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OROGRAPHIC FLOWS IN THE PHOENIX AREA AND THEIR IMPLICATIONS FOR VERTICAL MIXING

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1. INTRODUCTION

The occurrence of episodes of high ozone concentration constitutes a significant health hazard in urban areas. Increasingly, it is recognized that both chemical processes and atmospheric transport and mixing determine ozone concentrations and that the distribution of ozone and other pollutants cannot be understood by considering either chemistry or atmospheric structure in isolation. To improve our understanding of factors affecting O_3 concentrations, the U.S. Department of Energy (DOE) supported a field measurement program in Phoenix in June 2001. Called the 2001 Phoenix Sunrise experiment, this campaign was designed to investigate the interaction between chemical processes and vertical mixing by turbulence during the morning transition from thermodynamically stable to unstable conditions. This field program is described in detail by Doran et al. (2003).

During the Phoenix Sunrise campaign, observations of atmospheric temperature and winds were made using a combination of wind profilers with radio acoustic sounding systems (RASSes), sodars, in situ temperature sensors, and radiosondes. Observations of a number of chemical species were also made at the surface and at two levels on a downtown skyscraper. These observations led to the discovery of a curious phenomenon with respect to the morning onset of mixing downtown. Based on the chemical observations at multiple heights, Doran et al. (2003) reported that vertical mixing typically began an hour or more earlier than would be expected from the development of convective mixing by solar heating of the ground in the morning. In this paper we will describe an orographically driven diurnal circulation that appears to be related to this premature mixing, review the description of the mixing onset, and discuss mechanisms that may link the two phenomena.

2. THE OBSERVATIONS

2.1 Topography and Winds

The Phoenix metropolitan area is located in a broad desert valley approximately 350 m above sea level that rises gradually from west to east at a latitude of about 33.5 N (Figure 1). The valley is surrounded by mountain ranges that reach elevations of approximately 2000 m. These ranges are broken by narrower valleys and canyons that empty into the larger valley.

The early summer weather is dominated by the eastern Pacific subtropical high, which commonly leads to weak large-scale horizontal pressure gradients and light winds. As the summer progresses, the large-scale circulation becomes dominated by southwesterly monsoonal flow that advects significant moisture from the Gulf of Baja in Mexico (Meitin et al. 1991). For most of this study, the atmosphere was characteristic of early summer, with light winds and very low dew points. For a few days in mid-campaign, the atmospheric flow became more monsoonal in character but returned to the early summer pattern for the remainder of the observational period.

Because of the weak pressure gradients and the slope of the terrain, one would expect the diurnal heating cycle to produce low-level daytime winds with a pronounced westerly component and nighttime winds with a perhaps weaker easterly flow. This general pattern has, in fact, been observed in the Phoenix area in previous studies (Ellis et al. 1999, Fast et al. 2000).

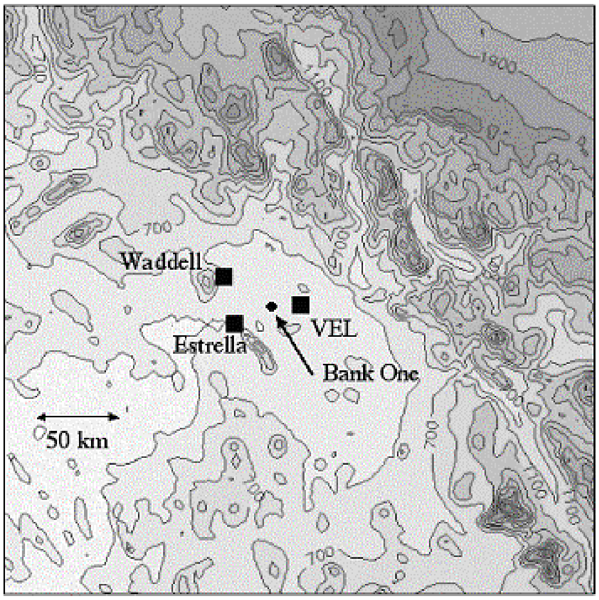

Figure 1. Topographic map of the Phoenix area showing the locations of the Vehicle Emissions Laboratory (VEL), Estrella Mountain Regional Park, Waddell, and the Bank One building.

