Understanding Local Wind Circulations over White Sands Missile Range

Armand Silva

Academic Affiliation, Fall 2006: Senior, Pennsylvania State University

SOARS® Summer 2006

Science Research Mentors: Dr. Thomas T. Warner & Dr. Andrea Hahmann
Writing and Communication Mentor: Thomas Hopson
Community Mentor: Lance Jones
Peer Mentor: Alisha Fernandez

ABSTRACT
This study builds a local wind-field climatology and analyzes the resulting wind patterns at White Sands Missile Range (WSMR) in southern New Mexico. Mesoscale circulations in mountain-valley desert regions have been previously studied in several regions of the Intermountain West, none of which included WSMR. Hourly surface mesonet (SAMS) data were collected at 13 stations across WSMR over five years from 2001 through 2005. The months and hours of approximate minimum and maximum temperature, along with a few intermediate times, were selected to analyze local mesoscale wind behaviors. These data were visualized in the form of wind roses, which plot wind speed, direction and frequency. Wind roses were plotted on a terrain map at the data locations for the analysis of topographic effects on wind circulations. This analysis shows that mesoscale patterns of upslope and downslope flows, as well as up-valley and down-valley flows occur, depending on the season of the year and hour within the diurnal cycle. Additionally, the analysis shows that significant variations occur across the different stations, depending on their locations on the valley floor or mountain slopes. The results of this study enhance the understanding of local wind patterns in desert valley regions in general. This has great importance because of today’s rapid growth of human population in these regions.
1. Introduction

The desert regions of the U.S. Southwest exhibit complex mesoscale weather patterns which give them complex climates. However, most U.S. desert regions, and arid regions around the world in general, have been understudied. Desert regions today are rapidly transforming from barren expanses of land into places populated by residences, new commerce, and military training and test facilities, among other things. Because of this rapid human expansion into arid regions, there is an increasing importance for studying their regional climate. It is thus pertinent that these regions be better understood.

There have been some meso-climate studies performed on a few regions of the Intermountain West. For example, in a study conducted by Stewart et al. (2002), thermally driven wind systems were analyzed in four regions of the Intermountain West: the Wasatch Front Valleys in the Great Salt Lake region of Utah, the Snake River Plain in Idaho, southern Nevada, and central Arizona. For this Stewart et al. study, high-density data from more than 70 independent meteorological networks were gathered as part of MesoWest, a collection of cooperative mesonets in the western United States. It was found that during the daytime hours winds are generally upslope and up-valley, and at nighttime winds tend to flow downslope and down-valley. At observing sites that are not influenced by external flows, winds on valley sidewalls conform to the Hawkes conceptual model, which shows clockwise and counterclockwise diurnal turning of the wind of the right and left of the valley sidewalls respectively, when facing down-valley. It was also found that narrow canyons with a constricted outlet can produce strong outflow into broader plains or valleys. Mesonet data were also used by Rife et al. (2002) in which a model simulation was performed for the selected area using MesoWest observations along with observations from the U.S. Army West Desert Test Center in Dugway, Utah.

Among the many sites within the U.S. that have not been thoroughly examined is the White Sands Missile Range (WSMR) in southern New Mexico (Fig. 1.1). The WSMR is located in a valley surrounded on three sides by mountains. Nastrom and Eaton (1995) provide a brief description of the geography of the region from the perspective of the Atmospheric Profiler Research Facility (APRF), which lies within WSMR. The area of the APRF, located in the Tularosa Basin at 1220 m above sea level, is relatively flat and covered by mesquite, but the San Andres and Organ Mountains, which run in a north-south orientation, lie just to the west of the basin. The mountains are steep and create a physical “knife edge” which affects eastward airflow. About 30 km to the east lie the Sacramento Mountains, which also run north-south (Fig. 1.2). Several studies by Nastrom and Eaton (1995) have been performed on vertical wind profiles in the WSMR. There is, however, a lack of observations of the surface conditions in this area. Because of the fact that population is on the increase in desert valley regions with similar physiographic features as those of WSMR, it is important to understand what occurs within the near-surface boundary layer.

