Table 3: CASES-99 nights with inertial oscillations beginning 0000 UTC and lasting for 14-16 hours at the boundary-layer profilers located at B, Beaumont, W, Whitewater, O, Oxford, E, El Dorado and S, Smileyberg (see Figure 3 for locations).

Event #	Date (JD)	Sites w/ IOs	IOP #	LLJ height, speed and dir overnight	GLASS winds available below 120m?
1	10/04-05 (278)	All	1	weak LLJ	no
2	10/05-06 (279)	All	2	LLJ at 100 m	sporadically
3	10/07-08 (281)	All	N/A	slab acceleration	yes
4	10/10-11 (284)	All	4	300 m, 12-18 m s-1, 50-100^o	yes
5	10/11-12 (285)	W, O, E, S	5	200-300 m, 10-15 m s-1, 180-210^o	no
6	10/12-13 (286)	All	N/A	300-400 m, 15-20 m s-1, 200-250^o	N/A
7	10/13-14 (287)	B, O, E, S	6	200 m, 12 m s-1, 120^o	none but at 0300 for E and S
8	10/22-23 (296)	All	10		only after 0700 UTC
9	10/27-28 (301)	All	N/A	400 m, 20 m s-1, 200^o	only at 1100 UTC

Table 2: IOP nights during CASES-99 field experiment. Column 4 contains the estimated maximum T_{20m} - $T_{0.5m}$ and a conversion of that value to $^{o}C\ km^{-1}$ in parentheses.The other columns are self-explanatory.

IOP #	Start Date-Time UTC	End Date-Time UTC	Short description and Max $\Delta T_{20.0\text{-}0.5\ m}$ in ^{o}C and equivalent lapse rate ($^{o}C\ km^{-1}$)	King Air flight times	Long EZ flight times
1	10/04 - 2200	10/05 - 1100	Clear skies, light winds. ΔT=5.3 (265)	Not available	10/04 2300 - 10/05 0200
2	10/05 - 2200	10/06 - 1300	S Jet ~ 10 m/s, near 110m AGL; Turbulence, K-H Billows; Morning Transition. ΔT=6.7 (335)	10/06 0100-0430	10/06 0430-0715 10/06 1100-1300
3	10/09 - 2200	10/10 - 1300	W Jet ~10 m/s, 60-120m AGL. ΔT=6.2 (310)	10/10 0200-0315	Not available
4	10/10 - 2200	10/11 - 1300	Post-frontal ENE Jet ~ 17 m/s, 100 - 200m AGL. ΔT=4.0 (200)	10/11 1030-1300	Not available
5	10/11 - 2200	10/12 - 1300	Weak sfc flow with strong flow aloft to 17 m/s near 250m AGL. Organized KH like and wave-like structures observed. ΔT=5.1 (255)	10/12 0400-0800 10/12 0900-1300	10/12 0000-0200 10/12 1000-1300
6	10/13 - 2200	10/14 - 1300	NE-E jet ~ 9-12 m/s, 120 - 180m AGL. Turbulence/wave sheets; gravity waves; turbulence bursting; KH activity; dissipation of LLJ. ΔT=5.4 (270)	10/13 0400-0830 10/13 0930-1300	10/13 0100-0400 10/13 1000-1300
7	10/17 - 2200	10/18 - 1300	Surface-based turbulent event.N->E->SE Jet ~ 10 m/s, 200 - 300 m -> 100 m AGL. ΔT=5.9 (295)	10/18 0200-0445 10/18 0945-1200	10/17 2300 - 10/18 0200 10/18 1030-1300
8	10/19 - 2200	10/20 - 1300	S-SW Jet ~ 11 m s^{-1}, 60 -120 m AGL. Little wave activity. ΔT=7.1 (355)	10/20 0800-1300	10/19 2230-10/20 0130 10/20 1000-1300
9	10/20 - 2200	10/21 - 1300	S-SW Jet ~ 10-12 m s^{-1}, 100 - 200 m AGL. A Fossil turbulence event and nearly continuous, weak surface-based turbulence. ΔT=4.8 (240)	10/20 2300-0300 2nd flight?	10/20 2330-0230 2nd flight
10	10/22 - 2200	10/23 - 1300	No Jet. Consistent dissipation at about 200 Hz. ΔT=5.5 (275)	Not available	10/23 1000-1400
12	10/26 - 1900	10/27 - 1300	Evening transition. No jet. ΔT=5.0 (250)	10/26 2215 - 10/27 0145 10/27 0400-0645	Not available

TABLES

Table 1: An alphabetical list of participants in the CASES-99 Field Experiment. Note that, for brevity, in some cases only one representative from an institution is listed although more than one representative participated.

Name	Affiliation
1. Ben Balsley	University of Colorado
2. Bob Banta	NOAA/ETL
3. Bill Blumen	University of Colorado
4. Sean Burns	NCAR
5. Mark Coleman	Army Research Laboratory
6. Dan Cooper	LANL
7. Rich Coulter	Argonne National Laboratory
8. Joan Cuxart	Instituto Nacional de Meteorologia
9. Henk deBruin	Wageningen Agric. Univ., Netherlands
10. Chris Doran	Pacific Northwest Lab
11. Richard Eckmann	INEL
12. William Eichinger	University of Iowa
13. Steve Frasier	University of Massachusetts
14. Dave Fritts	CoRA
15. Oscar Hartogensis	Wageningen Agric. Univ., Netherlands
16. Mark Hoder	University of Wyoming
17. Mike Jensen	University of Colorado
18. Jerry Klazura	ANL (onsite)
19. Julie Lundquist	University of Colorado
20. Larry Mahrt	Oregon State University
21. Dave Miller	University of Connecticut
22. Carmen Nappo	Oak Ridge/NOAA/ATDD
23. Rob Newsom	NOAA/ETL
24. Steve Oncley	NCAR
25. Greg Poulos	CoRA
26. John Prueger	National Soil Tilth Laboratory
27. Russ Qualls	University of Colorado
28. Maria Rosa Soler	University of Barcelona
29. Greg Stossmeister	UCAR JOSS
30. Jielun Sun	NCAR
31. Marv Wesely	Argonne National Laboratory

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Oct 1999, IOP-4. The + symbol indicates actual observations; some gaps exist in the winds portion of the dataset.

Figure 21. Wind profiler data from El Dorado through the night of 10-11 Oct 1999, IOP-4.

vertices a variety of instruments were placed. It was densely instrumented with sonic anemometers, standard weather stations with propeller vane wind measurements, thermocouples, radiative flux divergence instrumentation, CO_2 sensors, hot-wire anemometers and microbarographs.

Figure 4. The CASES-99 Main Site. See text for further details.

Figure 5. A photograph from the south-east of the 60 m tower at the CASES-99 main site. The tower in the near-view is 100 m from the base of the 60 m tower at the vertex of a concentric triangle.

Figure 6. A comparison of the temperature (^{o}C) from a 20 Hz thermo-sonic anemometer, an aspirated temperature sensor, and a 5 Hz thermocouple at 55 m on the 60 m tower.

Figure 7. The time-height plot of various atmospheric variables during the density current on 18 Oct 1999, near 0200 UTC, where the air temperature, the specific humidity, the wind speed, the wind direction, the vertical velocity, and the carbon dioxide concentration at 5 m are plotted from the top to the bottom, respectively.

Figure 8. Vertical profiles of high-frequency temperature fluctuations observed by three separate probes ascending sequentially through the 30-55m height range at 0.4 ms^{-1}.

Figure 9. a) Spectra of high frequency temperature and b) wind speed fluctuations obtained roughly one hour before and after the results shown in Figure 8. Note the marked increase in turbulence levels in both sets of spectra.

Figure 10. a) u, b) v, c) w, c) T and e) height AGL from a single leg of the Wyoming King Air during IOP-7 near sunrise. Note the very low flight levels and intermittent periods of high variability encountered by the aircraft.

Figure 11. A plot of wind direction from five 2-d sonic anemometers placed in the gully (see Figure 4 for gully location). Despite strong static stability, down-gully katabatic flows were intermittently interrupted by various NBL phenomena.

Figure 12. Potential temperature (solid line) and wind speed (dashed line) from the 0300 UTC sounding taken at El Dorado on Oct 6, 1999. during IOP-2. Strong shear and low Ri contributed to conditions conducive to Kelvin-Helmholtz billow development.

Figure 13. Various time series from 6 Oct 1999. (a) Thermocouple temperature, (b) sonic anemometer horizontal wind speed, and (c) sonic anemometer vertical wind speed. The instrument level and quantity of data have been shifted to reveal structures.

Figure 14. One representative scans from the NOAA HRDL (lidar) showing a mature stage of the shear instability observed on 6 Oct 1999, IOP-2.

Figure 15. Momentum and heat fluxes at 50 m AGL from the tall tower at the CASES-99 Main Site. The period shown is one hour in length, where the event was primarily confined to 20-45 minutes past the hour. Note larger 1 minute average fluxes during that time range.

Figure 16. Contours of wavelet energy density (e.g. Hauf et al., 1996) for the nighttime period 2000-0800 LT (0100 to 1300 UTC) from one of the 6 surface based microbarographs during IOP-2.

Figure 17. Temporal evolution of the wavelet transform energy for the three microbarographs (1m, 30m and 50 m AGL) integrated for periods between 2 seconds and 3 minutes.

Figure 18. The wavelet transform (energy density in $hPa^{2}s^{-1}$) for the microbarograph situated at 50 m AGL on the CASES-99 tall tower for the billow event of 6 Oct 1999 from 0500 to 0600 UTC.

Figure 19. The top panel is the hodograph of the winds observed from 0000 UTC to 1600 UTC at El Dorado at 361 m during IOP-4. The bottom two panels show time series of the zonal and meridional winds. The solid line represents the observed data; the dashed line is the “best-fit” IO; the dotted line is the noise remaining after the mean winds and the IO have been removed from the time series.

