On the Nature of Severe Orographic Thunderstorms near the Andes in Subtropical South America

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Abstract

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Atmospheric Sciences

Identifying common features and differences between the mechanisms producing extreme convection near major mountain ranges of the world is an essential step toward a general understanding of orographic precipitation on a global scale. The overarching objective of this dissertation is to understand and examine orographic convective processes in general, while specifically focusing on systems in the lee of the Andes Mountains. Diagnosing the key ingredients necessary for generating high impact weather near extreme topography is crucial to our understanding of orographic precipitating systems.

An investigation of the most intense storms in 11 yrs of TRMM Precipitation Radar (PR) data has shown a tendency for squall lines to initiate and develop east of the Andes with a mesoscale organization similar to storms in the U.S. Great Plains (Rasmussen and Houze 2011). In subtropical South America, however, the topographical influence on the convective initiation and maintenance of the mesoscale convective systems (MCSs) is unique. The Andes and other mountainous terrain of Argentina focus deep convective initiation in the foothills of western Argentina (Romatschke and Houze 2010; Rasmussen and Houze 2011). Subsequent to initiation, the convection often evolves into propagating MCSs similar to those seen over the U.S. Great Plains.
sometimes producing damaging tornadoes, hail and floods across a wide agricultural region (Rasmussen and Houze 2011; Rasmussen et al. 2014b).

The TRMM satellite was designed to determine the spatial and temporal variation of tropical and subtropical rainfall amounts and storm structures around the globe with the goal of understanding the factors controlling the precipitation. However, the TRMM PR algorithm significantly underestimates surface rainfall in deep convection over land (Nesbitt et al. 2004; Iguchi et al. 2009; Kozu et al. 2009). When the algorithm rates are compared to a range of conventional Z-R relations, the rain bias tends to be worse in storms with significant mixed phase hydrometeors, such as graupel and hail, that are similarly affected by assumptions in the TRMM PR algorithm (Rasmussen et al. 2013). A quantitative approach that mitigates this bias using TRMM PR data was developed and employed to investigate the role of the most extreme precipitating systems on the hydrological cycle in South America (Rasmussen et al. 2014c). Results from this study indicate that ~95% of the accumulated warm season precipitation in La Plata Basin in subtropical South America is contributed by echoes structurally related to MCSs and their life cycle. From a hydrologic and climatological viewpoint, this empirical knowledge is critical, as the type of runoff and flooding that may occur depends on the specific character of the convective storm and precipitation reaching the surface, and has broad implications for the hydrological cycle in this region.

Numerical simulations conducted with the NCAR Weather Research and Forecasting (WRF) model extends the observational analysis and provides an objective dynamical evaluation of storm initiation, development mechanisms, dynamics (Rasmussen and Houze 2014), and microphysics (Rasmussen et al. 2014d). The capping inversion in the lee of the Andes (Rasmussen and Houze 2011) is important in preventing premature triggering in the simulations. The impingement of the South American
Low Level Jet (SALLJ) on foothills and low mountains to the east of the main Andes range triggers extremely deep and intense convection. The simulated mesoscale systems closely resemble the storm structures seen by the TRMM satellite as well as the overall shape and character of the storms shown in GOES satellite data (Rasmussen and Houze 2014; Rasmussen et al. 2014d). Sensitivity studies removing and/or reducing various topographic features have shown the profound influence of the terrain on the initiation and upscale growth of the subsequent MCSs. The extreme vertical extent of the Andes tends to keep the South American storms tied to the topography during upscale organization and development longer than similar storms east of the Rocky Mountains in the U.S. and is related to enhanced lee cyclogenesis, flow deformation, and wake effects (Rasmussen and Houze 2014). From this research, an original conceptual model for convective storm environments leading to convective initiation was developed for subtropical South America.
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GLOSSARY

AMSR-E: Advanced Microwave Scanning Radiometer for EOS

ARM: Atmospheric Radiation Measurement

BRN: Bulk Richardson number

BSANDES: Big Southern Andes—20% increase in CTRL terrain south of 26.5°S

BSANDES TM: Big Southern Andes with the Sierras de Córdoba mountains removed

BSR: Broad stratiform region

C: Classifiability score

CAPE: Convective available potential energy

CIN: Convective inhibition

CTRL: Control topography—original topography, no modifications

CTRL TM: Control topography with Sierras de Córdobas mountains removed

DBZ: Unit of measurement for radar reflectivity; decibels relative to radar reflectivity (Z)

DCC: Deep convective core
DJF: December, January, and February

DOE: Department of Energy

DSD: Drop size distribution

DWCC: Deep and wide convective core

EHI: Energy helicity index

EOS: Earth Observing System

EPIC: Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System

GCE: Goddard Cumulus Ensemble

GFS: Global Forecast System

GOES: Geostationary Operational Environmental Satellite

GPM: Global Precipitation Mission

HANDES: Half Andes topography—50% reduction in CTRL terrain

HANDES TM: Half Andes topography with the Sierras de Córdoba mountains removed

HPA: Unit of measurement for atmospheric pressure; hectopascal

IR: Infrared
KI: K index

LI: Lifted index

LIS: Lightning Imaging Sensor

MCC: Mesoscale convective complex

MCS: Mesoscale convective system

MCTEX: Maritime Continent Thunderstorm Experiment

MST: Mean solar time

NADIR: Downward-facing viewing geometry of an orbiting satellite

NCAR: National Center for Atmospheric Research

NCEP: National Centers for Environmental Prediction

OLR: Outgoing longwave radiation

OTD: Optical Transient Detector

PR: Precipitation radar

SALLJ: South American low-level jet

SC: Sierras de Córdoba mountains

SON: September, October, and November
TMI: TRMM Microwave Imager

TRMM: Tropical Rainfall Measurement Mission

TRMM-LBA: Tropical Rainfall Measuring Mission–Large-scale Biosphere-Atmosphere

UTC: Coordinated Universal Time

WCC: Wide convective core

WDM6: WRF double-moment 6-class microphysics scheme

WRF: Weather Research and Forecasting model

WRF-ARW: NCAR Advanced Weather Research and Forecasting model

WSM6: WRF single-moment 6-class microphysics scheme

WSR-88D: Weather Surveillance Radar 1988 Doppler; Operational National Weather Service radars

YSU: Yonsei University

Z-R: Relationship between radar reflectivity ($Z$) and rain rate ($R$)
ACKNOWLEDGMENTS

I would like express my deep appreciation and gratitude to my advisor, Robert A. Houze, Jr., for the patient guidance and mentorship he provided to me during my graduate studies at the University of Washington.

I would also like to thank my committee members, Drs. Robert Wood, Clifford Mass, Dale Durran, and Edward Zipser for their constructive feedback on my research, friendly guidance, and thought-provoking suggestions over the years. I would also like to thank the numerous research collaborators who have contributed to the research in this dissertation, including Dr. Manuel Zuluaga, Dr. Socorro Medina, Stella Lina Choi, Aaron Hill, Megan Chaplin, and Alexandria Gingrey. Graphics and computer support from Beth Tully and Stacy Brodzik provided the necessary tools to publish my research. I would also like to thank my colleagues and friends in the Department of Atmospheric Sciences at the University of Washington. Although too numerous to name specifically here, I would like to express my general appreciation for the vibrant community in the department over the years.

Without the love and support from my parents, Roy and Audrey, and sister, Lisa, I would not have come this far. Thank you for your unconditional love and support of my academic career and life goals. You have all been an inspiration to me and I continue to be amazed by your dedication and support for our family.

Finally, I would like to thank my husband Mike for his unconditional love and support over the last 12 years. It is not easy being the spouse of a graduate student and I am forever grateful for your patience, flexibility, and enthusiasm for my success as a career scientist.
DEDICATION

to my family, Roy, Audrey, and Lisa, and my husband Mike for their abundant support and love.