Given all background information and previous studies, we seek to analyze data collected by the several observing stations in the area to explain the regional surface wind patterns and circulations. This will help to better understand not only the WSMR region, but all arid and orographically rugged regions around the world. The objective of this project is to investigate the wind circulations that take place due to local processes within the WSMR. In particular, the
main purpose of this analysis is to estimate how topography affects regional wind motions. Local mesoscale processes are important to this region, as in other arid valleys across the Intermountain West. That is, mesoscale winds, in addition to those on the synoptic scale, can affect significant factors such as the boundary-layer transport of dust and man-made pollutants, human comfort, and the hydrologic cycle through evaporation of surface water. In order to examine local processes in this project, hourly data over a five year period are stratified from 13 surface mesonet data stations, and used to build a local wind-field climatology. Visualization of these data is accomplished by plotting wind roses on a topographic background map, where these wind roses are based on calculated climate wind statistics for the surface mesonet locations. These wind-climate maps are used in an analysis of the physical processes that drive the local winds. Based on the resulting climatology, the wind patterns and their mesoscale dynamics are analyzed. The data are interpreted in terms of the diurnal wind circulations which prevail within the WSMR area, and the seasonal variations in these diurnal cycles.

The structure of this paper is as follows. The next section describes the WSMR dataset used in this study in detail. This section also describes the experimental procedure for analysis involving the use of this dataset. The results of the experiment are then presented in the Results section, along with a summary of the revealed wind-field climatology. The results of the study are interpreted physically with a discussion of the dynamics of the diurnal wind motions taking place at the different station locations.

2. Methods

a. Data-set description

The data used in this study were extracted from a compact disc, created by D. L. Rife, containing temperature, dewpoint temperature, wind speed and wind direction data collected over 48 stations across the White Sands Missile Range at each hour, for the period January 1, 2001-December 31, 2005. The data are based on surface mesonet (SAMS) observations, which are approximately 10 meters above ground level. To perform the analysis, only wind speed and direction data were used from this CD. Data are selected for the summer and winter seasons in terms of the approximate hours of the day that correspond to maximum and minimum temperatures. As a result, this project looks specifically at the months of January and July and the hours of 5 am and 5 pm. The intermediate times of 11 am and 11 pm are also studied. Out of the 48 stations in the data set, 13 stations are chosen to be analyzed for these months and times. The data for these stations and times were filtered out through the use of the NCAR Command Language (NCL) utility. This filtering involved writing code in NCL to select out only the data necessary for the project.

b. Experimental design

The primary tool used in this project for the visualization of the data is the wind rose. A wind rose is a visual plot of data that displays three attributes of the wind: speed, direction, and frequency (Fig. 2.1). Wind speed is displayed by the color of a petal, a line that emanates outward from the center of the rose. The petal color defines the average wind speed from a specific direction. Wind direction is shown by the position in which the line is plotted, indicating which direction the wind is coming from. For the wind roses used in this analysis, wind directions are from the eight general cardinal directions: north, east, south, west, and the
four intermediate directions. Wind frequency is represented by the length of the petal. Frequency is defined as the percentage of wind observations for one averaged time that the wind blows from a specific direction.

c. Station selection
For a simple visual inventory of the amount of available data at each station, a map was produced in which the station locations were plotted on a color terrain background (Fig. 2.2). Each station was represented by a square of a certain size. The larger the square, the more data were available at that station. Stations for analysis were chosen given this visual of station location and available data. To select the stations, the plot was searched for larger-sized squares and for locations in diverse terrain settings that had a reasonable amount of separation distance. Three stations were selected in upper-slope regions, which are near the tops of the mountain ranges: S5 in the southern part of the San Andres Mountains, S9 in the northern San Andres range, and S17 in the Sacramento Mountains. Three stations were selected in lower-slope regions: S31 in the central San Andres, S14 at the northern end of the valley, and S19 on the far northern end of the San Andres. In addition, several valley floor stations were chosen throughout different regions of the valley: S1, S18, S32, S7, S4, S26 and S27. The station S4 is located at the lowest elevation in the Tularosa Basin, on the northern edge of the White Sands National Monument. In total, 13 stations, each with sufficient data and geographic distribution were selected (Fig. 2.3).

