Final Report for use of the NSF Facilities for Education at the University of Colorado Boulder

CABL: Characterizing the Atmospheric Boundary Layer

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1. Overview

The "Characterizing the Atmospheric Boundary Layer" (CABL) educational deployment leveraged multiple outreach opportunities to provide scientific opportunities to high school, undergraduate, and graduate students in Colorado's Front Range. Several EOL facilities were deployed as part of CABL, including 12 sonic anemometers and 6 temperature/relative humidity probes mounted on the Boulder Atmospheric Observatory (BAO), 40 mobile GPS Advanced Upper-air Soundings (MGAUS), and the deployment of two Integrated Surface Flux stations, one at the BAO and in the vicinity of Erie High School.

These deployments occurred in conjunction with the XPIA experiment, conducted by the University of Colorado Boulder (CU) and the Earth Systems Research Laboratory at NOAA with colleagues from the University of Maryland Baltimore Country and the University of Texas at Dallas. The primary scientific goal of the XPIA experiment was to characterize the capabilities of remote sensing instrumentation, such as scanning lidar and radar, in a range of air quality conditions. As we had expected, spring conditions on Colorado's Front Range brought several rounds of precipitation (ranging from light to heavy, rain through snow) as well as strong diurnal cycles and the resulting cycle in atmospheric stability, providing an excellent testbed for evaluating the performance of lidars, radars, and radiometers.

Because of close cooperation between XPIA staff and Erie High School (EHS), located ~ 1 km from the BAO, we were able to work closely with environmental science and meteorology teachers at EHS, as well as with undergraduate and graduate students at the University of Colorado Boulder (CU) and local middle school students. This document highlights the educational impact of the CABL deployment. The atmospheric science research enabled by CABL and XPIA is summarized in an NREL technical report (in preparation) and a submission to the *Bulletin of the American Meterological Society* (in preparation) as well as several papers to be submitted to a special issues of *Atmospheric Measurement Techniques* (http://www.atmospheric-measurement-techniques.net/about/special_issues.html).

2. Educational Deployments

The CABL deployments supported educational outreach for a range of ages including high school (Erie High School), undergraduate (CU), graduate (CU), and middle school middle school (Watershed School). This section is organized by institution, with discussion regarding specific instrument platforms within each institution's section.

a. Erie High School

i. MGAUS

As we expected, launching radiosondes from Erie High School (EHS) inspired much enthusiasm and interest on the part of students (and staff and administrators) at the school. The CABL MGAUS truck visited EHS to launch two soundings. In the morning of 9 March, Prof. Lundquist, Mr. Tim Lin of NCAR, and several CU Boulder graduate students joined Mrs. Julie Mitchell's 7:30 am Meteorology class for a sonde launch (Figure 1, Figure 2). We also joined Mrs. Holly Marcus' afternoon Environment Science class that afternoon (Figure 3); St. Vrain school district staff also joined that launch, bringing a quadcoptor with a video camera to record the launch. Approximately 50 students total interacted with CABL team members. As recommended by NCAR staff, Prof. Lundquist provided a short introduction to weather observations and the XPIA experiment before moving the class outside for the launch. Data from the launch were archived for use in subsequent class visits. Meteorological topics covered in the discussion included:

- inversions and why the morning inversion was much lower than the afternoon inversion, and
- similarities and differences between the wind profiles measured by the sounding and by the lidar systems and why those differences occur.

Figure 1: Tim Lin (NCAR) explaining the components of a radiosonde at EHS, 9 March 2015 (early morning launch).

Figure 2: EHS Meteorology student preparing to release morning sounding, 9 March 2015.

Figure 3: EHS Environmental Science student preparing to release the afternoon sounding, 9 March 2015. The 300-m Boulder Atmospheric Observatory tower can be seen to the left of the balloon in the background. The gentleman to the right of the student, leaning against the vehicle, was a pilot for the St. Vrain School District who brought a quadcopter with a camera in order to film the launch of the sonde for the school district website.

ii. ISFS

CABL also provided the opportunity to introduce Erie High School students to boundary-layer meteorology through the presence of a surface flux station with radiation measurements directly north-northwest of their school. Considerable assistance with administrative matters and legal issues was provided by St. Vrain School District Assistant Superintendent of Operations Brian Lamer. Directly north-north-west of the school, EOL staff installed the equipment 9 March and withdrew the equipment on 20 April. Dr. Steve Oncley and Prof. Lundquist led class visits to Mrs. Julie Mitchell's Meteorology (morning) and Mrs. Holly Marcus' Environmental Science (afternoon) classes, including visits to the surface flux stations (Figure 4-Figure 6).

Figure 4: Dr. Steven Oncley explaining the equipment on the 10m surface flux station to Mrs. Julie Mitchell's Meteorology class.

iii. 200S lidar

Although CABL did not directly support the deployment of NOAA's WindCUBE 200S scanning lidar on the roof of EHS, data from the sounding launched on 9 March was used in-class on 11 March to compare to lidar measurements from that lidar and from the NOAA High Resolution Doppler Lidar deployed ~ 2 km away from EHS. (The NOAA deployments were supported by NOAA and XPIA.) Prof. Lundquist visited the Environmental Science and Meteorology classrooms with Drs. Alan Brewer and Aditya Choukulkar of NOAA's Environmental Science Research Laboratory (ESRL) to provide a brief overview of lidars and how they work. This visit provided the students with an opportunity to work with the MGAUS data collected two days previously. We prepared an exercise for the class in which they used Microsoft Excel to looked at the wind measurements from their sounding, and compared those measurements to the wind measurements from the lidar at the same time. One "lesson learned" from this experience is to ensure that "lecture time" is no longer than ten minutes for this age group. Further, the morning class needed to integrate the sounding and the lidar datafiles together, which was challenging for some students. In the afternoon class, we integrated the files together before the students accessed them, which saved considerable time and allowed the students to clearly identify jet structures in the winds and the associate of jets with inversions (using the morning 9 March soundings). This class visit also afforded an opportunity to interact with the NCAR-provided datastreams from the 300-m BAO tower, which one of the teachers used in a subsequent class on her own.

Figure 5: Steve Oncley explaining the range of meteorological instrumentation on a surface flux station to Mrs. Mitchell's Meteorology class on the morning of 13 March 2015.

Figure 6: Steve Oncley explaining surface radiation measurements to Mrs. Marcus' Environmental Science class, afternoon 13 March 2015.