Chapter 1

INTRODUCTION

1.1 Scientific motivation

Thunderstorms, mesoscale convective systems (MCSs), and mid-latitude frontal systems are vital to both hydrologic and energy cycles on Earth. As the global climate changes, patterns of these critical weather systems are likely to shift. In order to eventually include all types of storms in numerical forecasts, general circulation models, and climate projections, the physical mechanisms and specific details involving convection initiation, propagation, lifecycle, topographical effects, environmental influences, and hydrometeorological impacts from such storms need to be more fully understood. Around the globe, topography on every major continent influences the distribution of precipitation, cloud occurrence and type, climate regimes, convective storms, floods, high-impact weather, variations in hydrometeorology, and much more.

Before the launch of satellites with spaceborne radars, it was difficult to study the physics and characteristics of storms in remote regions; however, radar observations from the Tropical Rainfall Measuring Mission (TRMM) satellite have revolutionized our ability to study storms in these regions. In the present climate, extreme convection tends to concentrate in the vicinity of mountain ranges, and the Andes in subtropical South America help spawn some of the most intense deep convection in the world (Zipser et al. 2006). Other hot spots of extreme deep convection are located over the plains east of the Rocky Mountains in the United States, near the western Himalayas in South Asia, and the Sahel regions west of the Ethiopian highlands in Africa. These hot spots typically occurring near mountain ranges indicates the orogenic\(^1\) nature of

\(^1\)Originally defined in Tripoli and Cotton (1989) as genesis under orographic influences.
storms in these locations. Over the United States Great Plains, a moist low-level flow originating from the Gulf of Mexico is typically capped by warm and dry air flowing off the Mexican Plateau and the Rocky Mountains. This capping inversion inhibits the release of instability over large areas, while enhancing the intensity of convective outbreaks in narrowly focused regions (Carlson et al. 1983).

Velasco and Fritsch (1987), Zipser et al. (2006), and others have pointed out that a topographically-guided low-level jet bringing moist air poleward affects the occurrence of intense convection east of the Andes in South America, in a manner similar to processes east of the Rocky Mountains in the U.S. Severe convection in the U.S. and Andes regions, however, is released differently. Low-level moisture from the Amazon is capped by lee subsidence, as a result of the mechanical displacement of air flowing over the Andes (Rasmussen and Houze 2011). Convective initiation typically occurs as the moist northerly low-level flow encounters small foothills and a secondary mountain range east of the main Andes barrier (Romatschke and Houze 2010; Rasmussen and Houze 2011), whereas other features such as frontal or dry line convergence, gust front propagation from prior convection, or mountain-plains solenoidal circulations are primary triggering mechanisms in the United States. On average, South American cloud shields associated with the most intense MCSs are 60% larger than those over the United States (Velasco and Fritsch 1987), the convection is deeper (Zipser et al. 2006), and the disturbances have larger and longer-lived precipitation areas than those over the United States or Africa (Durkee et al. 2009). In order to more fully understand and predict terrain induced and affected deep convection, it is critical that we understand these different manifestations and evolutions of the convection process.

Cecil (2009, 2011) used TRMM Microwave Imager (TMI) data to objectively identify hailstorms and found southeastern South America to be a likely region of large hail production. More recently, Cecil and Blankenship (2012) found that northern Argentina and Paraguay have the highest frequency of significant hail (≥ 1 inch
diameter) using AMSR-E data globally. Extreme convective storms over subtropical South America are also associated with significant crop damage and a large number of fatalities, flooding events, and tornadoes (Altinger de Schwarzkopf and Russo 1982; Nascimento and Marcelino 2005; Rasmussen and Houze 2011). Thus, subtropical South America is both an important and understudied natural laboratory for investigating the climatological factors controlling severe weather and MCSs associated with a major mountain range.

Identifying common features and differences among the mechanisms producing extreme convection near major mountain ranges of the world is an essential step toward a general understanding of orographic precipitation on a global scale. The objective of this dissertation is to contribute to this needed understanding by examining deep convective processes affect by the presence of the Andes. Diagnosing the key ingredients necessary for generating high impact weather near extreme topography is crucial to our understanding of orographic precipitating systems. The dissertation research presented herein will use data from the Tropical Rainfall Measuring Mission (TRMM) satellite, global reanalysis data, and high-resolution regional modeling to investigate the structure, characteristics, and factors controlling intense convection occurring east of the Andes. The results of this dissertation contribute not only to an improved overall perception and understanding of the processes leading to high-impact weather affected by mountain ranges but also on the societal impacts of such weather events with the potential to save life and property.

1.2 Dissertation outline

A comprehensive investigation of the severe thunderstorms that occur near the Andes in South America has produced multiple peer-reviewed publications, which I have lead authored and which are included or previewed in this dissertation. Chapters 2-4 are published papers and Chapters 5-7 will be submitted in fall 2014. Each study is presented in complete form, including an introduction, results, and conclusion sections
for each paper.

Chapter 2 (Rasmussen and Houze 2011) was published in *Monthly Weather Review* and presents the hypothesis that lee subsidence downstream of the Andes provides a capping inversion preventing low-level unstable air from breaking the cap until it reaches the Sierras de Córdoba Mountains in subtropical South America. This chapter also confirmed that MCSs in South America have similar mesoscale organization to MCSs in the U.S. as had been suggested for over 30 years prior to this study.

Chapter 3 (Rasmussen et al. 2014b) was accepted for publication in *Geophysical Research Letters* in October 2014. This study represents the first peer-reviewed article to discuss the seasonal and diurnal characteristics of lightning in subtropical South America. Additionally, the first published spatial maps of severe weather impacts, including floods, hail and tornadoes, are presented in this paper.

Chapter 4 (Rasmussen et al. 2013) was published in *Geophysical Research Letters* and investigated the precipitation bias from the TRMM Precipitation Radar rain algorithm in South America. Storms with deep convective cores show the greatest underestimation, and the bias is unrelated to their echo top height. The bias in wide convective cores relates to the echo top, indicating that storms with significant mixed phase and ice hydrometeors are similarly affected by assumptions in the TRMM algorithm.

Chapter 5 (Rasmussen et al. 2014c, in preparation) examines the relative contribution from extreme storms to the total climatological precipitation in South America. This study is in the final stages of preparation for submission to the *Journal of Hydrometeorology* in fall 2014.

Chapter 6 (Rasmussen et al. 2014d, in preparation) examines the behavior of several microphysical schemes in simulations of MCSs over Argentina. Since the

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4 Included with the permission of the American Geophysical Union.
prediction of realistic cloud and precipitation patterns of these MCSs is critical to
the simulations of Chapter 7, it is important to determine the range of uncertainty in
storm structures that is associated with the microphysical schemes used in the WRF
simulations on which the next chapter is based.

Chapter 7 (Rasmussen and Houze 2014, in preparation) investigates the role of the
Andes Mountains in convective initiation and upscale growth of MCSs in subtropical
South America. Mesoscale modeling and terrain modification experiments parse the
relationship between terrain and intense MCSs in this region. This study will be
submitted to the *Journal of Atmospheric Sciences* in fall 2014.

Chapter 8 is a synthesis of the combined conclusions from Chapters 2-7.
Chapter 2

OROGENIC CONVECTION IN SUBTROPICAL SOUTH AMERICA AS SEEN BY THE TRMM SATELLITE

Extreme orogenic convective storms in southeastern South America are divided into three categories: storms with deep convective cores, storms with wide convective cores, and storms containing broad stratiform regions. Data from the Tropical Rainfall Measuring Mission satellites Precipitation Radar show that storms with wide convective cores are the most frequent, tending to originate near the Sierras de Córdoba range. Downslope flow at upper levels caps a nocturnally enhanced low-level jet, thus preventing convection from breaking out until the jet hits a steep slope of terrain, such as the Sierras de Córdoba Mountains or Andean foothills, so that the moist low-level air is lifted enough to release the instability and overcome the cap. This capping and triggering is similar to the way intense convection is released near the northwestern Himalayas. However, the intense storms with wide convective cores over southeastern South America are unlike their Himalayan counterparts in that they exhibit leading-line/trailing-stratiform organization and are influenced by baroclinic troughs more similar to storms east of the Rocky Mountains in the United States. Comparison of South American storms containing wide convective cores with storms in other parts of the world contributes to a global understanding of how major mountain ranges influence precipitating cloud systems.

