J12.3 ON THE ROLE OF THE ANDES ON WEATHER PATTERNS AND RELATED ENVIRONMENTAL HAZARDS IN CHILE

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1. INTRODUCTION

The complex topography and unique climatic conditions combined with emissions from highly populated urban areas causes the Chilean territory to exhibit poor air quality and vulnerability to flooding and other natural hazards.

The most rigorous scientific tool for forecasting such hazards and evaluating ex-ante the effectiveness of preventive actions and mitigation strategies is numerical modeling, appropriately downscaled via models of different skills. At the present, however, even models such as the Weather Research and Forecasting (WRF) model, which is a new-generation mesoscale numerical weather prediction system widely employed for both research and routine weather prediction, appear to fail in fulfilling this goal, such weaknesses and failures being strictly related to the complex topography of the Chile region and the inability of the model to resolve it. The Andes is a continual range of highlands along the western coast of South America and represents the longest continental mountain range in the world. It is about 7000 km long, and about 200 km to 700 km wide (widest between 18° south and 20° south latitude). The average height is about 4000 m, but it reaches more than 6000 m in Northern Chile, the area where the largest biases in temperature and relative humidity are usually found in the model results. Given the steepness of these slopes, the horizontal grid resolution adopted in WRF plays a crucial role in the model ability to capture the flow patterns and phenomena at the mesoscale.

The aim of this work is investigating the role of the Andes and the meteorological conditions responsible for the unique rainfall event over the Atacama Desert, and high pollution events formation in Santiago metropolitan area where the impact of the Andes and the other surrounding mountains seems to be adversely affecting air quality in the city. The weather conditions accountable for the worst air quality in Temuco urban area (being considered by the local authorities as one of the most polluted regions in the Country) are studied in addition. Only isolated hills are located in this area; therefore, the effect of unresolved complex topography should be inconsequential.

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2. MODEL CONFIGURATION

The WRF model was employed to simulate flow pattern in three different areas - Santiago (Central Chile) and Temuco (South Chile) urban areas, and Atacama Desert region in North Chile. WRF is a state-of-the-art mesoscale numerical weather prediction system widely employed for both research and routine weather prediction. National Center for Atmospheric Research (NCAR) supports the WRF system to the user community and maintains the WRF code (http://www.mmm.ucar.edu/wrf/users). Model version used in this study is WRF-ARWv.3.5.

2.1 Modeling domains

Four nested domains of 27, 9, 3 and 1 km grids were based on a Lambert Projection with diverse central point for different areas: Atacama Desert (26.3°E; 70.2°S), Santiago (33.5°E; 70.7°S) and Temuco (39.7°E; 73.0°S) regions. Domains used for simulations are shown in Figure 1. It should be noted that, due to the unique topography with very steep slopes in Northern Chile (somewhere gradient is about 300 m per 1 km), the model failed to predict with 1 km grid by calculating unrealistic vertical speeds. Due to this reason, numerical results for Atacama Desert area (Figure 1a) are provided with 3 km grid for the inner domain. Different domains were tested (with grid ratio 3, 4 and 5) and those presented in Figure 1 were identified after model verification and comparison made between different configurations. The choice of the boundary conditions is crucial and leads to significant difference in the model outcomes. Exploiting different inner domains (due to applied grid ratio) affects the results especially in correspondence with the lateral boundary conditions. It is difficult to select boundary away from the mountain peaks due to the complex terrain and the large orographic gradients. Our analysis suggests the effect of unresolved complex topography to be the main reason for the poor model performances for the inner domains in North Chile and Santiago region.

