The Effect of Complex Terrain on Ozone Distribution and Transport in the Colorado Front Range Area

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ABSTRACT

We investigated the distribution and transport of ozone in the Colorado Front Range area by deploying an airborne ozone lidar and flying several missions over the last couple of summers. In 2008, we augmented the lidar measurements with a small network of radar wind profilers, a Doppler lidar, and a surface meteorological station in order to better characterize the flow patterns.

For the majority of flights, we observed that polluted air from the Denver metro area was transported by easterly winds towards and into the adjacent mountains. The highest ozone levels were typically found over the western suburbs of the Denver metro area and along the eastern slope of the mountains. In one case, we observed a very deep mixed layer with the easterly winds extending above mountain top level. As a result, the ozone plume was transported further west across the Continental Divide.

We also used the ozone and wind measurements to evaluate how well we can predict pollutant transport in and near complex terrain using the FLEXPART Lagrangian particle dispersion model coupled with high-resolution Weather Research and Forecasting (WRF) model runs.

1. INTRODUCTION

The greater Denver, Colorado area violated the U. S. National Ambient Air Quality Standard (NAAQS) for 8-hour average ozone concentrations in 2005 – 2007, and as a result, was designated a non-attainment area by the U.S. Environmental Protection Agency (EPA) [1]. Since then, the 8-hour ozone air quality standard has been lowered from 84 to 75 ppb. Thus, meeting the new ozone standard will be a challenge for the Denver area and will require additional research to understand the causes for ozone violations, including the role of pollutant transport.

Denver lies at the western edge of the Great Plains just to the east of the Front Range Mountains, which are part of the Rocky Mountains. The Continental Divide runs along the spine of the Front Range Mountains and the highest peaks reach more than 4000 m above sea level (ASL). The proximity to mountainous terrain strongly influences the flow patterns and pollutant transport pathways in the Colorado Front Range area. On a typical summer day, in the absence of any synoptic-scale weather patterns, easterly flow develops around mid-morning over the Front Range area due to heating of the mountains and the resulting upslope flow. The winds above the boundary layer usually come from westerly directions and are often stronger than the easterly boundary layer flow (Figure 3). Pollutants from the Denver area are typically transported towards and into the mountains where they interact with the complex terrain. Not much is known about the fate of the pollutants once they enter the mountains. Almost all routine monitoring stations for pollutants such as NO_x, CO, O_3, and aerosols are located in the Front Range area east of the mountains. Only two stations are situated in the mountains east of the Continental Divide and none to the west of the Divide. When pollutants are carried up into the mountains by upslope winds they may be pushed further west across the Continental Divide if the mixed layer is deep enough and the easterly winds extend above the mountain tops. Alternatively, pollutants may be vented into the free troposphere and transported back east over the Denver area and beyond by predominantly westerly winds above the boundary layer. The pollutants may also be carried back down to the greater Denver area by downslope flows that usually develop in the evening and overnight.

To study these complex transport patterns and the resulting distribution of ozone in the Colorado Front Range we deployed NOAA's airborne ozone lidar on a Twin Otter aircraft and flew several missions over the last couple of summers. In 2008, the airborne lidar measurements were complemented by a ground-based Doppler lidar, a small network of radar wind profilers, and a surface meteorological station on the Continental Divide. We used the FLEXPART dispersion model coupled with high-resolution WRF model runs to forecast pollutant transport, guide flight planning efforts, and compare model output with our measurements.

Here, we will focus on the findings from one mission on 31 July 2008, when we undertook two consecutive flights to investigate the transport of pollutants into and out of the Colorado Front Range Mountains.

2. INSTRUMENTATION

Ozone profile measurements were obtained with TOPAZ (**T**unable **O**ptical **P**rofiler for **A**erosol and o**Z**one), NOAA's airborne ozone and aerosol lidar [2]. TOPAZ incorporates the latest solid-state laser technology, its transmitter is tunable in the UV spectral region, and the system is light-weight and compact, so it can be flown on a rather small research aircraft, such as the NOAA Twin Otter. The aircraft typically flew at altitudes of about 5 km above sea level and the downward-looking lidar provided profiles of ozone and aerosol backscatter at high spatial and temporal reso-

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lution from just below the aircraft to the ground. The vertical resolution of the ozone measurements is 90 m and the time resolution is 10 s, corresponding to a horizontal resolution of about 700 m.

