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MIDTROPOSPHERIC INFLUENCES ON BOUNDARY LAYER EVOLUTION IN THE MEXICO CITY BASIN

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1. INTRODUCTION

Mexico City lies in a horseshoe-shaped basin at 2250 m AGL. The city is surrounded on three-sides by mountains with mean elevations at least 500 m higher than the basin. Mexico City is well-known as one of the most polluted cities in the world, and its unique topographic setting in the subtropics is an important influence on this pollution problem, as described in Bossert (1997) and Fast (1998). These authors have simulated the effects of thermally-forced local to regional-scale circulation patterns on the ozone distribution within the basin. On most of the case days studied a relationship could be found between the spatial and temporal evolution of wind patterns and ozone concentration, particularly in the southwestern part of the basin. In this paper, we focus upon defining the relationship between the vertical structure of the atmosphere, by examining stability and wind shear, and the near surface pollution. This work was prompted by the need to better understand the role of midtropospheric flow in contributing to, or alleviating, the pollution problem in the basin. The role of vertical exchange processes in this locale has so far been only peripherally explored. From this investigation we hope to assess the importance of upper level winds in contributing to ventilation of pollutants out of the basin above the mountaintop level, in flushing the polluted airmass out of the basin, and in the development of basin-wide recirculation patterns. The following describes the results of preliminary data analyses. Further analyses and numerical modeling work will be presented at the conference.

2. DATA

Standard twice-per-day rawinsonde observations from the Mexico City Airport are used in the ensuing analyses and were obtained from the National Climatic Data Center's Radiosonde Data of North America. These data encompass the period from 1946-1993. Surface observations of meteorological and pollution variables are from the Mexico City Red Automatica Monitereo Atmosferic (RAMA) network of (up to 16) stations and cover the period of 1988-1997. Wind profiler, sodar, and ground station data from 4 sites around the Mexico City basin are also available from the IMADA-AVER field experiment of 24 February to 22 March 1997. Finally, data for RAMS model initialization is from the National Center for Environmental Prediction's 2.5 degree reanalysis data set. Only data from the first two sources will be presented in this paper.

3. RAWINSONDE CLIMATOLOGY

Sounding observations from the Mexico City Airport have been compiled into a 14-year rawinsonde climatology for the years of 1980-93, to define the mean vertical structure of the atmosphere above the basin as a function of time of day and season (Fig. 1). This analysis was obtained by averaging over several hundred soundings for each time and for each month for every 50 hPa interval. The atmospheric stability is shown in Fig. 1a. The stratification is very strong near the surface at 1200 UTC, except in summer when persistent cloud cover and a humid tropical airmass prevent nocturnal radiative cooling. Above the surface, the stability is more uniform throughout the year, but is weakest in the spring. We interpret this as possible evidence of weak stability residual layers affecting the climatology. These layers can result when a deep vertical mixed layer from the previous afternoon is decoupled from the surface by strong radiative cooling. The afternoon soundings (Fig. 1b) show weakest stability in the springtime, centered on April, with values less than zero (unstable) in the lowest layers. This figure shows that spring is the time of deepest boundary layer development on average in Mexico City. This climatological result is also borne out by several field studies undertaken in February 1991 and February-March 1997, where special soundings through the afternoon have shown explosive growth of the mixed layer to depths averaging 2.4 km AGL and often exceeding 3 km AGL (Bossert 1997; Doran et al. 1998).

