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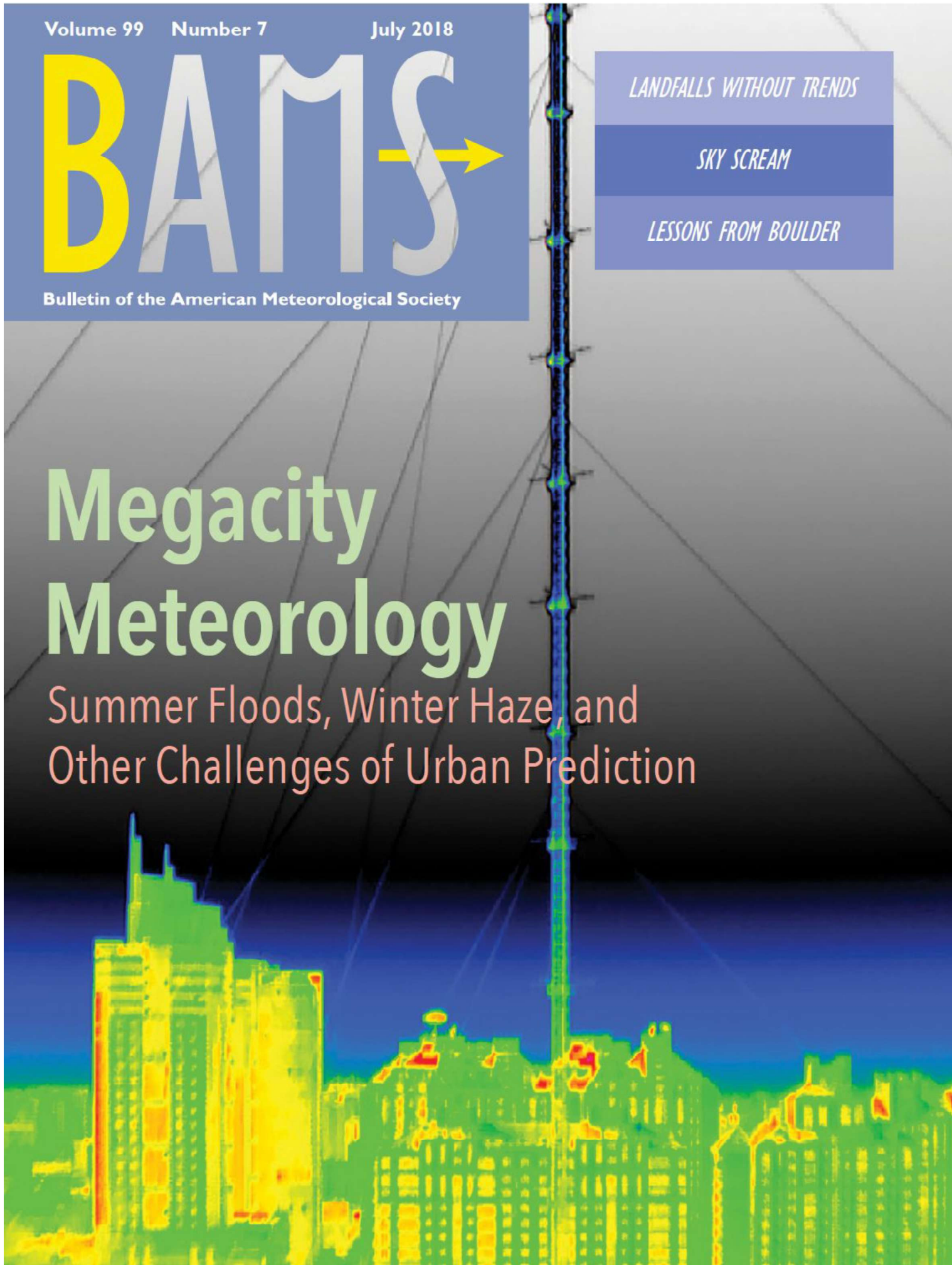
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ON THE COVER

Urbanization forms distinct features such as urban heat islands (UHIs) and enhanced or decreased precipitation. These produce significant challenges to science and society, including rapid and intense flooding, heat waves strengthened by UHIs, and air pollutant haze. The Study of Urban Impacts on Rainfall and Fog/Haze (SURF) seeks a better understanding of urban terrain, convection, and aerosol interactions for improved forecast accuracy. (Image: Ju Li, Institute of Urban Meteorology, China Meteorological Administration)

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BOULDER ATMOSPHERIC OBSERVATORY: 1977–2016

The End of an Era and Lessons Learned

DANIEL E. WOLFE AND R. J. LATAITIS

This essay summarizes the nearly 40-yr history of the Boulder Atmospheric Observatory and its contributions to the research community.

The Boulder Atmospheric Observatory (BAO; Kaimal and Gaynor 1983) was a research facility located near Erie, Colorado, about 32 km northeast of Boulder. It included a unique 300-m-tall meteorological tower (Fig. 1) from which a wealth of fundamental atmospheric turbulence and chemistry data were collected from its installation in 1977 until its decommissioning in 2016. It was most recently maintained and operated by the Physical Sciences Division of the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL), formerly the NOAA Wave Propagation Laboratory (WPL), and later the NOAA Environmental Technology Laboratory (ETL). For almost 20 years beyond an initial estimated useful lifespan of 20 years, the BAO was used for a wide array of planetary boundary layer (PBL) studies and for the validation of novel remote sensing systems spanning radar, lidar, acoustic sounder (sodar), and related technologies. The BAO also hosted solar radiation and greenhouse gas baseline

FIG. 1. The southeast face of the 300-m Boulder Atmospheric Observatory (Photograph courtesy of Dr. Shelby Frisch).



measurements used as part of global networks. The following article is a brief description of the BAO and its nearly 40-yr history, including some of the key studies and their findings that might not have been possible if not for this unique facility. Lessons learned from this research facility can be used to help guide and facilitate the evolution of both existing and future research observatories.

MOTIVATION AND EARLY OBSTACLES.