Three 915 MHz wind profilers [3] were deployed roughly along a west-east line extending from Granby (GNB, west of the Divide) to Erie (ERE, north of Denver) and a surface meteorological station [4] was placed near the Continental Divide at an altitude of approx. 3700 m ASL. The Doppler lidar was situated at Table Mountain (TBM). Figure 1 shows a map of the Colorado Front Range area with instrument locations.

Figure 1. *Map of the Colorado Front Range area. The locations of the three wind profilers (GNB, TBM, ERE) and the surface meteorological station (CDE) are indicated by triangles.*

3. MODEL APPLICATIONS

For daily forecasts during the experiment and to guide flight planning efforts we employed the FLEXPART dispersion model driven by high-resolution WRF model output [5,6]. We also assessed model performance by comparing model results with the airborne ozone lidar and wind profiler measurements. The WRF model was run at high resolution (5 km grid) in order to capture small scale features in the meteorological fields associated with the complex terrain west of the Denver area. The application of the high-resolution WRF model coupled with FLEXPART served as a testbed for the upcoming CALNEX study in California in May – July 2010 [7], where complex terrain and its impact on pollutant transport and distribution will also be a major factor.

4. RESULTS

Figure 2 shows ozone vertical cross section data from the first research flight on 31 July, flown in the late afternoon local time. We observed high ozone values of up to about 110 ppb extending up to 4600 m ASL on the north-south transects NS1, NS2, and NS3. Southeasterly winds that developed around 15 UTC (Figure 3) advected pollutants from the Denver metro area towards Boulder and farther west into the Front Range Mountains. During transport, photochemical production of ozone occurred leading to the high ozone values observed over the mountains to the northwest of Denver. The consistently highest ozone values were observed on transect NS2 just east of the Divide. The data measured during transect NS3 show that the ozone plume was transported west across the Divide, indicating that easterly winds extended to above mountain top level. This is confirmed by the data shown in Figures 3 and 4. The TBM wind profiler measured easterly winds extending up to above 4 km

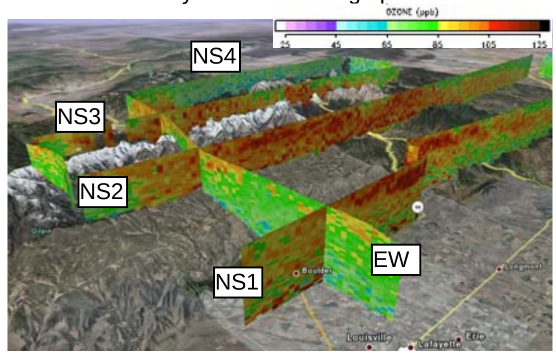

Figure 2. *Vertical cross section of ozone measured with the TOPAZ lidar on 31 July, 21:30 – 1 August, 00:30 UTC. Data extend from near the surface to about 4.6 km ASL.*

ASL at 23 UTC, when transects NS2 and NS3 were flown. Data from the surface meteorological station on the Divide (CDE) show light winds from easterly directions between 21 and 23 UTC. On the westernmost transect (NS4) we sampled mostly rather clean background air (~ 65 ppb ozone). At the southern end of NS4, just before turning east onto transect EW, we observed a sudden increase in ozone when we encountered the leading edge of the ozone plume that had spilled over the Divide. Data taken during NS1 and EW show higher ozone concentrations aloft, which may be evidence that some of the pollutants were lofted into the lower free troposphere and transported back east by the westerly winds (Figure 3).

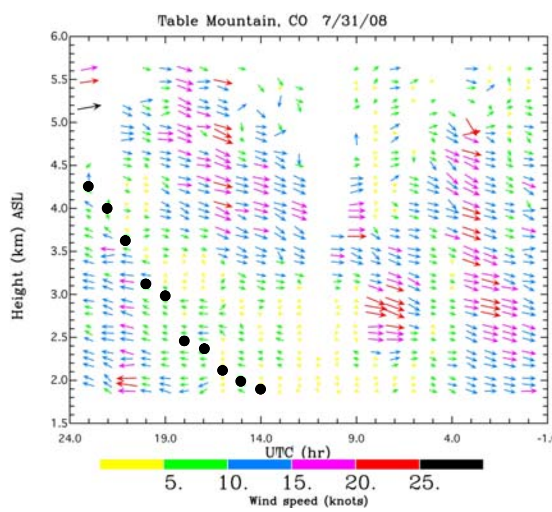

Figure 3. *Profiles of wind speed and direction from wind profiler at Table Mountain (TBM) for 31 July. Black dots indicate boundary layer height estimates derived from backscatter signal intensities.*