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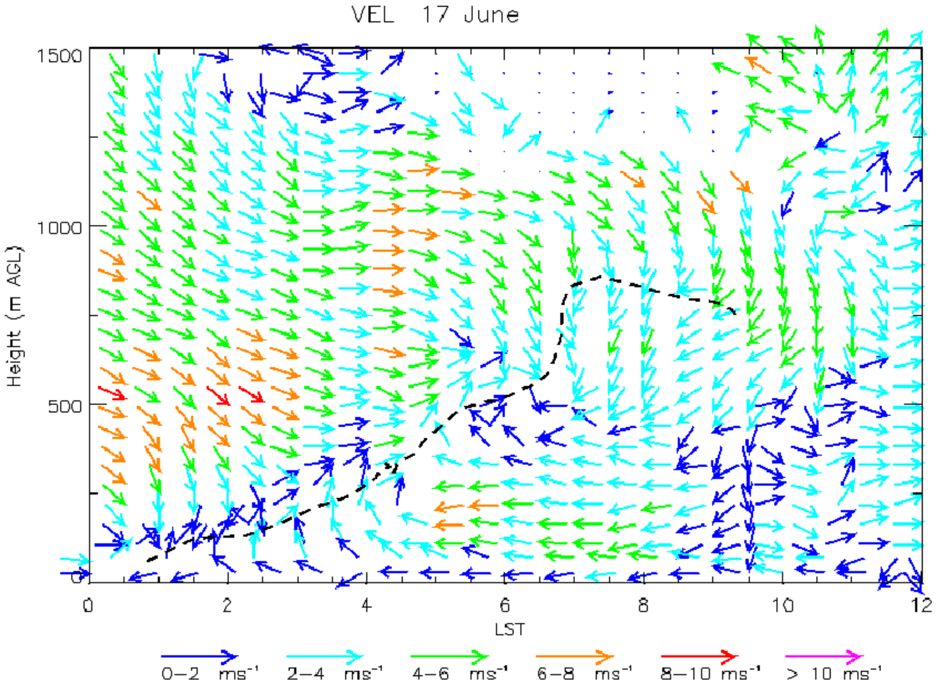

Figure 2. Time-height cross sections of wind velocities from the radar wind profiler and sodar at VEL for 17 June 2001. The dashed line shows the approximate boundary for lower level winds with an easterly component.

2.2 Instrumentation

In addition to depicting the regional topography, Figure 1 also shows the locations of primary measurement systems used in this study. Three 915 MHz wind profiling radars were sited near Phoenix during the study. One system, owned and operated by the Arizona Department of Environmental Quality (ADEQ), was located at the vehicle emissions laboratory (VEL) east of downtown. Two similar profilers were sited west and southwest of Phoenix at Waddell and at Estrella Mountain Regional Park, respectively. These systems provided consensus estimates of the vector wind profile with 60-m vertical resolution every 30 min. All three systems were also equipped with radio acoustic sounding systems (RASSes), which operated for five minutes each half hour to provide profiles of virtual temperature. In the atmospheric conditions of Phoenix, the profilers were able to routinely provide wind profiles to heights in excess of 2 km and virtual temperature profiles to nearly 1 km. Unfortunately, the profiler at Waddell was damaged by a nearby lightning strike five days into the field program and provided no data afterward.

To provide detailed thermodynamic structure in the vertical during the morning transition, we launched radiosondes hourly from 0500 to 1000 Local Standard Time (LST) at VEL and at Waddell. The measurements were made using Vaisala Corporation's DigiCora™ ground stations and RS-80 sondes. The sondes were carried aloft by 100 g balloons that were inflated to provide a target ascent rate of 3 m s^{-1}.

