Mapping the Major Axis of Tephra Dispersion with a Mesoscale Atmospheric Model:

Cerro Negro Volcano, Nicaragua

by

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ABSTRACT

Models of tephra fallout are used to assess volcanic hazards in advance of eruptions and in near-real-time. Current models often approximate the wind field using simplistic assumptions of the atmosphere that cannot account for typical variations in wind velocity that occur in time and three-dimensional space. Here, a widely used mesoscale atmospheric model is used to improve forecasts of the location of the major axis of dispersion for erupting plumes. The Pennsylvania State University-National Center for Atmospheric Research fifth-generation Mesoscale Model (MM5) specializes in atmospheric prediction for regions on the order of ten to hundreds of kilometers on a side. MM5 generates realistic wind fields based on the laws of conservation of mass, energy, and momentum, along with land surface data and atmospheric forecasts and observations. It is particularly effective at resolving circulation patterns in areas with sparse meteorological observations, and/or mountainous terrain. MM5 is applied to the 1995 eruption of Cerro Negro, Nicaragua. Estimates of particle settling velocities are used in conjunction with MM5-derived wind fields to forecast the plume track. Particle trajectories generated from MM5 winds are compared to those produced by other wind models. The complex wind fields generated by MM5 explain non-linear plume...
dispersion. MM5 winds are shown to be more accurate than the other models in reproducing the observed tephra deposit, and satellite imagery is used to confirm the accuracy of MM5 winds. The appropriate application of meteorological data sets and mesoscale models should ultimately improve the utility of tephra fallout hazard assessments, especially in the absence of abundant meteorological observations.
Chapter One

Introduction

Tephra, commonly known as volcanic ash, is defined as airborne volcanic ejecta of any size (Tilling et al. 1987). It is a frequent product of volcanic eruptions. Because tephra poses numerous hazards to human interests, volcanologists have modeled its motion in the atmosphere and ground deposition for over two decades. Although these models have increased in complexity over time, the meteorological component of these models was conventionally simple, often out of necessity. The incorporation of winds from a high-resolution atmospheric model could make tephra dispersion modeling more robust. This thesis takes winds produced by the atmospheric model MM5 and applies them to the 1995 eruption of Cerro Negro, Nicaragua (Figure 1.1). Particle trajectories are generated using MM5 winds as well as winds from other sources used in dispersion modeling. These trajectories are compared to observed deposition patterns and satellite imagery, in order to determine if MM5 provides an improvement over more commonly-used wind fields.

Tephra fall hazards

Volcanoes create numerous natural hazards that pose a risk to society. Lava flows and ballistics generally affect the area proximal to a volcano, and are for the most part easy to avoid. Vent collapses, meanwhile, can result in massive rock avalanches that are
extremely destructive. Pyroclastic flows often form when part the eruption column itself collapses and are primarily composed of volcanic ash (tephra), and heated gases. Moving down slope due to gravity, pyroclastic flows can travel over 40 meters per second, and cover great distances. They represent a particularly deadly volcanic hazard. Volcanic gases can also pose a threat to surrounding populations, but deaths generally are rare (Latter 1989).

Figure 1.1. The 1995 eruption of Cerro Negro, Nicaragua, as viewed from the northwest. Courtesy of Dr. Brittain Hill.

It is wind-driven tephra, though, that threatens far larger areas than any other volcanic hazard. Tephra has been observed to completely circle the globe after some eruptions. When tephra, often colloquially termed volcanic ash, settles from the atmosphere onto Earth’s surface, it creates a number of consequences. Following an
eruption, large tephra deposits often become remobilized by precipitation. The lahars made of tephra and water often pick up more water and rock debris as they travel, and can move at speeds of over 10 meters per second. The deadliest lahar on record, formed after the eruption of Colombia’s Nevado del Ruiz in 1985, killed over 25,000 people (Sigurdsson and Carey 1986). Tephra deposited on roofs can easily cause building collapse, which accounted for most of the 300 deaths caused by Mt. Pinatubo’s 1991 eruption (Wolfe 1992).

Tephra can clog airplane engines, and then melt inside due to high heat, destroying the mechanisms (Scott et al. 1995). Air traffic is advised to completely avoid tephra clouds, which can lead to disruption of transportation routes, resulting in massive delays and wasted funds (Turner and Hurst 2001). When settled in populated areas, tephra can cause similar problems with automobiles. Vehicles frequently stir up the recently settled particles, extending the problem for even longer. Tephra can also cause power outages when settling on electrical equipment such as transformers (Scott et al. 1995).

Tephra often causes water contamination, which can kill land animals and fish and destroy crops. Health consequences of tephra for humans include adverse effects on respiration, and irritation of eyes and nose. Direct exposure to tephra in the air is obviously best avoided (Latter 1989, Baxter 1990).

Tephra modeling

In order to better understand tephra plumes and hazards, many volcanologists have engaged in numerical simulation of volcanic eruptions (Suzuki 1983, Carey and
In every model, some physical assumptions are made, and eruption parameters are estimated. These assumptions apply not only to the characteristics of the eruption and the eruption column, but also the tephra plume (Figure 1.2).

![Figure 1.2. A typical tephra plume encountering wind. From Gardner et al. 1995. Tephra is forced up through the eruption column, and is advected downwind in the plume. Wind continues to affect particle movement throughout tephra fall.](image)

The movement of tephra in the atmosphere is crucial for modeling tephra deposits. Once tephra particles in the eruption column have achieved their maximum height, their movement depends upon their characteristics (density, shape, terminal fall velocity) and very importantly, wind. Eruptions with little or no wind can produce bulls-eye tephra deposits centered on the volcanic vent (Bonadonna and Phillips 2003). However, much more commonly, tephra plumes are advected by winds, and become more diffuse with time and distance downwind. In general, ballistic ejecta reach the
ground very quickly, smaller tephra fragments fall out more slowly, and the finest tephra settles last (Figure 1.3). Changes in wind speed and direction with distance or height, known as wind shear, can create irregular deposition patterns. While many tephra deposits exhibit axisymmetrical patterns, isopach maps of tephra deposits often reveal non-linear axes, multiple deposition axes, and multiple thickness maxima (Ernst et al. 1994).

Figure 1.3. A weak tephra plume advected by wind. From Bonadonna and Phillips 2003. In general, large particles fall close to the vent, and smaller particles are deposited farther away. $X_w$ represents the distance that a particle is transported by wind during particle fall.

The last 25 years of plume modeling have used wind assumptions ranging from the most basic and static to relatively complex and dynamic (Woods et al. 1995, Bursik 1998, Turner and Hurst 2001, Bonadonna et al. 2005). Despite these observations of complex tephra deposits, winds, more often than not, are assumed to be uniform (Hill et al. 1998). This assumption may be made for simplicity’s sake, or because wind data is
not easily accessible, difficult to retrieve, and in many cases, incomplete. It is not uncommon to find that wind data have been extrapolated from a single observation from a weather station tens of kilometers away (Barberi et al. 1990, Macedonio et al. 1994). This is a serious problem because the simplistic wind assumption neglects a major impact on deposition location.

This infrequency of application of detailed wind is symptomatic of the fact that there has been minimal collaboration between volcanologists and meteorologists in tephra prediction models. In addition, much of the research on tephra dispersion that has involved atmospheric models has addressed the issue as it related to aviation interests. The role of wind in the surface accumulation of tephra can be explored in greater detail. Atmospheric models can fulfill this pressing need in volcanological models. While employed most commonly for forecasting weather conditions, they have also been used extensively for tracking particles, pollutants, and for atmospheric chemistry. Mesoscale models would be of particular importance because they deal with the same spatial scales as a typical tephra plume. Mesoscale refers to weather phenomena that are on the scale of ten to hundreds of kilometers across (Brasseur et al. 1999).

**Project Goals**

*Apply models to well studied eruption*

This project has several specific objectives and goals. To determine if atmospheric models are appropriate for volcanological modeling, a mesoscale atmospheric model is applied to the tephra plume from a well-studied volcanic eruption, the November 19-December 6, 1995 eruption of Cerro Negro, Nicaragua. The
The meteorological model employed for this project is version 3 of the Pennsylvania State University-National Center for Atmospheric Research (NCAR) fifth-generation Mesoscale Model, or MM5. A particle fall program is created to simulate the movement of tephra particles in the atmosphere, and the forecast wind fields produced from MM5 are used as input.

**Determine if winds mimic deposit**

To evaluate the utility of MM5 for predicting tephra dispersion and deposition, the model needs to be tested using actual eruption data. Because there are no consistent soundings available for the area during the period of the eruption, global wind data and distant station data are used by MM5 in order to reconstruct the wind field. The MM5 output is used in a particle trajectory model, and the predictions are compared to the tephra deposit. The extent to which particle trajectories match the observed tephra deposition pattern will determine how accurately the MM5 predicted winds within the Cerro Negro study area.

**Determine necessary sophistication of atmospheric model**

MM5 is evaluated at two different spatial resolutions, in order ascertain the minimum resolution needed in order to sufficiently simulate winds for the region during the eruption. The results of the MM5 output winds are also compared to those generated from archived global reanalysis winds, and from a uniform wind field.

This research tests whether the MM5 output winds are closer to the true local wind patterns, and therefore more useful to volcanologists, than are reanalysis wind data.
or uniform winds. The assumption of uniform wind in a three-dimensional space over an
extended time period is investigated to exhibit its inadequacies. The temporally variable,
three-dimensional MM5 winds are used to improve the model winds away from the vent,
and possibly illuminating large downwind shifts that would go undetected in the uniform
wind models. If MM5 performance sets itself apart from the conventional input winds
for volcanologists, it will have clearly demonstrated the need for a more advanced wind
model. This project will also test if low-intensity volcanic eruptions produce enough
tephra in the atmosphere to require a complex wind model.

Establish a link between Volcanology and Meteorology

This research project provides a link between the disciplines of volcanology and
meteorology, using methods that already have proven useful in their respective fields.
The study creates a template that could be used to improve future models, or at the very
least encourage more collaboration between the two fields. It is also hoped that the
project marks an improvement in tephra deposition forecasting.

Looking towards possible future research, the combination of a meteorological
model with a true tephra dispersion model that can account for many features of a
volcanic eruption should lead to a more complete methodology and more robust results.
It is anticipated that the results of this study could eventually lead to a re-examination of
tephra and lahar hazards, and could serve as an important step in improving the
methodology of tephra fall prediction, hazard assessment, and issuing warnings in the
event of an imminent eruption.
Chapter Two

Literature Review

Tephra Modeling

This chapter first reviews some of the past work conducted in tephra dispersion modeling, focusing on the wind fields used in each study. Following that, examples of dispersion modeling using atmospheric models are explored. Finally, several case studies involving MM5 in particular are presented.

Suzuki Model

Tephra dispersion models have been in existence for over twenty years. Suzuki (1983) was the first to numerically model the dispersion of tephra in the atmosphere. The model uses a line source for particles, whose maximum height is calculated from the energy and mass flow of an eruption (Connor et al. 2001). The particles’ settling velocities are a function of particle shape, size, and density, while horizontal movement is governed by the diffusion-advection equation using a uniform wind field, where direction and magnitude are held constant in three-dimensional space and in time.

Glaze and Self (1991) adapted Suzuki’s (1983) dispersion model for an investigation of the 16 September 1986 eruption of Lascar, in Chile. Like the Suzuki (1983) model, tephra diffused horizontally while falling to the ground in a time $t$, which is independent of horizontal motion. The model was modified so that it could account for
variations in wind speed and direction with height above the vent. In this temporally uniform, stratified wind model, wind magnitude and direction were uniform within each atmospheric level, but varied over the vertical domain. Variations in wind direction caused a bimodal tephra deposition pattern for Lascar in the model (Glaze and Self 1991). They found that the model could give a reasonable approximation of distal tephra deposits for short-lived eruptions, and is best suited for instantaneous (vulcanian) blasts, rather than continuous eruptions. The researchers suggested that future improvements to the model would include more attention to the motion of small particles, and capability to simulate ballistic fallout (Glaze and Self 1991).

A model designed by Armienti et al. (1988) to describe tephra deposition following the 1980 eruption of Mt. St. Helens slightly modified the Suzuki (1983) model by using a vertically stratified wind field and a gradual (rather than instantaneous) release of particles. Using a wind field from 3 soundings in Spokane, Washington, on the day of the eruption, the model, like Suzuki (1983), reproduced the double maximum that was observed. It was concluded that this phenomenon was created by the stratified, varying winds, aggregation of the finest particles, and the distribution of mass in the eruption column. The researchers found that forecast deposit was too wide, because particle aggregation that had taken place was not modeled. They also mentioned that topography and variation of wind velocities in the horizontal plane are not taken into account, which are both a source of model error (Armienti et al. 1988).

The Suzuki model was further adjusted to account for the conservation of mass within the eruption column (Connor et al. 2001, Bonadonna et al. 2002). The model was integrated into a probabilistic hazard assessment for Cerro Negro, Nicaragua, taking into
account a variety of possible eruption characteristics and atmospheric conditions (Connor et al. 2001).