Initially accepted from the contractor in October 1977, planning for the BAO started back in February 1974 with a workshop held in Boulder, Colorado. The BAO was proposed as a joint meteorological observing facility, and the workshop was attended by representatives from NOAA, the National Center for Atmospheric Research (NCAR), and the Cooperative Institute for Research in Environmental Sciences (CIRES). Why build such a facility? Even though Boulder and the Colorado Front Range were then, as now, a hub for atmospheric research, this was not the primary motivation for the BAO. The former WPL was tasked with the mission of developing instruments to remotely sense and monitor the atmosphere. For 10 years prior to construction of the BAO tower, that research was carried out on a 150-m-tall tower near Haswell, Colorado, 267 km southeast of Boulder. The importance of this work and limitations of the Haswell site, being far from Boulder and with a tower too short to sample the full height of the PBL, prompted WPL to redefine its needs for an improved facility. Moving closer to Boulder was not without its own challenges. Scientifically, the tower had to be placed sufficiently east of the Front Range, so that the PBL development would be relatively unaffected by the Rocky Mountains, and in a region

with minimal residential and commercial development that could impact low-level atmospheric flow. Nonscientific requirements included adherence to Federal Aviation Administration (FAA) aircraft safety restrictions and acquiring a suitable expanse of land with a location large enough and geologically sound enough for the necessary 17-m-deep foundation and guy wire anchors that extended horizontally 244 m from the tower base.

The scope and cost of this project [\$1.5 million (in 1977 U.S. dollars) for the tower along with \$1.5 million for instrumentation] naturally led to media interest and questions as to the need for such a facility. Approval by local governments took time and met with opposition. In today's political climate, a similar project would undoubtedly be met with scrutiny and opposition without clearly articulating the societal benefits relative to the costs. To better inform the public and local decision-makers, public forums were held and news articles were published explaining the goals and virtues of such a facility. Dr. C. Gordon Little, then director of the WPL, in a news article stated that without the BAO, WPL could not develop "instrumentation that can see the weather and instruct computers to devise three-dimensional pictures of the weather patterns that may someday be used to warn citizens of severe storms and prevent airplane crashes" (*Denver Post*, 7 November 1976). Hall (1977) described the BAO tower during its final stages of construction and explained the site selection process, including some of the scientific goals. He also stated the tower would be treated as a national facility open to government and private agencies and universities. Remote sensing within WPL was in its infancy. In addition to hosting fundamental atmospheric studies, Dr. William H. Hooke, one of the original advocates for the facility and head of the WPL Atmospheric Studies Division, stated, "One long-range objective of the BAO research program is to provide a kind of womb for the growth and development of various remote-sensing devices that can ultimately be sent off on their own as mobile atmospheric-probing packages, no longer requiring verifications by in-situ sensors" (WPL Annual Report 1978). Such discussions and justifications were required 40 years ago, and we must continue this conversation today and leverage the success of the BAO and similar observatories to promote the critical need for continuous, long-term atmospheric observations.

In addition to the development and testing of novel remote sensing instrumentation, WPL also realized the need for the transfer of associated technologies, not only of the instruments but of the products they

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The abstract for this article can be found in this issue, following the table of contents.

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produced. This effort focused on developing what was called a Prototype Regional Observing and Forecasting Service, later renamed the Project for Regional Observing and Forecasting Service (PROFS; Schlatter et al. 1985), a forerunner of the work now conducted in ESRL's Global Systems Division with the Advanced Weather Interactive Processing System (AWIPS). Thus, the ground-based observations made at the BAO played a critical role in the development of today's weather forecasting technology, which ultimately saves lives and money.

TECHNICAL DETAILS. The centerpiece of the facility was a 300-m-tall triangular tower (designed for 500 m should the need arise and necessary funding become available) initially instrumented at eight levels with both fast- and slow-response air temperature, relative humidity, and wind sensors. The site, near Erie, Colorado, was located in relatively flat terrain, initially surrounded by agricultural and rangeland fields. Today, urban development has encroached quite near to the site. The tower and its instrumentation were the focal points of the BAO, but its two elevator systems made it one of the most unique and user-friendly research towers in the world. At the time of its construction it was one of the

tallest meteorological towers. Although over the years many taller towers have been erected, few if any had the capabilities of the BAO. With a three-passenger inside elevator, scientists could easily transport and mount instrumentation at any of the fixed levels or to the many other platforms throughout the height of the tower. The outside instrument carriage (IC) took the research capabilities of the BAO to another level, making it possible to profile the atmosphere from the surface to 300 m, something that had not been possible before. At 300 m, the tower extended above the nocturnal boundary layer and was able to track the evolution of the daytime convective boundary layer until late morning on most days. Under conditions of strong subsidence or downsloping winds, a capping inversion associated with air pollution events in the Denver area remained within the height of the tower.

Several remote sensing systems were part of the facility along with near-real-time processing and publicly available display capabilities greatly enhancing its usefulness to scientists and the public. As part of the design concept, data were collected 24–7 with a near-real-time output every 20 min. Data were also archived on nine-track tapes. Figure 2 shows Dr. Chandran Kaimal annotating a strip chart recorder in the computer systems trailer. Figure 2 shows Dr. Chandran Kaimal annotating a strip chart recorder in the computer systems trailer

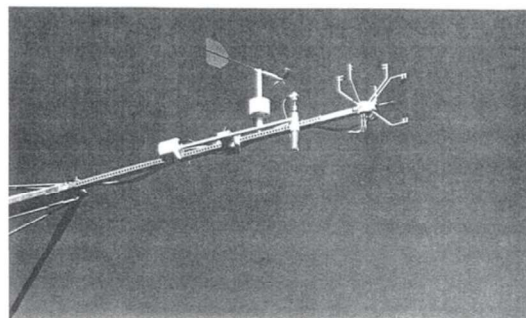


FIG. 2. (left) Dr. Chandran Kaimal annotating a strip chart recorder in the systems trailer. (right) The initial set of instruments (sonic anemometer, propeller-vane anemometer, and aspirated temperature and relative humidity sensor) mounted on one of the eight fixed booms.

and the instrumentation mounted on one of the eight instrumentation booms. Figure 3 shows an example of a 20-min computer output that included turbulent-flux parameters from the fast-response sensors (10 Hz), mean data from the slow-response sensors (1 Hz), and output from the microbarograph array (Hooke 1979; Bedard and Georges 2000) and optical triangle (Hooke 1979; Lawrence et al. 1972; Tsay et al. 1980). The initial on-site data collection system used a Digital Equipment Corporation (DEC) PDP-11/34 minicomputer. The data were sent in real time to Boulder where it could be visualized and analyzed by NOAA and visiting scientists.

Some of the instrumentation, their design concepts, and the data collection system for the BAO tower came from the Air Force Cambridge Research Laboratories under the direction of Dr. Kaimal (Kaimal et al. 1974) and had been a part of the groundbreaking 1968 Kansas and 1973 Minnesota boundary layer field studies (Izumi 1971; Izumi and Caughey 1976). Included were redesigned sonic anemometers with fast-response platinum-wire thermometers.

KEY EXPERIMENTS AND CONTRIBUTIONS FROM THE BAO.

