant fraction of the layers (33%) were found where the upper-tropospheric large-scale vertical velocity was clearly descending ($w < -1.5 \text{ cm s}^{-1}$). Microphysical properties were computed for that subset of cirrus events that were optically thin (infrared emissivity $< 0.85$) and occurred with no lower cloud layers. This subset of cirrus had mean values of ice water path, effective radius, and ice crystal concentration of $8 \text{ g m}^{-2}$, $35 \mu m$, and $100 \text{ L}^{-1}$, respectively. Although all the cloud properties demonstrated a high degree of variability during the period considered, the statistics of these properties were fairly steady throughout the annual cycle. Consistent with previous studies, it is found that the cloud microphysical properties appear to be strongly correlated to the cloud layer thickness and mean temperature. Use of these results for parameterization of cirrus properties in large-scale models is discussed.

1. Introduction

The representation of cirrus clouds in large-scale models continues to be a problem of considerable contemporary importance. These cloud systems occur over large areas of the earth’s surface, tend to occur in all climatic regimes, and demonstrate a high degree of variability in their macro- and microphysical properties (Liou 1986; Dowling and Radke 1990; Mace et al. 1997). Furthermore, cirrus can significantly influence the overall heating of the atmosphere and surface, where the sign of the heating can be positive or negative and depends on the cloud properties (Stephens et al. 1990).

Building on earlier studies that used a combination of research aircraft (e.g., Heymsfield 1975a), and numerical modeling (e.g., Heymsfield 1975c; Starr and Cox 1985), a series of field programs were conducted beginning in the middle to late 1980s [i.e., the First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment (FIRE); Starr 1987; the International Cirrus Experiment; Rashke et al. 1998]. These programs utilized a unique combination of research aircraft and ground-based active and passive remote sensors to study cirrus. Owing to the high intensity and high cost, the field phase of these projects lasted roughly a month during which typically two or three cirrus events were intensively probed. Detailed study of these cases revealed much about cirrus that was not
previously known. This additional knowledge tended to concentrate on spatial and temporal scales comparable to the observations (i.e., from meters to kilometers) and has since been used in the development of intricate cirrus microphysical models that are able to explain much of what we observe in natural cirrus (Jensen et al. 1994; Lin et al. 1998). However, while the short duration and high intensity of these early programs enabled detailed study of cirrus clouds on small time- and space scales, the relationships between the cirrus and the larger spatial and temporal scales (e.g., those resolved by a GCM) were largely unsampled. That is, while we have increased our understanding of the smaller-scale physical processes that lead to the formation and maintenance of cirrus microphysical and radiative properties, we are as yet unable to place that knowledge into a context suitable for the parameterization of cirrus in large-scale models.

Such a large-scale context can be viewed in the following manner; consider some spatial domain of a size typical of a GCM model grid box (tens to hundreds of kilometers on a side). Within this grid box there exists some set of resolved-scale dynamic and thermodynamic variables that can be described in terms of their gridbox mean values and, perhaps, their first or second moments. Assume that this spatial volume also contains a field of cirrus clouds whose macroscale properties (layer height, layer thickness, and layer mean temperature) and microphysical properties (ice water content, mean particle size, particle concentration) can be described in terms of a set of probability density functions. The higher-order moments of such probability density functions can be interpreted as representing a coupling between the subgrid-scale dynamics and the small-scale microphysical processes that have been studied by recent field programs. It is implicitly assumed in parameterization development that the lower-order moments of the probability density functions (i.e., the gridbox means and standard deviations) represent a coupling between the collective results of the physical processes over the grid box and the resolved-scale dynamics. A physically based parameterization of cirrus suitable for large-scale models, therefore, at least requires an understanding of how the physical processes operating in a collective sense over a grid box, gives rise to the low-order cloud property moments that ultimately feed back through the radiative properties on the radiative heating rates.

It is generally assumed that the low-order cloud property moments are correlated to the resolved-scale dynamics. However, this assumption as it pertains to cirrus clouds, while intuitive, has not been demonstrated in any quantitative fashion with data. We are unable at the present time to define with quantifiable certainty a mean and standard deviation of any fundamental cirrus property, valid over a GCM grid box, given a set of resolved-scale dynamic and thermodynamic properties. It is precisely this lack of quantitative information relating the large-scale dynamics to the cloud property moments existing within grid boxes that has delayed the application of the knowledge derived from programs like FIRE to GCM parameterization validation and improvement. Our purpose in this paper is to begin to bridge the gap between the smaller spatial- and temporal-scale observations collected by field programs and the scales resolved by climate models. Following the general philosophy outlined in Stokes and Schwartz (1994), we investigate the properties of cirrus clouds as observed by continuously operating instrumentation at the Atmospheric Radiation Measurement Program (ARM) site in Oklahoma.

Anticipating the extensive datasets that are now being generated at the ARM sites, Mace et al. (1997, hereinafter M97) present a pilot study using approximately 900 h of cloud radar data collected during a 2½-month period over central Pennsylvania with the Pennsylvania State University (PSU) 94-GHz radar (Clothiaux et al. 1995). Macroscale cirrus properties, such as cirrus base, top, layer thickness, and the vertical distribution of radar reflectivity within cirrus layers, were examined and compared with temperature and synoptic-scale ascent. In this work we examine cirrus cloud properties derived from 1 yr (December 1996–November 1997) of 35-GHz radar data collected at the Southern Great Plains (SGP) ARM site in Oklahoma. We also use additional data streams from the ARM site to examine the retrieved bulk microphysical properties of cirrus.

2. Instruments, data analysis, and methodology

The primary instrument that we use in this study is the millimeter-wave cloud radar (MMCR) described by Moran et al. (1998). The MMCR became operational at the SGP site in early November 1996 and ran nearly continuously through the first year of operation and beyond. The MMCR is a vertically pointing, single-polarization radar that operates at a frequency of 35 GHz (8 mm). The primary differences between the MMCR and other research-grade radars (e.g., Clothiaux et al. 1995) are the overall sensitivity of the MMCR, the MMCR approach to Doppler signal processing, and the optimization of the MMCR to accurately sense a broad range of atmospheric hydrometeors using a continuously cycling set of operational modes. Clothiaux et al. (1999) argue that for the current radar and processor hardware four operating modes of the radar are sufficient for detection of most hydrometeors at any height within the troposphere with reflectivities ranging from approximately −50 to 20 dBZ\textsuperscript{1} and with vertical velocities of up to 20−30 m s\textsuperscript{−1}. The lower limit in reflectivity of

\textsuperscript{1}The quantity dBZ\textsubscript{e} refers to the liquid water equivalent radar reflectivity factor and can be shown to be equivalent to the sixth moment of a particle distribution of liquid Raleigh spheres that produce the observed radar backscatter cross section (Doviak and Zrnić 1993).
−50 dBZ represents the minimum detectable reflectivity of the MMCR at 5-km range when all four modes are combined, while return powers from boundary layer hydrometeors with 10−20 dBZ reflectivities cause the radar receiver response to become nonlinear for all four modes.

