Toward a Diurnal Climatology of Cold-Season Turbulence Statistics in Continental Stratocumulus as Observed by the Atmospheric Radiation Measurement Millimeter-Wavelength Cloud Radars

D.B. Mechem and Y.L. Kogan
Cooperative Institute for Mesoscale Meteorological Studies
University of Oklahoma
Norman, Oklahoma

M.E. Childers and K.M. Donner
School of Meteorology
University of Oklahoma
Norman, Oklahoma

Introduction

Numerous observational studies of marine stratocumulus have demonstrated a pronounced diurnal cycle. At night, longwave flux divergence at the top of the cloud drives negatively buoyant eddies that tend to keep the boundary layer well mixed. During the day, solar absorption by the cloud tends to reduce the turbulent intensity and often decouples the planetary boundary layer (PBL) into cloud- and sub-cloud circulations. The delicate balance between turbulent intensity, entrainment, and fluxes dictates cloud geometry and persistence, which can significantly impact the shortwave radiation budget.

Millimeter-wavelength cloud radars (MMCRs) have been used to study the turbulent structure of boundary layer stratocumulus (e.g. Frisch et al. 1995; Kollias and Albrecht 2000). Analysis is confined to nondrizzling or lightly drizzling cloud systems for which precipitation contamination is negligible. Under such assumptions, the Doppler velocity field becomes a proxy for vertical velocity. Past research has consisted mainly of a few case studies of specific cloud systems using radar scan strategies optimized for this particular cloud type. The MMCR operating at the Atmospheric Radiation Measurement (ARM) Climate Research Facility's (ACRF's) Southern Great Plains (SGP) site is broadly configured to be able to detect many different cloud types over a broad range of reflectivities and altitudes, so it is not specifically optimized for PBL clouds. Being in more or less continuous operation since the end of 1996, it does, however, have the advantage of long data coverage, which suggests that statistically significant measures of the diurnal cycle of turbulence should be attainable.

This abstract summarizes the first few steps toward this goal, using 7 months of cold season MMCR data.

Methodology

We make use of the ARSCL VAP (Active Remote Sensing of Cloud Layers Value-Added Product (ARSCL VAP; Clothiaux et al. 2000, 2001) to identify cloud base and cloud top. We classify nonprecipitating PBL clouds as having

- cloud top below 1500 m
- column maximum reflectivity of -20 dBZ.

The -20 dBZ threshold conservatively identifies nondrizzling cases. However, ice phase precipitation is sometimes present at reflectivities lower than this threshold, generally when at least some part of the cloud is colder than -5°C, the warm side of the range for the nucleation of ice phase particles. Some cloudy segments that obviously belong in the classification are excluded because of occasional radar hardware malfunctions or problems with incorrectly identified cloud boundaries (particularly cloud base). Any velocity in an echo whose reflectivity is <-35 dBZ is excluded from the analysis. While the -35 dBZ threshold is arbitrary and well within the theoretical sensitivity of the radar, Doppler velocity estimates at these low reflectivity values, particularly near cloud boundaries, are often unphysical. Enough energy may be backscattered to produce sensible reflectivities, though the velocity spectra may be seriously in error. Imposing a threshold in signal-to-noise ratio, rather than reflectivity, may screen out these unrepresentative moments in a more physically meaningful way.

Once the initial data processing is complete, the vertical coordinate is transformed to a nondimensional, cloud-normalized height. In this coordinate, "0" corresponds to cloud base and "1" to cloud top. The data can then be analyzed on a segment-by-segment basis or by compositing into hour-by-hour bins to evaluate the diurnal cycle. We show examples of each.

The effective data sampling frequency lies somewhere between the frequency of the data in the archive (10 s) and the time it takes the radar to cycle through the four operational modes (~40 s). This range is generally thought to be too long to capture coherent boundary layer eddy structures, but profiles may be independent samples and should provide sensible statistics. In spite of conventional wisdom, a time series below shows more coherent behavior than one might expect from such a sampling strategy. One must also be aware that some form of averaging over each operational mode (~10 s) is involved in each scan, either of the profiles themselves or coherent integration to enhance the radar sensitivity. Thus, some smoothing of the moments takes place.

Examples of Turbulence Statistics from Continental Stratocumulus

Four hours of reflectivity and Doppler velocity data from 29 March 2001 are shown in Figure 1. Cloud top and base are remarkably stable over the period. Radar echo below cloud base hints at the presence of precipitation, particularly from 0000-0100 Universal Time Coordinates (UTC) where the vertical velocities in the lower part of the cloud are predominantly negative. Soundings during this period imply the possibility of a mixed-phase cloud.

