WRF model validation for complex terrain and integration with pollutant dispersion models

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Abstract

The health and environmental conditions in the Central Andes city La Oroya, Peru, has been seriously damaged by the heavy metal mining activities developed in the region. This situation is even more critical due to the complex topography of the ground, which prevents proper mixing and dissolution of particles and gases released into the lower atmosphere. It is important to have a good understanding of how pollutants are dispersed over the populated regions especially over this particular scenario. The CALPUFF and HYSPLIT dispersion/deposition models were used to estimate the dispersion of pollutants. WRF model simulations were used to produce the required meteorological fields from April 25th to April 28th, 2008 on a 85 by 85 point with 3 kilometer resolution, centered at 11.62S – 75.62 W. The performance of WRF model was evaluated by comparing model forecasts with meteorological data gathered from three special surface weather stations at La Oroya, located close to the main source (750 m NW), Junín (42 km NNW), and Huancayo (96 km SE). Very good agreement was found in the atmospheric temperature field, although there was a bias in the forecasted surface temperature. Precipitation forecasted by WRF for the three stations were not as accurate as WRF forecasted significant precipitation when none was measured at the monitoring sites. Both dispersion models have shown a high degree of similarities and they respond to wind trajectory, topography and planetary boundary layer height forecasts made by WRF.

Introduction

The city of La Oroya is located in the central Andes of Peru, at 3,700 meters above sea level and approximately 80 km from Lima. The city has grown without planning at the side of the metallurgical complex bearing the same name. For this reason, the city center is mere meters from the smelter. La Oroya is a long, thin city that lies along the central highway and the Mantaro River, surrounded by the peaks of the Andes. Because of the topography, climactic temperature inversions cause environmental contamination to cover the city and remain for long periods of time instead of dispersing rapidly beyond the mountains. The metallurgical complex was built in 1922 by the US Cerro de Pasco Copper Corporation. It consists of three main metallurgical circuits: a copper circuit, operating since 1922, a lead circuit, operating since 1928, and a zinc circuit, operating since 1952. The circuits include smelting and refining processes for these metals as well as some other processes for the production of cadmium, silver, gold, and other metals. According to Doe Run, the current owners of the smelter, although copper, lead and zinc are produced in large quantities, the silver production is what actually makes the smelter profitable. While Doe Run has asked for more time to meet its environmental commitments, the continued mining activity has caused serious health problems for the residents of La Oroya. Emissions at La Oroya plant come from stacks and fugitive sources like open buildings, building vents and transport (Integral Consulting Inc, 2005), exceeding on many times the World Health Organization Guidelines (Table 1) for each of the pollutants delivered to the atmosphere (Cedersta, 2002 and Klepel, 2005).

To better understand the dispersion of pollutants after releasing the source, to improve the quality of the existing air monitoring network (Klepel, 2005) and possibly adequate the environmental mitigation for mining activities, a description of how the particulates and gaseous emissions are dispersed is needed.

Gas/PM	**24 hours**	**10 minutes**
SO_2	20 $\mu g/m^3$	500 $\mu g/m^3$
PM_{10}	50 $\mu g/m^3$	500 $\mu g/m^3$

Table 1: WHO, 2005 guidelines.

The California Puff (CALPUFF) and the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) models are commonly used to diagnose pollutant dispersion by the atmosphere. Each model has its own strengths and weaknesses and how well each would perform in the complex terrain and high altitudes of La Oroya were not well documented. In order to test the performance of each model, SO_2 dispersion was simulated.

To obtain reliable results from either CALPUFF or HYSPLIT, it is crucial to have an accurate description of the meteorological conditions (at surface and upper air levels). Unfortunately, Peru, as most of the countries in South Hemisphere, does not have meteorological data with the temporal and spatial resolution needed for the models. As part of a program sponsored by the Catholic Arch-Bishop of the Huancayo province, an environmental monitoring network was created to better describe the condition in and around La Oroya. Three surface observation stations, SO_2 and particulate monitors were installed in the region around La Oroya. Data from the surface observation stations were combined with forecasts created by the Weather Research and Forecasting Model (WRF) to produce the required meteorological fields over a study area domain of 252 by 252 km (85 by 85 grid points), centered at 11.617384S - 75.622521W from April 25th to April 28th, 2008.

