Dynamics of Local Circulations in Mountainous Terrain during the RHUBC-II Project

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(Manuscript received 17 August 2012, in final form 16 April 2013)

ABSTRACT

The Radiative Heating in Underexplored Bands Campaign (RHUBC-II) project was held from August to October 2009 in the Atacama Desert in Chile at 5320-m altitude. Observations from this experiment and a high-resolution numerical simulation with the Weather Research and Forecasting Model (WRF) were used to understand the structure and evolution of the atmosphere over a region with complex terrain and extremely dry environmental conditions. The mechanisms driving the local circulations during synoptically unperturbed conditions at the field site were studied. The study suggests that the field site is mainly affected by a mountain-scale and a plateau-scale thermally driven circulation. The latter seems to dominate. The advection of warm air by downslope flows from higher heights during nighttime may be the mechanism that counteracts the longwave radiative cooling at the surface, causing a small decrease of near-surface temperature during the night. WRF represents the near-surface and upper atmosphere reasonably well above the RHUBC-II site. Important orographic features are misrepresented in the model terrain, which may cause the observed differences in near-surface winds. The zonal pressure gradient between both sides of the mountain and the static stability of the air mass on the windward side of the terrain control the local circulations over the field site. Consequently, a misrepresentation of these mechanisms in the model may cause differences between the simulated winds and observations.

1. Introduction

Northern Chile is an extremely arid region bounded by the Andes Cordillera to the east and the Pacific Ocean to the west (Fig. 1). It includes the Atacama Desert, a strip of land that covers approximately 1000 km in the north–south direction (17°–25°S) that has been labeled as the driest desert on Earth. Quite different conditions exist on both sides of the Andes, with an arid climate with dry and stable conditions predominating from the Pacific coast to its western slope while moist and rainy conditions prevail over its eastern slope and beyond.

The arid climate of the Atacama Desert is attributed to two factors. First, the location of the Andes to the east blocks the transport of humid air from the interior of the continent (Lenters and Cook 1995; Rutllant et al. 2003; Insel et al. 2010). Second, the permanent subtropical southeast Pacific anticyclone is maintained by slow adiabatic subsidence from the downward branch of the Hadley cell (Rodwell and Hoskins 2001). The southeast Pacific anticyclone circulation induces southerly winds along the coast of Chile, causing the advection of colder waters from the south and the upwelling of deeper cold waters due to the wind stress on the sea surface. Warm and dry air aloft due to adiabatic compression and cold...
and moist air in the marine boundary layer generates a thermal inversion that is usually capped by stratus clouds (Bretherton et al. 2004; Comstock et al. 2005; Hannay et al. 2009). These dry and stable conditions inhibit deep convective development over the ocean and in conjunction with steep mountains slopes along the coast, prevent the flow of humid air from the ocean to the continent (Rutllant et al. 2003). Some studies have suggested that the southeast Pacific permanent anticyclone and cold waters along the Chilean coast are the primary contributors to the Atacama Desert climate (Cannariato and Ravelo 1997; Zachos et al. 2001; Garreaud et al. 2010).

Large-scale circulations over the Atacama region undergo a seasonal variation during the year. Mid- and upper-level westerly winds predominate from May to October linked to the northward displacement of the subtropical westerly jet stream, which brings dry air to the region, favoring clear skies and stable atmospheric conditions. The circulation anomalies during these months are mainly due to transient midlatitude disturbances embedded in the mean westerly flow (Garreaud et al. 2003). During summer months (December–February), low-latitude easterly winds extend far to the south to latitudes greater than 20°S, associated with bad weather and storm formation (Garreaud 2009).

The Atacama Desert is a region with few atmospheric observations, which limits its study. Numerical simulations have become a very useful tool to understand the behavior of the atmospheric processes over the region. The second phase of the Radiative Heating in Underexplored Bands Campaign (RHUBC-II) was a field experiment conducted by the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) program in the Atacama Desert from August to October 2009 at an altitude of 5320 m (Turner and Mlawer 2010). A number of instruments were deployed by ARM and other collaborators with the main objective of measuring the radiative properties of the atmosphere in extremely dry conditions and under temperatures and pressures that are typical of the midtroposphere.

The current study has two main purposes. First, to analyze whether a high-resolution numerical simulation with the Weather Research and Forecasting Model (WRF) reproduces the observed atmospheric features over the field site. A number of astronomical observatories are currently operating in the Atacama Desert because of its excellent conditions for astronomical activities. These observatories need accurate weather forecasts to have better observational planning and to reduce operational costs since the observations are strongly influenced by atmospheric properties like turbulence and the water vapor content. Second, this unique instrumentation suite complemented with numerical simulations is used to study the structure and evolution of the atmosphere over complex topography in the Chajnantor plateau (located 5000 m MSL). Particularly, the mechanisms driving the local circulations, which are strongly influenced by the complex orography surrounding the field site, are investigated.