Publication reference:


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2.1 Introduction

Observations from the Tropical Rainfall Measuring Mission (TRMM) satellite have led to the realization that intense storms just east of the Andes in southeastern South America are among the most intense anywhere in the world (Zipser et al. 2006). The other hot spots of extreme deep convection are over the plains east of the Rocky Mountains in the United States and near the western Himalayas in South Asia. All three hot spots occur near a major mountain range that is indicative of the orogenic\(^1\) nature of storms in these locations. Supercell thunderstorm formation and mesoscale storm structure over the Great Plains of the United States have been extensively studied. For example, Carlson et al. (1983) documented the conditions associated with supercell development, and Houze et al. (1990) showed the tendency for storms over the Great Plains to develop into mesoscale convective systems with leading lines of intense convection and trailing-stratiform precipitation. Both the central United States and southeastern South America, moreover, have large numbers of mesoscale systems satisfying Maddox's (1980) criteria to be classified as mesoscale convective complexes (MCCs). On average, South American MCC cloud shields are 60\% larger than those over the United States (Velasco and Fritsch 1987), the convection is deeper (Zipser et al. 2006), and they have larger precipitation areas than those over the United States or Africa (Durkee et al. 2009). Cecil (2009, 2011) has used TRMM Microwave Imager (TMI) data to objectively identify hailstorms and found southeastern South America to be a likely region of large hail production. Extreme convective storms over southeastern South America are also associated with a large number of fatalities, flooding events, hailstorms, and tornadoes (Altinger de Schwarzkopf and Russo 1982; Nascimento and Marcelino 2005). Thus, southeastern South America is an im-

\(^1\)Originally defined in Tripoli and Cotton (1989) as genesis under orographic influences.
portant natural laboratory and socioeconomic venue for studying the climatological factors controlling severe weather near a major mountain range.

Over the U.S. Great Plains region, a moist low-level flow originating from the Gulf of Mexico is typically capped by drier air flowing off the Mexican Plateau and the Rocky Mountains. This capping inversion inhibits the release of instability over large areas, while enhancing the intensity of convective outbreaks in narrowly focused regions (Carlson et al. 1983). Similar low-level moist flows capped by drier air coming across a major terrain feature characterize convection upstream of the western Himalayas (Houze et al. 2007). The severe convection in the U.S. and Himalayan regions, however, is released differently. The western Himalayan convection is released by flow over topography (Medina et al. 2010), whereas other features such as frontal or dryline convergence are the primary triggering mechanisms in the United States. Garreaud and Wallace (1998) and Romatschke and Houze (2010) have shown that, during the summer season in southeastern South America, frequent passages of baroclinic troughs and frontal systems over the Andes are associated with deep convection east of the mountain range. Velasco and Fritsch (1987), Zipser et al. (2006), and others have further pointed out that a topographically guided low-level jet bringing moist air poleward affects the occurrence of intense convection east of the Andes in South America in a manner similar to processes east of the Rocky Mountains in the United States. In the western Himalayan region, it is the low-level flow streaming onshore from the Arabian Sea through the gap between the Western Ghats to the south and Himalayan and Afghan mountains to the north that feeds the severe convection (Sawyer 1947; Houze et al. 2007).

Identifying common features and differences between the mechanisms producing extreme convection near the different major mountain ranges of the world will be an essential step toward a general understanding of orographic precipitation on a global scale. In this paper, we focus on the region near the Andes to better understand its similarities to and differences from orographically influenced convection in other parts
of the world. We use the methodology developed by Houze et al. (2007), Romatschke et al. (2010), and Romatschke and Houze (2010) to characterize the TRMM Precipitation Radar (PR) data in regions of extreme convection. Their technique capitalizes on the TRMM PRs ability to observe fine details of the vertical and horizontal structures of radar echoes. They determine which storms have radar echoes with exceptionally intense convective cores and which storms contain extremely broad stratiform precipitation regions. Separating South American extreme storms into these categories and determining the preferred times and locations of each type will provide a basis for comparison to the structure, organization, and behavior of extreme storms in the other regions of the world observed by the TRMM satellite. The following specific questions are addressed by the present study:

- What are the most common types of extreme storm structure in South America?
- Where do these storm structures preferentially occur?
- What are the vertical and horizontal size distributions of the storm structures?
- How does storm evolution affect the geographical distribution of storm types?
- What is the preferred mesoscale organization of the major storm types?
- How do they compare with precipitating convective systems near other major mountain ranges?

In answering the first three questions, we build on the work of Romatschke and Houze (2010). They provided a climatological mapping of the storm types over the whole continent. We further examine this mapping to determine the relative importance of the different categories of storm types that they identified. We will show that the most frequent type of storm contains cores of intense convection that tend to be organized in lines with trailing-stratiform precipitation, and that these storms are most common
in the La Plata Basin of Argentina and surrounding areas, the exact region singled out in Zipser et al. (2006) as having some of the most intense convection in the world. We further show that these storms are primarily responsible for the severe weather events (hail, tornadoes, and floods) in this region.

The work of Romatschke and Houze (2010) suggested that the climatological pattern of occurrence of the storm types that they identified might be explained by mesoscale storm evolution wherein storms form as more isolated deep convective cells at the edge of the Andes, move eastward and grow into mesoscale systems, and ultimately develop broad stratiform precipitation regions far to the east of the mountains. However, since they were analyzing the snapshots of data provided by TRMM, they could not verify this hypothesis. In this study, we include geosynchronous satellite data to better understand how mesoscale systems in the La Plata Basin region evolve. We examine two representative case studies with the geosynchronous data, synoptic observations, and other information to elucidate the fundamental mechanisms responsible for the formation, growth, and propagation of severe convection in southeastern South America and to compare it with storms in other parts of the world. This work will lay the groundwork for a high-resolution mesoscale modeling study of storms in this region in a future study.

2.2 Data and methods of analysis

This study uses 11 yr (1998–2008) of version 6 data from the TRMM Precipitation Radar (PR) during the austral spring through fall months (September–April). The following data products are used:

- **2A23** — rain characteristics (Awaka et al. 1997), which classifies rain into three categories: convective, stratiform, and other; all references to convective and stratiform precipitation in this paper are based on these classifications; and

- **2A25** — rainfall rate and profile (Iguchi et al. 2000a, b), which provides the
attenuation-corrected three dimensional reflectivity data.

From these resources, we compile a database of the most intense storms in the three storm categories used by Houze et al. (2007), Romatschke et al. (2010), and Romatschke and Houze (2010). Following these studies, we identify those contiguous three-dimensional echo structures that have 1) deep convective cores (40-dBZ echo $\geq 10$ km in maximum height), which are associated with severe weather and vigorous convection; 2) wide convective cores (40-dBZ echo $\geq 1,000$ km$^2$ when projected onto a horizontal plane), which are normally associated with mesoscale convective systems (MCSs) in a fairly early stage; and 3) broad stratiform regions (stratiform echo $\geq 50,000$ km$^2$ when projected onto a horizontal plane), which are normally associated with later-stage MCSs. These properties identify the most extreme vertical and horizontal structures exhibited by the PR echoes.

To identify storms with these properties, we follow data-processing procedures described by Houze et al. (2007). The PR data are remapped and interpolated into Cartesian coordinates, with a vertical resolution of 0.25 km. From the Cartesian data, we identify the top 50 storms, by height or area, in each category and compile a set of three-dimensional analyses detailing their structures. Horizontal and vertical cross sections of each case are then examined to gain insights into the structures of the convective cells and stratiform regions of the most intense storms. Automated procedures are used to determine the characteristics of echoes satisfying the three extreme-structure categories. Geostationary Operational Environmental Satellite (GOES) data, Twentieth Century reanalysis data (Compo et al. 2009), and National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data (Kalnay et al. 1996) are examined to determine the larger-scale context of the extreme storms.

