Statistics of Cirrus Horizontal Inhomogeneity in the Southern Great Plains

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Variability of cloud properties on scales smaller than a general circulation model (GCM) grid is potentially important for parameterizations of cloud microphysical processes and cloud radiative effects. Considine et al. (1997) present a simple model of marine stratocumulus variability, assuming Gaussian statistics of lifting condensation level (LCL) and hence cloud depth that might be associated with cloud-scale and mesoscale vertical velocity fluctuations. For reasonable choices of the mean and variance of cloud depth, the model can explain observed features of liquid water path histograms inferred from Landsat imagery as a function of cloud fraction. For cirrus clouds, there is no *a priori* reason to anticipate a similar relationship, given a) the lack of a solid surface and consistent overlying inversion to bound cloud vertical motions, and b) the possibly greater contribution of horizontal fluxes to variability in the more stratified upper troposphere.

Atmospheric Radiation Measurement (ARM) Millimeter Wave Cloud Radar (MMCR) data at the Southern Great Plains (SGP) will eventually provide long-term statistics on cloud variability as an aid to parameterization. Before the existence of MMCR climatologies, however, we used aircraft and cloud radar data for 14 FIRE II (First ISCCP [International Satellite Cloud Climatology Program] Regional Experiment) flights over the nearby Coffeyville, Kansas, area to test the applicability of the Considine et al. model to cirrus (Smith and Del Genio 1999a). We also examine statistics of ISCCP DX cloud optical depth accumulated over a somewhat larger area (Smith and Del Genio 1999b) to get a sense of the extent to which our results may be biased by the spatial scale and sampling limitations of the aircraft flight patterns. Cirrus are unique in their downward growth via sedimentation from an initial generating layer, so we make a small modification to the Considine et al. model, defining the LCL as the lowest altitude of ice saturation and calculating adiabatic ice water path by integrating up from that level rather than the radar cloud base. Ice water content is then derived by dividing the ice water path by the actual cloud depth, thus allowing for depletion of local ice water content by sedimentation.

Ice water mixing ratio statistics for most flights exhibit behavior similar to that observed by Considine et al. (Figure 1). For overcast skies, the histogram is almost Gaussian, but with a slightly longer tail at the high ice end. As cloud cover decreases, so does the mode ice water value. Below about 90% cloud cover, the lowest ice mixing ratio is the most frequent, with the probability distribution function (PDF)

