THE LAKE THUNDERBIRD MICRONET PROJECT

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An observing network formed by University of Oklahoma faculty and researchers supports hands-on education projects and environmental research on microscale variability of weather and climate.

A 1987 survey on university instruction in meteorological instrumentation and observations concluded that "a serious imbalance appears to have developed between observational and theoretical/numerical components of the atmospheric sciences" (Serafin et al. 1991). On the basis of a follow-up survey, Takle (2000) offered several recommendations to mitigate this imbalance, including the expansion of field opportunities for students to gain experience with sensor problems and sampling limitations. National educational reform studies (e.g., NSF 1996; Somerville 1997; Olson and Loucks-Horsley 2000) have suggested that hands-on field and laboratory experiences and active learning strategies can give students a sense of ownership of their data, spark interest and curiosity, and foster critical thinking. The benefits of fieldwork in the instruction of geology, hydrology, and meteorological instrumentation are discussed in Manner (1995), Trop et al. (2000), and Cohn et al. (2006), respectively. A common theme in these and other studies in science education is that "real world" experiences are a powerful motivator, can help students make connections between concrete observations and abstract theory, and can improve retention of concepts.

As part of a grassroots effort to provide undergraduate and graduate students with hands-on experience with meteorological instruments, data collection, analysis, and interpretation, a team of faculty and researchers at the University of Oklahoma (OU) established the Lake Thunderbird Micronet in central Oklahoma. Located on a ~10-acre plot of land on the southern exposure of one of the gently rolling hills on the north shore of Lake Thunderbird, the Micronet consists of a dense network of environmental sensors and an instrumented meteorological tower. Activities at the Micronet complement traditional classroom instruction by providing opportunities for students of meteorology and related environmental sciences to gather environmental data, to think critically about data quality and representativeness, and to test and verify the physical algorithms and parameterizations

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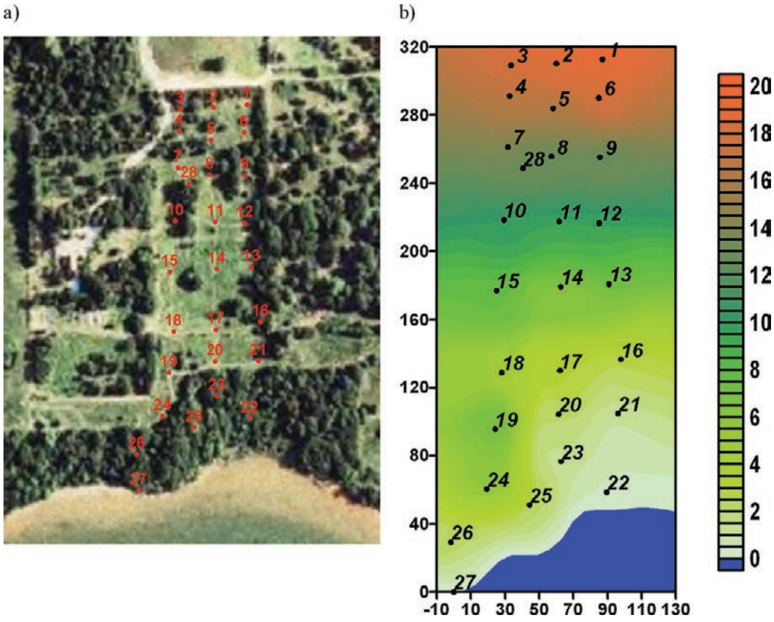

Fig. 1. (a) Aerial photograph and (b) elevation map of the Lake Thunderbird Micronet. Sensor locations are indicated by dots with corresponding station IDs plotted nearby. All distances are given in meters, and terrain elevation is indicated by the color bar.

that underpin environmental models. The Micronet also provides a wealth of data for case studies and climatological analyses and thus can be used as a basis for independent study, capstone, and honors projects as well as for graduate research. This report describes the history and design of the Micronet, presents examples of interesting weather sampled at the Micronet, discusses integration of Micronet activities in the undergraduate and graduate curricula at the OU School of Meteorology (SoM), and summarizes the Micronet's main expenses and funding sources. The sensor specifications and a description of the wireless transmission of tower data are given in the appendix.

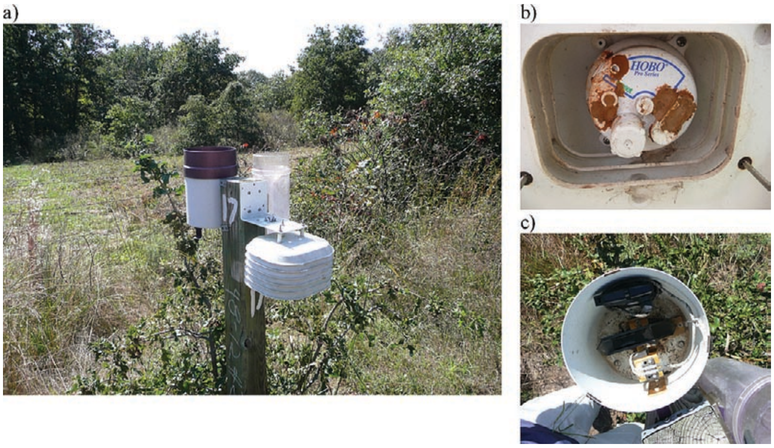

Fig. 2. Micronet site 17. (a) The radiation shield that houses the HOBO H8 Pro temperature/humidity sensor and logger, the data-logging rain gauge (white cylinder with black top), and an additional double cylinder accumulation rain gauge (Plexiglas cylinder) is mounted on a wooden post. (b) Dried mud associated with insect nests can accumulate on the temperature/humidity sensor. (c) The rain gauge is susceptible to small insect activity (especially spiders) and contamination by "dust rain."

GEOGRAPHY AND HISTORY OF THE MICRONET. The Micronet's dense network of environmental sensors is deployed on ~10 acres of rural land in central Oklahoma, about 15 km east-northeast of the National Weather Center (NWC) in Norman, Oklahoma, bordering the north shore of Lake Thunderbird (Fig. 1). The terrain at the Micronet slopes down along a nearly southward-directed topographic fall line with a slope angle of ~5° from a hilltop just a few tens of meters north of the northern edge of the Micronet to a relatively flat, open field and adjacent forest on the southern part of the Micronet. The elevation drop from the northern edge of the Micronet to the lake on the southern edge is about 22 m. Vegetation at the Micronet is an inhomogeneous mix of forest (oak, cedar, and pine trees typically 10–15 m tall) and open field (Fig. 1). Most of the Micronet is on private land, whose owner allows us to deploy the Micronet sensors on his property, but the southern section bordering the lake is on federal land. The Lake Thunderbird State Park, which oversees this federal land, grants us a use permit that we renew annually.