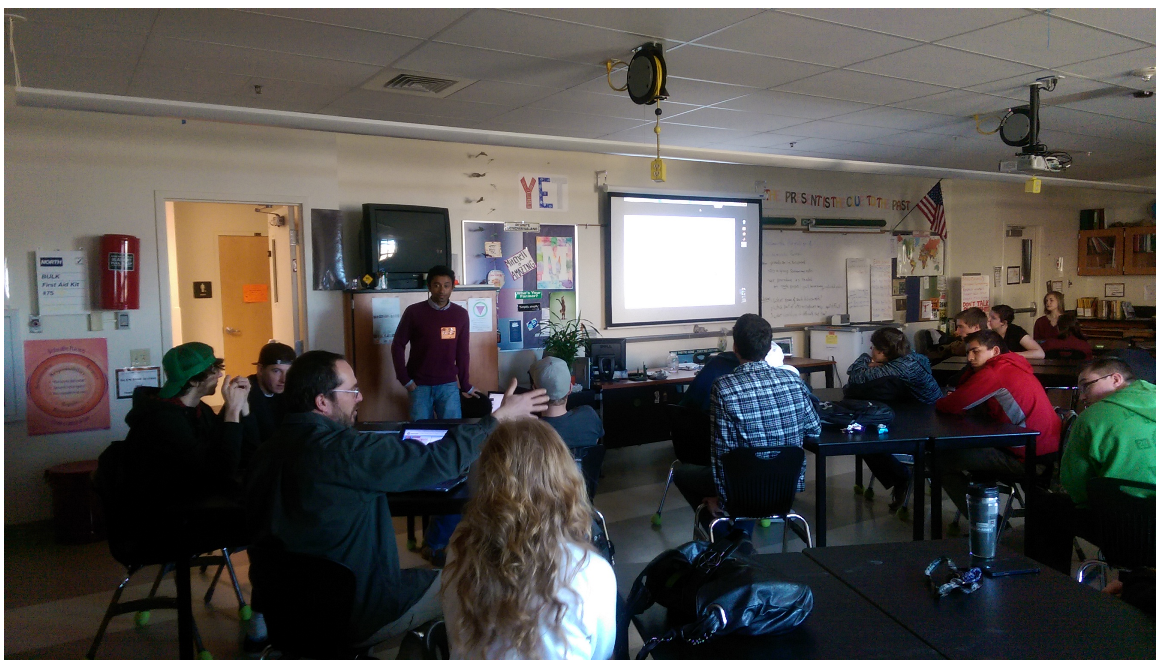


Figure 7: EHS Environmental Science students ask lidar questions of Dr. Aditya Choukulkar (CIRES/NOAA, standing in red sweater at front) and Dr. Alan Brewer (front left gesturing with hands) on 11 March 2015.

b. CU-Boulder

Undergraduate and graduate students at CU benefitted enormously from the EOL resources deployed through CABL. Graduate students participated in the deployment of one of the ISFS stations at the BAO, learning more about instrumentation and field deployment issues in one morning than could probably be taught in a classroom in several weeks. Graduate and undergraduate students were also trained on launching soundings, and a group of graduate students had primary responsibility for sonde launching for several weeks of CABL. Finally, the CABL equipment deployed on the 300-m BAO tower, as well as the real-time and interactive web interface to access those data, enabled the tower data to be used in undergraduate and graduate classes at CU.

i. ISFS station

On 20 February 2015, six CU graduate students in Atmospheric and Oceanic Sciences met Dr. Steve Oncley and Mr. Kurt Knudson at the BAO to prepare for the installation of an ISFS station southeast of the main BAO tower. Dividing up into “soil moisture / radiation” and “meteorological station” groups (Figure 8-Figure 12), the students helped deploy the instruments while learning about considerations for field deployments.

Figure 8: Steve Oncley explaining some of the component of the soon-to-be-installed ISFS to Rochelle Worsnop, Joseph Lee, and Clara St. Martin.

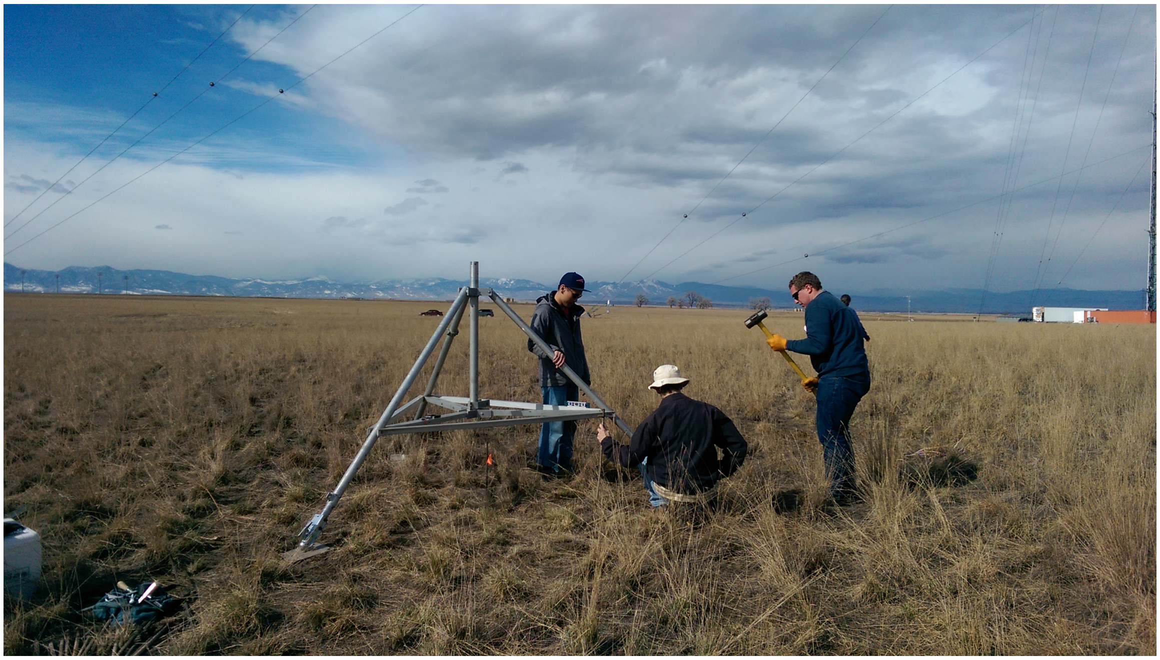


Figure 9: CU students Ken Tay, Brian Vanderwende, and Paul Quelet helping install the ISFS station southeast of the BAO tower, 20 Feb 2015.