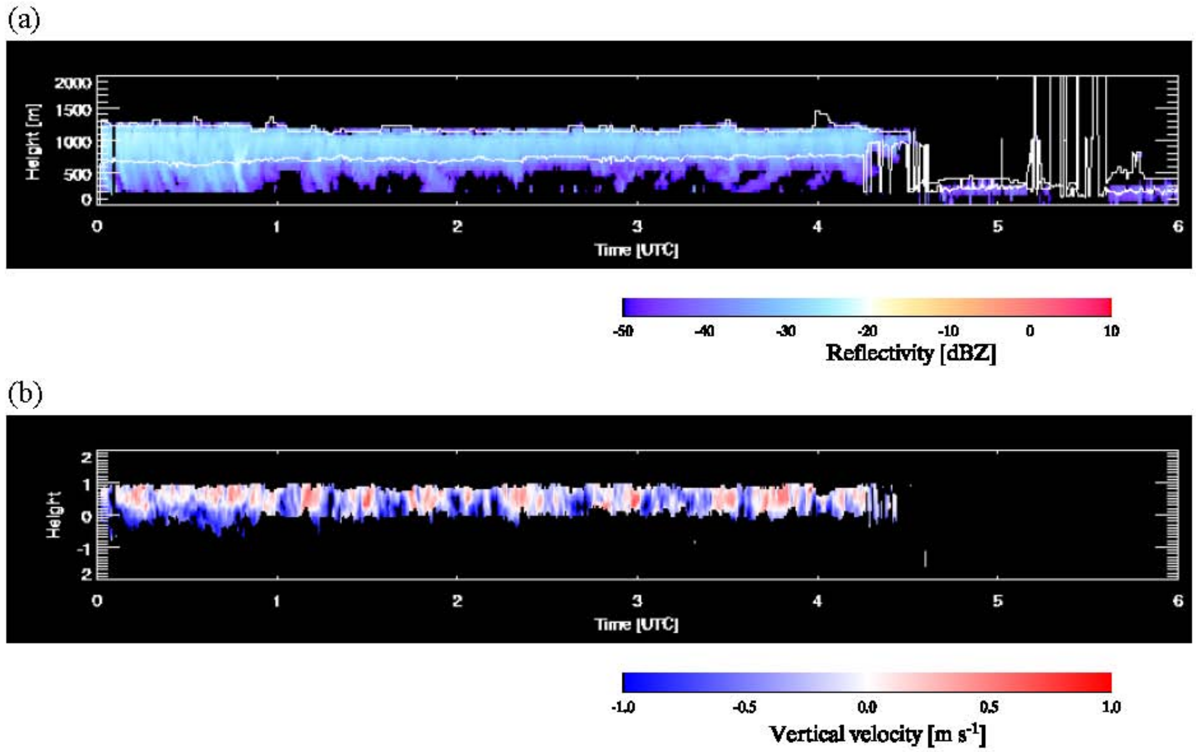

Figure 1. MMCR imagery from 0000-0600 UTC 29 March 2004. (a) Reflecting, plotted as a function of time and geometric height. (b) Doppler velocity, as a function of time and nondimensional height. A nondimensional height of 0 corresponds to cloud base; 1 corresponds to could top.

Time series of vertical velocity at three levels in the cloud (η = 0.25, 0.50, 0.75) in Figure 2a show remarkable coherence in vertical structure and time. Mean profiles of vertical velocity variance and skewness in 2b and c (after sunset) show a well-mixed cloud layer but decreasing variance in the lower part of the cloud, possibly indicative of decoupling. The skewness is predominantly negative, implying strong, narrow downdrafts arising from cloud-top cooling.

