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MORNING PEAK OF AIR POLLUTANT CONCENTRATIONS IN URBAN AREAS: EFFECT OF TIME LAG BETWEEN EMISSIONS AND TURBULENCE.

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1. Introduction

Primary air pollutants in urban environments, like CO and PM10, show a distinctive diurnal cycle characterized by periods of maximum concentrations in the morning and in the evening. These peaks occur during the times of the day when high emissions combine with a relatively small dispersive capacity of the atmospheric boundary layer (ABL). Moreover, during the morning and evening hours, both the emission rates and the ABL turbulence are highly transient. Therefore, it is reasonable to expect that the timing and the magnitude of the concentration peaks are controlled by the time evolution of the emission rates, the turbulence intensity, and the *relative phase* between emissions and turbulence.

To explore the phase effect, we consider the cases when local official time (OT) changes due to Daylight Saving Time (DST) observance. The abrupt 1-hour change in OT due to DST produces a shift in the emission time profile with respect to the turbulence evolution. All anthropogenic emission processes tied to OT will "move forward" in the fall DST change (when official time "falls back"), and then "move back" in the spring DST change (when OT "springs forward"), as compared to the turbulence cycle that we assume fixed (Figure 1). DST changes, therefore, are in a sense a dispersion experiment, in which a known change occurs in the emission temporal pattern and corresponding changes can be measured in the resulting concentrations. Among the possible outcomes of this experiment we expect first a simple 1-hour shift in the concentration pattern (if no explicit reference to OT is made, all time analysis are based on a fixed time coordinate like UTC). In this case, the timing of the peaks in the concentration diurnal cycles will move forward in the fall DST, and back in the spring. A second possible outcome is a change in the magnitude of the peaks. For example, the emission pattern moving forward in the fall may induce a decrease in the magnitude of the morning concentration peak, because the later in the morning the pollutants are emitted, the more intense is the turbulence dispersing them. The strength of these effects in timing and magnitude of the peaks will certainly depend on the shapes of the emission and turbulence temporal patterns, as well as on the fraction of the emissions that are tied to OT.

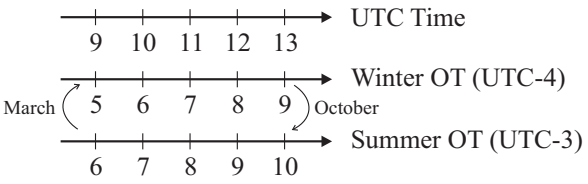

Figure 1. Scheme describing DST adjustments in the Official Time in Chile

Effects of DST on air pollution have been mentioned in public policy documents (Reincke and van den Broek, 1999), but their documentation in the scientific literature is, to our knowledge, very limited (Cohen, 1991; Hecq et al., 1993) and focusing mainly on the effect on ozone. Methodological difficulties to detect the DST effect, as described in Section 2, may be a reason for this paucity.

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In this work we analyze concentrations of CO and PM10 measured in Santiago, Chile (33.5°S, 70.6°W, 550 m.a.s.l.). The air pollution problem of Santiago is known to be one of the most serious in the world (Molina and Molina, 2004; Koutrakis et al., 2005), what is explained by natural and anthropogenic emission of pollutants, as well as by geographic and meteorological factors (Romero et al., 1999; Rutllant and Garreaud, 1995). During the cold season (April-August) the main air pollutant in the city is particulate matter, although CO shows also a marked increase. Figure 2 compares the annual mean PM10 concentrations and populations for 16 cities in the Americas as listed in a recent World Bank report (World Bank, 2003). Santiago stands out by having the highest mean PM10 concentrations with a relatively small population.

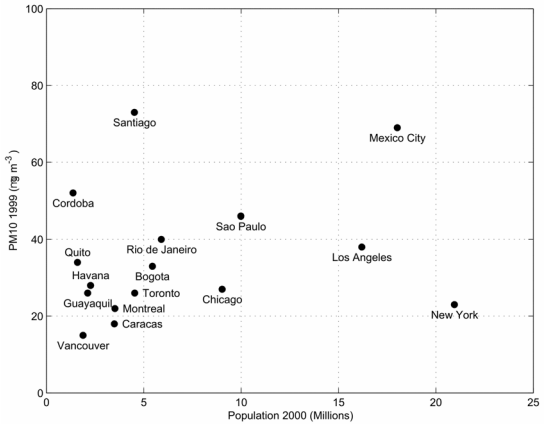

Figure 2. Mean PM10 concentrations in 1999 and 2000 population for 16 cities in America according to Table 3.13 (Air Pollution) in World Bank WDI report (2003).