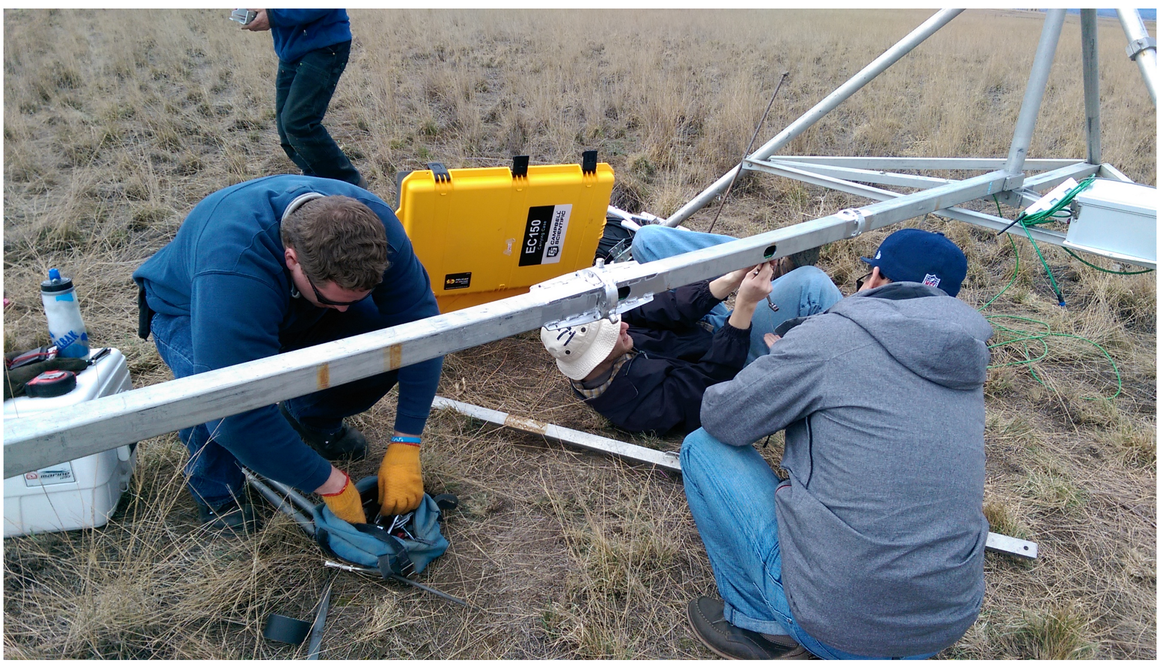


Figure 10: CU students Paul Quelet, Brian Vanderwende, and Ken Tay preparing tower structure, 20 Feb 2015.

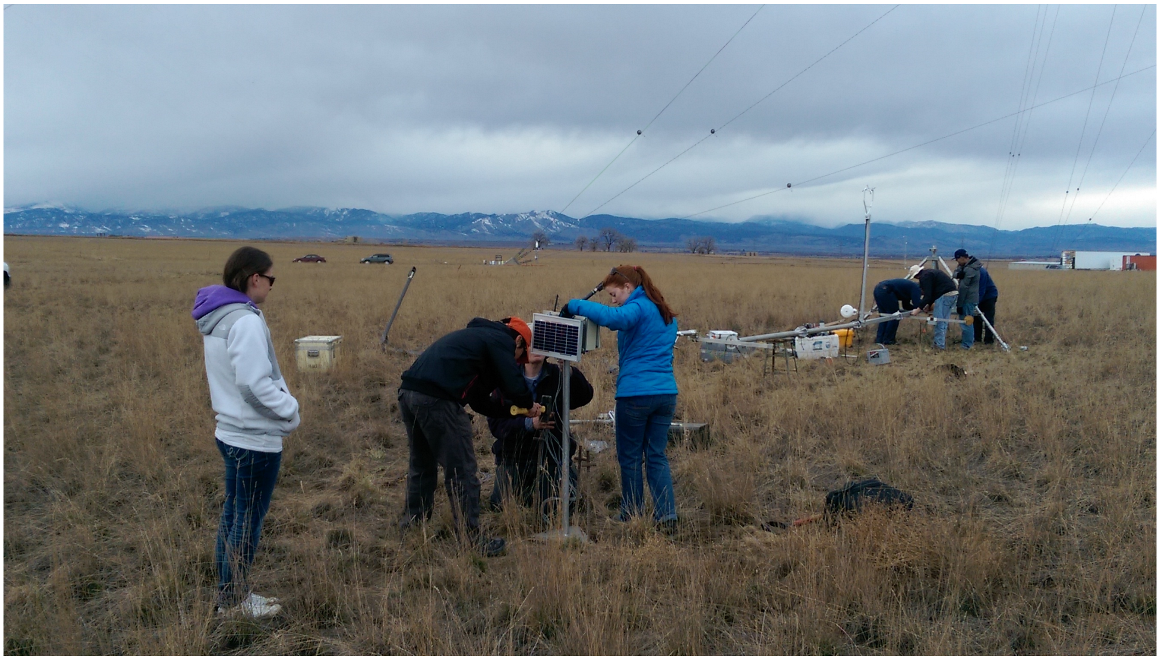


Figure 11: CU students Clara St. Martin, Joseph Lee, and Rochelle Worsnop assist Steve Oncley with power and network connections in the foreground while Paul Quelet, Brian Vanderwende, and Ken Tay prepare the tower in the background, 20 Feb 2015.

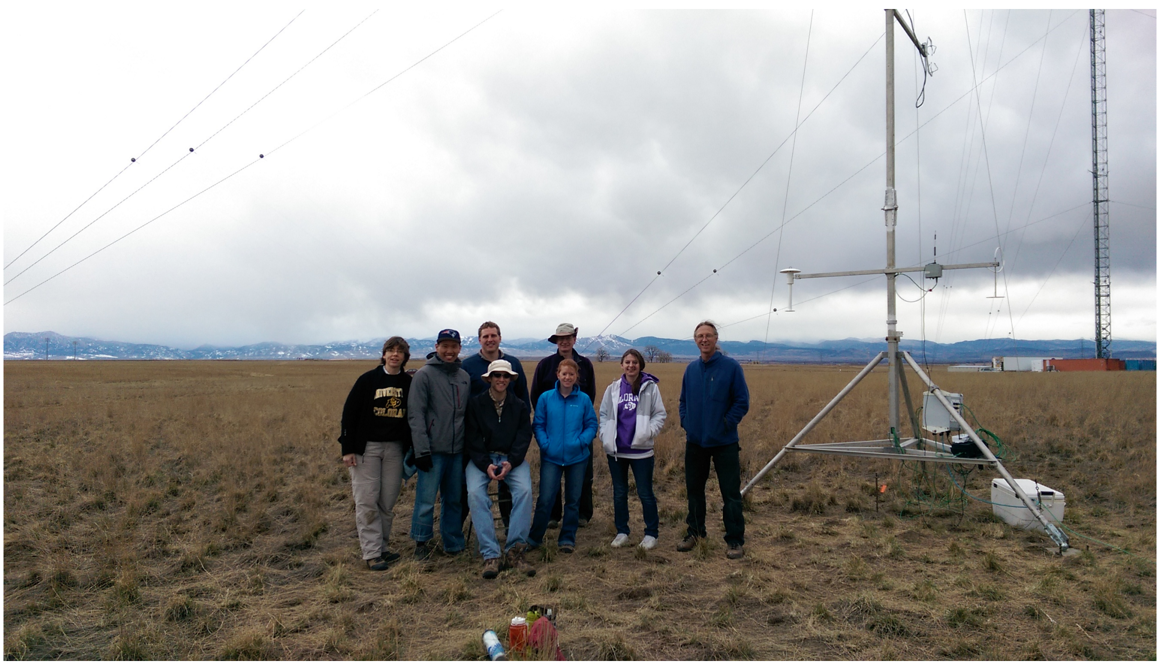


Figure 12: Group photo after the intallation of the ISFS tower, 20 Feb 2015. Left-to-right: Julie Lundquist, Ken Tay, Paul Quelet, Brian Vanderwende, Steve Oncley, Rochelle Worsnop, Clara St. Martin, and Kurt Knudon. Joseph Lee took the photo.