The first two major experiments at the BAO took place in the spring and fall of 1978 and required wiring and instrumenting of the tower to be completed in just six months (October 1977–March 1978) under some very challenging conditions. The first experiment was a site evaluation to help understand the effects of the uneven terrain on the temporal and spatial characteristics of the PBL. The results from this evaluation showed an atmospheric structure similar to flat terrain (Kaimal et al. 1982a,b; Haugen 1978; Haugen and Schwiesow 1979). Measurements of convective plumes (Wilczak and Tillman 1980) resulted in a better understanding of plume structure and transport. Using the continuous data to examine wind flow patterns, Hahn (1981) found diurnal wind oscillations within the PBL for days with southerly geostrophic winds. The second experiment, Project Phoenix (Hooke 1979), again was a study of the PBL looking at its growth and decay, with the goal of evaluating and comparing many of the remote sensing systems being developed by WPL as well as creating a complete dataset of the convective

BOULDER ATMOSPHERIC OBSERVATORY DATA SUMMARY										
AVERAGING PERIOD= 20.00 MIN									26 SEP 78 640 MST	
Z[M]	VWES	VSDU	W	VH	AZ	PVS	PVD	T	TD	L
10	-0.26	2.34	-0.07	2.35	174.	2.24	172.	11.89	7.62	15.98
22	-0.42	3.87	-0.12	3.89	174.	3.77	173.	13.46	7.96	-2.47
50	0.68	2.82	-0.13	2.90	193.	2.83	194.	14.50	4.48	*****
100	1.61	1.36	-0.12	2.11	230.	2.11	230.	15.22	1.34	*****
150	2.13	-0.60	-0.06	2.22	286.	*****	****	16.69	-1.73	*****
200	2.60	-2.85	-0.22	3.86	318.	4.26	307.	17.17	-1.65	*****
250	2.89	-3.51	-0.27	4.55	321.	*****	****	18.50	-3.85	*****
300	2.15	-2.66	-0.12	3.42	321.	4.07	331.	18.55	-3.92	*****
Z[M]	UU	VV	WW	TT	UV	VW	UT	VT	UW	WT
10	0.1112	0.0740	0.0267	0.1034	-0.0121	-0.0002	0.0050	-0.0339	-0.0110	-0.0060
22	0.0228	0.0144	0.0053	0.0500	0.0022	0.0013	0.0161	-0.0007	-0.0016	0.0022
50	0.0919	0.0598	0.0116	0.0988	0.0023	-0.0013	-0.0688	0.0146	0.0072	-0.0015
100	0.1767	0.0313	0.0054	0.1163	0.0176	-0.0005	-0.1266	-0.0022	0.0010	-0.0005
150	0.1061	0.1430	0.0170	0.0437	0.0892	0.0133	-0.0585	-0.0575	0.0112	-0.0048
200	0.5532	0.3183	0.0355	0.2985	-0.3418	-0.0214	-0.3641	0.2115	0.0403	-0.0293
250	0.1468	0.0421	0.0204	0.0123	-0.0306	0.0014	0.0234	-0.0118	0.0139	0.0018
300	0.2766	0.3177	0.0435	0.0438	-0.2578	-0.0083	0.0693	-0.0842	0.0171	0.0022
Z[M]	UWV	UWV	VWV	UWV	VWV	UWV	UWV	VWV	UWV	UWV
10	0.00072	-0.00360	-0.00075	0.00262	-0.00023	0.00058	-0.00279	0.00098	0.00459	-0.00152
22	-0.00022	0.00040	0.00013	0.00001	-0.00011	0.00009	0.00053	-0.00004	-0.00012	0.00044
50	-0.00111	-0.00197	-0.00025	-0.00158	0.00123	0.00052	0.00109	0.00152	0.00284	0.00025
100	0.00013	-0.00028	0.00043	0.00160	0.00017	-0.00011	-0.00058	-0.00013	0.00051	0.00012
150	-0.00011	-0.00053	0.00006	-0.00279	0.00004	-0.00003	0.00134	-0.00013	0.00080	-0.00054
200	0.00508	-0.00487	0.00281	-0.00439	-0.00386	0.00102	0.00753	-0.00794	0.00399	-0.00948
250	0.00094	-0.00247	0.00012	-0.00365	-0.00005	-0.00015	-0.00051	-0.00002	-0.00025	0.00008
300	-0.00140	0.00643	-0.00804	0.00397	-0.00284	0.00284	-0.00084	0.00227	0.00254	-0.00071
OPTICAL TRIANGLE					RMS PRESSURE VALUES [MICROBARS]					
V [M/SEC]	AZ[DEG]	CONV[1/SEC]	CN-SQR*10**12		STN 1	STN 2	STN 3	STN 4	STN 5	
1.09	195.	-0.00059	0.00673		2.167	1.905	1.379	2.220	1.543	
PRESSURE[MB]					SOLAR RAD[LY/MIN]					
844.14					0.18					

FIG. 3. Copy of original 20-min computer printout. (top) The mean parameters for all eight levels, (middle) the temperature and momentum fluxes calculated from the sonic anemometer and platinum-wire temperature sensors, and (bottom) the optical triangle and microbarograph array data.

boundary layer and many of its underlying atmospheric processes. Both experiments used research aircraft and surface observations from the Portable Automated Mesonet (PAM; Brock and Govind 1977). The fall experiment brought together a variety of remote sensors from the Boulder research community (radars, lidars, sodars, aircraft, microwave radiometers, optical wind sensors). This initial experiment, and so-called christening of the BAO facility, led to several more important studies and research efforts over the next 10 years. These again included boundary layer studies (nocturnal and diffusion) and various instrument comparisons such as sodars and an Environmental Protection Agency (EPA) study to look at the performance characteristics of various wind sensors to measure atmospheric turbulence. Because the BAO operated 24–7 a large dataset covering a wide range of meteorological conditions was available to researchers for analysis.

Over the years, the BAO hosted several large national and international experiments and numerous smaller ones. One of the largest was the Boulder Low-level Intercomparison Experiment (BLIE), a World Meteorological Organization (WMO)-sponsored workshop/experiment (Baynton et al. 1981; Kaimal et al. 1980a) with 11 WMO member nations participating.

A total of 23 different measurement systems/sensors were deployed including radars, sodars, tethered and free-flying balloon packages, a short-instrumented tower, and some of the first instrumented unmanned aerial vehicles (UAVs; Fig. 4). The objective of these intercomparisons was to better understand the different low-level atmospheric sounding techniques. The first use of the instrument carriage was during BLIE, during which radiosonde and tethered balloon instrument packages were transported up and down the tower for both intercomparison and comparison with the tower sensors. This resulted in the refinements that appear in today's radiosondes, tethersondes, and dropsondes.

