N91-10321

BOUNDARY LAYER ROLL CIRCULATIONS DURING FIRE

Hampton N. Shirer and Tracy Haack
Department of Meteorology
The Pennsylvania State University
University Park, PA 16802

The probable mechanisms underlying the development of boundary layer roll circulations are studied using wind and temperature profiles measured by the NCAR Electra during the stratocumulus phase of the FIRE experiment. The expected, or preferred, roll orientations, horizontal wavelengths and propagation periods are determined by finding the minimum values of the dynamic and thermodynamic forcing parameters, which here are the eddy Reynolds number Re and moist Rayleigh number Ra_m. These minimum values depend on the height z_T of the capping temperature inversion and on the values of the Fourier coefficients of the background height-dependent vector wind profile. As input to our nonlinear spectral model, descent and ascent runs by the Electra provide good initial estimates of the inversion height and the wind profiles. In the first phase of the investigation presented here, a mechanism is said to be a probable contributor to the development of roll circulations within the stratocumulus-topped boundary layer if the modeled roll orientations and wavelengths agree with their observed values.

Possible mechanisms for roll development are the well-known thermal and inflection point instability mechanisms (e.g. Brown, 1980) and the recently identified shear instability mechanism of Haack-Hirschberg (1988). The first mechanism leads to thermal modes dominated by one wavenumber in the vertical, while the second two lead to dynamic modes requiring two wavenumbers in the vertical. Several low-order spectral models that are capable of accepting observed data for determination of the expected modes have been developed at Penn State; these include the pure thermal model of Shirer (1986), the pure inflection point model of Stensrud and Shirer (1988), and the mixed thermal/dynamic model of Haack-Hirschberg (1988). Linear analyses of the solutions to these models produce estimates of the preferred values of the orientation angles, horizontal wavelengths, and dimensionless frequencies for the above three modes, and these values can be readily compared with observations.

Preliminary results using the 14-coefficient model of Haack-Hirschberg (1988) are discussed for the 7 July 1987 Electra Mission 188-A (Flight 5). This mission was flown across a sharp cloud boundary that was within a Landsat/SPOT scene (Kloesel et al., 1988). The stratocumulus deck was relatively solid in the eastern part of the scene, while there was a rapid decrease in cloud cover to scattered cumulus clouds aligned in streets to the west. These cloud streets were oriented nearly parallel to the mean wind direction in the layer, which was approximately 340°. The hypothesis that roll circulations occurred in both the relatively clear and the cloudy regions is investigated using as model input a descent profile obtained in the relatively clear air and an ascent profile obtained in the cloudy air. Initial results for the clear air case are that the pure inflection point mode is not possible and the pure thermal mode was oriented 35° to the right of the mean wind direction. The origin of this unacceptably large discrepancy between the observed and modeled results will be investigated further and the conclusions reported at the next FIRE workshop.

The results for the cloudy case are more promising. In Fig.1 are shown the measured cross-roll U_M and along-roll V_M wind components (jagged curves), together with the fit to the data implied by the model representation (smooth curves). Clearly the limited resolution of the 14-coefficient model is able to represent the observations rather well. As shown by the solid and dashed lines in Fig. 2, two thermal modes are possible in this case. The quadrilateral in Fig. 2 encloses the estimated range of observed values of Re and Ra_m, where $Re = |\underset{\sim}{V}(z_T)|z_T/(\pi\nu)$, $Ra_m = gz_T^3\Delta_zT/(\nu\kappa T_{00}\pi^4)$, $|\underset{\sim}{V}(z_T)|$ is the wind at the inversion base z_T, ν and κ are the eddy viscosity and thermometric conductivity respectively, and Δ_zT is a combined measure of the sea surface/air temperature difference and the environmental lapse rate of equivalent potential temperature. The mode whose transition curve passes to the left of the estimated range of observed values for Ra_m and Re is associated with orientations that are 10^o to the right of the mean wind direction (335^o); this preferred orientation angle β_p is 75^o south of east, or -75^o. The expected aspect ratio a_p of 0.6 corresponds to a horizontal roll wavelength $L = 2z_T/a_p$ of approximately 2500 m. This value of L is consistent with the wavelengths found from preliminary vertical velocity spectra for the horizontal flight leg between the descent and ascent profiles. Finally the dimensionless frequency ω_p of 31.7 corresponds to a propagation period of approximately 30 minutes. Thus, the model results suggest that a thermally driven roll circulation supported the stratocumulus clouds observed on 7 July 1987.

Acknowledgments. Mark Laufersweiler helped us read the FIRE data tapes using a program written by Jeff Nucciarone, who also computed the preliminary vertical velocity spectra. The research reported here was partially supported by the National Science Foundation through Grant ATM- 8619854 and by the Office of Naval Research through Contract N000014-86-K-06880.

References

Brown, R.A., 1980: Longitudinal instabilities and secondary flows in the planetary boundary layer. A review. Rev. Geophys. Space Phys., 18, 683-697.

Haack-Hirschberg, 1988: Boundary layer roll circulations in a stratified atmosphere. M.S. Thesis, Department of Meteorology, Penn State University, 161 pp.

Kloesel, K.A., B.A. Albrecht, and D.P. Wylie, 1988: FIRE marine stratocumulus observations--summary of operations and synoptic conditions. FIRE Technical Report Number 1, Department of Meteorology, Penn State University, 171 pp.

Shirer, H.N., 1986: On cloud street development in three dimensions: Parallel and Rayleigh instabilities. Contrib. Atmos. Phys., 59, 126-149.

