IOP Conf. Series: Earth and Environmental Science **1** (2008) 012002 doi:10.1088/1755-1307/1/1/012002

Application of sodar to interpret CO_2 and CO profiles and their dependence on boundary layer structure

W. Neff, A. Andrews, D. Wolfe

NOAA Earth System Research Laboratory, 325 Broadway, Boulder Colorado 80305

william.neff@noaa.gov

Abstract. The Boulder Atmospheric Observatory (BAO) tower was constructed and became operational in 1977. This 300-m tower, although originally supporting the development and improvement of ground-based remote sensing devices, has been used extensively in the study of the atmospheric boundary layer as well as plume dispersion and air quality. It was used in studies of the Denver Brown Cloud during the winters of 1987-1988 and 1996-1997. Located about 20 km east from the foothills of the Rocky Mountains, it is subject to a wide range of weather conditions ranging from night-time drainage winds with a low-level jet structure, to down-slope wind storms and upslope snow storms. During the summer of 2007, three levels of CO_2 and CO gas sampling (at 22, 100, and 300 m) were added as the tower became part of the NOAA ESRL/Global Monitoring Division CO_2 tall-tower network. The tower's location in complex terrain and its proximity to urban areas will provide a number of challenges in the interpretation of the data it provides. In this paper, we will describe some of the history of the tower in past air quality studies, examples of its complex meteorological setting and initial examples comparing diurnal variation in CO_2 and CO with boundary layer depths and structure observed with an acoustic sounder.

1. The use of sodar to characterize near-surface chemical processes at the BAO tower

Sodars have long been used to characterize the behavior of the planetary boundary layer. In many cases the characterizations have been qualitative in nature or, in some analyses, sodar facsimile records and Doppler-derived wind fields have been used to describe changes in near-surface chemistry with time. Although automatic detection of the mixing layer depth using sodars has been problematic [1, 2], some progress has been made in idealized situations such as those at the South Pole where there is no diurnal cycle and the boundary layer is largely stable and slowly changing [3]. In addition, sodars have been used in combination with balloon profiling of chemical species to better elucidate boundary layer mixing processes that affect surface concentrations [3-5].

ESRL's Global Monitoring Division (GMD) began making measurements from tall towers across the US in the 1990s (http://www.esrl.noaa.gov/gmd/ccgg/towers/index.html). Recently, the 300-m tower at the Boulder Atmospheric Observatory (BAO) was added to the network (Figure 1). The BAO tall tower site is the first to be located near complex terrain and a large urban area. However, extensive past studies of the meteorology and air quality along the Colorado Front Range will aid in the analyses of the complex data expected at this site. Completed in 1977, the BAO has been a unique research facility for studying the planetary boundary layer and for testing and calibrating atmospheric sensors. The centerpiece of the facility is a 300-m tower instrumented at five levels with slow-response temperature and wind sensors, a variety of remote sensing systems, and a real-time processing and display capability that greatly reduces analysis time for scientists (http://www.esrl.noaa.gov/psd/technology/bao/site/). The BAO has been the host of several large national and international experiments and numerous smaller ones. The field programs at the BAO have included 1) instrument evaluations, 2) plume dispersion studies, and regional air quality studies including the 1987-1988 Denver Brown Cloud Study and the 1996-1997 Northern Front Range Air Quality Study (NFRAQS) [6].

Figure 1. The 300-m BAO tower located east of the Rocky Mountains. Although located initially in 1979 in a predominately rural area, urbanization in the area is increasing with housing developments, gas wells, and a high-traffic interstate highway a few km to the east (evident near the top of the figure.) Located in an area dominated by nighttime drainage flows, small urban areas to the west of the tower (to the right of the figure) can contribute to the emissions observed at the tower. Southerly winds can bring emissions from the major Denver metropolitan area to the tower. Easterly winds can bring either aged pollution or relatively clean air from the Great Plains to the site.