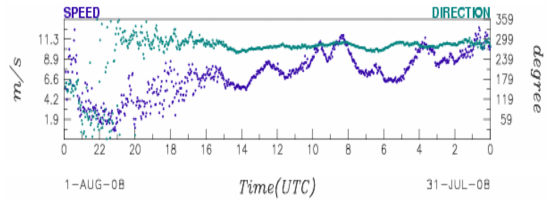

Figure 4. *Wind speed and direction measurements from the Continental Divide meteorological station (CDE) at 2 m AGL for 31 July.*

To investigate the fate of the ozone plume that we observed over the Front Range Mountains and west of the Divide during the afternoon of 31 July, we flew another mission with the airborne lidar during the early nighttime hours on the same day. The ozone cross sections in Figure 5 show that except for a few pockets of elevated ozone, the ozone distribution over the mountains was rather uniform and ozone levels had subsided to about 80 ppb. Given that the 8-hour ozone NAAQS is 75 ppb, these are still significantly high ozone concentrations. West of the Divide, ozone levels were lower (about 65 ppb) and we did not find any

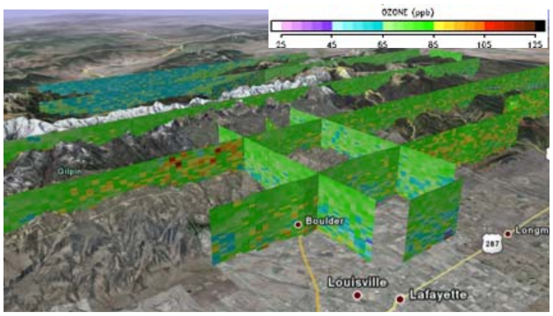

Figure 5. *Vertical cross section of ozone measured with the TOPAZ lidar on 1 August, 02 - 06 UTC. Data extend from near the surface to about 4.0 km ASL.*

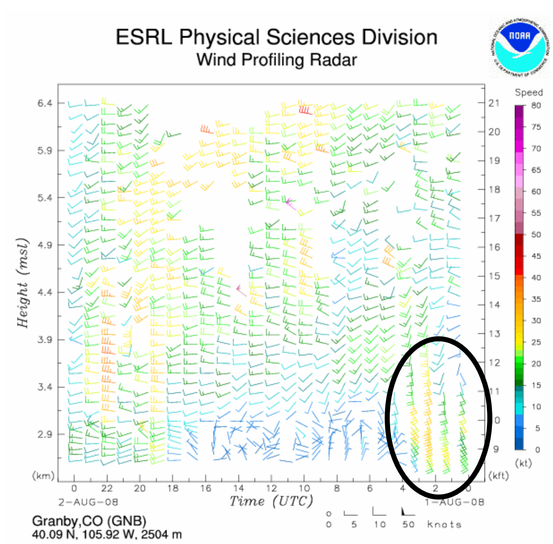

Figure 6. *Profiles of wind speed and direction from profiler at Granby (GNB) for 1 August. Encircled area denotes strong southerly low level jet around 02 UTC.*

evidence of the ozone plume that we had observed there during the earlier flight. Data from the Granby wind profiler (Figure 6) show that around 02 UTC a strong southerly low level jet developed that must have flushed the pollutants out of the area west of the Divide.

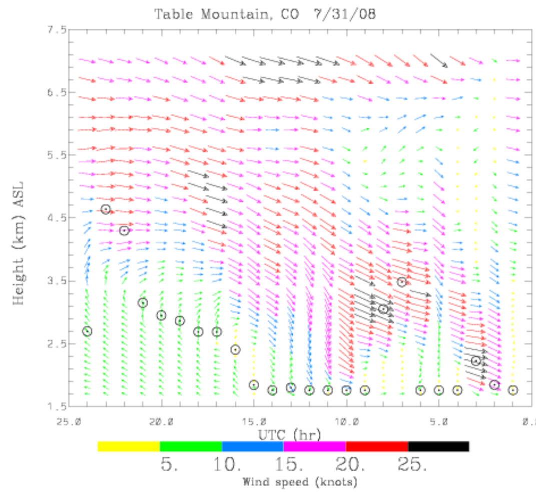

Figure 7. *Hourly wind profiles produced by high-resolution WRF model at the TBM profiler location for 31 July.*