We further categorize the three extreme types of radar echo structures by their mesoscale organization in a method similar to that of Houze et al. (1990) and Schiesser
et al. (1995). These previous studies applied this methodology to storms producing major rainfall in Oklahoma (Houze et al. 1990) and hailstorms in Switzerland (Schiesser et al. 1995) to determine the degree to which the radar echoes in storms consisted of leading convective lines and trailing-stratiform regions. Additionally, local media sources in southeastern South America contribute to the storm analysis by corroborating extreme storm impacts. A summary of these severe storm reports by storm category is shown in Table 2.1. Our study of the same properties of South American storms facilitates comparisons to storms over the central United States and other regions.

### 2.3 Climatology of storms containing deep convective cores, wide convective cores, and broad stratiform regions

To obtain an overview of the occurrence of the three categories of radar echo structure defined in section 2.2, we broadly examine their interannual, seasonal, and regional variabilities. The regions we focus on in this study are indicated in Fig. 2.1. The deepest and most horizontally extensive intense convective echoes occur in the areas called the Sierras de Córdoba (see inset in Fig. 2.1) and La Plata Basin South. Atmospheric moisture located over the Amazon basin generally flows southward in a narrow zone just east of the Andes through the regions denoted as the North Foothills and Central Foothills and is commonly referred to as the South American low-level jet (SALLJ; Nogues-Paegle and Mo 1997; Vera et al. 2006; Saulo et al. 2000, and others). Convection forming and growing in these regions typically moves eastward toward the Brazilian Highlands and the Atlantic Ocean. Romatschke and Houze (2010) found that deep convective cores tend to be triggered at about 30°–35°S in the Andean foothills and in the Sierras de Córdoba range, a smaller, north–south-oriented mountain chain just east of the Andes (Fig. 2.1, inset).
<table>
<thead>
<tr>
<th></th>
<th>Fatalities</th>
<th>Hail</th>
<th>Tornado</th>
<th>Flood</th>
<th>Heavy/record rain</th>
<th>Power outages</th>
<th>Strong wind</th>
<th>Evacuated</th>
<th>Crop damage</th>
<th>Injured</th>
<th>Total storm reports</th>
<th>Total people affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCC</td>
<td>23</td>
<td>29</td>
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<td>15,096</td>
<td>20</td>
<td>65</td>
<td>179</td>
<td>15,204</td>
</tr>
</tbody>
</table>

Table 2.1: Number of storm reports by storm category, collected from local media sources in South America. Any fatalities, hail reports, tornado reports, flood reports, power outages, and people wounded from storm-related events were counted. For the heavy/record rain category, rain rates exceeded 7.6 mm hr\(^{-1}\) or total accumulation exceeded 1 m during the storm. Strong wind reports were based on the Beaufort scale from categories 9 to 12 (wind speed >20 m s\(^{-1}\)). The number of people evacuated due to a storm had to exceed 200 people to be included as a storm report.
Figure 2.1: Topographical map of South America showing the Andes mountain range and associated terrain features. Selected regions for this study are outlined in black and labeled. Circular inset highlights the Sierras de Córdoba mountain range that is of particular importance to this study.
Figure 2.2: Bar graph showing the average percentage of storms that occur in each storm category in all regions combined. Averages were taken from 11 years of data (1998–2008).
2.3.1 Overall statistics of extreme radar echo structures

The relative percentage of storms that occur per storm category each year in all of the regions combined is shown in Fig. 2.2. The wide convective category is the most frequent throughout the year on average. Assuming that the TRMM PR seldom resamples the same storm, this statistic shows that storms with wide convective cores do not necessarily evolve from storms with deep convective cores, nor do they always evolve into storms with broad stratiform regions.

Individual instances of storms containing deep convective cores, wide convective cores, or broad stratiform regions are usually embedded in a larger contiguous echo region. These contiguous echoes typically contain a mix of convective and stratiform precipitation. Figure 2.3a shows the volume of rain falling from larger echoes containing deep convective cores, wide convective cores, and broad stratiform regions. Most of the storms containing the 50 deepest convective cores had a very high convective rain percentage (80%–100%) and relatively low volumetric rain rate. In contrast, storms with broad stratiform regions had low convective rain percentages (0%–40%) and substantially higher volumetric rain rates. The storms with wide convective cores span the two other categories in convective rain percentage with a range of 40%–100%, but their volumetric rain rates were similar to the broad stratiform areas. These statistics indicate that the separation of storms according to whether they contain these three categories of extreme echo structures effectively characterizes storm variations by both precipitation type and amount.

Figure 2.3b compares the volumetric rain rate to the number of lightning flashes, which is derived from the Lightning Imaging Sensor (LIS) aboard the TRMM satellite. Consistent with Fig. 2.3a, most of the storms with broad stratiform regions have little to no lightning. The storms containing deep convective cores show a large range in the number of lightning strikes, from 20 to over 700. Overall, storms containing wide convective cores have more lightning flashes than those containing deep convec-
Figure 2.3: (a) Scatter plot of convective rain percentage (%) and volumetric rain rate (kg s$^{-1}$) for the three storm categories. Deep convective cores are represented by circles, wide convective cores are squares, and broad stratiform regions are x marks. (b) Scatter plot of the number of lightning flashes observed by the Lightning Imaging Sensor (LIS) aboard the TRMM satellite and volumetric rain rate (kg s$^{-1}$). (c) Scatter plot of the minimum 37 GHz brightness temperatures (K) from the TRMM Microwave Imager (TMI) and number of lightning flashes as a proxy for hailstorms as defined in Cecil (2009). Symbols are the same for all panels. All values are derived from TRMM PR and TMI data and algorithms. Note the values on the abscissa are log scale for (a) and (b).
tive cores, probably because they cover more area. In an effort to validate hailstorms around the world, Cecil (2009, 2011) found that the minimum 37-GHz microwave radiometer brightness temperatures below 180 K form an excellent proxy for hailstorms. Figure 2.3c compares the number of lightning flashes to the hailstorm proxy defined by Cecil (2009, 2011). The lightning data separate distinctly among the three types of storms. Only one storm with a broad stratiform region has a brightness temperature below the threshold, but there are many storms with deep and wide convective cores that fit this criterion and thus most likely contain large hail, with the wide convective cores (probably because of their greater area coverage) generally having the most flashes. According to Cecil (2009), 60% of storms with at least 125 lightning flashes per minute have hail reports, and many of the storms with deep and wide convective cores fit into this category as well.

Figure 2.4 compares composite hodographs that were extracted from the NCEP/NCAR reanalysis data from the inflow region of the storms with the 50 most intense deep and wide convective cores. Proximity soundings extracted from the NCEP/NCAR reanalysis dataset were used by Brooks et al. (2003) to identify regions around the world that are favorable for severe or tornadic thunderstorms. Southeastern South America was identified as a very favorable region for both severe and tornadic thunderstorms based on various thermodynamic and wind shear criteria. While the usefulness of this technique was demonstrated by Brooks et al. (2003), they also mention that magnitudes of the low-level wind shear are generally less than are seen in rawinsonde data, consistent with the idea that strong vertical gradients are not reproduced well in the reanalysis. For the current study, Fig. 2.4 shows that the vertical profile of the environmental horizontal wind vector for storms with wide convective cores (dotted line) exhibits a much stronger low-level jet signature, producing a counterclockwise turning of the shear with height. In the United States, this type of curved hodograph has been associated with supercell storms, which produce both tornadoes and hail (Maddox 1976). The curved hodograph in Fig. 2.4 is consistent with the storms with
wide convective cores in southeastern South America being supercellular, with attendant tornadoes and/or large hail, as has been found to be the case by Altinger de Schwarzkopf and Russo (1982) and Nascimento and Marcelino (2005). We will show in section 6 that tornadoes and hail are indeed associated with the storms classified as wide convective cores. In contrast, the deep convective cores are associated with a straight hodograph.