Due to the importance of the problem, the Chilean Health Department operates since the 1990's a comprehensive air pollution network, measuring criteria pollutants and meteorology at seven points in the urban area (Figure 3). With regard to Daylight Saving Time in Chile, it is a long-standing practice mandated by official government regulations. During the winter period the Official Time in Chile is UTC-4, while during the summer it is UTC-3. The change from summer to winter (winter to summer) time occurs normally the second weekend of March (October).

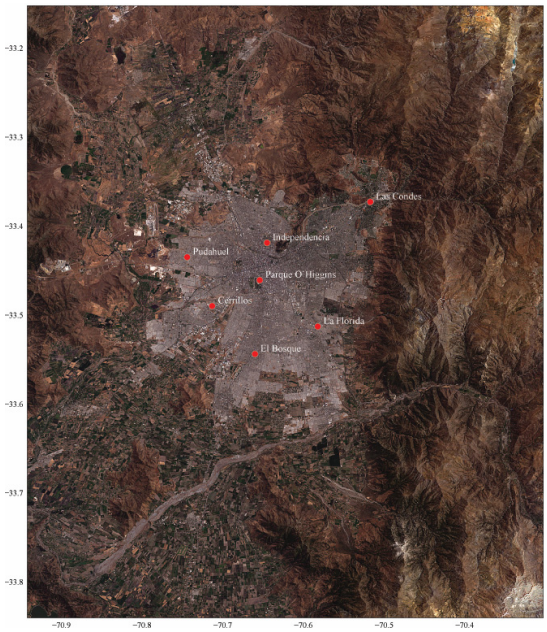

Figure 3.Topography of Santiago and Air Quality measurement network.

2. Data analysis

CO and PM10 are measured continuously at the Santiago air pollution network. A description of the network and the measuring techniques can be found in Jorquera (2002). The concentrations database used here corresponds to hourly averages for years 2000-2004, referred always to a constant winter time reference (UTC-4). Admittedly, a 1-hour shift in the emission pattern might be considered too subtle to be detectable using hourly concentration time series. Direct comparison of the concentration time series of the day after the DST change to that of the day before it would be meaningless, because the meteorological variability among specific days will hide any DST-related difference. It is necessary, therefore, to compare differences in the *mean* diurnal cycles for sets of days representing the conditions before and after the DST change. The larger the number of days considered in each set, the more robust the comparison would be. There is still a problem, however, if the averaging periods are too long, because then the strong seasonal trend in the concentrations will mask the effect of the time change. The problem is partially solved by using relatively short averaging periods around the DST weekend, but considering several years of

data. In this way, the mean diurnal cycles are computed over many days, but all being representative of periods relatively close to the DST weekend.

The actual methodology used to detect the effect of DST is straightforward. We form four sets of days. Set P-1 groups all weekdays of the two weeks prior to a DST change, and set P+1 includes all weekdays of the two weeks following a DST change. Additionally, we define set P-2 with all weekdays occurring 3 and 4 weeks before a DST change, and set P+2 with all weekdays occurring 3 and 4 weeks after a DST change. The reason for including sets P-2 and P+2 is trying to distinguish between the DST and the seasonal effects. Once the sets are formed, the mean diurnal cycles are computed for all days in each set. Thus, each mean diurnal cycle is computed over a maximum of 50 days (10 weekdays per year in a 2-week period, for 5 years). Concentrations in Santiago have a strong synoptic forcing, and thus the 2-week period chosen above is assumed to include approximately two synoptic cycles for each year.

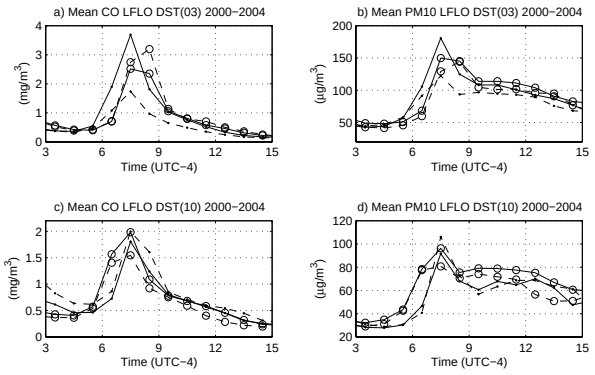

Figure 4. Mean concentrations around the morning hours for station La Florida (LFLO). a) CO concentrations around DST change in March. b) PM10 concentrations around DST change in March. c) CO concentrations around DST change in October. d) PM10 concentrations around DST change in October. Line symbols correspond to averaging P-2 (dots-dashed), P-1 (dots-continuous), P+1 (circles-continuous), and P+2 (circles-dashed), as defined in the text. Note that vertical scales are different in all panels.