Measurements of numerous chemical species were made at the 16th and 39th floors [50 m and 140 m above ground level (AGL), respectively] of the Bank One building in downtown Phoenix. Of particular interest here is CO, which was measured by infrared absorption with a time resolution of 2 min.

3. MORNING EVOLUTION OF THE BOUNDARY LAYER

3.1 Wind Structure

Figure 2 shows a time-height cross section of wind vectors measured by the wind profiler at VEL on 17 June. This cross section shows a number of features that were characteristic of the morning transition on most days with weak synoptic-scale pressure gradients. Overall, the profiles show light to moderate winds with a pronounced westerly component. However, beginning about 0100 LST, the lowest winds became very light and developed an easterly (downslope) component. The low level flow with its easterly component remained very light but gradually deepened until about 0500 LST. At 0500 LST the easterly flow strengthened, developing a maximum speed of 6-8 m s^{-1} about 200 m above the surface. It also deepened more rapidly, ultimately reaching a depth of approximately 800 m by 0700 LST. The maximum speed diminished by 0600 LST, but the easterly flow continued until 0930 LST, when the flow again shifted to westerly (upslope). Although only part of the diurnal cycle is shown, we note that the westerly flow normally persisted throughout the day and into the following evening and was strongest in the late afternoon. This general pattern is consistent with

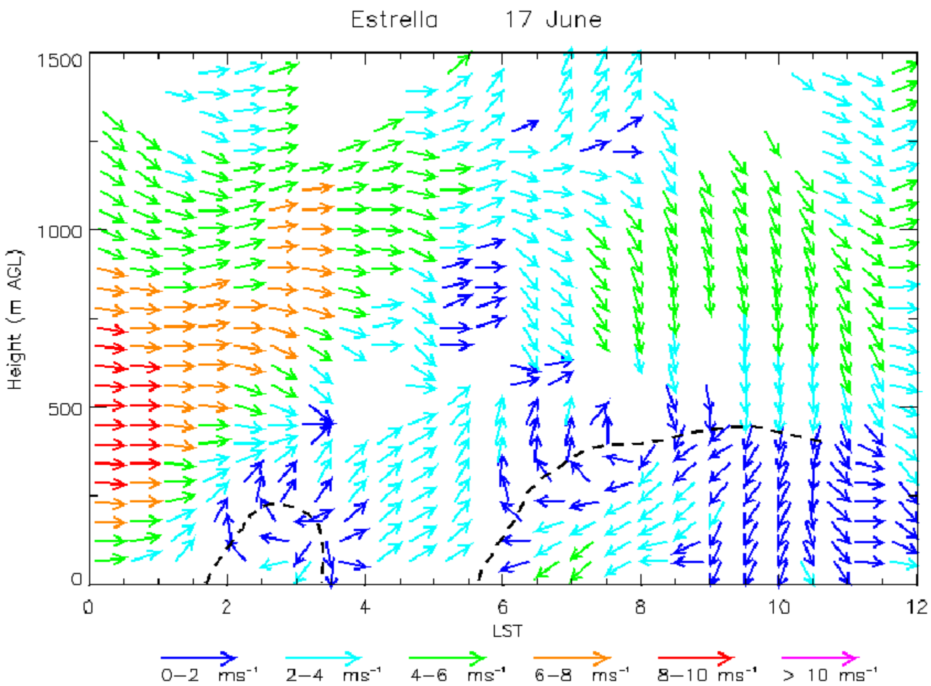

Figure 3. As in Figure 2 except for wind profiler data from Estrella.

thermally direct circulations driven by heated or cooled terrain.

Figure 3 shows the corresponding time-height cross section of the vector wind as measured by the wind profiler at Estrella Mountain Regional Park on 17 June. These data reflect a wind pattern that is broadly similar to that observed at VEL. There is some indication of easterly flow as early as 0200 LST, but the easterly flow did not become established at Estrella until 0600 LST. Its maximum depth was also lower.