Figure 20. Profiles of wind speed and potential temperature from radiosonde data on the night of 10-11

ible flows.Part II: Instability, structure, evolution and energetics. *J. Atmos. Sci*. **53**, 3192-3212.

Pielke, R.A., W.R. Cotton, R.L. Walko, C.J. Tremback, M.E. Nicholls, M.D. Moran, D.A. Wesley, T.J. Lee, and J.H. Copeland, 1992: A comprehensive meteorological modeling system - RAMS. *Meteor. Atmos. Phys.*, **49**, 69-91.

Poulos, G.S., 1996:The interaction of katabatic winds and mountain waves. Ph.D. Dissertation, Colorado State University, Fort Collins CO, 300pp.

Poulos, G. S., and J. E. Bossert, 1995: An observational and prognostic numerical investigation of complex terrain dispersion. *J. Appl. Meteor.*, **34**, 650-669.

Revelle, D. O., 1993: Chaos and "bursting" in the planetary boundary layer. *J. Appl. Meteor.*, **32**, 1169- 1180.

Rider, N.E., and G.D. Robinson, 1951: A study of the transfer of heat and water vapor. *Quart. J. Roy. Meteor. Soc.*, **77**, 375-401.

Saiki, E. M., C-H. Moeng, and P. P. Sullivan, 2000: Large eddy simulation of the stably stratified planetary boundary layer. *Bound.-Layer Meteor.*, **95**, 1-30.

Scorer, R.S. 1997: Dynamics of meteorology and climate. John Wiley & Sons, Chichester, U.K., 686 pp.

Thorpe, S. A., 1973: Experiments on instability and turbulence in stratified shear flow. *J. Fluid Mech*., **61**, 731-751.

Thorpe, A.J., and T.H. Guymer, 1977: The nocturnal jet. *Quart. J. R. Met. Soc.*,**103**, 633-653.

Uccellini, L.W., 1980: On the role of upper tropospheric jet streaks and leeside cyclogenesis in the development of low-level jets in the Great Plains. *Mon. Wea. Rev.* **108**, 1689-1696.

van Doorn, E., B. Dhruva, and K.R. Sreenivasan, 2000: Statistics of wind direction and its increments. *Phys. Fluids*, **12**, 1529-1534.

Weber, A.H. and R.J. Kurzeja, 1991: Nocturnal planetary boundary layer structure and turbulence episodes during the Project STABLE field program, *J. Appl. Meteor.*, **30**, 1117-1133.

Werne, J., and D. C. Fritts, 1999. Stratified shear turbulence: Evolution and statistics. *Geophys. Res. Lett.* **26**, 439-442.

Werne, J., and D. C. Fritts, 2001: Anisotropy in a stratified shear layer. *Phys. Chem. Earth (B)*, **26**, 263-268.

Zhong, S., J. D. Fast and X. Bian, 1996: A case study of the Great Plains low-level jet using wind profiler network data and a high resolution mesoscale model. *Mon. Wea. Rev.*, **124**, 785-806.

Table captions

Table 1:An alphabetical list of participants in the CASES-99 Field Experiment. Note that, for brevity, in some cases only one representative from an institution is listed although more than one representative participated.

Table 2: IOP nights during CASES-99 field experiment. Column 4 contains the estimated maximum $T_{20m} - T_{0.5m}$ and a conversion of that value to ^{o}C/km in parentheses.The other columns are self-explanatory.

Table 3: CASES-99 Inertial oscillations

Figure captions

Figure 1. The Arkansas River Watershed and sub-domain of the ARM-CART site within which the CASES-99 Field Experiment was held. Note that the Walnut River Watershed represents a minor basin within the larger watershed.

Figure 2. The Walnut River Watershed and site of CASES-99 field program. The CASES-99 Main Site is outlined in the small rectangle just to the right of the ABLE Central Site, southeast of Leon, KS (see Figure 4 for details). The filled circles indicate areas of existing, meso-β scale instrumentation of ABLE (towers, sodars, wind profilers).

Figure 3. The ABLE instrumentation as supplemented by CASES-99 sensors, and the 60 m tower which was located at the Main Site. The 60 m tower was the center of a series of concentric triangles at whose

Funk, J.P., 1960: Measured radiative flux divergence near the ground at night. *Quart. J. Roy. Meteor. Soc.*, **86**, 382-389.

Gopalakdrishnan, S. G., M. Sharan, R. T. McNider and M. P. Singh, 1998: Study of radiative an turbulent processes in the stable boundary layer under weak wind conditions. *J. Atmos. Sci.*, **55**, 954-960.

Grund C. J., R. M. Banta, J. L. George, J. N. Howell, M. J. Post, R. A. Richter, A. M. Weickmann, 2000. High-Resolution Doppler Lidar for boundary-layer and cloud research. *J. Atmos. Oceanic Technol*., **18**, 376-393.

Gryning. S.-E., 1985:The Oresund experiment- A Nordic mesoscale dispersion experiment over a land-water-land area. *Bull. Amer. Meteor. Soc.*, **66**, 1403-1407.

Hartel, C. and L. Kleiser, 1998: Analysis and modeling of subgrid-scale motions in near-wall turbulence. *J. Fluid Mech.*, **356**, 327-352.

Hauf, T., U. Finke, J. Neisser, G. Bull, and J.-G. Strangenberg, 1996: A ground-based network for atmospheric pressure fluctuations. *J. Atmos. Sci*., **13**, 1001-1023.

Hill, R. J., 1997: Applicability of Kolmogorov's and Monin's equations of turbulence. *J. Fluid. Mech*., **353**, 67-81.

Holton, J. R.: 1967, The diurnal boundary layer wind oscillation above sloping terrain. *Tellus*, **19**, 199-205.

Howard, L.N.,1961. Note on a paper by John Miles. J. Fluid Mech. 10, 509-512.Horst, T.W. and J.C. Doran, 1986: Nocturnal drainage flow on simple slopes. *Bound.-Layer Meteor.*, **3**, 263-286

Howell, J. and L. Mahrt, 1997: Multiresolution flux decomposition. *Bound.-Layer Meteor.*, **83**, 117-137.

Howell, J. and J. Sun, 1997: Surface layer fluxes in stable conditions. *Bound.-Layer Meteor.*, **90**, 495-520.

Kunkel, K.E., and D.L. Walters, 1982: Intermittent turbulence in measurements of the temperature structure parameter under very stable conditions. *Bound.-Layer Meteor.*, **22**, 49-60.

LeMone, M., R. L. Grossman, R. L. Coulter, M. L Wesely, G. E. Klazura, G. S. Poulos, W. Blumen, J. K. Lundquist, R. H. Cuenca, S. F. Kelly, E. A. Brandes, S. P. Oncley, R. T. McMillen and B. B. Hicks, 2000: Land-atmosphere interaction research, early results and opportunities in the Walnut River Watershed in southeast Kansas: CASES and ABLE. *Bull. Amer. Meteor. Soc*., **81**, 757-779.

Lenschow, D.H., X.S. Li, C.J. Zhu, and B.B. Stankov 1988a: The stably stratified boundary layer over the Great Plains. Part I: Mean and turbulence structure. *Bound.-Lay. Meteor.*, **42**, 95-121.

Lenschow, D.H., S.F. Zhang, and B.B. Stankov 1988b: The stably stratified boundary layer over the Great Plains. Part II: Horizontal variations and spectra. *Bound.-Lay. Meteor.*, **42**, 123-135.

Louis, J. F., 1979: A parametric model of vertical eddy fluxes in the atmosphere. *Bound.-Layer Meteor.*, **17**, 187-202.

Lundquist, J. K., 2000:Inertial oscillations and boundary-layer dynamics: The evening transition of the atmospheric boundary layer. Ph.D. Dissertation, University of Colorado at Boulder. 130 pp.

Mahrt, L., 1998: Stratified atmospheric boundary layers and breakdown of models. *J. Theor. Comp. Fluid Dyn.*, **11**, 263-280

Mahrt, L., 1999: Stratified atmospheric boundary layer. *Bound.-Layer. Meteor.*, **90**, 375-396.

Mahrt, L., J. Sun, W. Blumen, T. Delany, and S. Oncley, 1997: Nocturnal boundary-layer regimes. *Bound.-Layer Meteor.*, **88**, 255-278.

McNider, R. T., D. E. England, M. J. Friedman, and X. Shi, 1995: Predictability of the stable atmospheric boundary layer. *J. Atmos. Sci.*, **52**, 1602-1623

Miles, J.W., L. N. Howard, 1964: Note on heterogeneous shear flow. *J. Fluid Mech*. **20**, 331-336.

Muschinski, A. and C. Wode, 1998: First in-situ evidence of coexisting submeter temperature and humidity sheets in the lower free troposphere. *J. Atmos. Sci.*, **55**, 2893-2906.

Nappo, C., 1991: Sporadic breakdowns of stability in the PBL over simple and complex terrain. *Bound.-Layer Meteor.*, **54**, 69-87.

Nappo, C. J., and P.-E. Johansson, 1998: Summary report of the Lovanger international workshop on turbulence and diffusion in the stable planetary boundary layer. *Bull. Amer. Met. Soc.*, **79**, 1401-1405.

Newsom, R. K. and R. M. Banta, 2001: Shear-Instability Gravity Waves in the Stable Nocturnal Boundary Layer as Observed by Doppler Lidar during CASES-99. *J. Atmos. Sci.* (submitted).

Nkemdirim, L.C., 1978: A comparison of radiative and actual nocturnal cooling rates over grass and snow. *J. Appl. Meteor.*, **17**, 1643-1646.

Palmer, T.L., D. C. Fritts, O. Andreassen, 1996. Evolution and breakdown of Kelvin-Helmholtz billows in stratified compress-

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5. References

Balsley, B. B., J. W. Birks, M. L. Jensen, K. G. Knapp, J. B. Williams, and G. W. Tyrrell, 1994: Ozone profiling using kites, *Nature*, **369**, 23.