d. Plotting data
Once the stations for the analysis were chosen, the wind climate for the selected times and months was displayed by plotting wind roses on a topographic map background at each location corresponding to a certain SAMS station. A program for plotting wind roses, created at the National Center for Atmospheric Research (NCAR) by Diane Strassberg, was implemented, which generated roses showing an average of wind for each hour of the day, over a given month, over all years in the dataset. Additionally, two stations were selected to display each hour of the entire 24-hour diurnal cycle, in order to see the shifting of wind directions between the hours selected for the primary analysis.

e. Climate maps
The result of this process was eight data maps, each with wind roses at the selected 13 stations. The plots represent the wind-field climatologies at 5 am, 11 am, 5 pm and 11 pm for the months of January and July. Additional wind rose plots of all 24 hours in January and July were generated for the stations S27 and S31. (See Appendix for the results of these 24-hour analyses)

3. Results and Discussion
A total of eight plots was produced to visualize the data for this analysis: the averages for the hours of 5 am, 11 am, 5 pm and 11 pm over all days in January and July over all five years in the dataset. The objectives of analyzing the study are to characterize the diurnal cycle in the near-surface winds, to look at the seasonal variation in the diurnal cycle, and to compare the cycle of winds at valley stations versus those located on or near the mountain slopes.
a. Background dynamics

This study analyzes the generated wind-field climate by explaining the associated physical processes operating in this region. It is necessary to understand the basic dynamics of wind phenomena that are expected in mountain-valley desert regions. These processes can be categorized into two general types: thermally-driven circulations and terrain-barrier flows.

1.) THERMALLY-DRIVEN WIND CIRCULATIONS

The dominant phenomena reflected in these observations are thermally-driven wind circulations. From the observations for different times of day in January and July, it can be concluded that, in general, winds tend to favor upslope and up-valley motion during the day, and downslope and down-valley motion at night. In this study region, the San Andres and Sacramento mountain ranges both generally run from north to south. As a result, the length of the valley is oriented from north to south, with the northern end having slightly higher elevation than the southern end. This means that we can define up-valley flows as southerly and down-valley flows as northerly. Upslope winds are oriented from the valley floor to the mountain top and downslope winds flow from the mountain top to the valley floor, parallel to the gradient of the terrain. The reason for the generation of these diurnal slope and valley winds is the differences in horizontal temperature and pressure across the varying topography. Horizontal temperatures vary spatially between valley and mountain slopes, and they change over the course of the day with the varying patterns of incoming shortwave radiation and outgoing longwave radiation. This affects not only the temperature patterns at the surface, but the thermal structure of the entire boundary layer (Fig. 3.1). In desert regions in particular, the depth of the boundary layer is greater than in temperate climates due to higher surface temperatures, and thus a greater amount of sensible heat fluxes to the air from the ground and stronger turbulent mixing (Warner 2004). The changing wind dynamics, which are directly related to the diurnal change in the structure of the boundary layer, can be divided into four phases within a 24-hour time period: the evening transition period, the decoupled or nighttime period, the morning transition period, and the coupled or daytime period. During the evening transition period, the amount of outgoing radiation exceeds the amount of incoming radiation from the sun, and the terrain both at the valley floor and on the mountain slopes cools as a result. Colder air on the mountain slopes is more negatively buoyant, and sinks down onto the valley floor, thus causing downslope winds to occur (Fig. 3.2). As cold air accumulates above the valley floor, a stable inversion layer builds and deepens, bringing dense cold air to the valley floor and leaving the valley sidewalls relatively warm (Fig 3.3). This air mass is called an inversion layer because a temperature inversion occurs where the colder air meets the warmer air of the residual layer above it (Fig. 3.4). With the build up of a cold, stable air mass over the valley floor, cold air, as it remains negatively buoyant, continues to move in the down-valley direction, thus causing down-valley flows after the occurrence of downslope flows. Once this stable inversion layer fills the depth of the valley, the nighttime, or decoupled period has begun. This period is called decoupled because of the fact that the valley atmosphere has a different vertical temperature profile than the residual layer above it. This pattern continues until sunrise, when incoming solar radiation once again begins to dominate outgoing terrestrial radiation. This is where the morning transition period begins. At this point, the warmer air above the mountain slopes, as it rapidly becomes positively
buoyant, moves upwards to create upslope flows. Down on the valley floor, where a much deeper stable inversion layer is still present, thermals begin to rise into the air above with the heating of the day. As more and more thermals are released, the deep stable layer present above the valley floor is eventually eliminated from the ground upward (Fig. 3.5). With the elimination of the nighttime stable inversion layer, the heated air forms a warm convective boundary layer, eventually promoting up-valley flows to occur alongside upslope flows on the mountain slopes. These upward flows continue to thrive in a growing convective layer, which builds to its largest depth in the late afternoon. At this time of the day, the fastest wind speeds in the valley floor typically occur due to the large amount of turbulent mixing taking place. Shortly after sunset, the evening transition period begins and the cycle resumes once again (Whiteman 2000).