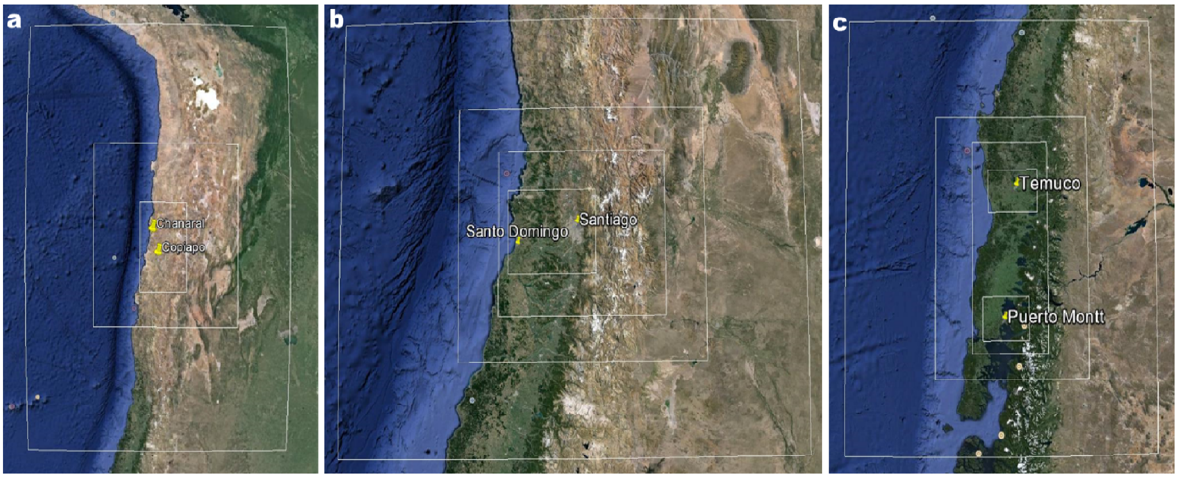


Figure 1. Domains used for simulations with WRF model for Atacama Desert (a), Santiago (b) and Temuco (c).

The vertical grid was set to 61 terrain following (eta) levels based on preliminary model evaluation with a total of 31, 41, 51 and 61 levels. Detailed flow description needs more levels near the ground, especially in complex terrain, to be able to resolve small vorticity and layer structure especially during stable conditions.

2.2 Modeling periods

Modeling periods relate to the different tasks considered in this study. The period 23–27 March, 2015 was simulated to investigate the intense rainfall and flood event at Atacama Desert, one of the driest places on Earth. Measurements from Pastillo pluviometric station, south-east of Copiapo city, recorded a total of 65 mm of accumulated rain over 3 days, the equivalent of several years according to the climatology of the area. The event, accompanied with several human losses and failure in electricity and water services, caused an economic cost of approximately 1.5 billion dollars according to government authorities, with the cities of Chañaral, Copiapo and Diego de Almagro being among the most damaged areas. Unique rainfall combined with steep topography of the Andes and extremely low permeability of the Atacama soil and rocks, caused a torrential runoff leading to catastrophic flash floods over the regions of Atacama, Antofagasta and Coquimbo (Figure 2).

For Santiago and Temuco study, several periods of high air pollution were investigated in terms of meteorological conditions favorable to poor air quality events. With 6 million inhabitants, Santiago de Chile is an example of the dichotomy between opportunities and risks. Following strong economic and urban growth experienced in 1980-1990, Santiago faced environmental degradation and health risks due to extremely high levels of air pollutants (Rutllant and Garreaud 1995, Romero et al., 1999), frequently exceeding standards set by World Health Organization (WHO). According to WHO, inhalable particulate matter (PM_{10}) 24-h mean in a city should not exceed 50 µg/m^3 (WHO 2006), but in Santiago alerts are issued only when this level approaches 195 µg/m^3. Since 1990, numerous efforts have been made towards improving air quality (Rutllant and Garreaud 1995, Jorquera et al., 2004); nonetheless, high pollutant levels still happen at Santiago. Driven by anthropogenic emissions, air pollution levels in Santiago appear to be highly correlated to the geomorphology, land cover and meteorology of the region. The city of Santiago is located in an inland valley of central Chile and is almost completely surrounded by high mountains (Figure 3). Owing to this complex topography and its latitude, mountain and valley winds and subsidence due to blocking effects dominate the local weather patterns of the area especially during the austral autumn-winter (April-August).

Figure 2. Picture of the catastrophic flood in El Salado at 25 March, 2015 (left) and topography in North Chile (right).

Figure 3. High pollution event in Santiago (left) and topography surrounding the city (right).

The air quality along with the meteorological data were analyzed to identify high pollution events in both Santiago and Temuco areas. The investigation consisted of several periods (called henceforth events) for Santiago region: 11-13 May 2007, 6-8 June 2012, 18-20 July 2012, 14-18 June 2014, and 18-24 June 2015. At the present, the Chilean authorities issue three different air quality alerts: 1) Environmental alert, 2) Pre environmental emergency and 3) Environmental emergency are declared when PM_{10} 24-h mean exceeds 195, 240 and 330 µg/m^3, respectively. The first four events started as an Environmental alert and ended with Pre environmental emergency, while the last event corresponds to an Environmental emergency, the first in 16 years.

