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Forecasting urban PM10 and PM2.5 pollution episodes in very stable nocturnal conditions and complex terrain using WRF–Chem CO tracer model

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A B S T R A C T

This study presents a system to predict high pollution events that develop in connection with enhanced subsidence due to coastal lows, particularly in winter over Santiago de Chile. An accurate forecast of these episodes is of interest since the local government is entitled by law to take actions in advance to prevent public exposure to PM10 concentrations in excess of 150 μg m^{-3} (24 h running averages). The forecasting system is based on accurately simulating carbon monoxide (CO) as a PM10/PM2.5 surrogate, since during episodes and within the city there is a high correlation (over 0.95) among these pollutants. Thus, by accurately forecasting CO, which behaves closely to a tracer on this scale, a PM estimate can be made without involving aerosol-chemistry modeling. Nevertheless, the very stable nocturnal conditions over steep topography associated with maxima in concentrations are hard to represent in models. Here we propose a forecast system based on the WRF–Chem model with optimum settings, determined through extensive testing, that best describe both meteorological and air quality available measurements. Some of the important configurations choices involve the boundary layer (PBL) scheme, model grid resolution (both vertical and horizontal), meteorological initial and boundary conditions and spatial and temporal distribution of the emissions. A forecast for the 2008 winter is performed showing that this forecasting system is able to perform similarly to the authority decision for PM10 and better than persistence when forecasting PM10 and PM2.5 high pollution episodes. Problems regarding false alarm predictions could be related to different uncertainties in the model such as day to day emission variability, inability of the model to completely resolve the complex topography and inaccuracy in meteorological initial and boundary conditions. Finally, according to our simulations, emissions from previous days dominate episode concentrations, which highlights the need for 48 h forecasts that can be achieved by the system presented here. This is in fact the largest advantage of the proposed system.

1. Introduction

Santiago de Chile (33.5S, 70.5W, 500 m.a.s.l.) is a city with 6 million inhabitants located in a basin by the high central Andes. The city regularly faces severe air pollution related to particulate matter (PM) in winter due to emissions of particles and precursor gases, complex terrain and poor ventilation and vertical mixing (Rutllant and Garreaud, 1995, 2004; Garreaud et al., 2002; Gallardo et al., 2002). These conditions result in high PM concentrations (>300 μg m^{-3} hourly PM10 sometimes reaching 600 μg m^{-3}) known as "episodes". Maximum PM concentrations occur mainly during the night, and in the western parts of the Santiago basin (e.g., Gramsch et al., 2006).

The first air quality attainment plan was implemented in 1997, and it has been subject to revisions, the latest in 2009. Measures targeting large sources of emissions due to heating, transportation and industry resulted in reduced emissions and some improving in air quality. The plan includes a stipulation that a forecast model

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must be used to predict air pollution episodes in advance (MINSEGPRES, 2010). Three kinds of PM10 pollution episodes are defined based on Chile's 24 h mean PM10 standard of 150 μg m^{-3}, inspired by the former USEPA Air Quality Index for PM10, with the intention to limit acute exposure to air pollution. Alert is declared for 24-h average PM10 concentrations between 195 μg m^{-3} (30% over standard) and 240 μg m^{-3} (60% over standard), for which wood burning stoves are banned from operating. Pre-emergency is declared for concentrations between 240 μg m^{-3} and 330 μg m^{-3} (120% over standard) for which emissions are further reduced by restricting private transport use in the city by up to 40%, alongside with restricting operation of ~500 industries that do not meet a strict emissions standard of 30 mg m^{-3} of PM; and finally, an emergency is declared for concentrations over 330 μg m^{-3} and this triggers even stricter pollution reduction measures (60% ban on private transportation, and up to 900 industries are banned from operating). However, the percentage of compliance with these regulations and the effective emission reduction during episodes is unknown. Measures must be announced at 8 pm to be applied from 7:30 am the next day.

The forecast model currently used by the authorities is the so-called "Cassmassi model", which is a multivariate regression tool that weight tendencies on PM10 concentrations and 24 h forecasts of five discrete meteorological categories associated with synoptical and subsynoptical features linked to atmospheric stability (i.e., PMCA, Meteorological Potential of Atmospheric Pollution index) (Cassmassi, 1999). The decision on declaring episodes is not completely based on the results from the Casmassi model; it also involves a decision made by experienced air quality forecasters followed by a final political decision. For the moment, the focus is on PM10 and there is no prediction or measures taken for PM2.5 or any other pollutant.