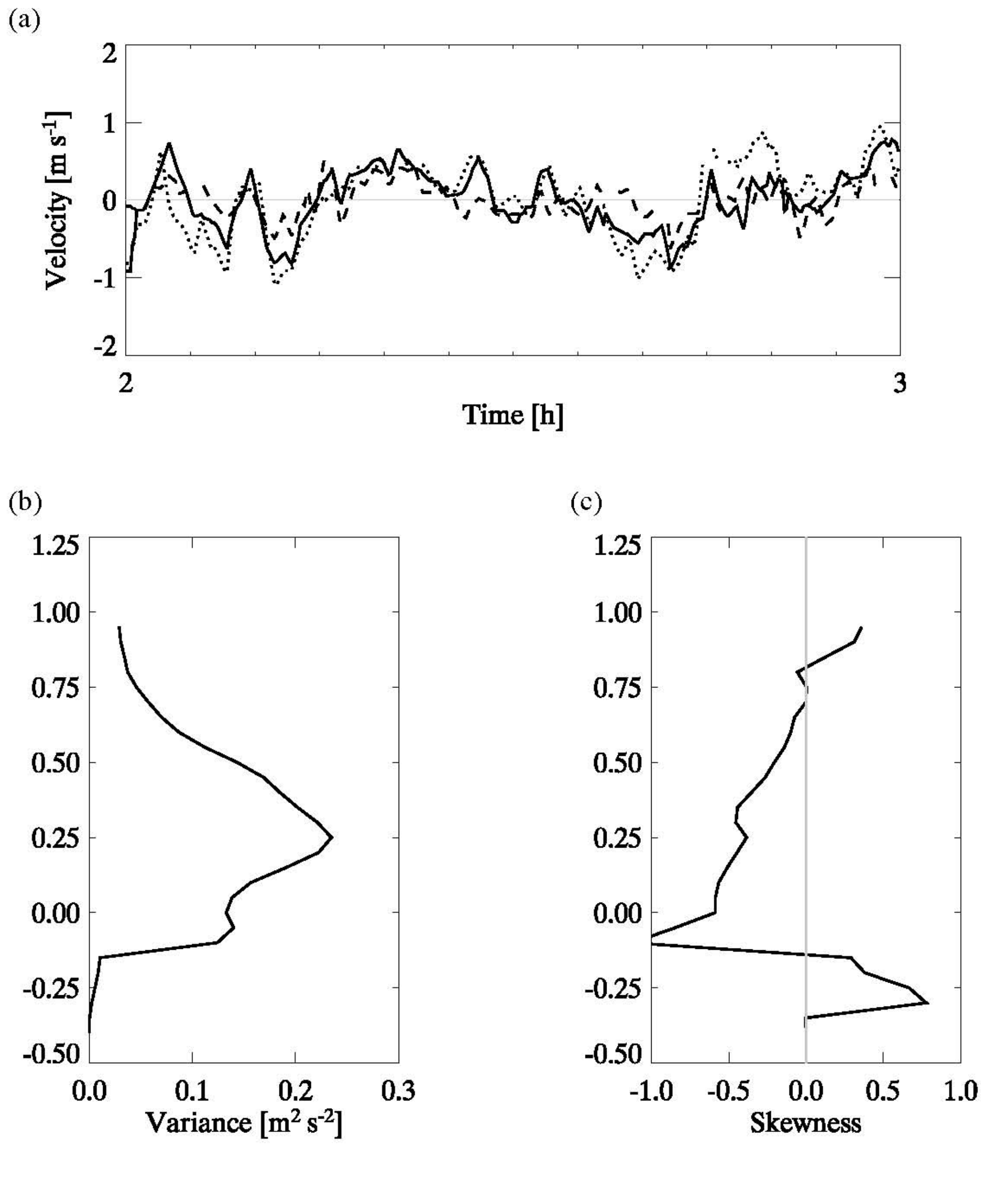

Figure 2. MMCR data from 0200-0300 UTC 29 March 2001. (a) Time series of vertical velocity at nondimensional height 0.25, 0.50, and 0.75. (b) Vertical velocity variance. (c) Vertical velocity skewness.

Variance and skewness taken over 1400-1500 UTC on 3 December 1997 in Figure 3 indicate a well-mixed cloud, extending down into the subcloud layer. Skewness is generally positive, implying a more surface-based forcing. Profile shapes and mean turbulent intensity vary significantly from case-to-case,