WRF was run to improve the temporal resolution to 1 hour and the spatial resolution to 3 km for 38 upper air levels.

The objective of the present paper is to study the response of WRF model to complex terrain topography and test how CALPUFF and HYSPLIT models simulate SO_2 dispersion over this particular scenario.

Section 2 describes the study area domain and the data used in the study, section 3 explains the methodology applied, section 4 exposes the results, section 5 presents the conclusions and section 6 the studies to be achieved in the near future.

Study area domain and data

Two domains, centered close to the source were selected for this study (figure 1). The outer domain was set to 55 by 55 grid points with 9 km resolution whilst the inner domain to 85 by 85 for 3 km resolution and covers the three monitoring sites: La Oroya, 750 m NW from the main stack, Junín, 42 km NNW, and Huancayo, 96 km SE, and it is shown in figure 2.

The topography of the area is very complex. The highest elevations extend from Northwest to Southeast with tops of 5000 meters. On the other hand, the lowest terrain is located Northeast at 800 meters and Southwest at MSL, where the lower left corner encompasses a small part of the Pacific Ocean. As it can be seen in figure 1, not only the area is complex due to its high altitude but also for the large topographic variations in the zone.

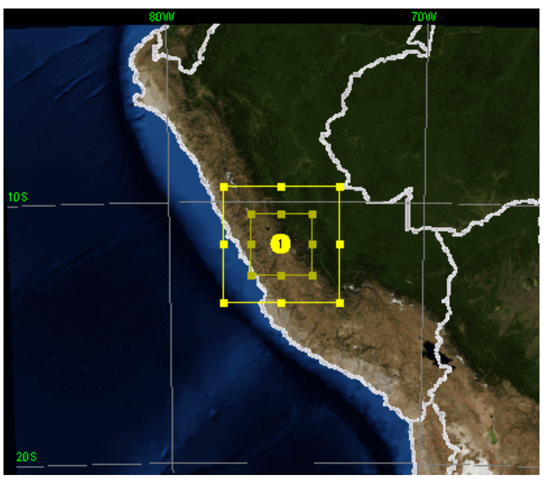

Figure 1: Domain 1, 55 by 55 grid points, 9 km resolution; and domain 2, 85 by 85 grid points, 3 km resolution.

The sample sites and the emission source are situated in the center of the reference area, lying also from Northwest to Southeast and surrounded by higher elevations.

Ten minute average of surface meteorological data (temperature, relative humidity, atmospheric pressure, wind direction, wind speed and precipitation) for the three locations and sulfur dioxide concentrations for La Oroya and Junín (Table 2) were provided by the surface observation network. The surface data was by Weatherhawk instruments and SO_2 measurements by a Thermo analyzer, model 43i using pulsed fluorescence technology.

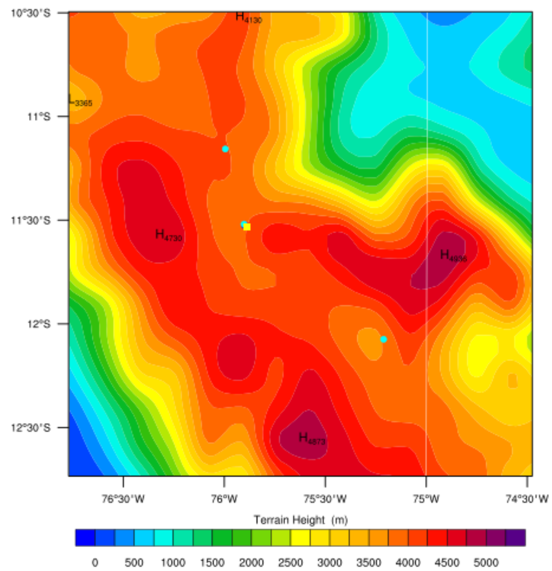

Figure 2: Study area topography, main stack in yellow and cities in Blue (Junín north, La Oroya center, and Huancayo south).

Unfortunately surface pressure measurements were unreliable due to the high altitude of the observation sites and improper altitude corrections in the pressure sensor. The pressure sensor altitude correction was only good to 3000 meters.

Hourly data from the European Center for Medium-Range Weather Forecasts (ECMRWF) model was used to initialize the WRF model from April 25th, 2008 at 00:00 UTC to April 28th, 2008 at 00:00 UTC.