The Micronet was established in February 2002 by a team of faculty and researchers at the SoM and the OU Department of Geography (DoG). Seed funding of ~$11,000 provided by the OU Research/Creative Activity Program and ~$3,000 from the SoM covered the cost of 28 HOBO H8 Pro temperature/humidity loggers and solar radiation shields [to be mounted 1 m above ground level (AGL) on wooden posts], three data-logging tipping-bucket rain gauges, two global

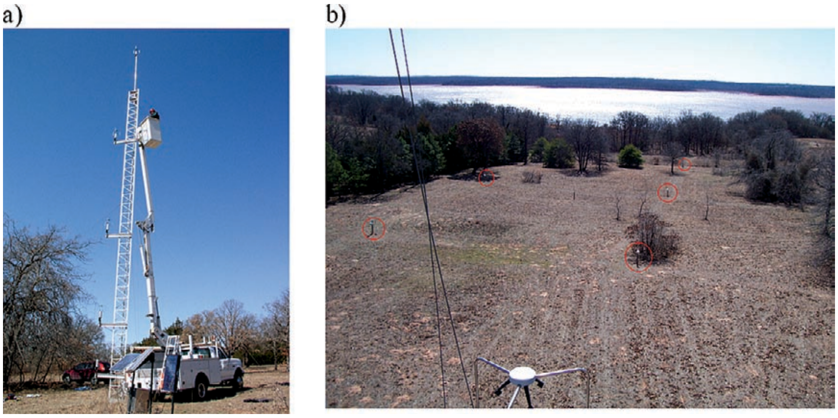

Fig. 3. (a) Micronet tower during the upgrade in March 2007; (b) and view to the south from the top of the tower. Nearby Micronet sites are circled in red.

positioning system (GPS) receivers, three HOBO data shuttles to manually download data and relaunch the loggers, a laptop computer for data archiving and analysis, and miscellaneous hardware. Undergraduate and graduate students at OU participated in the setup of the Micronet and assisted with the manual downloading of data from the temperature/humidity sensors, which typically takes ~3 h every 6–10 weeks (with data currently recorded every 5 min, the dataloggers would fill up shortly after a 10-week period). The average spacing between the Micronet's temperature/humidity sensors is ~30 m. In contrast, the average station spacing is ~30 km for the Oklahoma Climatological Survey's (OCS's) Mesonet stations (Brock et al. 1995) and ~100 km for the first-order National Weather Service (NWS) stations. A close-up view of a Micronet site and its sensors is shown in Fig. 2.

In the spring of 2004, as part of a capstone project conducted by two senior SoM students, a 15-m-tall meteorological tower obtained through the National Science Foundation (NSF) Federal Excess Personal Property (FEPP) program was installed at the Micronet (Figs. 3 and 4). The tower replaced station 8 (Fig. 1) in a field in the north-central part of the Micronet. The tower was instrumented with RM Young 81000 sonic anemometers at 1.5, 3, and 6 m AGL, a polling interface to synchronize the wind measurements, and a Campbell Scientific CR5000 datalogger, which was powered from the landowner's electricity line. In the summer of 2004, additional RM Young 81000 sonic anemometers were installed at 10 and 15 m AGL.

During the spring of 2005, a 100-Ah battery and three solar panels with a peak output of 120 W were added to ensure that tower data could be collected without an external power supply. Wind data were initially downloaded manually and only collected during intensive observation periods (IOPs).

In the spring of 2007, three Vaisala HMP35C temperature/humidity probes were installed on the tower at 1.5, 3, and 10 m AGL, two different shortwave radiometers (permanent) and a net radiometer (temporary, for IOPs) were installed at the base of the tower (Fig. 4), and the power supply was augmented with an additional 30-W solar panel. The data acquisition and transmission systems were also upgraded to include two dataloggers (CR5000 and CR3000) and a wireless link to allow direct data transmission to the SoM office space in the NWC. Tower data

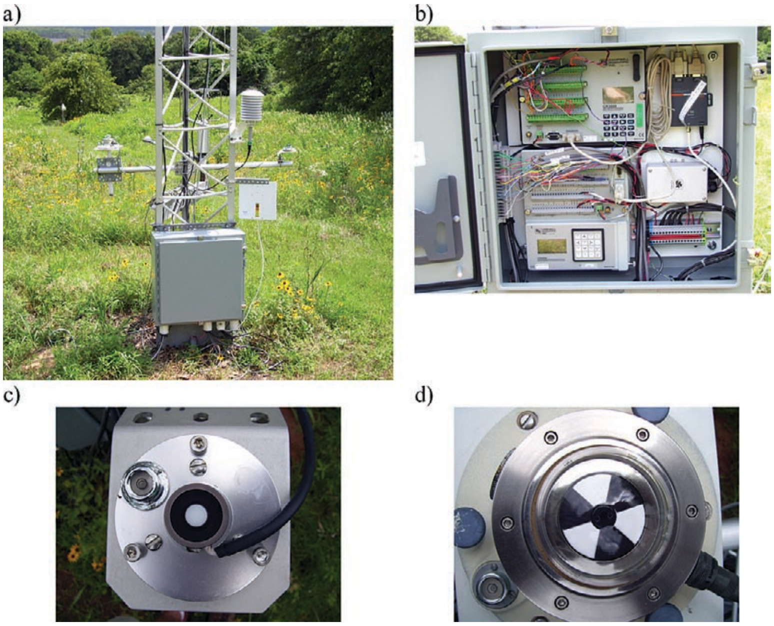

Fig. 4. (a) Instruments and logger enclosure at base of tower. (b) Data acquisition and transfer equipment inside enclosure: WiBox is in top right corner, polling interface is beneath WiBox, CR3000 datalogger is above CR5000 datalogger on left. (c); (d) Close-up views of the (c) LI-COR 200SZ pyranometer and (d) Eppley black and white pyranometer.

are now collected more or less continuously, with occasional gaps due to failures of the dataloggers or battery power insufficiency during periods of prolonged cloudiness. Tower data are available at the NWC in near–real time (see Fig. 5 and description of data acquisition and transmission procedures in the appendix). Global data access is available online at our recently developed Micronet Web site (http://micronet.ou.edu/ltm/).