To gain as much information from the radar data as possible, data from the four individual modes must be combined into a merged rendition of the Doppler moments. The first step in this process is the identification of significant (i.e., nonnoise) power return in the data from each mode individually. Once this is accomplished using the technique described by Clothiaux et al. (1995), the corresponding data for each Doppler moment from the modes are merged into a single time–height dataset that represents the most accurate data obtainable from the MMCR. The algorithm described by Clothiaux et al. (2000) attempts to perform these steps.

One of our goals in this work is to compare the properties described in M97 and those from the ARM dataset. Aside from the location and duration differences, the primary difference is instrumental; the MMCR is approximately an order of magnitude more sensitive than the PSU radar. The M97 study was unable to accurately determine what fraction of cirrus clouds were below the detection threshold of the PSU radar but estimated that fraction to be on the order of 20%. Since the MMCR is operated next to a lidar system and a Belfort laser ceilometer, we are able to more accurately estimate the fraction of cirrus that are typically below the MMCR detection threshold. During a period from late 1997 to mid-1998 the MMCR observed 94% of all hydrometeor layers observed by the laser-based systems. If we consider 5-min data windows, this statistic increases to 97% of all layers. This difference in sensitivity must be carefully considered when comparing these results. Otherwise, the MMCR data are treated in every other respect as described by M97 with the following exceptions.

1) In order to improve the sensitivity of the PSU data, M97 use 5-min averages. We perform no such averaging of the MMCR data. The nominal temporal and vertical resolution of the MMCR is 30 s and 90 m, respectively.

2) The calibration of the MMCR is known to within 1 dB (K. Moran and M. Miller 1999, personal communication). Therefore, no calibration corrections are imposed on the MMCR data.

3) In M97, thermodynamic profiles were extracted from the Rapid Update Cycle (RUC) model output (Benjamin et al. 1991, 1996). In this investigation we use radiosonde data collected at the SGP site when possible. If a sounding is not available within 6 h of the MMCR data, RUC model output are used for the thermodynamic profiles. The large-scale ascent is determined, as in M97, using the kinematic technique applied to 200-km-averaged divergence profiles extracted from the RUC output.

4) Our definition of cirrus from the reflectivity is somewhat more refined as compared to M97. In the present study we require the radar echo top to occur at temperatures colder than −35°C and the maximum dBZ to occur at temperatures colder than −20°C. This definition ensures that ice microphysical processes are dominant in the generation region near cloud top while not imposing any arbitrary constraints on the bottom and top of the cloud layer. As in Mace et al. (1997), this definition excludes deep cloud layers that are capped by ice-phase clouds. We chose to alter the definition due to the microphysical retrievals—the present definition avoids certain ambiguous situations but has no noticeable effect on the comparison of the PSU and SGP datasets.

In this study we also examine the bulk microphysical properties of a subset of the cirrus that were observed during this annual cycle. The ice water path (IWP), layer mean effective radius (r_e), and the layer mean particle concentration (N) have been calculated using the approach described by Mace et al. (1998a,b). Briefly, this scheme, similar to Matrosov (1992), combines the layer mean radar reflectivity with downwelling radiance observations from a zenith-viewing interferometer (AERI; Smith et al. 1993) in the 10−12-μm region. For a particular cirrus volume, the algorithm searches for an assumed first-order modified gamma particle size distribution (Kosarev and Mazin 1991) that best represents the average size distribution of the cirrus layer. The sixth moment of this size distribution returns the observed radar reflectivity factor, and when the distribution is used to generate radiative properties (Fu and Liou 1993) and used in the Modtran-3 radiative transfer model, it returns the radiance observed by the AERI. This retrieval algorithm requires the cirrus layer to be optically thin such that the cloud layer emittance is less than 0.85. It is also necessary that no lower clouds obscure the cirrus layer from the AERI. This algorithm has been successfully applied to all candidate cirrus layers during the study period using the approach outlined in Mace et al. (1998b). The temporal resolution of the retrieved properties is determined by the AERI—nominally, 3-min averages are generated every 8 min.

Mace et al. (1998a,b), and Sassen and Mace (2001) present validation of this specific algorithm using aircraft data collected during various field programs and also use downwelling solar radiation fluxes as validation during other case studies. Matrosov et al. (1994) conducted a thorough examination of algorithm uncertainty for the reflectivity–radiance-type approaches. His results have remained consistent with our own studies (Matrosov et al. 1998) and indicate that the layer mean water paths and effective sizes can be determined to within an uncertainty of 30% and 20%, respectively.

In Fig. 1a, we extend the idea of using observed
Fig. 1. (a) Binned comparison of observed solar flux at the surface measured by the BSRN to downwelling surface solar flux calculations using cirrus microphysical properties from the reflectivity–radiance retrieval algorithm. The cloud forcing is expressed in terms of the fraction of the clear flux removed by the cloud. The thin solid line shows the mean of the calculated forcing values binned in 0.025 forcing increments, and the error bars separate one standard deviation. The heavy solid line is the 1:1 line drawn for reference. Additional information is provided in the text. (b) Comparison of the top-of-atmosphere albedo calculated from GOES data by Minnis et al. (1998) to that calculated using the retrieved cloud properties from all satellite retrievals available between Dec 1996 and May 1998. The solid line is a linear fit to the data. (c) Comparison of the ice water content distributions in 5-K temperature intervals from Heymsfield and Platt (1984, their Table 2) shown in red with similarly binned distributions of layer mean ice water content derived from the reflectivity–radiance algorithm shown in blue.
surface solar fluxes as a source of algorithm validation to a statistical comparison over the annual cycle considered in this paper. The observed fluxes are from the Baseline Solar Radiation Network (BSRN) pyranometer and are expressed as a fraction of the clear-sky flux removed by the cloud layer, that is, the cloud effect, where the observed clear-sky fluxes are determined following Long and Ackerman (2000). The comparison of calculated and observed cloud effect suggests that, although significant scatter between observations and retrievals does occur, on average we calculate a reasonably accurate estimate of the ice water path and effective particle size. The comparison of albedo derived from Geostationary Operational Environmental Satellite (GOES) radiances using the approach by Minnis et al. (1998) also shows a reasonable comparison with the retrievals. At this point, estimating how much of the scatter in both parts of Fig. 1 is due to the algorithm generating incorrect results and how much is due to heterogeneity in the cloud fields is not possible but studies are underway to address this issue. Both effects would lead to scatter in the comparisons at the surface and top of the atmosphere. What we can say from this comparison is that the bulk cloud microphysical properties derived from the reflectivity–radiance algorithm should, when averaged over a significant number of cases, provide a meaningful description of the bulk cirrus cloud microphysical properties that actually occurred.