According the recent Chilean emission inventory (2011) published in the report of the Chilean Ministry of Environment (Report 2013) about 90% of the fine particles $PM_{2.5}$ are emitted through the burning processes (open biomass burning, residential heating and cooking) and small portions through fossil fuel combustion, industrial production and power plants. The contribution of the burning processes is the most pronounced in the south part of the country and reach 100000 tons per year (Los Lagos for example) and more than 10 times less for the Santiago area (< 10000 tons per year). The report shows exceedances over the annual (20 µg/m^3) and 24-h mean (50 µg/m^3) national standards that occurred mostly in large urban areas in South Chile based on data for 2013. The annual $PM_{2.5}$ concentration is more than doubled for Temuco ~ 45 µg/m^3 and the 24-h mean is more than three times over the standard ~ 180 µg/m^3. Similar situation exists with PM_{10} concentration for the Osorno region – more than 100 µg/m^3 annual mean (the primary norm for Chile is 50 µg/m^3) and about 300 µg/m^3 for 24-h mean (the standard for Chile is 150 µg/m^3). All these numbers indicate serious problems in terms of air quality and related risks for human health, and the contribution of high emissions in the south part of the country is significant. Temuco is one of the most highly wood-smoke-polluted cities in the world (Figure 4). Its population in 2004 was 340000 inhabitants with 1587 annual deaths, of which 24% were due to cardiovascular and 11% to respiratory causes (Sanhueza et al. 2009). Several episodic periods were selected for investigation at Temuco region based on several days lasting pollution events: 26-28 July 2005; 29-30 July 2006; 29-30 June 2007; 1-3 June 2009; 22-26 July 2009.

Figure 4. High pollution event in Temuco (left) and topography (right) surrounding the city.

Time series of PM_{10} observed concentration at Cerro Navia, site located in Santiago metropolitan, and Las Encinas located in Temuco, are shown (Figure 5). The systematic exceedances for 24-h mean over the National Standard exist for both areas with increasing trend of in South Chile due to urban growth in the last decade (Sanhueza et al., 2009).

The initial and boundary conditions for WRF simulations are based on the National Centers for Environmental Prediction (NCEP) operational Global Forecast System (GFS) analysis and forecast with 0.25 by 0.25 global latitude longitude grid available on every 3 hours (http://rda.ucar.edu/datasets/ds084.1/) for modeling 2015 events, and on NCEP Final Operational Global Analysis data (FNL) with 1 by 1-degree grids available on every 6 hours (http://rda.ucar.edu/datasets/ds083.2/) for modeling periods previous to 2015.

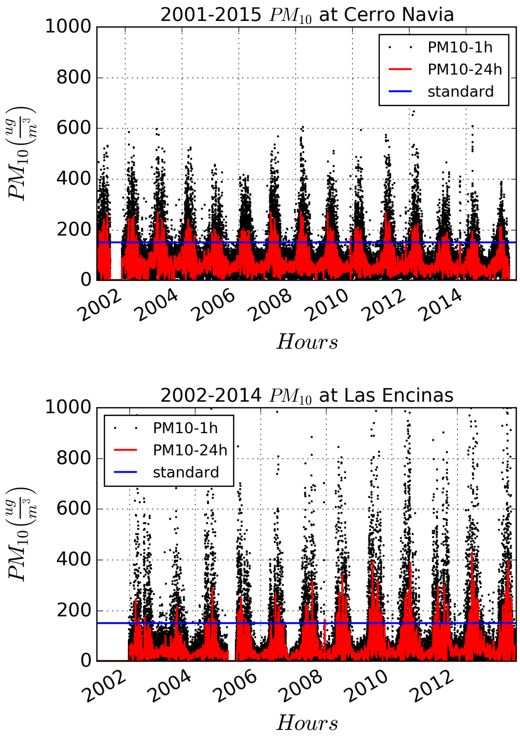


Figure 5. PM_{10} concentration time series - hourly data (black dots) and 24-h averaged (red line) compared with the national standard 150 µg/m^3 (blue line) for Cerro Navia (Santiago) and Las Encinas (Temuco).

2.3 Experiment with different physical options

Several model configurations (using different microphysics, cumulus (Cu_physics), planetary boundary layer (PBL), long and shortwave radiation schemes; other physics options like diffusion, advection and damping) have been tested. Experiments with different options for each of the three regions were made in order to select the best choice for model configuration for specific orographic and meteorological conditions. Full description of available options in WRF model can be found in NCAR technical note (NCAR/TN–475+STR 2008). Summary of physical options tested for the precipitation event at North Chile are shown in Table 1, and for high pollution events in Table 2.

	Microphysics	*Radiation*	*PBL*	*Top (hPa)*
Test 1	Lin et al.	RRTM/Dudhia	YSU	1000
Test 2	Lin et al.	RRTM/Dudhia	YSU	5000
Test 3	Lin et al.	RRTMG	YSU	5000
Test 4	Goddard	RRTM/Dudhia	YSU	5000
Test 5	Goddard	RRTM/Dudhia	MYJ	5000

Table 1. Summary of physical options tested for intense rainfall event - North Chile.