Since its inception in 2002, Micronet activities have been documented in a diary kept by the first author. The diary provides a detailed look of the evolution and workings of the Micronet. It describes the installation and maintenance of the sensors and associated infrastructure, the status and conditions of the sensors and radiation shields, and the seasonal conditions of field hazards such as poison ivy, nettles, brambles, goatheads, ticks, wasps, and other biting or stinging insects.

WEATHER AT THE MICRONET. A variety of interesting weather phenomena has been observed at the Micronet including passage of warm and cold fronts, heavy rain events, gravity waves, turbulent mixing events, katabatic flows, and the formation of small-scale cold pools. In this section we present Micronet data for a few of these phenomena. The quality assurance and processing of these data is discussed in Bodine et al. (2009).

Figure 6 depicts the passage of a strong cold front at the Micronet and at the Norman Mesonet site (NRMN; ~17 km west of the Micronet) on 13 June 2005. During the initial 12°C temperature drop attending frontal passage and for approximately 6 h after frontal passage during a period of strong winds, the temperature time series at each of the 28 stations are in very close agreement, suggesting that the atmosphere has become well mixed down to the ground surface. (The Micronet tower anemometers were not operational at this time, but the wind speeds at NRMN were on the order of 10 m s^{-1} at the time of cold front passage. In this strongly synoptically forced example, the NRMN winds can be used as a proxy for the winds at the Micronet.)

In contrast to the close agreement of the Micronet sensors during the strong cold front passage on 13 June 2005, there is a dramatic separation of the temperature traces at the Micronet in the early evening of 3 April 2006 (Fig. 7) during a period of radiational cooling [Automated Surface Observation System (ASOS) and Automated Weather Observing System (AWOS) stations indicated skies were clear over central Oklahoma] and nearly calm conditions. During a ~3-h period beginning around the time of local sunset (shortly before 100 UTC; 8:00 P.M. CDT) and extending to 400 UTC (11:00 P.M. CDT), a ~4°C temperature difference develops from the coldest station (station 22, in the forest bordering the lake) to the warmest stations (stations 2 and 3, on the northern edge of the Micronet). However, at approximately 400 UTC, an abrupt increase in wind speeds to ~6 m s^{-1} at NRMN heralds the onset of a sudden warming of all the Micronet stations. The warming is followed by a steady temperature decrease throughout the remainder of the night. Interestingly, the winds attending the sudden temperature increase are actually associated with a synoptic-scale cold front. A surface analysis (not shown) depicts a cold front with a weak temperature gradient (large frontal width) but strong surface wind convergence. A sudden warming was also apparent from 400 to 500 UTC in the reports of over 10 Surface Weather Observation Stations extending along the leading edge of a convergence line from southwest Oklahoma to southeast Missouri. Similar episodes of abrupt temperature increase associated with

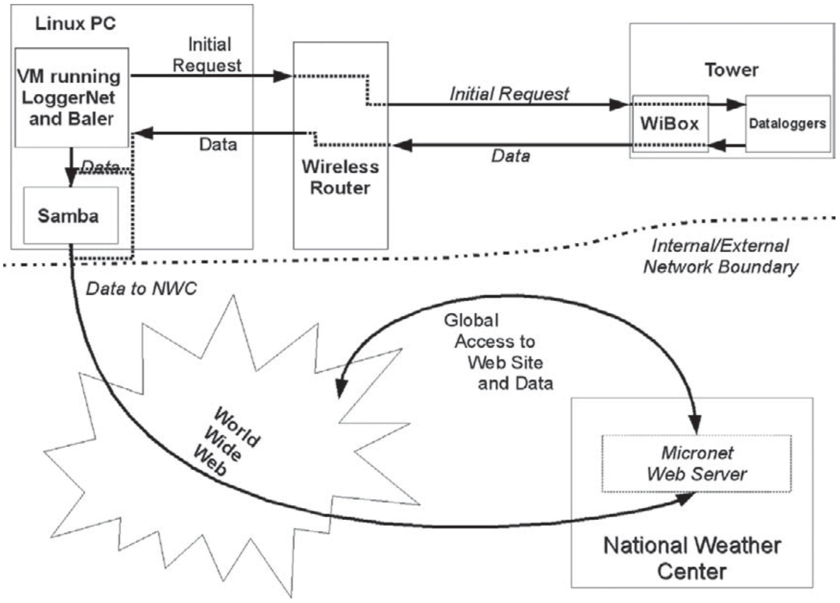

FIG. 5. Communication infrastructure for wireless transmission of tower data.

