ON THE USE OF THE BOULDER ATMOSPHERIC OBSERVATORY AS A CO_2 TALL TOWER SITE

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The BAO

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. 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).

Meteorology of the site and urban influences

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

- Nocturnal drainage flows that follow the South Platte River from the southwest to the northeast through Denver. The nocturnal drainage jet structure (Neff et al., 1990), because of a nearly laminar layer that forms between 100m and 200m, 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 (Toth and Johnson, 1985), including regions with significant ammonia sources.

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.

- 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, these winds were most likely to occur during the afternoon but were also observed at many other times of the day and night (Crow, 1973; Neff, 1990; Neff et al. 1990) and sometimes as a result of mesoscale eddies that form along the Front Range (e.g. Levinson and Banta, 1995). 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 (Sloane et al., 1990). 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 behavior. When below the 300 m level, only the 30-m and 100-m levels may show these urban influences.

- 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 SO2 to sulfate, that depend on the presence of clouds (McHenry and Dennis, 1994). 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.

- 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, 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 over the coming winter.

Local Influences

I-25 lies to the east of the tower so winds form the NNE to SSE are likely to influence the tower measurements, depending on boundary layer conditions. Similarly the small town of Erie and surrounding subdivisions may have an influence with westerly winds.

The CO_2 Tall Tower Program

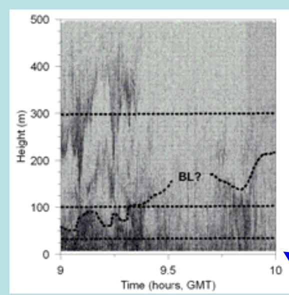
The NOAA ESRL/GMD tall tower network provides regionally representative measurements of carbon dioxide (CO_2) and related gases in the continental boundary layer. Recently we have also begun sampling gases that are relevant for air quality studies. We collect meteorological data that can be used to study boundary layer dynamics. The tall tower sites are part of the North American Carbon Program and are a primary data source for ESRL's Carbon Tracker CO_2 data assimilation system.

Background

ESRL's Global Monitoring Division (GMD) began making measurements from tall towers in the 1990s in order to extend long-term carbon-cycle gas monitoring to continental areas. Existing television, radio and cell phone towers are utilized as sampling platforms for in-situ and flask sampling of CO_2 and other atmospheric trace gases, including carbon monoxide (CO). Carbon dioxide is the principal carbon greenhouse gas, and measurements of its abundance are sensitive to upwind fluxes, including fossil fuel emissions and uptake and release by vegetation and soils. Carbon monoxide is an indicator of combustion, and elevated levels can result from urban or industrial emissions or from biomass burning. CO data contribute to the interpretation of CO_2 measurements by helping to identify and quantify pollution episodes. Plans call for the addition of six more towers distributed throughout the continental US over the next several years.

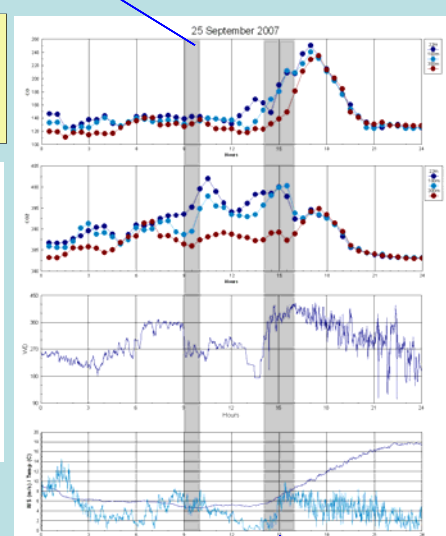
The BAO tall tower site is the first to be located near complex terrain and a large urban area. However, extensive past studies of the meteorology and air quality along the Colorado Front Range will aid in the analyses of the complex data expected at this site.

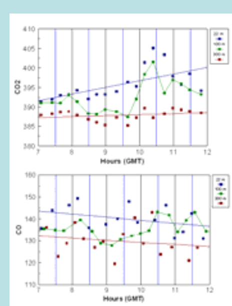
Example: September 25, 2007

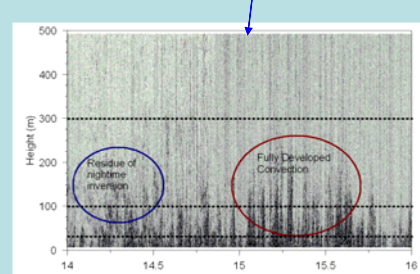


In this nocturnal boundary layer case, the sodar shows a mixing layer increasing in depth between 0900 and 1000 GMT from about 50 m to about 200 m. Note that the 300m-level CO_2 is nearly constant or decreases from its initial value at 0800 GMT (local midnight) to 1600 GMT in the early morning whereas 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 GMT. The detailed figure (below, left) shows opposing trends in CO_2 and CO between 22 m and 300 m suggesting a surface source for CO_2 that is not combustive.

Figure (above): Sodar facsimile records from 25 September 2007 between 0900 and 1000 GMT.
Figure (left): Time series of CO, CO_2, Wind Direction, Wind Speed, and Temperature for September 25, 2007. CO and CO_2 data are smoothed with a 3-point filter.
Figure (below): Detail of CO and CO_2 data (unsmoothed) from 0700 to 1200.







With sunrise, the wind shifts back to a northerly direction and by 1630 (0830, local) both CO_2 and CO appear well-mixed through the tower height. One should also note the relative increase in CO compared to CO_2 during this morning period.