2. CO_2 and CO in the surface layer

Carbon dioxide (CO_2) concentrations in the atmosphere depend on a number of sources and sinks, anthropogenic and natural. CO_2, in particular, is subject to a strong diurnal cycle with uptake by vegetation in the daytime and release from the surface through ecosystem respiration at nighttime. Because of the surface character of the sources and sinks of CO_2, boundary-layer mixing plays a key role governing its concentration. Carbon monoxide (CO), on the other hand, has its source in combustion sources, both at the surface and elevated. Examining the covariance of CO and CO_2 at various heights can suggest the origin of the observed CO_2. For example, a distinct diurnal cycle in CO_2 near the surface in the absence of a CO signal would indicate a dominance of biogenic sources and sinks of CO_2. The complications occur when surface sources of CO_2 and CO, such as vehicle and other combustion sources, comingle with the biogenic sources and sinks. This paper addresses the potential value of sodar profiling of the boundary layer in the interpretation of these various sources in combination with fixed level measurements of tall towers such as that at the BAO.

3. CO_2 and CO Measurements

CO_2 is measured using a non-dispersive infrared gas analyzer [Li-Cor 7000 CO_2/H_2O], and CO is measured using gas filter correlation [48C Trace Level, Thermo Electron Corporation]. These detectors are embedded in a customized trace gas analyzer system such that both gas analyzers are

IOP Conf. Series: Earth and Environmental Science **1** (2008) 012002 doi:10.1088/1755-1307/1/1/012002

housed in temperature-controlled enclosures and are equipped with active pressure and flow control ["A High-Precision CO_2 and CO Analysis System for Automated Semi-Continuous Profile Sampling from Tall Towers", Andrews et al., manuscript in preparation]. The analyzers are calibrated two to four times per day through an external sample selection manifold using a set of 8 on-site reference gases (5 for CO_2, 3 for CO). The CO baseline drift is monitored every 30 minutes using ambient air that is scrubbed of CO using a catalytic reagent [Sofnocat]. CO_2 baseline drift is monitored every one to two hours by measuring a standard with near ambient concentration. The CO_2/CO analyzer is housed in a building at the base of the tower. Air is drawn down from the tower through three sampling lines positioned at 22, 100 and 300 meters above ground level. The tubes are flushed continuously at a flow rate of five to ten liters per minute. The analysis system operates on a five minute cycle. The average value for the final 30 seconds of each five minute interval is used to compute CO_2 and CO mixing ratios, so a complete profile is obtained every 15 minutes. This sampling sequence allows for full equilibration of the CO_2 mixing ratio even for large amplitude transitions between inlet heights.

4. The meteorology of the BAO Tower site

Four regimes dominate air quality along the eastern slopes of the Rocky Mountains:

1) Nocturnal drainage flows that follow the South Platte River from the southwest to the northeast through Denver. The nocturnal drainage jet structure [7], because of a nearly laminar layer that forms between 100 m and 200 m, may result in the trapping of urban surface emissions in a thin layer below the jet and may isolate elevated emissions (from point sources) in the air flow above the wind maximum: This drainage system extends well into northeastern Colorado during summer [8]. *Implications for CO_2 observations:* At the BAO these drainage winds are generally from the southwest or west and do not originate from major urban areas. In these cases, comparison of CO and CO_2, particularly at nighttime, should allow distinguishing combustion versus biogeochemical sources.
2) Thermally and/or dynamically driven northeasterly winds (upslope, toward the foothills), often associated with a shallow front-like or surge structure only a few hundred meters deep, that can transport cool air from the lowlands of the South Platte, northeast of Denver, southwestward into the foothills. During the Brown Cloud Study[6], these winds were most likely to occur during the afternoon but were also observed at many other times of the day and night [7, 9, 10], sometimes as a result of mesoscale eddies that form along the Front Range (e.g.[11, 12]). These upslope and recirculating flows enable aged aerosol and/or precursor gases such as ammonia to return to Denver and may contribute to a rapid degradation of visibility [13]. The stability of the shallow air mass limits vertical mixing and allows further buildup of pollution. When alternating with a nocturnal drainage wind, they may lead to a day-to-day recycling of the same airmass. *Implications for CO_2 observations:* Under these conditions, urban sources are likely to dominate boundary layer CO_2 and CO behavior. When below the 300 m level, only the 22-m and 100-m levels may show these urban influences.
3) Moist, cool northeasterly upslope winds, usually in response to lee cyclogenesis southeast of Denver and/or cold, surface high pressure developing over the Great Plains to the northeast of Denver, sometimes result in snowfall along the base of the mountains, but also in fogs and low clouds. Such conditions can support rapid chemical transformations, such as SO_2 to sulfate, that depend on the presence of clouds [14]. A related area that merits further investigation is melting and evaporation into the shallow boundary layers that often follow snowstorms. *Implications for CO_2 observations:* During the initial phase of these upslope conditions, urban residue may dominate; as the upslope continues, cleaner air from the plains may change the CO/CO_2 behavior significantly.
4) Downslope westerly winds that usually are strongest near the foothills west and north of Denver and which are associated with falls of pressure along the foothills in combination with higher surface pressure to the east over the plains, contributing to shallow upslope flows along the Platte