2.3.2 Seasonal and regional variabilities of extreme radar echo structures

A seasonal summary of all three storm categories by geographic region is shown in Fig. 2.5. Figure 2.5a shows the number of deep convective cores for all eight regions separated by month. The Sierras de Córdoba and Central Foothills regions have different overall numbers, but their seasonal cycles have a similar peak around December–January. This peak occurs during the austral summer season in which the southernmost extent of warm and moist air reaches the Sierras de Córdoba region, as will be shown in section 2.4. Both regions are located along the foothills of the Andes, implying a tendency for deep convective cores to be triggered along the lower foothills of the topography, as has been found in the Himalayan region (Houze et al. 2007; Medina et al. 2010). A contrasting seasonal cycle occurs in the Amazon and Atlantic regions, where a minimum occurs during December and January with few or zero deep convective cores. The Brazilian Highlands and La Plata North and South regions show a general increase during the spring, summer, and fall, with October being a particularly active month for all three.

The statistics for storms exhibiting wide convective cores (Fig. 2.5b) are similar to those for storms with deep convective cores (Fig. 2.5a) in the Sierras de Córdoba and Central Foothills regions. The Sierras de Córdoba region has higher overall numbers with a similar seasonal pattern to the Central Foothills region. The La Plata South region follows a similar seasonal cycle as these two regions with a strong increase in October. However, the Amazon and Atlantic region frequencies are strikingly different.
Figure 2.4: Composite hodographs for the fifty storms with the most intense deep and wide convective cores. Individual wind profiles were extracted from NCEP/NCAR reanalysis data in the inflow region of each storm before compositing. Numbers outside the largest circle are meteorological wind directions and dotted rings in the interior indicate wind speeds (m s$^{-1}$). Vertical profiles of wind direction and speed are for storms with deep convective cores (solid) and wide convective cores (dashed). Diamond symbols indicate the 1000 hPa level, circle symbols indicate 700 hPa, and square symbols indicate the 400 hPa level.
Figure 2.5: (a) Number of storms with deep convective cores seen by the TRMM PR in each region outlined in Figure 2.1, separated by month. Each month is represented with a different color, shown in the legend. Panels (b) and (c) are the same as (a), except for storms with wide convective cores (b) and storms containing broad stratiform regions (c). Note the values on the ordinate are different for (a)-(c).
from those in Fig. 2.5a, exhibiting not a minimum but instead a significant number of events in the summer. The Amazon region shows a strong preference for the spring and early summer seasons and the Atlantic region shows a strong preference for the late summer and fall seasons. The statistics of storms with wide convective cores in the Brazilian Highlands, La Plata North, and North Foothills regions (Fig. 2.5b) mirror those of storms with deep convective cores (Fig. 2.5a), where both exhibit large numbers of events and decrease gradually throughout the three seasons. Figure 2.5c shows the Atlantic region as the most prevalent location for storm systems with broad stratiform areas, containing almost twice as many cases as any other region. Unlike Fig. 2.5b, the peak values occur at the beginning of spring and then a gradual decrease occurs through autumn. The Amazon region has more broad stratiform cases during the summer and fall seasons, which is a different distribution than that for the wide convective cores. The seasonal cycle in the North Foothills and La Plata North regions is similar to that of the Amazon basin. The Brazilian Highlands and La Plata South regions show a slight decrease in the spring seasons with an increase in the late summer through the fall seasons. The Sierras de Córdoba and Central Foothills regions have very few broad stratiform areas throughout all three seasons. Comparisons between regional distributions of the three storm categories are consistent with the idea that the storms tend to trigger near the foothills of the Andes, propagate eastward, and then grow to form storms with both wide convective cores and (later) broad stratiform areas.

Figure 2.6 shows the size distribution of storms with deep convective cores, wide convective cores, and broad stratiform regions by geographical region. For storms containing deep convective cores (Fig. 2.6a), the regions with the most intense events (highest extent of the 40-dBZ echo) are the Sierras de Córdoba and La Plata South regions. This result is consistent with those of Zipser et al. (2006), which indicates this exact region as the location of some of the deepest convection in the world. The Central Foothills region has a substantial number of storms containing deep
convective cores, but they are not as numerous as in the regions to the south. A possible explanation for this difference is the triggering of deep convective cells by the Sierras de Córdoba range or more frequent baroclinic zones due to frontal passages in subtropical South America (Nogues-Paegle and Mo 1997; Garreaud and Wallace 1998; Liebmann et al. 1999).

The regions consistently containing the most frequent wide convective cores in any size category are the La Plata North and La Plata South regions, especially the southern choice (Fig. 2.6b). These two regions are east of the Andes and their relative abundance of storms with wide convective cores supports the hypothesis that echo regions containing convective cores expand as they propagate to the east. However, there are also numerous wide convective cores occurring in the Sierras de Córdoba region, which could indicate that echoes expand horizontally before moving out of this region or without propagating eastward at all in some situations.

For the broad stratiform category (Fig. 2.6c), the regions with the most extreme events (largest horizontal extent of contiguous stratiform pixels) are the Atlantic and La Plata South regions. As pointed out by Romatschke and Houze (2010, their Fig. 5), this regional distribution is also consistent with systems beginning as more isolated storms with deep convective cores, then propagating eastward while growing into storms containing wide convective cores. Even later, the storms develop broad stratiform areas by the time they reach their most eastward destinations. The Brazilian Highland region has fewer intense stratiform areas but is also consistent with this idea.

2.4 Synoptic climatology of extreme radar echo structures

From the climatology in section 2.3, storms with wide convective cores stand out as being significant. They are the most frequent type of extreme convection (Fig. 2.2), and they are associated with large volumetric rainfall, which is contributed by a combination of convective and stratiform components (Fig. 2.3). According to Fig.
Figure 2.6: (a) Vertical height of the 40 dBZ echo for storms with deep convective cores separated by region. Each region is represented with a different color. The most intense deep convective cores are characterized by having the highest extent of the 40 dBZ echo. (b) Horizontal extent of the contiguous 40 dBZ echo for storms with wide convective cores separated by region. The most intense wide convective cores have the largest extent of the 40 dBZ echo. (c) Horizontal extent of contiguous stratiform pixels, as identified by the TRMM 2A23 algorithm, for storms containing broad stratiform regions divided by region. The largest broad stratiform regions have the greatest extent of stratiform pixels. All classifications and measurements are derived from TRMM PR data. Note the values on the ordinate are log scale and different for (a)-(c).
storms with wide convective cores have a strong counterclockwise wind shear rotation with height, which has been associated with tornadic supercells in other regions of the world (Maddox 1976). The data in Figs. 2.5 and 2.6 further show that the storms with wide convective cores are most frequent and largest over the Sierras de Córdoba and La Plata Basin North and South regions. These facts led us to focus the remainder of this paper on storms with wide convective cores in the Sierras de Córdoba and La Plata South and North regions.