The output files of WRF were transformed to CALPUFF and HYSPLIT meteorological input files according to their specifications.

Site	Lat.	Lon.	Height
Junín	11.16S	75.99W	4,117 m
La Oroya	11.52S	75.90W	3,710 m
Main stack	11.53S	75.90W	168 m
Domain center	11.62S	75.62W	4,039 m
Huancayo	12.08S	75.21W	3,240 m

Table 2: Location of the sample sites, main stack (above surface layer), and center of the study area domain.

The output files of WRF were transformed to CALPUFF and HYSPLIT meteorological input files according to their specifications.

With reference to the pollutant sources, only SO_2 emissions at a unit mass flow rate were considered and due to the difficulty to quantifying fugitive sources, only the main stack was taken into account.

The dispersion models were set for a chimney of 168 m height and 12 m diameter. The SO_2 exit velocity was assumed to be $7.5 m.s^{-1}$ and the exit temperature to 350.15 °K.

Methodology

WRF model was run for the entire period with restart option, hourly averages, WRF Single Momentum (WSM) 6 Class Graupel Microphysics Scheme, Rapid Radiative Transfer Model (RRTM) scheme for long wave radiation, Dudhia scheme for short wave radiation, Monin-Obukhov (Janjuc Eta) scheme for surface layer, and Noah model for land-surface interactions, while the dynamic options were left as default.

Time series (TS) of surface temperature, relative humidity, pressure, wind direction, wind speed, and rainfall for the three sample sites were obtained from WRF model for the four closest grid points for each of the locations. Then, these data were interpolated to the exact geographic position (latitude – longitude) of each monitoring site. The method employed was two dimensions bilinear interpolation on the grid square (Press, 1989).

A second set of WRF forecasts using observation nudging (Liu, 2005) to include the special surface observation stations was made. Since the pressure data was corrupted only the temperature field was assimilated into the model.

TS of WRF model, with and without assimilated data, were correlated against data gathered by the surface meteorological network.

Moreover, detailed analyses of wind field and planetary boundary layer heights were performed because of the importance of these two factors on determining the final pollutant trajectories.

Sea surface temperature (SST) over the small Southwest corner of the study area domain covered by the Pacific Ocean was not computed properly by WRF model. In consequence, and for CALPUFF initialization purposes, the SST was set to 296.65°K according to Aqua/MODIS satellite data set.

Finally, CALPUFF and HYSPLIT dispersion models were initialized with WRF outputs and run for SO_2 dispersion from La Oroya mining smelter main stack.

Concentration measurements at the sample sites were used to estimate SO_2 releases from the chimney. An emission rate of $907.2 T.day^{-1}$ ($10{,}500 g.s^{-1}$), given by Doe Run (Integral Consulting Inc, 2005) was assumed in order to estimate possible concentrations at the sample sites. Results between the models and measurements were compared to evaluate CALPUFF and HYSPLIT performances.

Results

WRF predicted precipitations for the three sample sites, 15.4 mm at Junín, 6.8 mm at La Oroya, and 13.1 mm at Huancayo, however they were not registered by observations.

The temperature field shows a good correlation (0.71 – 0.83) between WRF and measurements for each of the stations (table 3).

	Junín		La Oroya		Huancayo	
	before	**after**	**before**	**after**	**before**	**after**
Pmsl	.67	.57	.56	.45	.63	.52
WD	.34	.43	-.12	-.09	-.29	-.17
WS	.02	.16	.16	.12	.41	.47
T	.71	.73	.83	.84	.71	.73
RH	.23	.14	.32	.34	.21	.19

Table 3: Correlation coefficients between meteorological variables measured in the field and WRF results with no assimilation (before) and with observation nudging for temperature (after).

WRF temperature assimilation improves not only the air temperature correlation on 2% for each of the locations but also the wind speed prediction in Junín 14%, and Huancayo 4%. Nevertheless at La Oroya, the correlation decreases 4%.

The observation nudging did not increase the forecast of pressure at MSL, wind direction and relative humidity.

The TS of temperature (figures 3-5) show that peaks were very good resolved, and a cool bias of 7°K detected is agreed with other studies (Kozich, 2010).

With respect to TS of pressure at MSL, magnitudes cannot be considered due to the sensor design problem, but minimum and maximum peaks occurred at the right time.