	Microphysics	*Cu_physics*	*Radiation*	*PBL*
Test 1	WRF Single Mom. 6 class	Kain-Fristsch	CAM	YSU
Test 2	New Thompson et al.	Grell- Freitas	RRTMG	QNSE
Test 3	Lin et al.	Kain-Fristsch	RRTM/Dudhia	QNSE
Test 4	Lin et al.	Grell- Freitas	RRTMG	MYNN
Test 5	Lin et al.	Grell- Freitas	RRTMG	YSU

Table 2. Summary of physical options tested for high pollution events in Santiago and Temuco regions.

The WRF model outputs were validated against observations for the selected episodes and examples are shown (for selected configurations only) in next section. Presented results in following sections for Santiago metropolitan region correspond to Test 4 configuration, for Temuco – Test 5 (Table 2). Results for several test cases are shown for rainfall event in North Chile.

3. RESULTS AND DISCUSION

3.1 Extreme rainfall event

The Atacama Desert is one of the driest places on the Earth, due to the presence of the subtropical anticyclone over the south-east Pacific, the influence of the cold Humboldt Current and the presence of the Andes in close proximity. From a climatological point of view, the rainfall event during March 2015 is therefore rather unique and exceptional. The extreme rainfall event was the result of several concomitant factors which allowed a cut-off low (COL) pressure system to move unusually further north–east, toward the Atacama Desert and stay several days over the area. The synoptic weather conditions conducive to this event were investigated using NCEP GFS 0.25 Degree Global Forecast Grids Historical Archive (http://rda.ucar.edu/datasets/ds084.1/) and analyzed by maps of geopotential height contours, wind vectors and temperature colored contours at 300 hPa together with precipitable water over the entire layer (Wilcox et al., 2016). Only discussion on the local meteorological conditions obtained by simulations with WRF model are presented here.

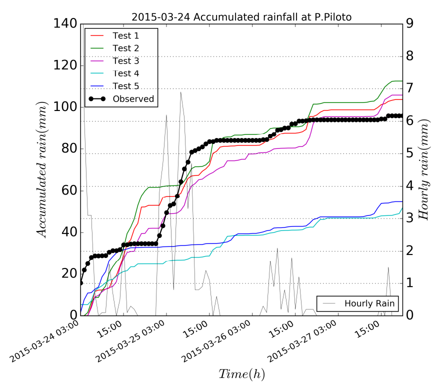
Several model configurations (see Table 1) were tested and compared against observations at three sites Pastillo, Carrizalillo and Planta Piloto, located in the mountain area where torrential runoff caused floods in Copiapo area. The local area is shown in Figure 6 and stations elevation in Table 3. Planta Piloto is the highest point of measurement (2645 m), Pastillo is the lowest point (1203 m) with 1442 m difference in altitude between them. Carrizalillo is located in a very narrow valley surrounded by steep slopes and therefore challenging to model.

Figure 6. Mountain area used for model validation.

Station	**Lat**	**Lon**	**Altitude (m)**
Pastillo	-28.004	-69.977	1203
Carrizalillo	-28.145	-69.771	2054
Planta Piloto	-28.145	-69.646	2645

Table 3. Location and altitude of meteorological stations used for model validation.

Plots with accumulated and hourly precipitation from the two high elevated sites are shown in Figure 7. The maximum in hourly rain (7.2 mm per hour) was measured first at Planta Piloto (the highest elevation site) at 3 am and three hours later at Carrizalillo (7.6 mm per hour) at 6 am. The second maximum was detected on the next day again first at Planta Piloto (6.9 mm per hour) at 7 am, and at 10 am at Carrizalillo (6.4 mm per hour). All tested physical options used in WRF experiment were found to play a role on accumulated precipitation at the three sites, with the most significant difference due to the selected microphysics. Lin et al. scheme (Tests 1, 2, 3) produces more precipitation than Goddard scheme (Tests 4, 5) at high elevation. No significant difference was detected for Pastillo site based on the selected microphysics. Local MYJ (Mellor-Yamada-Janjic) PBL scheme improves the rain predictions at Carrizallilo station probably due to better description of the local flow inhomogeneities under low wind conditions (mountain blocking effect) in complex topography in comparison with non-local YSU (Yonsei University) scheme (lines correspond to Test 4 and Test 5).



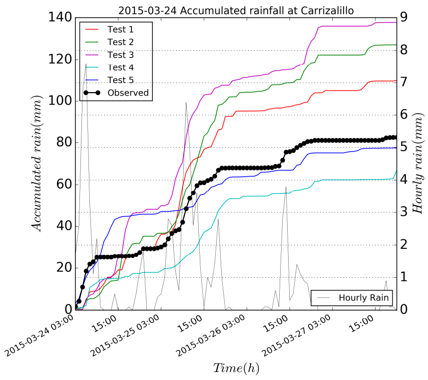


Figure 7. Evaluation of the precipitation at two stations Planta Piloto (upper panel) and Carrizalillo (bottom panel) for all cases.