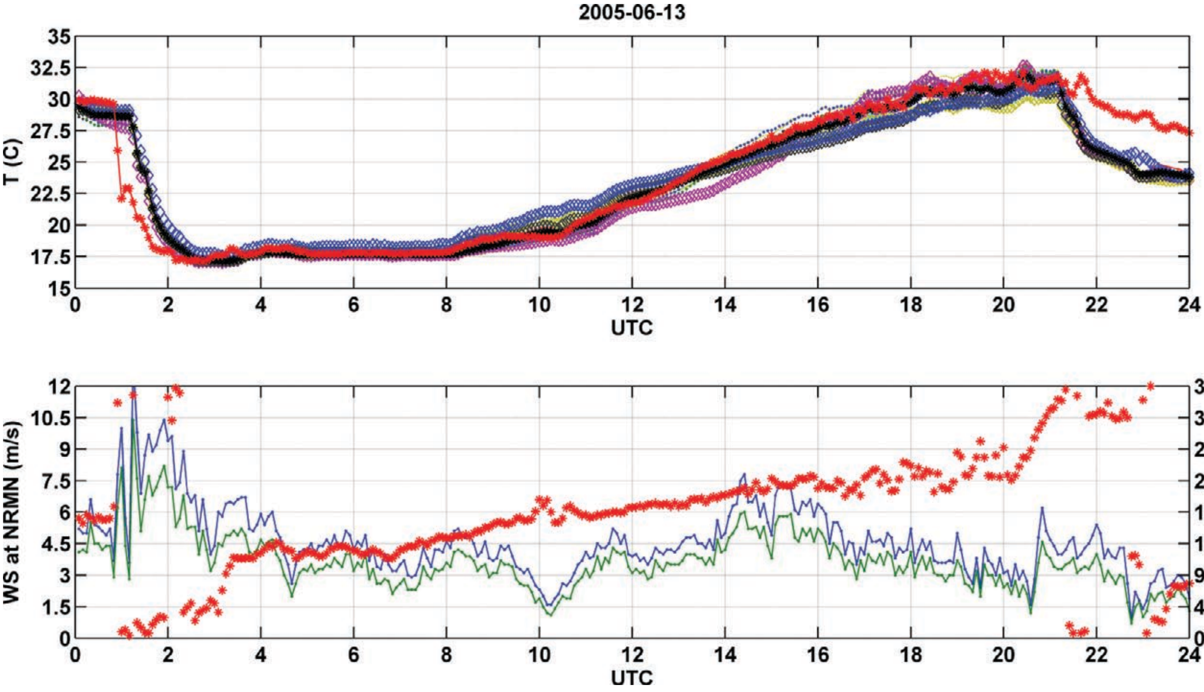

Fig. 6. Frontal passage at the Micronet sites and at the NRMN Mesonet site on 13 Jun 2005. (top) Temperature time series at NRMN (red line) and at all 28 Micronet sites (various plotting symbols). Black line represents spatial average over all Micronet sites. (bottom) Time series of wind speed (WS) at NRMN at 2 (green) and 10 m (blue) and wind direction (WD) at NRMN at 10 m (red).

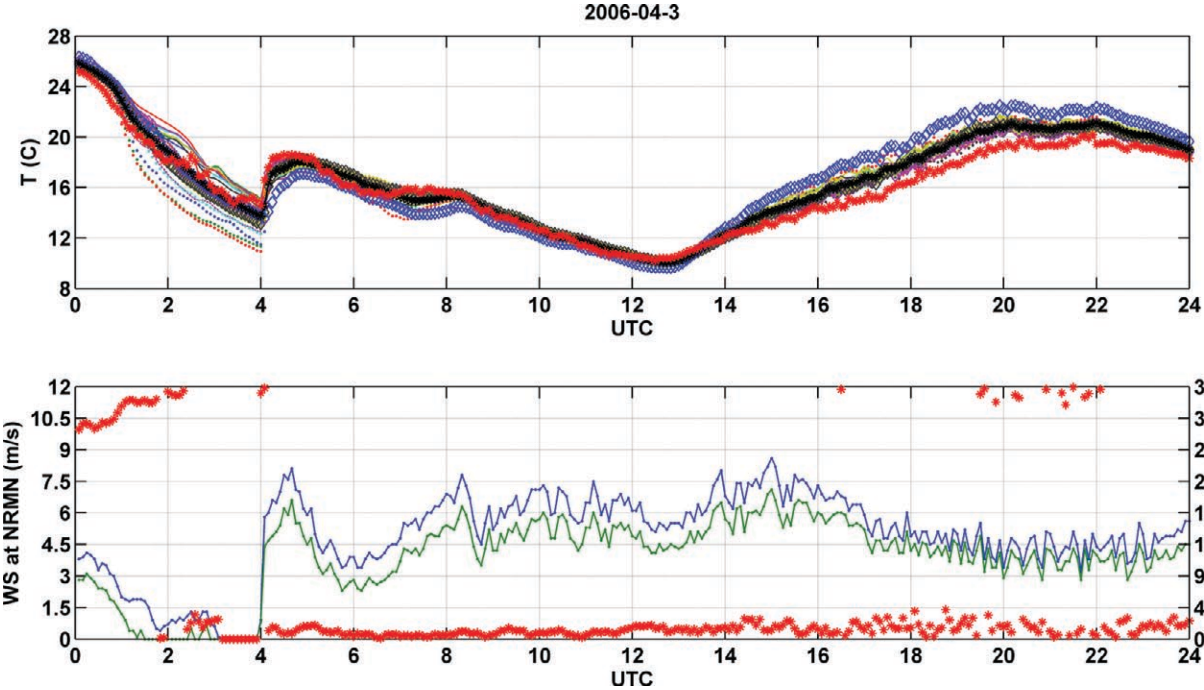

Fig. 7. As in Fig. 6, but for an episode of sudden warming that occurred on 3 Apr 2006.

nocturnal cold frontal passage under clear skies have been reported by Smith et al. (1995), Sanders and Kessler (1999), Reeder et al. (2000), and Doswell and Haugland (2006). Those studies suggested that the presence of an inversion in advance of the cold front was a key precursor for a warming event. In those cases and in the case considered here, warming was likely due to strong and gusty winds accompanying the frontal passage mixing warm air above the inversion down to the surface.

The formation and eventual dissipation of a strong small-scale cold pool on the evening of 3 April 2005 is presented in Figs. 8 and 9. Associated with strong radiational cooling (skies were clear over central Oklahoma) and light southerly winds is a separation of the Micronet temperature traces, with a peak ~7°C temperature difference between the coldest and warmest stations. The coldest air is in the south-central and southeastern part of the Micronet, in the forest adjacent to the lake and in the clearing just to the north of that forest. The warmest air is in the northern part of the Micronet and also, notably, at station 27, which is on the shoreline on the southwestern corner of the Micronet. Because the winds are southerly and station 27 is consistently warmer than the cold pool, advection of lake-modified air was likely not a factor in the formation of the cold pool (more specifically, the cold pool formed in spite of possible warm air advection). It is perhaps counterintuitive that the coldest air would be in the forest because radiation trapping by the forest would be expected to produce a positive temperature anomaly. However, in the presence of radiational cooling, a reduced mechanical mixing associated with flow sheltering by the forest or the local slope may well have played a role in the cold pool formation. Flow sheltering by topography or vegetation has previously been implicated as an important factor in the development of some small-scale and mesoscale cold pools (Tabony 1985; Thompson 1986; Gustavsson 1995; Gustavsson et al. 1998; Karlsson 2000).

Finally, even though the distance along the slope from the tower to the hilltop is only on the order of 100 m, analyses of the tower wind data suggest that very shallow katabatic flows do develop on some clear nights characterized by weak winds aloft. An example of such a katabatic flow is presented in Fig. 10. During the evening of 20 March 2005, the winds are weak but there is a pronounced increase of the downslope (northerly, $v < 0$) wind component as the ground is approached. The sense of the curvature of the v-wind profile suggests that the location of the peak northerly wind actually occurs beneath the level of the lowest anemometer (at 1.5 m). The magnitude of this katabatic flow (~1 m s^{-1}) and the height of the jet maximum (<1.5 m) are consistent with previously reported values for pure katabatic flows on slopes extending laterally just a few hundreds of meters (Ohata and Higuchi 1979; Mahrt and Larsen 1982; Doran et al. 1990). The landowner reports having seen evidence of katabatic flows at his land on several occasions. In particular, one fall evening shortly after sunset, while burning weeds, the landowner noted smoke drifting slowly downhill to a depth of approximately 5 m. Then, after a very shallow vertical transition region (estimated to be on the order of a few inches), the smoke plume abruptly shifted direction and flowed westward.