Other modifications to the Suzuki model included parameterizations for winds, particle aggregation, and variations in particle density (Bonadonna and Phillips 2003). Using two different vertically stratified wind models, their study acceptably modeled the spreading current of the 1980 Mt. St. Helens eruption, as well as several other historic eruptions.

**Aviation**

Alternative approaches to tephra dispersion modeling are dedicated to the interests of aviation and commerce. The following section describes some of these models.

**VAFTAD**

The Volcanic Ash Forecast and Transport And Dispersion model (VAFTAD) was developed by the National Oceanic and Atmospheric Administration (NOAA) specifically to track ash and its hazards affecting aviation interests in real-time (Heffter and Stunder 1993). For their study, input winds were acquired from the NOAA National Meteorological Center (NMC) at 12-hour intervals. The model required some input on eruption characteristics, but assumed that particles were all spherical, with uniform density, and diameters ranging from 0.3 to 30 μm. These fine-grained particles generally have considerable residence times in the atmosphere. In the model, tephra was advected horizontally and vertically, descending according to Stokes’s Law with a slip correction.
A unit source for the eruption mass was used, because actual eruption masses are rarely available during eruptions. Eruption duration was assumed to be no more than three hours, at which point the eruption column was expected to have achieved its maximum height. Model verification was conducted using satellite imagery, as large-scale ground observations were constrained by time and funds for the eruptions that were investigated. Although the model moved particles vertically, it did not track tephra accumulation on the ground, because it focused on hazards to aircraft.

**CANERM**

CANERM (CANadian Emergency Response Model) is a three-dimensional Eulerian model that has been used extensively for forecast threats to aviation interests (Simpson et al. 2002). It uses terrain-following $z$ coordinates, has a maximum wind resolution of 25 kilometers, and like the VAFTAD model, its purpose is to track tephra particles within the atmosphere. Although the model accounts for wet and dry deposition, it is not programmed for estimating tephra deposition (D’Amours 1998).

**PUFF**

PUFF is a high-resolution model designed specifically to track volcanic ash in the atmosphere (Searcy et al. 1998). It was developed to aid real-time hazard warnings, especially in cases where visual observation of the ash cloud may be hampered by weather or other factors. PUFF is most adept at predicting dispersal for ‘young’ particles, within the first 48 hours after an eruption. It acts as a pollutant tracer model, using a three-dimensional Lagrangian formulation of pollutant dispersion, using a finite number
of tephra particles to represent the entire tephra plume. Separate trajectories are then calculated for each particle, one by one, from one time step to the next, using a “random walk” formulation. Because PUFF requires approximately real-time wind forecasts, the input data used were 4-dimensional wind fields from UCAR's twice-daily forecast runs. These data are available from the surface up to the 100 hectopascal (hPa) level, and have a grid resolution of 5 degrees longitude by 2.5 degrees latitude. Although PUFF allows particles to settle out of the atmosphere, it does not predict tephra deposition on Earth’s surface (Searcy et al. 1998).

Other Tephra Models

Probabilistic tephra hazard modeling has a heightened importance in areas where large populations lie close to volcanoes. Barberi et al. (1990) created probabilistic tephra hazard maps for a theoretical large-scale eruption of Mt. Vesuvius in Italy. By using historic eruption data to calculate the annual magma supply rate, the likelihood of an extreme eruptive event was determined. With 15 years of archived wind profiles from the meteorological station in the city of Brindisi, 300 kilometers to the east, the group determined the historical distribution of wind velocity, to calculate the probability of tephra being transported to a particular area (Barberi et al. 1990).

A similar project was undertaken by Macedonio et al. (1994). In this study, the hazard posed by tephra plumes on the dense aircraft transit in the vicinity was determined. The researchers modeled theoretical plumes for each wind profile from a 10-year archive from Brindisi. It should be noted that Vesuvius borders the Tyrrhenian Sea, on Italy’s west coast, while Brindisi lies on the Adriatic, on Italy’s east coast. Local wind
trends will not be captured when using wind data from a distant source. Results of the study indicated that there were two seasonal shifts in wind patterns: at the beginning and the end of summer, when weaker and variable winds prevail (Macedonio et al. 1994). The rest of the year has stronger winds, uniformly out of the west. The highest plume hazards, then, were located directly east of the volcano.

Tephra modeling is also commonly used to reconstruct the dynamics of long-past eruptions, such as the A.D. 79 eruption of Vesuvius (Macedonio et al. 1998). In this project, the model accounts for diffusion and advection by wind, and calculates settling velocities based on tephra particle granulometric data. The researchers depict the terrestrial deposits from both phases of the eruption as relatively axisymmetric. This suggests that winds were relatively uniform in proximal regions for the estimated 19-hour combined duration of the two phases. Because a large percentage of the tephra was deposited in the sea, deposit thickness had to be interpolated from the small number of land-based sample points. The mapped deposit, therefore, has some level of uncertainty. To apply a wind field to their model, the researchers found the mean wind velocity at different altitudes for summer months, as recorded from two stations, Rome and Brindisi. Because mean winds were found to move from east to west, this result was rotated clockwise 60 degrees to better fit the observed deposit. The predicted model deposit was found to agree well with the results from interpolation.

**RAMS/HYPACT**

One of the most similar research projects to this study involved a combination of meteorological and volcanological models to forecast tephra deposition for Mt. Ruapehu
(Turner and Hurst 2001). These researchers used the Regional Atmospheric Modeling System (RAMS) along with the Hybrid Particle And Concentration Transport model (HYPACT). RAMS is a three-dimensional atmospheric model that is capable of simulating the effects of rough terrain and a reasonably high-resolution inner grid (2.5 km). HYPACT is a dispersion model that treats plumes as Lagrangian particles, which undergo advection and turbulence.

The study assumed that tephra particles were entirely between 1 and 200 µm in diameter, with a uniform distribution of sizes. Fall velocities were approximated by Stokes’s law, although the authors acknowledged that this assumption might be unsuitable for particles over 80 µm in diameter. Best results for the 1995 Ruapehu eruption occurred when the tephra plume was simulated to range from 7 to 10 kilometers in height. Certain forecasted isopachs were found to exceed ground observations, but the researchers attribute this to overestimation of initial eruption volume. Other areas that observed deposition of tephra were not predicted to have any by the models. Simulations also predicted that the main axis of the eruption plume to be 10 degrees rotated from its actual position. The researchers concluded that the initial eruption parameters were of paramount importance in determining tephra deposition location, because particles can encounter high wind variation depending on where they are “released” in simulations. Initial and lateral boundary conditions for RAMS were another limitation of model accuracy. It was also reasoned that while the ability of HYPACT in tracking tephra plume movement had merit, it was inappropriate for quantifying tephra deposition, because of shortcomings related to particle fall velocities.
ASHFALL

Turner and Hurst (2001) compared their methodology to that used by the New Zealand government for ash fall advisories, the ASHFALL model, which simplifies the Suzuki (1983) model. They found that ASHFALL had many of the same limitations regarding boundary conditions and eruption characteristics, but its results were not as accurate at the RAMS/HYPACT suite. ASHFALL presented several other drawbacks when the models were compared. It can account for vertical and temporal variation in winds, but not for horizontal spatial variation in winds. The maximum horizontal grid spacing is 5 kilometers, requires height levels without regard to local topography, and showed little sensitivity to variations in particle fall velocities (Hurst and Turner 1999).

Mesoscale Atmospheric Models applied to non-tephra dispersion

CANERM

D’Amours (1998) used CANERM to simulation dispersion of tracers for the 1994 ETEX (European Tracer EXperiment) releases of October 23 and November 14, 1994. The model uses three-dimensional Eulerian advection-diffusion to determine atmospheric concentrations of particles. The study used 6-hour analysis data provided by the European Centre for Medium Range Weather Forecasting (ECMWF), which was interpolated from a 73 by 55, 0.5-degree grid to a 101 by 101, 25-kilometer grid. The simulated tracer cloud appeared “quite plausible,” but surface concentrations were overestimated in all areas. The model appeared to be more accurate in predictions within the first 30 hours, and less accurate for times after that.
**RAMS**

A 1999 study explored terrain influence on surface ozone concentration in a mountainous region of eastern Spain (Salvador et al. 1999). Using the Regional Atmospheric Modeling System (RAMS), the researchers tried to pinpoint atmospheric transport processes that contribute pollutants at four monitoring stations. The input data was one-degree resolution from the ECMWF (European Centre for Medium-Range Weather Forecasts). Large diurnal variations in wind were apparent. The researchers also discovered that certain wind patterns were only captured at higher grid resolutions, and that some local effects could not be reproduced by the model at all. Resolution had the biggest impact on modeled vertical winds.

**LEDI**

Mesoscale modeling has also been implemented for tracking radioactive contaminants. Wind and rainfall were simulated by LEDI (Lagrangian-Eulerian DIffusion model) for the 12 days following the 1986 Chernobyl nuclear disaster, and were found to effectively describe $^{137}$Cs contamination due to both wet and dry deposition (Talerko 2005). The project used a time step of 10 minutes and a uniform particle size of 1 µm. Topography and land use data had a resolution of 10 kilometers.

**MM5**

*Description*

The MM5, like other mesoscale atmospheric models, simulates an atmosphere that evolves based on the physical laws of motion, and the laws of conservation of
energy, mass, and momentum. It is designed to forecast weather phenomena at a regional scale, on the order of ten to hundreds of kilometers. The current version is non-hydrostatic, removing the previous 10-kilometer limit imposed by the hydrostatic assumption. MM5 uses a terrain-following vertical coordinate system, referred to as the “sigma” coordinate system (Figure 2.1), a 1- or 2-way nested grid system (Figure 2.2), model physics, lateral and vertical boundary conditions. The upper radiative boundary condition allows the reflection of gravity waves (Grell at al. 2000). The physics of the model, described in detail by Dudhia (1993) can be summarized as:

- Cumulus parameterization represents sub-grid scale vertical motions that are due to convective clouds.
- Boundary layer and vertical diffusion schemes handle friction and other processes such as turbulent motion in the lowest layer of the atmosphere.
- Microphysical schemes treat cloud and precipitation processes on a resolved scale
- Horizontal diffusion represents sub-grid horizontal eddy mixing and serves as a horizontal filter.
- Radiative schemes represent radiative forcing in the atmosphere and at the surface, e.g., the reduction of solar radiation due to cloud cover.
- Surface schemes represent the effects of land and water surfaces, e.g., sub-soil temperature profile or movement of water through root systems.
Figure 2.1. The MM5 vertical coordinate system, or sigma levels (courtesy NCAR/MMM). This coordinate system follows surface terrain. The gray object at the bottom represents a mountain. This example has 15 full vertical levels and 5 half-levels.

Originating from models developed in the 1970s, MM5 is a well-known and often used mesoscale model, with a community of users, an online how-to tutorial, help guides, and a standby expert for user support. Versions of MM5 have been in use for over 20 years, and it has been updated and improved throughout its history of use.

White et al. (1999) found that the MM5 was the most developed research model tested in their comparative study, and that it produced superior forecasts to other research models. MM5 accounted for more dynamical atmospheric processes than the other existing models that were tested, and provided the best forecasts at short-range timescales (White et al. 1999).
Figure 2.2. The nested grid system of MM5 (courtesy NCAR/MMM). Domain 1 is the “parent” domain; Domains 2 and 3 are nested inside 1, and Domain 4 is nested inside Domain 3. Domain 4 would have the highest resolution in this configuration.

The model has already been used to track gas and particle pollutants, including dust, demonstrating its utility to this project. A more extensive description of these studies will follow. MM5 is a relatively thorough model that considers many environmental factors, which are generally specified by the user. These variables include topography, land use and land cover, vegetation type, soil type, soil temperature, sea surface temperature, archived meteorological forecasts, available surface weather observations recorded at stations, and upper-air observations from weather balloons.

The MM5 is effective at resolving circulation patterns in areas that have a dearth of meteorological observations and/or rough terrain. This is not much of an issue in the United States and Europe, but less wealthy countries often do not have plentiful resources, and may have even less archived weather information, going back in time a decade or more. Large bodies of water such as seas or oceans generally have even fewer
direct observations, so the importance of MM5 is elevated in studies involving such areas. It is also competent at simulating orographically driven circulation such as gap winds, downslope winds, lee waves, and topographically forced precipitation (White et al. 1999, Zängl 2002).

The MM5 produces realistic winds in four dimensions, varying in $x$-$y$-$z$ space and in time. A typical model domain is depicted in Figure 2.3.

![Figure 2.3. A mesoscale model domain (from the COMET website “How mesoscale models work”). Features and parameterizations are depicted using the three-dimensional coordinate system. The horizontal and vertical grids are spaced on different scales.](image)

This complexity is necessary for supplying a more accurate wind field for a tephra dispersion model. The MM5 is also well-equipped to handle small-scale areas of interest, using nested grids. Up to 6 domains can be used, with one inside another. The maximum
resolution is a grid cell that is 1 kilometer on a side. The ability to generate wind patterns on large and small scales in the same model run is particularly helpful for different types of volcanic eruptions.