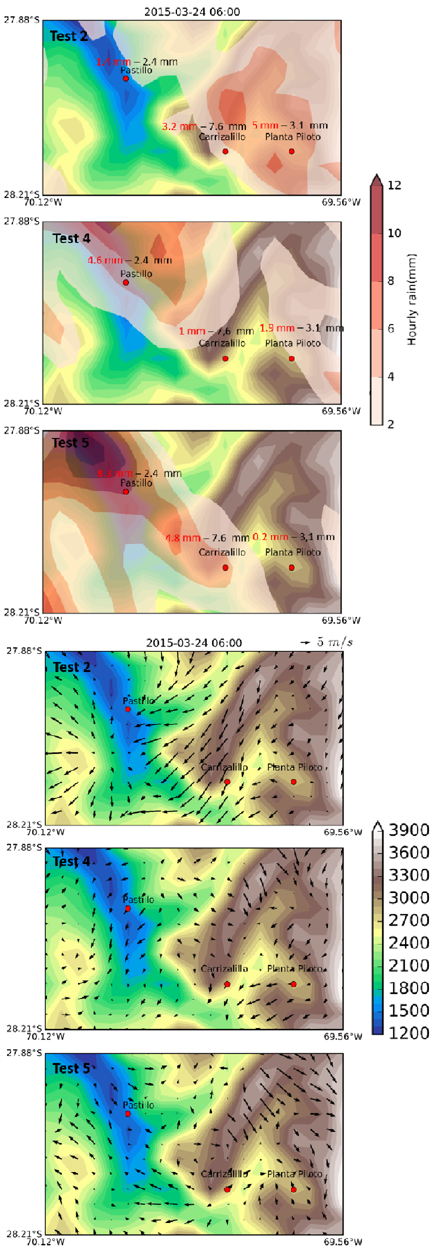


Figure 8. Precipitation accumulated for 1 hour (upper panel) and flow field (bottom panel).

Precipitation spatial distribution for three tests are shown in Figure 8, with measured and simulated rainfall at each station indicated in black and red colors, respectively. The difference between Tests 2 and 4 is the microphysical scheme, between Tests 4 and 5 the PBL scheme. Lin et al. scheme is better in reproducing the precipitation pattern at higher elevations. MYJ PBL scheme provides more precipitation at lower elevation station producing stronger winds inside the valley (canalization effect) and flow acceleration above the mountain peaks than YSU PBL scheme.

All schemes greatly underestimate temperature, probably due to the coarse representation of the local topography in WRF. For example, very steep slopes characterize the area around Carrizalillo station (Figure 9). The average grid cell (over 3 km grid) is larger than actual altitude and modeled temperature is lower than measured. There is no significant difference in using different radiation schemes. All schemes were however able to capture the drop in temperature induced by cold air advection during the second day, but not on the third day of the event.

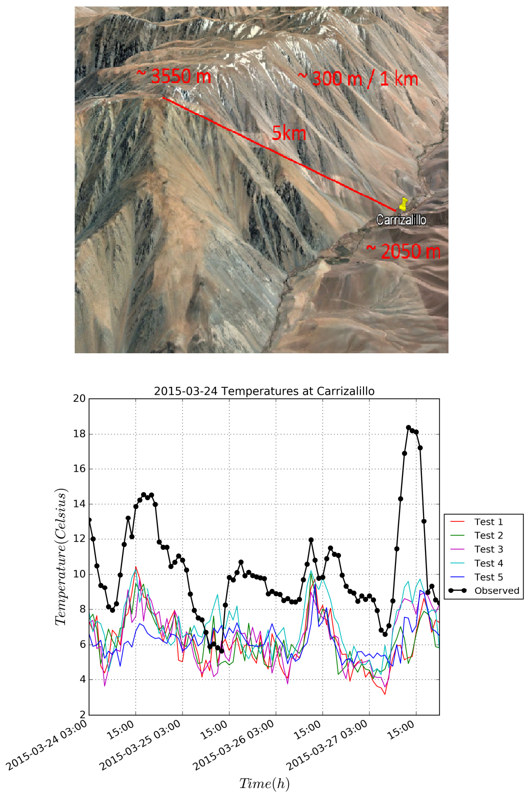


Figure 9. Topography and temperature evaluation at Carrizalillo station.