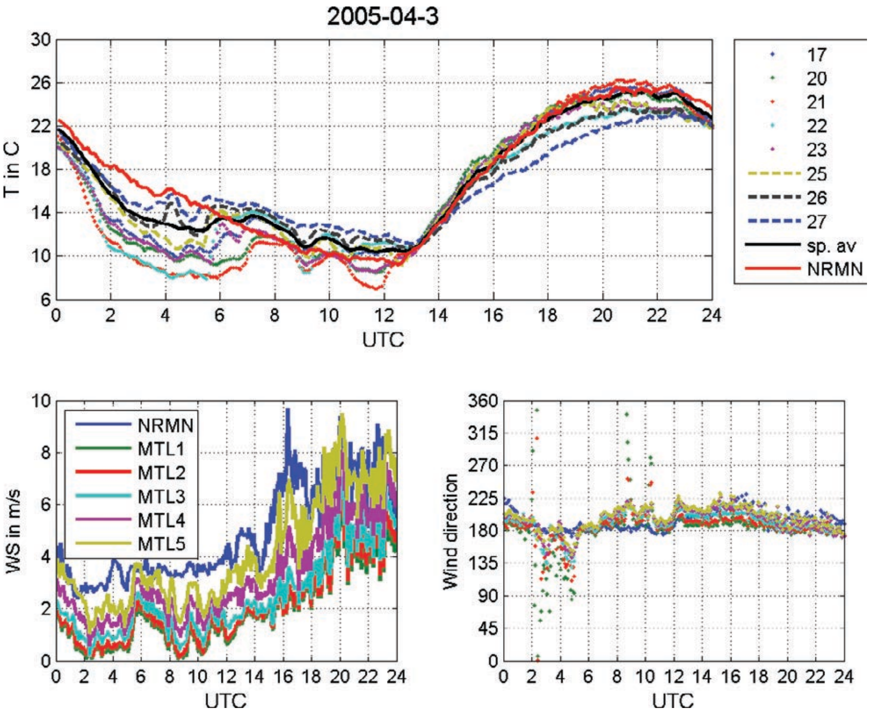

Fig. 8. Formation of cold pool on 3 Apr 2005. (top) Temperature time series at selected Micronet sites (dotted and dashed lines) and spatial average over all Micronet sites (black line) and NRMN Mesonet (red line). (bottom) Time series of wind speed and wind direction at Micronet tower (MTL1-5 = 1.5, 3, 6, 10, 15 m) and at 10 m at NRMN.

EDUCATIONAL ACTIVITIES. The Micronet provides numerous opportunities for student training, education, and research. Potential research topics include studies of microclimate and environmental variability, dependence of small-scale variability on

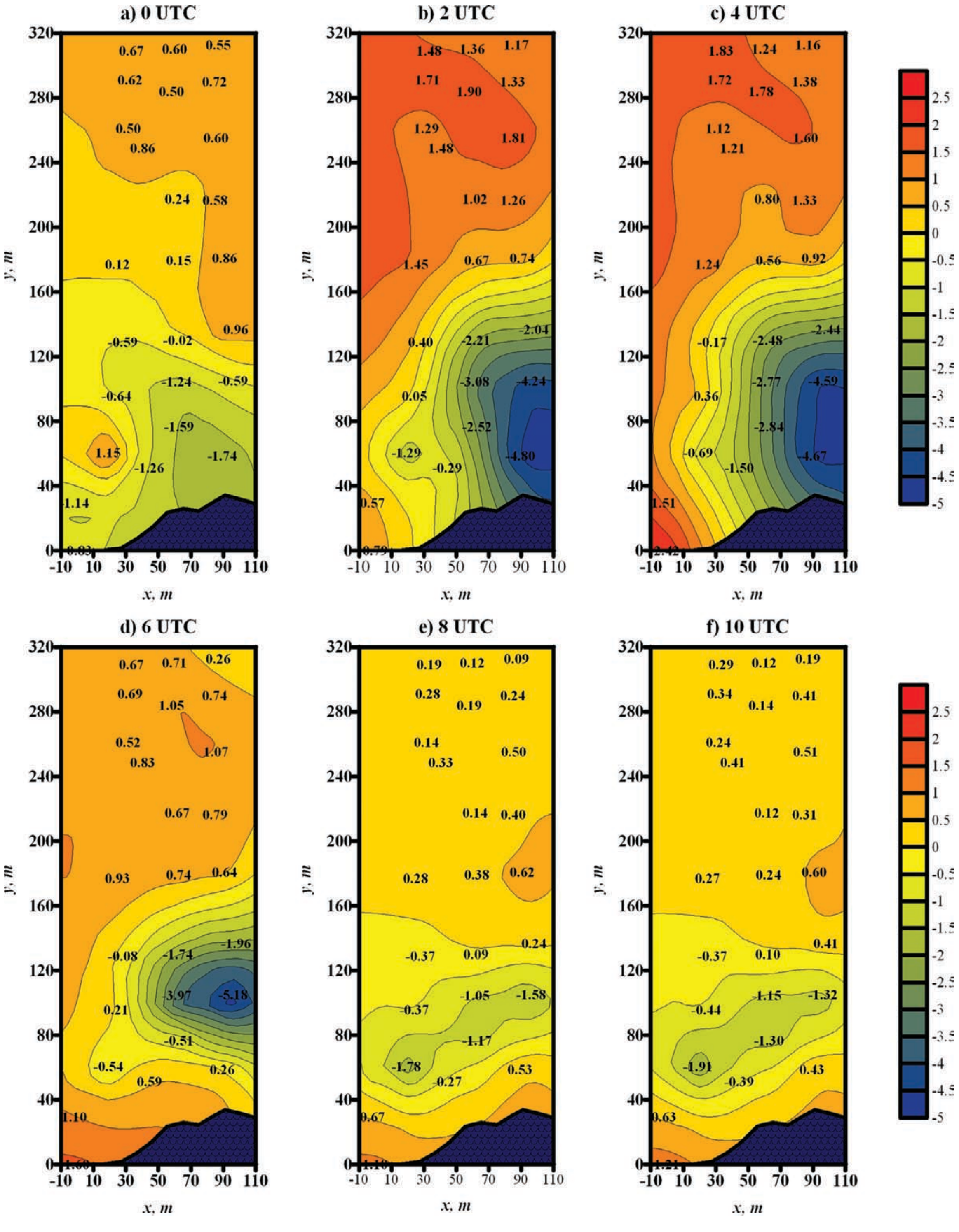

Fig. 9. Spatial distribution of temperature perturbation (station temperature minus Micronet-averaged temperature in °C) across the Micronet during the life cycle of the cold pool on 3 Apr 2005.