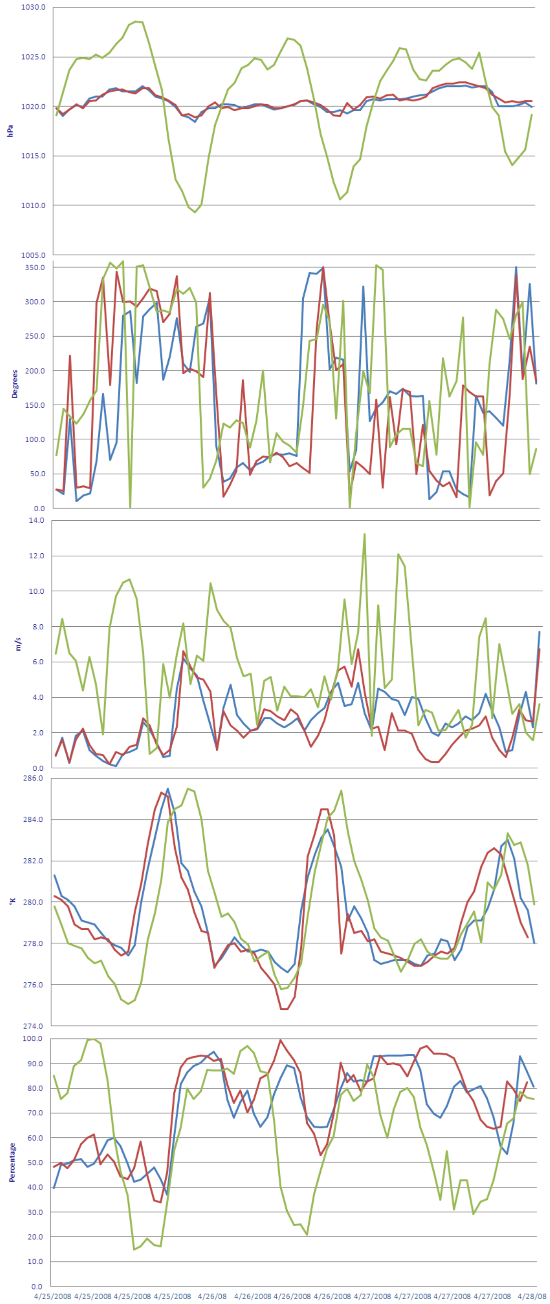

Figure 3: Time series of P at MSL, wind direction, wind speed, temperature and relative humidity at Junín. The station data is plotted in green, WRF results in blue and assimilation results in red.

The timing on relative humidity, wind direction and wind speed fields were correct but it was not much improvement after assimilation.