Further evidence for this statement is shown in Fig. 1c where we compare the statistical distributions of layer mean ice water contents with layer mean temperature from the ARM data to the results reported by Heymsfield and Platt (1984). We find that the ice water content scales exponentially with layer mean temperature (this will be discussed further below) over the entire temperature range we consider. The mean values of our results are somewhat larger than those of Heymsfield and Platt although over most of the temperature range the scatter in the datasets overlap significantly. We note that the Heymsfield and Platt results reveal a scale break near temperatures of $-45^\circ$C while the trend in our data remains fairly smooth with temperature. At temperatures above $-45^\circ$C, we find quite good agreement between the two datasets. We may conjecture several explanations for the differences in these statistics although it is impossible at this time to identify which explanation may be correct. For instance, if we consider that the MMCR is missing the more tenuous cirrus layers, we would expect our results to be biased high. On the other hand, it is well known that the early aircraft particle measurements were biased toward underestimation of the ice water content [see Heymsfield and Platt (1984), appendix b]. Furthermore, the sample size of the Heymsfield and Platt dataset is limited. They show in their Table 2 that the amount of data collected at temperatures colder than $-45^\circ$C was significantly less than the amount of data collected at warmer temperatures.

3. Results: Macroscale properties

We examine approximately 8300 h of radar data between December 1996 and November 1997. This amounts to approximately 95% of the total hours possible during this 12-month period. The monthly, seasonal, and annual statistics that we discuss initially are presented in Fig. 2 and Table 1. With the exception of Fig. 2 where we show monthly statistics and Table 2 where we concentrate on the climatological seasons [December–January–February (DJF), (MAM), (JJA), (SON)] we generally base our discussion of cirrus statistics on what we define as the cold (November–March) and warm (May–September) seasons. When discussing the cold season, we include the cirrus observed during November 1996. Examining warm versus cold period statistics is revealing for several reasons. The statistics of the clouds tend to be more or less stationary during the cold and warm seasons as we define these periods. This has the effect, obviously, of increasing the number of events used in compilation of means and variances over that for the typical climatological seasons. Furthermore, cirrus that occur over Oklahoma during the cold season are typically associated with synoptic-scale meteorological events, such as subtropical jet streams, migratory cyclones, and so on. During the warm season, however, the cirrus are more likely to be associated with smaller-scale phenomena, such as convective systems or other disturbances typical of subtropical continental latitudes during summer. Beyond these temporal divisions, we make no attempt in the present work to further classify the events based on their meteorological context. Classification based on objectively determined synoptic type is currently underway and will be the subject of future reports.

From Figs. 2 and 3 we find an interesting periodicity to cirrus occurrence in particular and overall cloud occurrence in general. While it is beyond the scope of this work to explore the details of the relationships between the meteorological conditions of this annual cycle and cloud occurrence, we do note that the climate of this period over the south-central United States became increasingly influenced by the developing El Niño of late 1997 and 1998. We also find a substantial degree of inter- and intraseasonal variability likely not associated in any way with the 1997/98 El Niño. For instance, cloud occurrence in all layers increased substantially between December and February with a major decrease in March followed by another increase in April. The large-scale flow patterns were near normal over the western and central United States during December and January with a slight negative 500-mb height anomaly over the American Southwest during February. A significant positive 500-mb height anomaly extended across the North American continent during March, which likely contributed to the dearth of cloudiness during this month since the climatological jet stream and associated synoptic-scale weather patterns were dis-
placed northward. Patterns returned to near normal by April and May. By late in 1997, negative height anomalies were found over the Southwestern United States and eastern Pacific with an anomalous dry northwesterly flow over the Great Plains. The decrease in cloudiness during the latter portion of this study period correlates well with the expected response of cloud formation to a relatively dry northwesterly flow. These anomalies were also associated with a substantial drought in the plains during and after this period.

Cirrus clouds, as defined herein, are a predominant cloud type during much of this annual cycle and are particularly evident in Fig. 3 during the late spring and early summer of the study period. Figure 2b reveals that cirrus occurrence peaks near 30% during February, May, and June of 1997. Not surprisingly, a minimum is observed in March when overall cloud occurrence appears to have been suppressed. The low frequency of cirrus occurrence in April is somewhat surprising given the overall frequency of cloudiness shown in Fig. 3. A quick scan of the data reveals that the cloud events that led to the overall high cloud fraction were due primarily to deep cloud features associated with synoptic-scale weather events. Relatively few isolated upper-tropospheric cloud layers were observed during this month. Cirrus occurrence increased steadily from April to June and then began a steady decrease through October. The overall cloudiness during this period also decreased, although the frequency of low clouds below cirrus increased from August to October (Fig. 2c). This increase is likely related to the increasing frequency of boundary layer clouds evident in Fig. 3 during the late summer and autumn of 1997.