2.) TERRAIN BARRIER WIND FLOWS

Another set of important phenomena to consider in the analysis of the plotted data is that of terrain barrier flows. In the WSMR study area, the stations that are most influenced by this process are those located on or near the mountain ranges. It can be predicted that the upper-slope stations experience faster winds than do those lower into the valley. This would be most notable at the two upper-slope stations of the San Andres Mountains (Fig. 3.6). At S9, frequent strong winds from the south and southeast can be expected as a result of airflow around higher terrain to the southwest of the station. This would be caused by stable air that is forced to flow around this higher terrain, and the winds are accelerated as they flow around the barrier (Fig. 3.7). Similarly, strong wind flow would be expected farther south and west of this higher terrain (however no mesonet station exists there). It can also be noted that the mountain ridgeline in this part of the range assumes a concave orientation with respect to the valley. This shape allows the winds to gradually converge into the range’s horizontally oriented bowl and accelerate across the topographic barrier (Whiteman 2000). Near the southern end of the San Andres range, S5 is predicted to experience strong easterly and westerly wind flow. One plausible explanation for this is that this station is located on the ridge, but with higher terrain immediately to the north and to the south. This means that the station lies in a relatively narrow gap of lower elevation along the ridgeline of the mountain range. The expected result is a channeling effect in which winds are forced into a smaller area and accelerated due to an increased pressure gradient (Fig. 3.8).

b. Projected results

Understanding these basic dynamical processes allows several predictions to be made about what will be seen in the climate data. It is expected that, in general, upslope and up-valley flows will occur during the daytime, and downslope and down-valley flows will occur at night. At stations that are located on, adjacent to, or nearby the mountain ranges, a greater slope wind component is expected than at those stations more distant from the mountains. From what is understood about terrain-forced flows, it can be predicted that the two upper-slope stations in the San Andres Mountains will show greater wind speeds than stations located in lower-slope regions and on the valley floor. We will now discuss the observed results in detail for each time and month.
c. Results of data analysis

1.) 5 AM JANUARY

This hour is the coldest of the analysis, as it is before sunrise in the heart of winter. Valley floor stations are observed to have spatially varying wind directions, however the wind flows are generally from the north, indicating a dominant down-valley wind field as expected (Fig. 3.9a). The eastern valley floor stations exhibit a frequent northeasterly component, while the stations on the western side of the valley floor show a frequent northwesterly flow. Similarly, the stations located on lower mountain slopes show a frequent wind flow from the direction of the top of the mountain range. Faster wind flow can be seen at both S5 and S9, the two upper-slope stations of the San Andres Mountains, with S5 in the southern San Andres showing strong easterly and westerly flow. The S17 station in the Sacramento Mountains shows unexpected observations as general upslope flow is occurring when downslope flows are expected.