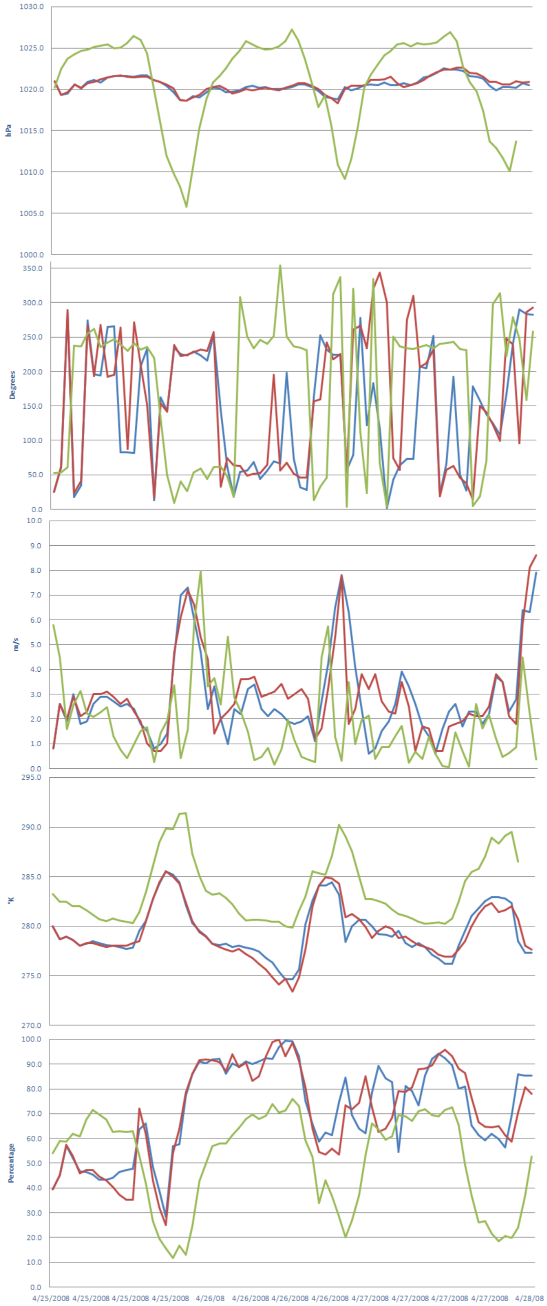

Figure 4: Time series of P at MSL, wind direction, wind speed, temperature and relative humidity at La Oroya. The station data is plotted in green, WRF results in blue and assimilation results in red.

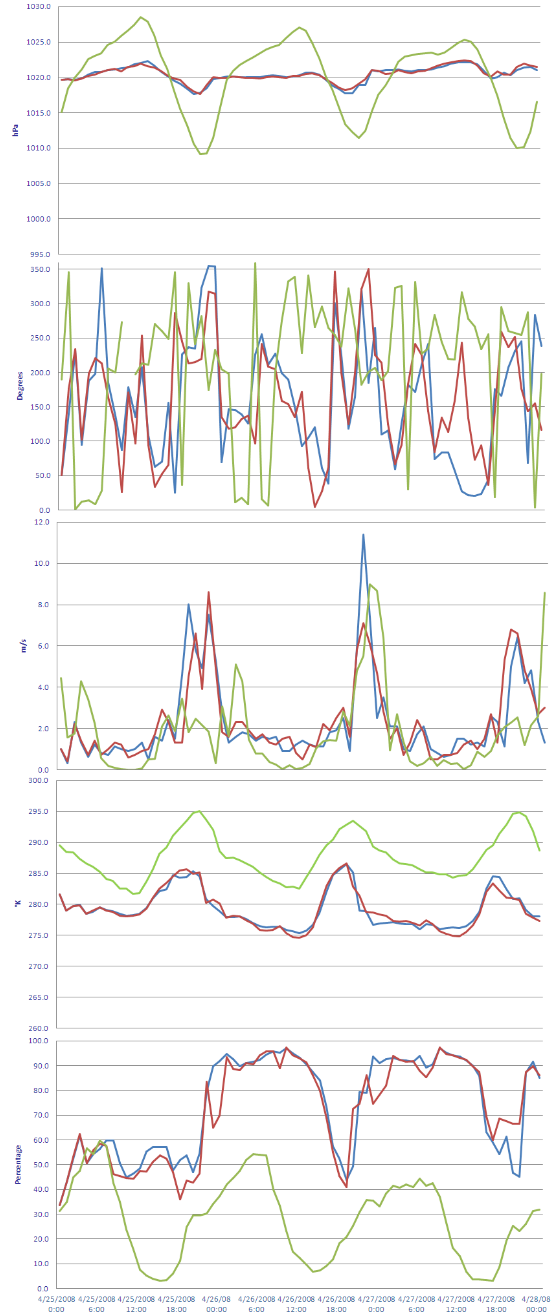

Figure 5: Time series of P at MSL, wind direction, wind speed, temperature and relative humidity at Huancayo. The station data is plotted in green, WRF results in blue and assimilation results in red.

With respect to the air quality models, they agreed each other, placing maximum concentrations and pollutant dispersion quite similar. Figure 6 overlaps topography, wind vectors and pollutant contours for both models at a particular time. After 28 hours simulation, the shape and evolution of the two plumes with respect to time were almost similar, and responded to wind flow direction and topographic effects; where the axis of the plumes were situated right of the highest elevations.

Also, forecasted winds blowing from South to North agrees with SO_2 accumulation at north of the emission point, being a good verification of the model performance besides standard statistic techniques.