Figure 2.7a shows a composite sea level pressure and wind climatology computed from the Twentieth Century reanalysis data from 11 yr (1998–2008), on days when the TRMM PR showed storms containing wide convective cores over the Sierras de Córdoba and La Plata South and North regions. Persistent high pressure systems dominate over the Pacific and Atlantic Oceans (Fig. 2.7a). The Andes mountain range clearly affects the surface wind field by deflecting westerly winds to the north as part of the high pressure system over the Pacific. Over the continent, there is a general low pressure area on the lee side of the Andes mountain range, which is frequently referred to as the northwest Argentina low, often generated as a lee trough by approaching synoptic systems (Seluchi et al. 2003b). Ahead of these approaching baroclinic waves, warm air from the Amazon basin is channeled southward along the Andes Mountains by the northerly component winds of the SALLJ (Saulo et al. 2000; Vera et al. 2006; Marengo et al. 2004; Nogues-Paegle and Mo 1997). Previous studies have implicated the SALLJ in the occurrence of convection in southeastern South America (Salio et al. 2007; Anabor et al. 2008; Borque et al. 2010; Romatschke and Houze 2010). The seasonal progression of precipitable water and temperature, composited from days containing storms with wide convective cores, is presented in Figs. 2.7b and 2.7c. These figures show the influence of the SALLJ in bringing moist, warm air from the Amazon region into the higher latitudes in situations supporting storms with wide convective cores in southeastern South America during the austral spring–fall seasons.
Figure 2.7: Climatological composite maps for days on which the TRMM PR showed storms containing wide convective cores over the Sierras Córdoba and La Plata North and South regions. (a) Sea level pressure (hPa) climatology composite for South America. Wind vectors at 1000 hPa were composited for the same time period and show a strong SALLJ and easterly flow into the Amazon Basin. (b) Composite of the monthly progression of precipitable water (28 mm contour) in South America. Each month is represented by a color contour and the color scale is located on the eastern ordinate of (c). (c) Composite of the monthly progression of near-surface air temperature (23°C contour). Each month is represented by a color contour and the scale is the same as (b). The topographic scale for (a)-(c) is located on the ordinate of (b). Climatology data is from the 20th Century Reanalysis Dataset (Compo et al. 2009) and is used for higher resolution maps over South America.
As mentioned earlier, previous studies have hypothesized that the synoptic setting for storms in southeastern South America bears a resemblance to storms over the Great Plains of the United States (Carlson et al. 1983; Velasco and Fritsch 1987). In the United States, dry subsiding air from the large elevated desert region of the Mexican Plateau forms a capping inversion over moist air from the Gulf of Mexico. The capping inversion holds back the release of instability until the cap is broken by lifting, usually along a front or ahead of a midlevel trough. Smaller-scale topographic features over the plains states sometimes trigger strong convective events. An example is the Cap Rock escarpment in northwest Texas (Smull and Houze 1985). However, these features do not dominate the statistics of extreme convective events as strongly as do the Sierras de Córdoba range and surrounding Andean foothills in southeastern South America (Romatschke and Houze 2010).

In South America, moist air from the Amazon is also capped, but for a different reason. The vertical motion composite climatology at 700 hPa for days on which storms with wide convective cores were identified in the Sierras de Córdoba and La Plata Basin regions is presented in Fig. 2.8a. In subtropical South America (from 20 to 40°S), mean upward motion occurs on the windward side of the Andes mountain range and is coupled with downward motion on the leeward side. This vertical motion signature is a nondiurnal effect clearly associated with the mean westerlies crossing the Andes at these latitudes. The mean values of the downward motion are not very large, but they are evidently sufficient to cap the convection just east of the Andes. Borque et al. (2010) examined a high-resolution model case study and noted that preceding the outbreak of a large MCS, the genesis region (near the Sierras de Córdoba range) experienced midlevel drying resulting from subsidence preceding the passage of an upper-level trough over the Andes Mountains (see their Figs. 7 and 14). Their results thus corroborate the pattern in our Fig. 2.8.

For intense convection to break out in the Sierras de Córdoba region, it must be triggered by low-level convergence sufficient to break through the cap. The 1000-hPa
Figure 2.8: Climatological composite maps for days on which the TRMM PR showed storms containing wide convective cores over the Sierras Córdoba and La Plata North and South regions. (a) Omega or vertical motion (Pa s\(^{-1}\)) climatology contours at 700 hPa. Negative values (red contours) indicate upward motion and positive values (blue contours) indicate downward motion. (b) Composite wind vectors at 1000 hPa.
composite wind pattern for the same days is shown in Fig. 2.8b. The SALLJ is strongly evident and flows underneath the downslope subsidence. The convergence that occurs as the SALLJ encounters the Sierras de Córdoba range is in the location where Romatschke and Houze (2010) showed that intense deep convective cores prefer to form. They also showed that convective triggering is partly synoptic, as it is also favored by the presence of a trough. In the case of the Himalayan region, it has been found that lower mountains provide enough lift to break the cap and allow deep convection to break out (Medina et al. 2010). Previous studies of the storms in southeastern South America (Salio et al. 2007; Borque et al. 2010) have speculated that complex mesoscale flow patterns and frontal lifting are important in convective initiation and destabilization of the environment. Nevertheless, it is hard to ignore the robust statistics from Zipser et al. (2006) and Romatschke and Houze (2010) showing that the highest frequency of deep convective cores is found in the Sierras de Córdoba range and nearby Andean foothills. In addition, Borque et al. (2010) found an MCS genesis region directly over the Sierras de Córdoba Mountains. A high-resolution model study of severe zonda wind cases (foehn effect in South America) revealed that preceding frontal passages, zonda winds are associated with a vertical motion pattern consistent with Fig. 2.8a (Seluchi et al. 2003a). Air motions qualitatively similar to the zonda may occur to a lesser extent in many cases.

Elevated convective initiation (Wilson and Roberts 2006; Marsham et al. 2011) is also not likely to be an alternative explanation for the deep convective triggering in southeastern South America as that mechanism involves air lying above a preexisting cold pool associated with a front or earlier MCS. The SALLJ flowing along the edge of the Andes traverses a path in which such low-level cold layers are generally not present. The unambiguous signature of orographic convective triggering centered on the Sierras de Córdoba Mountains (section 2.3.2 and Romatschke and Houze 2010) further indicates that it is the SALLJ encountering terrain features that is mostly responsible for the convective triggering in the western part of Argentina. Elevated
convection may, on the other hand, occur above MCS cold pools or cold fronts farther to the east, over central Argentina. As also noted in section 2.3.2 and by Romatschke and Houze (2010), larger mesoscale systems with wide convective cores and broad stratiform regions occur frequently over that region. Analyzing satellite infrared imagery, Velasco and Fritsch (1987) and Laing and Fritsch (1997) also noted long-lived mesoscale systems moving eastward over central Argentina, and elevated initiation might be expected to contribute to the continued redevelopment in their eastward progression. Orographic triggering is clearly important, if not dominant, in southeastern South America, and deserves further investigation using a high-resolution model.

2.5 Case studies of storms with wide convective cores in the La Plata Basin

The analysis of TRMM data is limited to the statistics of snapshots in different storms, where they are randomly at different stages of development. As noted above, the statistics of the TRMM PR data summarized in Figs. 2.5 and 2.6 and the results of Romatschke and Houze (2010) suggest that the storms with wide convective cores represent a mature stage of storm development and that these storms are systematically orogenic, forming over the lower mountains to the east of the Andes and moving eastward across the plains toward the ocean. To determine if these statistical impressions are valid, we undertook case study examinations of some of the best defined cases. Analyses of these cases can include other types of data, allowing for the TRMM data to be placed within the context of the life cycles of the storms. For the case study analyses, NCEP/NCAR reanalysis data were used due to the scarcity of surface and upper-air observations in southeastern South America. Storms with wide convective cores occur in connection with a low-level northerly jet (Fig. 2.4), which implies that they are more likely to contain tornadic convection. To prepare for an in-depth case study analysis, we conducted an informal perusal of the data for 50
cases containing the most intense deep convective cores, wide convective cores, and broad stratiform regions. The following two case studies exemplify the results of our case study analysis.

2.5.1 26 - 27 December 2003

A wide convective core case of particular practical interest was detected by the TRMM PR at 1002 UTC on 27 December 2003. According to local media, this storm caused four fatalities, 90 injuries, 400 evacuees to flee the area, a strong tornado in Córdoba (eastern foothills of the Sierras de Córdoba), hail, winds up to 35 m s$^{-1}$, very heavy rainfall rates, flooding, and power outages. With 326 lightning flashes and a convective rain percentage of 74%, this case falls within the midrange of wide convective cores in Figs. 2.3a and 2.3b. The geosynchronous infrared satellite data show the temporal context of this case (Fig. 2.9). At 1745 UTC on 26 December 2003 (Fig. 2.9b), convective cells were triggered on the eastern side of the Sierras de Córdoba range. These cells were generated before the TRMM PR data captured this case as a wide convective core, which is consistent with the idea that the smaller mountains trigger deep convective cores, which organize into wide convective cores. The cold cloud top remained tied to the Sierras de Córdoba through about 1145 UTC the following day. Another interesting feature of this case is that its circular structure in the cloud-top temperature field could be classified as an MCC by the criteria of Maddox (1980) from 0845 to 1445 UTC. Velasco and Fritsch (1987) and Salio et al. (2007) have previously noted such systems in South America. The TRMM PR data add three-dimensional structural information to this prior research.