Balsley, B. B. Williams, G. W. Tyrrell, and C. L. Balsley, 1992: Atmospheric research using kites: Here we go again! *Bull. Amer. Meteor. Soc.*, **73**, 17-29.

Banta, R.M. and P.T. Gannon Sr., 1995: Influence of soil moisture on simulations of katabatic flow. *Theor. Appl. Climatol*., **52**, 85-94.

Blackadar A.K., 1957: Boundary layer wind maximum and their significance for the growth of nocturnal inversions. *Bull. Amer. Meteor. Soc.*, **38**, 283-290.

Blumen, W., and R.L. Grossman, and M. Piper, 1999:Analysis of heat flux, dissipation and frontogenesis in a shallow density current. *Bound.-Layer Meteor.*, **91**, 281-306.

Blumen, W., R. Banta, S. P. Burns, D. C. Fritts, R. Newsom, G. S. Poulos and J. Sun, 2001: Turbulent statistics of a Kelvin-Helmholtz billow event observed in the nighttime boundary layer during the CASES-99 field program. *Dyn. Atmos. Oceans* (to appear June).

Buajitti, K. and A. Blackadar, 1957: Theoretical studies of diurnal wind-structure variations in the planetary boundary layer. *Quart. J. Roy. Meteor. Soc.*, **83**, 486-500.

Caughey, S.J., and C.J. Readings, 1975: An observation of waves and turbulence in the Earth’s boundary layer. *Bound.-Layer Meteor.*, **9**, 279-296.

Chen, F., Z. Janjic and K. Mitchell, 1997: Impact of atmospheric surface-layer parameterization in the new land-surface scheme of the NCEP mesoscale Eta Model. *Bound.-Layer. Meteor.*, **85**, 391-421.

Cheney, N.R., and J. A. Businger, 1990: An accurate fast response temperature system using thermocouples. *J. Atmos. Ocean. Tech*. **7**, 504-516.

Denholm-Price, J. C. W. and J. M. Rees, 1999: Detecting waves using an array of sensors. *Mon. Wea. Rev.*, **127**, 57-69.

Derbyshire, S.H., 1995: Stable boundary layers: Observations, models and variability Part I: Modeling and measurements. *Bound.-Layer Meteor.*, **74**, 19-54.

Derbyshire, S.H., 1999: Boundary-layer decoupling over cold surfaces as a physical boundary instability. *Bound.-Layer Meteor.*, **90**, 297-325.

De Silva, L.P.D., Fernando, H.J.S., Eaton, F, Hebert, D.,1996: Evolution of Kelvin-Helmholtz billows in nature and laboratory. *Earth and Plan. Sci. Lett*. **143**, 217-231.

Djuric, D. and D.S. Ladwig, 1983 Southerly low-level jet in the winter cyclones of the southwestern Great Plains. *Mon. Wea. Rev.*, **111**, 2275-2281.

Elliott, W.P. 1964: The height variation of vertical heat flux near the ground. *Quart. J. Roy. Meteor. Soc*., **90,** 260-265.

Fernando, H.J.S., 1991: Turbulent mixing in stratified fluids. *Ann. Rev Fluid Mech.* **23**, 455-493.

Finnigan, J.J., F. Einaudi and D. Fua, 1984: The interaction between an internal gravity wave and turbulence in the stably-stratified nocturnal boundary layer. *J. Atmos. Sci.*, **41**, 2409-2436.

4 scientific goals. These goals are, in short, (see Section 1 for more detail): 1) to provide a time history of NBL phenomena, and to evaluate their contributions to intermittent heat, moisture and momentum fluxes, 2) to measure fluxes and their divergences throughout the nocturnal boundary layer and surface layer, to assess the departures from similarity theory under otherwise dynamically stable conditions, 3) to define the relative importance of surface heterogeneity on NBL evolution, and 4) to compare measurements with existing models of the transition periods, and to assess the role of the transition period in the initiation of inertial oscillations and the enhancement of low-level jets.

Information provided herein shows that what at the surface may appear, due to weak winds and strong static stability, to be a relatively quiescent nocturnal boundary layer, may in fact be intermittently populated with a variety of atmospheric phenomena that provide deviations from a dynamically stable condition. In Kansas, these phenomena are frequently generated from the upper levels of the NBL and have influence downward due nocturnal jets that form with influence from inertial oscillations. These jets are not confined to a particular orientation, such as the Great Plains Low-level Jet (e.g. Zhong, 1996) which is generally considered to be a southerly phenomena, with a jet maximum at altitudes 100 m or more above the jet maxima observed during CASES-99. The fluxes generated from one event are shown to have a significant effect on the vertical structure of the NBL despite its short-lived existence (~25 min). Ongoing efforts investigating the wide variety of events sampled during the CASES-99 field experiment are yielding additional information on their sources and characteristics, such that a robust understanding of the NBL can be achieved. Further, many modeling techniques and theoretical tactics are being applied within CASES-99 to improve model performance during conditions where intermittent turbulence predominates. This is a long-standing problem that is in dire need of solution.

We encourage all interested parties to pursue investigations utilizing the CASES-99 data archive which is freely available at http://www.joss.ucar.edu/cases99/.

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We would like to acknowledge the following people for their significant role the success of CASES-99 experiment; Jerry Klazura of Argonne National Laboratory, who was instrumental in the logistics of the set-up and operation of the COT, contacting landowners and keeping the local community informed; Holly Hayes of Colorado Research Associates in helping to organize the Operational Plan; Steve Oncley, Carolyn Simerly and colleagues at NCAR ATD for their fine support, administration, and deployment of the Lower Atmospheric Observing Facility, and especially the heavily instrumented 60 m tower; and Rich Coulter, Jerry Klazura for the ABLE wind profiler data. .On the whole, the active participation in planning and cooperative efforts at bringing a wide variety of relevant instruments to the field by the CASES-99 participants should be pointed to as the primary means for our success.

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is considered Gaussian, the time series of winds is judged to represent an IO. Otherwise, it is assumed that the IO is not present or that other motions dominate the winds. Figure 19 depicts one time series that fulfills the criteria to be considered an IO.

This technique has been applied to the data from the lowest 2 km of the five CASES-99 915 MHz boundary-layer wind profilers from 3 - 29 October. Of the 27 evenings examined, nine nights show evidence of IOs commencing at 0000 UTC (see Table 3), one to two hours after the surface heat flux changes sign, and lasting for 14-16 hours at two or more profiler sites. Winds below 150 m are not available from boundary layer profilers, and are often not available from GPS-soundings, so it is not possible to determine if IOs are present at or below the inversion level on these nights.

One of these nights can illustrate the role of IOs in the development of the jet profile in the winds of the stable boundary layer. The day of 10 October is marked by moderate winds, warm temperatures, few clouds, and the growth of a convective boundary layer. The mixed layer, sampled by a sounding at the main Leon site, grows to 1400 m by 2300 UTC on 10 October (see Figure 20). The ELD profiler indicates that winds are 4-5 m s^{-1} from the north. Based on tower measurements the surface heat flux changes sign at 2230 UTC. By 0100 UTC on 11 October, the wind profiles confirm LLJ development (Figure 21). The 0300 UTC sounding and profiler data show a distinct jet structure in the wind. This jet persists through the night, with the wind direction rotating through the east as the wind speeds in the jet increase to 18 m s^{-1} by 0700 UTC. The speed in the jet maximum remains constant through 1200 UTC, and then starts to diminish. Throughout the night, all jet development is confined to below 600m; profiler resolution does not reveal whether the jet max rises or lowers over the course of the night. Thermodynamic data from the radiosonde at midnight local (0700 UTC) reveals that atop a sharp surface inversion (4 K over 150 m), a statically stable layer (7 K over 450 m) exists from 150 m to 600 m. Above 600m, the residual mixed layer survives the entire night (Figure 20).

Analysis of the IOs on this night shows that IOs occur only in the very stable layer below 600m. Additionally, they constitute a large component of the LLJ. The inertially oscillating component of the wind, which commences its oscillation at 0000 UTC, has an initial wind direction of approximately 290^{o}. It will take seven hours for this component of the wind to align with the mean wind (which is easterly). These two components line up at 0700 UTC, the same time that the jet reaches its maximum. On this night, inertial oscillations in the stable layer enhance the development of the maximum in wind speed in the lower levels of the boundary layer by 30 percent through the vertical extent of the jet, although a weaker jet profile would still be evident without the influence of the IO.

4. Summary

CASES-99 is an investigation of the NBL and its transitions, whose primary focus is on data analysis from a field experiment held during October 1999. A broad range of instruments were utilized, including many useful remote sensing instruments, aircraft, surface-based and elevated high frequency sensors in overnight sampling for 11 IOPs. The data from these IOPs are shown, here in preliminary form, to begin to address portions of each of the observed by the lidar (between 0518 and 0545 UTC) is well captured. The wave phase is almost simultaneous in the recordings at 50 and 30 m (about 1 s lag), but the lag is ~ 9s is larger between 30 and 1 m recordings. The maxima of energy density have periods below 2 min at 5:18, 5:23, 5:30 and 5:34 (Figure 18). Such periods are typical of turbulent motion, and Figure 18 reveals a pattern of intermittency during the billow event.

c. IOP-4, 11 Oct 1999, Inertial oscillations

As shown in Table 3 (Lundquist 2000), inertial oscillations were frequently observed during the CASES-99 field experiment, and are an example of the data that can be utilized to meet our fourth scientific objective. Inertial oscillations (IOs) have a period of about 19 hours throughout the CASES-99 domain. During the evening transition of the boundary layer, IOs develop; they later enhance the evolution of the low-level wind maximum (or jet) that becomes a prominent feature atop the growing nocturnal surface inversion (Buajitti and Blackadar 1957, Blackadar, 1957, Thorpe and Guymer 1977, Mahrt 1999). Though other sources have been posited for the development of the low-level jet, including cooling over sloped terrain (Holton, 1967) and synoptic-scale pressure gradients (Uccellini 1980, Djuric and Ludwig 1983), a careful modeling study (Zhong et al 1996) concludes that over the Great Plains of the United States, the effect of the IO dominates any effect from baroclinicity due to sloping terrain. Despite their significance to the LLJ, and though they are thought to be ubiquitous in the stable boundary layer, there has not been a quantitative climatology of the presence of IOs in the stable boundary layer, or an observation-based verification of their generation during the evening transition.