In 1982 the Boulder Upslope Cloud Observation Experiment (BUCOE; Gossard 1982; Gossard et al. 1982) was conducted. After instrumenting the carriage with a suite of fast-response sensors (Fig. 5; Kaimal and Gaynor 1983) it could both profile the atmosphere or be placed at an altitude between one of the fixed tower levels (10, 22, 50, 100, 150, 200, 250, and 300 m) recording data as turbulent features of interest oscillated up and down the height of the tower. In addition to increasing the understanding of the fundamental properties of the lower atmosphere, the BAO played a key role in atmospheric chemistry

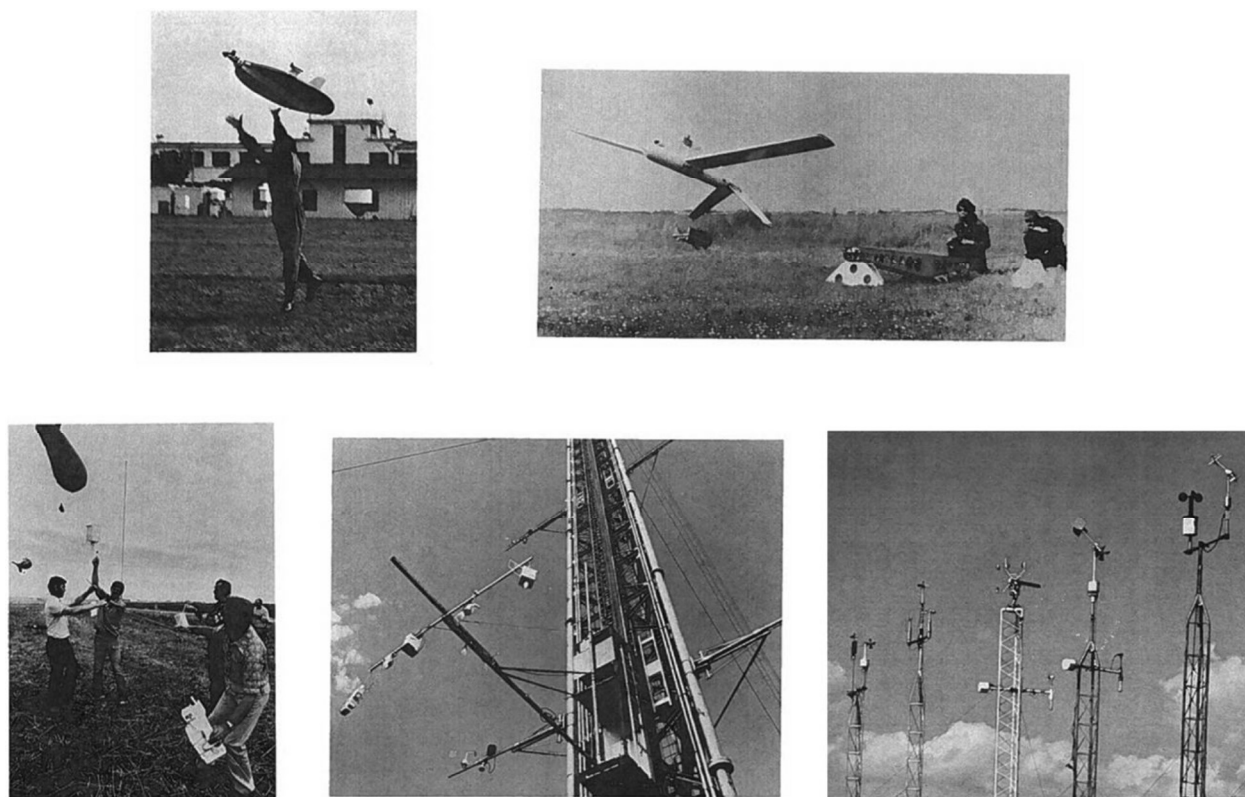


FIG. 4. Pictures from BLIE 1979 and (bottom right) EPA comparison 1985.

and air pollution studies. In 1988–89 two large air pollution studies were conducted along the Front Range. The Denver Brown Cloud Studies (Neff 1997), a joint effort with NOAA, local agencies, and universities, set out to collect meteorological, aerosol, and air chemistry data to help better understand the air pollution issues in the Denver Front Range region. Results from these studies helped shape some of the early plans to improve regional air quality. The BAO was one of the major sampling sites and a major contributor to understanding the meteorology along the Front Range.

BAO AS A NUCLEUS FOR OTHER PROJECTS. As mentioned earlier, two nontower sensors were a part of the initial BAO configuration. The microbarograph array (Hooke 1979; Bedard and Georges 2000) consisted of four ground sites, one located near the base of the tower and three others located approximately 128 m away, capable of measuring the speed and direction of various infrasound signals. In the early days arrays similar to this were used to detect underground nuclear tests by the pressure waves generated as the Earth's crust was deformed. Over the years the research focused on

naturally occurring infrasound as clues to avalanches, meteors, tornadoes, volcanoes, severe-weather systems, and turbulence (Bedard 2005). One famous event observed in the data from the BAO infrasound array was the May 1980 eruption of Mount Saint Helens. The optical triangle (Hooke 1979; Lawrence et al. 1972; Tsay et al. 1980) consisted of three short towers located 244 m from the main-tower base forming an equilateral triangle 450 m on a side. On top of each tower was a laser source and receiver that could measure the average wind along a light beam using scintillation techniques. Wind flowing perpendicular to each leg of this triangle represented either convergence or divergence into and out of this triangle. These data have been used to study gravity waves and were also compared to microbarograph data.