2.) 11 AM JANUARY

At this time, the sun has risen and has warmed the ground for a few hours. Wind directions at valley floor stations vary greatly at this hour (Fig 3.9b). No consistent pattern is present, although most stations show more meridional (north-south) frequency than zonal (east-west) frequency. The exceptions are the stations in and around the Tularosa Basin, which show frequent easterly wind components. Upslope flow is now present at the lower slope stations. The upper San Andres stations show varying directions as they are near the ridge tops, while the Sacramento station, just to the west of the mountain top, shows even more frequent upslope flow now than at 5 am.

3.) 5 PM JANUARY

As the sun sets, valley floor stations are found to have a very random distribution of wind directions and there is no distinct wind flow pattern present (Fig. 3.9c). Some upslope flow is notable at the lower-slope stations, especially at S14 on the northern valley slope. Westerly flow appears to dominate the upper-slope stations at this time.

4.) 11 PM JANUARY

Long after sunset, wind directions vary once again across the valley floor stations (Fig. 3.9d). However, stations in the eastern half of the valley exhibit a more easterly wind component while those in the western half show a more westerly wind direction. This is indicative of downslope drainage flows now reaching the valley floor. Lower-slope stations now show strong downslope flows as well. Stations located near the mountain tops continue to show general east-west flow, with the exception of the northern San Andres station, which continues to display random wind directions.

5.) JANUARY SUMMARY

In January, down-valley flows persist into the day, as a fair amount of northerly wind is present in the 11 am analysis. It can be seen at all hours that, in general, winds do not follow a consistent pattern across the valley floor. Winds at the upper-slope San Andres stations are generally the strongest, especially at S5, where winds are commonly found to be from the west at 10-20 m/s.

SOARS® 2006, Armand Silva, 7
6.) 5 AM JULY
This is the first of the long daylight hours that are present in the peak of the
summer. Wind directions are variable across the valley floor stations (Fig. 3.10a). One
interesting observation is that the stations in the southern half of the valley have more
frequent southerly components while those in the northern half show more northerly wind
components. Stations on the east side of the valley show a slight additional easterly
component, just as those on the west side of the valley show a small westerly component.
Particularly notable is S18, which reports consistent southeasterly flow at this hour.
Lower mountain slope stations show frequent wind flow from the direction of the
mountain top. The upper slope stations of the San Andres Mountains show a frequent
and relatively strong upslope flow, whereas the station near the top of the Sacramento
range reports generally downslope motion. One observation that is not consistent with
what is expected is the fact that the southern half of the valley floor at this hour
experiences up-valley flows when down-valley flows are expected. The S18 station, in
the south-central portion of the valley, experiences very frequent southeasterly flow at
this time.

7.) 11 AM JULY
Well into the morning, southerly flow predominates across the valley floor (Fig.
3.10b). In and around the Tularosa Basin, winds exhibit a frequent southeasterly
direction. Lower-slope stations show a fair amount of upslope flow. Upper-slope
stations also generally feature upslope flows. One unexpected observation, however, is
S9 in the northern San Andres, which shows a frequent northeasterly wind flow.

8.) 5 PM JULY
During the hottest hour of the analysis, a very distinct pattern of wind speeds and
directions occur across most of the valley floor stations (Fig. 3.10c). Wind speeds are
relatively strong throughout the valley, and frequent southeasterly flows are present,
especially in and around the Tularosa Basin. This is indicative of a healthy up-valley
wind flow. Lower-slope stations report general upslope flows. Upper-slope stations
show frequent wind flow parallel to the topographic gradient of the mountain range.

9.) 11 PM JULY
A few hours after sunset, south to southeasterly flow continues to dominate the
valley floor (Fig. 3.10d). Wind speeds in several locations are still found to be relatively
strong. Downslope drainage flows at the lower-slope stations are evident, but still
generally not too pronounced. Downslope motion is apparent, however, at the
Sacramento upper-slope station, with zonal motion still present at S17 and S5, and
meridional flow present at S9.