Figure 4 shows results for Station La Florida (LFLO), for which the effect of DST on the morning concentration peak is most clear. Each panel in Fig. 4 shows the mean diurnal cycles (between hours 3-15 UTC-4) for the 4 Sets described previously. Panels a) and b) show, for the March DST change, the mean diurnal cycles of CO and PM10, respectively. Panels c) and d) are the corresponding diurnal cycles, but for the periods around the October DST change. The effect of the March DST on the CO morning peak (panel a) is very evident. Sets P-2 and P-1 (before the DST time change) have a peak at 8 AM, while it occurs later (and with smaller magnitudes) in Sets P+1 and P+2, after the DST change. The seasonal trend explains, in our view, the magnitude differences between Sets P-2 and P-1, and Sets P+1 and P+2. In fact, later in the cold season the morning concentration peak keeps growing and occurring later in the morning (not shown) because of the seasonal trend in the turbulence. The time shift of the morning concentration peak is similar for PM10 (panel b), as well as the reduced magnitude of the peak in the days after the DST change. The DST change in October (panels c and d) show the reverse effect in the timing of the morning peaks, occurring they earlier and somewhat stronger in the days after the DST change.

In Figure 5a and 5b we show the differences in diurnal cycles between Sets P+1 and P-1 (right after and right before the March DST change), considering the 50% (median), 75%, and 90% percentile of the hourly concentrations in each set. It is apparent that the DST effect is larger if the more extreme values of concentrations are considered. Figure 5c and 5d, on the other hand, show the corresponding differences in the 75% percentile cycles for all monitoring stations. Not all stations show as marked a concentration shift pattern as station La Florida, probably due to the local differences in the emission and meteorological cycles. In particular, stations La Florida and El Bosque show best the DST effect on the morning peak, and both are located in residential areas rather far from downtown. In these stations, the morning traffic peak may then occur earlier than in other stations, and the phase relationship with the turbulence be different.

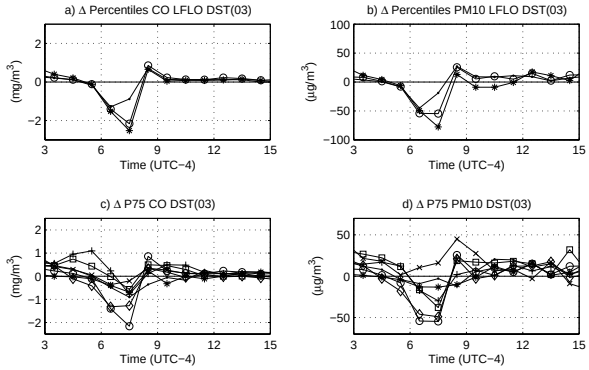

Figure 5. Differences between concentrations after and before the DST change in March. a) Percentiles 50% (dots), 75% (circles), 90% (stars) for CO at station La Florida. b) As a) but for PM10. c) Differences in percentiles 75% of CO for stations La Paz (dots), La Florida (circles), Las Condes (stars), Parque (crosses), Pudahuel(x), Cerrillos (squares), and El Bosque (diamonds). d) as c) but for PM10. Note that vertical scales are different in all panels.

Figures 4 and 5 have focused the attention on the morning peak, because for this peak the DST effects in timing and magnitude of the concentrations appear clearer. In fact, in the morning peak the DST and the seasonal effects play opposite roles, and therefore it is more striking that in the March DST change, for example, the morning peak reduces its magnitude in the weeks after the DST, in spite of the transition towards generally worse dispersion conditions (Figures 4a and 4b). The time shift of the emissions, however, might have an effect in the evening and night time concentrations as well. Indeed, Table 1 shows that the 4 sets of days have different mean CO and PM10 concentrations during the early night hours, with changes in magnitude that could be related in part to the DST change. However, since the mean evening concentration peaks are much broader than the morning counterparts, it is more difficult to detect a time shift, and the differences in magnitudes could be just the seasonal effect.