The five 915 MHz boundary-layer profilers located at Beaumont, Whitewater, Oxford, Smileyburg, and El Dorado, located in Figure 3, provide hourly averages of winds from approximately 150 m to 2000 m sufficient for IO analysis. In these analyses wind speed and direction contamination from migrating songbirds has been partially removed, but some evidence still exists of slight contamination. The regular soundings at the main Leon site and the auxiliary Beaumont, El Dorado, and Smileyburg sites provide thermodynamic profiles of the NBL.

Each time series of wind speed and wind direction from one profiler level over one night is presumed to consist of a mean wind, an inertially oscillating component, and noise. For details on the IO extraction, see Lundquist (2000). To determine the significance of an extracted IO, the amplitude of the IO is compared to the noise component of the wind speed:

$$R_{ws} = \frac{|noise|}{A_{IO}} \tag{1}$$

where A_{IO} is the calculated amplitude of the IO and $|noise|$ is the average value of the wind speed remaining after the mean wind and the IO are removed from the time series. Based on a review of hundreds of calculations of R_{ws}, it has been empirically determined that when $R_{ws} \leq 0.5$, the IO should be considered significant. As a second check, the probability density functions (PDFs) of the wind direction of the noise component have been inspected to ensure that they are Gaussian; Gaussian wind direction fluctuations imply that only noise remains in the leftover signal (Vandoorn et al., 2000). If the amplitude fulfills the criterion above, and if the PDF of the “noise" component ure 14 is highly suggestive of significant mixing well above that level (to the height of the billows). Indeed, these fluxes appear to be significant, even when compared to the strong fluxes during convective daytime conditions, though short-lived. Mixing processes for heat, calculated from the 5 minute heat fluxes correspond to ~0.6^{o}C of cooling across a 10 m layer in 1 minute (0527.5 UTC). The mixing is distributed across the height of the billow and for a period of 25 minutes at a lower magnitude. Integrating the fluxes in the period from 0520-0545 UTC gives an average value of ~-0.03 C m s^{-1} and assuming cooling across the ~ 30 m depth of the event we find an average cooling of 1.5^{o}C. This upward redistribution of thermal energy cools upper layers and is validated by the ~1.5^{o}C cooling during the period shown in Figure 12 at all tower levels, but most appropriately at the 54.1 m level. Corresponding changes in horizontal wind speed consistent with the indicated fluxes are also evident in Figure 13. Thus we find that this intermittent turbulence inducing phenomenon has caused significant changes in the vertical structure of the NBL.

Further corroborating evidence of the character and influence of this event on the NBL can be extracted from the CASES-99 microbarograph array (see Figure 4 for locations). In the absence of absolute proof of what this event might be, we can refer to these signatures in the microbarograph measurements as ‘coherent pressure disturbances’ (CPD). A coherent pressure disturbance (CPD) is any feature in the pressure field which maintains its structure as it moves across the pressure sampling array. Examples include gravity waves, pressure jumps, drainage currents, wind gusts, and eddies.

Figure 16 shows the contours of wavelet energy density in μb^{2} s^{-1} (e.g Hauf et al., 1996) for the nighttime period 0100 to 1300 UTC from one of the 6 surface based microbarographs during IOP-2. Intense disturbances occur during the first half of the night, with maximum energy found in eddies with periods near 30 minutes. Using the beam steering technique in the slowness plane to determine disturbance speed and direction we find that the billow event in question between 0500-0600 UTC has a phase speed of about 15 m s^{-1}, a direction of 124^{o}, and a wavelength of about 14 km. The period of the disturbance is ~ 15 minutes which corresponds reasonably well with the observed period of the disturbance at upper levels of 25 minutes. The difference may be attributable to the surface based location of the microbarographs.

Unique microbarograph measurements on the 60 m tower at 1, 30 and 50 m AGL, also help clarify the nature of this intermittent turbulence event. A Wavelet transform (WT) has been applied on the recordings, using a Morlet mother wavelet, and is shown in Figure 18 for the 50 m level. The integrated WT energy for periods between 2 seconds and 3 minutes for 0500-0600 UTC (Figure 17) shows similar structure at the three heights, but with an increase of the associated energy with height. The similarity in WT structure at different heights is evidence of vertical influence of an elevated turbulence event, reinforcing the observation that despite strong static stability, intermittent turbulence events in the NBL can influence atmospheric structure well outside their generation elevation.The recorded signal at 50 m (not shown) and its integrated WT (Figure 17) show evidence of oscillatory behaviour similar to that in the horizontally distributed microbarographs. The interval of maximum activity mocouples the mean temperature gradient between the surface and the top of the 60 m tower was approximately 140 C km^{-1} about one hour prior to the event. During the 15 min period prior to the event the mean wind shear between 30 m and the top of the tower was approximately 0.17 s^{-1}. A series of large intermittent bursts in turbulence began at about 0520 UTC and persisted until about 0545 UTC. The most intense bursts occurred above the 20m tower level.

Between 0525 and 0542 UTC HRDL performed shallow vertical-slice scans in the general direction of the mean flow. The scan plane was oriented at an azimuth of 10 degrees and the lidar scanned from 0^o to 10^o in elevation at a rate of 0.33^o s^{-1}, producing in a full 10^o scan in 30 s. The lidar recorded 33 sequential scans during this period. Figure 14 shows a representative HRDL scan during the event. Coherent propagating wave structures are clearly evident in animations of all scans (see http://www.co-ra.com/cases99/billowevent.mpg). In several scans the lidar observations show distinct evidence of what appear to be overturning wave structures or “billows” with a phase speed of 5.5+/-0.8 m s^{-1}. The wavelength of these features based on both visual inspection and spectral analysis is between 350 and 400 m, with the strongest wave activity between 40 and 70 m AGL. The first relevant scale after a sheared layer of thickness *h* becomes unstable is the wavelength of maximum amplification, *L* (e.g. Miles and Howard (1964), Scorer (1997). The measured *L* for this billow is 400 m, which when used in the theory of Scorer (1997) gives a wave amplitude of 32 m. This value compares favorably to the observed billow height, although other aspect of Scorer’s (1997) theory are less well matched. However, the work of De Silva et al. (1996) suggests that this billow may be in an early growth stage, rather than the final mixed state (Thorpe 1973). Perhaps, the mixing efficiency within a billow may be quite different under actual environmental conditions.

Tower measurements clearly indicate a substantial increase in turbulent activity between 0520 and 0545 UTC on 6 October 1999. To examine the relationship between the wave-scale motions and small-scale mixing we examine the statistics of the vertical velocity field from 20 Hz sonic anemometer data located at 8 levels on the CASES-99 main tower. Spectral analysis of sonic anemometer data at 30, 40, 50, and 55 m levels indicated that the principal wave period, between 0518 and 0545 UTC is approximately 100 s. Height-time displays of vertical velocity variance and kurtosis (not shown) show transient increases in vertical velocity variance during several distinct times, which suggests the passage of individual billow cores (Palmer et al. 1998). These results are consistent with the direct numerical simulation of Kelvin-Helmholtz billows described by Werne and Fritts (1999).

One question that arises when considering short-lived atmospheric disturbances in the generally quiescent NBL, is the influence of those events on atmospheric structure. Some of these influences can be inferred from fluxes calculated from the 60 m tower sonic anemometers. Figure 15 shows 1 minute averaged heat and momentum fluxes from the 55 m level for the period 05-06 UTC 6 Oct 1999. Clearly, all of the fluxes show a marked increase in magnitude during the event period, 0520-0545 UTC, with minimal fluxes both before and after the event. Therefore, the billow event has induced significant mixing at this level, and at other levels on the 60 m tower (not shown). Although, sonic anemometer measurements were not taken above 55 m, the billow depth indicated by Figevents corresponded to moderate turbulence reports from airborne personnel. Efforts are underway to better correlate the variety of measurement platforms sampling these events from this IOP.

4) The horizontal extent of intermittent events - Gully data

Among some of the interests of the CASES-99 investigators is the horizontal extent of intermittent turbulence events in the NBL. Figure 11 shows observations from the gully to the SW of the 60 m tower as drawn in Figure 4. Although the gully is ~ 1 km from the 60 m tower where three primary events were measured and the gully experienced very strong static stability with persistent katabatic flow on this night, each of the three events that occurred during IOP-7 as measured by the tower influenced gully flow. Note the sudden oscillation in wind direction during three periods in Figure 11; ~ 2300 LST (0400 UTC), ~ 0130 UTC (~0530 UTC) and again at 0530 LST (1030 UTC). Surprisingly, such influences on apparently well-established katabatic flow has been reported by Poulos (1996) for much longer, deeper and wider valleys in the Rocky Mountains. This interesting result suggests that intermittent turbulent events in the NBL are not isolated horizontally in their influence. These influences are manifested by changes in momentum characteristics in gully, where katabatic flow is temporarily interrupted on three separate occasions.

b. IOP-2, 6 Oct 1999, 0515 - 0545 UTC, short-lived instability

The NOAA HRDL and in-situ tower sensors captured what appeared to be waves and turbulence associated with a shear instability propagating in a horizontal direction over the CASES-99 field site between 0520 and 0545 UTC (2320-2345 Local Standard Time) on 6 Oct 1999. A radiosonde observation taken at 0300 UTC at a site located 16 km north-northwest of the main site is displayed in Figure 12. The flow is southerly, and the positive shear layer and inversion are confined to approximately a depth of 85 m. The layer Richardson number for this flow is sub-critical at 0.15. The later measurements at low levels at the main site do not indicate any significant departures from these conditions. This event is investigated in considerably greater detail in Blumen et al. (2001) and Newsom and Banta (2001).