MM5 accounts for atmospheric parameters lacking in most tephra models, providing realistic atmospheric conditions for a wide range of spatial resolutions. Its handling of boundary layer mixing and eddy diffusivity make it applicable for use in particle dispersion.

**Case study prediction**

White et al. (1999) tested six atmospheric forecast models, including MM5, for comparison over the western United States. Modeling involved a single 65 by 65 cell grid with a spacing of 27 kilometers, and 27 half-sigma levels in the vertical dimension (see Figure 2.1). Half-sigma levels do not include all information that a full sigma level has. Input data were bilinearly interpolated to fit the MM5 domain grid points. Grid nudging was also employed in the study. Model validation was determined by bias error and mean square error for variables including wind and geopotential height, though in their study, the error for \( u \) and \( v \)-winds are combined into one value. Bias error shows whether values in the model are generally over- or underestimated, while the mean square error provides the typical magnitude of error (White et al. 1999). Highly resolved models expressed high apparent error when compared to gridded analysis data, because of great differences in resolution between the two data sets. Comparison with point observation, as conducted here, resulted in smaller, more believable model errors (White et al. 1999). Topographic features seemed to influence not only the MM5, but all model forecasts.
A study by Cox et al. (1998) demonstrated that regions of complex topography have marked localized wind effects, and thus require high-resolution reconstructions in order to be realistic.

During the Special Observing Period (SOP) of the Mesoscale Alpine Programme (MAP), Ferretti et al. (2003) tested the ability of MM5 to forecast heavy precipitation. Although they reported underestimated rainfall amounts and shortcomings regarding surface temperature prediction, especially in areas strongly influenced by marine air masses, the model showed better results when a higher resolution grid was used. The study employed MM5 Version 2 (MM5V2), an older version than used in this tephra deposition study. MM5 produced accurate results for surface pressure values, and performed well in regions of complex terrain (Ferretti et al. 2003). The researchers also noted that MM5 seemed to resolve circulations better during cloudy skies that clear ones. They found high RMS errors for zonal (\(u\)) and meridional (\(v\)) wind during the early stages of the forecast, but these gradually decreased. RMS errors for temperature and relative humidity, on the other hand, increased over the course of the forecast.

MM5 has been applied for high-resolution forecasting in mountainous, tropical regions such as Colombia (Mapes et al. 2003b). Using a 4-domain setup with a maximum grid resolution of 2 kilometers, the researchers found that MM5 could replicate diurnal shifts in precipitation, as well as other very localized phenomena (Warner et al. 2003).
Modeling particles and pollutants

Not only has MM5 been used for forecasts specific for weather, it has also been used to track many types of particles in the atmosphere. The following details several projects that applied MM5 in various locations.

Sand

A 1998 sand “event” in China was simulated using winds generated by MM5 (In and Park 2001). The winds were then fed into an aerosol transport model, which was capable of accounting for diffusion, advection, and wet and dry deposition. Aggregation of sand particles is not a common occurrence, so this was not considered in the study. The simulated particle sizes ranged from 0.1 to 1000 µm. The study found that predicted arrival of suspended sand in Korea was well predicted by the model. Two large dust rises, spaced 4 days apart, were transported along different paths, and this was verified by the models (In and Park 2001).

Gas pollutants

The MM5 has been employed to help track anthropogenic air pollution as well. A recent study used MM5 winds in a transport-chemistry-deposition model (Kitada and Regmi 2003) for the mountainous region of Kathmandu, Nepal. The primary pollutants tracked were Sulfur Dioxide (SO2) and Nitrogen Dioxide (NO2). The investigation used a high-resolution (1 km by 1 km) grid to map pollution levels and model winds. It revealed large diurnal changes in wind patterns in the valley containing the city, as well as a double-layered flow. MM5 also helped elucidate seasonal peaks in air pollution.
Grell et al. (2000) applied MM5 to the VOTALP (Vertical Ozone Transports in the ALPs) Valley campaign in order to model the wind flow and pollutant concentration in mountain valleys. They found that the MM5 simulated pollutant transport from the Po valley to smaller alpine valleys quite well, at the highest resolution.

*Particulates*

Another application of MM5 took place in Berlin, Germany, where it was used in conjunction with a Lagrangian particle trajectory model (Becker and Keuler 2001a). The study examined source attribution of pollutants in 4 dimensions, using probability density distributions. Rather than attempt a model using backwards trajectories, the researchers used millions of potential particles, then tracked them to determine which matched the locations of observed pollution within the city. The researchers found that heterogeneity in wind fields led to an increased contribution of nearby pollution sources, while homogenous winds tend to make distal pollution sources more important (Becker and Keuler 2001b). The research concluded that wind pattern changes from one day to the next caused a shift in pollution sources.

Using a two-nest domain for the eastern United States, Seigneur et al. (2003), tracked the movement of anthropogenic Benzene and Diesel particles over a 5-day period. The grid resolution used was 12 and 4 kilometers, with a 48-hour period of model spin-up. Particles were released into the MM5 wind field using multiple point sources, and rose as plumes according to the SMOKE modeling system. Simulations corresponded very well to observations, with urban concentrations of the pollutants much
higher than remote areas, and peak concentrations occurring during the busiest vehicle commute hours.

These examples strongly suggest that MM5 can provide realistic wind fields for a variety of different needs, conditions, and locations. Because it has already been proven adept at handling various particle dispersion problems, it should prove quite useful for modeling tephra dispersion and deposition.
Chapter 3
Methodology

This chapter is separated into two parts: 1) the methods used to set up and run the models applied in the study, and 2) methods and results for MM5 model validation.

Initial Setup

Computational and data resources of several institutions were used during this project. At the University of South Florida, accounts were set up on Linux servers dedicated to research using parallel processing and administered by the Research Computing Core Facility. The MM5 suite of programs was downloaded from the MM5 website, http://www.mmm.ucar.edu/mm5/ and installed on the USF Linux servers mimir and wyrd. Accounts were also established at the NCAR Scientific Computing Division (SCD) in order to retrieve additional meteorological and environmental datasets. A significant part of the data processing and troubleshooting of the simulations was conducted while the author was a visitor at the NCAR Mesoscale and Microscale Meteorology Division in Boulder, Colorado. The methodology represented in Figure 3.1 is described in the following sections.
Data Acquisition

MM5 can incorporate input data from a variety of different sources and formats. This section describes the data that were acquired specifically for this project.

Gridded surface and atmospheric data

To initialize the mesoscale atmospheric model, a subset of retrospective global data on low-resolution 2.5-degree grids were collected. The surface and atmospheric data used in this study are called NNRP, which stands for the NCEP-NCAR Reanalysis Project (Kalnay et al. 1996). The NNRP data are 6-hourly (0000, 0600, 1200, 1800
UTC) at 17 different pressure levels: 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 hectopascals (hPa). The NNRP dataset that is archived by the NCAR SCD was formatted for direct input into the MM5 modeling system.

The NNRP data were obtained by editing the script “get_nnrp.deck” for the desired dates, and then executing the program. The retrieved data then had to be transferred by ftp to the local USF server and integrated into the MM5 setup.

Surface and upper air observational data are also archived by the NCAR Scientific Computing Division. These data, required by MM5 to improve on initial forecast values, were retrieved by editing and running the “fetch-little_r-data.deck.ibm” script from NCAR’s server.

**Soundings**

Atmospheric soundings, used in the validation of the MM5 simulations, were acquired from the University of Wyoming’s Department of Atmospheric Science website, found at http://weather.uwyo.edu/upperair/sounding.html. Although meteorological station data were incorporated as a part of the MM5 model initialization, data for each individual station were not readily available as plain text files. The University of Wyoming has a user-friendly Graphical User Interface (GUI) that allows the user to select the station from a map, or enter the 5-digit station number to retrieve the information in a text, image, or portable document format. Finding a comprehensive list of meteorological station numbers requires a visit to another website. A list of stations can be found at http://badc.nerc.ac.uk/data/radiosglobe/world.html, where the stations are grouped by continent.
MM5 output was tested against meteorological station observations to determine if a model run provided realistic results. For the purposes of comparison, all of these stations were located within the spatial domain of the model. A total of 19 stations in 9 different countries were chosen for model validation: Brownsville, Tampa, Miami, Cape Kennedy, Key West, and San Juan in the United States, Veracruz, Merida, and Cancun in Mexico, Belize City in Belize, San Jose in Costa Rica, Grand Cayman in the British West Indies, Kingston in Jamaica, Nassau in The Bahamas, Panama City in Panama, Bogotá, Leticia, and San Andres Island of Colombia, and Curacao in the Netherlands Antilles (Figure 3.2).

Figure 3.2. The 19 meteorological stations used for model validation.
The files were saved as plain text, for statistical tests, and in portable document format (.pdf), for visual comparisons. An output “sounding” along with the corresponding atmospheric sounding is shown in Figure 3.3.

Figure 3.3. An atmospheric sounding and the corresponding MM5 output sounding generated for the same observation time. Comparisons were made for the temperature profile (right bold line), dewpoint profile (left jagged line), and wind velocity (wind barbs along right side of graphs).
Model Setup

**TERRAIN**

It has been shown that higher resolution grids are necessary to depict realistic wind patterns in regions of complex terrain (Salvador et al. 1999). Local effects such as a mountain wake may not be simulated at resolutions 6 kilometers and lower. However, a 2-kilometer resolution grid can account for 95 percent of the terrain variance, a 0.5 kilometer resolution grid can explain 99 percent. Similar findings were found when simulating flow of atmospheric pollutants in the Alps. Only the highest resolution grid was able to reveal the fine-scale particle paths from valleys to mountains (Grell et al. 2000). Because this study modeled winds that are essentially in the wake of Cerro Negro, the highest possible resolution available in this version (1 kilometer) was utilized.

The following sections deal with MM5 setup as it pertains to the winds modeled for the 1995 Cerro Negro eruption. A flow chart of the MM5 modeling system is shown in Figure 3.4. The first program in the MM5 model is called TERRAIN. Here the user sets all the parameters of the model domains, and all the model terrestrial information that is used in the model is then generated. Data accessed by the TERRAIN step include USGS elevation, land use and vegetation, land/water mask, soils, and soil temperature. For a more thorough description of these data, the reader is directed to the MM5 online tutorial page, http://www.mmm.ucar.edu/mm5/mm5v3/tutorial/teachyourself.html or the MM5 technical memo (Grell et al.1995).
Separate MM5 trials were run using three nested domains (at a maximum resolution of 9 kilometers) and five nested domains (with a maximum resolution of 1 kilometer). The three largest domains in the 5-domain setup were identical to the 3 domains in the lower resolution run (Figure 3.5). The domains were set up one grid at a time, from largest to smallest. The first grid was 61 by 61 cells, centered at 12.0 degrees North, 85 degrees West (-85.0), and had grid cells 81 km on a side. A summary of the Cerro Negro domain setup is shown in Table 3.1. Detailed descriptions of all
modifications made to the default terrain.deck file can be found in the appendix, along with the final version used for the project.

Figure 3.5. The three-domain setup vs. the five-domain setup. Domain 1 comprises the entire map area. Domain 2 is the largest white box. The five-domain setup has two additional high-resolution nested inner domains in the Cerro Negro region.

<table>
<thead>
<tr>
<th>Number of domains</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time steps</td>
<td>15</td>
</tr>
<tr>
<td>Vertical levels</td>
<td>23</td>
</tr>
<tr>
<td>Large-scale input data</td>
<td>NNRP</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Domain</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain size</td>
<td>61x61</td>
<td>49x52</td>
<td>40x40</td>
<td>49x49</td>
<td>49x49</td>
</tr>
<tr>
<td>Grid cell size (side)</td>
<td>81 km</td>
<td>27 km</td>
<td>9 km</td>
<td>3 km</td>
<td>1 km</td>
</tr>
</tbody>
</table>

Table 3.1. Domain parameters used in the Cerro Negro model run. The time steps were spaced 12 hours apart. Each parent domain must maintain a 3:1 grid cell resolution compared to its child domain.

REGRID

After the TERRAIN module has been successfully completed, the next step is REGRID. REGRID accesses archived weather analyses and forecasts and trims and
interpolates them to fit the domains specified in TERRAIN. These forecasts act as a first guess for the model. The output files generated here are used in the LITTLE_R and INTERPF steps that follow. The user input for pregrid is limited to specifying a choice for input data format, the beginning and end dates of the model run, and the time interval that the output data will have. It is often necessary to allow for a 24 to 72-hour period of “spin-up,” during which the model is given time to create dynamically and physically consistent meteorological fields. The model is able to sufficiently develop mesoscale circulation patterns before the actual time period of interest is simulated. Spin-up is especially necessary for the innermost domain, because initial conditions are simply interpolated input data when the model is initiated (White et al. 1999). To account for spin-up, the start date of the model was set to November 25, though the continuous phase of the eruption did not begin until the 27th.