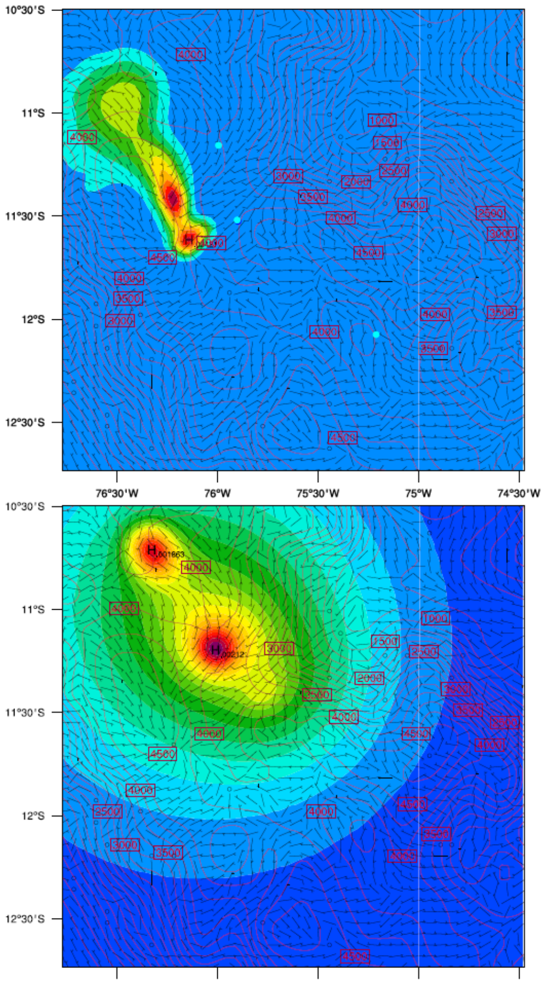

Figure 6: Topography [m] (brown contours), wind vectors and SO_2 [$\mu g/m^3$] plume modeled by CALPUFF (top) and HYSPLIT (bottom) on April 26th, 2008 at 04:00 local time.

The time series comparison of SO_2 concentrations obtained by the dispersion models and measurements made at each of the sample sites are displayed on figure 7. CALPUFF estimations stabilize after 6 hours of model run; nevertheless HYSPLIT needs almost 24 hours to get a steady level. When the emission rate was set to 10,500 g/s, HYSPLIT approximated very well to SO_2 measurements for La Oroya and Huancayo, but CALPUFF underestimated sulfur dioxide loads.

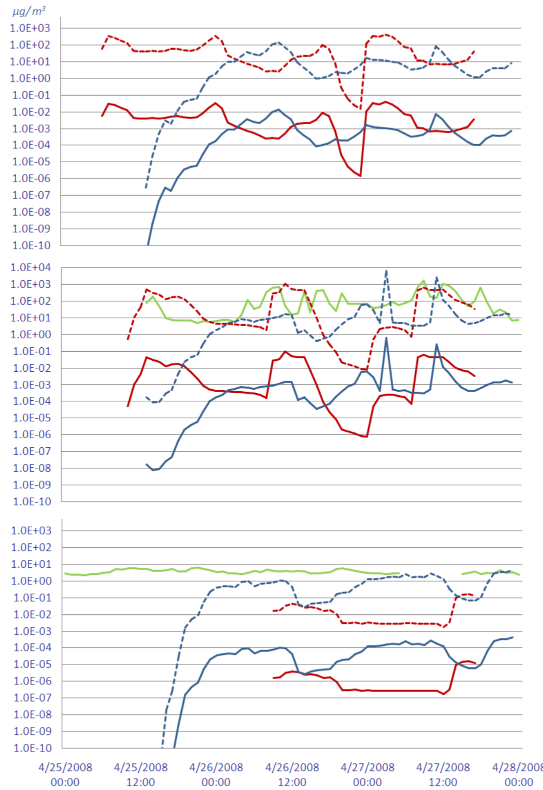

Figure 7: Time series of SO_2 measurements (green), CALPUFF (solid red), calibrated CALPUFF (dashed red), and HYSPLIT (solid blue), calibrated HYSPLIT (dashed blue); at Junín (top), La Oroya (center) and Huancayo (bottom). Solid lines correspond to emissions at a unit mass whereas dashed lines belong to an estimated emission rate given by the smelter. Junín doesn't have air quality measurments.

There was a negative correlation between PBLH and SO_2 loads, where the relationship between lower PBLH and higher SO_2 concentrations is clearly appreciated in figure 10.