A one-hour time series of the temperature, and horizontal and vertical wind speeds is presented in Figure 13. The billow event is characterized by the larger amplitude, high-frequency responses during the approximate period 0520-0545 UTC. Although the atmosphere appears to be in a state that promotes instability a few hours before the 0520 UTC event occurred, the observing systems in place did not record any other event that could be related to the onset of shear instability. This circumstance does not violate the theoretical underpinnings of the derived stability criterion, $Ri < 1/4$ (Howard, 1961). The condition, $Ri < 1/4$, is a necessary, but not sufficient condition for the instability to occur. Events similar to the one observed may, however, have occurred outside the range of the CASES-99 observing systems. A low-level jet was established during the observation period, with peak winds of 9 m s^{-1} at 120 m AGL. The jet structure, as determined by a VAD analysis of the lidar data, was characterized by a strong wind shear between the surface and ~85 m, a jet maximum at ~120 m and a gradual tapering of the profile above that level. Winds at the surface were light (< 2 m s^{-1}). Based on high-rate tower data from sonic anemometers and thercold air intrusion triggered large temperature oscillations with the gravity wave period around 12 min at all the heights. The strong wind surge followed the density head generated the strong shear turbulence with the eddy size much smaller than the early gravity waves. This analysis of the mixing event illustrates that the unprecedented high vertical resolution thermocouples, and sonic anemometers captured the detailed structure of the density current, especially where the density head leads to a `upside-down' nocturnal boundary layer.

2) Kite/Balloon information

An example of one interesting, but as yet unexplained, phenomenon was captured by a TLS (tethered launching system, Balsley et al. 1992, 1994) flight during a period when turbulence activity at low altitudes was being measured by aircraft. Figure 8, which was obtained during a TLS ascent near 1155 UTC 18 October, depicts high-frequency temperature fluctuations between 30 m and 55 m AGL measured by three separate sensor packages separated by 6 m and ascending at about 0.4 m s^{-1}. Although the TLS obtained data to 400 m, only the lower portion of these profiles is presented here. The unusual feature of these results is the fairly intense (~0.3^{o}C) sinuous temperature fluctuations with vertical scale of only a few meters that are apparent on all the sensors. These fluctuations did not occur on earlier ascents. They were also observed on other sensors (low-frequency temperature sensors and Pitot tubes) on the same packages. One point of interest is the coherence of these fluctuations during the 30 s interval between the passage of the first and last package through the region. A second point is the apparent upward motion of the envelope of the fluctuations of about 1 meter. This suggests either a true vertical motion of the structure of a few cm s^{-1}, or a tilted horizontal structure advected past the sensors, with a 1 meter tilt in ~150 m (30 s x 5 m s^{-1} wind speed). The TLS data alone are insufficient to resolve this question.

The relative turbulence intensity levels in the 45-50 m region before and after the Figure 8 profiles are shown in Figure 9. Figure 9a shows high-frequency temperature fluctuation spectra from the cold-wire sensors on package #3. Note that the spectral levels about 1 hour prior to the Figure 8 profile are at least a factor of fifty weaker than those obtained about 1 hour later. A somewhat smaller increase, yet still more than a factor of twenty, is apparent in Figure 9b which shows spectra for the turbulent wind speed fluctuations (from the hot-wire sensor) for the same periods is apparent in Figure 9b. Note that comparable turbulent levels above 55 m during this period did not exhibit such an increase. On the other hand, turbulence fluctuations at higher heights during other periods were at times much more variable, and occasionally quite intense.

3) Aircraft information

Data from the Wyoming King Air are shown in Figure 10 for the period 1212-1217 UTC 18 Oct 1999 where zero on the x-axis represents the meridional location of the 60 m tower. Note in Figure 10e that the altitude AGL flown by the aircraft was quite low and allows for a reasonable comparison with instruments sampling between 40 m and 100 m. Plots of u and v indicate that NE flow existed at all levels sampled by the King Air during this leg, with significant variability at meridional distances 0, +7 and +10 km. These localized events are accompanied by significant vertical wind speeds and rapid variability through a range exceeding |0.5| m s^{-1}. As stated above these

Because it calculates turbulence directly, the DNS technique has the unique ability to quantify all terms in the fundamental budgets, even those that cannot be measured. This is especially important with the intermittent turbulence in stratified flows, where locally strong turbulence and sharp thermal or constituent gradients may lead to strong, spatially and temporally localized, mixing and transport, which may differ greatly from mean turbulence statistics. In combination with the LES and mesoscale models, DNS should contribute significantly to the evaluation of deficiencies in parameterizations subjected to stable atmospheric conditions.

3. Preliminary results

a. IOP-7, 18 Oct 1999, intermittent phenomena

IOP-7 was characterized by two density current passages and another event with some density current characteristics around 1200 UTC. This CASES-99 IOP serves as a prime example of the variety of phenomena that populate and influence the evolution of the primarily dynamically stable NBL, and is being emphasized by a number of investigators. Data obtained during this eventful overnight period is shown below to contribute significantly toward the achievement of the scientific goals described in Section 2. Whereas the first two events had typical characteristics of density currents, the third event near 1200 UTC had unusual characteristics.

1) Tower measurements

The high vertical resolution thermocouples captured many interesting intermittent mixing events, such as density currents and gravity waves. One of the density currents passed through the main tower was on October 18, 1999, 01:40 UTC (October, 17, 1999, at 20:40 CDT, Figure 7). The density current is characterized by cold, moist, and high carbon dioxide air with significant vertical wind shear from the ENE. As the cold air passed by, the wind direction switched from the ENE to NNE, then back to the ambient wind direction. The wind direction change is in response to the local pressure drop associated with the density current. The downward propagation of the large temperature drop indicates that the head of the density current was elevated from the ground surface as Figure 7 illustrates. The cold, moist, and high CO_2 air intrusion at the higher level leads to thermal instability, resulting in large upward heat transfer, and downward moisture and CO_2 transfer between 30 m and 40 m (the ‘upside-down’ boundary layer), and large temperature oscillations at the upper levels. While at the lower level, where the temperature was still stable, there was downward heat transfer, and upward moisture and CO_2 transfer, as expected in a typical stable nocturnal boundary layer.

Associated with the density current, there was a wind surge lagging behind the cold air intrusion. As the wind surge propagated downward, the wind shear increased especially close to the ground surface, where the wind speed remained near zero. As a result, turbulence is generated by strong wind shear (middle two panels, Figure 7). As the stratification at the upper level is reestablished quickly after the relatively cold current passes by, the turbulence is significantly reduced. In contrast, at lower levels shear generated turbulence increases. The stronger stratification after the current passes is related to downward motion behind the head of the density current.

Spectral analysis (not shown) based on the Haar wavelet transform (Howell and Mahrt, 1997) indicates that the ment of entirely new parameterization schemes.

2) Large-eddy simulation

LES are planned by some investigators for more detailed investigation of several aspects of stably stratified, surface/boundary layer turbulence, such as the nature of intermittence, coherent structures, and fluxes in stably stratified planetary boundary layer (PBL) flows and explore how these PBLs differ from their unstable and neutral counterparts. In order to carry out this research, a critical review of subgrid-scale (SGS) modeling practices in LES is being undertaken since one can anticipate that the current SGS models, developed primarily for unstable and neutral flows, are inadequate for the stable regime. Because the optimal simulation scale of the LES lies between that of the mesoscale model and that of the DNS, simulated stable NBLs using LES are an important part of determining the flaws in SGS parameterization (Saiki et al. 2000). With regard to the issue of SGS modeling, the question arises as to how to parameterize the effects of small eddies (smaller than a typical LES grid volume, in LES for stably stratified turbulence). Some LES solutions are very sensitive to the stability corrections. In combination with the mesoscale modeling analysis, reformulation of these parameterizations for the stable NBL should be possible with sensitivity case studies of CASES-99 IOPs in comparison with its supporting measurements. Similarly, comparisons with DNS will show where, perhaps, the unrealistic viscosity in the DNS fails to allow the development of sufficiently chaotic features. Such comparisons will ensure the proper interpretation of the dynamical evolution in all three modeling techniques.

3) Direct Numerical Simulation

A central science goal of CASES-99 is quantifying the role of intermittency in turbulent mixing and transport. The causes of the intermittency are the Kelvin-Helmholtz and gravity wave instabilities that are in turn caused by larger-scale forcing such as drainage flows, elevated jet maxima and radiative fluxes. DNS of the initiation of these instabilities and the evolution of the resultant turbulent layers is uniquely suited to quantifying the intermittency, because DNS is not subject to turbulence parameterization errors, and are adequate if executed at sufficiently high Reynolds number, Re. The large-scale flows observed during the CASES-99 field phase, determine the initial conditions for the DNS and hot-film, sonic anemometer and hot-wire measurements of turbulence statistics can validate the subsequent evolution calculated by DNS. Focussed case study simulations using the DNS technique will examine flow instability within and above the NBL, the occurrence, intensity, and intermittency of turbulence, and its penetration into the observed CASES-99 stable NBL, and the structure of, and the turbulence fluxes accompanying, such penetration events. Since DNS is subject to using Re that are almost always smaller than those measured in the NBL (except at very small scales, Muschinski 1998), one can question its applicability here. However, current computational advances have allowed DNS to use $10^4 < \mathrm{Re} < 10^5$, yielding a buoyancy/inertial sub-range of turbulence spanning a decade or more, and enabling assessment of turbulent fluxes and transport accompanying such events (Werne and Fritts 1999, 2001). These simulations will be used to further evaluate and improve parameterizations in LES and mesoscale models and allow high spectral frequency comparisons to CASES-99 field data.

were then verified by observations during an IOP. This information was otherwise unavailable from any other resource, and was often used to prepare observational strategies during the field phase.

d. Numerical modeling within CASES-99

The CASES-99 data sets will enable investigators to address some of the primary deficiencies of current model parameterizations in the stable boundary layer. While the focus is primarily on turbulent diffusion and surface layer parameterization, a number of physiographic parameterizations could also be validated. These parameterizations are used in models from the global to micro-γ scale, and in both operational and research environments. Thus, the common goal of those researchers using numerical techniques is to combine various approaches to achieve the most comprehensive improvements to the model when the atmosphere is statically and dynamically stable, on average. The various types of numerical modeling activities anticipated as a part of CASES-99 are described below. It is anticipated that careful merging of theoretically based modeling with mesoscale, LES and DNS techniques, and quantitative comparison with the comprehensive field phase measurements will produce scientific advances in the ability to model and parameterize stable NBL phenomena.