The frequency of cirrus occurrence that we find during this annual cycle are similar to those identified by other researchers. For instance, Wylie et al. (1994) finds approximately 30% cirrus occurrence at 35°N for JJA during the 1989–93 period. They also found a somewhat greater frequency than we did (approximately 40%) for cirrus occurrence during DJF in a global average. Woodbury and McCormick (1986) found approximately 30% cirrus occurrence over the central United States using Stratospheric Aerosol and Gas Experiment data collected between 1979 and 1981. They did identify substantially more cirrus on average during summer over the central United States (60%) than we find here. Mace et al. (1997) observed substantially more cirrus during the autumn of 1994 over central Pennsylvania than found here with a larger fraction of the Pennsylvania cirrus occurring above lower-level clouds. These differences, while partly due to the observing systems, point out the substantial interannual variability of cirrus cloud occurrence over the central United States. This variability underscores the need to understand and correctly account for the coupling between the large-scale meteorological conditions and the physical process of the upper troposphere in cirrus occurrence parameterization.

Fig. 2. Cirrus occurrence frequency distributions. (a) Number of radar reflectivity profiles examined during each month. (b) Fraction of profiles in (a) that indicated the presence of cirrus as defined in the text. (c) Fraction of cirrus that occurred above lower-level clouds (histogram) and the fraction for which microphysical retrievals were calculated (*). The fractions in (c) do not add to 1. The difference is cirrus events that were either optically thick or for which some necessary data were unavailable.
Various averaging periods for the data presented in the rows. NDJFM denotes the cold season months of Nov 1996–Mar 1997 while MJJAS denotes the warm season months of May–Sep 1997. The values outside of brackets or parentheses are mean quantities, values in parentheses denote standard deviations of the mean quantities, and values in brackets denote means derived from the optically thin single-layer subset of cloud events for which microphysical retrievals were conducted.

<table>
<thead>
<tr>
<th></th>
<th>M97</th>
<th>Annual</th>
<th>NDJFM</th>
<th>MJJAS</th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
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<tr>
<td>Frequency (%)</td>
<td>32</td>
<td>22 [37]</td>
<td>24</td>
<td>23</td>
<td>26</td>
<td>[33]</td>
<td>21</td>
<td>[41]</td>
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<tr>
<td>Frequency with low clouds (%)</td>
<td>54</td>
<td>21 [1.0]</td>
<td>20</td>
<td>18</td>
<td>16</td>
<td>8</td>
<td>21</td>
<td>35</td>
</tr>
<tr>
<td>Base (km)</td>
<td>8.5</td>
<td>9.1 [1.3]</td>
<td>8.4</td>
<td>10.2</td>
<td>8.2</td>
<td>8.8</td>
<td>8.8</td>
<td>8.8</td>
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<tr>
<td>Top (km)</td>
<td>9.9</td>
<td>10.9 [1.8]</td>
<td>10.2</td>
<td>11.8</td>
<td>10.2</td>
<td>10.7</td>
<td>10.7</td>
<td>10.7</td>
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<tr>
<td>Midcloud z (km)</td>
<td>9.2</td>
<td>9.9 [1.7]</td>
<td>9.3</td>
<td>11.0</td>
<td>9.1</td>
<td>9.7</td>
<td>9.7</td>
<td>9.8</td>
</tr>
<tr>
<td>Top–tropopause distance (km)</td>
<td>1.6</td>
<td>1.5 [1.4]</td>
<td>1.6</td>
<td>1.7</td>
<td>1.4</td>
<td>1.3</td>
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</tr>
<tr>
<td>Thickness (km)</td>
<td>1.6</td>
<td>2.0 [1.4]</td>
<td>2.0</td>
<td>2.0</td>
<td>2.1</td>
<td>1.9</td>
<td>2.0</td>
<td>2.0</td>
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<tr>
<td>DBZe</td>
<td>-26</td>
<td>-24.5 (12.3)</td>
<td>-25.4</td>
<td>-24.0</td>
<td>-24.6</td>
<td>-25.4</td>
<td>-23.6</td>
<td>-25.1</td>
</tr>
<tr>
<td>Vertical velocity (cm s⁻¹)</td>
<td>+0.7</td>
<td>+0.2 (4.4)</td>
<td>-0.03 (4.3)</td>
<td>-0.5 (4.4)</td>
<td>-0.6 (4.4)</td>
<td>-0.02 (3.9)</td>
<td>+0.9 (3.2)</td>
<td>+1.1 (3.9)</td>
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<tr>
<td>Temperature (K)</td>
<td>223</td>
<td>224 (13)</td>
<td>224 (13)</td>
<td>222 (13)</td>
<td>226 (12)</td>
<td>222 (12)</td>
<td>223 (13)</td>
<td>225 (12)</td>
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</table>
TABLE 2. Sensitivity of the bulk microphysical properties derived from the retrieval subset to large-scale ascent derived from the RUC model. The rows listed as the smallest, middle, and largest one-third signify the respective third of the cirrus that occurred within that region of the vertical velocity frequency distribution (Fig. 5a). Quantities in bold letters signify those distributions that are significantly different (as defined by the Student’s t test at the 95% level) from the distributions in vertically adjacent cells.

<table>
<thead>
<tr>
<th>VVEL</th>
<th>IWP (g m(^{-2}))</th>
<th>Effective radius ((\mu)m)</th>
<th>Concentration (L(^{-1}))</th>
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<tr>
<td></td>
<td>Cold season</td>
<td>Warm season</td>
<td>Cold season</td>
</tr>
<tr>
<td>Mean</td>
<td>8.1</td>
<td>8.1</td>
<td>36.3</td>
</tr>
<tr>
<td>Smallest one-third</td>
<td>7.4</td>
<td>7.8</td>
<td>36.9</td>
</tr>
<tr>
<td>Middle one-third</td>
<td>7.4</td>
<td>7.7</td>
<td>35.2</td>
</tr>
<tr>
<td>Largest one-third</td>
<td>8.7</td>
<td>8.5</td>
<td>36.6</td>
</tr>
</tbody>
</table>

Fig. 3. Vertical monthly cloud fraction as determined by a combination of the laser-based sensors and the millimeter-wave cloud radar at the Oklahoma ARM site from Dec 1996 to Nov 1997, i.e., the nominal annual cycle considered in this paper. The cloud fraction presented here is a simple ratio of the number of times significant radar returns existed in a resolution volume divided by the number of times the resolution volume was sampled.
operational RUC mesoscale model is at least able to capture the correct sign of the synoptic-scale vertical motions, studies with other model output [such as the European Centre for Medium-range Weather Forecasts (ECMWF)] is currently underway. It is also quite likely that the general poorly defined relationship between large-scale ascent and cirrus occurrence can be refined based on meteorological type. Mace et al. (1995) found a fairly strong coupling between the large-scale ascent and cirrus occurrence in a case where the local generation of condensate appear to dominate over the horizontal advection of the ice.