synoptic conditions, effects of microclimate on biological processes (e.g., time of seasonal leaf out, blooming, spawning of insects, emergence of mold and mildew), relationships between plant species distribution and atmospheric variables, and evaluation of surface layer parameterization schemes. The Micronet has already served as the primary resource in several student research projects. Two undergraduate capstone projects that focused on upgrading the Micronet and studying flow variability across the Micronet were conducted in 2004 and 2006. As part of a senior honors project in 2005, the elevations of all Micronet sites were calculated with surveyors' tools (a magnifying camera mounted on a tripod was used in conjunction with a measuring pole), and the results were compared with time-averaged GPS readings (averaging was required to remove large fluctuating errors). Two years of Micronet temperature data complemented with IOP tower wind data were analyzed in an undergraduate research project on nocturnal cold pool development and climatology, resulting in the production of a journal article (Bodine et al. 2009). In an M.S. thesis on flow and turbulence characteristics at the Micronet (Arms 2006), analysis of sonic anemometer time series data showed that even though the vegetation at the Micronet is rather patchy, flow structure at the tower is similar to that in the canopy layer over dense vegetation. Most of the analyzed velocity profiles were not logarithmic but were characterized by an inflection point near the mean canopy height, and a constant flux layer was not observed.

The Micronet is also an excellent resource for developing hands-on teaching modules and integrating inquiry-driven learning experiences into meteorology courses. Although a lack of funding has hindered a broader integration of such modules into the SoM curriculum, several modules have been developed and integrated into two SoM courses: a junior-level core course, Meteorological Measurement Systems (METR3613), and an elective course, Micrometeorology (METR4603/5603), for seniors and graduate students. The goals of the teaching modules are for students to gain skills in several important areas, including

- conceptual understanding: enhancing student comprehension and proficiency of meteorological concepts;
- technological proficiency: improving student skills in using state-of-the-art measurement techniques in meteorology;
- evaluation and utilization: developing student skills in critical thinking, particularly in evaluation and utilization of environmental models; and
- career preparation: preparing students for successful professional careers in their areas of specialization.

Different approaches are used to accomplish these goals in the junior- and senior/graduate-level courses. Juniors enrolling in METR3613 generally have little research experience and have limited technical skills in meteorological measurements and data analysis. Accordingly, for this course, we have developed and integrated highly focused and structured semester-long projects. A structured project-based approach was also motivated by the large number of students enrolled in METR3613 (~55–75), which would make integration of interactive modules into lectures in a standard classroom setting difficult (it did not seem realistic to provide effective feedback in a classroom setting with large numbers of students all working with meteorological instruments or developing data analysis routines at a computer terminal). On the other hand, highly structured project-type assignments could be designed to systematically guide students through the steps involved in conducting experimental atmospheric research: data collection, assessing data quality, performing basic statistical data analysis, comparing measured data against previous findings or existing theories, and documenting the findings in a well-organized report.

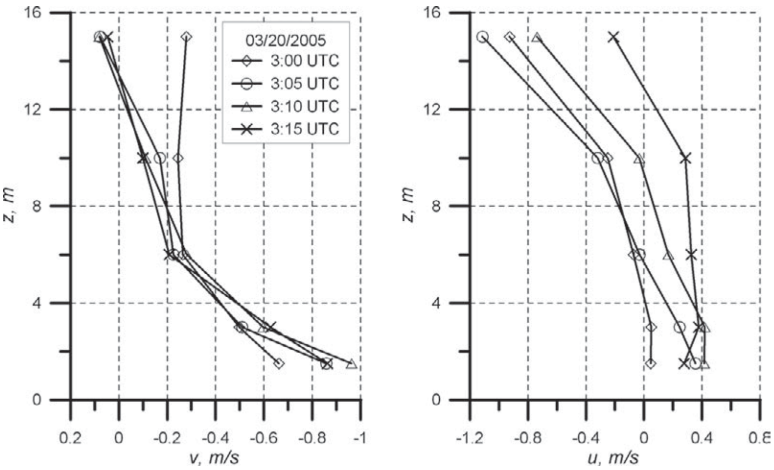

Fig. 10. Tower data for *u* and *v* wind components for katabatic flow on 20 Mar 2005. Because the terrain slopes down from the north, a negative value of *v* corresponds to a downslope wind.

The structured projects in METR3613 currently focus on specific sets of questions within four broad areas: temperature and humidity measurements, wind measurements using anemometry, solar radiation measurements, and upper air measurements using rawinsondes. Micronet data are used most heavily in the first three of these areas. Each project involves field trips to collect data from the Micronet sites. Depending on the project, students might also deploy additional equipment, such as tripods with temperature and humidity probes, for short time periods.

Students choose one of the four topics and work in a team of 4 or 5 students all semester long. For each project, we have developed extensive project descriptions that summarize background information, describe the specific measurement sites and instrumentation involved in the project, and provide ideas for the appropriate types of data analysis expected from the students. As an example, we expect students in the temperature/humidity project to investigate whether and under what conditions nocturnal cold pools such as the ones shown in Figs. 8 and 9 are observed during their study period. Using the temperature and wind profile data from the Micronet, they can then assess the atmospheric stability observed during cold pool and non–cold pool nights and discuss any significant differences. To assess sensor performance, one of the assignments is to compare measurements from two different types of sensors that were sited close to each other. Students prepare scatterplots for the data collected by the two sensors, calculate the slope of a best-fit line and the correlation coefficient, and discuss the significance of the values obtained.