1) Mesoscale modeling

Although no results are shown here, post-field phase mesoscale numerical simulations will use a variety of mesoscale models (e.g. RAMS, above), depending on the investigator, to describe the coupled land-atmosphere system, boundary layer fluxes, and NBL structure observed by CASES-99 instrumentation. Such models are capable of capturing large-scale forcing on a larger grid and using grid-nesting to telescope down to the scales of interest, but are hindered by deficiencies in parameterization capability during conditions where turbulence is suppressed by stratification and weak wind or weak wind shear. These models use a variety of parameterizations; radiation parameterization, a soil/vegetation model (temperature and moisture) and can ingest high-resolution physiographic data (terrain heights, vegetation, soil type and land percentage), all of which will affect NBL evolution (Pielke et al. 1992). Mesoscale models will be utilized in four main ways: 1) to reconstruct, at very high horizontal (O[100]m grid spacing and vertical O[10] m grid spacing) resolution, the micro-α scale features of the NBL for case nights of interest from CASES-99, considering also item 3, below, 2) to provide guidance (shear values, initial Richardson number profiles, etc.) to the LESs and DNSs described below (with due respect to the following), and 3) to reveal the deficiencies of the existing stable surface layer and subgrid-scale parameterizations, 4) in idealized studies of various NBL features.

For case study reconstruction and testing of the stable surface layer and subgrid-scale parameterizations, emphasis will be placed on comparison and validation against measurements from the CASES-99 field experiment. This will provide the foundation for analysis of simulation quality and the performance of the parameterizations. Inaccuracies in the simulation of the very stable surface layer will be evaluated to pose new solutions to that problem, as hypothesized by various CASES-99 participants, and will hopefully lead to the improvement or develop-month of October there were 12 designated IOPs (although number 11 was cancelled), far exceeding our expectations, and all of the resources were easily used. On average from the surface to 20 m AGL, according to temperature data taken on the 60 m tower, the temperature increase was 5.5 C (or 275 C km^{-1}), showing that CASES-99 sampled very statically stable conditions during IOPs. This unexpectedly large number of IOPs was due to an exceptionally dry October, particularly from Oct 1-27. Indeed, there are a number of non-IOP nights that should contribute significantly to stable NBL research.

Throughout the field phase of CASES-99 it was recognized, via real-time instrumentation and daily IOP summaries from various investigators, that we were successfully capturing the events that would make our scientific goals achievable. Thus, we have attempted to compile tables of significant turbulence events and events where atmospheric change was significant, based on data obtained from instrumentation on the 60 m tower, the ABLE data array, and the Wyoming King Air. Our event summary is not shown here, but can be found at www.co-ra.com/cases/CASES-99.html. To briefly summarize the contents of those tables, we found the following number of different events from overnight periods during October 1999: four synoptic frontal passages, 10 density current passages (e.g. Blumen et al. 1999), 6 low-level and 3 upper-level (aircraft) episodic turbulence events, 7 miscellaneous events (such as unusually large-amplitude wave activity or short timescale temperature changes), inertial oscillations (Table 3) and 13 low-level jets observed in the height range $100 < z < 300$ m.These tables are likely to be incomplete for a number of reasons, including 1) not evaluating the entire CASES-99 data set, 2) incomplete data sets, 3) location of the instruments chosen for review, and 4) the inadequacy of some instruments in detecting events. The tables have been compiled as a guide for investigators seeking particular, individual events, but the user should expect other events in addition to those listed, and, perhaps, a reinterpretation of a cited event.

c. *Operational forecast guidance*

During the CASES-99 field phase, operational forecast guidance was provided by the UCAR JOSS in cooperation with the Wichita NWS and numerical weather prediction using the RAMS being run on a Linux cluster at Colorado State University. The RAMS forecasts used 3.5 km and 25 m grid spacing in the horizontal and vertical, respectively. These mesh sizes are considered exceptional resolutions for operational forecasting and our operation benefited significantly from their presence. The model set-up for these forecasts is available to those using the CASES-99 data set, who also wish to use RAMS for case study investigations or other purposes, at www.joss.ucar.edu/cases99.

The RAMS forecasts for these clear, generally weak surface wind nights, were made available each afternoon for that night and the following night. Interestingly, RAMS, like most modeling systems today, is subject to the known parameterization errors in dynamically stable near-surface conditions described in Section 1. Thus, we should expect that these forecast should be error-prone and, indeed, quite often the surface features were in error (i.e. surface temperature) and the observed heterogeneity of the NBL could not be captured. However, RAMS was quite frequently able to portray the orientation and development of a near surface jet from 50-250 m AGL which sensor, which the sonic anemometer lacks.

In order to study all the heating sources and sinks which affect the validity of Monin-Obukhov similarity theory, radiative flux divergence was carefully measured by 10 Eppley precision infrared radiometers positioned at 48 m and 2 m AGL. The contribution of the vertical divergence has been measured in previous experiments (Funk, 1960; Nkemdirim, 1978, Gopalakdrishnan, 1998) but the interpretation of the results is controversial and not in agreement with the theoretical study (Rider and Robinson, 1951; Elliott, 1964). This is the first time that both the radiative flux divergence and the sensible heat flux divergence can be calculated using simultaneous observations. With the 8 vertical levels of turbulent flux measurements, the total heat budget can be studied under stable nocturnal boundary layer conditions.

Approximately 200 m to the northeast of the 60 m tower a variety of instruments were placed that also sampled the atmosphere in the vertical (Figure 4). The FM-CW radar continuously measured C_N^2 in this area, providing constant real-time evaluation of turbulent phenomena from 60 m to over 1 km at 2 m vertical resolution. This information was of great use, along with the other instruments capable of real-time display such as the sodar, HRDL and kite, in guiding airborne resources toward regions of significant instability. Also, in this area was the TEP, whose experimental capability to detect 3-dimensional winds in a ~ 25 degree cone above it, may give some of the first information of this kind for intermittent NBL turbulence. Also, in this area was the GPS rawinsonde.

Other instruments also sampled the vertical structure of the NBL on the Main Site (Figure 4). To the southeast of the 60 m tower, a sodar sampled the winds and turbulent quantities at ~ 8 m vertical resolution to 100 m AGL, frequently detecting shear instability and overturning. Also in this area was a tethersonde capable of high vertical resolution vertical profiles of mean atmospheric quantities during relatively quiescent periods ($U < 7\ ms^{-1}$), where U is the total horizontal wind speed. To the west of the 60 m tower, a cluster of instruments, including 2 lidars and a vertically profiling kite (with balloon for calm periods) added further information. The kite was able to frequently take vertical profiles and, with multiple high-rate instruments hanging from its tether, sample elevated turbulent events with a high sampling rate for long periods. The Raman lidar provides high vertical resolution information (~ 4 m) about specific humidity distribution, and, combined with a co-located scanning aerosol backscatter lidar, identify significant layers within the NBL, and possibly instabilities that are generated at those levels.

To the south, at approximately the same altitude as the base of the 60 m tower, the HRDL lidar detected Doppler velocities in variety of flexible scanning strategies (Grund et al. 2000). When scanning repeatedly at one orientation (generally into the mean wind) over a variety of elevation angles, the HRDL was able to capture wave activity and shear layers not seen clearly by any other instrument. When staring vertically this instrument was able to capture the vertical velocity associated with horizontally propagating internal gravity waves. Other scanning strategies allowed the HRDL to capture variances of the horizontal components of velocity.

b. Intensive observational periods (IOPs)

Table 2 lists the date, time, short events summary and aircraft availability for CASES-99 IOPs during the worldwide. In the gully were two 10 m towers instrumented with thermo-sonic anemometers and slow-response sensors, 18 thermocouples in the along and cross-valley axis directions, and a number of 2-d sonic anemometers placed in strategic locations. Despite strong gully stability, its katabatic flow was frequently influenced by flow above it, as is discussed in Section 3a below.

2) Vertical information

One of the most important aspects of quantifying the influence of various NBL phenomena on NBL evolution and the ambient atmosphere is observing the relevant atmospheric fields with height. Analysis of dynamic and static stability was considered a crucial part of the CASES-99 measurements. During CASES-99 a 60 m tower, a kite profiling system and vertically profiling lidars (the NOAA HRDL, the University of Iowa Wind lidar and Scanning Aerosol Lidar, and the LANL vertical profiling lidar), tethersondes, radars and sodars were the primary instruments in use (see Figures 3 and 4). Additionally, during IOPs frequent rawinsondes were released, most often at one hour intervals but varying from half-hourly to bi-hourly during the overnight period. Unfortunately, wind data from the rawinsondes is unavailable below ~ 150 m AGL during many flights.