10.) JULY SUMMARY
July experiences relatively fast winds across the valley floor at 5 pm when strong
solar heating is taking place. Winds continue to remain relatively strong a few hours into
the night, as is shown by the July 11 pm analysis. The 11 pm plot also shows that
southerly flows persist longer into the nighttime in July, which is indicative of the fact
that up-valley motion has a long duration after the peak time of heating during the day. Once again it can also be seen that winds at the upper-slope stations of the San Andres Mountains experience the fastest wind speeds. Up-valley motion occurring on the southern valley floor during the early morning hours was the primary unexpected result for this month.

d. General observations

From these averaged results, several general observations can be made. We observe a diurnal upslope/downslope cycle in the wind patterns in both January and July. By looking over all eight analyses, it can also be seen that January and July show several opposite wind-field climate characteristics. In January, downslope and down-valley flows are present over more hours of the day, whereas in July upslope and up-valley flows are more often present. Downward drainage flows from nighttime persist for long into the daytime in January, while in July upward flow from the day persists long into the night. January very often features somewhat inconsistent wind directions, at the observed hours as several of the wind roses show short petal lengths of varying direction. In July, wind patterns assume a much more consistent behavior as wind directions are more pronounced at most locations, as indicated by the longer wind rose petal lengths. From these general observations which compare the diurnal cycle in January and July, it can be deduced that July has a more dramatic diurnal wind cycle in terms of both speed and direction.

d. Unexpected results

Although many of the observations over the various times and stations are consistent with what has been found before in other desert valley regions, a few unexpected results were found in the analyses.

1.) JANUARY

In January, S17 in the Sacramento Mountains experiences almost constant upslope flow and seldom shows downslope flows, even during the nighttime hours. This can be explained by the fact that synoptic-scale flows have more of a dominant effect on regional weather patterns in the winter than do mesoscale processes. This is attributed to the fact that a lower solar angle is present during the winter, therefore less intense solar heating takes place. As a result, thermally-induced slope and valley flows are much weaker, so the synoptic patterns of motions take over, especially higher in the atmosphere, as this station is located at about 2500 m above sea level. Because the general synoptic flow in the mid-latitudes is from west to east, westerly winds are almost always reported at this station in January.

2.) JULY

The southern half of the valley floor at 5 am in July experiences up-valley flows when down-valley flows are expected. The S18 station, in the south-central portion of the valley, experiences very frequent southeasterly flow at this time. A possible explanation for this is that a deeper convective boundary layer is present in the summer. Because of this, the stable nighttime inversion layer has a very weak presence in this portion of the valley, as compared to the northern half of the valley (Fig. 3.11). A shallow stable inversion layer is not sufficient to overcome the effects of the daytime
convective boundary layer, even at this time of approximate minimum surface temperatures. As a result, up-valley flows continue to persist in this region. The other unexpected observation occurring in this region is the very frequent southeasterly flows taking place, especially in the early morning. One plausible explanation for this is that downslope drainage flows are occurring at the region of elevated terrain to the southeast of the southern valley floor, to the south of the Sacramento Mountains. This gives a strong easterly wind component to this part of the valley at 5 am. When combined with the northerly up-valley wind components taking place here, strong southeasterly wind flow results. It is also possible that the influence of the synoptic-scale subtropical highs in summer causes south to southeasterly flow. The S19 station, on the lower slope at the northern end of the San Andres Mountains, experiences downslope flows over much of the day during both seasons, even at 5 pm, which is expected to have the maximum daytime heating.