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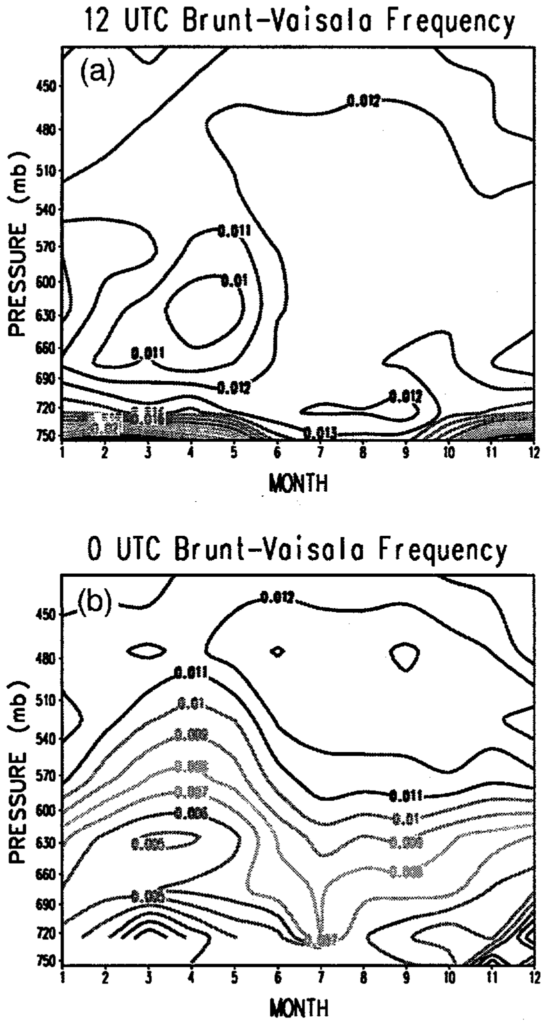

Figure 1. The Brunt Vaisala frequency in the lower troposphere over Mexico City as determined from 50 hPa rawinsonde observations for (a) 1200 UTC, and (b) 00 UTC.

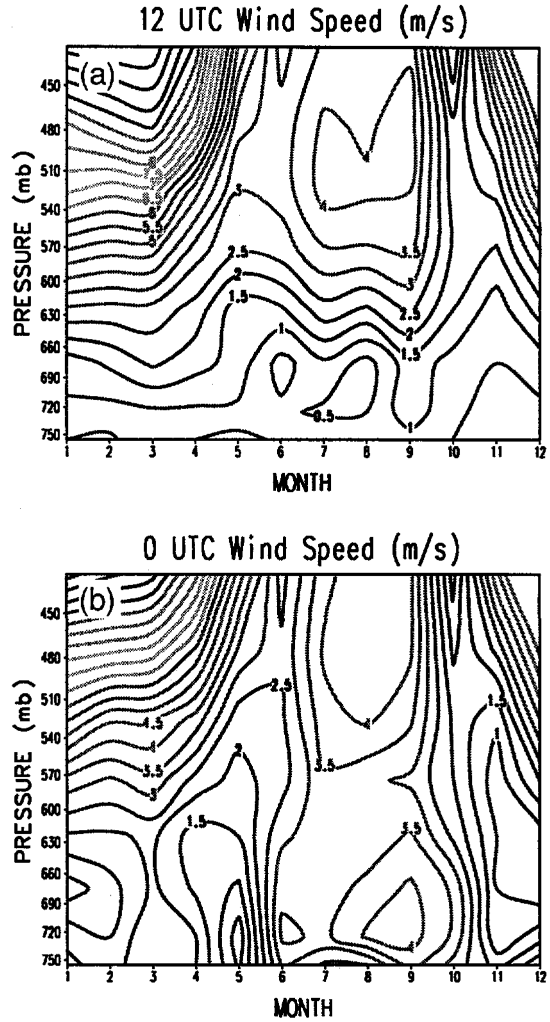

Figure 2. As in Fig. 1, but for wind speed.

The wind speed climatology is shown in Figure 2. The most notable feature is the strongly sheared (westerly) flow in the winter season, which changes between April and May to weakly sheared (tropical easterly) flow. The wind speed is a maximum in March, reaching 8 ms^{-1} at 500 hPa at 12 UTC (Fig. 2a). Winds near the surface are weak throughout the year at 1200 UTC. At 00 UTC (Fig. 2b), the winds in March have decreased to 6 ms^{-1} at 500 hPa, while at the same time increasing below 650 hPa. This behavior seems to indicate that a downward transfer of higher momentum air is occurring between the mid-troposphere and the deep boundary layer. Thus, in springtime, deep mixing creates a strong coupling in afternoon between the boundary layer and the mid-troposphere.