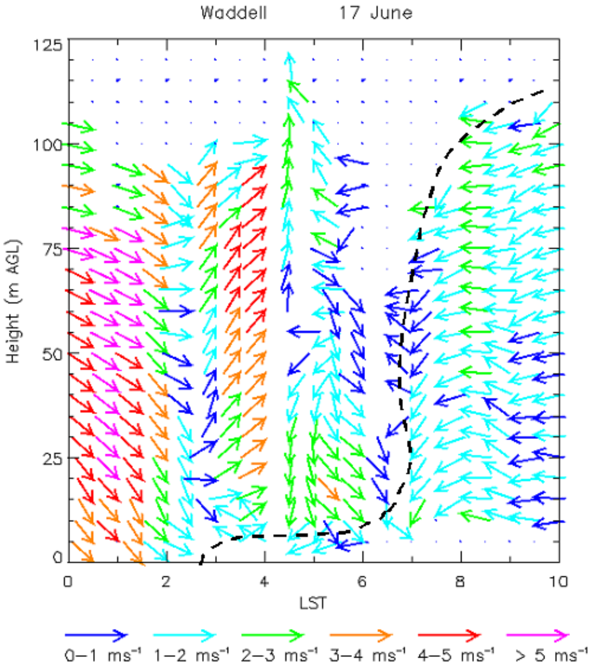

Figure 4. As in Figure 2 except for sodar data at Waddell.

The flow pattern described above for VEL was seen on a number of occasions, although flow with an easterly component usually started several hours later than the 0100 LST start time found on 17 June. At Estrella easterly winds near the surface were also found but they were typically weaker and less well organized than those seen at VEL.

Although the profiler at Waddell was damaged by lightning, the sodar operating there was not. This instrument also showed winds with an easterly component developing in the mornings, but the transition times were typically later than those at VEL and the flows seemed less well established. Figure 4 shows an example of the winds at this site for 17 June, the same day represented in the previous two figures.

While observations of the vertical wind structure at many more locations would be necessary to fully describe the nocturnal flow, the behavior of the wind at these three locations suggests that the Phoenix area experiences a nocturnal drainage flow that originates on the mountain slopes to the east. Further, this flow continues down the valley, regularly reaching downtown Phoenix but apparently weakening as it progresses to Estrella Mountain Regional Park and Waddell.

3.2 Temperature Structure

Figure 5 shows the cumulative potential temperature change between 0500 LST and 0800 LST at VEL for 17 June. Figure 5a depicts the cooling as a function of altitude during the first hour. Overall, the layer between