ii. MGAUS

Before the MGAUS launches at EHS discussed above, Tim Lin brought the MGAUS system to CU-Boulder to expose CU students in ATOC 4770/5770, a mixed graduate-undergraduate course in "Wind Energy Meteorology" to soundings (Figure 13-Figure 14). This demonstration (6 March 2015) also provided a teaching opportunity for the CU graduate students who would launch soundings throughout March from the BAO site.

Following this demonstration, from 9 March through 18 March, CU students Rochelle Worsnop, Paul Quelet, Clara St. Martin, Joseph Lee, and Brian Vanderwende took primary responsibility for launching radiosondes from the BAO Visitor Center. Following the launch, they used NCAR's ASPEN software (https://www.eol.ucar.edu/software/aspen) to prepare basic plots of the soundings and summarized the launches and meteorological conditions at the project blogsite, http://a2expia.blogspot.com. Several of the students mentioned that using aspen was a useful experience. An example post is shown in Figure 15.

Finally, these data were used in ATOC 1050, a large undergraduate general science requirement course ("Weather and the Atmosphere") by Dr. Melissa Nigro. Her in-class exercise appears in Figure 21 and Figure 22, in the "Examples of Student Work" section below.

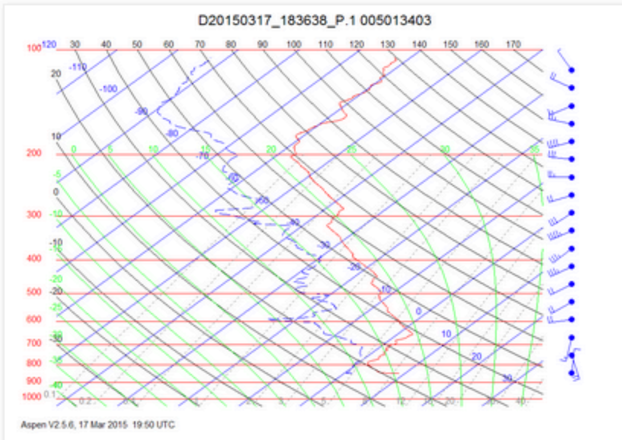
Figure 13: A subset of the CU students who attended Tim Lin's 6 March sounding demonstration. Left to right: Rochelle Worsnop, Spencer Huff, Joseph Lee, Rory Laiho, Ken Tay, Paul Quelet, and Jordan Laser.

Figure 14: Spencer Huff and Jordan Laser (CU undergraduates from ATOC 4770, "Wind Energy Meteorology") launching a radiosonde from CU Main Campus, 6 March 2015.

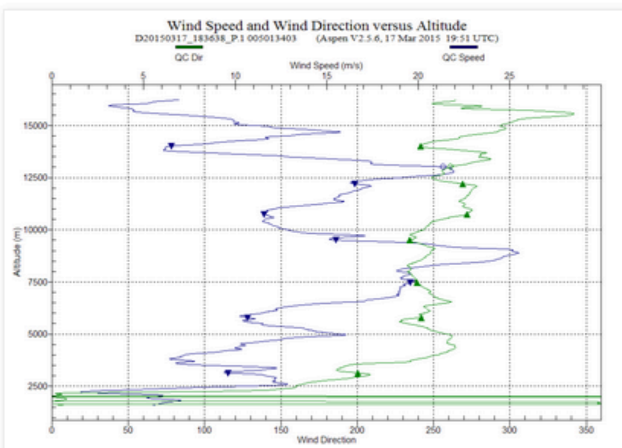
Tuesday, March 17, 2015

2015 03 17 1800Z Radiosonde Launch Report

Radiosonde was launched at 1836 UTC (1236 MDT local) due to visitation from middle school students from Watershed School in Boulder. Many thanks to Bill Brown of NCAR for leading the discussion and engaging with the students. In any case, the skew-T ln-p diagram is here:



As always, wind speed/wind direction vs. height also:



Remarks are as follows: Surface temperatures were warming up to the time of the launch as increase sunshine eroded low level stratus clouds. Sky was broken with stratus and having high level cirrus at time of launch. Light breezy winds at the surface. Highly variable wind speed and direction in boundary layer. Balloon ascended toward south, but turned toward north in southerly flow above the boundary layer. Daytime lapse rate and modest lapse rate above, evidence of layer ascent from earlier in day. High Relative Humidity near Boundary Layer top indicative of thin cloud intercept. (Quelet)

Figure 15: Blog post from CU graduate student Paul Quelet showing data from MGAUS launch and meteorological remarks. From http://a2expia.blogspot.com/2015/03/2015-03-17-1400z-radiosonde-launch_17.html.

iii. BAO tower datastreams

The considerable investment in sonic anemometers and temperature/relative humidity measurements at the BAO tower as part of CABL provided significant educational opportunities for a range of students at CU Boulder. For example, CU graduate students participating in XPIA are utilizing the data as part of their research. Data from the towers are being incorporated into a revision of the ATOC 1070 Weather Lab – each semester, approximately 250-280 students are enrolled in ATOC 1070 to complete their general science requirements. Finally, although Prof. Lundquist's ATOC 4770/5770 class (26 students) was scheduled to visit the BAO in person for a field trip on 26 February 2015, inclement weather required that the trip be cancelled due to safety concerns regarding transportation out to the BAO. Because the CABL datastreams from the tower and from several of the XPIA lidars on-site at the BAO were available online, however, a "virtual" field trip took place. In addition to learning about the instrumentation, a guided worksheet enabled students to apply and test their developing understanding of wind profiles and the relationship between atmospheric stability and winds. The worksheet is provided in Section 3 of this report.