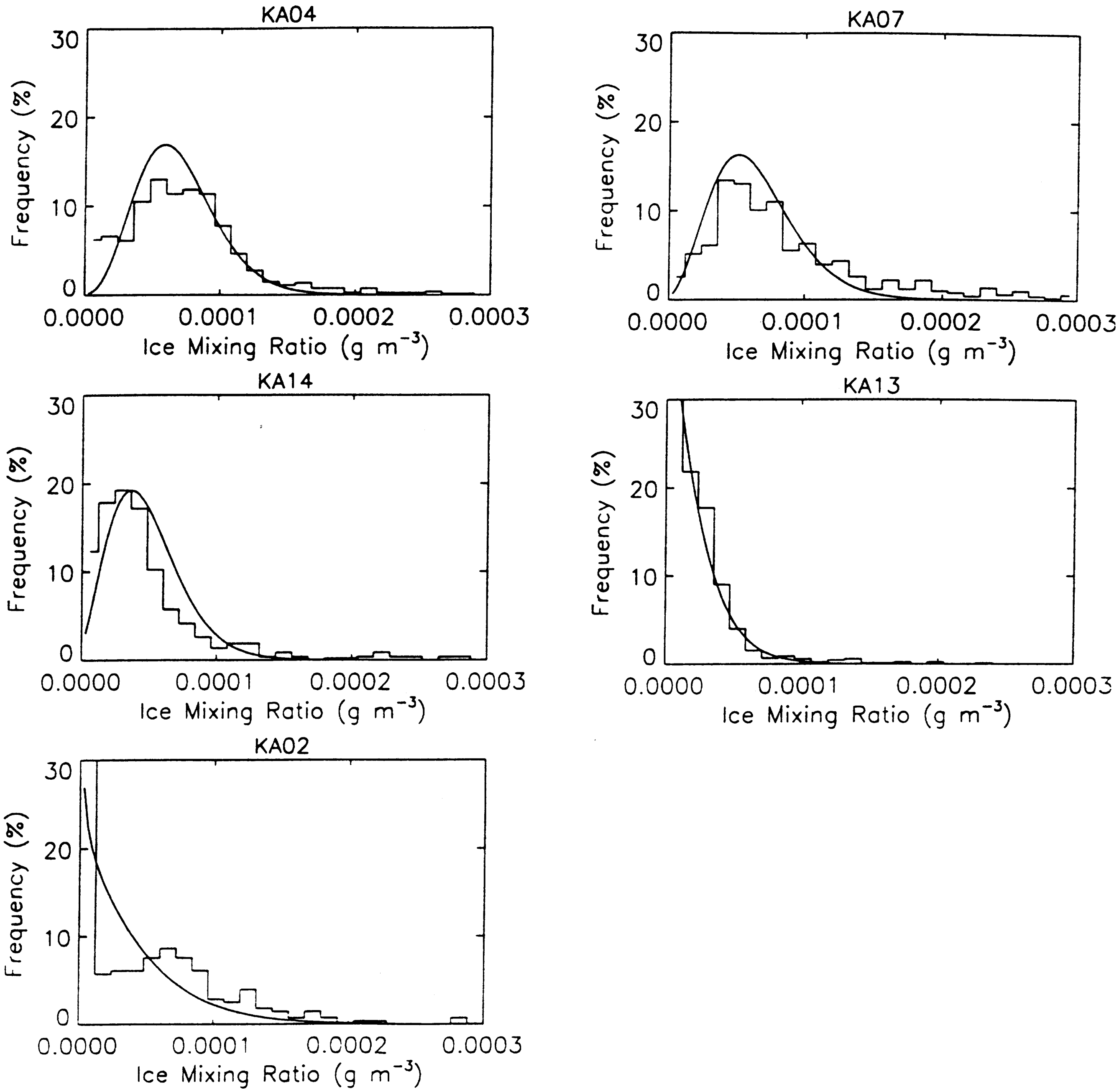

Figure 1. Aircraft-derived ice water mixing ratio histograms for five FIRE II flights with coincident cloud radar cloud depth data, in decreasing order of cloud cover moving from left to right and top to bottom. Superimposed are PDFs predicted from the modified Considine et al. model with all free parameters specified from the observations.

decreasing approximately exponentially for higher values. ISCCP DX optical depth histograms at the time closest to each flight were aggregated over an area including the flight pattern but large enough to ensure stable statistics while not incorporating data from adjacent regions with dissimilar characteristics.

(Since ISCCP samples a 5-km pixel every 25 km to 30 km, an area several hundred kilometers on a side is required to accumulate 100 pixels.) Optical thickness data for cirrus with no underlying cloud are available for ten of the flights. The ISCCP data exhibit histogram behavior similar to that of the aircraft data, but with the transition to shapes with a distinct mode value greater than the lowest bin value occurring at somewhat smaller cloud cover.

For flights in which cirrus passed over the location of the cloud radar, radar and aircraft statistics can be compared. Observed cloud depth histograms over time intervals during which the mean cloud depth was not rapidly trending are indeed approximately Gaussian, with the width well-characterized by the observed standard deviation of cloud depth. Support for the idea that the Considine et al. model might be applicable is provided by the positive correlation observed between the normalized standard deviations of aircraft-observed ice water content and radar-observed cloud depth, and the negative correlation between cloud cover and the normalized standard deviation of cloud depth (Figure 2). Thus, given aircraft profiles of T and q, we derive generating layer depth and integrate upward from the ice saturation level to calculate the vertical gradient of ice water content and the adiabatic ice water path. Together with radar-derived mean and standard deviation of cloud depth, this fully constrains the model described above for five flights in which the cirrus advected directly over the cloud radar. For each of the five cases, the model-predicted PDFs (the smooth curves in Figure 1) match the observed histogram shapes and widths well, suggesting that similar physics are operating in these cirrus and in the marine stratocumulus considered by Considine et al. The mean cloud cover is predicted in each case to no worse than 16% and the mean ice mixing ratio to no worse than 34%, well within the observational errors.