River. Warm westerly winds several hundred meters aloft and light, cool easterly winds near the surface enhance the low-level temperature inversion creating strong trapping conditions unless there is a strong differential acceleration of the wind across the inversion layer. During the Brown Cloud field study, the inversion often proved remarkably resistant to erosion by the strong westerly winds above it. *Implications for CO_2 observations:* Because of the position of the BAO, closer to the foothills, it usually is dominated by high winds from the mountains which should show minimal urban influence. However, sometimes the boundary between the clean mountain air and the polluted air masses over the plains may oscillate back and forth through the BAO site as the mountain wave phase shifts. These will provide interesting cases for analysis.

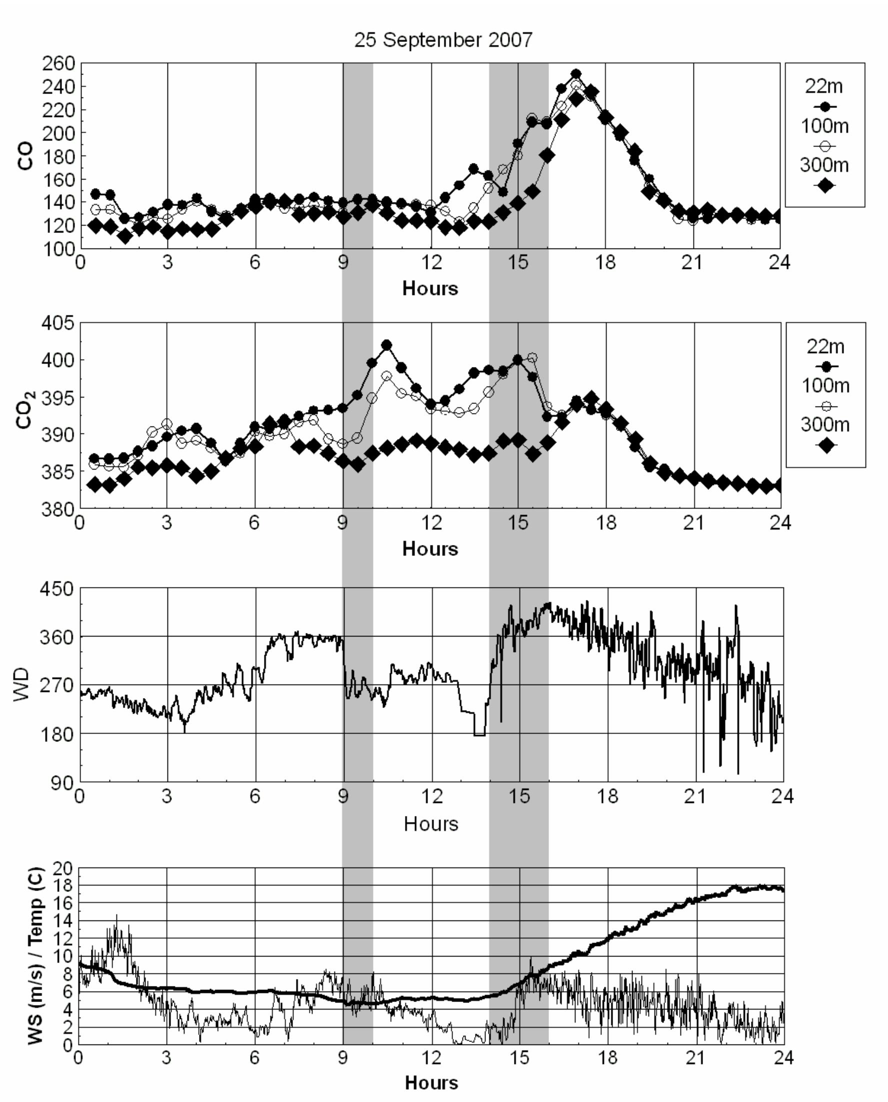

Figure 2: Time series of a) CO (ppb), b) CO_2 (ppm), c) Wind Direction, and d) Wind Speed (thin line) and Temperature (thick line) for September 25, 2007. CO and CO_2 data are smoothed with a 3-point filter. Gray shading indicates specific periods called out for discussion.

5. Case Study

Figure 2 shows an example over a full 24 hour period on 25 September 2007 (UTC) of CO, CO_2, temperature, and surface wind speed and wind direction. Wind directions on this day varied from southwest to northeast with daytime convection beginning around 1500 UTC with an increase in wind speed and temperature together with a shift of wind direction to the northeast (upslope toward the mountains). During the night, winds were predominately from the west and decreasing in speed from 0800 UTC to 1400 UTC, characteristic of typical nocturnal drainage flows.

During the night period, the sodar facsimile record (Figure 3) shows a mixing layer increasing in depth between 0900 and 1000 UTC from about 50 m to about 200 m. The 300m-level CO_2 is nearly constant or decreases from its initial value at 0800 UTC (local midnight) to 1600 UTC in the early morning whereas lower levels increase in relative value. This increase in concentrations of CO_2 at lower levels coincides with a wind shift from northerly to westerly at 0900 UTC. Because there is no sudden collapse of the boundary layer after 0930 UTC, one might assume that the lowest tower levels are simply seeing a different source of CO_2, perhaps associated with downslope flow off the mountains to the west.