An important topic in ATOC 4770/5770 deals with how tower wakes might influence meteorological measurements. A bonus problem on the "Virtual Field Trip" worksheet suggested that students consider the idea that the tower itself might wake the instruments on the booms. Several weeks later, this tower waking was clearly evident, as captured in a blogpost (http://a2expia.blogspot.com/2015/04/distinct-mast-effects-on-se-sonics.html), which included an example from NCAR's ncharts plots (Figure 16).

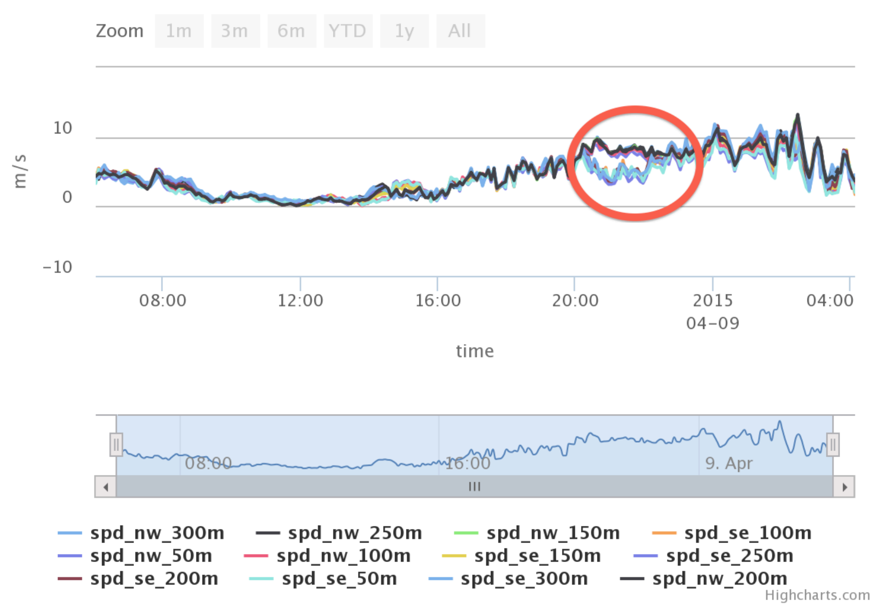


Figure 16: Snapshot from ncharts showing a distinct tower wake (see http://a2expia.blogspot.com/2015/04/distinct-mast-effects-on-se-sonics.html for more information). This image was later used in ATOC 4770/5770 lecture.

The NCAR investment in developing the ncharts platform that enabled this data access and data browsing is greatly appreciated considering its great utility for both educational and research purposes.

c. Watershed School

This educational outreach opportunity presented itself when this middle school requested a sounding demonstration from NCAR. A CU student, Paul Quelet, shifted his sounding launch time to accommodate the visit and interaction with the students from the Watershed School (Figure 17). Paul expressed great appreciation that Dr. Bill Brown from NCAR joined the school visit.

Figure 17: Middle school students from the Watershed School visit the BAO tower and launch a radiosonde with CU student Paul Quelet (center figure, white sweater) and Dr. Bill Brown (photographer). The 300-m BAO tower appears at right.

3. Examples of Pedagogical Materials

In this section, we provide selected examples highlighting how CABL data were used in the classroom during Spring 2015. CABL data are also being incorporated into the curricula for future classes, and at least one CU graduate student is incorporating CABL and XPIA data into his dissertation research. In this section, we highlight implementation into the ATOC 4770/5770 mixed graduate-undergraduate curriculum, the ATOC 1050 large undergraduate meteorology lecture, as well as some research results on the BAO tower wake.

a. ATOC 4770/5770 Virtual field trip documentation

As discussed above, Prof. Lundquist’s “Wind Energy Meteorology” class had a planned field trip on 26 February to visit the BAO. Due to heavy snowfall and icy roads, this trip was cancelled that morning and a virtual field trip was instead prepared. The following three pages include the material guiding that “virtual field trip”. A presentation including photos was also included in the class that day.

Name:

ATOC 4770/5770: Wind Energy Meteorology

Spring 2015

In-class virtual tour of the BAO

The data being collected this month at the Boulder Atmospheric Observatory provides us with an opportunity to investigate some of the weather phenomena that we have discussed in class. We will use the data browser that NCAR has built for us as part of the “Characterizing the Atmospheric Boundary Layer” (CABL) educational outreach project (https://www.eol.ucar.edu/field_projects/cabl) . You can see some cool pictures of the BAO at http://www.esrl.noaa.gov/psd/technology/bao/ . For this experiment, NCAR and NOAA have installed sonic anemometers on booms to the southeast and the northwest of the tower at 50m, 100m, 150m, 200m, 250m, and 300m above the surface. NCAR has also installed a short (10m) meteorological flux station about 200m to the southeast of the main tower.

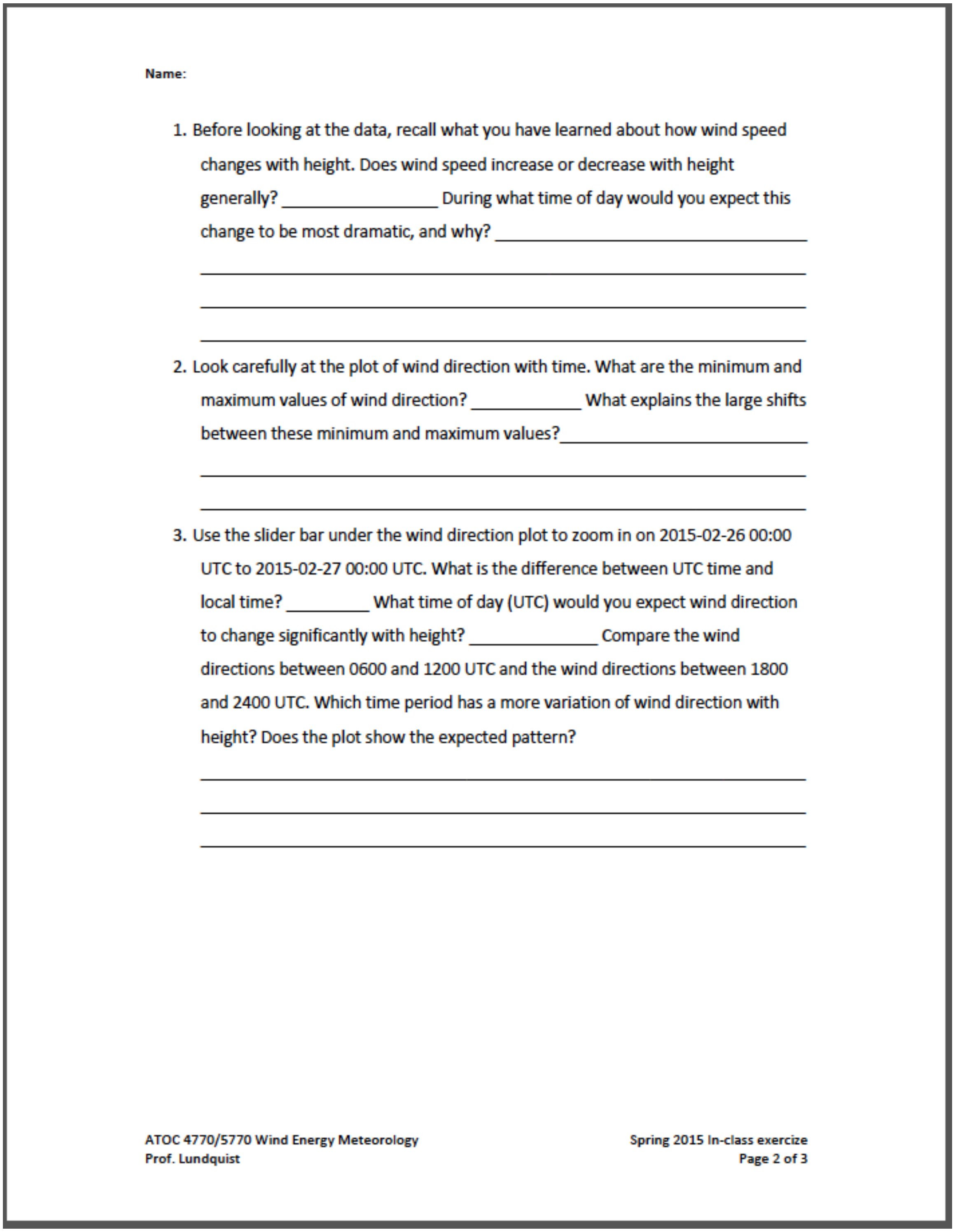
The data browser is available at http://datavis.eol.ucar.edu/ncharts/projects/CABL/geo_notiltcor ; there you will find a long (and awkward) list of available variables to plot. Just follow the directions here, though, for guidance!