In 1985 ESRL's Global Monitoring Division (GMD; formerly the Climate Monitoring and Diagnostics Laboratory) first began using the BAO for some of their research and installed a suite of radiometers to measure various components of incoming and outgoing solar radiation (Dutton 1990). In 1992 these measurements were expanded (diffuse and direct measurements) and incorporated into the World Climate Research Programme (WCRP) Baseline

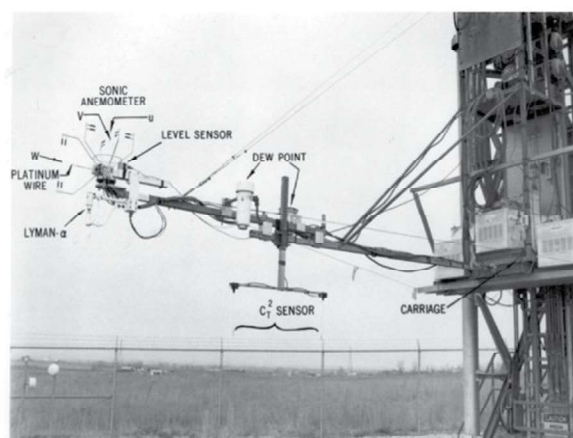
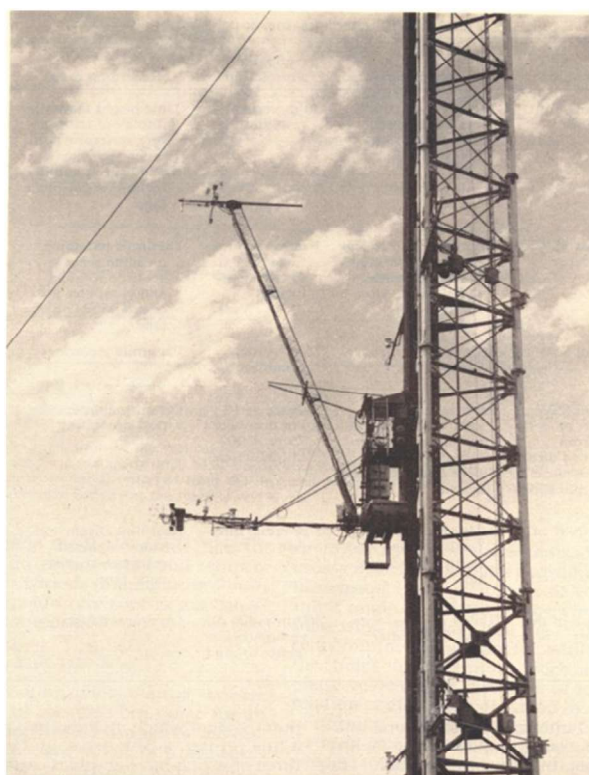


FIG. 5. (left) The movable IC during BUCOE 1982 with an additional 10-m boom added for increased vertical resolution on top of the standard fixed tower booms. **(right)** A suite of turbulence instruments mounted on the carriage boom along with data collection systems on the main carriage platform.

Surface Radiation Network (BSRN) (König-Langlo et al. 2013), 1 of 68 sites worldwide. The BSRN is a worldwide network of monitoring sites designed to provide high-quality short- and longwave surface radiation measurements for validation of satellite-based estimates and comparisons to global climate model (GCM) simulations. In 2007 GMD added the BAO to its tall-tower network (Andrews et al. 2014). Three levels (22, 100, and 300 m) on the tower were sampled continuously and provided regionally representative measurements of carbon dioxide (CO_2). These data were then used to help identify long-term trends, seasonal variability, and spatial distribution of carbon cycle gases as part of the Global Greenhouse Gas Reference Network. Also at 300 m a weekly flask sample was taken and analyzed for CO_2 , methane (CH_4), carbon monoxide (CO), dihydrogen (H_2), nitrous oxide (N_2O), and sulfur hexafluoride (SF_6) and by the University of Colorado (CU) Institute for Arctic and Alpine Research (INSTAAR) for the stable isotopes of CO_2 and CH_4 and for many volatile organic compounds (VOCs). These measurements formed one of only six such global sites.

Many studies made use of previously collected BAO tower data. One such study was in support of the Department of Energy's (DOE) wind energy research efforts (Kaimal et al. 1980b). At about the same time the BAO went operational the world's first wind farm also came online in New Hampshire. This endeavor was not totally successful because of the lack of understanding of wind variability and turbulence effects on wind turbines. In cooperation with the DOE, turbulence data from the BAO tower during two high-wind events were used to validate gust models and better understand the stresses a wind turbine might experience. These results were then applied to the design of future wind generators and farms. In the nearly 40 years since this study, remote sensors (sodars and lidars) have become extremely useful for mapping the winds of potential or existing wind farms (Banta et al. 2013, 2015; Wilczak et al. 2015; Lundquist et al. 2017).

UNIQUE APPLICATIONS. Many interesting uses of the tower and its data have taken place throughout its history. In March of 1982 the instrumentation running on the tower and the then-operational PROFS mesonet (Brock and Govind 1977; Pratt and Clark 1983) captured the passage of a very intense cold front. Shapiro (1984) used these data to analyze the microscale structure of a density current, which is known to be a triggering mechanism for mesoscale convective systems. The

high-temporal-resolution data revealed that the horizontal gradients of the front were concentrated within a narrow 200-m horizontal distance. One of the more unique uses included a study whose purpose was to discredit the results of earlier tower measurements that seemed to show that Newton's $1/r^2$ gravity law was wrong for "short" distances, where r is the distance between two objects (Cruz et al. 1991). Another nonstandard dataset collected at the BAO was from a web camera. Installed at 300 m and facing approximately south, it had a field of view from 34° to 334° . The camera was programmed to capture images at a variety of different angles and time resolutions. Two of the more interesting sets of images were a zoom looking at downtown Denver every 10 min and an hourly panorama with $6\text{--}50^\circ$ panels. The view of downtown Denver showed the evolution of many pollution events and the impact of a trapping inversion. ESRL's Global Science Division devised a method to simulate clouds and aerosols (Fig. 6) using the 300° panorama data in conjunction with the Local Analysis and Prediction System (LAPS) to validate existing algorithms and assimilating observed data in numerical models (Fig. 7; Jiang et al. 2015). The web camera had also captured many interesting events, including the Fourmile Canyon Fire in 2010 showing the smoke plume flowing eastward toward the plains. Stone et al. (2011) used this event to analyze the impacts of smoke on incoming solar radiation at the BAO along with other sites impacted by the plume. Not to be forgotten is the opportunity to drop objects off the top of a very high tower without the danger of hitting someone or something below. This capability proved useful for studying different parachute designs for dropsondes (Fig. 8) and testing how well newly designed unmanned aerial vehicles can glide to a "soft" landing.

LATER YEARS AND DECOMMISSIONING.

The site itself and the surroundings changed over the years. Commercial and private development, especially in the last five years, had crept closer and closer. The pros and cons of the scientific impact of these changes have been discussed. Boundary layer meteorologists and some climatologists felt this encroachment had a negative impact. Others felt the BAO could capture important anthropogenic changes to the local environment. Development also meant increases in pollution and particulates. The BAO happened to be located in the middle of the Denver–Julesburg Basin (first discovered in 1901) that underlies the Denver metropolitan area and the

eastern side of the Rocky Mountains where there has been major oil and gas exploration. Around 2005 ESRL's Chemical Science Division started planning experiments collocated at the BAO to study the effects of increased oil and gas activity.