4. MIDTROPOSPHERIC INFLUENCES ON SURFACE POLLUTION

Considering the increase in dilution and ventilation, one might expect that Mexico City's pollution problem would be alleviated by the deeper mixing depths and stronger winds of spring. This is not the case, however. On average, ozone pollution in the basin tends to maximize in the spring (Streit and Guzman 1996), although it can easily exceed the Mexican standard of 110 ppb on any day of the year. The highest pollution episodes often occur in February and March, especially in the southwestern part of the basin. Of course, ozone production and spatial distribution is a result of many factors which drive the photochemistry. These include trapping of precursor species near the surface in stratified morning air, increasing insolation due to seasonal changes and lack of cloudiness, and thermally-generated local flows that can transport the polluted airmass into various parts of the basin. The influence of these factors on ozone production are being investigated with a chemical transport model (McNair et al. 1998). Our objective here is to further investigate any connection between midtropospheric flow and the measured surface pollution within the Mexico City basin.

An analysis with simple correlations has been used to define what midtropospheric variables are most influential. In this analysis, we consider only correlations found to be significant at the 95% confidence level with a Student-T test. Using simple time series correlations, we have investigated the relationship of temperatures and winds to ozone concentrations for surface stations in various sectors of the Mexico City, though here we only discuss results from the Plateros station in the southwestern portion of the basin. The data for these correlations includes only the months of March and April for the five years of 1988, 1989, 1990, 1993, and 1997. This data set excludes the years of 1991 and 1992, which had nearly all rawinsondes missing. We are in the process of obtaining data for 1994-1996 to supplement our comparison data base. The correlations were done for the mandatory pressure levels of 700, 500, and 300 hPa and for both 12 and 00 UTC.

4.1 Temperature Correlations

Somewhat surprisingly, correlations between midtropospheric temperatures and surface based ozone concentrations were nearly all below the 95% confidence level. While the correlations were all positive, only the 1200 UTC correlation between 500 hPa temperature and Plateros station ozone concentration at 2000 UTC was found to be significant. This result indicates that ozone production is fairly independent of weather systems that can affect the area and whose signature is strongly apparent in midtroposphere temperatures. Also surprising was to find negative correlations between atmospheric stability as defined by the Brunt-Vaisala frequency at both 1200 and 00 UTC with surface ozone concentrations at Plateros. Although the correlations were weak, the result indicates that conditions with deep mixing are more likely to have higher ozone concentrations. These results are discussed further below.

4.2 Wind Component Correlations

The highest correlations found in the data were between the v-component wind and the ozone concentration at the Plateros station in the southwestern part of the basin. This correlation was strong and negative at both 700 and 500 hPa and at both 12 and 00 UTC, but was not significant at 300 hPa. The ozone concentrations at Plateros were also significantly negatively correlated with u-component winds at 12 UTC only. These negative correlations in both wind components indicate that northeasterly winds favor highly polluted days, while southwesterly winds tend to prevent high pollution concentrations. This result is in agreement with those of previous data analysis (Bian and Whiteman 1988) and modeling studies (Bossert 1997; Fast 1998), which found that deep northeasterly flow was in place during several severe ozone episodes at stations in the southwestern portion of the basin.