While we have identified some differences between the PSU data and the cirrus properties found from the ARM data, many of the statistics are quite similar. The relationship between cirrus occurrence and large-scale vertical motion is one such similarity. Similarities also extend to the distribution of the radar reflectivity factor as a function of temperature (Fig. 6). From Table 1 we find that the mean of $-26 \text{ dBZe}$ reported in Mace et al. (1997) is within $1.5 \text{ dB}$ of the mean reflectivity factor found in the ARM data, and the seasonal means of the ARM data remain within $2 \text{ dB}$ of the annual average. We also find that the radar reflectivity of the cirrus in Oklahoma is somewhat better correlated with temperature in comparison with the Pennsylvania data. While an obvious correlation can be seen between temperature and reflectivity, Fig. 6 also reveals differences between the warm and cold season cirrus. As we expect, given the greater depth of the tropospheric region in which cirrus can occur during the summer season, cirrus tend to occur over a broader range of temperatures and a broader range of reflectivities in comparison with their cold season counterparts. One aspect of this seasonal comparison that does not appear to be strictly a function of the seasonal deepening of the troposphere is that the upper limit of reflectivity increases during the summer. As expected, given the colder tropopause, we find a higher incidence of very cold and tenuous clouds. However, the warmest clouds during the summer tend to have reflectivities higher than the warmest clouds in the cold season. One explanation for this observation is that some fraction of the cirrus are still, or have recently been, in contact with deep convective sources. Also, cirrus clouds formed in the deeper and colder summer upper troposphere are able to sediment through greater depths and can therefore generate larger crystals, assuming sufficient water vapor is available for deposi-
Fig. 5. Sensitivity of cirrus occurrence to large-scale vertical velocity. (a) Frequency of occurrence of large-scale vertical velocity when cirrus are observed. (b) Frequency of cirrus occurrence for a given large-scale vertical velocity. Vertical velocity values are calculated from 250-km-average RUC divergence profiles centered on the ARM site.

In the tropical growth. Consistent with these inferences, we find that the standard deviation of the distribution during the warm season tends to increase because of the presence of cirrus with both higher and lower radar reflectivity.

4. Results: Microphysical properties

The statistics we present in this section are derived from approximately 2700 retrievals during the period from November 1996 to December 1997. Since these retrievals represent 3-min averages, we are considering a total of 135 continuous hours (a little more than 5.5 days) of cirrus clouds. This equates to a sample volume of approximately $10^{11} \text{ m}^3$ of cloudy air given typical cirrus layer properties. By comparison, the Particle Measuring Systems 2DC probe mounted on a research aircraft samples approximately $6 \text{ L s}^{-1}$. To equal the sample volume of cloudy air, one would have to consider something like $10^{13} \text{ s}$ of aircraft data. We present this anecdotal comparison not to belittle the use of aircraft data for cloud studies. On the contrary, data generated by remote sensors and data collected in situ are clearly complimentary. However, we do contend that the derivation of broad generalizations regarding cloud properties from comparatively small aircraft datasets, including the development of parameterizations intended for global models, is a hazardous proposition if the sample size issue is not carefully addressed.

Since the reflectivity–radiance algorithm requires a cirrus layer to be optically thin and be the only layer in the vertical column, we first examine how representative this optically thin single-layer subset of cirrus is to the total cloud population examined in the previous section (bracketed values in Table 1). On average, microphysics are derived from approximately 50% of the cirrus layers examined in the previous section. Of the remaining layers, approximately 25% of them occurred above lower cloud layers and the rest were either optically thick or some necessary data needed as input to the retrieval algorithm were not available. We find that the optically thin, single-layer subset of cirrus occur somewhat higher in the atmosphere and are slightly geometrically thinner than the full dataset. We also find that the radar reflectivity of the optically thin, single-layer cirrus is slightly higher and the distance of radar cloud top from the tropopause is slightly greater than the full set. This curious combination of statistics suggests that the dynamical setting and associated characteristics of thin, isolated cirrus are somewhat different from the full set of cirrus. This finding is not surprising given the constraints imposed by the retrieval algorithm. Optically thin, single-layer cirrus tend to occur only in specific meteorological conditions that tend to be characterized by otherwise benign weather. We conclude that the statistics of the bulk microphysics derived from the optically thin, single-layer cirrus may not be rigorously representative of the full spectrum of cirrus that occurred during this annual cycle over Oklahoma. However, regardless of the representativeness of this specific set of cloud layers, consideration of long-term microphysical statistics of any cirrus has not been possible up to now. For the first time we are able to examine a major class of cirrus observed over an annual cycle and make certain statements regarding the statistics of their microphysical properties and how those properties relate to the resolved-scale environment.

The frequency distributions of ice water content (IWC), ice water path (IWP), effective radius ($r_e$), and particle concentration ($N$) of thin isolated cirrus are shown in Fig. 7. We find that for all quantities the most frequently occurring values tend to be nearly the smallest that we can resolve and the frequency of occurrence decreases exponentially for larger values. Similarly shaped distributions have been identified recently from other cloud datasets. Smith and Del Genio (2001, manuscript submitted to *Quart. J. Roy. Meteor. Soc.*) show exponentially shaped frequency distributions of IWC derived from aircraft data collected during FIRE II, and Considine et al. (1997) find distributions of similar character in marine stratocumulus data. Since GCM parameterizations predict gridbox mean values of microphysical properties, the characteristics of the distributions in Fig. 7 raise interesting questions regarding the representativeness of such gridbox means. The ultimate goal of a parameterization is to predict correctly the column distribution of radiative heating within the grid box.
Fig. 6. Histogram of cirrus occurrence as a function of the vertically resolved radar reflectivity and the temperature at each range gate. The relative frequency increases from blue to yellow. (a) The cold seasons (Nov 1996–Mar 1997) for which approximately 10 million cirrus range gates are included, and (b) the warm season (May–Sep 1997) for which approximately 9.5 million range gates are included.

Given the nonlinear nature of radiation transfer in a cloudy atmosphere, there is no a priori reason to expect that the actual mean radiative heating arising from an exponentially shaped distribution of cloud properties is necessarily equivalent to the radiative heating derived from the mean value of the cloud properties. Since Fig. 7 represents a composite of many cirrus events and not a geographic distribution of cloud properties from a single case, our speculation regarding the representativeness of gridbox means in determining appropriate radiative heating rates may be somewhat premature, however.