**LITTLE_R**

The LITTLE_R step incorporates the first-guess forecast information from REGRID, and then uses actual meteorological observations or indirect measurements such as satellite-derived variables, to improve on them. This procedure is called objective analysis. Objective analysis techniques used by MM5 include Cressman-based analyses (distance- and prevailing wind-weighting options that are dependent on which meteorological field is being analyzed) and multi-quadratic analyses (Nuss and Titley 1994). Since poor observations can lead to bad analysis, the objective analysis step applies various tests to screen the data for spurious observations. The user has a choice of two programs for this task, RAWINS or LITTLE_R. For this study, LITTLE_R was
used, as it allows greater flexibility in the types of observations that can be used as input. With RAWINS, only standard rawinsonde (upper-air) observation formats are allowed. With LITTLE_R, users may create idealized data or use non-standard atmospheric data. The output information from LITTLE_R is used in the following interpolation step.

**INTERPF**

INTERPF simply prepares all the data that will be fed into the main MM5 program. The user input required includes start and end dates, and listing the sigma levels that will be used as vertical coordinates. Sigma levels are calculated using both topography and air pressure, and serve as an alternate $z$-coordinate, as opposed to altitude or simple pressure levels, as shown in the previous chapter.

**MM5**

The numerical weather prediction step of MM5 is appropriately called MM5. It incorporates all the previous information generated and specified by the user, so user input at this stage is minimal. Required entries include the number of domains to consider (this must agree with TERRAIN), maximum dimensions of any domain, and number of half sigma levels in the model. The model run uses the default physics options, except for the planetary boundary layer, which was set to Blackadar (2) for all domains, instead of MRF (5). Another option used was Four-Dimensional Data Assimilation (FDDA). This technique “nudges” forecast values towards meteorological reanalysis data to ensure that output does not substantially diverge from realistic values over time. This was recommended for longer simulations by Grell et al. (2000).
The MM5 step of the modeling program is unquestionably the most complex and temperamental. This study utilized MM5’s multi-processor mode (MPP), which involved using a different set of programs than single-processor mode. Using MPP saves computing time by assigning the tasks of the program to several computers at one time. In fact, any model runs with more than 3 domains require the use of MPP. For this mode, the user must specify how many processors will be needed for the model run, and what the configuration of the processors will be.

**INTERPB**

INTERPB vertically interpolates the MM5 output from sigma levels back to pressure levels, so that it can be used for meteorological and statistical analysis. The output from INTERPB was converted to ASCII format for two purposes: validation of the wind and geopotential height field at the upper air stations, and as input for particle fall modeling.

**GRAPH and RIP**

The GRAPH program is a user-oriented visualization tool that provides quick plots of output from any of the MM5 steps. It can be used to look at topography, view skew-t plots, 2-dimensional plots of winds for any of the output domains, cross sections, and many other forms of output. To run GRAPH, a table named g_plots.tbl must be edited so that settings match the MM5 model runs, and to specify which results of the model need to be plotted. Because GRAPH was used to visualize many different output
files, the entire process will not be discussed. While GRAPH is a very useful tool, it is not a required step in MM5 modeling.

RIP is another plot utility available for MM5, but it was not used for this project. There are two utility programs, readv3.f and ieeev3.csh, which are used to convert MM5 output data to manageable text files.

**Post processing**

After the MM5 step was complete, one of more of the individual domain output data files, named MMOUT_DOMAINx (Domain 5 in this case), were interpolated from sigma levels back to pressure level data, using INTERPB. The resulting file was named MMOUTP_DOMAINx. A FORTRAN script modified from the original readv3.f program provided with the MM5 package was next run to extract \( u \)- and \( v \)-wind and geopotential height for a user-specified three-dimensional grid within the domain in question. For the 1995 eruption, this was a 40 km (\( x \)-direction) by 32 km (\( y \)-direction) by 20 vertical pressure level grid. The pressure levels ranged from 100 hPa, increasing incrementally by 50 hPa up to 1000, and 1001 hPa (essentially the surface). The program outputs 4 files: one for \( u \)-wind, \( v \)-wind, geopotential height, and one for corresponding pressure level. These output files were then downloaded so that particle fall modeling could be performed.

A PERL script was then run to prepare the output data for use. The script accessed the four MM5 files, then extracted and stored the information in an array. The script next used the geopotential height information to vertically interpolate both the \( u \)- and \( v \)-winds, from the initial 20 pressure levels to 34 height levels. The height levels
have a 500-meter vertical interval, ranging from 0 meters altitude to 16,500 meters. In addition, the wind values were temporarily multiplied by 100 and converted to integers, for easier data storage. The horizontal grid spacing is approximately 1 kilometer, and its extent was based on the geometry of the 1995 tephra deposit. The grid was expanded after initial runs to track particles that may not be predicted to fall within the mapped deposit area (Figure 3.6). The output file was formatted to input directly into the particle fall program.

Figure 3.6. The 40 km by 32 km grid used in the particle fall model, showing mapped deposit isopachs in centimeters (from Hill et al. 1998).

For the wind model comparison, MM5 winds were also extracted at 9-kilometer resolution in the same way. These data were then applied to the particle fall grid.
**Reanalysis winds**

Because MM5 winds are compared to other wind models, archived global retrospective wind data was collected from the National Centers for Environmental Prediction (NCEP) at http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html. The download requires the user to specify the dates needed, the area of interest bounded by specified latitudes and longitudes, the type of data required (in this case $u$- and $v$-wind and geopotential height), and the time interval of the data. Extraction of the data required a pre-processing step, using a command-line script called ncdump provided with the data.

The reanalysis wind data consists of a matrix of points spaced 2.5 degrees apart along both latitude and longitude. Each data point in the grid consists of 4 times daily observations of $u$-wind, $v$-wind, and geopotential height ($h$), at 0000 UTC, 0600 UTC, 1200 UTC, and 1800 UTC, at 17 different pressure levels, from 10 hectopascals (hPa) down to 1000 hPa.

Using geopotential height data, the wind information was first interpolated vertically, to the particle fall grid used for MM5 winds. Using a 1/d distance-weighted mean, the wind data for 0000 UTC and 1200 UTC at each altitude were then interpolated horizontally, from the two closest NCEP grid points to each of the 1280 $x$-$y$ grid points in the particle fall grid.

Figure 3.7 shows the significant difference in resolution between the MM5 output winds and the NCEP reanalysis winds. At 12 degrees north, 2.5 degrees of longitude are approximately equal to 270 kilometers. A grid cell from NCEP data is 900 times larger than the “low-resolution” 9-kilometer MM5 output, and 73,000 times larger that a 1 square kilometer MM5 grid cell.
Figure 3.7. A comparison of grid cell resolution for the wind models. MM5 high-resolution winds have a cell size of 1 km, depicted as the tiny pink boxes. MM5 mid-resolution winds, at 9 km cell size, are the larger black boxes. NCEP reanalysis winds have a resolution of 2.5 degrees, which corresponds to 270 km at this latitude.

**Particle Fall Model**

The particle fall model used in this study uses a simple approach. The number of parameters involved in tracking particles as they erupted from a volcanic vent is enormous. To test the suitability of MM5 winds for tephra dispersion modeling, a
number of assumptions were made. First, tephra particles from the 1995 eruption are all assumed to be released into the atmosphere at the exact same location, at an initial height of 2400 meters above sea level, directly above the center of the volcanic vent. Ground observations during the eruption estimated a maximum column height of 2000 to 2500 meters. This release assumes stationary particles, i.e. there is no upward or horizontal motion left over from the eruption. In reality, particles emerge from the buoyant eruptive column over a range of altitudes, and may have residual momentum.

In addition, the program does not take into account any complex particle / atmosphere interaction. Although friction in the vertical direction is accounted for in calculating the terminal fall velocity of each particle, no friction in the horizontal direction is modeled. Turbulence, eddies, and convection are also neglected in the model. Horizontal motion of tephra particles is determined solely from MM5-predicted winds.

Three-Dimensional Grid

The three-dimensional grid that contains the wind fields was designed to enclose the 1995 tephra deposit out to the 0.1-centimeter isopach, as described by Hill et al. (1998). For reference, the grid extends roughly 38 kilometers west of Cerro Negro, 2 kilometers to the east, 10 kilometers to the north, and 22 kilometers to the south. The x-y dimensions of the grid correspond to the (roughly) 1 kilometer by 1 kilometer spacing of the innermost domain in the MM5 setup. The domain grid centers were converted to latitude-longitude points within the model, and then these points were in turn projected into UTM Zone 16N, so that a metric scale could be used. This reprojection of the MM5
Domain 5 coordinates from decimal degrees to UTM caused grid cell locations to shift slightly. The reprojection revealed that the Domain 5 cells are actually closer to 978 meters east-west by 972 meters north-south, on average, over the 40 by 32 cell x-y grid.

**Particle Fall Program**

The particle fall program stores $u$ and $v$ wind fields within the 40x by 32y by 34z grid. The respective position of each released particle is advanced second by second, based upon which three-dimensional grid cell the particle falls within. When a particle crosses from one cell to another, it acquires the horizontal velocity field of the new cell, while falling according to its calculated terminal velocity. The particle continues this motion until its $z$-coordinate reaches zero, which is sea level.

**Fall velocity**

As a particle is “released” into the wind grid, it is advected in one second increments by the wind vectors it encounters based on its position. A positive value for $u$ means winds are blowing from west to east, and a positive value for $v$ means winds are blowing from south to north. If a particle is within a wind field with values of –5 meters per second for $u$ and –2 meters per second for $v$, the particle will move 5 meters to the west and 2 meters to the south each second, until the particle crosses into a new grid cell. Tephra particles are generally oblong and cannot be regarded is spheres in modeling (Armienti et al. 1988). The settling velocity of a particle is tied mainly to its dimensions and density. Particles between 1 µm and 1 cm can reach their settling velocity in 5 meters or less, so they can be assumed to have this fall velocity upon release (Armienti et
Particles fall vertically as determined by Suzuki’s (1983) equation for settling velocity.

(Eq. 3.1) \[ v_a(\phi) = \frac{\rho_t g \phi^2}{9 \eta p_f^{-0.32} + \sqrt{81 \eta^2 p_f^{-0.64} + 1.5 \rho_t \rho_a g \phi^3 \sqrt{1.07 - p_f}}} \]

where

(Eq. 3.2) \[ p_f = \frac{p_b + p_c}{2p_a} \]

where \( \rho_t \) = tephra density in kg/m\(^3\), \( \rho_a \) = air density in kg/m\(^3\), \( \eta \) = air viscosity in Ns/m\(^2\), \( g \) = gravitational acceleration in m/s\(^2\), \( p_f \) = particle shape factor, and \( \phi \) = grain size.

In Equation 3.1, however, most have the variables are held constant, at assumed values. The tephra density \( \rho_t \) was set at 1100 kg/m\(^3\). Air density \( \rho_a \) is assumed to be 1.229 kg/m\(^3\), whereas the true air density is inversely related to altitude. Air viscosity \( \eta \) is set at 1.73 x 10\(^{-5}\) Ns/m\(^2\), and gravitational acceleration \( g \) is 9.8 m/s\(^2\), a common assumption. The particle shape factor, \( p_f \), is a dimensionless parameter held at 0.5. This would occur for tephra particles where the major axis is twice as long as either of the minor axes of the particle. Grain size is the one “variable” in the Suzuki equation that was truly varied. Diameter \( \phi \) was tested at 0.26, 0.5, 1, 2, and 5 mm. The 0.26 mm grain size was chosen because it produced a simple terminal fall velocity of 1.0 meter per second, which made error checking easier. Because air viscosity and air density are held constant, this particle fall model should only be applied to the lower atmosphere. These variables change significantly with height.
Model Validation

To check the accuracy of the MM5 predictions, the model output was compared with actual meteorological observations. Atmospheric soundings were generated by model runs by horizontally interpolating MM5 output to the latitude/longitude coordinates of each of the meteorological stations. The model predictions were compared both visually and statistically to the observations, to ensure that the MM5 forecast was sufficiently accurate to use for the particle fall model. Initially, large errors between model and observed values were found, but this was simply due to inconsistencies regarding ordering of $x$-$y$ coordinates. The variables tested statistically are twice daily winds ($u$ and $v$ directions) and geopotential heights for the 850 hPa, 500 hPa, and 200 hPa levels. These heights are representative of the atmospheric boundary layer, the middle-tropospheric steering level, and the approximate height of the subtropical jet stream during winter, exhibiting upper atmospheric flow. To quantify model error over time and space, the root mean square (RMS) errors for horizontal wind components $u$ and $v$, geopotential height $h$ were computed for the available soundings in the outermost domain.