4.3 Coupling Mechanisms

Here we explore mechanisms that involve coupling of boundary layer and midtropospheric winds and investigate their influence on Mexico City pollution. These mechanisms include air mass ventilation, flushing of the basin airmass, and recirculation of the airmass within the basin. In the preliminary analyses shown below we use only the 700 and 500 hPa wind observations at 00 UTC from the Mexico City twice-daily rawinsonde, as these levels are generally available from most soundings. This is indeed a shortcoming, since 700 hPa is at least 500 m above the surface and, as such, may miss thermally-driven wind systems that transport the surface pollution. There is also a 2.7 km gap between 700 and 500 hPa, which may be too distant in some cases to define coherent circulation systems. But in this analysis, we are trying to decide if these mechanisms exist and whether they can affect surface conditions before performing more elaborate studies. Should we find encouraging results, we intend to perform a more detailed analysis using the 50 hPa observations, as in the preceding climatology.

For this simple analysis, we define ventilation as conditions with weak stability and high wind shear between 700 and 500 hPa (high 500 hPa wind speeds relative to those at 700 hPa). In all but a few cases, stability, as defined by $d\theta/dz$, is very small at 00 UTC. In a well ventilated situation, the boundary layer airmass grows in response to strong surface heating, and weak winds within the basin. These conditions produce weak stability between 700 and 500 hPa by 00 UTC. As polluted parcels approach the top of the boundary layer they are quickly transported laterally by fast winds out of the basin. This process should be an efficient mechanism for cleaning the polluted airmass within the basin. In Figure 3, we show two scatter diagrams of the wind speed magnitudes at 500 hPa (Fig. 3a) and 700 hPa (Fig. 3b) at 00 UTC against peak ozone concentrations at 2000 UTC from the

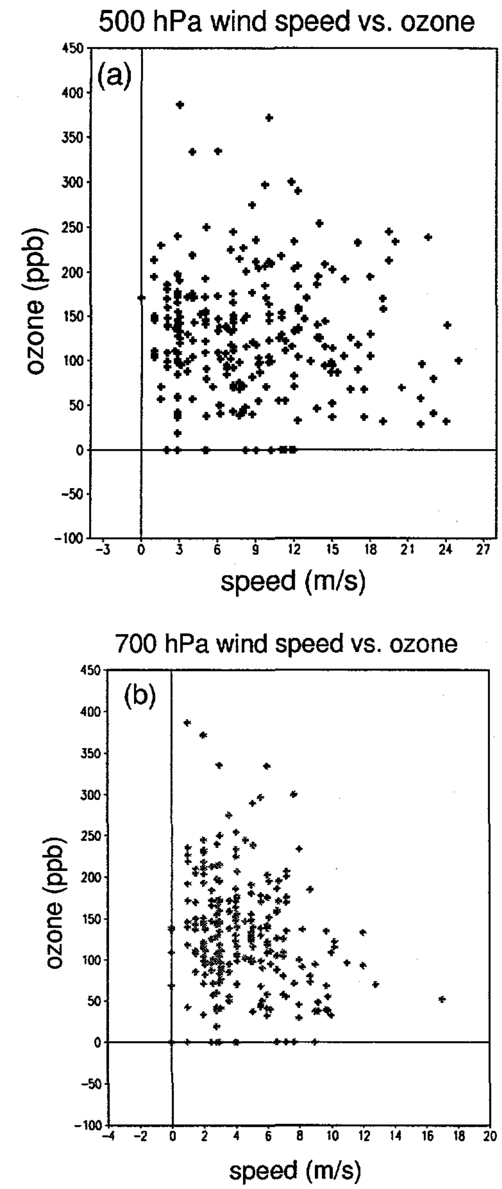

Figure 3. (a) wind speed at 500 hPa at 00 UTC plotted against ozone concentration at 2000 UTC at the Plateros surface station. (b) as in (a), but for wind speed at 700 hPa.

Plateros station. We hypothesize that if ventilation were effective, the 500 hPa wind speeds should plot as an inverse exponential function against ozone concentration and that days with large differences in wind speed between 700 and 500 hPa should be relatively clean. In fact, we find that up to 250 ppb, concentration shows no dependence at all on 500 hPa wind speeds. Above 250 ppb, the winds are generally weak at both levels. From this analysis, we conclude that ventilation, as we have defined it, does not appear to be an important factor in controlling low level pollution.