Other observational campaigns have been conducted in the region but they have mainly focused on determining whether the atmospheric conditions at a specific location are favorable for the installation of astronomical
observatories (Schöck et al. 2009; Otárola et al. 2010). To our knowledge, this is the first study that aims to understand the dynamics of the local circulations in the region.

Section 2 briefly describes the RHUBC-II project and the observations used in the study. Details of the numerical model and the configurations employed in the simulations performed are explained in section 3. Section 4 discusses the results and conclusions are presented in section 5.

2. RHUBC-II project and data

RHUBC-II was held from August to October 2009 on Cerro Toco, a mountain near the Chajnantor plateau in the Atacama Desert in northern Chile (22.954°S, 67.769°W, 5320 m MSL). The precipitable water vapor (PWV) over the region is very low during the year, showing values lower than 1 mm over an appreciable period of time in the austral winter and spring. This was the main reason why ARM decided to carry out the RHUBC-II project in this region.

Because the site was isolated and located at a very high altitude, it limited the number of days when the scientific and operations personnel were physically present. For this reason, several instruments that needed manual interaction only operated during specific periods or “operational days.” They represented 57% of total days. Another group of instruments took measurements or “operational days.” They represented 57% of total days. Another group of instruments took measurements continuously during the entire experiment. A more detailed description of the RHUBC-II field project, its goals, the instrumentation deployed at the site, and preliminary results can be found in Turner and Mlawer (2010) and Turner et al. (2012).

a. Near-surface observations

An automatic weather station (AWS) was deployed during RHUBC-II. It included an HMP45AC temperature–humidity probe and an PTB220 barometer from Vaisala and a 05105 R M Young Anemometer to sample 2-m temperature, 2-m relative humidity (RH) and 2-m vapor pressure, surface pressure and 10-m wind speed, and direction at 1-Hz resolution during the project. The data were later quality checked and averaged to 1 min before being stored. The probes were calibrated in May 2009 by the ARM program.

b. Radiosondes

Three to five Vaisala RS-92 radiosondes were launched during operational days between 0500 and 1500 LT at 75–90-min intervals. Almost the same number of radiosondes were launched each month (August, September, and October) but more than 82% of them were deployed between 0900 and 1300 LT. Radiosondes were launched with the main objective of profiling temperature and humidity during daytime, clear-sky conditions. Although they cannot provide the entire diurnal variation of the atmospheric boundary layer and free troposphere, they are useful to understand its daytime evolution.

The accuracy of radiosonde RH measurements has been the focus of extensive research. In the case of Vaisala RS92 radiosondes, several studies have investigated some of the measurements uncertainties such as solar heating of the RH sensor and lag-time response of the instrument at low temperatures (Miloshevich et al. 2004, 2006; Vömel et al. 2007; Cady-Pereira et al. 2008; Miloshevich et al. 2009). As a result, several corrections have been derived to remove the mean bias error as a function of different parameters. The original radiosonde humidity profiles from RHUBC-II were corrected following the procedure outlined in Miloshevich et al. (2009). This procedure corrects for the small humidity model calibration error in the Vaisala processing, the solar heating of the sensor (if any), and the time-lag correction. The corrected RH profiles were used in this study.

3. WRF configurations

WRF is a numerical weather prediction system freely available on the web that can be used for operational and research purposes (Skamarock et al. 2008). Two high horizontal resolution simulations were performed with version 3.2 of the Advanced Research WRF core (ARW-WRF). Four model nested domains were employed in both simulations as depicted in Fig. 1. Table 1 shows the model domains characteristics. Results from the smallest domain [domain 4 (D4)], with the highest resolution, were used in the study. The innermost domain covers an area of approximately 4900 km² in the Atacama Desert at 1-km resolution that includes the RHUBC-II field site. Simulations use the terrain height and land-use data from the standard 30-arc-s U.S. Geological Survey (USGS) dataset, which provides this information for domain 4 at approximately 0.9-km horizontal resolution.

The simulations included 54 vertical levels with variable resolution. Eight model levels were located within the first kilometer in the vertical with resolutions varying...
between 60 and 200 m. At the field site, the first model level was 25 m above the USGS terrain. The model pressure top was 50 hPa and no damping was used at the upper boundary. The simulations were initiated each day at 1200 UTC from 15 August to 25 October 2009. They were run for 48 h and outputs were stored every 1 h. The Global Forecast System (GFS) model analyses (at 1200 UTC) and corresponding forecasts at 0.5° horizontal resolution and 27 vertical levels provided the initial and boundary conditions every 6 h. A time series was created each day from the 12- to 35-h forecasts to obtain the complete diurnal cycle and to avoid the initial model perturbations (i.e., spinup errors). Despite the general decrease in model performance with forecast hours, a negligible increase in model error was shown in the first 12 h of simulations. The model output on sigma levels was interpolated to constant height levels for proper physical interpretation of the results over complex topography.