3.2 High pollution events in Santiago

The presence of the Andes and the other mountains surrounding Santiago adversely affect air quality in the city. Wind regimes are often associated to weak ventilation conditions, especially during the nighttime, allowing more pollution to build up and cause hazardous concentration levels (Fernando, 2010). Consequently, extreme events occur frequently during the high pollution season extending from April to August. The meteorological conditions concurrent with those extreme events are mainly associated with the regime of the Pacific high pressure system further enhanced by coastal lows, which bring down the base of the subsidence inversion reducing the diurnal growth of the surface mixed layer (Rutllant and Garreaud 1995, Gallardo et al. 2002). Several periods described in section 2.2 were investigated and all of them relate to high pressure system, low wind conditions and inversion up to 850 hPa. One example of model validation at Santo Domingo is shown in Figure 10. Santo Domingo is located far away from Santiago (about 80 km westerly, situated close to the coastal line and in a relatively flat area). The station is representative of westerly synoptic conditions for the region. The WRF model captures well the temperature and relative humidity vertical profiles, except in close proximity to the ground. Typical conditions that are related to high pollution - temperature inversion and low humidity are shown.

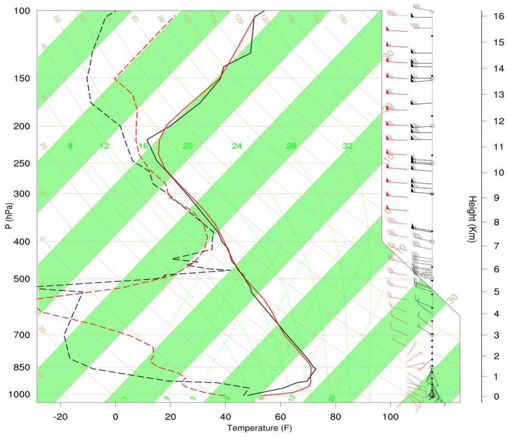


Figure 10. Skew-T diagram for WRF model (red) and observations (black) at Santo Domingo (11 May 2007 at 12 UTC).

High resolution (1 km) numerical simulations were performed for Santiago area. Main meteorological variables were compared with observations for all cases at seven locations inside the city. One example for 11-12 May, 2007 is given in Figure 11. Dash green lines marks peaks in PM_{10} concentration measured in Santiago. Most of the episodes of elevated concentrations correspond to stable night conditions (10 pm) or morning transition periods (8 – 10 am). The wind remains weak (about 1 m/s) for about 1.5 days and a drop in relative humidity (from 80 to 40%) is recorded twice during the same period, which precedes the peak of 400 µg/m^3 in PM10. WRF captures these patterns, although it underestimates the value for the relative humidity. The known problem of overestimation of nocturnal temperature in complex terrain reported in previous studies (Dimitrova et al., 2015) is also pronounced. Also the model failed to predict the trend of temperature decreasing after the first day of calculations.

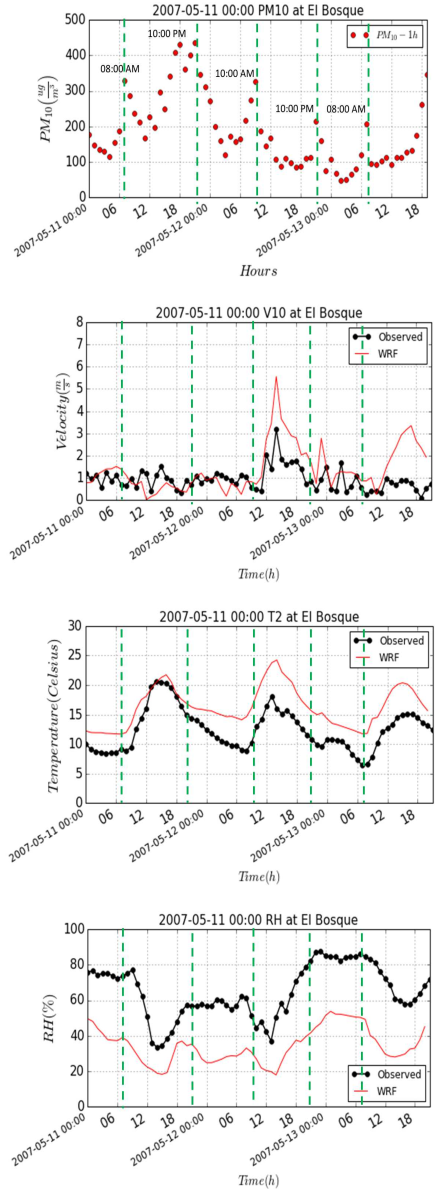


Figure 11. PM_{10} concentration, wind speed, temperature and relative humidity for El Bosque station

Calm conditions (wind speed about 1 m/s) and stable stratification were predicted from the model over entire Santiago metropolitan area in agreement with observations during the elevated pollution episodes and one example is shown for 11 May, 2007 at 10 pm (Figure 12).