Another mechanism that can result from the coupling of boundary layer and midtropospheric winds is flushing, which we define here as a strong southerly wind at 700 hPa at 00 UTC combined with either positive or negative wind shear to 500 hPa. The reason for only considering southerly flow is because strong westerly component winds are rare at 700 hPa within the basin at this time of year and because the basin outlet is to the north, requiring southerly winds to effectively sweep out the polluted airmass.

The last mechanism involving coupling is recirculation, which is defined here as a flow situation with moderate northerly flow at 700 hPa combined with strong positive wind shear to 500 hPa. This ensures at least a weak southerly component wind at 500 hPa. This flow regime provides the means for polluted air parcels to be carried southward through the basin at low-levels, lofted to higher altitudes via thermally-direct slope flows or within boundary layer eddies, and then carried back over the basin in southerly flow above mountaintop (as depicted by the 500 hPa wind) to potentially be recycled within compensating subsident motion over the basin. Of course, this process could also occur entirely within the basin airmass well below the 500 hPa level, but here we examine only how feasible recirculation may be. Recirculation conditions will also lead to some ventilation of the polluted airmass, and ventilation will dominate the higher the southerly component winds become between 700 and 500 hPa.

We can show the regimes for both flushing and recirculation on another scatter plot which has v-component wind plotted against v-wind shear between 700 and 500 hPa (Figure 4). In this diagram it is relatively simple to show the wind and wind shear regimes where flushing and recirculation might be found. From the plot, we find that flushing could be a fairly common occurrence, and often is found with higher winds at 700 hPa than at 500 hPa (negative shear regime). These cases may involve the addition of thermal forcing induced low pressure within the basin, which can induce strong southerly flow through a gap in the southern mountains (Doran et al. 1998). The flushing case with strong southerly winds and positive shear is consistent with downward momentum transfer, as discussed in Bossert (1997), but appears to be less common. In the northwest quadrant of the plot we have the recirculation regime as we have defined it. The best cases for recirculation would be those with moderate northerly winds of 0 to -6 ms^{-1} and to the right of the line drawn. The line indicates the shear necessary to have southerly flow at 500 hPa. Northerly winds

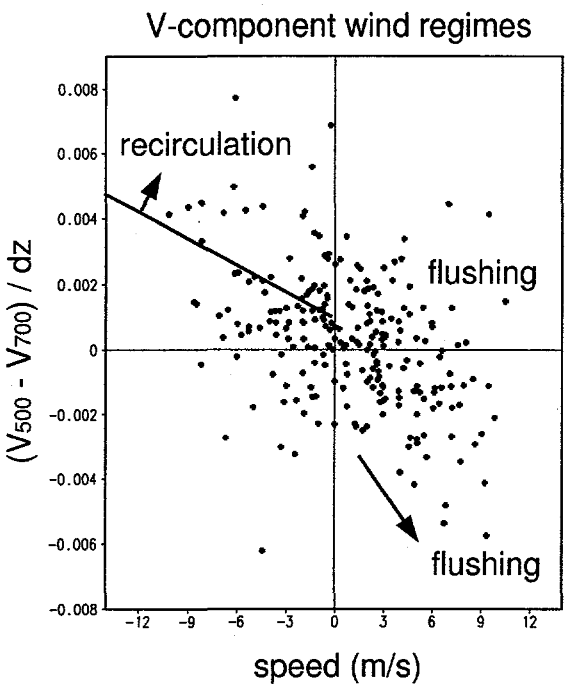

Figure 4. V-component wind at 00 UTC plotted against wind shear between 700 and 500 hPa, showing hypothesized recirculation and flushing wind regimes.