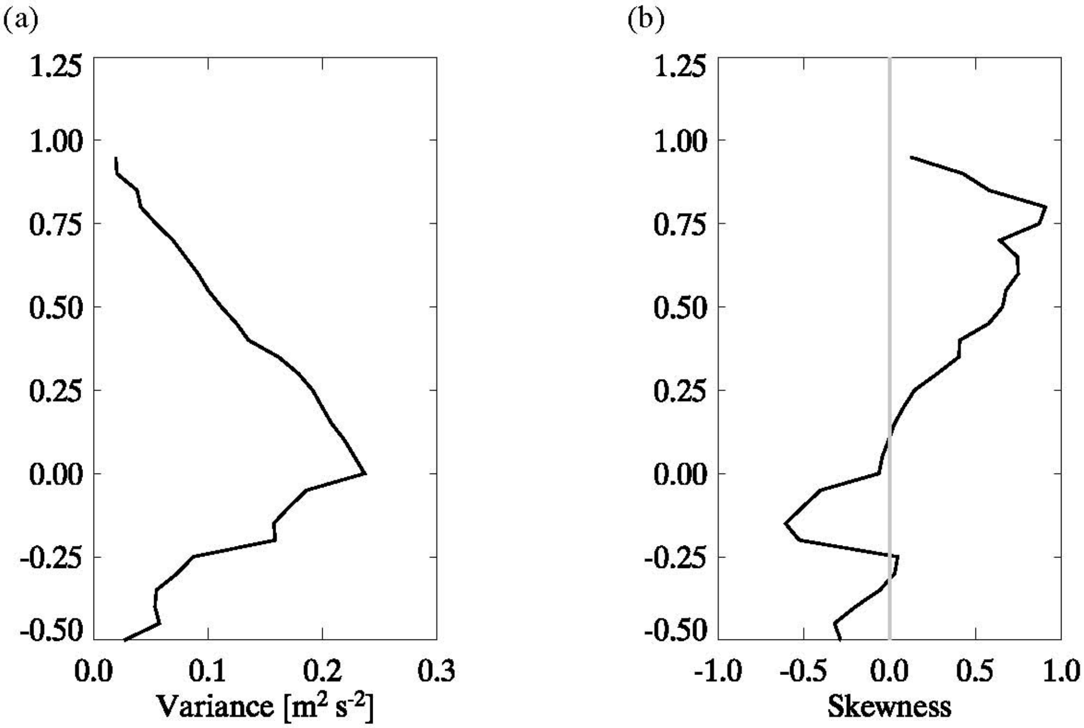

Figure 3. MMCR data from 1400-1500 UTC 3 December 1997. (a) Vertical velocity variance. (b) Vertical velocity skewness.

though not in the two examples shown here. Turbulent intensity, represented by the vertical velocity variance, generally tends to be less than that observed in previous studies, both over marine and continental locations. This may be somewhat due to the 9 s averaging interval.

Preliminary results in Figure 4 show little diurnal variability in cloud-mean turbulent intensity.

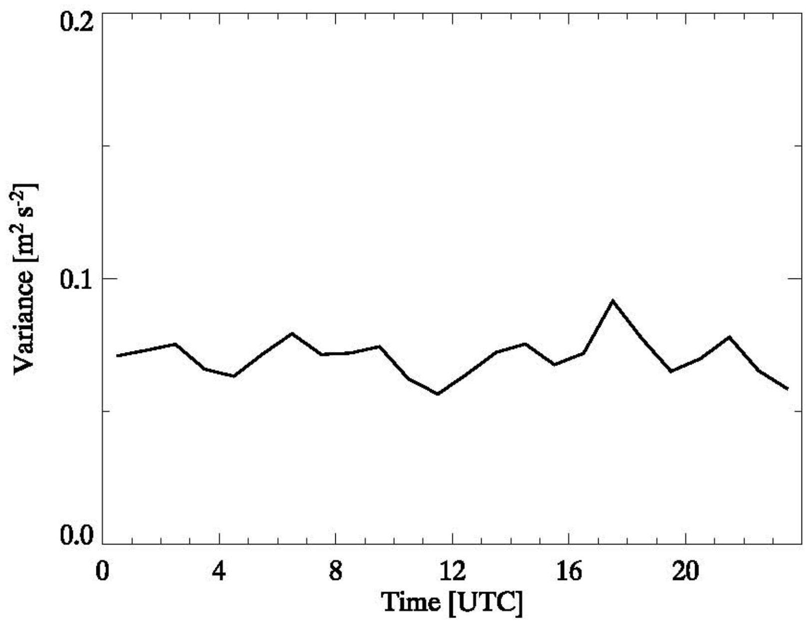

Figure 4. Diurnal cycle of cloud layer averaged vertical velocity variance, calculated from all seven months of cold season data.

Acknowledgements

This research was supported by the Environmental Sciences Division of the U.S. Department of Energy (through Battelle PNR Contract 144880-A-Q1 to the Cooperative Institute for Mesoscale Meteorological Studies) as part of the Atmospheric Radiation Measurement Program, and by ONR N00014-96-1-0687 and N00014-03-1-0304.

Corresponding Author

DB Mechem, dmechem@ou.edu, 405-325-6103.

References

Clothiaux, EE, TP Ackerman, GG Mace, KP Moran, RT Marchand, MA Miller, and BE Martner. 2000. "Objective determination of cloud heights and radar reflectivities using a combination of active remote sensors at the ARM CART sites." *Journal of Applied Meteorology* 39, 645-665.

Clothiaux, EE, MA Miller, RC Perez, DD Turner, KP Moran, BE Martner, TP Ackerman, GG Mace, RT Marchand, KB Widener, DJ Rodriguez, T Uttal, JH Mather, CJ Flynn, KL Gaustad, and B Ermold. 2001. "The ARM millimeter wave cloud radars (MMCRs) and the active remote sensing of clouds (ARSCL) value added product (VAP)." DOE Technical Memorandum ARM VAP-002.1, U.S. Department of Energy, Washington, D.C.

Frisch, AS, DH Lenschow, CW Fairall, WH Schubert, and JS Gibson. 1995. "Doppler radar measurements of turbulence in marine stratiform cloud during ASTEX." *Journal of Atmospheric Science* 52, 2800-2808.

Kollias, P, and B Albrecht. 2000. "The turbulence structure in a continental stratocumulus cloud from millimeter-wavelength radar observations." *Journal of Atmospheric Science* 57, 2417-2434.