Days	March DST change		October DST change	
Sets	CO (mg/m^3)	PM10 ($\mu g/m^3$)	CO (mg/m^3)	PM10 ($\mu g/m^3$)
P-2	0.63	77	1.87	99
P-1	0.89	87	1.55	98
P+1	1.49	126	1.18	78
P+2	1.77	135	0.84	67

Table 1. Mean concentrations for hours 20-24 (UTC-4), Station LFLO, 2000-2004

3. Simple model of the morning peak effect

The observed effect of the time shift in the emission pattern upon the morning peak concentrations can be described qualitatively with a simple one-dimensional model of a mixed layer growing in time. The pollutant mass conservation equation (per unit surface area) will be

$$\frac{d(ch)}{dt} = q \qquad (1)$$

where *c* is the pollutant concentration, *h* is the height of the mixed layer and *q* is the emission rate per unit area. We assume that the ABL is horizontally homogeneous (no horizontal advections are considered) and that the air above it is clean (no entrainment of pollutants above). Equation (1) can be transformed into an equation for the concentration, as

$$\frac{dc}{dt} = \frac{1}{h}\left(q - c\frac{dh}{dt}\right) \qquad (2)$$

The two terms in the right hand side of (2) represent emissions and dilution by vertical mixing, respectively. The occurrence of a morning peak in concentrations depends in this model on the relative importance of these two terms. Early in the morning the emission

term must dominate, producing *dc/dt* >0. After some time, the dilution term must be more important so that *dc/dt* changes sign. We can use (2) to define conditions under which a maximum in *c(t)* can be observed. Differentiating (2) with respect to time we obtain

$$\frac{d^2c}{dt^2} = \frac{1}{h}\left(\frac{dq}{dt} - 2\frac{dc}{dt}\frac{dh}{dt} - c\frac{d^2h}{dt^2}\right) \qquad (3)$$

The mathematical conditions of a maximum concentration are *dc/dt=0* and *d2c/dt2<0*, and therefore at the maximum concentration we must have

$$\left.\frac{d^2c}{dt^2}\right|_{C\max} = \frac{1}{h}\left(\frac{dq}{dt} - c\frac{d^2h}{dt^2}\right) < 0\,. \qquad (4)$$

An interesting aspect of (4) is that if *dq/dt≥0* we can have a peak in concentrations only if d^2h/dt^2 *>0*. In other words, to have a maximum in concentrations during a period in which the emissions grow or are constant, it is not sufficient that the height of the mixed layer grows, but it must grow in a non-linear way.

To determine *c(t)* using (2) we must prescribe the time evolution of *q(t)* and *h(t)*. To facilitate the analysis we choose simple forms for these functions, as

$$h(t) = \begin{cases} h_o & t < 0 \\ h_o + at^2 & t \geq 0 \end{cases} \qquad (5)$$

$$q(t) = \begin{cases} 0 & t < t_o \\ (t - t_o)q_o / \tau_q & t_o < t < t_o + \tau_q \\ q_o & t > t_o + \tau_q \end{cases} \qquad (6)$$

where h_o, a, q_o, t_o, τ_q are constant parameters. The quadratic form for h(t) was chosen because of the need of having d^2h/dt^2 *>0*, as discussed previously (the model is intended just for the first few hours in the morning, since later in the day the ABL growth rate must necessarily decrease). The shape for the emission function is an approximation of the diurnal cycle of emissions used by the air pollution modelers in Santiago. The time origin in this model is tied to the moment in which the ABL begins to grow. The parameter t_o defines the phase lag between the growth of the emissions and the growth of the ABL. The parameter τ_q defines the timescale of the morning growth in the emission rate.

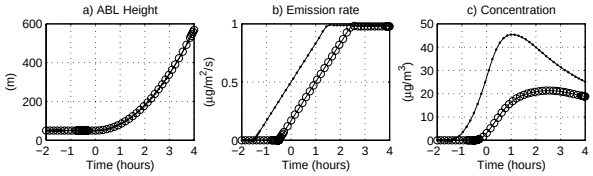

Figure 6. Input functions of ABL height (a), emission rates (b), and resulting concentrations (c) for the mixed layer model described in the text. In one case (lines with dots) emissions begin to grow 1 hour earlier than in the other case (lines with circles).