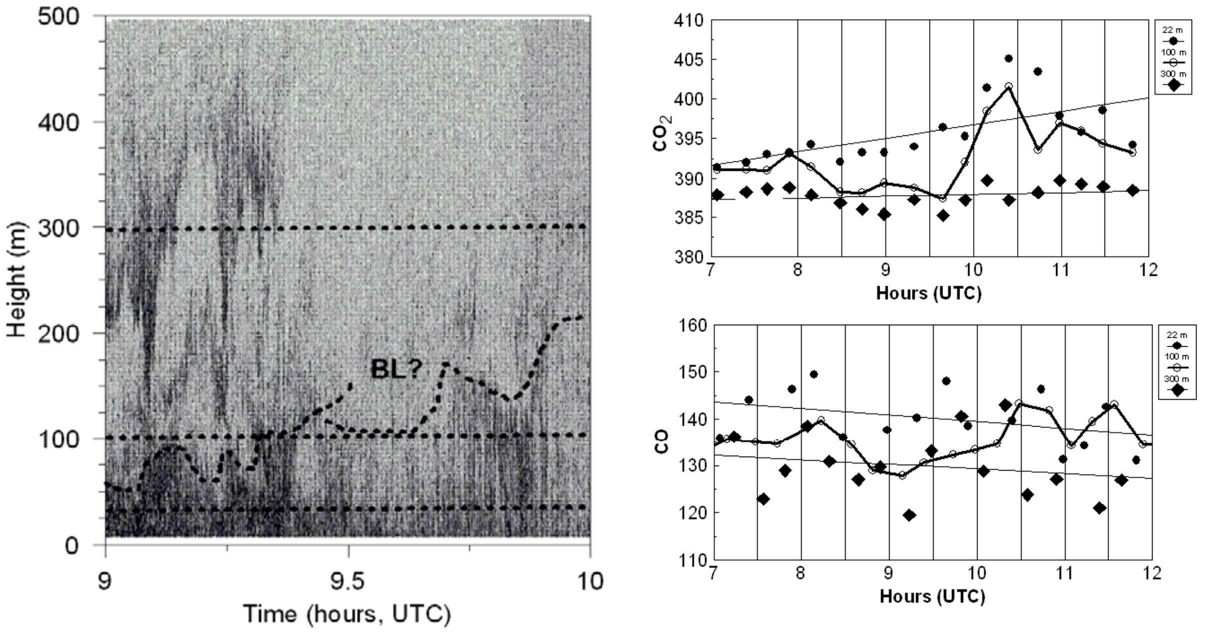

Figure 3. Sodar facsimile record from 25 September 2007 between 0900 and 1000 UTC (left) with expanded time series of CO and CO_2 (right) bracketing the period of interest.

Figure 2 showed the effect of the transition from nocturnal inversion conditions to a convective regime as the traces for CO and CO_2 at all levels converge by 1700 UTC. Figure 4 shows the sodar record for this period with a residual of the nocturnal