Figure 9 is a timeline of some of the more important events and field campaigns throughout the history of the tower. In the earlier years of the BAO the focus was on the boundary layer and instrumentation spanning both remote sensing and in situ studies. In the latter years the focus changed more to atmospheric chemistry and aerosol research with some intercomparisons of remote sensors (lidars) whose technology had been transferred to the private sector. In 2011 and 2014, a portable instrument shelter with amenities (PISA; Fig. 10) was placed on the instrument carriage filled with various air chemistry and

aerosol measuring instruments. Nearly 300 vertical profiles were made over a 26-day period during the Nitrogen, Aerosol Composition, and Halogens on a Tall Tower (NACHTT) experiment (Brown et al. 2013).

Even though the BAO has been decommissioned, one can still access some of its data. In 2007 a new data collection system was implemented with continuous measurements at three levels (10, 100, and 300 m). One-minute-average temperature, relative humidity, and wind speed and direction along with surface pressure and precipitation are available. At about the same time a laser ceilometer and a monostatic sodar were acquired and run continuously. These data can be accessed through the BAO data browser described in the BAO Data Browser appendix. Data from special experiments such as the Front Range

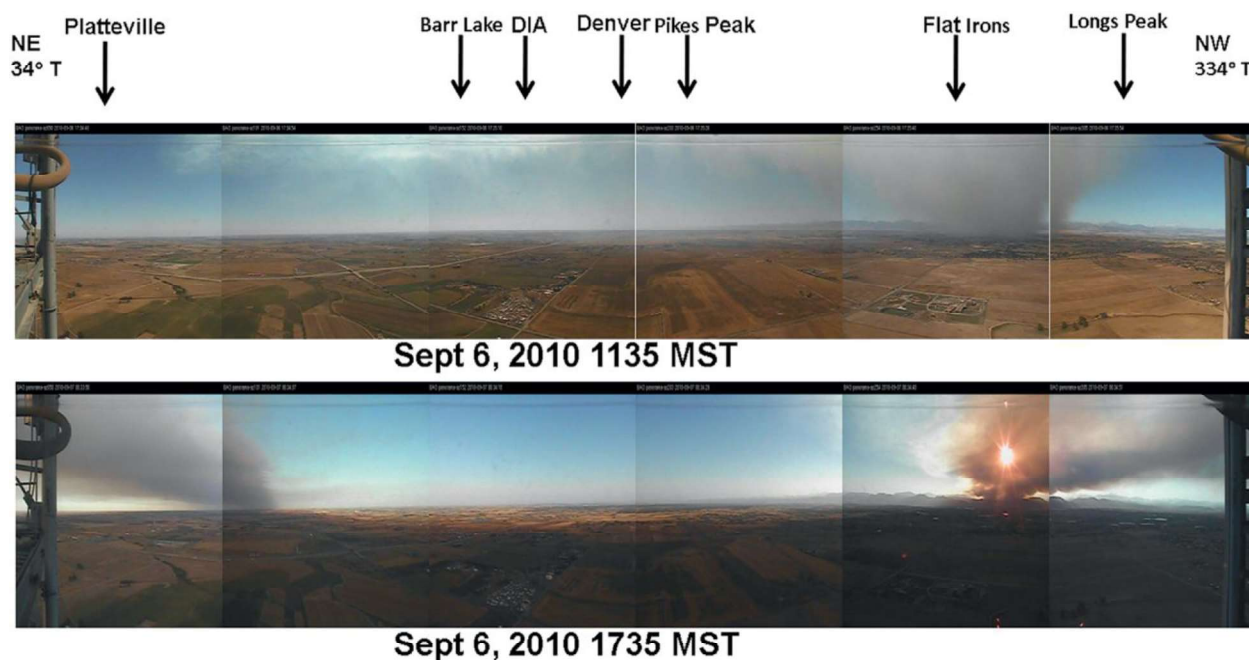


FIG. 6. Panorama (34°–334°) created from a web camera located at 300 m. (top) The Fourmile Canyon Fire in its early stages. (bottom) The setting sun behind the smoke plume coming toward the BAO off the mountains to the right and the smoke plume flowing eastward out to the plains away from the BAO on the left.



FIG. 7. (top) LAPS simulation and (bottom) actual BAO web camera panorama.



FIG. 8. Various parachute drop tests, including (bottom right) NCAR dropsonde.