The simulations used the Dudhia (1989) and Rapid Radiative Transfer Model (RRTM; Mlawer et al. 1997) parameterizations to calculate shortwave and longwave radiation, respectively. The Kain–Fritsch (Kain 2004) scheme was used to calculate convective processes in domains 1–3 and the WRF single-moment 3-class (Hong et al. 2004), a simple and efficient scheme with ice and snow processes (three classes: vapor, cloud/ice, and rain/snow), was used for microphysics in domains 2–4. The Yonsei University (YSU; Hong et al. 2006) nonlocal parameterization was used for PBL processes.

Two simulations were performed in this study, where the simulations were only different in the land surface model used. The first control (CTL) simulation used the simple five-layer soil model, which forecasts temperature at five layers and soil moisture is obtained from climatological values. The second simulation (Noah) used the Noah land surface model (Chen and Dudhia 2001), which forecasts soil temperature and moisture at four layers. The CTL simulation is presented in sections 4a and 4b to show the validity of the model to study this region and to provide some insight in the structure of the PBL surrounding the field site. The Noah simulation, presented in section 4c, is used to assess the performance of a different land surface model representing the near-surface conditions at the field site. Finally, both simulations are discussed in section 4d to illustrate the processes that control the local circulations over the field site.

4. Results

a. The near-surface atmosphere

To investigate the evolution of the near-surface atmosphere during the RHUBC-II campaign, daily versus hourly plots of 2-m temperature, 2-m water vapor mixing ratio, surface pressure, 10-m wind speed, and downward longwave radiative fluxes are shown in Fig. 2 from 11 August to 25 October 2009.

Negative 2-m temperatures predominate during the project, with temperatures increasing from August to October as spring approaches in the Southern Hemisphere (Fig. 2a). The diurnal variation is superimposed on a day-to-day variability with alternating periods of colder and warmer days, highly correlated with surface pressure. Warmer days occur during higher pressure periods and colder days are associated with lower pressure periods (Fig. 2b). The daily mean geopotential height at 550 hPa from GFS forecasts, also shown on the plot (solid thick line), increases and decreases during periods of higher and lower pressure, respectively.

The 10-m wind speed varies from small values during periods of increasing pressure and temperature to quite large values during periods of decreasing pressure and temperature (Fig. 2c). The 2-m water vapor mixing ratio was extremely low during the project (values <1 g kg$^{-1}$ or <30% relative humidity) only interrupted by short periods of increasing humidity (>2.5 g kg$^{-1}$ or >80% relative humidity) (Fig. 2d). A number of strong wind speed episodes (1–3 September, 16–18 September, 27–29 September, and to a lesser extent 13–15 October) are associated with an increase in both near-surface humidity and downward longwave radiative surface fluxes (Fig. 2e) indicating the presence of a moister atmosphere and cloudiness.

Figure 3 shows daily means of 2-m temperature, surface pressure, and 10-m wind speed and direction. They illustrate that the day-to-day variability of the near-surface atmosphere during RHUBC-II is marked by the influence of extratropical cold troughs embedded in the westerly flow (Vuille and Ammann 1997; Lenters and Cook 1999; Garreaud and Fuenzalida 2007), which bring about periods of lower pressure, colder temperatures, and stronger winds flowing from the west-northwest (Fig. 3). Some of these synoptic perturbations result in moister conditions and cloudiness (Figs. 2d,e). After the passage of the lows, periods of higher pressure, warmer temperatures, and lighter winds are established (Fig. 3), strongly influenced by the South Pacific anticyclone. The stronger the influence of cold troughs or the South Pacific anticyclone over the region, the closer the wind flows from the west-northwest or the west-southwest direction, respectively.

Figures 4 and 5 show the relative vorticity, geopotential height, and wind fields at 500 hPa for a “perturbed day” under the influence of a cold trough (at 0600 UTC 27 September) and an “undisturbed day” under the influence of the South Pacific anticyclone (at 1800 UTC...
3 October 2009), illustrating the different typical synoptic conditions during both periods. Maps were created from the Climate Forecast System Reanalysis (CFSR) at 0.5° × 0.5° horizontal resolution (Saha et al. 2010). The analysis of synoptic maps from CFSR reanalysis at several levels every 6 h, satellite images, and near-surface RHUBC-II observations (Fig. 3) were used to select days that were influenced by the passage of cold lows over the region and days that were not. These periods are shown in Table 2. Thus, the unperturbed days, characterized by clear-sky anticyclonic conditions, are used below to illustrate the evolution of the atmosphere at the field site as well as to study the mechanisms that drive the local thermally induced circulations.