In general, model simulations are not expected to be perfect, but rather to be reasonable. The observational data being used to initialize the model are scarce; all soundings are from more than 380 kilometers from the volcano, and there are no soundings at all for Nicaragua. Because of the absence of soundings, it is impossible to directly validate MM5 in the Cerro Negro vicinity. Furthermore, high-resolution models can resolve small circulation features that are sometimes not apparent in observational data. In the study verifying precipitation in the Mesoscale Alpine Program, Ferretti et al.
(2003) found that, even with an exceptionally high-density observation network, some observation sites missed nearby features. Their RMS errors for the horizontal wind components ranged from 2 to 9 meters per second during their intense observation periods. In addition, White et al. (1999) showed that when using gridded data, large errors could be found at high resolution. However, gridded data can be better analyzed at different vertical levels over a wide area. Consequently, in this study, gridded data from the model forecast were generated and analyzed at various levels and compared with horizontal NCEP reanalysis data.

Another method to verify the accuracy of the model is comparison of the predicted airborne tephra distribution and tephra deposition patterns with contour maps of tephra thickness and satellite images of the tephra plume. The latter methodology was used by Turner and Hurst (2001) in their simulation for Ruapehu, New Zealand. Similar methods were used in this study.

**Sounding data**

Before any statistical analyses could be conducted to check MM5 performance, the soundings that were downloaded for each of the 19 stations had to be formatted for statistical analysis. A PERL script was written that removes header information, extracts the 4 variables (pressure, geopotential height, wind direction, and wind speed) from the 11 variables included in each sounding, calculates $u$- and $v$-wind for each observation, and appends the soundings from November and December into one file for each station. Only three pressure levels are considered for model validation, 850, 500, and 200 hPa, so all observations at other pressure levels were discarded.
Root Mean Square errors

To compare MM5 output directly to observations, simulated soundings were created by horizontally interpolating data from the nearest grid points in the outermost domain (Domain 1), and vertically interpolating from terrain-following sigma levels to pressure levels. Observed sounding data was compared to MM5 predicted values at each of the 19 meteorological stations, at three levels, every 12 hours from 27 November 0000 UTC to 4 December 0000 UTC. The Root Mean Square (RMS) errors were calculated, with the goal of validating MM5 performance.

Two separate sets of RMS errors were calculated for model validation. This was first done station by station. The difference between the model-predicted value and the observation given by a sounding is defined as the model error for a particular variable ($u$, $v$, or $h$), at each time, pressure level, and station. Ideally, there would be an error for each of the 19 stations at each pressure level (850, 500, and 200 hPa) for each variable. This corresponds to 171 unique values. In the station-by-station method, the squared errors of each variable (i.e. $u$-winds at 850 hPa, height at 200 hPa, etc.) were summed over the 9-day model run. This sum was then divided by the number of entries, and the square root of this quotient is the RMS error for the variable. The model performed significantly better at certain stations, but this may be related to the number of available soundings for each station. Some stations had sounding data available every 12 hours over the entire duration of the eruption for a total of 57, while Leticia, Colombia had only 3 soundings in total. One complete sounding was removed from the data set because of anomalous values. Station 3, Bogotá, had an unreasonable geopotential height value at 500 hPa on November 28 at 1200 UTC. The $u$-winds were found to have an anomalously high error.
for this sounding too, suggesting that the instrument used on this date was not working correctly. The RMS errors for each station are summarized in Table 3.2, and Figure 3.8.

<table>
<thead>
<tr>
<th>STATION</th>
<th>Total Obs</th>
<th>U 850</th>
<th>H 850</th>
<th>U 500</th>
<th>H 500</th>
<th>U 200</th>
<th>H 200</th>
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<td>2.1</td>
<td>17</td>
<td>22.7</td>
<td>5.1</td>
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<td>16.8</td>
<td>4.3</td>
<td>15.6</td>
<td>9.1</td>
<td>25</td>
</tr>
<tr>
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<td>–</td>
<td>–</td>
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<td>28.4</td>
<td>2.9</td>
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<td>8.0</td>
<td>2.4</td>
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<td>3.5</td>
<td>16.9</td>
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<td>14.5</td>
<td>1.5</td>
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<td>2.0</td>
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<td>2.8</td>
<td>24.8</td>
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<td>31.9</td>
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<td>5.2</td>
<td>32.0</td>
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<td>2.1</td>
<td>14.0</td>
<td>3.3</td>
<td>34.3</td>
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<tr>
<td>MIAMI</td>
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<td>6.2</td>
<td>3.1</td>
<td>18.1</td>
<td>4.0</td>
<td>29.5</td>
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<td>7.6</td>
<td>3.9</td>
<td>13.0</td>
<td>2.8</td>
<td>16.4</td>
</tr>
<tr>
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<td>19</td>
<td>4.9</td>
<td>13.7</td>
<td>3.0</td>
<td>16.9</td>
<td>8.3</td>
<td>9.3</td>
</tr>
<tr>
<td>SAN JUAN</td>
<td>55</td>
<td>1.5</td>
<td>9.7</td>
<td>1.8</td>
<td>18.2</td>
<td>2.6</td>
<td>30.9</td>
</tr>
<tr>
<td>TAMPA</td>
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<td>2.8</td>
<td>17.6</td>
<td>2.8</td>
<td>21.9</td>
</tr>
<tr>
<td>VERACRUZ</td>
<td>54</td>
<td>2.3</td>
<td>28.1</td>
<td>2.0</td>
<td>37.8</td>
<td>2.7</td>
<td>37.3</td>
</tr>
</tbody>
</table>

Table 3.2. RMS errors for the 19 meteorological stations. “Total Obs” shows how many observations were available for each station for the model simulation. “U 850” represents the RMS error, in meters per second, for $u$-winds at the 850 hPa level. RMS errors for geopotential height $h$ are in meters. There are no observations for Bogotá at the 850 hPa level because the surface pressure at 2,600 meters is lower that 850 hPa.

The method for validating model consistency compared the overall results hour by hour. This required summing the squares of the errors of all stations, for each sounding time. The RMS errors for the 850 and 500 hPa levels at most stations were less than 3 m/s for both wind variables, and 20 meters for height (Figures 3.9, 3.12, and 3.13).

**U-winds**

For east-west ($u$) winds, the model seems to perform better closer to the surface. The RMS error at 850 hPa was the lowest for 13 of the 19 observation times. The 500 hPa $u$-winds had slightly higher errors than the 850 hPa, while the error for the 200 hPa winds were the highest and highly variable.
Figure 3.8. Geographical distribution of station RMS errors for the 850 hPa level of the atmosphere. Values for $u$-wind (red) and $v$-wind (yellow) are in meters per second, while values for geopotential height $h$ (blue) are in meters, at a different scale.

Looking at a plot of $u$-wind error vs. time (Figure 3.9), it is clear that the model performed better, at least in the lower atmosphere, for observations that were recorded at 0000 UTC (Hours 0, 24, 48…), as opposed to 1200 UTC (Hours 12, 36, 60…).

Assuming all things in the model are relatively consistent, the likely explanation for this artifact is that the model is simply more accurate at those stations that have consistent
soundings at 0000 UTC, while the model does not perform as well at certain stations that only reported at 1200 UTC. Differences may also be due to the MM5 not adequately representing changes in the boundary layer due to the diurnal cycle. During daylight hours, there is more convective turbulence, and a higher boundary layer, as heat, momentum, and moisture are mixed up from the surface. At nighttime, the convection diminishes dramatically, there is more laminar flow, the boundary layer is shallower, and mixing is more mechanical (Mapes et al. 2003a).

Figure 3.9. RMS error over time for $u$-winds. The 850 hPa level, lowest in the atmosphere, generally has the smallest error, shown in blue. The 200 hPa level, in yellow, consistently has the highest errors over time.

It is worthwhile, then, to compare the model consistency over time using all the 0000 UTC soundings and all the 1200 UTC soundings separately (Figures 3.10 and 3.11). Here we can see that the $u$-wind errors are fairly consistent through the duration of the model run at the two higher pressure levels, ranging between 1 and 3 meters per second at the 0000 UTC observations, and between 2 and 4 meters per second at the 1200 UTC
Figure 3.10. RMS error over time for $u$-winds, 0000 UTC only.

Figure 3.11. RMS error over time for $u$-winds, 1200 UTC only.
observations. At 200 hPa, however, the 0000 UTC observations show a more pronounced up-and-down variation of error in the model. For the Cerro Negro eruption, though, it is important to remember that the eruption column did not exceed 2,500 meters in altitude, and the 200 hPa height is generally above 12,000 meters.

**V-winds**

For the north-south ($v$) winds, MM5 performed best at the 500 hPa level, with an RMS error mostly between 1 and 3 meters per second (Figure 3.12). The error for 850 hPa was only slightly higher, while the 200 hPa level again had highly variable RMS errors, mostly ranging from 3 to 6 meters per second. The up and down pattern from 0000 UTC to 1200 UTC that is present for the $u$-wind RMS error is not apparent here.

![RMS Error by Model Hour](image)

Figure 3.12. RMS error over time for $v$-winds. Here the lowest errors are found at the 500 hPa level, although all error is relatively consistent over time.
**Geopotential Height**

Geopotential height RMS errors follow a distinct trend: the lowest pressure level, 850 hPa, has the lowest errors and the lowest variation of error, generally between 10 and 20 meters (Figure 3.13). As pressure decreases, both the error and the variation in error increase. Errors at 500 hPa mostly range from 15 to 25 meters, while errors at the 200 hPa level vary from about 25 to 40 meters. Despite two peaks at all three levels at hour 72 and hour 216, there does not seem to be any distinct temporal trend that would suggest that the MM5 is inconsistent over the 9-day period.

Looking at the time series for each of the three variables used in model validation, no dubious time-dependent trends of model error are apparent. No runaway processes are present in the model, meaning that the forecast values do not become more and more unrealistic over time. This is significant considering error trends exhibited in the study by White et al. (1999). RMS error increased in almost every subsequent model time step, for every atmospheric model tested, meaning that model error at $0 < 12 < 24 < 36$ hours. Higher errors after 36 hours were believed to be the result of air masses from the Pacific Ocean moving over the research domain, the western United States. The Pacific is essentially a data “void,” since very little atmospheric data can be collected in the region. For the Cerro Negro study, however, the volcano is downwind of the Caribbean Sea, and there is a good network of weather stations both on islands and along the mainland perimeters of adjacent water bodies. If the prevailing wind in this area of the tropics moved west to east, this study would probably have encountered the same “data void” problems as the study by White et al. (1999).
Figure 3.13. RMS error over time for geopotential height. Error increases with height, but is consistent over time.

Geopotential height RMS error for this study was significantly lower on the whole than those reported by White et al. (1999). A comparison is shown in Table 3.3.

<table>
<thead>
<tr>
<th>Level</th>
<th>Error (m)-White et al. 1999</th>
<th>Error (m)-Cerro Negro</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 / 850</td>
<td>26.3</td>
<td>12.9</td>
</tr>
<tr>
<td>500</td>
<td>30.6</td>
<td>20.6</td>
</tr>
<tr>
<td>300 / 200</td>
<td>42.4</td>
<td>27.0</td>
</tr>
</tbody>
</table>

Table 3.3. Root Mean Square error for the White et al. (1999) study vs. this project. White et al. (1999) tested the 700, 500, and 300 hPa levels, while this study used the 850, 500, and 200 hPa levels.

Summary

In summary, model RMS error increased with height, and error values compared favorably to similar studies. Mapping and creating a time series of model error did not reveal any spatial or temporal trends in the simulation. One factor that likely influenced station RMS error was availability of soundings. Stations with fewer observations
generally had higher error. Model validation has demonstrated that MM5 produced realistic simulation of wind fields for this study.
Cerro Negro

Cerro Negro volcano is situated on the northwest slope of Volcan El Hoyo, located among the central Marrabios Range, which runs parallel to Nicaragua’s Pacific coast. Other Nicaraguan volcanoes located this chain are Masaya, Telica, San Cristobal, and Momotombo, all of which are capable of tephra-producing eruptions. The chain runs northwest to southeast throughout Central America, marking a convergent plate boundary where the Cocos plate is subducted under the Caribbean plate (Figure 4.1).

Figure 4.1. Tectonic setting of Cerro Negro. The Cocos Plate is moving to the NE as it subducts under the Caribbean Plate. Modified from Scripps Institution of Oceanography.
Standing approximately 728 meters in elevation, Cerro Negro is located at 12.5 degrees north latitude, 86.7 degrees west longitude (Figure 4.2). It sits 20 kilometers east-northeast of León, which is Nicaragua’s educational and cultural capital, and at approximately 150,000 residents, its second-largest city.

Figure 4.2. The location of Cerro Negro within the Americas.

1995 Eruption Parameters

A basaltic cinder cone, Cerro Negro has had 23 eruptions since its formation in April 1850. The 1995 eruption took place between November 19 and December 6. Beginning with a series of relatively weak Strombolian eruptions followed by a lava
flow, the event maintained a continuous eruption column between November 29 and
December 2, the period of the most prolific tephra output. The total volume of tephra
erupted was estimated at a dense rock equivalent of $1.3 \times 10^6$ m$^3$ (Hill et al. 1998).