The 500-hPa geopotential height anomalies for the 27 December case study (Fig. 2.10a) show a low pressure anomaly (trough) directly over the southern Andes. Moderate northwesterly winds at 500 hPa flowed over the region of the storm. At the surface, a moderate low pressure anomaly was located east of the Andes (Fig. 2.10b). The surface map also shows a signature of the SALLJ located just east of the Andes.
Figure 2.9: Sequence of infrared satellite images (K) showing storm triggering and evolution for the 26-27 December 2003 wide convective core. Infrared data is from the GOES-12 satellite. The closest infrared satellite image to the TRMM PR swath identified as a storm with a wide convective core is shown in (h), highlighted by the * symbol. The thick black contour outlines the 0.5 km topography.
Figure 2.10: Synoptic setting for the 27 December 2003 case that was identified as a storm with a wide convective core by the TRMM PR. Climatological conditions are defined as September through April (1948-2009). (a) Geopotential height anomalies and wind vectors at 500 hPa. The contours show the departure of the height (m) from the climatological 500 hPa surface. (b) Surface pressure anomalies, 1000-500 hPa thickness and surface wind vectors. Colored contours show the departure (hPa) of the sea level pressure field from climatological conditions. Dotted contours show the 1000-500 hPa thickness (m) with greater thickness values indicating a warmer 1000-500 hPa layer. (c) Surface air temperature (°C) shown in colored contours and surface wind divergence. Dotted lines show negative values of divergence, or convergence of wind vectors. (d) Equivalent potential temperature (K) shown in color contours and dew point depressions at 925 hPa. Dotted lines indicate dew point depressions where higher values indicate drier air. Note that the topographic scale for (a)-(d) is the same as Figure 2.7.
Figure 2.10b further shows that the Sierras de Córdoba range lies within a strong 1000–500 hPa thickness gradient, indicating that conditions in the region were baroclinic. Strong downslope flow off the Andes occurred directly to the west of the Sierras de Córdoba range. Warm air was present in most of southeastern South America (Fig. 2.10c) from two different sources: the Amazon basin via the low-level jet and the Atlantic Ocean. The warmest air was concentrated against the foothills of the Andes in the exact location of the storm. Figure 2.10d further shows that an extremely strong meridional gradient in the equivalent potential temperature was centered over the Sierras de Córdoba range. Large values of dewpoint depression are almost parallel to contours of equivalent potential temperature close to the Andes foothills, which are associated with dry air flowing off the mountains. Strong low-level convergence directly over the Sierras de Córdoba mountain range (Fig. 2.10c) was consistent with the triggering of cells directly over and to the east of this topographic feature. All of these observations together indicate that low-level orographic convergence, where the SALLJ encountered the Sierras de Córdoba terrain, was able to lift warm, moist air enough to break through the capping effect, which is likely due to lee-side subsidence (Fig. 2.8) and, thus, allowed violent convection to occur and grow into the mesoscale system seen in Fig. 2.9.

The TRMM PR reflectivity data containing the wide convective core embedded in the storm were obtained at 1002 UTC 27 December 2003 and are overlaid on GOES-12 infrared satellite brightness temperature data in Fig. 2.11a. This time was in the period when the satellite image properties qualified the storm as an MCC (Fig. 2.9). The wide convective core had a 40-dBZ contiguous echo exceeding 15,000 km² in area, in addition to a 16-km 40-dBZ echo height, which also qualified the storm for the deep convective core category. The radar echo had mesoscale organization with an east-southeastwestnorthwest- oriented leading line of convection on its northern side and stratiform precipitation to the south of the line. Smaller, discrete lines of intense convection lay within the band; furthermore, these smaller elongated convect-
Figure 2.11: Storm that was identified by the TRMM PR as containing a wide convective core on 27 December 2003 at 1002 UTC. (a) Reflectivity from the TRMM Precipitation Radar in dBZ at 4 km overlaid on the infrared satellite brightness temperature (K). The white lines indicate the TRMM PR swath and the red line indicates the location of the vertical cross-section. The thick black contour outlines the 0.5 km topography. (b) Vertical cross-section taken along the red line in (a) of the TRMM PR data. (c) Sounding extracted from NCEP/NCAR reanalysis data at the location of the red dot in (a). The red line indicates the vertical temperature profile and the green line indicates the dew point temperature profile. Wind barbs are plotted to the right corresponding to each vertical level and a hodograph is inset in the top right corner. Various severe storm indices are visible in the top left corner.
tive elements had a south-southeast north-northwest orientation forming at an acute angle to the main line of convection. The horizontal radar echo structure is reminiscent of cases analyzed by Houze et al. (1990), who determined that the tendency for major rainstorms in Oklahoma was to have mesoscale radar echo structures with a leading-line/trailing-stratiform structure.

A vertical cross section of the TRMM PR data shows a deep convective core with very intense values of reflectivity and a region of stratiform precipitation (as indicated by the brightband) behind it (Fig. 2.11b). The convective core contained a 40-dBZ echo up to 12 km and had an overall echo top over 16 km. Also evident is an anvil-like structure to the right (ahead) of the convective cell, indicating strong upper-level outflow on the forward side of the storm. Because of the limited sensitivity of the TRMM PR (17-dBZ minimum threshold), the full extent of this anvil structure cannot be seen. A sounding extracted from the NCEP/NCAR reanalysis fields in the inflow region of the storm (location indicated by the red dot in Fig. 2.11a) shows a stable layer near the surface, with a conditionally unstable layer from 850 to 600 hPa. Orographic lifting over the Sierras de Córdoba and/or cold-pool outflow from the developed storm must have removed this inversion in order for the air to have obtained the buoyancy to produce the deep convective core. Winds were veering (Fig. 2.11c, inset) with height, indicating warm-air advection. A low-level jet was present, with a counterclockwise hodograph favorable for tornadic storms [applying the results of Maddox et al. (1980) and Maddox (1976) in a Southern Hemisphere context]. A high value of convective available potential energy (CAPE) of 2747 J kg\(^{-1}\) and severe lifted index and K index values were also consistent with the intensity of the convection and severe weather reports.

2.5.2 12 November 2003

It is not uncommon for storms containing wide convective cores to cause severe damage, injury, and loss of life in the La Plata Basin region. Here, we present another
example. In this case, a storm containing a wide convective core (according to local media) caused 14 fatalities, at least one strong tornado, winds in excess of 60 m s\(^{-1}\), tennis-ball-sized hail, power outages, flooding, and intense rain rates. Of all the wide convective cores identified in 11 yr of TRMM data, the wide convective core in this storm was the largest, with a 40-dBZ contiguous echo covering about 38,000 km\(^2\). The storm had 663 lightning flashes and a large convective rain percentage (94%). This case contrasts with the one from the previous section in that it occurred in conjunction with stronger baroclinic forcing. Romatschke and Houze (2010) have pointed out the tendency for storms with wide convective cores in South America to be associated with the passage of midlatitude baroclinic troughs. Our examination of approximately 50 of the largest wide convective core cases in all of South America indicates that 80\% of them were associated with the passage of baroclinic troughs. The frontal forcing in the current case probably contributed to the excessive size of the system. According to Maddox (1983), both MCCs and tornadic storms often precede or accompany frontal passages.