FIG. 2. Daily vs hourly (y axis) values of (a) 2-m temperature, (b) surface pressure, (c) 10-m wind speed, (d) 2-m water vapor mixing ratio, and (e) downward longwave radiative fluxes from RHUBC-II observations. The thick solid line drawn on pressure data represents the daily mean geopotential height at 550 hPa from the GFS model, normalized to take values between 0 and 24.

FIG. 3. Daily means of (top) 2-m temperature and surface pressure, and (bottom) 10-m wind speed (Wsp) and 10-m wind direction (Wdir) observations from RHUBC-II. Wind direction observations before 1 Sep 2009 were not available because of bad measurements.
1) DIURNAL VARIABILITY

Figure 6 shows the mean diurnal variation of 2-m temperature, 2-m water vapor mixing ratio, 10-m wind speed and direction from RHUBC-II observations, and the WRF control (CTL) and Noah simulations averaged over the perturbed (gray lines) and unperturbed (black lines) days shown in Table 2. Only the control simulation is analyzed in this section. The Noah simulation will be analyzed in section 4c. Observations show that the daily evolution of the near-surface layer is nearly similar during both synoptic situations except for the 10-m wind direction. In addition, notable differences in magnitude are shown between them.

The most notable feature of the 2-m temperature diurnal evolution (Fig. 6a) during unperturbed days is its small decrease during the night and early morning, with even a small increase between 2200 and 2300 LT. A similar but colder diurnal variation is observed during perturbed days. The CTL simulation forecasts colder temperatures in both situations. However, the WRF performance during perturbed days is better, especially at night. Ruiz et al. (2010) obtained colder biases in the region using a number of WRF runs, attributing the error to the misrepresentation of the real orography by the model terrain.

The 2-m water vapor mixing ratio during unperturbed days shows a larger diurnal variation than during perturbed synoptic conditions (Fig. 6b). A moister near-surface layer predominates in the latter situations. The CTL simulation largely overestimates the near-surface humidity at the field site during both situations. A sensitivity analysis to the land surface model is performed in section 4c to find out whether a more complex scheme (Noah), which forecasts the soil moisture, provides better results.

The observed 10-m wind speed (Fig. 6c) during typical unperturbed days shows a large increase during the day compared to nocturnal values. The perturbed days show a similar diurnal evolution but with larger wind speeds. The CTL simulation reproduces the near-surface wind

**TABLE 2.** Perturbed days (L) under the influence of cold upper-level lows and unperturbed days (H) during the RHUBC-II project.

<table>
<thead>
<tr>
<th>Low pressure periods (L)</th>
<th>High pressure periods (H)</th>
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<tr>
<td>1–3 Sep</td>
<td>5–7 Sep</td>
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<td>8–11 Sep</td>
<td>12–14 Sep</td>
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<td>21–23 Sep</td>
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<td>26–27 Sep</td>
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pretty well at the field site during unperturbed days although the maximum values during the day are underestimated. The performance is worse on perturbed days since the model simulation underestimates much more the observed strong wind speeds.

The near-surface wind direction during unperturbed days (Fig. 6d) indicates that the wind flows between the west and west-northwest during the night and changes its direction to the west/west-southwest during daily hours, and then changes again to flow from the west/west-northwest after sunset. It is important to note, however, that the wind direction change is small (approximately $20^\circ$ during the day). Synoptically perturbed flows during the passage of cold troughs show a similar diurnal evolution as unperturbed days but the wind always flows between the west and west-northwest during nighttime and changes to a more westerly flow during daytime. The wind direction is very well simulated for perturbed days but notable differences are shown for unperturbed days. The wind reversal twice per day is a general characteristic of mountain winds (Whiteman 1990, 2000; Martínez et al. 2008). However, small wind direction changes as those presented here is not what would be expected for slope flows at the field site; one would expect wind changes from northwest to southeast or from northeast to southwest. A closer inspection to the details of the topography at and around the field site is made in section 4a(2) to shed some light on the behavior of the near-surface wind.

Figure 7 shows the mean diurnal variation of surface pressure. Both synoptic situations show a semidiurnal (12 h) variation, which is associated with a diurnal tide of the entire atmosphere, first discovered by Haurwitz (1956), due to the warming of the upper atmosphere by solar radiation. Observations of this effect have been described by Whiteman and Bian (1996), Chen et al. (1998), and Dai and Wang (1999), among others, using different observational data. This phenomenon has also been observed near the RHUBC-II field site by Hardy et al. (1998), who took surface pressure measurements at the summit of Nevado Sajama, which is located in the western Andean Cordillera of Bolivia (6542 m).