The eruption produced a bent-over plume (Figure 4.3), indicating that the vertical
velocity of the eruption column was the same order of magnitude as the crosswinds it
encountered.

![Figure 4.3. The 1995 bent-over plume of Cerro Negro. The plume is moving towards
the west-southwest. The photo was taken at 9:50 am on December 1, 1995. Courtesy of
Dr. Brittain Hill.](image)

Figure 4.3. The 1995 bent-over plume of Cerro Negro. The plume is moving towards
the west-southwest. The photo was taken at 9:50 am on December 1, 1995. Courtesy of
Dr. Brittain Hill.
The maximum column height was calculated at 2400 meters, and visual estimates support this calculation (Hill et al. 1998). The Volcanic Explosivity Index (VEI) for the 1995 eruption was 2. For comparison, the 1991 eruption of Mt. Pinatubo had a VEI of 6, and the 1992 eruption of Cerro Negro had a VEI of 3 (Connor et al. 2001).

Although the 1995 eruption did not cause any human fatalities, it forced the evacuation of 1,200 people, and totaled $700,000 of damage to agriculture and infrastructure (Connor et al. 2001).

**Tephra Deposit Pattern**

The tephra deposit from the 1995 eruption was sampled immediately after the eruption, and isopachs were calculated using a geographic information system, commonly known as GIS (Hill et al. 1998). Thicknesses of 30 centimeters extend 2 kilometers west of the vent, and the deposit was about 0.5 cm thick as far away as León. The most striking feature of the deposit is that it has two lobes. The major axis runs west-southwest directly from Cerro Negro to León; the minor northern axis is directed west-northwest, towards the town of Telica (Figure 4.4). The deposit is only mapped to the 0.1-centimeter isopach, and the exact location of this isopach is uncertain due to difficulties in sampling such a small thickness, even a short time after accumulation.

**Results**

The trajectories predicted by the high-resolution MM5 wind field correspond very well to deposit measurements. Figure 4.5 shows all trajectories generated for the 5 chosen grain sizes, from 27 November 0000 UTC to 4 December 0000 UTC. The
coordinate system used in all particle trajectory figures is Universal Transverse Mercator (UTM) zone 16 North (16N), North American Datum 1927 (NAD27).

Figure 4.4. Tephra deposit distribution from Cerro Negro. From Hill et al. (1998). Isopachs are in centimeters. Cerro Negro itself is within the 50 cm isopach (upper right).

Only 2 of the 75 particle paths terminate outside of the 0.1-centimeter isopach, and the path locations appear to mimic the thickness contours rather well on the whole. These trajectories can account for deposition along both major axes of the deposit. The trajectories demonstrate that wind speed and direction changed significantly during this 216-hour modeled period. Figure 4.6 highlights the 0.26 mm diameter particles. The more distant paths that reach León represent stronger winds encountered by these smaller particles, nearing 9 meters per second. Some of the shorter paths for small particles terminate in the middle of the mapped deposition region, and represent mean horizontal wind speeds of 4 meters per second. The two trajectories that terminate beyond the outermost isopach do not deviate dramatically from the major axes of deposition.
Figure 4.5. MM5-forecast trajectories with 1995 deposition pattern.

Figure 4.6. MM5-forecast trajectories for 0.26 mm particles.
Wind shifts over time

The major axis of dispersion shifts between the azimuths of 240 and 280 degrees over the course of the 9-day model run, a range of 40 degrees. For the most part, the winds encountered by the majority of erupted particles are just north of easterly (70 degree azimuth, towards 250 degrees), as evidenced by the deposit.

Bilobate Deposit

Figure 4.7 is a vertically exaggerated three-dimensional view of the particle trajectories, exhibiting how the northern particle tracks highlighted in blue can account for the creation of the smaller northern lobe of the 1995 deposit. These tracks were generated from wind fields on November 27th, 28th, and 30th, all at 1200 UTC. According to MM5 winds, there is clearly a diurnal wind shift during the first few days of the eruption. Morning winds (1200 UTC) have a greater tendency to have a southerly component, blowing tephra to the northwest, while evening winds (0000 UTC) tend to have a northerly component, distributing tephra towards the southwest.

Wind shifts with altitude

Figure 4.7 also demonstrates how wind velocities change significantly with altitude. The most dramatic shifts in wind direction in the entire wind grid domain are found just above the surface during most evenings (0000 UTC). It is most pronounced on November 30th, December 1st, and December 2nd. Several trajectories, especially when viewed in two dimensions, appear to take sharp turns back toward the vent near the ground surface. In three-dimensional view, it is clear that winds in the bottom 750...
meters of the atmosphere generally decrease and may reverse direction, such that in the very bottom layer of grid cells, these winds are slightly out of the west instead of easterly. In Figure 4.7, this is evidenced by the trajectories in the foreground just east of León. Cox et al. (1998) illustrated that weak winds are generally associated with higher deviations in direction than are strong winds, so we would expect the most variable winds in the model to come from the atmospheric boundary layer.

![Figure 4.7](image)

**Figure 4.7.** Three-dimensional view of MM5-predicted particle trajectories. Blue trajectories represent contributions to the northern lobe. Isopachs are symbolized as varying gray fill. The cities of León and Telica are shown as orange and pink polygons.

**Wind model comparison – particle trajectories**

Figures 4.8, 4.9, and 4.10 show predicted particle trajectories resulting from a 9-kilometer resolution MM5 run, NCEP reanalysis winds, and uniform winds, respectively. For trajectories generated by the high-resolution MM5 run, refer to Figure 4.4. It appears that the 9-kilometer resolution MM5 output has a slight shift towards the southwest.
compared to the 1-kilometer output. This could be due to a stronger influence of the four-dimensional data assimilation (FDDA) nudging and a decreased role for localized topographic effects.

Figure 4.8. 9-km resolution MM5-forecast trajectories with 1995 deposition pattern.

The particle trajectories produced by the reanalysis winds seem to follow two major axes, which are not aligned with the major axes of the deposit. One axis runs toward the southwest at 235 degrees, and the other runs nearly west at 265 degrees. The major axes of deposition are approximately 250 and 280-degree azimuths. The reanalysis winds, then, predict trajectories that are 15 degrees over-rotated, counterclockwise overall. Seven of the 75 forecast particle tracks fall outside the 0.1-centimeter isopach, still a reasonably accurate prediction. Studying the geometry of all the trajectories, it appears that the reanalysis winds have an overestimated northerly component, which
Figure 4.9. NCEP reanalysis wind trajectories with 1995 deposition pattern.

Figure 4.10. Uniform wind-predicted trajectories with 1995 deposition pattern.
results in tracks that push too far to the south. This appears true in particular on 27 November 0000 UTC, 29 November 0000 UTC, and 1 December 0000 UTC. The winds also produce fewer northerly tracks that could account for the smaller lobe in the tephra deposit.

The uniform wind field matched the large southern lobe of the deposit very well, but completely fails to account for the deposition in the northern lobe.

*Wind shifts over x-y space*

Wind shifts within any one layer of the three-dimensional grid for a particular time period were not severe. The grid domain in only 32 kilometers wide by 40 kilometers across, so sizeable changes in wind velocity should not be expected. In the case of a much larger eruption, a correspondingly larger wind grid would be necessary, and bigger changes in wind velocity would be expected. Figure 4.11 shows wind fields generated by MM5 and NCEP reanalysis data for 28 November 1200 UTC, at 500 meters altitude. The MM5 winds, shown in blue, have noticeable changes in direction, but very large changes in magnitude. In the northern central part of the grid, MM5 winds exceed 20 meters per second, while in the northwest they are as low as 5 meters per second. NCEP winds are essentially uniform over the x-y grid, with winds blowing from the northeast at just under 10 meters per second. The uniform wind assumption is similar to this observation. Standard deviations of MM5 winds for every x-y domain at each altitude level in the particle fall program were calculated. Winds had the highest spatial variability closer to the ground, and temporally speaking, were more variable in the first few days of the simulation, November 27th – November 29th.
Figure 4.11. A wind field comparison. MM5 winds are shown in blue, and NCEP reanalysis winds are in red. Wind barbs are on the “tail,” indicating wind direction. Each small barb represents 5 meters per second, while long barbs are 10 meters per second. MM5 winds show much greater variation in speed and direction.

Wind model comparison - Satellite Imagery

In Meteorology, winds are conventionally described by the direction they are blowing from, i.e., a south to north wind would have an azimuthal direction of 180 degrees. In describing the tephra plume as it moves horizontally, it is more intuitive to describe it in terms of the direction to which it is moving. Because the plume visible in these satellite images is primarily finer-grained tephra than what was selected in the particle fall model, a smaller grain size of 0.01 mm diameter was tested, to simulate
particles that stay in the atmosphere longer. These particles remain in the 2000-meter wind level for the duration of their paths in the wind grid, over 40 km from the vent. These trajectories should more closely resemble the visible plume on satellite imagery, as they stay in higher parts of the atmosphere longer. These higher-level winds have a greater variation in direction over the 9-day period. There is a more significant southerly component to these winds, as shown by 4 particle tracks moving northwest away from the volcano (Figure 4.12).

Figure 4.12. 1-km resolution MM5-forecast trajectories for 0.01 mm particles.

Particles 0.01 mm in diameter were run through the particle fall model using 9-km resolution MM5 winds (Figure 4.13) and NCEP reanalysis winds (Figure 4.14) as well. Trajectories from the three wind models were then compared to satellite imagery.
Figure 4.13. 9-km resolution MM5-forecast trajectories for 0.01 mm particles.

Figure 4.14. NCEP reanalysis wind-predicted trajectories for 0.01 mm particles.
On November 27\textsuperscript{th} at 1315 UTC (Figure 4.15), the tephra plume is barely visible on satellite imagery, and appears very diffuse. The plume is blowing to the west, towards the 265-degree azimuth. The MM5 (1 km) at 27 November 1200 UTC predicts winds blowing slightly to the west-northwest and then turning directly west. The 9-km winds blow the plume directly west. The NCEP reanalysis winds have the plume moving towards the 265-degree azimuth.

On November 27\textsuperscript{th} at 2215 UTC (Figure 4.16), cloud cover over the deposition area makes discerning the tephra plume in visible satellite image extremely difficult. For 28 November 0000 UTC, the 1 km MM5 winds predict the high-level plume moving west-southwest directly over León, while the 9 km winds take the axis just north of the city. The NCEP winds essentially mimic the 9 km MM5 winds at this time.

On November 28\textsuperscript{th} at 1315 UTC (Figure 4.17), the plume is clearly blowing to the north-northwest at an azimuth of about 320 degrees, and is visible to the Honduras border. MM5 (1 km) predicts its most northern track for 28 November at 1200 UTC, at an azimuth of 315 degrees. The 9 km winds have the plume track slightly more to the west at 310 degrees, while the NCEP winds predict the plume axis at an azimuth of 285 degrees.

On November 28\textsuperscript{th} at 2215 UTC (Figure 4.18), the tephra plume appears to be blowing directly west from Cerro Negro, and is visible well over the Pacific Ocean, beyond the western extent of Nicaragua. For 29 November at 0000 UTC, both resolutions of MM5 predict tracks moving to the west at 265 degrees, while NCEP winds take the plume over León, at an azimuth of 245 degrees.
On November 29\textsuperscript{th} at 1315 UTC (Figure 4.19), satellite imagery shows that the plume is blowing towards the west-southwest at an azimuth of about 235 degrees, is visible over Pacific Ocean, and appears to be spreading laterally at a constant rate. The 28 November 1200 UTC MM5 forecast sends the plume to the west at 280 degrees at 1 km resolution, and 270 degrees at 9 km resolution. The NCEP winds move the plume southwest at 240 degrees, close to the satellite observation.
On November 30\textsuperscript{th} at 2215 UTC (Figure 4.20), the plume is blowing towards west-southwest from the vent, towards approximately 250 degrees, and is clearly visible to the Pacific Ocean, at which point it appears to bend towards the west-northwest. For 1 December at 0000 UTC, MM5 predicts the plume to move towards 250 and 245 degrees for 1 and 9 km resolution, respectively. NCEP winds bring the plume farther south, at 235 degrees.
On December 1st at 1315 UTC (Figure 4.21), the plume is not clearly distinct from clouds that are close to vent, but it appears to be moving towards the west-southwest at 250 degrees. The 1 December 1200 UTC MM5-predicted winds take the plume towards azimuths of 255 and 260 degrees at 1 and 9 km resolution, while NCEP winds move the plume toward the 265 degree azimuth.

On December 1st at 1745 UTC (Figure 4.22), the plume oscillates and fans between 265 and 235 degrees, and is visible over the ocean. This observation sits between two MM5 forecast times. For 2 December at 0000 UTC, MM5 high-resolution
winds move towards the west and then bend towards the west-southwest at 250 degrees. The 9 km MM5 winds take the plume towards 260 degrees, while the NCEP winds move the plume towards the 240-degree azimuth.

Figure 4.21. Satellite Imagery for December 1st at 1315 UTC (left). Figure 4.22. Satellite Imagery for December 1st at 1745 UTC (right).