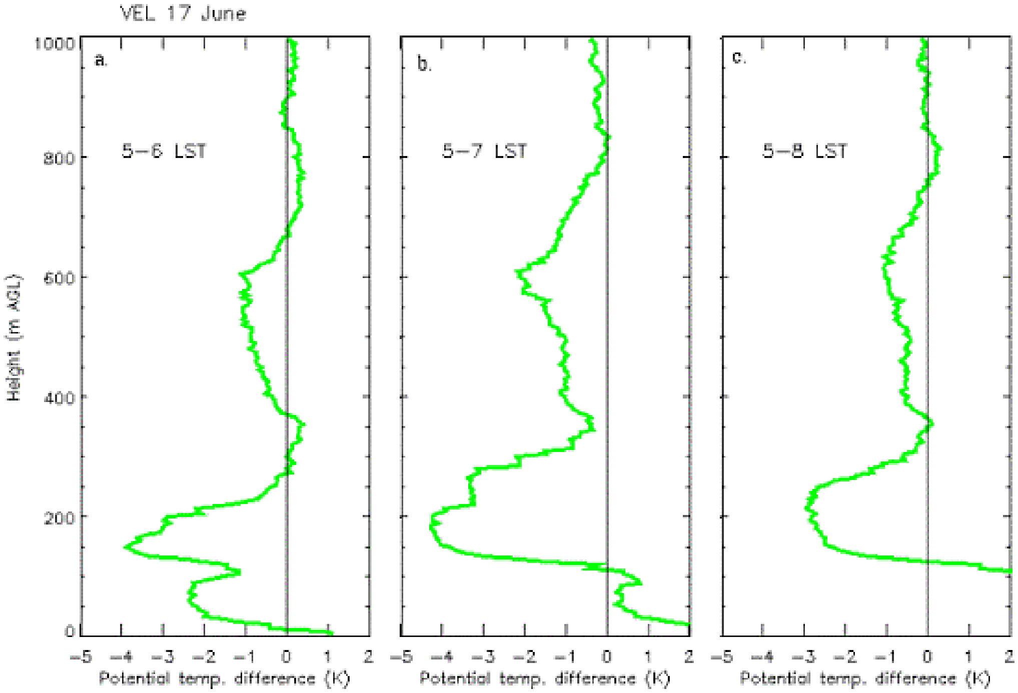

Figure 5. Cooling between (a) 0500 and 0600 LST, (b) 0500 and 0700 LST, and (c) 0500 and 0800 LST measured at VEL on 17 June 2001.

50 and 250 m cooled appreciably during this hour; there was also somewhat weaker cooling of approximately 1 K between 450 m and 600 m. Over the two-hour period from 0500 to 0700 LST (Figure 5b), cooling occurred at all levels above approximately 100 m to a height of nearly 800 m. This altitude corresponds roughly to the maximum height for which winds had an easterly component during this period. Figure 5c shows that the overall effect for the three-hour period from 0500 to 0800 LST was cooling above 120 m to an altitude of about 750 m. This cooling profile is anomalous in that one would have expected cooling to cease at all levels shortly after sunrise.

Figure 6 shows profiles of potential temperature change at Waddell, also for 17 June. In the initial hour, from 0500 to 0600 LST (Figure 6a), there was warming of roughly 1 K throughout the lowest 1000 m above the surface. Figure 6b shows net cooling below 600 m (except at the surface) in the two hours following 0500 LST. Because of the warming in the first hour, the actual temperature decrease near 200 m during the second hour (0600 to 0700 LST) approached 3 K. Overall (Figure 6c), the layer between 50 m and 650 m AGL cooled during the period 0500 to 0800 LST.

During the course of the field campaign we had twelve intensive operating periods (IOPs) during which we launched morning radiosondes at VEL and Waddell. On eight of those IOPs cooling aloft was observed at VEL during the 0500-0800 LST time period, but on three of those occasions the cooling seemed to be associated with larger scale synoptic influences. On the remaining five occasions (16, 17, 27, 28, and 29 June), however, there was little or no temperature change observed above approximately 800 m AGL. This suggests that the observed cooling was localized and not associated with the passage of synoptic systems. For each of these five IOPs, cooling aloft was also observed at Waddell but typically occurred somewhat later than at VEL.

3.3 Vertical Mixing

Carbon monoxide is produced primarily by human activity, notably traffic, in urban areas. Because the air adjacent to the ground becomes thermodynamically stable, mixing is inhibited, and CO accumulates during the nighttime hours. Carbon monoxide reacts slowly, and the accumulation at the surface produces a significant negative vertical gradient of CO overnight. As a result, sharp increases of CO at the upper floors of the Bank One building are good indicators of the onset of vertical mixing in the morning.