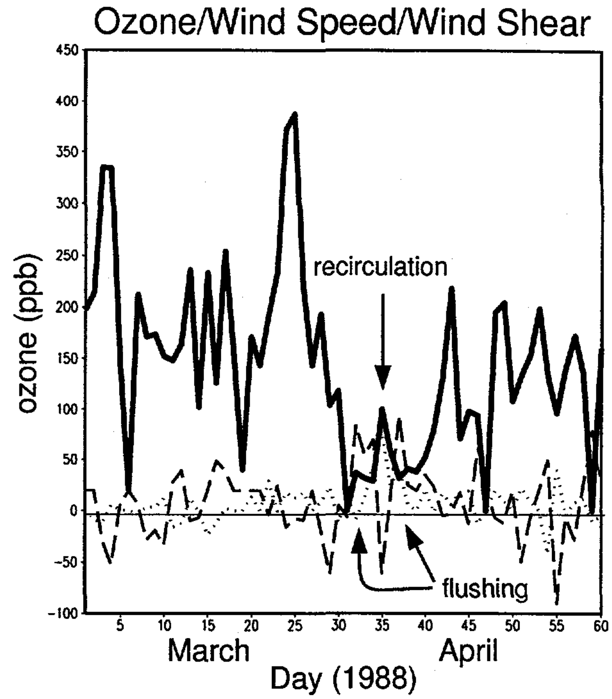

Figure 5. Time-series of ozone concentration (ppb) at Plateros at 2000 UTC (solid), v-component wind speed * 10 (dashed), and v-component wind shear * 10000 between 700 and 500 hPa (dotted), showing potential examples of wind regimes defined in text and shown in Fig. 4.

that are too strong near the surface with weak shear may still be northerly at 500 hPa and carry pollution out of the basin to the south. This could serve as another, albeit less efficient, form of ventilation. The figure shows that recirculation is quite possible in springtime, although the number of potential cases shown here relative to the total is unremarkable. In the southwest quadrant of the figure is the situation of northerly winds increasing with height. This is a rare occurrence in spring, but is more common in summer, as indicated by the wind speed climatology (Fig. 2).

Having defined the midtropospheric/boundary layer coupling mechanisms of interest in a general sense, we now turn to some specific examples of how these mechanisms may affect the pollution within the Mexico City basin, by looking at a time-series plot of ozone concentration at 2000 UTC at Plateros with wind speed at 700 hPa and wind shear between 700 and 500 hPa at 00 UTC (Fig. 5). Of course, the actual extent to which these mechanisms were operational on these particular days is unknown and needs to be confirmed via numerical model simulations. The figure shows how these factors can all come together to affect pollution in the basin. Cases that seem to exhibit a flushing type of wind behavior have higher southerly wind speeds and lower pollution concentrations. Events with recirculation have northerly component winds, positive wind shear, and higher pollution. Also of interest but not shown, cases with high thermal stability at 00 UTC tend to have lower ozone concentrations, despite the indication of shallower mixing depths. This is probably due to an increase in winds and clouds and reduced temperatures associated with disturbed weather that produces higher afternoon stability.

5. SUMMARY

We have shown that springtime in Mexico City tends to have significantly deeper mixing depths and stronger winds than at other times of the year. At first glance, this would seems to indicate conditions of lesser pollution within the basin. Other factors conspire, however, to defeat this simple conclusion. In light of this, we have tried to define several mechanisms (ventilation, flushing, and recirculation) involving a coupling of winds and temperatures between the boundary layer and midtroposphere that may influence the pollution within the basin. We have shown that these mechanisms may exist by looking at only two mandatory levels in twice-daily rawinsonde observations. We have also shown that ventilation appears to be unimportant for determining ozone levels in the basin, while recirculation and especially flushing have a stronger influence.

Further work will attempt to quantify the relationship between these vertical wind circulation patterns and boundary layer conditions using more extensive rawinsonde observations, and the intensive data sets from 1991 and 1997 field campaigns. Results from these data analyses will be further refined with mesoscale model simulations for specific cases and idealized conditions to understand how these various wind conditions evolve and influence boundary layer flows.

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