The RHUBC-II mean surface pressure amplitude is 1.7 hPa with pressure minima shown at 0500 and 1700 LT.
and maxima at 1200 and 2300 LT, similar to that found by Hardy et al. (1998) and Dai and Wang (1999). The CTL simulation overestimates the surface pressure and does not reproduce its observed semidiurnal variation. Since the model top is located at 50 hPa, sun-driven tides in the upper atmosphere should not be represented. Two sensitivity simulations were run for two days (not shown): one with the model top located at 10 hPa and the other using diffusive damping at the upper boundary. None of these simulations showed an improvement representing the observed semidiurnal pressure cycle.

2) TERRAIN FEATURES EXAMINATION

Figure 8 shows a height–longitude cross section of terrain height from Google Earth, the 30-arc-s USGS data and WRF domain 4. Google Earth clearly shows the steep terrain features surrounding the field site that are not represented in the USGS 30-arc-s dataset. The model creates its terrain from the USGS dataset at a similar resolution, but the model terrain is notably smoothed during initialization when meteorological fields are interpolated on terrain-following sigma surfaces. Since wind flows at the field site are largely forced by topographic features, the smoothed terrain in the model causes the simulated winds to be weaker than observations.

A horizontal plane view of the topography from Google Earth (Fig. 9) reveals that a higher hill is located to the northwest of the field site. In addition, there are large topographic gaps southwest/west-southwest from the site. Local-scale katabatic winds coming downhill along the northwest hill may arrive at the field site during the night. During the day, anabatic winds may be coming uphill along the largest west-southwest slope and through the terrain gaps to the field site. Figure 6d, however, shows that the wind is predominantly flowing from the west during unperturbed days, with a very small

![Fig. 7. As in Fig. 6, but for the mean diurnal variation of surface pressure.](image-url)

![Fig. 8. Height–longitude cross section of terrain height from Google Earth, the 30-arc-s USGS data, and WRF domain 4. The black square indicates the RHUBC-II field site. The smaller plot in the bottom-right corner shows a zoom view of terrain height at the field site.](image-url)
wind direction reversal from the west/west-northwest to the west/west-southwest and vice versa during the day. Local-scale thermally forced upslope and downslope winds coming from the west-southwest and northwest, respectively, must be occurring, but they seem not to be the predominant thermally forced circulation that affects the field site. Another mechanism may be causing the winds to flow predominantly from the west at the field site. This will be better analyzed in section 4d.

b. Upper-air analysis

1) Model validation

Radiosondes launched during the RHUBC-II project sampled pressure, altitude, temperature, and humidity. As mentioned in section 2b, a new RH, obtained after correction of RH measurements from Vaisala sensors, was used in this section. Radiosondes provide a good opportunity for model validation at this remote site. Therefore, radiosondes launched on synoptically perturbed (L) and unperturbed (H) days were selected and compared with vertical profiles from the WRF control simulation at the model forecast time closest to the sonde launch time.

The mean bias and RMSE between radiosondes and the WRF simulation averaged over each period of days show that the model reproduces the tropospheric temperature and RH reasonably well during both situations (Fig. 10). The model simulates a drier and warmer troposphere during unperturbed days and a colder and moister layer below 7 km in days affected by the passage of cold troughs. The warmer and drier biases shown during unperturbed days decrease in the lower levels of the atmosphere to values close to zero. Colder and moister conditions are shown at the surface (Figs. 6a,b). There is no sounding information between the surface (5320 m) and the first radiosonde level (5380 m) to analyze whether the low-level biases change to that shown at the surface. We believe that this is what happens: the surface and boundary layer parameterizations and the misrepresentation of the model topography results in colder and moister biases at the surface that are transferred upward to the lower levels of the model.

Model validation with near-surface and upper-air observations provides confidence to use it to investigate the evolution of the PBL around the field site and to investigate the mechanisms that control the thermally driven circulations under weak synoptic forcing, which will be presented in the next sections.

2) The PBL evolution around the field site

The diurnal variation of the PBL structure and its characteristics cannot be well studied with current observations. Radiosondes were only launched during the daytime to fulfill RHUBC-II goals. Despite this limitation, available radiosondes still provide a good opportunity to understand the PBL evolution at this remote site during these hours of the day.