Regarding vertical structure, the 60 m tower, provided by NCAR ATD and shown in Figures 3 and 5, acted as the centerpoint for the CASES-99 experiment, with an unusually large number of sensors with high sampling rates mounted upon it. At 6 levels, from 2.5 to 60 m 10 or 20 Hz sonic anemometers or thermo-sonic anemometers were mounted in roughly 10 meter intervals (see Figure 3). Between those sensors slow-response sensors provided additional information at 5 m separation. Also, below 10 m AGL, hot-film sensors recorded winds at 200 Hz. At 10 m, 20 m and 40 m, hot-wire anemometers gathered data for dissipation evaluation at 4.8 KHz. Additionally, microbarographs sampling to 1 Pa at 2 Hz were mounted at 1 m, 30 m and 50 m, with the intent of providing a unique observation of vertical propagation of coherent pressure disturbances.

34 thermocouples (E-type, Chromel/Constantan, 0.0254 mm diameter) capable of 5 Hz absolute temperature measurements were distributed in 1.8 m increments from the 2.3 m to 58.1 m AGL, providing unprecedented vertical resolution of temperature changes induced by the various NBL phenomena sampled. The advantage of thermocouple temperature is its accuracy of the temperature difference between different vertical levels. The high accuracy of the thermocouple temperature is achieved by logging thermocouples from different vertical levels to a same data logger where a common reference temperature is referred. The thermocouples deployed in CASES-99 are the same as the one discussed in Cheney and Businger (1990), with an estimated accuracy for ΔT of 0.01^{o}C. The absolute accuracy of the reference thermistor is 0.25^{o}C for the range of 0 to 40^{o}C.

Comparisons during nighttime between aspirated and thermocouple temperatures indicate that the absolute temperature difference between the two types of temperature measurements is about 0.1^{o}C. Comparing the three types of temperature measurements on the main tower, Figure 6 indicates that the thermocouple temperature captures all similar high-frequency temperature fluctuations as the sonic anemometer does, which are missed by aspirated temperature sensor. In addition, it has the absolute accuracy of the slow-response aspirated temperature

Kansas-Oklahoma region, and surrounded the CASES-99 Main Site on at scale of ~ 150km. ARM-CART participated only during IOPs with enhanced rawinsondes and wind profiler observations for CASES-99 use. Also at the meso-β scale, the pre-existing and slightly enhanced Argonne Boundary Layer Experiment (ABLE) instrumentation was utilized at the vertices of a triangle of approximately a 60 km on a side (see Figure 2). The ABLE wind profilers were temporarily modified to provide half-hourly interval winds and RASS data were also available. ABLE also provided convenient, continuous, on-line data access, additional surface stations within the Walnut River watershed and the infrastructure for the CASES-99 Operations Trailer at the Argonne Project Office, not far from the CASES-99 Main Site. The next roughly concentric triangle that defined instrument locations was on the scale of ~ 15 km, and was supplied by NCAR's Atmospheric Technology Division via Integrated Sounding Sites (Figure 3). Each ISS consisted of a surface station with a GPS rawinsonde and continuous monitoring by a wind profiler. These larger-scale triangles, relative to the scale of the CASES-99 Main Site, provide context and horizontal heterogeneity information during stable NBL conditions.

At the meso-γ and microscale (2 - 2000 m), four additional concentric triangles define the CASES-99 Main Site (Figure 4), all of which center upon the 60 m tower. These triangles sequentially decrease in scale (as defined by the radii to the triangle vertices) as follows: 1800 m, 900 m, 300 m, 100 m. The vertices of each triangle are instrumented with 10 or 20 Hz recording thermo-sonic anemometers and other instrumentation depending on the supplier. Thus, heretofore unprecedented information is available regarding the horizontal distribution of stable NBL phenomena and the associated fluxes. At the vertices of the innermost triangles (100 m and 300 m) microbarographs sampling at 1 Hz were installed to capture gravity wave phase speed, amplitude and orientation as well as the pressure fluctuations associated with various NBL phenomena (e.g. Denholm-Price and Rees, 1999).

Important information on the horizontal scale of NBL phenomena is also obtained from a variety of other instruments in the CASES-99 Main Site, including the scanning NOAA High-resolution Doppler lidar, the LANL Raman lidar, multiple scintillometers with measurements horizontally-averaged turbulence parameters (e.g. Kunkel and Walters, 1982, C_T^2, but with differing path lengths) and to some extent the Turbulent Eddy Profiler. Additionally, two aircraft, the NOAA Long-EZ and the Wyoming King Air, were available for IOP flights, occasionally flying twice per night. The aircraft were able to sample the wind components, H_20, CO_2 and temperature (among others) at 25 Hz and provide valuable information linking the fixed-location instrument observations to the phenomena observed. During the late afternoon transition and morning transition, when some light remained, the Wyoming King Air was able to fly as low as 50 m AGL along certain flight paths, allowing for comparison with some instruments on the 60 m tower.

Data on small horizontal scales (O[10]m) was also provided by dedicated instrumentation arranged in a shallow gully to the south-southwest of the 60 m tower. This gully (see Figure 4) is ~ 10 m deep but experienced regular katabatic flow as measured by a variety of instrumentation. The gully measurements are able to show how overlying turbulence in strongly radiative conditions can influence near surface flows over land surfaces common improve these parameterizations a more accurate physical basis must be found for the clear-sky NBL case, which, often leads to dynamically stable conditions (Ri > 0.25).

2. Field Experiment Description

The CASES-99 field experiment was held during the month of October, 1999 in southeast Kansas (Figure 1). This period was chosen, based on data archived by the Wichita National Weather Service, for its climatologically high frequency of clear, calm nights and therefore increased likelihood of stable boundary layer development. Further, a review of measurements from ABLE for October 1997 showed that approximately 40% of the nights had mostly clear skies and light near-surface winds. The remainder of the nights had partial or complete cloud cover, altering the radiative balance significantly, and would be appropriate for study of the NBL under cloudy conditions. Given this information the research group believed that 4-6 IOPs would be logistically possible during October, 1999. In fact, eleven IOPs were completed.

To measure the atmosphere sufficiently to achieve the science goals, in-situ boundary/surface layer instrumentation provided jointly by the CASES-99 investigators, NCAR ATD, ARM and ABLE (see Tables 1 and Figures 3 and 4) were deployed with specific vertical and horizontal sampling strategies. In the horizontal, many of the instruments were focused on defining the meso-γ scale (2-20 km) and smaller NBL evolution of temperature, moisture, wind, and constituent profiles and the wave and turbulence fluxes of heat, and momentum. Existing data sources in and around the Walnut River Watershed field site, such as from the ongoing Argonne Boundary Layer Experiment (ABLE, see Figure 2), the National Weather Service in Wichita and the Atmospheric Radiation Measurements CART site (Figure 1), provided enhanced observation of mesoscale features to the meso-β scale (20-200 km). The assimilation of both standard and state-of-the-art instrumentation provided the opportunity to construct the most comprehensive observational depiction of the structure, evolution, and instability of the NBL in this region to date.

a. Experimental design

CASES-99 field observations were organized by the horizontal and vertical scales of interest. In the horizontal plane, relatively scarce information is available to describe the extent of intermittent flux sources and stable NBL heterogeneity. Whereas in the convective boundary layer it is well known that regularly overturning eddies are largely responsible for the fluxes and that these eddies have a certain size determined partly by CBL depth, such statements cannot be made with certainty in the stable NBL. In fact, little is known about the horizontal variability of NBL characteristics, which is a significant factor when attempting to understand the significance of intermittent NBL turbulence events, regardless of source.

1) Horizontal information

In the horizontal plane, the vertices of a concentric set of triangles determined the instrument locations (Figures 3 and 4). The outermost triangle (not shown) was a part of the existing ARM-CART instrument array in the effectively applied in modern numerical weather prediction models (Chen et al. 1997).

Formulating surface fluxes in stably-stratified conditions is made difficult by a number of factors. First, the NBL, as verified in the CASES-99 data analysis shown in Section 4, is often characterized by intermittent turbulent bursts that may last from 10s of seconds to minutes. These sporadic or episodic events which populate the night-time stable boundary layer (Nappo, 1991, Blumen et al. 2001) do not lead to statistically steady state turbulence, which underlies one of the major assumptions of existing theory. Data taken, for example, in the Walker Branch Watershed near Oak Ridge Tennessee during 1987-88 (Nappo, 1991) and in the CASES Walnut River Watershed field site during March 1995 (Mahrt, 1999; Mahrt et al., 1997) indicate that a significant fraction of the nighttime vertical fluxes of heat, moisture and momentum occur during such intermittent bursts (Howell and Sun, 1997). Other measurements have shown that intermittent bursts of turbulence and mixing can also occur multiple times on a given night (Weber and Kurzeja 1991). Such behaviour is verified by the detailed measurements taken during CASES-99, on the majority of IOPs. One-dimensional modeling of this intermittent behavior in the nighttime boundary layer has been reported by Revelle (1993), but the underlying turbulent transfer mechanisms are not yet clearly understood. Quantitative formulations of NBL and surface layer fluxes requires a detailed understanding of the processes responsible for the turbulent burst activity, which we believe will be partly achieved by the scientific community with CASES-99 observations. Furthermore, recent advances in direct numerical simulation techniques have begun to show promise in the study of this problem with solutions for Re > 10,000 (Werne and Fritts 1999).