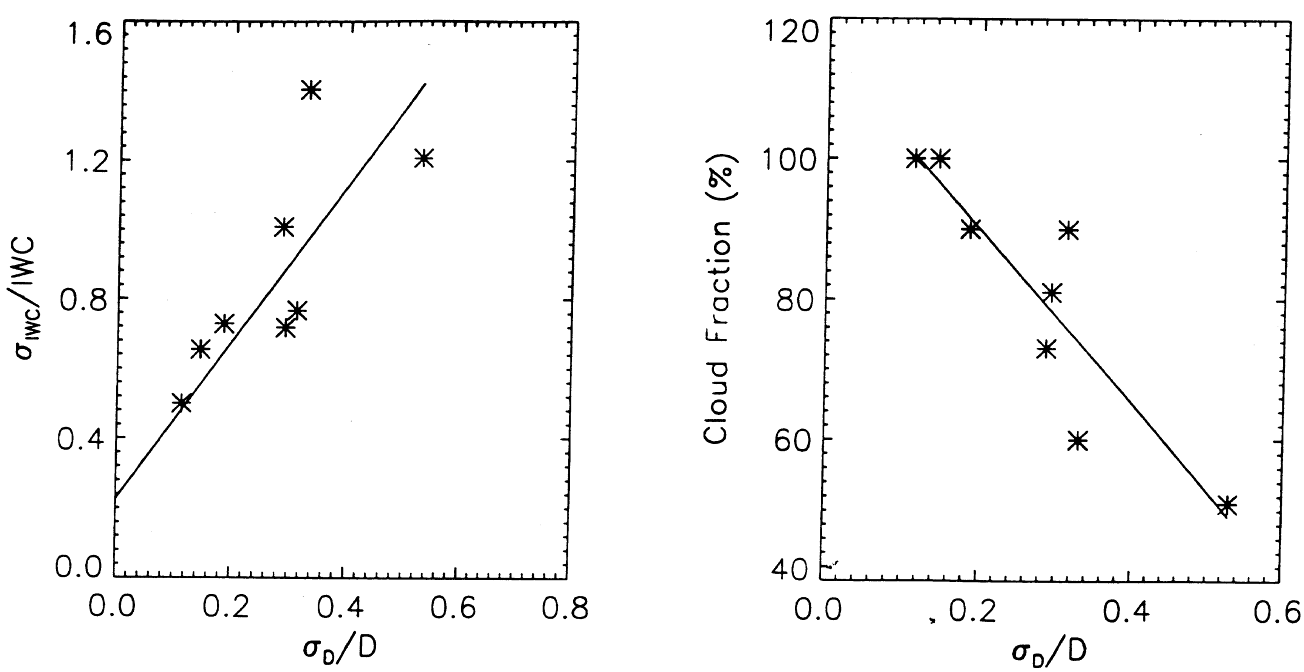

Figure 2. Observed normalized standard deviation of ice water content (left) and cloud fraction (right) plotted versus observed normalized standard deviation of cloud depth for cases with coincident radar data.

For seven other flights for which coincident radar data are not available, if we crudely estimate cloud depth as the altitude difference between the highest and lowest in-cloud aircraft runs, a value of the standard deviation of cloud depth can be chosen that gives a realistic ice water mixing ratio distribution, albeit with larger errors in cloud cover and mean ice water content in several cases. However, the model is completely unsuccessful for two remaining cases:

1. For flight SA07, the vertical gradient of adiabatic ice water content must be doubled to give a reasonable fit, suggesting that perhaps the base of the generating layer is overestimated in this case, but for no apparent reason.

2. For flight KA05, halving the depth of the generating layer produces a reasonable fit, but is inconsistent with the observed depth of the supersaturated layer. However, this case occurred under exceptionally calm, highly sheared, stably stratified conditions without convection. It is therefore possible that vertical motions were limited to thin layers within the supersaturated region, reducing ice production, or that horizontal transport of ice in the shear layer reduced local ice concentrations while increasing cloud cover, effects not included in the Considine et al. model.

Our results tentatively suggest a path forward to parameterization, if MMCR can provide insight on the environmental conditions that determine the variation of cloud depth relative to its mean value. A GCM would need sub-km vertical resolution to diagnose convective vs. non-convective cirrus layers; this is at or beyond the current capabilities of GCMs that are used for decadal climate change simulations.

References

Considine, G., J. A. Curry, and B. Wielicki, 1997: Modeling cloud fraction and horizontal variability in marine boundary layer clouds. *J. Geophys. Res.*, **102**, 13,517-13,525.

Smith, S. A., and A. D. Del Genio, 1999a: A simple model of cirrus horizontal inhomogeneity and cloud fraction. *J. Atmos. Sci.* Submitted.

Smith, S. A., and A. D. Del Genio, 1999b: A comparison between ISCCP cloud optical depths and values estimated from in-situ aircraft data for cirrus clouds observed during FIRE II. *J. Atmos. Sci.* Submitted.