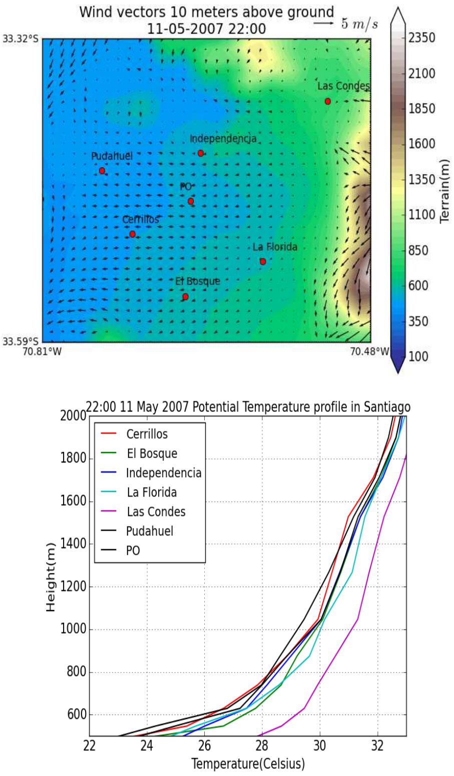


Figure 12. Wind field and temperature vertical profiles for Santiago area at 10 pm local time corresponding to maximum concentration observed.

3.3 Pollution events in Temuco

The synoptic regimes showed the prevalence of anticyclonic conditions during the episodes which are typically associated with severe air pollution events in Temuco. The high pressure system persisted over the region for several days, with meteorological conditions conductive to an extended smog episode. Surface winds were generally light, especially during evening and early morning periods when calms were frequently observed. The temperature is greatly moderated by its proximity to the ocean with only small variability with season and diurnal amplitude. Several periods described in section 2.2 were investigated with PM_{10} concentrations reaching 800 - 900 µg/m^3 during episodes 29-30 June 2007 and 22-26 July 2009.

One example for model validation at Puerto Montt site is shown in Figure 13. The model performs very reasonably with the main disagreement with observations for temperature close to the ground (failed in predicting measured sharp temperature gradient) and wind direction. The skew-T diagram indicate stable stratification due to warm dry air overlapping the colder moisture air near the ground. Puerto Montt is located far away south of Temuco area but approximately on the same distance from the costal line. Unfortunately radiosonde data nearby Temuco are not available, but the selected station can be used as representative site for the synoptic flow over the region.

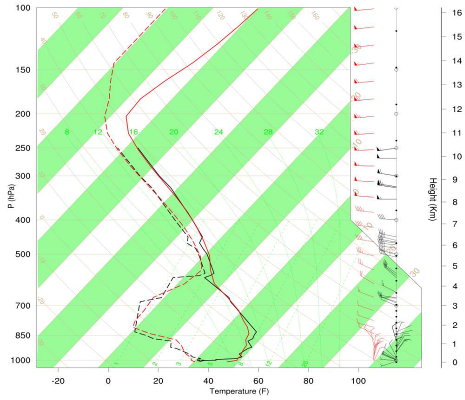
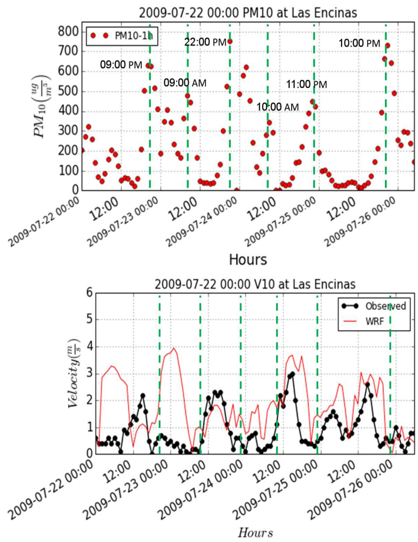


Figure 13. Skew-T diagram for WRF model (red) and observations (black) at Puerto Montt (21 July, 2009 at 12 UTC).

High resolution (1 km) numerical modeling was performed for Temuco area in order to study local meteorological conditions. Modeled meteorological variables corresponding to high pollution events for all cases were compared with observations at two locations inside the city. One example for 22 - 30 July, 2009 is shown (Figure 14). Dash green lines marked elevated PM_{10} concentration measured in Temuco. Most of the peaks correspond to low wind conditions (about or below 1 m/s) in early evening (9 pm) or morning transition periods (8 – 9 am). Pronounced periodicity can be seen in the relative humidity and wind speed. Winds with speed about 2 – 3 m/s advect dry air corresponding to the drop in relative humidity just before the elevated pollution period. PM_{10} concentration reaches 900 µg/m^3 on the second day of simulations. Described period relates to periodic change in wind speed and direction (Figures 14-15) with advection of dry air from the south changing to low northern wind during periods of elevated pollution.