FIG. 9. Terrain features surrounding the RHUBC-II site (black mark) from Google Earth. The vertical and horizontal lines in the bottom-left corner mark the north–south and east–west directions.
Figure 11 shows hourly mean vertical profiles of potential temperature $\theta$ and water vapor mixing ratio from 0900 to 1300 LT below 7 km of height averaged over the unperturbed days. Radiosonde data in the lowest 80 m of the atmosphere were removed to avoid errors associated with the initial ventilation of the radiosonde sensors directly after launch. Therefore, observations start at 5.4 km MSL. Potential temperature and water vapor mixing ratio profiles indicate the development of a superadiabatic layer at the lowest levels and a well-mixed boundary layer above it from 0900 to 1300 LT that deepens to a height below 5.8 km. Since relatively strong near-surface wind speeds are observed at the field site during these hours (Fig. 6c) and they are stronger aloft, the properties of the well-mixed PBL should be linked to the large-scale atmosphere surrounding the field site and not locally determined. Height–longitude cross sections of mean potential temperature and water vapor mixing ratio from the control simulation averaged over the unperturbed days were analyzed to obtain a clearer picture of the PBL evolution around the field site during these days (Figs. 12 and 13). In addition, the well-mixed PBL height was estimated just like in the idealized numerical study of de Wekker et al. (1998), as the height where the potential temperature gradient first reaches a value larger than 0.001 km$^{-1}$.

At 1000 LT, a shallow well-mixed PBL is shown along the windward slope of the terrain and over the mountain under predominant static stability conditions. The PBL top along the windward slope is lower than the mountaintop at this time but continues to develop through the day. At 1700 LT, a deep well-mixed PBL develops at the windward slope and over the plain to the west. Its top seems to be located above the interpolated mountaintop but just below the real location of the field site. A smaller well-mixed PBL is shown above the basin and high mountains to the east of the field site.

Other numerical studies have simulated the daytime development of a well-mixed deep convective PBL along the windward slope of a mountain that largely surpasses its top (de Wekker et al. 1998; Demko and Geerts 2010). The model simulations show a daytime cold bias (approximately $-2 K$) at the surface and a warmer bias above during unperturbed days.
conditions may result in enhanced stratification during the day with the subsequent limitation of the convective boundary layer development. Therefore, the PBL depth may be probably diminished over the model domain. In summary, the WRF control simulation forecasts a shallow well-mixed PBL over the mountains, in agreement with daytime radiosonde observations during unperturbed conditions. A deep convective PBL develops in the western plain whose top can reach and even surpass the mountaintop.

It is important to note that the Antofagasta radiosondes launched at 1200 UTC (0800 LT) during unperturbed days show a well-defined and strong PBL inversion at 1–1.5 km. This marine boundary layer probably does not reach the high plateau where the Cerro Toco is located. However, since the radiosondes are only launched once per day (at 1200 UTC), little can be said about their diurnal evolution.

c. Sensitivity analysis to the land surface model

A second WRF simulation using the Noah land surface model (Noah) was also compared with near-surface observations (Figs. 6 and 7) in order to assess its performance with the control (CTL) simulation during synoptically perturbed (L) and unperturbed days (H). The Noah simulation shows a closer 2-m water vapor mixing ratio and nocturnal 2-m temperature to observations than the CTL simulation during unperturbed days. However, the simulated daytime 2-m temperature and the 10-m wind speed and direction are better reproduced by the CTL simulation. It is important to note the poor representation of daytime 10-m wind speed by the Noah simulation. In the case of surface pressure, just a slight improvement is observed in Noah compared to the CTL simulation. In general, the perturbed near-surface conditions are better represented by the CTL simulation.

Overall, the CTL simulation with the simple five-layer soil model represents the near-surface conditions at the field site better than the Noah simulation (except for the near-surface humidity), which uses the complex Noah land surface model that forecast soil humidity. Reeves et al. (2011) showed that changing some parameters within the Noah land surface model can
improve near-surface forecasts in complex terrain, which would be worth trying to assess in a future study.

d. Local circulations at the field site

Thermally driven winds in the mountains (slope winds, valley winds, mountain-plain winds) are produced by the differential heating and cooling of different atmospheric layers. They occur at different spatial scales and flow from regions relatively cold to regions relatively warm. To understand the mechanisms responsible for driving the thermally driven circulations over the RHUBC-II site, the three-dimensional atmospheric structure from the control simulation was analyzed. Figures 14–16 show height–longitude cross sections of mean zonal wind, wind divergence, and wind vectors at 1000 LT from the WRF control simulation, at 22.956°S, averaged over the unperturbed days (Table 2).

At midnight (0000 LT), plain-to-mountain winds (winds flowing from the plain to the mountain) are shown at the field site and at both sides of the mountain, decreasing in magnitude downward along the windward slope (Fig. 14).

Fig. 12. Height–longitude cross sections of mean water vapor mixing ratio (shaded; g kg$^{-1}$) and potential temperature (white isolines) at 1000 LT from the WRF control simulation, at 22.956°S, averaged over the unperturbed days. The thick dashed white line shows the mixed PBL height. Vertical and horizontal lines indicate the grid points where the vertical potential temperature and horizontal pressure gradients shown in Fig. 17 were calculated, respectively. The black circle represents the real location of the RHUBC-II field site, which is shown above the interpolated WRF terrain.