Figure 7 shows time series of CO measured at 50 m and 140 m above the surface at the Bank One building together with hourly averages of CO obtained from a nearby surface monitoring station. In general, the surface monitor indicated large CO values in the early morning, often with a maximum in the predawn hours. The predawn maximum is consistent with the overnight accumulation described above and the increase in traffic shortly before sunrise. The steady decrease in surface CO following sunrise is consistent with the mixing of CO through a deepening boundary layer as turbulence intensifies with increasing insolation. After about 0600 LST, CO measurements at both heights on the tower are essentially the same as the surface values. This is also consistent with vigorous mixing,

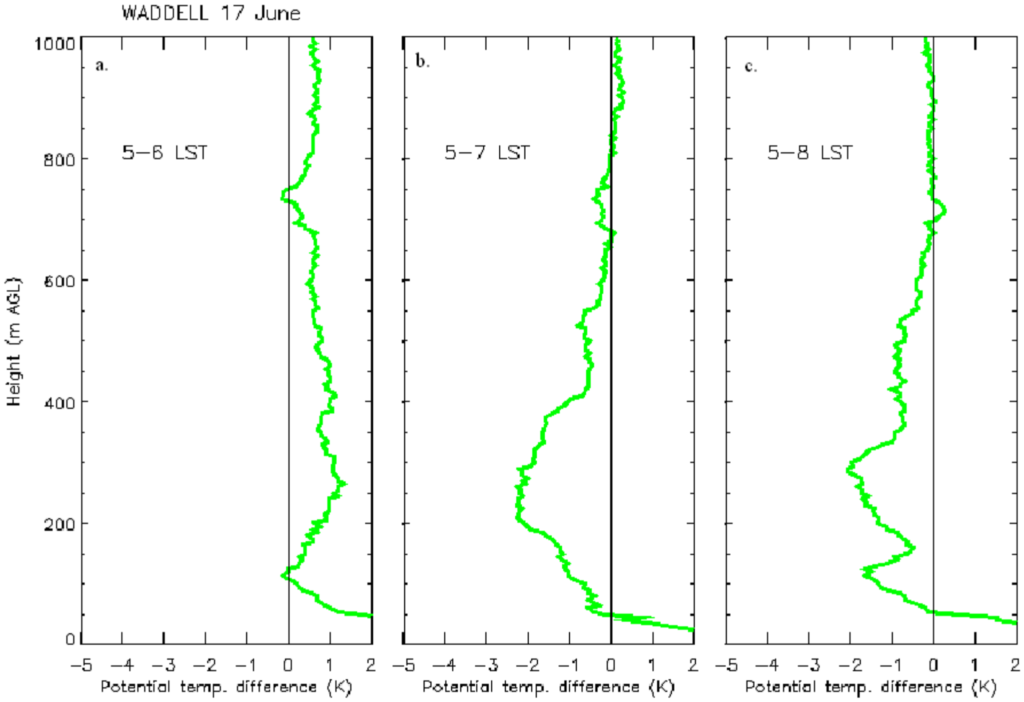

Figure 6. As in Figure 5 except for radiosondes released at Waddell.

which tends to produce constant CO values over the depth of the turbulent layer.

Figure 7a shows at the 50 m height a dramatic increase in CO that began about 0300 LST on 17 June. There was no corresponding increase at 140 m AGL. Just after 0500 LST there was a second sharp increase in CO, this time at both heights. Because both of these events occurred prior to sunrise, they cannot be attributed to turbulence driven by solar heating. Similarly, Figure 7b also shows what may be termed “premature mixing” on 28 June. Between 0300 and 0400 LST, CO at the 50 m measurement height increased significantly. Just after 0500, and still before sunrise, CO at the 140 m height increased to the same value as measured at 50 m. Following sunrise, CO values increased rapidly again at both levels and closely matched the surface measurements through mid-morning.