inversion still present at 1400 UTC and then transitioning to fully developed convection by 1600 UTC. The increase in CO during this period coincides with the morning rush hour and with a wind direction that would bring automobile emissions toward the tower from the interstate highway just to the east of the tower site.

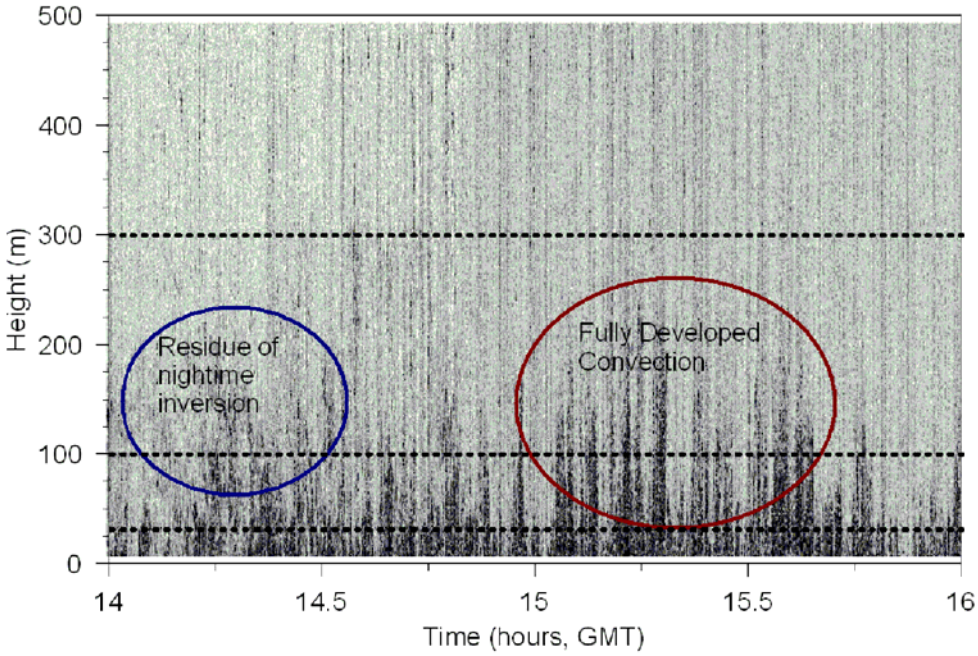

Figure 4. Sodar record during the morning transition from 1400 to 1600 UTC on 25 September 2007.