The goal of a parameterization is to use physical reasoning along with variables predicted by the model to narrow the range of variance found in nature and exemplified for a particular cirrus property by Fig. 7. We consider three such resolved-scale variables in the following paragraphs and examine the sensitivities of the distributions shown in Fig. 7 to these variables. One must bear in mind the horizontal scales represented by these observations, assuming typical upper-tropospheric wind speeds of 20 m s\(^{-1}\), each retrieval represents approximately 3.5 linear kilometers of cloud. This horizontal scale is small and the characteristics of the distributions would likely change if taken over a larger domain. Development of distributions over larger scales would, however, reduce the statistical significance of this relatively small dataset. For example, 50-km averages would require roughly 14 retrievals, reducing the number of samples from 2700 to 192. This result illustrates the need for datasets that span multiple years at a single site or the addition of global-scale datasets that can be generated from orbiting sensors.

a. Sensitivity to large-scale vertical motion

As shown in Table 1, we find little statistically significant evidence relating ascent on the large scale with cirrus occurrence overall or with single-layer, thin cirrus occurrence. However, it has been hypothesized and shown with numerical models that large-scale ascent is important in the formation and maintenance of cirrus clouds (Starr and Cox 1985; Heymsfield and Donner 1990). Mace et al (1997) found essentially no correlation between large-scale ascent derived from model output and the mean, or integrated, radar reflectivity of cirrus layers in the Pennsylvania data. We have examined the sensitivity of the derived microphysical properties to the synoptic-scale vertical motion (Table 2). While individual comparisons of the retrieved microphysics and
significant increase in the IWP for cirrus that existed in the largest one-third of the vertical motion distribution (greater than 1.5 cm s\textsuperscript{-1}) in the cold and warm seasons. This significance does not extend to the particle sizes during the cold season, although the warm season does indicate that effective radii increase slightly in the more strongly ascending third of the distribution. The number of concentrations tend to decrease significantly in the largest one-third of vertical motion cases of both seasons.

We emphasize that these tendencies are only marginally significant in the present dataset. They do suggest, however, a consistent sensitivity of cirrus layer properties to stronger ascent on a scale resolvable by a GCM. We will continue to explore the correlation of the large-scale vertical motion with the retrieved cloud properties as our sample size grows and we can examine composites of certain specific meteorological conditions. Certainly horizontal advection of condensate in the upper troposphere is a dominant mechanism for the local rate of change of IWC. Consequently, only under certain meteorological conditions do we expect that the local large-scale vertical motions will have an identifiable effect. Mace et al. (1995), for instance, examined a case during FIRE II where cirrus that developed in the exit region of a jet streak appeared to be quite sensitive to the local large-scale ascent, while other researchers have found mixed results (Starr and Wylie 1990).

\subsection*{b. Sensitivity to temperature}

We find that the derived microphysical properties are quite sensitive to the layer mean temperature \( T_m \). To illustrate this sensitivity, we have segregated the dataset by temperature and compare frequency distributions of the coldest one-third (\( T_m < 220 \) K) and the warmest one-third (\( T_m > 230 \) K) of the retrievals (Fig. 8 and Table 3). The ice water contents of cirrus have been shown to be related to temperature in numerous studies (e.g., Heymsfield and Platt 1984; McFarquhar and Heymsfield 1997; Platt and Harshvardan 1988). Figure 8 demonstrates that the mean and median water contents do tend to increase with \( T_m \), although the modes of the distributions remain near the minimum observable values. This result is significant since it implies that even in warm cirrus that may have a significant mean IWC the most likely values are still small, at least on the spatial scale of these observations. The relationship between temperature and IWC can be understood by considering the distributions of \( r_e \) and \( N \) and their sensitivity to \( T_m \). Both \( r_e \) and \( N \) are clearly sensitive to temperature but in an opposing sense with respect to their influence on IWC. The mode of the effective radius distribution nearly doubles from near 20 \( \mu \)m for the coldest one-third of the data to more than 50 \( \mu \)m for the warmest one-third, while the mean concentration decreases from 138 L\textsuperscript{-1} for the coldest one-third of cirrus to 67 L\textsuperscript{-1} for the warmest. The mode of the concentration distribution

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7.png}
\caption{Frequency distributions of layer mean microphysical properties derived from combined radar reflectivity and AERI radiance data for optically thin, single-layer cirrus from Dec 1996 to Nov 1997. Approximately 3000 3-min averages were used in each frequency distribution.}
\end{figure}
FIG. 8. Frequency distributions of layer mean microphysical properties segregated by layer mean temperature for the period Dec 1996–Nov 1997. The left-hand column corresponds to the coldest one-third of all layers and has a high temperature cutoff of approximately 220 K. The right-hand column is the warmest one-third of all layers and has a low temperature cutoff of approximately 230 K.
remains small for both temperature classes of cirrus. Since IWC depends on something like the third moment of the size distribution, IWC is effectively linear in \( N \) (assuming constant effective size) and strongly nonlinear in effective size (assuming constant \( N \)). The trend of the IWC with temperature is, therefore, dominated by the change in effective size. However, to fully characterize the sensitivity of IWC to temperature, both the effective size and particle concentration must be considered.

Given the variable climate regimes that dominate the SGP, it is reasonable to suspect that the microphysical properties of cirrus may show a seasonal dependence. Cirrus that form in association with synoptic events during winter may have a maritime air mass source many thousands of kilometers upstream while the air mass source of summer cirrus may be much more local in nature. The different dynamics and aerosol source regions associated with these air mass regimes may lead to cirrus of substantially different properties such as in Sassen et al. (1995) where volcanic aerosol was shown to influence cirrus characteristics associated with a subtropical jet streak. Such dependencies of cirrus properties on the season are perhaps, however, only weakly evident in the present dataset. Consider Table 3, which shows the temperature-segregated statistics of the derived microphysical properties of the cold and warm seasons. Overall, we find a strong similarity between the cirrus layer statistics for different seasons. The IWC and \( r_e \) statistics of the coldest layers during the cold season are nearly identical with those of the coldest layers during the warm season. The statistics of \( N \) do show a tendency for larger concentrations during the cold season, although an explanation for this result is not immediately evident and this tendency is not found in the warmest layers. However, we do see some indication that the summer warm cirrus has a slightly larger median IWC due primarily to more occurrences of larger effective particle sizes. Note that the mode and median \( r_e \) for the warmest one-third of cirrus are nearly identical between the seasons, while the mean and variance of \( r_e \) are larger during the warm season. This indicates an increasing frequency of large particle events during the warm season.