The nonstationarity associated with shear flow instabilities, overturning Kelvin-Helmholtz billows, terrain-generated phenomena, surface heterogeneity and heat and radiative flux divergences contributes to the uncertainties and conceptual difficulties encountered in the various attempts to construct a physical basis for events and concomitant vertical transports that occur under statically stable regimes. Most studies to date have not been able to establish the source(s) of intermittent turbulence that is often observed at ground level. This lack of knowledge inhibits the development of reliable parameterizations of the very dynamically and statically stable nighttime boundary layer. Several efforts, for example, have attempted to identify the source(s) of errors in surface layer parameterizations for stable flows (Poulos, 1996, Mahrt, 1998). It is argued by Poulos (1996) that an oscillation created in the stable surface layer parameterization can induce occasionally unrealistic cooling under low wind conditions. The resulting gradient is enhanced by the turbulence parameterization and, in some cases, “runaway” cooling can occur. This undesirable effect is also discussed by Mahrt (1998) to be the result of radiatively driven heat loss that is not sufficiently compensated for by the heat flux calculated in the stable surface layer parameterization. This aspect is further complicated by the important influence of soil moisture on NBL evolution, a variable which is generally poorly initialized in numerical models (Banta and Gannon, 1995). In many cases, the parameterized surface layer fluxes are inadequately addressed by the turbulent diffusion parameterization that is responsible for diffusing strong radiative cooling to greater heights. Derbyshire (1999) has recently examined this problem by a combined numerical and theoretical study. He refers to this modelling deficiency as a "physical boundary instability". To sources of chemical constituents (see Figure 2). From the perspective of the atmospheric scientist, the fact that the WRW is nested within the ARM-CART site and the ABLE from which climatological norms can be established, is a significant benefit. ABLE instrumentation is partially shown in Figure 2. The first CASES field program was CASES-97, which had a variety of goals within the disciplines of meteorology, ecology, chemistry and hydrology (LeMone et al. 2000). The CASES-99 field experiment was considerably smaller in geographic extent and focussed on exchanges in the soil/biosphere/atmosphere interface, specifically those during stable atmospheric conditions.

a. Participants

The program was fortunate to have participants from a broad spectrum of institutions and geographic locations (see Table 1). By cooperatively organizing the experiment from the early stages, each participant was able to leverage their instrumentation into a considerably more complete, unique, field experiment than they could field themselves. For CASES-99, this structure thus far has resulted in strongly collaborative research efforts, a comprehensive consideration of viewpoints when setting mutually beneficial scientific goals and experimental design and a broad approach to the solution to the various questions under investigation.

b. Background

CASES-99 is motivated by the generally large number of outstanding questions regarding atmospheric behaviour in the NBL, and particularly the stable NBL (Nappo and Johansson, 1998). There have been several practical reasons why this is so, 1) the logistics of field work during nighttime hours are somewhat more difficult than during the daytime, 2) the magnitude of turbulence during the nighttime is generally less than that during the daytime, in mid-latitudes, particularly under clear skies, such that this period is considered relatively quiescent, 3) the generally stable conditions during the clear-sky NBL make the characterization of fluxes difficult, and 4) the period of observations does not coincide with the typical human wake-cycle.

Regardless of these factors, utilizing some traditional, non-traditional and experimental instrumentation, during CASES-99 we found that the NBL can be sampled sufficiently to achieve our scientific goals, as outlined in our preliminary analysis described in Sections 3a-c. A large part of the motivation for CASES-99 was the need to resolve problems encountered by numerical models attempting to capture atmospheric phenomena on scales from a few meters to a few hundreds of kilometers during stably-stratified nocturnal conditions (McNider et al. 1995). Our modeling approach, both during and after the field experiment is described in Section 2d. Most numerical models on these scales depend, in the surface layer, inasmuch as the surface layer is defined for the NBL, on similarity theory-based parameterizations (e.g. Louis (1979) and variations), although a variety of approaches have been attempted (Hartel and Kleiser, 1998) As discussed by Mahrt (1998, 1999), however, stably stratified atmospheric surface fluxes, are not adequately described by existing Monin-Obukhov similarity theory, which is more appropriately applied to the weakly stable, neutral, and convective boundary layers (Derbyshire 1995). Still, this theory is

1. Introduction

CASES-99 considers four scientific questions primarily related to the stable, nocturnal, boundary layer, including the transition periods.The CASES-99 field program attempted to identify the sources and to quantify the physical characteristics of atmospheric phenomena occurring from the formative stages of the NBL until its eventual breakup during the morning transition. The follow-up program of data analyses, theoretical study, and numerical simulations is focussing on investigations of the CASES-99 scientific goals which are:

1) to provide a time history of internal gravity waves, Kelvin-Helmholtz shear instabilities, and turbulence events in the nighttime stable boundary layer, and to evaluate the relative contributions to intermittent heat, moisture and momentum fluxes that can be associated with the sources of these phenomena. Sources of turbulence outbursts include, but are not restricted to, surface and elevated shear layers and Kelvin-Helmholtz instability, internal gravity waves within the stable boundary layer, drainage current fronts, and surface vortex shedding,

2) to measure heat and momentum fluxes and their divergences accompanying the events contributing to turbulence, transports, and mixing throughout the nocturnal boundary layer, and especially within the surface layer (~ 10 to 20 m), to assess the departures from similarity theory under weakly stable and very stable conditions,

3) to define the relative importance of surface heterogeneity, particularly under very stable light wind conditions, on the initiation of shallow drainage currents (few 10s m in depth), and the horizontal and vertical transports that accompany such boundary undulations,

4) to acquire data during the transition from a convective to stable boundary layer regime and vice-versa to compare with existing models of this transition, and to assess the role of this transition period in the initiation of inertial oscillations and the enhancement of low-level jets approximately 100-300m above the surface.

In October 1999, largely due to the grass-roots, cooperative efforts of many scientists, a massive deployment of a variety of instruments took a series of observations of the generally stable nocturnal atmosphere over southeastern Kansas. As a result of that effort, the four scientific goals of the project appear to be not only achievable, but knowledge of those areas can be advanced significantly. In addition, this large data set represents a significant opportunity for progress toward scientific goals of other researchers interested in the PBL who did not actively participate in the CASES-99 field program. Although the widest variety of instrument platforms were utilized during the overnight IOPs, in fact, the majority of instruments operated throughout the diurnal cycle, including a number of instruments with high frequency (> 1 Hz) observations.

CASES-99 occurred within the umbrella of the more general goals of the CASES concept; which were to provide a long-term facility for scientists to study the mesoscale processes of meteorology, hydrology, climate, chemistry, ecology and their complex linkages, and to serve as a focal point to provide field experience for students of the natural sciences. The Walnut River watershed in southeastern Kansas (see Figures 1 and 2) was chosen by scientists from these many disciplines as an ideal location for the study of these exchanges. The WRW is a hydrologically confined region of relatively flat terrain, varied ecosystem characteristics and limited quantifiable external

List of Acronyms

ABLE	Argonne Boundary Layer Experiment
AGL	Above ground level
ANL	Argonne National Laboratory
APO	Argonne Project Office
ARM-CART	Atmospheric Radiation Measurement-Clouds and Radiation Testbed
ARO	Army Research Office
ATD	Atmospheric Technology Division (of NCAR)
ATDD	Atmospheric Turbulence and Diffusion Division
CASES	Cooperative Atmosphere-Surface Exchange Study
CBL	Convective boundary layer
CoRA	Colorado Research Associates
COT	CASES-99 operations trailer
CPD	Coherent pressure disturbance
CSU	Colorado State University
DNS	Direct numerical simulation
DOE	Department of Energy
ETL	Environmental Technology Laboratory (of NOAA)
FM-CW	Frequency modulation-continuous wave
GLASS	GPS/Loran atmospheric sounding system
GPS	Global positioning system
HRDL	High-Resolution Doppler Lidar
INEL	Idaho National Energy Laboratory
INM	Instituto Nacional de Meteorologia
IO	Inertial oscillation
IOP	Intensive observation period
ISS	Integrated Sounding System
ISFF	Integrated Surface Flux Facility
JOSS	Joint Office for Science Support (of UCAR)
KH	Kelvin-Helmholtz
LANL	Los Alamos National Laboratory
LES	Large-eddy simulation
LIDAR	Light detection and ranging
LLJ	Low level jet
NBL	Nocturnal boundary layer
NCAR	National Center for Atmospheric Research
NOAA	National Oceanographic and Atmospheric Administration
NSF	National Science Foundation
NWS	National Weather Service (of NOAA)
OSU	Oregon State University
PBL	Planetary boundary layer
RADAR	Radio detection and ranging
RAMS	Regional Atmospheric Modeling System
RASS	Radio acoustic sounding system
SGS	Sub-grid scale
SBL	Stable boundary layer
SODAR	Sound detection and ranging
TEP	Turbulent eddy profiler
TLS	Tethered Lifting System
UCAR	University Corporation for Atmospheric Research
VAD	Velocity-azimuth display
WRW	Walnut River watershed
WT	Wavelet transform

Abstract

The Cooperative Atmosphere-Surface Exchange Study - 1999 (CASES-99) refers to a field experiment carried out in southeast Kansas during October 1999 and subsequent program of investigation. Comprehensive data, primarily taken during the nighttime but typically including the evening and morning transition, supports data analyses, theoretical studies and state-of-the-art numerical modeling in a concerted effort by participants to investigate four areas of scientific interest. The choice of these scientific topics is motivated by both the need to delineate physical processes that characterize the stable boundary layer, which are as yet not clearly understood, and the specific scientific goals of the investigators. Each of the scientific goals should be largely achievable with the measurements taken, as we begin to show with preliminary analysis within the scope of three of the scientific goals. Underlying this effort is the fundamental motivation to eliminate deficiencies in surface layer and turbulent diffusion parameterizations in atmospheric models, particularly where the Richardson number exceeds 1/4. This extensive NBL data set is available to the scientific community at large, and the CASES-99 participants encourage all interested parties to utilize it.

These preliminary analyses show that during nights where weak (< 2 m s^{-1}) surface winds and strong static stability near the surface (exceeding 150 C km^{-1} to 20 m AGL) might otherwise indicate essentially non-turbulent conditions, that various, sometimes undefined, atmospheric phenomena can generate significant turbulent mixing, and therefore significant turbulent fluxes. In many cases, a jet structure will form in the NBL between 50 and 200 m AGL, resulting in strong shear between the surface and jet maximum. Consequently, though surface winds are weak, turbulence can be significant feature in the stable NBL. Further, contrary to some previous work studying nocturnal jets over the Great Plains, the wind direction in the jet is often influenced by an inertial oscillation and seldom confined to the southerly quadrant (e.g. the Great Plains Low-level Jet).

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CASES-99: A Comprehensive Investigation of the Stable Nocturnal Boundary Layer

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