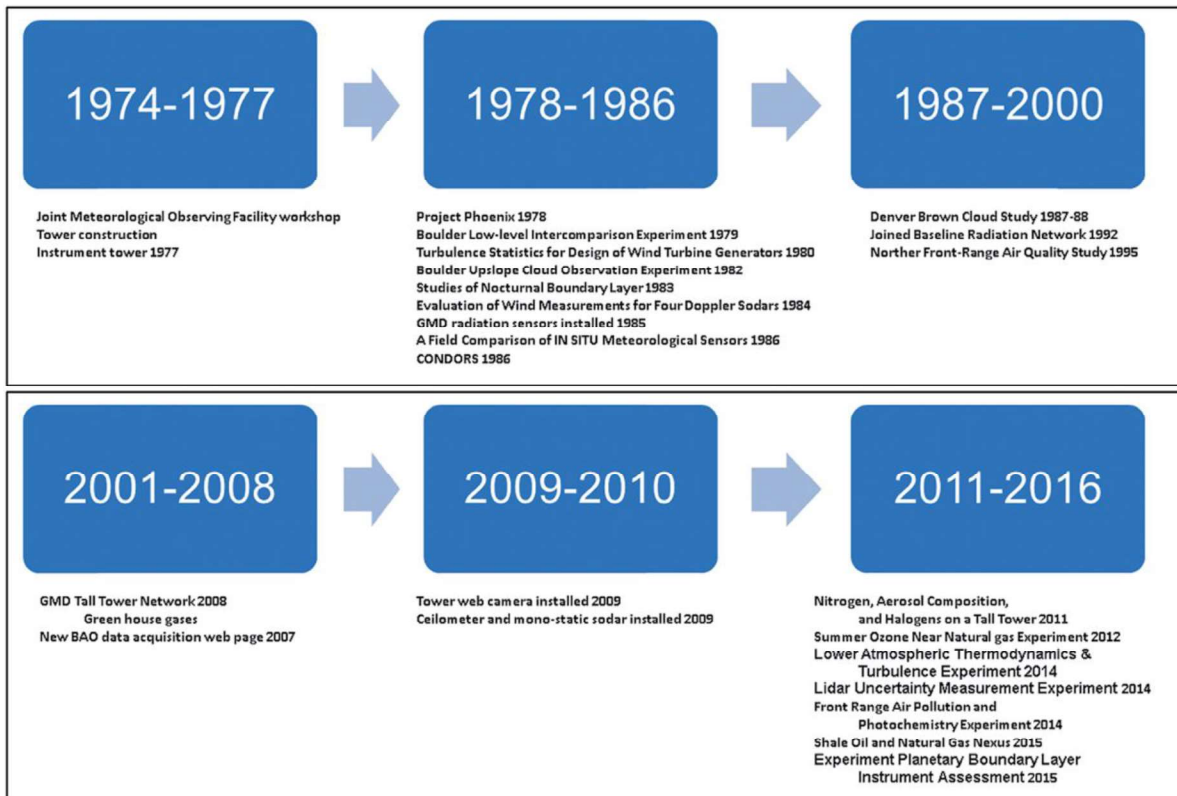


FIG. 9. Timeline of major events throughout the history of the BAO.



FIG. 10. BAO tower, PISA, and NASA P-3 during NACHTT 2011.

Air Pollution and Photochemistry Experiment 2014 (FRAPPE; Pfister et al. 2017) and the Experimental Planetary Boundary Layer Assessment 2015 (XPIA; Lundquist et al. 2017) are also available, including periods of fast-response sonic data at multiple levels on the tower. These periods are described in the “Tower Data” appendix. Data from other instrumentation operated at the tower are also often available during these periods, including wind profiler, microwave radiometer, laser, sodar, distrometer, and aerosol and chemical measurements. As mentioned above, the BAO Data Browser appendix gives a brief description of the BAO “data browser” that is still available for online access to BAO data.

CONCLUSIONS AND LESSONS LEARNED. Even though the BAO is no longer operational, its legacy lives on through the research, the development of new remote sensing instrumentation and technology, its data archive, and the more than 400 journal articles citing the BAO over the last 40 years. How might the BAO and its resources have been better used, and could the BAO have somehow survived? Although the lack of sustained support was the primary cause for its decommissioning, there were other reasons for sunseting this facility, including infrastructure age. Though the tower itself was structurally sound, components such as the passenger and instrument elevators were nearing the end of their life cycle and would require replacement at considerable cost.

The boom in housing and commercial development was impacting low-level atmospheric flow, making boundary layer measurements as they were originally envisioned no longer possible. Not all measurements would be negatively impacted by the encroachment.

For example, changes in atmospheric chemistry and changes in the boundary layer meteorology with the transition from rural to urban land cover could have been quantified. In addition, continuous air sampling was one way to track the impact of the growing oil and gas exploration throughout the region. Similarly, ongoing long-term continuous surface radiation measurements, as pointed out by Dutton (1990), were deemed important to understanding climatologically significant changes in cloudiness (global dimming and brightening) that occur over decadal scales.

Many avenues were pursued to promote the BAO during its lifetime, including asking the research community for their support and drafting a document to be sent to the National Science Foundation (NSF) requesting the BAO be considered a National Facility as proposed by Hall (1977). Support for the BAO throughout the research community was very strong, but only in terms of acknowledging its importance as a research facility. Funding by these same supporters was not available. Probably the biggest lesson learned was that no matter how useful the BAO was seen to be, it required more than just small individual research projects for support. In the early years many large, often international, research projects were conducted at the BAO. That pattern changed with a greater number of smaller projects replacing larger efforts with a corresponding reduction in core support for the facility.

Did the type of research that could be conducted at the BAO lead to its decommissioning? There is no evidence to suggest that this was the case, and in fact the ways in which the BAO was used continued to diversify. Even as the future of the BAO was being discussed research continued with the BAO serving as the centerpiece of FRAPPE (Pfister et al. 2017) and of XPIA (Lundquist et al. 2017) field programs. In hindsight everything possible was done to try to prolong the life of the BAO, but the resources needed to support it as a community facility were simply not available.

ACKNOWLEDGMENTS. We thank the many people who made the Boulder Atmospheric Observatory a world-class research facility. A great debt of gratitude is owed to the late Dr. C. Gordon Little, without whose vision and support the BAO would never have been constructed. Dr. Chandran Kaimal and his group from Air Force Cambridge Research Laboratories, who brought their boundary layer expertise to NOAA and Boulder, Colorado, were instrumental in launching initial groundbreaking studies. Finally, to the engineers, computer specialists, administrative support staff, and scientists over the years who supported the BAO and its science, we are deeply grateful.

APPENDIX: TOWER DATA

Tower (surface, 10, 100, 300 m)

- Start: 15 Jun 2007; end: 11 Jul 2016
- Surface precipitation, pressure, temperature (T), relative humidity (RH), wind speed, and wind direction
- <ftp://ftp1.esrl.noaa.gov/psd3/bao/Tower/Processed/monthly/>
- <ftp://ftp1.esrl.noaa.gov/psd3/bao/Tower/Processed/daily/>

300-m ozone (GMD)

- Start: 11 Jul 2008; end: 11 Jul 2016 <ftp://ftp1.esrl.noaa.gov/psd3/bao/Tower/Ozone/Processed/monthly/>
- <ftp://ftp1.esrl.noaa.gov/psd3/bao/Tower/Ozone/Processed/daily/>
- 10-m ozone (GMD) (www.esrl.noaa.gov/gmd/dv/data/index.php?parameter_name=Ozone&site=BAO)

TOWER SONIC DATA

Tower carriage sonic comparison

- Start: 13 Aug 2010; end: 4 Feb 2011
- ftp://ftp1.esrl.noaa.gov/psd3/bao/Special-Data-Sets/SONIC_Comparison/data/

University of Massachusetts

- Start: 7 Aug 2007; end: 27 Aug 2007
- Start: 15 Dec 2007; end: 31 Dec 2007
- Start: 1 Jan 2008; end: 5 Aug 2008
- <ftp://ftp1.esrl.noaa.gov/psd3/bao/Special-Data-Sets/UMASS/Processed/>
- Andreas Muschinski (www.nwra.com/people/235/)

FRAPPE

- Start: 31 Jul 2014; end: 8 Aug 2014 (on instrument carriage)
- <ftp://ftp1.esrl.noaa.gov/psd3/bao/Special-Data-Sets/FRAPPE/>

XPIA

- Start: 1 Mar 2015; end: 25 Jun 2015
- DOE data archive and portal (<https://a2e.energy.gov/auth/register>)
 - <https://a2e.energy.gov/data/xpia/ecor.z01.00>