Figure 6 shows an example of model results for two cases in which the only difference is a 1-hour shift in the emission time profile (Parameter values are: h_o=50 m, a=2.5x10^{-6} m/s^2, q_o=1 μg/m^2/s, t_o=-1.5 and -0.5 hours, τ_q=3 hours). In particular, panel c shows the resulting concentration time series. These results suggest that the time shift of the emissions can have a profound impact in the morning peak concentrations, making it to occur later and have a reduced magnitude. The same qualitative features have been suggested in Section 2 as being observed in the effect of the March DST change upon the morning peak in CO and PM10. We must stress here that there has been no attempt of quantitatively matching these model results to the observed concentration values, since that would fall beyond the scope of this work.

5. Results with mesoscale model

We have performed a numerical simulation of the problem using the WRF-Chem model, applied to compute PM10 concentrations for a real case in Santiago for March, 5, 2007. The model setup has 3 km horizontal resolution, 31 levels in the vertical, with the first layer 17 m above ground level. Turbulence is computed with the MYJ TKE scheme. We have performed 3 numerical

experiments, shifting the emission time profiles +1 and -1 hour with respect to the control case that corresponds to the profile estimated by the official emission inventory for Santiago. Figure 7 illustrates the results obtained for the location of La Florida station. The upper panel shows the time series of the 3 experiments, the middle panel shows the emission temporal profile of the control case, and the lower panel is a time-height cross section of the computed turbulence field.

The model results reproduce qualitatively the effect seen in the observed concentrations. As the emission profile moves forward in time the morning peak moves in time and its magnitude decreases because of the increased turbulence. An opposite effect occurs in the night-time peak.

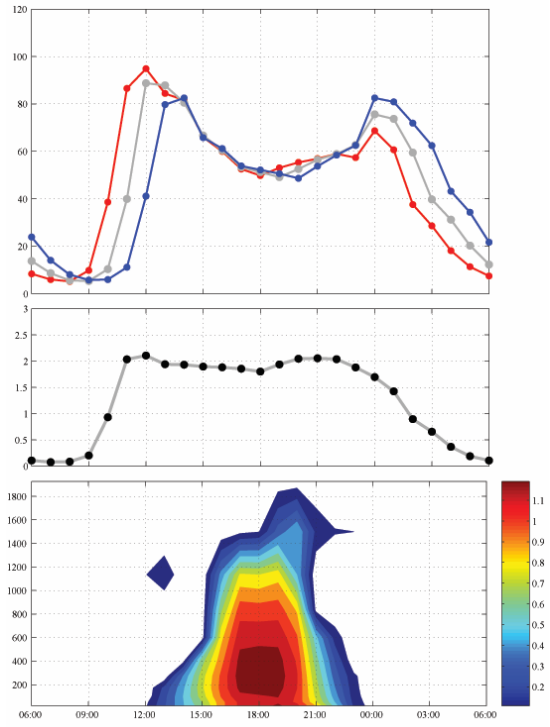

Figure 7. Results obtained with WRF-Chem model for March, 5, 2007. Upper: PM10 concentrations ($\mu g/m^3$) in La Florida for 3 experiments; Middle: Emission ($\mu g/m^2/s$) time profile for control case; Lower: time-hight cross section of TKE (m^2/s^2).

6. Conclusions

Results presented here suggest that the changes in official time occurring in March and October due to the DST rule have effects in the CO and PM10 concentrations in some of the monitoring stations of the Santiago air pollution network. The morning peak of these pollutants appears to occur later and have smaller magnitudes in the days after the March DST change, despite the transition to generally worse dispersion conditions. The opposite effect may occur on the evening peak, although in this case it is more difficult to distinguish between the seasonal and the DST effects. The October DST changes show the reverse effects on the concentration diurnal cycles.

Due to the opposite effects upon the morning and evening peaks, the net impact of the DST change upon daily averaged concentrations is uncertain and possibly small. The effect on short-term exposures at the times of the morning and evening peaks, however, may be more important. Additionally, the results presented here show the high sensitivity that the morning concentration peaks (in timing and magnitude) might have upon the emission rates, which could be used to infer some properties of the latter based on the observed concentrations at this time of the day. For example, it may be possible to use the simple model presented here in an "inverse" mode, to estimate the emission parameters that best reproduce the observed DST sensitivity of the concentrations. These estimated emissions can be next compared to the values produced, for example, by local emission inventories. This type of applications, however, fall beyond the scope of this note and may be pursued in the future.

Acknowledgements

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