4. DISCUSSION

In the preceding section, we have described two unexpected phenomena that may be closely related. First, during most nights, when synoptic scale pressure

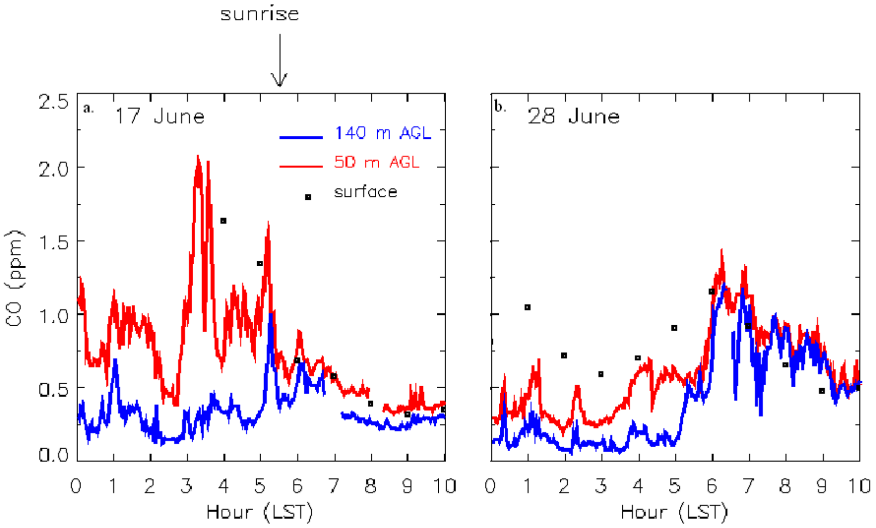

Figure 7. CO measured at the surface, 50 m, and 140 m AGL on (a) 17 June 2001 and (b) 28 June 2001.

gradients were weak, an easterly flow developed over downtown Phoenix sometime after midnight. It commonly reached a depth of 500 m or more just east of the city, but was generally shallower and later in arriving at measurement sites 35–40 km west of downtown. Further, this flow was associated with what we have termed anomalous cooling that was strongest a few hundred meters above the surface. It is not possible to identify from our observations alone what the source of the nocturnal flow is, but we speculate that it is a drainage flow that originates on the slopes and in the canyons of the surrounding mountains. Second, we have identified frequent episodes of premature vertical mixing in the downtown area of Phoenix. We have inferred vertical mixing from the time series of CO measured at the surface and at two heights on the Bank One building. These episodes are premature in the sense that they occur prior to sunrise and therefore prior to the onset of solar heating that would be expected to drive turbulence.

Because turbulence is weak or absent in a stably stratified atmosphere, mixing is suppressed until the atmosphere is destabilized either dynamically or thermodynamically. The early morning flow that we have described above may do this in one of two ways. First, because the easterly flow was generally stronger east of downtown and weaker or nonexistent to the west, it is possible that there was an area of convergence over downtown that acted to lift surface CO aloft. (Such lifting would also reduce the thermodynamic stability.) This effect would be even more pronounced if the onset of the easterly flow had a frontal structure similar to a sea breeze. Alternatively, the cooling above the surface would act to destabilize the temperature profile. In addition, the winds associated with the cooling (occasionally in excess of 5 m s^{-1}) would provide dynamic destabilization through increased shear.

Although the first mechanism described above may well play a role in the premature vertical mixing, we do not have direct evidence for it. The second mechanism, however, is consistent with observations described by Doran et al. (2003). They found that the normalized difference CO concentrations

$\left(\frac{CO_{39th} - CO_{sfc}}{CO_{sfc}}\right)$ measured at two heights on the Bank One building was a strong function of the bulk Richardson number. Thus it would seem likely that the cooling and winds associated with this nocturnal flow play a significant role in generating vertical mixing in the Phoenix area prior to sunrise. This may be an important consideration for modeling the chemistry associated with species that are more reactive than CO.

ACKNOWLEDGMENTS

This research was supported by the U.S. Department of Energy (DOE), under the auspices of the Atmospheric Sciences Program of the Office of Biological and Environmental Research of the Office of Science, under Contract DE-AC06-76RLO 1830 at the Pacific Northwest National Laboratory. Pacific Northwest National Laboratory is operated for the U.S. DOE by Battelle Memorial Institute. We are also grateful for the substantial assistance provided to us by the Arizona Department of Environmental Quality during the field program.

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