NONTOWER DATASETS

Surface flux (near 10-m tower)

- Start: Oct 2010; end: Sep 2011
- Surface, 15-cm, and 10-cm subsurface T, and surface volume water content (%)
- <ftp://ftp1.esrl.noaa.gov/psd3/bao/Special-Data-Sets/SurfFlux/>

University of Colorado (CU) 10-m flux tower

- Start: 26 Apr 2011; end: 26 May 2016
- <ftp://ftp1.esrl.noaa.gov/psd3/bao/Special-Data-Sets/CU/10mTower/>

Web camera

- Start: 22 Nov 2009; end: 26 May 2016
- ftp://ftp1.esrl.noaa.gov/psd3/bao/Web_Camera/

Sodar (monostatic ~2 KHz)

- Start: 6 Jul 2009; end: 22 Jul 2016
- <ftp://ftp1.esrl.noaa.gov/psd3/bao/Tower/Sodar/Raw/>
- <ftp://ftp1.esrl.noaa.gov/psd3/bao/Tower/Sodar/Images/>

Ceilometer (Vaisala CL31)

- Start: 12 May 2009; end: 17 Jul 2016
- <ftp://ftp1.esrl.noaa.gov/psd3/bao/Ceilo/raw/>

Radiometer (Radiometrics I100)

- Start: 13 Feb 2014; end: 10 Feb 2015
- <ftp://ftp1.esrl.noaa.gov/psd3/bao/Special-Data-Sets/Radiometer/MP-I100/raw/SCI/>

GMD Tall Tower (carbon tracker)

- www.esrl.noaa.gov/gmd/ccgg/carbontracker/

GMD solar radiation (WMO BSRN)

- Start: Jan 1992; end: Jun 2016
- www.pangaea.de/ddi?request=bsrn/BSRNEvent&format=html&title=BSRN+Stations

APPENDIX: BAO DATA BROWSER

Data Browser main window (Fig. A1; www.esrl.noaa.gov/psd/technology/bao/browser/)

- Level
 - Combined
 - Variable
 - T/RH time series, wind speed/direction time series, histogram T/RH (monthly), ozone 300-m time series
 - Surface
 - Variable
 - Pressure and precipitation time series
 - Ceilometer backscatter and cloud base (daily)
 - Sodar backscatter (daily)
 - 10, 100, 300 m
 - Variable
 - T/RH time series, wind speed/direction time series, wind rose (monthly)
- Year
 - 2007–16
- Month
 - Jan–Dec

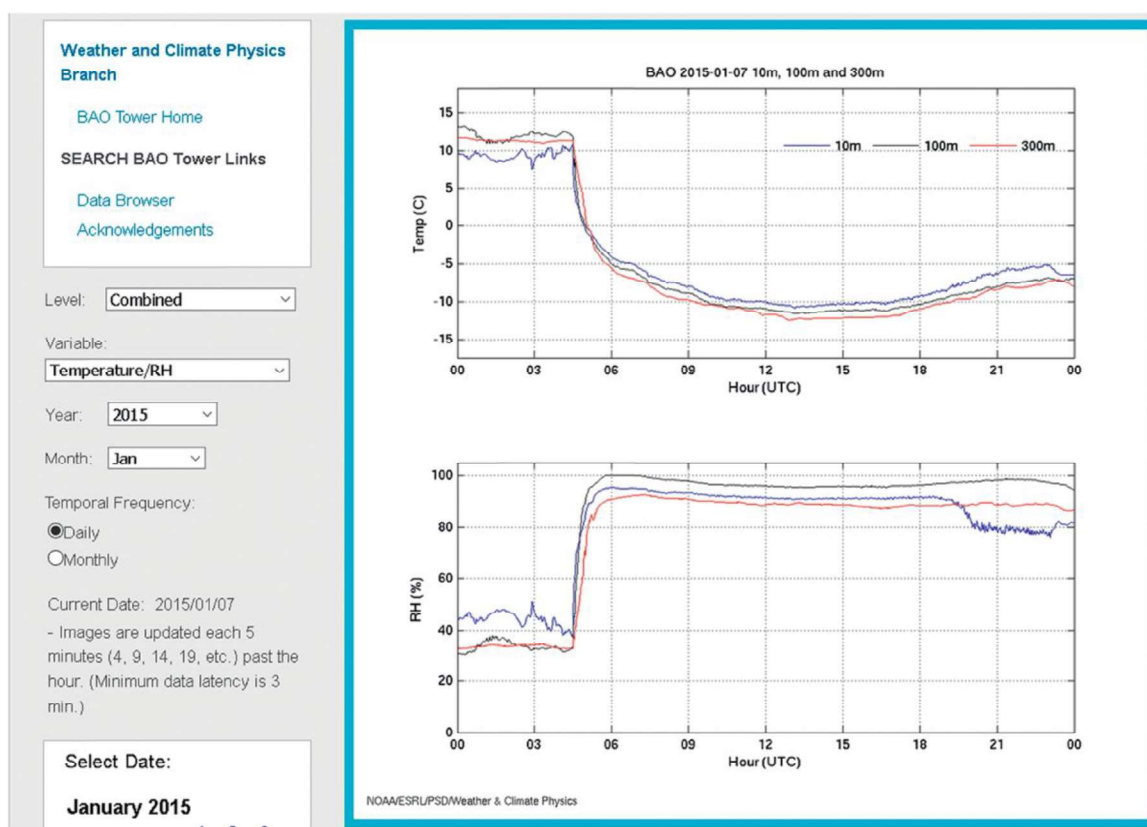


FIG. A1. Data Browser main window.

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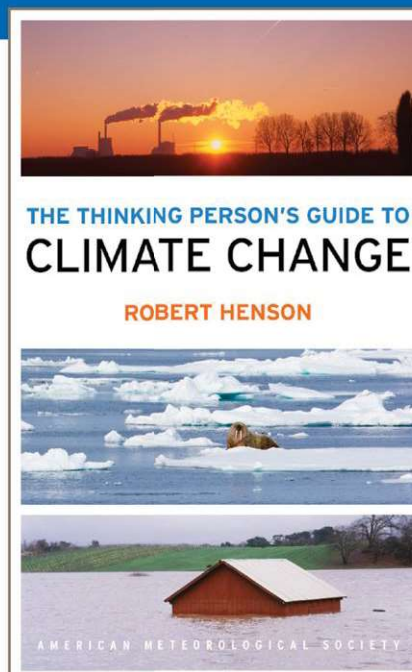
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