c. Consideration of layer thickness

The statistics presented earlier suggest that cirrus, on average, have tops close to the tropopause and the layers tend to be geometrically thin (~2 km) with an exponentially decreasing occurrence of thicker layers (Fig. 4b). It must also be true, within the bounds of seasonal and synoptic variability, that the thicker layers most often reach the warmest temperatures. Therefore, we consider here the possibility that the sensitivity of the cloud microphysics on \( T_m \) reported by numerous authors through the analysis of aircraft data implicitly includes a dependence on cloud layer thickness, \( \Delta h \). It is important to realize that that \( \Delta h \) is difficult to evaluate locally using aircraft data alone. Since Doppler velocity observations indicate that much of the particle motion below the nucleation zone is downward, the maximum water contents attained in a cirrus layer depend, to some extent, on (among other things) the amount of time a population of crystals spends in an ice-supersaturated layer. This notion borrows from the simple conceptual model of cirrus (Heymsfield 1975b) that particle nucleation occurs in water-saturated updrafts near cloud top. Particle growth subsequently occurs through vapor deposition as the detrained ice crystals sediment through ice-supersaturated layers, and sublimation ensues as the crystals reach subsaturated layers farther below. Evidence to support this model was found in the Pennsylvania data, where the radar reflectivity was shown to increase from the top down through the upper two-thirds of the cirrus layer and decrease in the lowest one-third of the layer (Mace et al. 1997). This effect was enhanced as the layer thickened (see their plate 5). Identical results were found in the ARM data irrespective of season (not shown).

To illustrate this result, Fig. 9 shows color-coded scatterplots of the layer mean IWC as a function of \( T_m \) and \( \Delta h \). A careful examination of Fig. 9a suggests that, while the IWC tends to increase for warmer temperatures and
Fig. 9. Scatterplot of the layer mean IWC to layer depth and layer mean temperature. The layer mean IWC is color coded and is also plotted along the vertical axis in (a). (b) The projection of (a) onto the temperature-layer depth plane.
thicker layers, the overall increase occurs with a large degree of variability. As we discuss below, this trend is indicative of a migration of the frequency distribution of IWC toward higher median values as the layers become warmer and thicker. Figure 9b also illustrates the broad trend of the IWC to increase along a diagonal from layers that are cold and thin to those that are warm and thick. Consider the limiting cases: for the coldest layers (T_m < 220 K) Δh seems to play only a minor role as there is little change in IWC for layers as thick as several kilometers; on the other hand, for warm layers (T_m > 230 K), an increase in Δh has a substantial correlation with IWC with some water contents rising rapidly toward the maximum values we are able to derive with this particular retrieval algorithm (since the layers become optically thick). Now consider the relationship between T_m and thin layers. As one moves along the abscissa from cold layers to warm, we find little correlation between T_m and IWC for thickness less than approximately 1 km. Drawing on our simple conceptual model of cirrus, we contend that the small Δh limits the water contents that are observed in such layers although other explanations are certainly plausible.

These contentions are supported by the statistics presented in Table 4. We find that the median IWC increases by approximately a factor of 2 for the coldest one-third of the layers as the layer thickness increases from less than 1 km to 2–4 km. For the warmest layers, the median IWC increases by nearly a factor of 5 as the layer thickness increases up to 2–4 km. A comparison between the coldest one-third and the warmest one-third of layers with similar thickness shows that thin layers (less than 1 km) tend to have very similar median and mode IWC. The influence of temperature becomes obvious in the comparison of the thicker layers. The warmest one-third of the 1–2-km-thick cirrus tend to have median and mean IWC approximately 2.5 times larger than the coldest one-third of 1–2-km-thick layers. This comparison increases to a factor of 3 in median IWC for the thickest layers (the mean IWC increases by only a factor 2 in the 2–4-km-thick layers). It is interesting to note that in all classifications of IWC except for the thickest and warmest layers, the mode of the IWC remains at the smallest IWC bin. A significant shift in the mode IWC only occurs for the warmest, thickest, and overall rarest class of cirrus we consider. We infer from this that the means of the distributions change because of the increasing frequency of occurrence of extreme events. Evidence for this can be seen in a comparison of IWC from the coldest and thinnest layers to the warmest and thinnest layers; the means are different by a factor of 2 and the standard deviations by a factor of 4, while the mode and median values are nearly unchanged.

 Inspection of Table 4 also shows the tendency noted above for r_s to increase and N to decrease with increasing temperature. However, several additional intriguing insights can be extracted from the statistics. The effective radius of the coldest clouds shows less sensitivity to layer depth compared to the warmer layers. This observation is important since it supports the hypothesis that particle growth tends to be limited at cold temperatures regardless of layer thickness. For the warmest layers the median particle size nearly doubles as the layer thickness increases. Unlike the IWC, the mode of the r_s distribution moves systematically toward larger values; note that the mean, mode, and median all increase by factors ranging from 1.5 to just larger than 2, while the standard deviation remains nearly unchanged. Based on our simple conceptual model of cirrus formation and maintenance, we expect N to show no sensitivity to layer thickness. The data support this idea only approximately. The mean and median values of N do not change significantly within a temperature class as the layers thicken. However, the modes of these distributions migrate toward significantly larger values for thicker layers while at the same time, the standard deviations become smaller. It is also interesting to note, however, that while we find mixed sensitivity of N to layer thickness within a given temperature classification, the N statistics of the colder layers tend to be approximately a factor of 2 larger than the warm layers.

5. Summary and conclusions

We have presented an analysis of the composite characteristics of cirrus clouds observed during an annual
cycle over the ARM site in Oklahoma using a continuous year of 35-GHz cloud radar data. Our goal is to take advantage of the continuous nature of the ARM data stream to begin to bridge the gap between the observational scales and the larger scales resolved by many models. Our approach is to examine the statistical nature of the macroscopic bulk properties of cirrus derived from cloud radar data, interferometer data, radiosonde data, and model output and to correlate this statistical description to resolved-scale variables. To accomplish this, we follow the general approach outlined in Mace et al. (1997) and compare the statistics of the Oklahoma cirrus with the cirrus statistics compiled from data collected in the autumn of 1994 over Pennsylvania. We extend this analysis to consider the statistical properties of the bulk microphysics derived from a subset of the cases (Mace et al. 1998a).