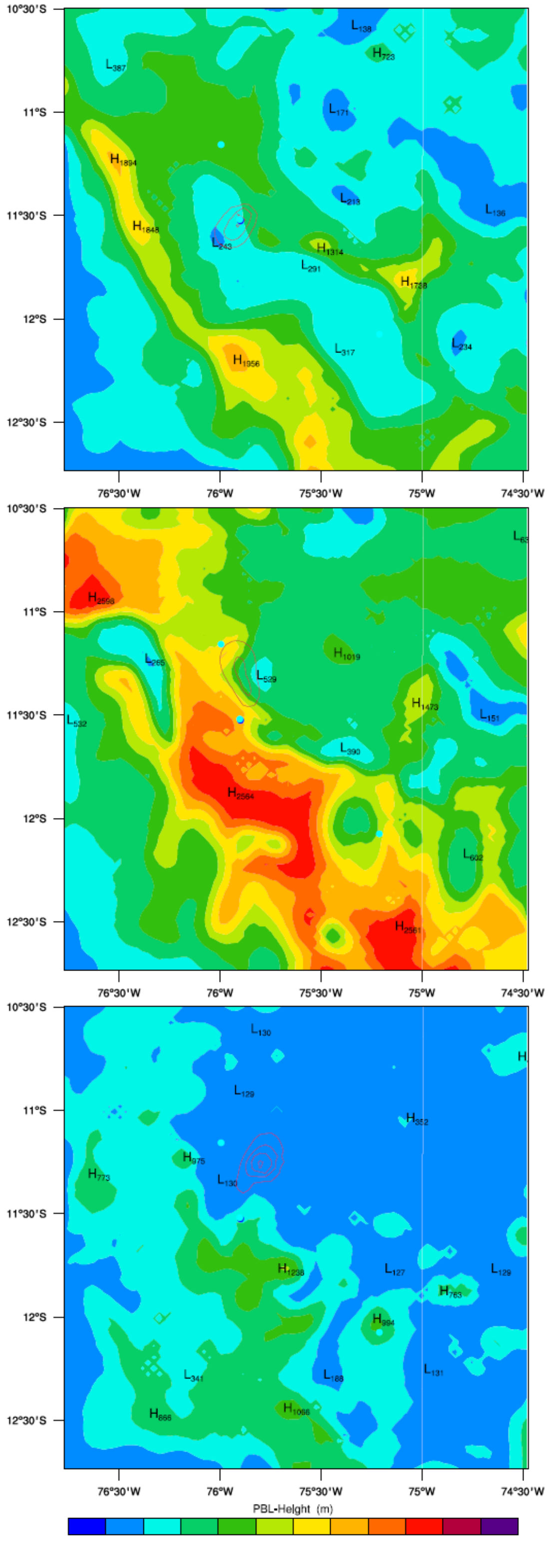

Figure 10: PBL heights [m] and SO_2 contours obtained from CALPUFF model simulation on April 26th, 2008 at 14:00 (top), 17:00 (center) and 22:00 hours, local time (bottom).

Conclusions

SST anomalies obtained by WRF could be attributed to the complex and deep terrain geography close to a small portion of ocean over the Southwestern part of the outer domain.

Despite of three monitoring sites were used for and the observational nudging was applied only for temperature, the results were quite good and better than expected for temperature and wind speed forecasts. The temperature field after the assimilation increased the accuracy for the three locations. Besides, wind speed also improved in Junín and Huancayo. The decrease on wind speed forecast at La Oroya can be attributed to the complex topography over the valley where the city is placed.

Difficulties to resolve other field predictions could be due to observational nudging was performed only for temperature, few monitoring stations were available, low spatial resolution, errors in the interpolation method applied from the grid points to the location of the measurement sites due to possible biases on the terrain heights.

The rainfalls predicted by WRF and not measured at the sample locations could result on a non realistic wet deposition and atmospheric cleaning estimation by the dispersion models.

Even though HYSPLIT model needed a longer time to stabilize, it performed better than CALPUFF on estimating SO_2 concentrations over this particular scenario and atmospheric conditions.

What is next?

The spatial resolution of WRF and dispersion models will be improved to 1 km in order to study their effects on the final results.

Sulfur dioxide estimations from AURA – OMI satellite measurements, with calibrated atmospheric optical depth for the study area, will be compared with CALPUFF and HYSPLIT dispersions and measurements made on the field.

Acknowledgements

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