**Summary**

In summary, the 1-kilometer MM5 winds exhibited the highest spatial variation and fit the tephra deposition pattern better than the 3 other wind models. MM5 wind-predicted trajectories from both resolutions were found to be accurate within 10 azimuthal degrees of satellite observations, with the exception of one image. NCEP
reanalysis winds agreed with the deposit somewhat less, forecasting particle tracks slightly too far to the south. Errors between NCEP winds and satellite observations were significantly higher than those of MM5, on the whole. The uniform winds only agree with the southern lobe of the tephra deposit, and match satellite image very well in half of available images.
Chapter Five

Discussion

Why should volcanologists use these models?

This study has shown that a mesoscale atmospheric model such as MM5 can provide a relatively accurate and high-resolution depiction of the winds that a volcanic plume will encounter after an eruption. Although this project focused on a historic eruption, mesoscale models are no less important as forecasting tools, and thus can be used in conjunction with eruption models to predict imminent tephra fall hazards for eruptions anywhere on Earth. MM5 would have heightened importance in regions where wind data are not readily available, such as isolated volcanic islands or impoverished nations, and where mountainous terrain causes localized wind effects for which a nearby sounding could not substitute. For large-scale eruptions, atmospheric models, or gridded reanalysis data, at the very least, should be used as input for tephra plume models. With strong eruption columns that are able to reach the stratosphere, tephra can be advected thousands of kilometers by wind. Over such large areas, winds are more likely to vary in magnitude and direction, rendering the assumption of uniform wind inadequate.

Model calibration

The promising performance of MM5 suggests that the forecast winds can be used as a control in order to better calibrate eruption models. Certain parameters describing an
eruption, as well as assumptions such as atmospheric diffusion, can be adjusted, given the greater certainty MM5 provides in the existence of variable wind patterns over time.

**Should this be used for probabilistic work?**

As useful as atmospheric models can be for volcanic plume forecasting, a 5-domain MM5 run, as used in this study, would be computationally expensive for probabilistic tephra hazard mapping. Each additional domain (along with 2-way nesting) adds a large factor of computing time to the run. The setup as described under methodology required 2780 minutes of processing time, for a model run of 12960 minutes. Each minute of computing time accounted for 4 minutes and 40 seconds of forecast time. If one needed to generate 1000 possible scenarios for a weeklong model run of winds in order to determine the probability of a plume traveling in a certain direction, it could take over 4 years of computing time in 8-processor mode, which was found to be the most stable configuration on the cluster used. With some modifications such as reducing the size of each domain, limiting the number of scenarios required, and most importantly using 3 domains or fewer, the enterprise becomes more practical.

**Should mesoscale models be used to forecast in near-real time?**

MM5 could be extremely useful for short-term forecasting of tephra dispersion for real-time eruptive events. Given adequate input data for initial and boundary conditions, the MM5 is a dependable forecasting tool. Upper-air sounding data taken near an erupting volcano are certainly useful, but the data cannot be extrapolated very far
into the future. A forecast from MM5, on the other hand, could provide a more comprehensive prediction of winds.

**Bilobate tephra deposition**

Ernst et al. (1994) studied the phenomenon of volcanic plume bifurcation resulting in a bilobate tephra deposit. They detail the 1981 eruption of Mt. Pagan in the Mariana Islands as the first well-documented bifurcated plume. Several eruptions within the last 30 years appeared to have had plume bifurcation when investigated on satellite imagery. There are several possible contributing factors leading to plume bifurcation: buoyancy, release of latent heat, geometry and orientation of the plume source, and interaction with a density surface. A plume with two vortices and constant buoyancy should split into two distinct plumes that continue to separate as they move downwind. Evaporation of water along the margins of a volcanic plume should increase the internal circulation in the plume and enhance bifurcation. If a double-vortex plume encounters a strong density interface such as the tropopause, the vortices may be forced to diverge. Ernst et al. (1994) asserted that bifurcation is typical of bent-over and “straight-edged” plumes, but does not develop within strong plumes in weak crosswinds. Bifurcation in plumes can occur at a wide range of plume heights and wind velocities nonetheless. The paper investigates the bilobate 1968 Cerro Negro tephra deposit, but concludes that this was likely caused by diurnal wind shifts rather than plume bifurcation (Ernst et al. 1994).
Wind shifts

Ernst et al. (1994) stated that diffusion-advection models that predict tephra deposition are applicable for eruptions with strong plumes, but not weaker plumes than can bifurcate. While tracking the central axis of dispersion would be meaningless for a plume with two distinct axes, satellite imagery from the 1995 Cerro Negro eruption essentially dismisses this possibility. Imagery indicates that the weak 1995 Cerro Negro plume did diffuse significantly, but did not bifurcate. Shifts in wind direction therefore account for the deposition pattern.

Chronology of deposition

Small lobe

The output MM5 winds suggest that the smaller, northern lobe of the 1995 Cerro Negro tephra deposit was created primarily before and at the beginning of the major phase of the eruption, on November 27th and 28th. Satellite imagery confirms that winds had a southerly component during this time, as evidenced by the tephra plume extending off to the west-northwest (Figure 4.17). High-level (fine) tephra continued to move to the northwest, while the larger particles settled and began to move more towards the west.

Large lobe

The larger southern lobe of the deposit was then created after November 28th through the remainder of the tephra-generating phase of the eruption. In several satellite images, tephra is seen reaching all the way to the Pacific Ocean. These particles are finer
than most of the particles modeled in this project, and did not result in a permanent deposit.

Model Limitations

Resolution

One of the drawbacks of a complex atmospheric model is the computing time required to make a reasonable, high resolution forecast. While the nested grid setup maximizes the efficiency of the model, spatial and temporal resolution problems still persist. The innermost model domain has a grid size of one kilometer, which is not small enough to accurately describe fine topographic features such as Cerro Negro itself. Although the volcano is identifiable in the MM5’s digital elevation model, the entire height of the structure is not accurately depicted. Because the volcano is only about 1 kilometer in diameter, its topography is effectively smoothed over in this elevation model. A 30-meter DEM would probably be sufficient to represent the volcano, but this would certainly increase the overall computing time significantly.

Particle aggregation

A major drawback in the particle fall model, and indeed many volcanic plume models, is that it neglects the effects of particle aggregation. Although there was no significant evidence of particle aggregation during the 1995 eruption of Cerro Negro (Connor, personal communication), this phenomenon is believed to take place in many tephra-producing eruptions, and can occur due to electric charge attraction, precipitation, or condensation (Brasseur et al. 1999). When particle aggregation does occur, clumps of
fine tephra are removed from the atmosphere more quickly than they otherwise would be, because the cluster essentially has a larger diameter, and thus a higher fall velocity.

Veitch and Woods (2001) detailed a number of examples of eruptions where particle aggregation significantly changes the pattern of tephra deposit. Fine-mode particles have been found to have constant diameter versus distance from the vent, suggesting that their distribution was dictated by the size of the aggregate with which the joined. Liquid water in the atmosphere is thought to be the primary binding agent for these aggregates (Veitch and Woods 2001). Carey and Sigurdsson (1982) postulated that the double maximum created from the 1980 Mt. St. Helens deposit could be explained by an aggregation of particles smaller than 63 µm in diameter clustering and dropping out of the atmosphere 325 km east-northeast of the volcano.

**Interaction with eruption column**

Although the MM5 digests many types of land surface information, including topography, vegetation, soil moisture, sea surface temperature, and others, it does not take into account the effects of the actual volcanic eruption. Heat transfer, convection, vertical momentum, and density differences are essentially unknown quantities as far as MM5 is concerned. For this reason, there is no attempt in this project to re-create the eruption column, instead, the tephra particles are “dropped” from the top of the column. There is no feedback from the eruption into the atmospheric model.
**Turbulence**

While MM5 produces higher-resolution winds than most wind fields used in volcanology, it cannot recreate atmospheric phenomena smaller than a few kilometers in width, exhibited in Figure 5.1 (Mann 2002). For this reason, small-scale eddies and turbulence within the plume cannot be simulated. Because the particle fall model only tracks particles along the major axis of dispersion, however, the diffusive effects of turbulence are not of primary concern. Most plume models that attempt to consider turbulence use a parameterization such as a coefficient of diffusion.

Figure 5.1. How features are represented in a mesoscale model. Only features of sufficient size can be represented.
**Fall velocity**

The particle fall program, as stated before, makes many simplifying assumptions. The fall velocity of each particle is calculated solely as a function of its size, because all particles are assumed to have the same shape and density. Changes in air density and viscosity are not considered. For this particular eruption, variability of the air column is not as crucial, because the particles are only falling through the bottom 2400 meters of the atmosphere. For more powerful eruptions, especially those whose columns reach the tropopause, changes in the air density become much more important to consider.

**Particles fall to zero**

To simplify the particle fall program, the tephra particles in the model are all assumed to fall to sea level (0 meters altitude). True elevations in the region of the deposit range from 50 meters towards the Pacific up to the base of the volcano, at around 450 meters altitude.

**Sources of Error**

There are several sources of error that can complicate a model run. Certain atmospheric features will be lost if grid resolution is not high enough. Interpolation from a low grid resolution to a high one may misrepresent data, just as using a low resolution grid for fine features can result in loss of data. Using the wrong coordinate systems may distort features in the model.

Physics schemes that may be applicable to some regions may not be appropriate for all. Many processes that need to be accounted for in mesoscale models are too
complex or are too small to be represented numerically. These phenomena are therefore parameterized, given best estimates based on existing knowledge. These parameterizations can create grave consequences if mis-specified. Forecasts can end up being changed drastically as a result.

Initial and boundary conditions of the model can also play a major role in the results. Models generally require a period in which atmospheric motions can evolve within it. This requires observation or forecast data, which can potentially propagate errors into subsequent model predictions.

Boundary conditions can also impact forecasts. The domain edge should be placed a reasonable distance from features of interest. MM5 requires that nested domains have a buffer from the edge of its parent domain.

Despite these possible sources of error, model validation showed that MM5 produced sufficiently realistic forecasts. The results of the particle fall model confirm that MM5 winds were highly accurate for the eruption.
Chapter Six

Conclusions and Recommendations for Future Work

Major Findings

The Pennsylvania State University-National Center for Atmospheric Research (NCAR) fifth-generation Mesoscale Model (MM5) was applied to the 1995 eruption of Cerro Negro, Nicaragua. The major axis of dispersion for this eruption was mapped as a series of particle trajectories for the period of highest tephra output, and showed very good agreement with the observed tephra deposit. The trajectories for particles down to 0.26 mm in diameter fell almost entirely within the 0.1 cm isopach for the eruption. It was also found that the axis of dispersion shifted dramatically in space and time over the course of the eruption. Ninety-seven percent of the axis tracks fall within the observed pattern of tephra deposition for the 1995 eruption. This is very promising, considering that MM5 had no input station observations within 380 km of the volcano, and did not utilize any data extrapolated from the tephra deposit.

Although the eruption parameters and atmospheric conditions seemed to be favorable for plume bifurcation (Ernst et al. 1994), MM5 winds and satellite imagery show that the bilobate tephra deposit from the 1995 eruption can be accounted for completely by variation of winds. In addition, evidence shows that the northern lobe of the tephra deposit was produced, in large part, at the outset of the continuous phase of the eruption, on the 27th and 28th of November.
Statistical analyses revealed considerable spatial and temporal differences between MM5-generated wind fields and NCEP reanalysis winds as well as uniform winds. The NCEP winds appear to move tephra farther to the south than MM5 winds, while the uniform winds match satellite observations for about half of the time.

The significant shifts in wind direction between each 12-hour simulation, verified by satellite imagery, show that the assumption of uniform winds, even for a relatively weak eruption such as this, is faulty. Model winds vary over x-y space noticeably, but vary by much greater differences for small changes in altitude.

The 9 km resolution MM5 wind field was found to be adequate resolution for producing trajectories that match the tephra deposit pattern. Reanalysis winds applied to the small 40 by 32 kilometer domain were reasonable, but forecast the plume too far to the south for most time periods. The uniform winds were adequate in producing the larger, southern lobe of the deposit, but could not account for the northern lobe. The MM5 reproduced an accurate 4-dimensional wind field for the 1995 Cerro Negro eruption, confirmed by tephra deposition patterns, satellite imagery, and meteorological station soundings.

Future Research - Improving the particle fall model

Release Heights

While the MM5 is a very complex atmospheric model, the particle fall program used to track tephra for this study was simplistic. There are a number of logical updates to the model that would make it more robust and realistic.
One relatively simple addition would be to incorporate varying release heights for the tephra particles. This would ideally be based on visual evidence or satellite imagery of the eruption column and volcanic plume, as they evolved from day to day. Particles would likely need to be released from multiple heights for each release time, as a single point source is not a realistic approximation of any eruption. Release heights from the eruption column could be modeled as a probability density function, such as the procedure used in Suzuki et al. (1983). Because the maximum column height of the 1995 Cerro Negro eruption is not believed to have exceeded 2400 meters in altitude, the variation in release heights would remain entirely below this “ceiling” value. The resulting trajectories, which would therefore start from heights less than or equal to those used in the study, would thus exhibit more proximal patterns.