Stensrud, D.A. and H.N. Shirer, 1988: Development of boundary layer rolls from dynamic instabilities. J. Atmos. Sci., 45, 1007-1019.

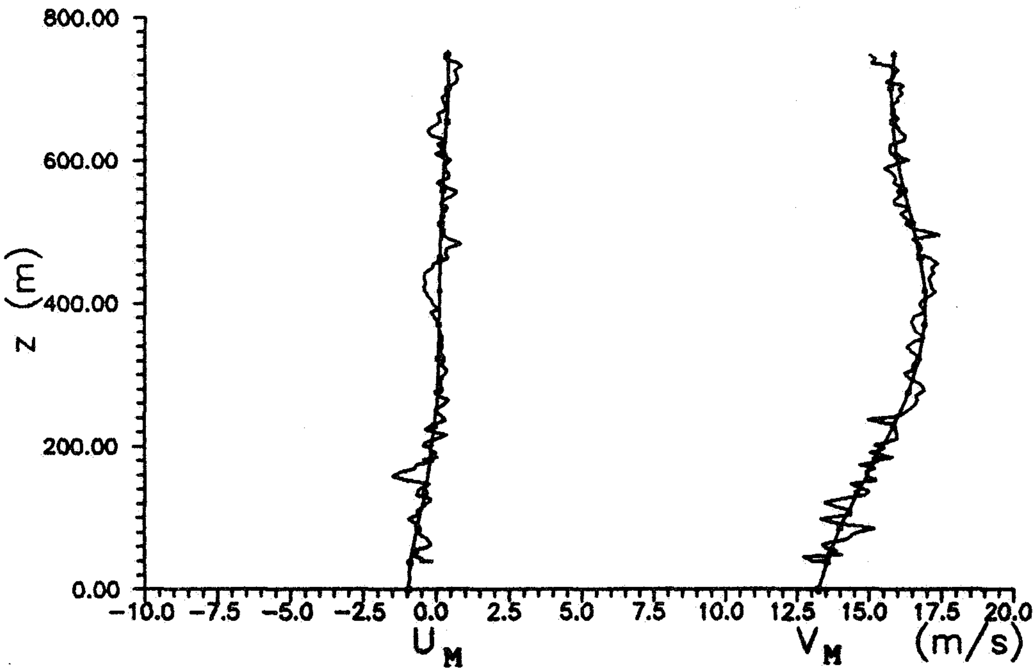

Figure 1. Cross-roll U_M and along-roll V_M wind profiles (jagged curves) measured by the NCAR Electra in the stratocumulus region on 7 July 1987 (Flight 5) between 2154:43 and 2156:49 UTC. The cross-roll, or x-, direction is 65° (~ENE), so that negative values correspond to winds having directions less than 335°. The representation of the data by the model is shown by the smooth curves.

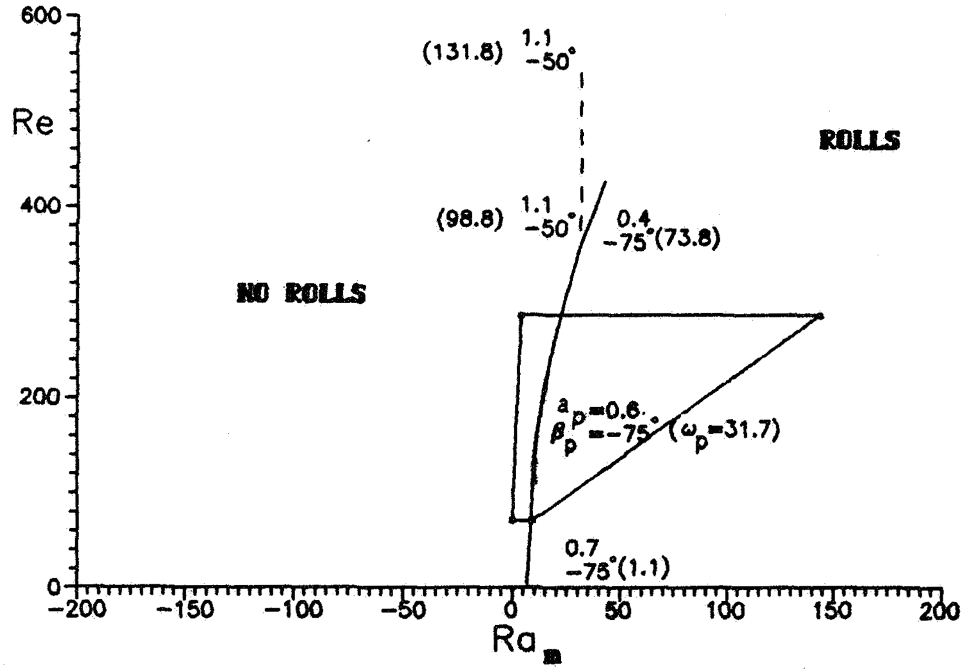

Figure 2. Results from the model analysis. The solid and dashed lines denote the transition curves for the two thermal modes supported by the observed wind profile given in Fig. 1. The numbers next to these curves denote the preferred orientation angle β_p, the aspect ratio a_p and the dimensionless frequency ω_p (in parentheses). The quadrilateral encloses the values of the moist Rayleigh number Ra_m and Reynolds number Re that are estimated to characterize the observed stratocumulus regime. These vertices are given approximately by (Ra_m, Re) = (0,70); (10,70); (145,285); (5,285). Here z_T = 750 m and ν and κ vary between 10 m^2/s and 50 m^2/s.