Mountain-scale downslope winds appeared at 2100 LT concentrated over a shallow layer close to the surface. At this time (0000 LT), they concentrate over a relatively deep layer with plain-to-mountain winds above.

Fig. 13. As in Fig. 12, but at 1700 LT.

Fig. 14. Height–longitude cross section of mean divergence field (shaded; $\times 10^{-2}$ s$^{-1}$), zonal wind (black isolines every 1 m s$^{-1}$, the thick black line represents the zero contour and the dashed lines represent the negative contours), and wind vectors at 0000 LT from the WRF control simulation, at 22.956°S, averaged over the unperturbed days. The vertical component in wind vectors was increased on purpose to better illustrate the local flow variations over the region.
Large values of divergence predominate above the mountain associated to mountain-scale downslope winds and to plain-to-mountain winds flowing over the mountain and into the basin to the east. Convergence is shown above divergence at the field site, similar to that shown in the numerical study of Demko and Geerts (2010) over the Santa Catalina mountains. As static stable conditions predominate everywhere, wind divergence at mountain-tops advects higher potential temperature air from higher to lower levels (Hughes et al. 2007). This may be the mechanism that counteracts the longwave radiative cooling at the field site during nighttime, resulting in a smaller decrease in 2-m temperature than would be expected from purely radiative cooling (Fig. 6a).

In the morning (1100 LT), mountain-scale upslope winds have developed along the windward slope (Fig. 15) and nocturnal downslope winds are shown in a residual shallow-layer above. Plain-to-mountain winds predominate over the model domain. Convergence is shown at the field site associated to mountain-scale upslope winds. At 1500 LT (Fig. 16), the air stability has decreased on both sides of the mountain. The wind speed has increased along the windward slope and over the field site (Fig. 6c), indicating the presence of daytime upslope flows from lower to higher terrain. As a result, wind convergence has increased at mountain tops and on the lee slope of the RHUBC-II site. It is important to note that terrain-scale upslope winds in the eastern slope of the mountain (the basinside) were not shown in the control simulation at any hour. A plain-to-mountain (westerly) flow predominated during the whole day.

The WRF control simulation represents reasonably well the magnitude but not the direction of the near-surface winds at the field site during unperturbed days. The differences between the simulation and observations may be the result of differences in model topography with the current orography (Fig. 8), which largely influence the magnitude and direction of the flows. In addition, the large cooling simulated during the night may be caused by a deficient representation of the terrain, although the Noah simulation shows that a different land surface model can provide better temperature results. Several studies have shown that increasing the horizontal resolution of numerical simulations over complex orography may result in a better representation of terrain-induced diurnal circulations or in the near-surface temperature and humidity (Davis et al. 1999; Chen et al. 2004; Billings et al. 2006; Reeves et al. 2011). Therefore, a higher-resolution topographic data-set would be needed in order for the model to capture all the local features induced by terrain heterogeneities and better simulate the near-surface atmosphere over the region.

The diurnal evolution of upslope and downslope winds are influenced by the stability of the air mass located upwind of the mountain barrier (Whiteman 2000). On the other hand, mountain-plain winds are produced by horizontal pressure differences between the air above the basin and the air at the same level above the plain (Kimura and Kuwagata 1993; de Wekker et al. 1998). To investigate these two effects on the thermally driven circulations at the field site, the air stability at longitude 68°W (along the vertical line in Fig. 12) and over the layer 3800–5400 m was calculated as well as the zonal pressure gradient at the height of 5.4 km between 67.9°W ($x_1$) and 67.6°W ($x_2$) longitudes (crosses in Fig. 1b) in
both simulations (CTL and Noah) using the following equations:

\[
\frac{d\theta}{dz} = \frac{\Delta \theta}{\Delta z} = \frac{\theta(5400 \text{ m}) - \theta(3800 \text{ m})}{5400 - 3800} \quad \text{and} \quad (1)
\]

\[
\frac{dp}{dx}_{5.4 \text{ km}} = \frac{\Delta p}{\Delta x}_{5.4 \text{ km}} = \frac{p(x_2) - p(x_1)}{x_2 - x_1}. \quad (2)
\]

Figure 17a shows the mean diurnal variation of the air stability at longitude 67.9°W from both simulations calculated from Eq. (1) and the mean diurnal variation of the observed 10-m wind speed. There is a clear correlation between both variables. The simulations show more stable conditions during nighttime, associated with weak-to-moderate winds at the field site whereas much more intense wind speeds are shown from sunrise to afternoon hours, coincident with a notable decrease in the static stability during the daytime, presumably due to surface forced convection. A large correlation is also shown between the observed 10-m wind speed and the simulated zonal pressure gradient at 5.4 km of height (Fig. 17b). A negative pressure gradient is always present between the two sides of the mountain, which forces plain-to-mountain winds to flow eastward from the lower plains to the mountain. During the daytime, the negative zonal pressure gradient intensifies and larger wind speeds are observed at the field site. The CTL simulation shows the largest decrease in air stability and the strongest zonal pressure gradient during the daytime and better represents the observed 10-m wind speed compared to the Noah simulation (Fig. 6c).