**Effects on Column Rise**

Another modification to the particle fall model would allow it to take into account the effects of wind during buoyant column rise. This is more applicable to bent-over plumes, where the vertical velocity of the eruption column is close to the magnitude of the crosswind. Most plinian eruptions, on the other hand, are sufficiently explosive that crosswind has little effect on the column until it approaches its maximum height. Strong plumes in weak winds generally exhibit the same behavior (Ernst et al. 1994).

**Diffusion term**

The current particle fall model simply tracks particles along the major axis of dispersion by advancing them through the wind field. A logical progression of the model
would be to add a diffusion term, so that spatial distributions of tephra on the ground can be forecast.

**Topography**

Unlike the MM5 model, which uses topography in creating a wind field for a particular region, the particle fall model does not have a built-in digital elevation model. Particles are assumed to fall to zero elevation, which is a simple approximation of the true surface. In the region where the majority of tephra fell in the 1995 eruption, slopes are gradual, dipping to the west-southwest, with elevations mostly between 50 and 300 meters. Another logical advance, then, would be to assimilate topography into the fall model, so that particle’s motion would cease when it reached the elevation of surface at a particular \( x, y \) location.

**Wind / friction effects**

The current version of the fall model assumes a uniform shape for each particle, which only affects the downward motion through the air column. The model already accounts for different particle diameters, which is the primary factor, in this setup, for determining the final distance from the vent. The particles are then simply assumed to be advected horizontally at the same velocity as the wind. The fall model could be adjusted by taking into account the complex effects of friction from winds. This friction affects the horizontal motion of particles, and varies depending on the shape of each particle.
**Additional future research**

*Apply to other eruptions*

To test their viability more thoroughly, the MM5 and particle fall models should be run to simulate tephra plumes of other well-studied eruptions. Two of these that have tephra deposits that have already been mapped extensively are the 1992 Cerro Negro eruption, and the 1996 eruption of Mount Ruapehu in New Zealand. The model has given accurate results for a relatively small-scale (VEI = 2) eruption, so applying it to larger and more far-reaching eruptions would do more to prove its value to volcanologists.

*Calibrate extent of diffusion*

One benefit of having model trajectories that vary in space and time is that they can be used to calibrate the extent of diffusion more realistically. Values for the diffusion term calculated from uniform wind certainly would lead to overestimates, because tephra would have to travel farther laterally away from the central axis of dispersion. With axes that move over time, the amount of diffusion required to produce the observed deposition pattern would be smaller and almost certainly more accurate. In other words, variable winds can deposit tephra across a wide area off the major axis of deposition, whereas a uniform wind could only accomplish this if tephra was spread far off axis by diffusion, due to high turbulence.
**TEPHRA Model incorporation**

Continuing research shall involve using MM5 output as input for the TEPHRA dispersion model. Currently, TEPHRA requires a single stratified wind profile as input. Thus it assumes that winds are uniform over each $x$-$y$ domain for each altitude. Downwind changes in direction and speed cannot be accounted for using this method, so the model is inherently limited. Coupling the MM5 to the TEPHRA model would likely yield more robust results, especially as the wind assumptions break down over great distances.
References


Mann, G., Mesoscale models - issues of resolution, presentation for *COMET Mesoscale Analysis and Prediction (COMAP)* training course, 2002.


Bibliography


Appendix A: MM5 Specifications

TERRAIN

Changes to the original terrain.deck file are described here; the default settings were used for anything that is not mentioned.

The largest grid has a resolution of 81 km on a side, while the next smallest grid had a resolution of 27 kilometers (the “parent” to “child” resolution ratio must be 3:1 for two-way nesting), starting at the point (24, 21) on the larger nest. Two-way nesting means that the parent and child domains are able to interact in both directions, so values from one are passed to the other and vice versa. The process of defining domains was continued until all 5 were set up properly. The TERRAIN output is used in all subsequent model programs, all using the domains described here, and some also requiring the terrestrial information.

The TERRAIN setup takes place by editing the terrain.deck file in the TERRAIN directory. The number of domains was changed from 2 to 5, and Domain 1 was re-centered to 12.0 North, 85.0 West. The domain resolutions were changed to 81, 27, 9, 3, and 1 kilometer.

- IIMX and JJMX were each increased from 100 to 150. This pertains to the maximum size, in cells, of any domain in the setup.
- ITRH and JTRH were both increased from 500 to 1000. These higher values are necessary because of higher resolution input data than the default.
• PHIC was changed from 36.0 N to 12.0 N, to center Domain 1 on Central America.

• IPROJ was changed from ‘LAMCON’ to ‘MERCAT’, because Mercator is a more appropriate projection than Lambert Conformal at 12.0 degrees North latitude.

• MAXNES increased from 2 to 5, as a 5-domain setup was necessary.

• NESTIX was changed from 35, 49, 136, 181, 211 to 61, 49, 40, 49, 49 and NESTJX was changed from 41, 52, 181, 196, 211 to 61, 52, 40, 49, 58 to better fit the study area.

• DIS was changed from 90, 30, 9, 3.0, 1.0 to 81, 27, 9, 3, 1, in order to maintain the 3 to 1 ratio from “parent” to “child” domain.

• NESTI was moved from 1, 10, 28, 35, 45 to 1, 24, 17, 14, 17 and NESTJ was moved from 1, 17, 25, 65, 55 to 1, 21, 17, 12, 16 to better fit the volcano location. These values describe the position of a domain within its parent’s grid.

When the following command is executed: “./terrain.deck”, the nested grids are set up, and all the surface data is compiled and interpolated to the grids. A successful run will create a log file, terrain.print.out, and files named TERRAIN_DOMAINx, where x represents the numeric order of the domain, 1 through 5. These files are used in all the subsequent steps of the MM5 modeling program.
REGRID

The pregrid setup required the following changes to the original pregrid.csh file, found in the /REGRID/pregrid/ directory:

- The “Data” directory was set to /MM5V3/REGRID/.
- The data source format was changed from ON84 to GRIB (gridded binary).
- The “InFiles” were changed from /NNRP_GRIB* to /nnrp/pgb* and /nnrp/SFCNNRP*, as these were the locations of the downloaded input data.
- The start date was moved from 3/13/1993 0000 UTC to 11/25/95 0000 UTC, and the end date was changed from 3/14/1993 0000 UTC to 12/04/95 0000 UTC, to bound the major phase of the Cerro Negro eruption.

The pregrid step culminates in issuing the command “pregrid.csh >& log”, which generates a log file and a plethora of gridded data files. Next, in the sub-step regridder, the data is converted to two-dimensional grids at each pressure level. This is virtually automatic, unless the user intends to add additional pressure levels into the three-dimensional grid. The REGRID output is passed on to the objective analysis step and to INTERPF.

The regridder step requires editing the namelist.input in the /PREGRID/regridder/ directory. Changes to the original template file are as follows:

- The beginning and end dates were changed to match pregrid.csh.
• The “root” files were pathed for GRIB format as is directed in the MM5 online tutorial: `../pregrid/FILE' '../pregrid/SST_FILE' '../pregrid/SNOW_FILE' '../pregrid/SOIL_FILE'.

• “constants_full_name” was changed to '../pregrid/SST_FILE:1995-11-25_00'.

Issuing the command “regridder >& log” creates a log file and the file REGRID_DOMAIN1, which is accessed in LITTLE_R and INTERPF.

LITTLE_R

The LITTLE_R namelist.input file was edited as follows:

• The beginning and end dates were changed to match previous steps.

• “obs_filename” was pathed to /FETCH/adp_upa/ and pointed to a list of files named in a sequence from “obs:1995-11-25_00” to “obs:1995-12-04_00”, with the observation time increasing at a 6-hour interval. “obs_filename” also pointed to the sequence of files from “upper-air_obs_r:1995-11-25_00” to “upper-air_obs_r:1995-12-04_00”, also increasing at a 6-hour interval.

• “sfc_obs_filename” was pathed to /FETCH/adp_sfc/ and pointed to a sequence of files from “surface_obs_r:1995-11-25_00” to “surface_obs_r:1995-12-04_00”, which increased at a 1-hour interval.

• “f4d” was switched from TRUE to FALSE, to turn off the creation of surface FDDA files.
After these changes were made, the step is completed by executing “little_r >& log”. In addition to the log file, the file LITTLE_R_DOMAIN1 is produced. This is used in the next step, INTERPF.

INTERPF

Changes to the namelist.input file for INTERPF involved simply changing the beginning and end dates to match the other steps of the model. The step is run by typing “interpf >& log”, which generates a log file, and three files that will be used in the MM5 step: BDYOUT_DOMAIN1, LOWBDY_DOMAIN1, and MMINPUT_DOMAIN1.

MM5

After creating the mm5.deck in this folder by typing “make mm5.deck”, the file is ready to edit. Below are the steps taken to prepare the mm5.deck for the simulation. The identical changes were made to the “mmlif” file, to ensure agreement between the two files. Model runs were done within the /MM5V3/MM5MPP/ directory, rather than the /MM5V3/MM5/ directory.

- TIMAX was increased from 720 to 12960 minutes, indicating a 9-day model run.
- TISTEP was reduced from 240 to 180, for better model stability and temporal resolution.
- SAVFRQ was changed from 360 to 720 minutes, to match the 12-hour output interval.
- CDATEST, the date of the starting file, was moved from 1993-03-13_00:00:00 to 1995-11-25_00:00:00.
• LEVIDN was changed from 0,1,2,1,… to 0,1,2,3,4,… to represent all 5 model domains.

• NUMNC was changed from 1,1,2,1,… to 1,1,2,3,4,… to represent the parent of each domain.

• NESTIX, NESTJX, NESTI, NESTJ were moved according to the domain locations specified in terrain.deck.

• XSTNES was changed from 0,0,900,0,… to 0,0,0,0 so that all domains are initiated at the outset of the model run.

• XENNES was increased from 1440,1440,1440,720,… to 12960,12960,12960,12960,… so that all domains terminate when the model run is complete.

• IOVERW was changed from 1,2,0,0,… to 1,2,2,2,… so that the highest-resolution topography is used for the nested domains, instead of being interpolated from the parent domain.

• FDAEND was increased from 780,0,0,0,… to 12960,0,0,0,… so that gridded 4-dimensional data assimilation will be applied for the entire model run.

• I4D was changed from 0,0,0,0,… to 1,0,0,0,… to turn on the gridded 4-dimensional data assimilation.

• DIFTIM for surface analysis nudging was increased from 180,180,0,0,… to 720,720,0,0,… to match the interval for three-dimensional analysis nudging.

Because MM5 requires MPP for any runs with more than three domains, a separate MM5MPP directory was created to house all the files for this mode. To run MM5 in either mode, the mm5.deck and mmlif files need to be edited, but multi-
processor mode requires the specifications of a third file, configure.user. The following steps detail how the configure.user file was edited specifically for this project.

- FDDAGD was switched from 0 to 1, indicating that gridded 4-dimensional data assimilation will take place.
- MAXNES was increased from 2 to 5, because there are 5 domains in this setup.
- MIX and MJX were increased from 49 and 52 to 61 and 61, respectively, matching the maximum grid cells of any domain.
- IMPHYS was changed from 4,4,1,1,… to 4,4,4,4,… because the simple ice moisture scheme is needed for all 5 domains in the model.
- ICUPA was changed from 3,3,1,1,… to 3,3,3,3,… so that the Grell Cumulus scheme is utilized in all 5 domains.
- IBLTYP was switched from 5,5,0,0,… to 2,2,2,2,… meaning that the planetary boundary layer changed from MRF to High-resolution Blackadar.
- PROCMIN_NS was increased from 1 to 4.
- PROCMIN_EW was increased from 1 to 2, giving 2 x 4 = 8 total processors solving the MM5 forecast in parallel.

After all the changes had been made, the MPP step was enacted by typing “make mpp” and then submitting the executable to a queue on the mimir server. The command “qsub mpp-parallel8.sub” calls up a file that tells the server to run the model on 8 nodes. Many model runs needed to be performed in order to determine the correct settings and produce reasonable results. After each model run, output files were archived, or else they would get overwritten during the subsequent run. In addition to “make mpp”, which
needed to be submitted before each run, two additional commands had to be executed before the next run could commence: “make mpclean” and “make uninstall”, both of which essentially clean up old files from the previous run.

**INTERPB**

The steps listed below were show changes to the namelist.input file in INTERPB:

- The input file to interpolate was re-pathed from /MM5/Run/ to /MM5MPP/Run/.
- MMOUT_DOMAIN1 was interpolated for the purposes of model validation, while MMOUT_DOMAIN5 was interpolated to produce the wind grid for the particle fall model.
- Start and end dates were changes to reflect the dates of the model run.
- The output interval was increased from 21600 to 43200 seconds (12 hours), to match the interval of available sounding data.