Several approaches have been developed to predict air pollution episodes in the Santiago basin. Rutllant and Garreaud (1995) first showed that meteorological indexes for the Santiago basin could be computed using measured variables such as temperatures at different altitudes that correlate with PM measurements, and these could be used to predict episodes 12 h in advance. Neural networks, linear algorithms and clustering algorithms have been developed to forecast PM10 (Perez and Reyes, 2002, 2006) and PM2.5 (Perez and Salini, 2008) episodes. These models use measured variables (Temperature, PM) and prediction factors such as maximum temperature or the PMCA index for the next day to provide 30 h forecasts of air pollution episodes. To the knowledge of the authors, PM forecasts using deterministic air pollution models have not been performed for the city of Santiago, at least on an operational basis.

Predicting air quality using deterministic air pollution models is not an easy task and several initiatives have addressed its challenges (e.g., Baklanov, 2006). These studies point out the importance of an accurate representation of meteorology conditions at the city scale (e.g., Fay and Neunhäuserer, 2006), the importance of the meteorological scales (e.g. Palau et al, 2005), the influences of terrain resolution on complex topography scenarios (e.g., Schroeder et al., 2006; Finardi et al., 2008; Shrestha et al., 2009), the PBL scheme (e.g. Pérez et al., 2006) and urban PBL representation (e.g., Hamdi and Schayes, 2007), accurate surface fluxes description (e.g., Baklanov et al., 2008), the use of meteorological and chemical data assimilation (Kim et al., 2010; Pagowski et al., in press), and the need for integration with health exposure models (e.g., Baklanov et al., 2007). Regardless of the type of model used to predict air quality, whether it is statistical or deterministic, most of them need an accurate forecast of meteorological variables.

In the case of Santiago, the key-meteorological condition to forecast is the establishment of coastal lows (CLs), which are disturbances that propagate along the coast such as the warm low-level lows. Rutllant and Garreaud (1995) identified two main patterns for the CLs: type A and type BPF. Type A corresponds to the onset of a CL in Central Chile moving southward along the coast. This coastal trough appears between an enhanced Pacific high to the west of the Andes and a migratory cold high east of the Andes. Type BPF is a prefrontal condition ahead of a weak and often occluded front, which slows down or becomes stationary when reaching Central Chile. Typically, CLs of type A produce more intensive air pollution episodes than those of type BPF. The start of the high concentration episodes associated with type A coastal lows coincides with a sharp decrease in boundary layer height due to the establishment of easterly winds in connection with the sub-synoptic disturbance. The easterly winds are forced to subside by the high Andes giving rise to adiabatic compression and therefore to an enhancement of the subsidence inversion and clear sky conditions, possibly accelerating secondary aerosol formation due to intense photochemistry (Gallardo et al., 2002). The end of the episodes typically occurs in connection with humid air advection from the coast along the east-west valleys and the appearance in the Central Valley of Chile of fog conditions, which follows from the reestablishment of westerly winds near the surface and a weakening of the subsidence inversion, which in turn diminishes rapidly the pollutant concentrations in the basin. The intensity and duration of CLs varies depending on the overall synoptic configuration, the intensity of the weather systems involved and both the large- and local-scale topography. Regional scale models capture these features but they have difficulties ascertaining the rapid changes associated with the onset and end of coastal lows (e.g., Garreaud et al., 2002; Gallardo et al., 2002).

There is a strong correlation between carbon monoxide (CO) and PM measurements in the Santiago monitoring network (Perez et al., 2004), especially for the high values (>4 ppm of CO). Hence, in principle, by predicting CO one can also forecast PM levels. In terms of air quality modeling, CO might be easier to forecast than PM for several reasons: 1) Santiago CO emissions are better constrained than PM emissions (Jorquera and Castro, 2010; Saide et al., 2009a); and 2) At the city scale CO behaves as an inert gas phase tracer only subject to atmospheric transport and mixing (e.g. Saide et al., 2009a) while PM responds to complex heterogeneous chemistry, aerosol dynamics and wet and dry removal processes (e.g., Seinfeld and Pandis, 2006).

In this paper we present a forecast system for CO for Santiago using the WRF–Chem platform (Skamarock et al., 2008; Grell et al., 2005). We evaluate the predictions of CO and meteorological data against local observations for different settings of the model trying to find an optimum configuration. We then explore the use of CO predictions to produce PM10 and PM2.5 forecasts by applying a linear conversion. The PM forecast is tested for a whole winter period and results are compared to the authority decisions. Finally, the need for two days or more forecast is discussed and the settings for the operational simulation are established.

2. Methodology

2.1. Observations

2.1.1. Air quality data

Data for 2008 were obtained over the internet from the Ministry of Health (SINCA, 2010). The official monitoring network MACAM2 consisted in 2008 of eight monitoring stations that reported different criteria pollutants on an hourly basis. All stations had CO and PM10 monitors and five had PM2.5 monitors for the period analyzed. These stations were also equipped with temperature, wind and relative humidity monitors. This network was recently