We will focus on wind speed and direction along the 300m meteorological tower and at the short meteorological station near the tower, called “bao”: check the boxes for “Spd” (spd_se_100m ☑ spd_se_150m ☑ spd_se_200m ☑ spd_se_250m ☑ spd_se_300m ☑ spd_se_50m spd_3m_bao) and for “Dir” (dir_se_100m ☑ dir_se_150m ☑ dir_se_200m ☑ dir_se_250m ☑ dir_se_300m ☑ dir_se_50m dir_3m_bao).

We will also look at how temperature changes with height: check the boxes for T_100m ☑ T_150m ☑ T_200m ☑ T_250m ☑ T_2m_bao ☐ T_300m ☑ T_50m. Using the “Time” box to the right or below the long list of variables, start your plotting on 2-21-2015 at 20:00 UTC and select a 12-day plot. Click “plot” at the bottom of the page, and several plots should emerge.

ATOC 4770/5770 Wind Energy Meteorology | **Spring 2015 In-class exercize**
Prof. Lundquist | **Page 1 of 3**

Figure 18: ATOC 4770/5770 in-class exercise, page 1



Name:

1. Before looking at the data, recall what you have learned about how wind speed changes with height. Does wind speed increase or decrease with height generally? _________________ During what time of day would you expect this change to be most dramatic, and why? __________________________________
____
____
____

2. Look carefully at the plot of wind direction with time. What are the minimum and maximum values of wind direction? ____________ What explains the large shifts between these minimum and maximum values?__________________________
____
____

3. Use the slider bar under the wind direction plot to zoom in on 2015-02-26 00:00 UTC to 2015-02-27 00:00 UTC. What is the difference between UTC time and local time? _________ What time of day (UTC) would you expect wind direction to change significantly with height? ______________ Compare the wind directions between 0600 and 1200 UTC and the wind directions between 1800 and 2400 UTC. Which time period has a more variation of wind direction with height? Does the plot show the expected pattern?
____
____
____

ATOC 4770/5770 Wind Energy Meteorology
Prof. Lundquist

Spring 2015 In-class exercize
Page 2 of 3

Figure 19: ATOC 4770/5770 in-class exercise, page 2

Name:

4. Use the slider bar under the wind *speed* plot to zoom in on 2015-02-26 00:00 UTC to 2015-02-27 00:00 UTC. Compare the wind speeds between 0000 and 1200 UTC and the wind directions between 1800 and 2400 UTC. Which time period has a more variation of wind speed with height? ________________________
   Describe the pattern: are the winds steadily increasing with height during one time of day and not with the other? Why might this be? (Note that the color scheme is not consistent between the wind speed and wind direction plots.)

   ____

   ____

   ____

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   ____

5. Use the slider bar under the *temperature* plot to zoom in on 2015-02-26 00:00 UTC to 2015-02-27 00:00 UTC. Do temperatures typically increase or decrease with height along the tower? ___________ Is this what you would expect? ________________. Use the slider bar to look at several days, and notice how the behavior of the 3m temperature measurement differs from those at 50m and above. What time of day does the 3m temperature frequently show more complex behavior? Can you suggest a reason why might this be?

   ____

   ____

   ____

BONUS ACTIVITIES

6. You can scroll earlier in time to look at winds and temperature for interesting events, like a cold front passage on the evening (local time) of February 20.
7. The tower will certainly influence winds, and may influence temperatures as well. After the northwest boom (nw) instruments are installed on March 2, see if you can identify a wind speed or wind direction difference between nw and se measurements at the same level. Is there a thermal influence as well?

ATOC 4770/5770 Wind Energy Meteorology **Spring 2015 In-class exercize**
Prof. Lundquist **Page 3 of 3**

Figure 20: ATOC 4770/5770 in-class exercise, page 3

b. ATOC 1050 (~ 300 undergraduate students) in-class clicker activity with soundings

Many of CU's large undergraduate courses employ "clickers" for in-class polling and student assessment. (More information on clickers can be found at http://www.colorado.edu/sei/documents/clickeruse_guide0108.pdf .) Dr. Melissa Nigro developed an in-class exercise, based on MGAUS data, for use in her large undergraduate ATOC 1050 course. The slides for this exercise are seen in Figure 21-Figure 22. (These are best viewed on-line and zoomed-in.)