To assess performance of the high resolution WRF model we produced hourly wind speed and direction profiles from the model output at the wind profiler locations. Figure 7 shows the model wind data for the TBM profiler location. The model data are remarkably similar to the profiler measurements (Figure 3). The model captures all the general features of the wind field and also reproduces some of the small scale structures (e.g. wind speed enhancements at 08 UTC/3 km ASL, wind speed minimum and wind shear at 08 UTC/5 km ASL). However, the model overestimates early morning wind speeds (10 – 15 UTC) in the lower part of the atmosphere and also slightly underestimates the depth of the boundary layer in the afternoon (after 21 UTC), evidenced by the easterly boundary layer winds turning to southerly and westerly directions at lower altitudes than in the measured profiles.

Figures 8a and 8b show, respectively, a plan view plot of CO column concentration over the Colorado Front Range area and a CO vertical cross section produced by the WRF-driven FLEXPART model for 1 August, 00 UTC. The FLEXPART/WRF model does not predict ozone concentrations, so we used CO as a tracer of the Denver urban plume. The vertical cross section (indicated by the black line in Figure 8a) was placed roughly parallel to the wind direction in the boundary layer and intersects flight legs NS1-4 of the first flight. The cross section shows that the urban pollution plume just reaches mountain top level at 1 August, 00 UTC. The lidar measurements, however, show that by that time the ozone plume had already crossed the Divide and had reached the valley to the west (left in Figure 8b). The FLEXPART CO cross section for 1 August, 02 UTC (not shown) correctly places the leading edge of the pollution plume on the west side of the Divide. This delay in transporting the urban pollution across the Divide is most likely due to the fact that the model slightly underestimated the depth of the boundary layer. It appears that the model correctly reproduced the strong southerly jet around 02 UTC measured by the GNB profiler (Figure 6) and also evident in the ERE profiler data (not shown). In the model runs, this southerly surge eventually pushed the pollution plume across the Divide rather than the easterly winds earlier in the day. The CO cross section also shows a recirculation of urban pollutants to the east at an altitude of about 4.5 km ASL after they were transported up the mountain slope and then lofted into the lower free troposphere. This is also evident in the ozone lidar cross sections from the first flight during transects NS1 and EW.

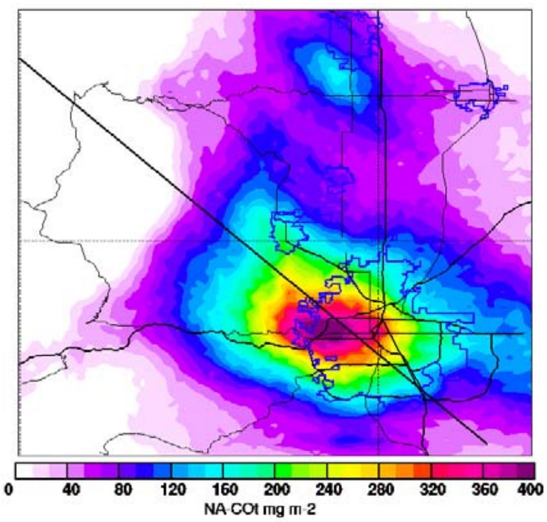

Figure 8a. *Colum concentration of CO derived from WRF-driven FLEXPART model in the Front Range area on 1 August, 00 UTC. Black line indicates location of vertical cross section shown in Figure 8b.*

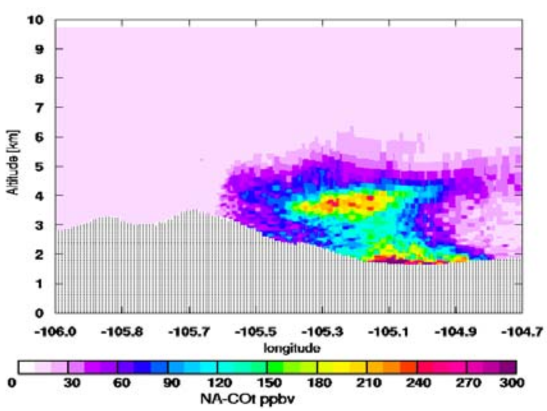

Figure 8b. *Vertical cross section of CO derived from WRF-driven FLEXPART model in the Front Range area on 1 August, 00 UTC. Location of cross section is shown by black line in Figure 8b.*

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