WRF capture very well the pattern of humidity, but shows some disagreement in wind speed prediction in the beginning of simulated period. The same problem registered for Santiago area with over-prediction of nocturnal temperature is also present here.



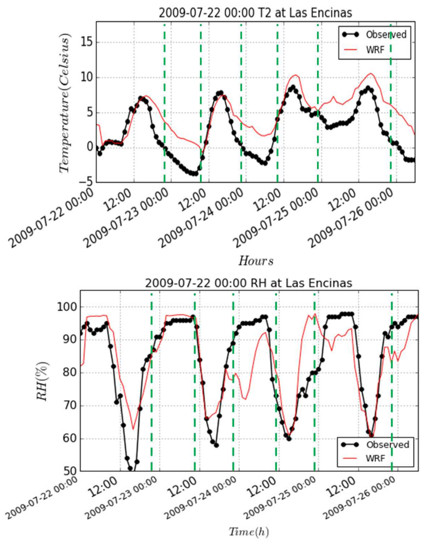


Figure 14. PM_{10} concentration, wind speed, temperature and relative humidity at Las Encinas station.

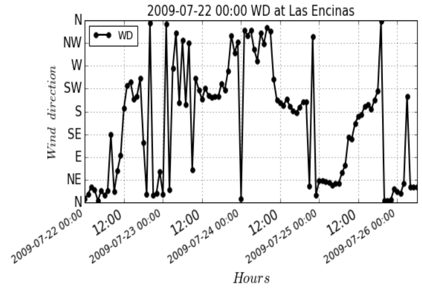


Figure 15. Periodical wind direction change for the selected period at Las Encinas station.

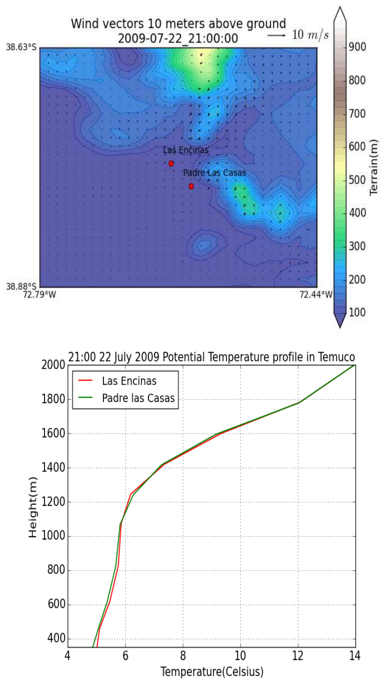


Figure 16. Wind field and temperature vertical profiles for Temuco at 9 pm corresponding to maximum concentration observed.

Spatial distribution of simulated flow corresponding to PM_{10} peaks is in agreement with quiescent conditions over the land. The wind field (Figure 16) corresponds to peak at 9 pm. Vertical temperature profile provided by the model shows cape inversion during the period of high pollution.

4. CONCLUSIONS

This work has been conducted to further understand the meteorological conditions and spatial flow distribution conducive to some of environmental hazards recently recorded in Chile, specifically the unique rainfall over the Atacama Desert on 24 -26 March, 2015 and some of high pollution events in Santiago and Temuco regions.

It is found that the COL lifecycle strongly related with the rainfall event. The time and spatial distribution of the rainfall were captured reasonably well by high resolution WRF numerical simulations. Several model configurations were tested and compared with observations at three different sites and all tested physical options used in WRF experiment appear to play a role on accumulated precipitation with most significant difference due to microphysical scheme. Lin et al. scheme produces more precipitation than Goddard scheme at high elevation and better agrees with observations. The horizontal grid resolution adopted in WRF plays a crucial role in model ability to capture flow and temperature pattern due to the complex topography and the presence of very steep slopes.

On the other hand, WRF model was able to capture the meteorological conditions during the major winter high pollution episodes observed. The modelling system reproduces the establishment of very low winds and the reduction in relative humidity, and stable conditions which inhibit vertical mixing and dispersion resulting in an increase of the surface PM_{10} concentration. Blocking effect of the Andes play significant role in forming calm conditions that sustain high pollution events over Santiago. The main reason for long-lasting inversions in Temuco region is high pressure system concomitant with warm advection from the south-west.

5. ACNOWLEGEMENTS

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