6. Future plans and challenges

CO and CO_2 data in combination with routine sodar facsimile recordings have been archived beginning in late summer of 2007. During 2008, we expect to be able to examine the full seasonal cycle from winter through the spring and summer growing period, into the next fall and winter. The challenge in this analysis will to develop, if possible, an automatic detection method for the nocturnal surface mixing-layer depth. Our earlier results from the South Pole suggest that this is quite feasible for slowly evolving stable layers. Examination of data from this last winter suggest that under very stable, light wind conditions, short-term wave modulation of the inversion layer depth leads to rapid variation in CO and CO_2 concentrations that will be difficult to link in a one-to-one fashion with observe depths.

References

[1] Beyrich F 1997 Mixing height estimation from sodar data - A critical discussion. *Atmos. Env.* 31(23):3941-3953.

[2] Seibert P, Beyrich F, Gryning SE, Joffre S, Rasmussen A, Tercier P 2000 Review and intercomparison of operational methods for the determination of the mixing height. *Atmos. Env.* 34(7):1001-1027.

[3] Neff W, Helmig D, Grachev A, Davis D 1998 A study of boundary layer behavior associated with high NO concentrations at the South Pole using a minisodar, tethered balloon, and sonic anemometer *Atmos. Env.* 42(12):2817-2830.

[4] Beyrich F, Weisensee U, Sprung D, Gusten H 1996 Comparative analysis of sodar and ozone profile measurements in a complex structured boundary layer and implications for mixing height estimation. Bound.-Layer Meteorol. 81(1):1-9.

[5] Helmig D, Johnson BJ, Warshawsky M, Morse T, Neff WD, Eisele F, et al. 2008 Nitric oxide in the boundary-layer at South Pole during the Antarctic Tropospheric Chemistry Investigation (ANTCI). *Atmos. Env.* 42(12):2817-2830.

[6] Neff WD 1997 The Denver Brown Cloud studies from the perspective of model assessment needs and the role of meteorology. *J. Air & Waste Manag. Assoc.* 47(3):269-285.

[7] Neff WD, Eberhard WL, King CW, 1990 Remote sensor observations of thermally and dynamically driven circulations in the South Platte River basin. *Preprints: Fifth Conf. on Mountain Meteorology*, Boston: American Meteorological Society 42-49.

[8] Toth JJ, Johnson RH 1985 Summer Surface Flow Characteristics Over Northeast Colorado. *Mon. Wea. Rev.* 113(9):1458-1469.

[9] Neff WD, 1990 Remote Sensing of Atmospheric Processes over Complex Terrain. In: Blumen W, editor. *Atmospheric Processes over Complex Terrain*. Boston: American Metoorological Society pp. 173-228.

[10] Crow LW 1973 Airflow study related to EPA field monitoring program Denver metropolitan area, November 1973. In: *Denver Air Pollution Study: Proceedings of a Symposium; Vol. I* Environmental Sciences Research Laboratory, Office of Research and Development, U.S. EPA

[11] Levinson DH, Banta RM. 1995 Observations Of A Terrain-Forced Mesoscale Vortex And Canyon Drainage Flows Along The Front Range Of Colorado. *Mon. Wea. Rev.* 123(7):2029-2050.

[12] Wilczak JM, Christian TW 1990 Case-Study Of An Orographically Induced Mesoscale Vortex (Denver Cyclone) *Mon. Wea. Rev.* 118(5):1082-1102.

[13] Sloane CS, Watson JG, Chow JC, Pritchett LC, Richards LW 1990 Size distribution and optical properties of the Denver Brown Cloud. In: Mathai CV editor *Transactions: Visibility and Fine Particles* Pittsburgh: Air & Waste Management Association 384-393

[14] McHenry JN, Dennis RL 1994 The Relative Importance Of Oxidation Pathways And Clouds To Atmospheric Ambient Sulfate Production As Predicted By The Regional Acid Deposition Model. J. Appl. Meteor. 33(7):890-905.