4. Conclusion

It can clearly be seen that the general results of this analysis are consistent with what has been found in previous studies. As found in the study performed by Stewart et al. (2002), winds follow a general upslope and up-valley orientation during the day, and a downslope and down-valley orientation at night. As was predicted, the diurnal cycle in July proved to be stronger and more pronounced than in January. Although a few unexpected results have been found, they can still be readily explained. Given what has been found in this study in the White Sands Missile Range, diurnal wind motions in all desert valley regions are now further verified and understood. As we look more specifically at the WSMR, plenty of opportunity for the study and discovery of atmospheric phenomena still exists. Using the same data CD that was utilized for this study, a climatology of temperature and dewpoint temperature patterns can be compiled. Once a network of precipitation collection and measurement is installed in this region, patterns of rainfall and snowfall can be analyzed. Looking further into wind dynamics, motions over mountain ranges can be observed by determining the height of the dividing streamline, which determines where winds are no longer dammed by a physical geographical barrier. Wind dynamics can also be analyzed by studying the effects of different surface types, such as terrain with vegetation and terrain of uncommon characteristics, such as that of the white gypsum sands from which the missile range and national monument within obtained their names.
REFERENCES


http://www.united-states-map.com/us402112.gif

sangres.com/maps/newmexbig.htm

meted.ucar.edu/mesoprim/gapwinds/print.htm
Fig 1.1) From http://www.united-states-map.com/us402112.gif and sangres.com/maps/newmexbig.htm: Location of the White Sands Missile Range, indicated by red circle, with respect to a) the western United States and b) New Mexico
Fig 1.2) Map of WSMR showing primary geographic features

Sacramento Mountains

San Andres Mountains

Tularosa Basin-
lowest point at
~1200 m ASL
Fig. 2.1) Wind rose model created by Diane Strassberg; petal colors represent average speeds, petal directions show where wind is coming from, petal lengths indicate frequency; circles give wind frequency by percentage, label bar shows speed in m/s.

Fig. 2.2) Topographic map plot showing all station locations; square size corresponds to amount of available data.
Fig. 2.3) Same map as in Fig. 2.2, now indicating the stations selected for analysis with red dots
Fig. 3.1) From Whiteman (2000): Diurnal cycle of the planetary boundary layer in a mountain-valley region

Fig. 3.2) From Whiteman (2000): Locations of slope winds and valley winds with respect to topography
Fig 3.3) Warmer air can be found on the valley sidewalls with colder air in the valley floor below during the nighttime hours.

Fig. 3.4) From Whiteman (2000): The nighttime stable inversion layer and associated downslope wind motions.
Fig 3.5) From Whiteman (2000): Wind layers and motions occurring during the morning transition period

Fig. 3.6) Contour map of terrain topography of WSMR; arrows point to stations for analysis of terrain barrier wind flows

SOARS® 2006, Armand Silva, 18
Fig. 3.7) From Whiteman (2000): Stable air forced to the sides of higher terrain, creating accelerated wind flows.

Fig. 3.8) From meted.ucar.edu/mesoprim/gapwinds/print.htm: Channeling wind flows through mountain gap region.
Fig. 3.9) Wind-climate maps represented by wind rose plots for January 2001-2005: a) 0500 LST, b) 1100 LST, c) 1700 LST, d) 2300 LST. Color label bar on left represents elevation in meters; label bar on right represents wind speed in m/s.

SOARS® 2006, Armand Silva, 20
Fig. 3.10) Wind-climate maps represented by wind rose plots for July 2001-2005: a) 0500 LST, b) 1100 LST, c) 1700 LST, d) 2300 LST. Color label bar on left represents elevation in meters; label bar on right represents wind speed in m/s.

SOARS® 2006, Armand Silva, 21
Fig. 3.11) Map of WSMR valley; upper blue square represents deeper stable inversion layer, lower and more transparent blue square represents shallow stable inversion layer; red arrows show easterly component contributed by flow from higher terrain
Appendix

The following plots show the 24-hour evolution of winds, every two hours, at Stations 27 and 31 in January and July. 

Note: The wind rose plots here are different than those used in the wind-climate maps in the primary study. Here, the wind speed (in m/s) is printed out at the end of each petal, and the different colors represent the fraction of the time, out of the total percentage of the time the wind is from a certain direction, that the wind blows within a particular speed range.
January - Station 31
July- Station 31