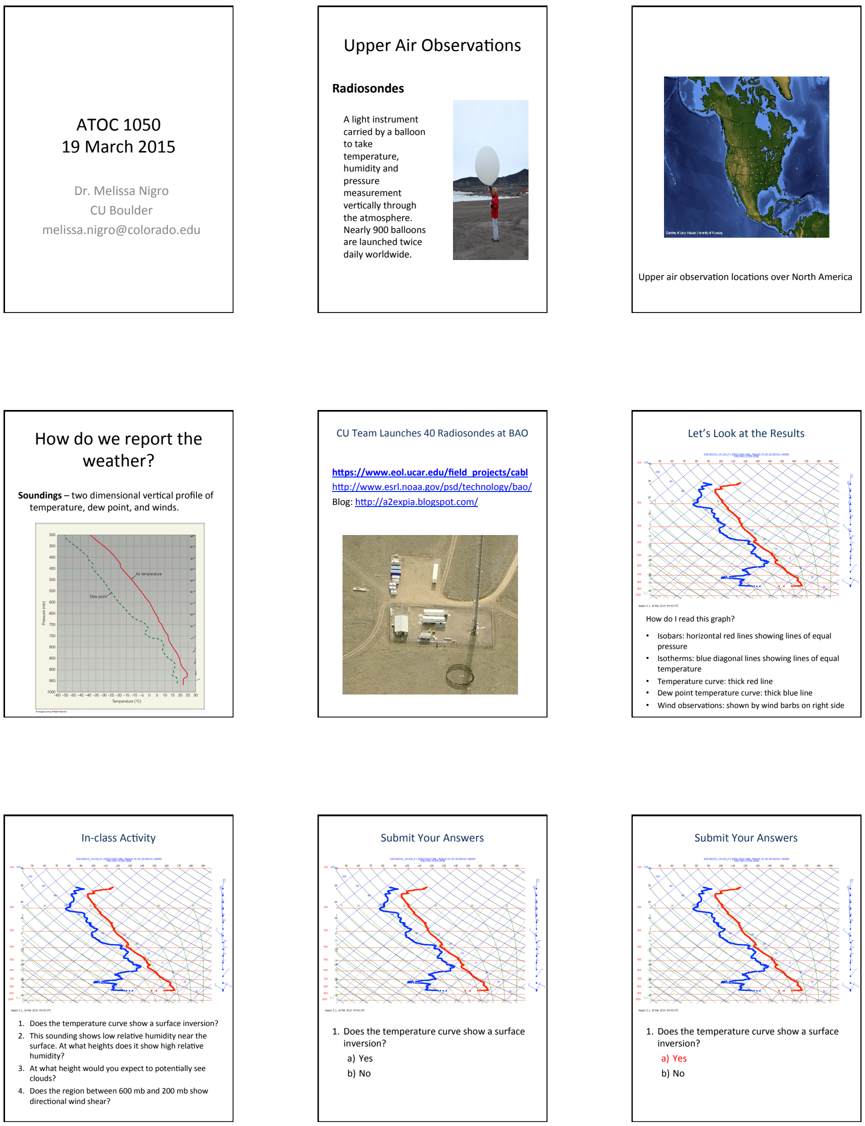

Figure 21: Incorporation of CABL data into ATOC 1050 (~ 300 undergraduate students) by Dr. Melissa Nigro (first nine slides).

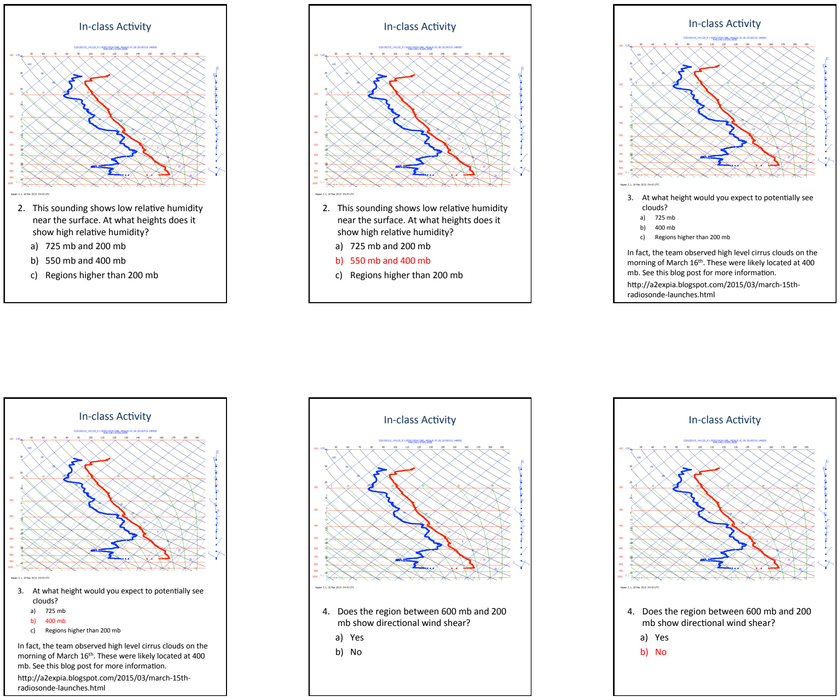

Figure 22: As in Figure 21, last six slides.

c. Graduate student research

CU graduate student Paul Quelet is investigating the performance of the wind profiling lidars located near the BAO tower. As part of that work, he assessed the occurrences of tower wakes on the sonic anemometers deployed on the tower as part of CABL. Distinct wakes are seen at the expected wind directions (Figure 23), and these wakes are not evident in the lidar data, from the system located 200 m south of the tower (Figure 24). Collaborators have assessed turbulence kinetic energy and turbulence kinetic energy dissipation rate from the tower sonics as well, with identical patterns in the wakes.

4. Summary

The "Characterizing the Atmospheric Boundary Layer" (CABL) educational deployment request provided unique scientific opportunities to high school, undergraduate, and graduate students in Colorado's Front Range by complementing and extending the reach of the eXperimental Planetary bound layer Instrumentation Assessment (XPIA) occurring in Spring 2015 at the Boulder Atmospheric Observatory (BAO). We are very grateful for NCAR EOL's superb support before, during, and after the CABL deployments, which included MGAUS, ISFS, and equipment for deployment on the BAO 300-m meteorological tower. As noted above, the on-line data access (through ncharts) proved to be very useful from both real-time research and pedagogical perspectives.

The extensive atmospheric science research enabled by CABL and XPIA is summarized in an NREL technical report (in preparation) and a submission to the *Bulletin of the American Meterological Society* (in preparation) as well as several papers to be submitted to a special issues of *Atmospheric Measurement Techniques*.