In addition to the use of the Micronet in structured projects, photographs of Micronet sensors and plots of Micronet data are also presented during regular METR3613 lectures to show state-of-the-art meteorological instrumentation and to support the discussion of topics such as exposure errors, sensor bias, and dynamic performance characteristics of sensors. As an example, observations of cold front passages, such as shown in Fig. 6, illustrate well how sensors respond to rapid changes in the environment. By comparing the data measured at the Micronet with the data from the Norman Mesonet site, at which the sensors' time constant are much lower than at the Micronet site, dynamic measurement errors can be nicely demonstrated.

Students who enroll in the senior/graduate elective course METR4603/5603 are scientifically and technically more mature than those who enroll in METR3613 (seniors have already taken METR3613, and graduate students generally take METR4603/5603 because of strong links to their research). Moreover, the number of enrolled students in METR4603/5603 is relatively low (~5–15). Accordingly, a slightly different approach has been used to incorporate hands-on Micronet experiences into that course. Students still work on a semester-long project, but the topics are more flexible and individually designed based on the students' research interests. Depending on the research topic, students may elect to use data from sensors at the Micronet or from a variety of other observation platforms. In addition to their use in semester-long projects, Micronet instrumentation and data form the basis of an interactive teaching module that focuses on measurement and calculation of turbulent fluxes in the atmospheric surface layer. After first visiting the Micronet to study the tower site and its instruments, students develop Matlab scripts to read raw sonic anemometer time series data, assess the data quality, perform rudimentary quality control (e.g., removing statistical outliers), and compute mean and turbulent flow quantities. Calculated turbulent heat and momentum fluxes are then compared with fluxes estimated with standard surface layer parameterization schemes such as Monin–Obukhov similarity theory profile methods. Our objectives with this module are for students to gain a working knowledge of the main components of the surface energy budget and of modern techniques for measuring and calculating turbulent fluxes, to understand the diurnal variability of the surface energy fluxes, to be able to critically evaluate surface energy budget parameterizations in numerical atmospheric models, and to gain an appreciation of how land use can affect the surface energy budget. The module includes a series of classroom computer exercises that are interlaced with regular lectures.

Formal assessment of these education activities is planned but has not yet been conducted, largely because of the limited resources available. The success of achieving the outlined goals at this point can thus only be based on the feedback that students provide in generic annual course evaluations and anecdotal evidence as some students have sent positive feedback even after leaving OU. In one case, a doctoral student at another institution who had taken the SoM Measurements class as an undergraduate wrote, "I just wanted to let you know how amazing your instruments class was. None of the other students took a class like that . . . I feel like I have had a huge advantage here knowing how dataloggers work . . ." While such feedback is encouraging it is not necessarily representative for the whole class, and it must be noted that the integration of the hands-on Micronet-focused teaching modules into the Measurements course was initially not very smooth; in fact, during the first year the response and feedback from students was mostly negative. This was largely due to the fact that not enough guidance was provided to the students about how they should approach their projects and analyze the collected data. The writing assignment of a project report proved to be an equally daunting task. We have thus continuously worked on improving the project descriptions and, as part of the course, we also offer help sessions that address writing and computing skills. The projects are continually revised and are now being offered for the fifth time. The ongoing time-consuming efforts necessary to improve the actual assignments is one major reason why a formal evaluation procedure has not yet been further developed. Based on student feedback on the generic course evaluations, the hands-on approaches in METR4603/5603 were very well received by students, as comments like "I enjoyed the application of theory on actual measurements" were typical. As for improving the course, some students recommended incorporating even more field work and even more assignments using actual data.

Finally, we note that links on our recently developed Web site http://micronet.ou.edu/ltm/ lead to current and archived Micronet data that may be used as a teaching resource for users outside of OU. Detailed descriptions of the student projects and teaching modules in the courses described above are also available at that Web site.

FUNDING OF THE MICRONET.

A major challenge in the establishment and maintenance of the Micronet was the securing of funds to purchase meteorological instruments and supporting infrastructure. Although this Micronet is a relatively low-cost venture with several key pieces of equipment donated to the project, the initial expenses and ongoing maintenance costs have required us to seek funding from a variety of sources. Here we summarize these expenses and the funding sources.

Approximately $11,000 of seed funding for the Lake Thunderbird Micronet was provided by the OU Office of the Vice President for Research through an award from the Research/Creative Activity Program (Principal Investigators: A. Shapiro, B. Hoagland, and F. Gallagher), with $3,000 of matching funds from the SoM. The meteorological tower was obtained through the OU FEPP program. Although the tower was obtained at no cost to our project, the five sonic anemometers and associated equipment represented the single largest Micronet expense. The second author's faculty start-up funds covered the ~$20,000 cost of those instruments. The Vaisala HMP35C temperature/humidity probes and the LI-COR 200SZ pyranometer were donated to our project by the OCS. The REBS Q7.1 net radiometer and Eppley black and white pyranometer were donated by a colleague, Claude Duchon. Funds for the 2007 tower upgrade were obtained through an NSF grant to the second author (NSF ATM 0547882). These funds, totaling ~$5,000 covered the cross-beams and mounts for the tower temperature/humidity and radiation sensors, improvements in the data acquisition system (second datalogger and the new enclosure), development of the data transmission system, and rental of a bucket-lift truck. The SoM Research Facilities Fund and the first author's Presidents' Associates Presidential Professor funds awarded through OU have supported routine maintenance operations and a major refurbishment of the Micronet. When annualized, the maintenance and refurbishment costs for the standard Micronet stations (i.e., excluding the tower instruments and associated infrastructure) come to approximately $800 yr^{-1}.

CONCLUDING REMARKS.

This report documents our grassroots effort to provide a natural laboratory for the education and training of our students. The Lake Thunderbird Micronet was established with financial support from a variety of sources, and with a tremendous amount of goodwill in the form of equipment donations, volunteer work from students, faculty, and researchers, and the landowner's willingness to permit a tower and numerous Micronet stations on his land.

We close with a brief update on our activities. Two Micronet sites were destroyed by a flood in the summer of 2007. In addition, one of the sites had not been functional for several years, many of the HOBO humidity sensors had become unreliable [in contrast, the temperature data appeared to be of consistently high quality; see discussion in Bodine et al. (2009)], and many of the radiation shields had become discolored by dirt and mold. Accordingly, in late 2007 we decided to refurbish the radiation shields and the HOBO temperature/humidity sensors. With the help of student volunteers we removed all of the sensors and radiation shields from the posts, cleaned the radiation shields, and sent the sensors to the Onset Computer Corporation to be recalibrated and in some cases replaced. Most of the sensors/shields have been redeployed in the field, and operations at the Micronet have resumed.