This study is an initial attempt at compositing a large cloud radar dataset in terms of a climatically useful description of a specific cloud type. As such, we chose to examine simple statistics of fundamental quantities compiled over monthly, seasonal, and annual periods in the hope that this basic approach would yield useful information about the nature of these clouds and illuminate directions for future research.

The main findings of this study are as follows.

1) Cirrus occurrence over Oklahoma during 1997 varied substantially on monthly timescales (Fig. 2) and was generally less frequent than reported by previous authors using satellite data (Wylie et al. 1994; Woodbury and McCormick 1986) and surface-based remote sensors (Mace et al. 1997). The occurrence of cirrus above lower-level clouds also showed considerable variability and tended to be anticorrelated with overall cloud occurrence, suggesting that when cirrus occurrence decreased, much of the decrease occurred in the radiatively important “fair weather” cirrus.

2) A seasonal oscillation in the vertical location of cirrus layers was found. This seasonality is related to our temperature-based definition of cirrus and arises from a seasonal oscillation in the depth and temperature of the tropopause (Table 1). Other statistics that are not so definition dependent showed that, while cirrus properties were highly variable, their statistics were quite consistent during this annual cycle and between the present dataset and that described in Mace et al. (1997). This finding includes layer thickness, distance of radar echo top from the tropopause, layer mean reflectivity, layer mean temperature, and bulk microphysics (Table 3).

3) The frequency distributions of layer mean IWC, $r_s$, and $N$ are exponentially shaped with modal values near the minimum resolvable. The frequency distribution of visible optical depth arising from the cirrus layer microphysical properties is exponentially shaped as well. We speculate that the spatial statistics of column radiative heating from such an exponentially shaped distribution of cloud optical properties may be quite different from the column radiative heating produced by using the mean of the cloud microphysics to calculate the optical properties. This issue requires further study.

4) While overall cirrus occurrence appears to be nearly insensitive to the large-scale vertical velocity, we did identify a marginally statistically significant dependence between the bulk microphysics and ascent on the synoptic scale. However, parameterizations that rely on synoptic-scale ascent (Heymsfield and Donner 1990) should be considered carefully. While it is generally accepted that ascent on some scale is required to nucleate ice crystals, positive large-scale vertical motion is neither a necessary nor sufficient condition for the occurrence of cirrus. There appears to be no a priori reason to assume that this cirrus-producing ascent is resolvable on synoptic scales and, if it is resolvable, that it must occur nearby. The weak correlation between cirrus properties and large-scale ascent found in these data suggest that large-scale ascent may be useful in some aspect but the relationship is not straightforward.

5) The properties of cirrus clouds depend significantly on both layer mean temperature and layer thickness (Figs. 8, 9, and Table 4). The cloud contents that evolve depend on the amount of water available for condensation (temperature dependence) and the amount of time the ice crystal populations spend in the supersaturated layers (thickness dependence). Consistent with this simple model, we find that cirrus layers occurring at cold temperatures are limited in their particle sizes and water contents regardless of layer thickness. Similarly, warm cirrus that occur in thin layers appear to be limited in ice water content and particle size.

These statistics, when considered as a whole, paint a unique picture of midlatitude cirrus clouds. We found that a basic property of cirrus clouds is large variability in many of the cloud properties. We also find that this variability remained temporally consistent during this annual cycle and the period examined in Mace et al. (1997). That is, the composite morphology of cirrus tends to be similar regardless of season in Oklahoma and between Oklahoma and Pennsylvania in different years. This finding, if generally applicable to other locations and times, would significantly reduce the complexity of parameterizing cirrus clouds in GCMs since the data suggest that cirrus formed in different dynamical regimes are similar. Assuming this to be the case, it remains, therefore, to explain the observed variability in terms of resolved-scale variables predicted by GCMs.

There is much precedent for parameterizations derived from empirical fits to some amount of data (e.g., Heymsfield and Platt 1984). While we could perform the same exercise here and present parameterizations of the microphysical and radiative properties of thin cirrus
in terms of the layer thickness and layer mean temperature, we consider this step to be premature and generally ill considered. This dataset is clearly not extensive enough to generate accurate empirical frequency-of-occurrence distributions of any cirrus property. We estimate that the number of data points would need to be increased by at least an order of magnitude and the spatial scales that each point represents would need to be increased to match that of the GCM under consideration.

One can envision how a parameterization might be formulated with the present dataset, however. For a given cirrus layer temperature and thickness one finds evidence for a probability distribution of IWCs (Fig. 9b). That is, the data suggest that a given occurrence of the two independent variables leads to a range of possible values of IWC, each value occurring with some probability. Simply predicting a mean value masks the natural variability found in the data. Given the nonlocal nature of the causes associated with the occurrence of any population of ice crystals in a given location, there seems to be no good reason to expect that a particular cirrus property should be representable as a single deterministic function of any set of large-scale variables. A diagnostic parameterization with these data of IWC in terms of layer thickness and layer mean temperature should, therefore, return an IWC frequency of occurrence distribution. For a GCM to predict the correct cloud properties in a statistical sense, a Monte Carlo approach could be used in each instance or the frequency distribution could be used as given to derive more accurate heating rates. A more scientifically satisfying approach would be to continue to explore the physical process that explains the variability seen in Fig. 9 and to include those physical processes in the development of a more physically based parameterization.

While we will consider the development of parameterizations from these data as the dataset grows, an application of more immediate use would be the comparison of these results with similar statistics compiled from model predictions. The study of Mace et al. (1998c) was a first step at using radar data to validate model predictions of clouds in the ECMWF model, and considerable skill was demonstrated by that model at predicting clouds during the winter season of the annual cycle considered in this paper. Given the potential for cirrus to significantly modulate any CO$_2$-induced climate change signal (Lohmann 1995), it is critical to extend these validation experiments to models that are developed for climate prediction. These comparisons must begin with a simple prediction validation as in Mace et al. (1998c) but should extend beyond occurrence-related validation to the cloud microphysical and radiative properties.

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