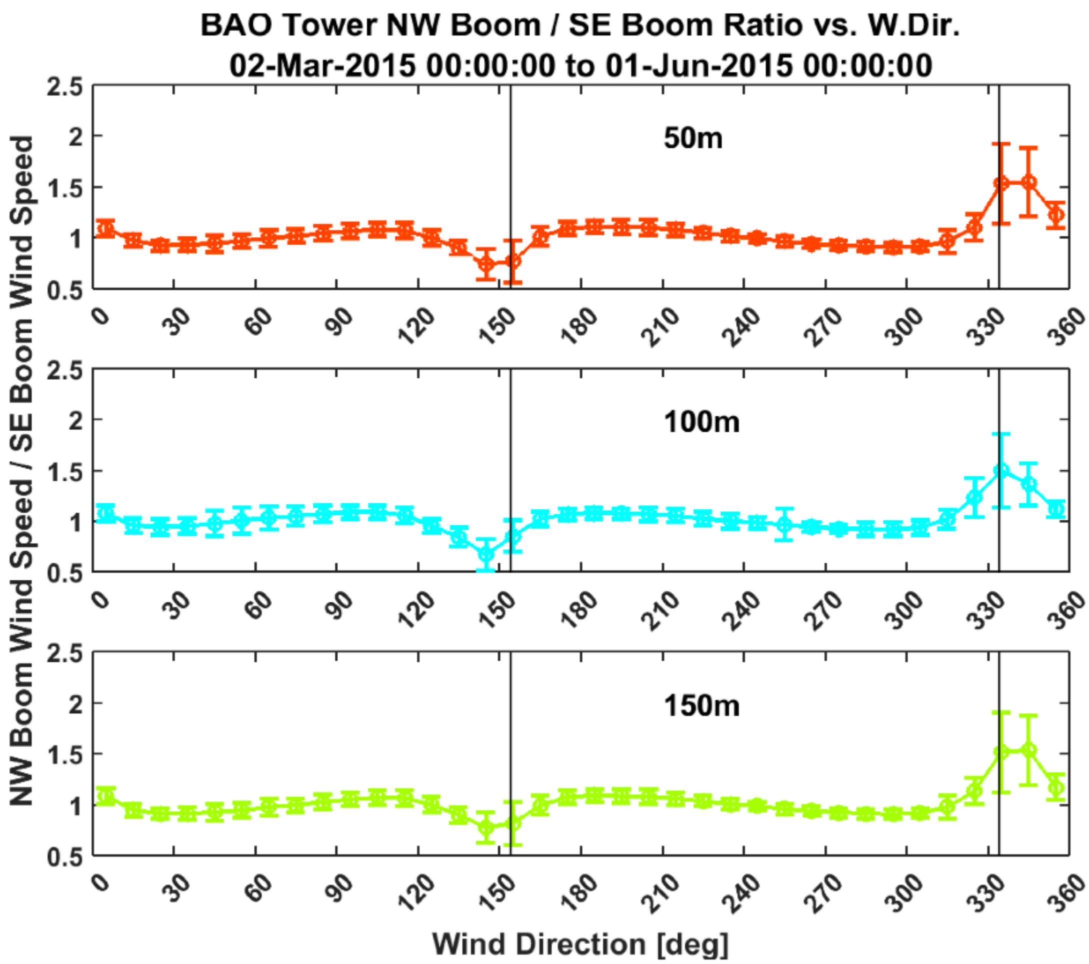

Figure 23: Ratio of wind speed from the sonic anemometer on the NW boom to that from the SE boom as a function of wind direction. Vertical lines mark the direction of the booms. Error bars indicate standard deviations for that wind speed bin. Courtesy Paul Quelet.

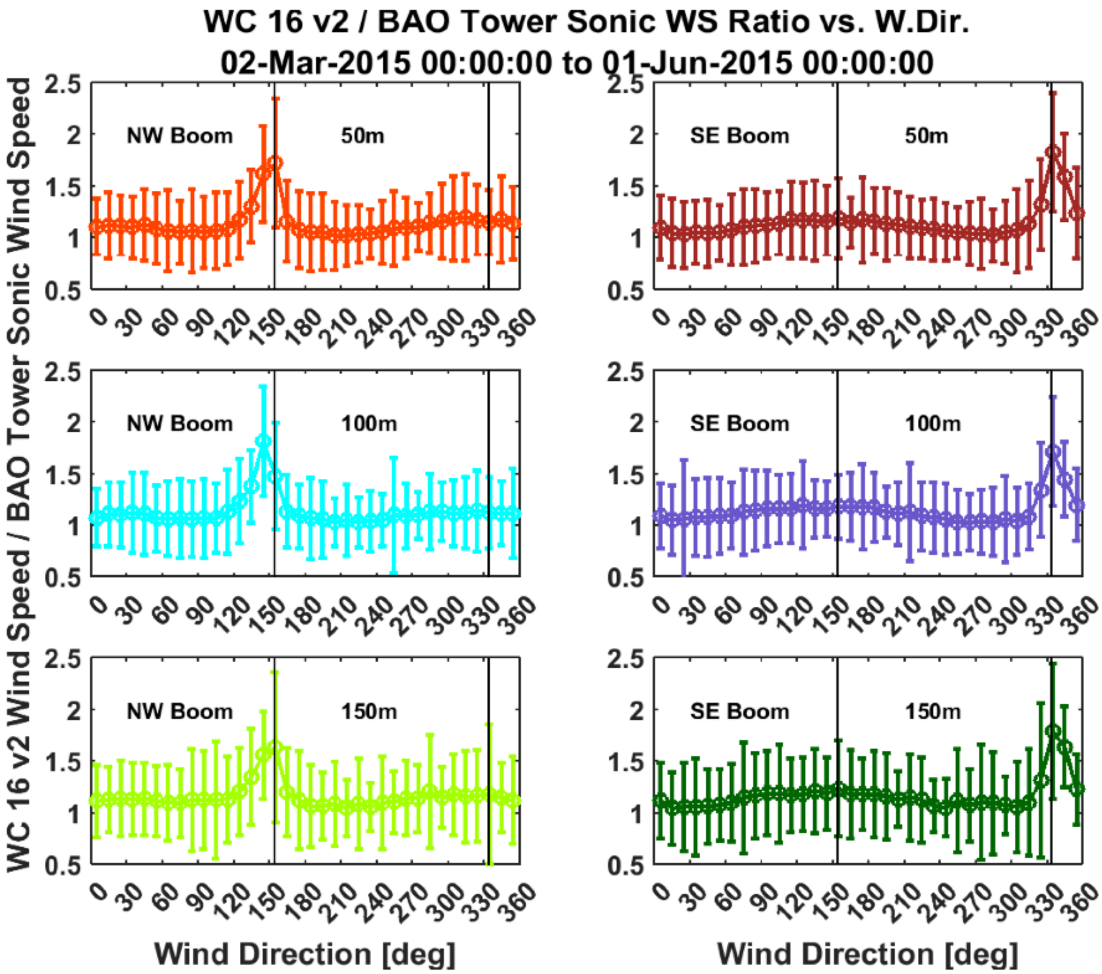

Figure 24: Comparison of wind speeds from BAO tower sonics at three levels (top, center, bottom) to profiling lidar data (WC16 v2) from the lidar supersite 200 m south of the BAO tower. Error bars indicate standard deviations for that 10-degree wind speed bin. Courtesy Paul Quelet.