ACKNOWLEDGMENTS. We are grateful to Ed Jessup for offering use of his property for the Micronet project. Without his generosity, this project would not have been possible. We also thank Sherman Frederikson (National Severe Storms Laboratory), Evgeni Fedorovich (SoM), Fred Carr (SoM), Claude Duchon (SoM), Bruce Hoagland (DoG), Aondover Tarhule (DoG), Frank Gallagher (Dugway Proving Ground), Chris Fiebrich (OCS), Renee McPherson (OCS), Mark Laufersweiler (SoM), Joe Grego (FEPP), Susan Hendon (Lake Thunderbird State Park), and the many undergraduate and graduate students who have

Table A1. Sensor specifications for HOBO H8 Pro temperature/humidity sensor.

Specification	Temperature sensor	Relative humidity sensor
Range	−30°C to +50°C	0% to 100% RH
Accuracy	±0.2°C at +21°C in high-resolution mode	±3% (up to ±4% in condensing environments)
Resolution	0.02°C at +21°C in high-resolution mode	NA
Response time in still air	34 min typical	5 min typical to 90%
Sensor operating environment	NA	0° to +50°C

assisted with the Micronet project since its inception in 2002. The second author acknowledges support from NSF grant ATM 0547882. Oklahoma Mesonet data are provided courtesy of the Oklahoma Mesonet, a cooperative venture between OU and Oklahoma State University supported by Oklahoma taxpayers.

APPENDIX: SENSOR SPECIFICATIONS, DATA ACQUISITION, AND WIRELESS TRANSMISSION OF TOWER DATA.

Temperature and relative humidity are measured at each of the Micronet stations with an Onset HOBO H8 Pro temperature/humidity logger. Sensor specifications from the Onset Computer Corporation are provided in Table A1. Liquid precipitation is measured at three stations (7, 17, and 28) with Onset data-logging tipping-bucket rain gauges (RG2, imperial version).

The RM Young 81000 sonic anemometers on the tower measure the three Cartesian wind components with a resolution and threshold of 0.01 $\mathrm{m\ s^{-1}}$. The accuracy is specified as ±1% rms ±0.5 $\mathrm{m\ s^{-1}}$ for wind speeds up to 30 $\mathrm{m\ s^{-1}}$. Wind direction is measured with a resolution of 0.1° and an accuracy of ±2° for wind speeds in the 1–30 $\mathrm{m\ s^{-1}}$ range.

The Vaisala HMP35C temperature/humidity sensors are housed under naturally ventilated radiation shields (10-plate Gill radiation shield, Campbell Scientific 41003). These sensors include a platinum resistance temperature detector and a capacitive relative humidity sensor. The accuracy of the humidity sensor at 20°C is specified as ±2% in the relative humidity range from 0% to 90% and as ±3% in the relative humidity range from 90% to 100%.

At the base of the tower are two shortwave radiometers (Fig. 4) that each measure direct and diffuse solar radiation. The LI-COR 200SZ, a photovoltaic-type pyranometer that produces a current proportional to incident solar radiation, was calibrated against a more accurate Eppley precision spectral pyranometer under natural daylight conditions and has a typical error of 5%. The Eppley black and white pyranometer model 8-48 uses a differential thermopile with hot and cold junctions connected to black and white surfaces, respectively. Instrument specifications from EPLAB (2006) are provided in Table A2. An REBS Q7.1 net radiometer is also deployed (temporarily) at the base of the tower. This radiometer also uses a thermopile sensor but generates a millivolt signal proportional to the net radiation level. A black surface minimizes reflections, and a hemispherical windshield reduces sensor temperature changes associated with turbulent heat transfer. Instrument specifications from Campbell Scientific are given in Table A3.

Table A2. Instrument specifications of the Eppley black and white pyranometer model 8-48.

Specification	Value
Sensitivity	≈10 $\mu\mathrm{V\ (W\ m^{-2})^{-1}}$
Impedance	~350 Ω
Temperature dependence	±1.5% over ambient temperature range from −20° to +40°C
Linearity	±1% from 0 to 1400 $\mathrm{W\ m^{-2}}$
Response time	5 s
Cosine	±2% from normalization zenith angle; ±5% zenith angle
Calibration	Integrating hemisphere
Size	5.75 in. diameter, 2.75 in. high
Weight	2 lbs
Orientation	Performance not affected by orientation or tilt

A Hoffman Enclosures, Inc., protective enclosure at the base of the tower houses equipment for the storage and transmission of the tower data (Fig. 4). The enclosure is rated type 4 by the National Electrical Manufacturers Association (NEMA). Data from the

Table A3. Instrument specifications of the REBS Q7.1 net radiometer.

Specification	Value
Nominal calibration factors	9.6 W m^{-2} (μV)$^{-1}$ for positive values 11.9 W m^{-2} (μV)$^{-1}$ for negative values
Uncorrected wind effect	Up to 6% reduction at 7 m s^{-1} for positive fluxes up to 1% reduction at 7 m s^{-1} for negative fluxes
Spectral response	0.25–60 μm
Time constant	~30 s
Size of sensing head	5.7 × 7.2 × 17.7 cm
Support arm dimensions	5.7 × 7.2 × 17.7 cm
Weight	4.1 lbs

HMP35C temperature/humidity sensors and the radiation sensors are stored on a CR3000 datalogger, which can hold several months of data at the current storage rate (1-min averages from 3-s samples). Data from the sonic anemometers are stored on a CR5000 datalogger, which can hold one week of data gathered at 10 Hz on a 512-MB storage card.

Recently, wireless transmission of tower data to the NWC has begun. An overview of the communication infrastructure is depicted schematically in Fig. 5. Every 5 min a data request is automatically generated inside the landowner's house by an Ubuntu Linux PC running Windows XP and Campbell Scientific's Baler and LoggerNet software on a virtual machine. The request is sent from the PC to the dataloggers, located on the tower, through a Linksys WRT54G-L wireless router and a Lantronix WiBox (WB21000EG) wireless-to-serial server. Once the request is received, the dataloggers send the data to the PC. The data are then written to a Samba share and immediately compressed and copied via SSH to a server in the NWC. Data on the server are processed, archived, viewed, and made available as default daily or 1-min average time series plots at the Micronet website (http://micronet.ou.edu/ltm/) in near–real time. An e-mail request for the raw data can also be made at the Web site.

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