The analysis performed suggests that the zonal pressure gradient between the two sides of the mountain and the static stability of the air mass on the windward side of the terrain control the near-surface wind speed over the field site. Consequently, a misrepresentation of these mechanisms in the model may cause differences with observations in the simulated winds. A better representation of them in the control simulation results in its better agreement with the local circulations at the field site.

In summary, the RHUBC-II near-surface observations and the WRF control simulation indicate that the local circulations at the field site during weak synoptic forcings are mainly affected by two thermally driven circulations: a mountain-scale circulation where winds flow upslope during the daytime and downslope during nighttime as a result of temperature differences between the heated or cooled slope and the adjacent atmospheric layers; and a large-scale (plateau scale) circulation where winds flow from the plain to the mountain during the whole day as a result of a negative horizontal pressure gradient between the two sides of the mountain. Since the wind flows predominantly from the west at the field site, this suggests that the large-scale thermally driven circulation dominates over the mountain-scale circulation.

5. Conclusions

The Radiative Heating in Underexplored Bands Campaign (RHUBC-II) project was held from August to October 2009 in the Atacama Desert in Chile at 5320 m of altitude. The instrumentation suite deployed at this site provides a unique opportunity to understand the structure and evolution of the atmosphere and to assess high resolution (1 km) numerical weather forecasts over a region with complex terrain, extremely dry environmental conditions, and limited observations. This study focused on the mechanisms driving the local synoptically unperturbed circulations at the field site.

Observations show that the near-surface atmosphere at the field site is marked by the influence of extratropical cold troughs embedded in the westerly flow, which cause periods of lower pressure, colder temperatures, and
stronger winds flowing predominantly from the west-northwest. Moister conditions and cloudiness are brought to the region by some of these synoptic perturbations. After the passage of the lows, periods of higher pressure, warmer temperatures and lighter winds are established, due to the influence of the South Pacific anticyclone circulation.

The WRF control simulation represents reasonably well the near-surface and upper atmosphere above the RHUBC-II site during synoptically perturbed and unperturbed days. The good performance of the model representing the tropospheric temperature and RH may be due, in part, to good GFS background fields. Important smaller-scale terrain features of the real orography are misrepresented in the model terrain, which may cause the observed differences in near-surface winds.

The small decrease of near-surface temperature during the night is likely caused by the advection of warm air from higher heights during nighttime by downslope flows, counteracting the longwave radiative cooling at the surface. The nocturnal near-surface air temperature is thus influenced by the local wind circulations over the site.

A sensitivity analysis to the land surface model shows a better performance of the model reproducing the near-surface atmosphere at the field site with the simple five-layer soil model than with the more complex and widely used Noah land surface model. This may be the result of the unique soils and the extremely dry conditions that predominate at the field site, posing the question whether the Noah parameterization is the most appropriate land surface model to use in this environment. However, Reeves et al. (2011) showed that changing some parameters within the Noah land surface model can improve near-surface forecasts in complex terrain.

The zonal pressure gradient between the two sides of the mountain and the static stability of the air mass on the windward side of the terrain control the local circulations over the field site. Consequently, a misrepresentation of these mechanisms in the model may cause differences in the simulated winds with observations. The better these mechanisms are reproduced in the simulation, the better the near-surface wind speeds are forecast.

The local circulations at the field site during weak synoptic forcings are mainly affected by two thermally driven circulations: a mountain-scale and a large-scale (plateau scale) circulation. RHUBC-II observations and model simulations suggest that the large-scale thermally driven circulation dominates over the mountain-scale circulation.

Acknowledgments. The RHUBC-II campaign was organized as part of the U.S. Department of Energy’s Atmospheric Radiation Measurement (ARM) program, which is sponsored by the Office of Science, Office of Biological and Environmental Research, Climate and Environmental Sciences Division. This work was supported in part by the U.S. Department of Energy by Grant DE-FG02-06ER64167 as part of the Atmospheric System Research program. This research was supported by ALMA-CONICYT Projects 31070020 and 31110005. The CFSR reanalysis is from the Research Data Archive (RDA), which is maintained by the Computational and Information Systems Laboratory (CISL) at the National Center for Atmospheric Research (NCAR). We thank two anonymous reviewers for their helpful comments during the review process that largely improved the quality of the manuscript.

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