The synoptic situation could be interpreted as the type described by Garreaud and Wallace (1998). They described a common synoptic situation in southeastern South America during the summer season, in which transient incursions of cold midlatitude air collide with warm, moist air over the continent, thus forming an ideal environment for deep convection in the Sierras de Córdoba and La Plata Basin South regions. The geopotential height anomalies at 500 hPa (Fig. 2.12a) show upper-level low pressure centered over the Andes around 35\(^\circ\)S. A strong surface low pressure anomaly was located east of the Andes with a center at about 32\(^\circ\)S (Fig. 2.12b). The low anomaly in relation to the thickness field has a classic frontal structure. A strong SALLJ was feeding warm air directly into the frontal zone. Southerly winds behind the front were advecting colder air toward the rear of the storm. Strong downslope winds were occurring over the foothills of the Andes, adding to the convergence in the region.

A warm pocket of air was located over much of southeastern South America,
Figure 2.12: Same as Figure 2.10 except for 12 November 2003.
extending from the Sierras de Córdoba range east to Uruguay and north to Paraguay (Fig. 2.12c). The SALLJ (seen in Fig. 2.12b) was advecting this warm air from the Amazon basin into the region of the storm. A large region of convergence occurred in the same area, with a strong maximum over the same region as the surface low pressure anomaly (Fig. 2.12c). A zonal gradient of equivalent potential temperature was located just east of the Sierras de Córdoba range (Fig. 2.12d), while relatively dry air from downslope flow off the Andes lay to the west and cold, dry air entered the region from the south. The dewpoint depression (dotted contours) field shows the contrasting humidity of the SALLJ air and the air behind the front (Fig. 2.12d).

The TRMM PR data show that the 12 November 2003 wide convective case was clearly line organized and large in horizontal extent in plan view (Fig. 2.13a). An infrared satellite loop from 10 through 13 November (not pictured) indicates that convective cells were triggered over or near the Sierras de Córdoba Mountains. Despite the fact that the TRMM PR swath truncated the radar echo, it is evident from this figure that the mature system had the structure of a classic leading-line/trailing-stratiform squall-line system (Houze et al. 1990). Its location along a frontal zone suggests that the mesoscale system was either forced or reinforced by frontogenetic processes after it was triggered. A vertical cross section running lengthwise along the convective line (Fig. 2.13b) shows that the very intense pockets of convection were typically confined to the lowest 4–6 km, which indicates that although this is a wide convective core of great horizontal extent, the heights of the 40-dBZ echoes were not generally extremely deep at this stage of the storm. A thermodynamic profile (Fig. 2.13c) extracted from the NCEP/NCAR reanalysis data shows that the inflow region of the storm (location indicated by the red dot in Fig. 2.13a) had the characteristics of a severe storm sounding. The sounding shows a conditionally unstable layer from 925 to 300 hPa, with a very large value of CAPE (3168 J kg\(^{-1}\)), severe values for the lifted and K indices, and a strong energy helicity index (EHI), indicating possible tornado formation. In addition, an inversion near the surface with
Figure 2.13: Same as Figure 2.11 except for 12 November 2003.
drying above indicates that subsidence on the leeward side of the Andes was inhibiting the outbreak of convection until the air was lifted by either the Sierras de Córdoba range, the front, or the cold-pool outflow from the mesoscale convective system. Very strong wind shear with winds turning counterclockwise with height (veering) indicates strong warm advection combined with a low-level jet. The wind shear was generally consistent with that conducive to mesoscale line organization (Weisman and Klemp 1982; Rotunno et al. 1988; Houze et al. 1990).

2.6 Mesoscale storm organization

Previous studies of storms in subtropical South America have focused mainly on individual case studies, storm tracks, and synoptic-scale features (Seluchi et al. 2003b; Anabor et al. 2008; Garreaud and Wallace 1998). After our case study examination of approximately 50 storms containing the largest wide convective cores seen by the TRMM PR, it appeared that these wide convective cores tended to be located within larger contiguous radar echoes containing a line organization such as that seen in the two example case studies previously summarized. To test this impression, we carried out a systematic analysis of the morphology of the storms in the La Plata Basin and surrounding regions that contained wide convective cores. For this test, we employed a method similar to that used by Houze et al. (1990) to study heavy rainstorms in Oklahoma and by Schiesser et al. (1995) to analyze hailstorms in Switzerland. Applying their methodology to the TRMM PR database of storms with wide convective cores in South America, we have ranked TRMM-observed storms according to their similarity to the leading-line/trailing-stratiform schematic used by Houze et al. (1990).

The schematic is shown in Fig. 2.14, flipped vertically on the page to create what we have observed to be the Southern Hemisphere equivalent of the Oklahoma schematic. The shaded regions in Fig. 2.14 indicate increasing levels of reflectivity echo, which is measured by the TRMM PR. Seven out of 10 storm characteristics
used by Houze et al. (1990) to characterize the storm structure relate directly to the leading convective line, and the more prominent of these are indicated in Fig. 2.14. The remaining three storm characteristics were used to classify the trailing-stratiform region. The 10 characteristics that they used are as follows:

1. The convective line should be arc shaped and convex toward the leading edge.

2. The line should be oriented in a northwest to southeast direction [changed for the Southern Hemisphere; Houze et al. (1990) used southwest to northnorth-east].

3. Line motion should be normal to the orientation of the line and must be > 10 m s\(^{-1}\). For this study, the relative line motion was estimated based on satellite data.

4. A solid leading line with intense convective cells should be connected by moderate reflectivity (see Fig. 2.14).

5. A strong reflectivity gradient must be present at the leading edge of the convective line.

6. As seen in Fig. 2.14, the leading edge of the convective line must be serrated or jagged, with protrusions at a wavelength of 5–10 km. This characteristic is now thought to be associated with roll vortices oriented parallel to the direction of the inflow to the mesoscale updraft maintaining the line; see Bryan et al. (2007) and further discussion in Houze (2004).

7. Cells within the convective line should be elongated with an orientation of 45–90° to the leading line. This characteristic is indicated in Fig. 2.14 and is related to the serrated leading edge.
8. The trailing-stratiform region must be large in size and cover a region > 10,000 km². The size was measured by the TRMM PR convective/stratiform echo separation algorithm.

9. As indicated in Fig. 2.14, a notchlike concavity should be present at the rear edge of the storm. This characteristic is associated with rear inflow at midlevels as described by Smull and Houze (1985, 1987). They found that this air was generally dry and eroded stratiform echo in this region.

10. The stratiform region must contain a secondary maximum in echo intensity that is separated from the leading convective line by a region of less intense reflectivity.

Skamarock et al. (1994), Pandya and Durran (1996), and Pandya et al. (2000) have shown that the mesoscale organization prescribed by those 10 characteristics is reproduced in numerical models. They further showed that the tendency for some storms to have an asymmetric structure, with the trailing-stratiform region located on the poleward side of the system, was induced by the Coriolis force acting on the aging systems.

We followed exactly the methodology of Houze et al. (1990), which was to visually examine the radar echoes of each convective system for the presence or absence of the 10 characteristics related to the idealized schematic. We rated 55 of the most intense wide convective cores identified in 11 yr of TRMM PR data in South America. To reduce the uncertainty, this procedure was repeated three times, with both authors present and viewing the same data each time as well as checking and rechecking previous ratings. During one of the three rating procedures, all images were randomized and flipped vertically (resembling storms in the Northern Hemisphere) to prevent recognition of individual cases from previous analyses. For each of the 10 storm characteristics, the degree to which the TRMM PR data resembled the leading-
Figure 2.14: Schematic of the leading-line/trailing stratiform archetype described in Houze et al. (1990), but reoriented for study in the Southern Hemisphere. Increasing levels of shading indicate more intense radar reflectivity. As described in Chapter 2.6, storms with wide convective cores were systematically compared to this idealized structure.
The leading-line/trailing-stratiform model in Fig. 2.14 was determined by scoring 1 point if the feature or threshold was unambiguously present and -1 if it was definitely not present. In cases where a particular characteristic was to some degree present or absent, a score of 0.5 or -0.5 was assigned, respectively. If the particular characteristic was indeterminable from the available data, a score of 0 was given. Once all 10 characteristics were scored, the C or classifiability score was determined by taking the sum of the individual characteristic rankings. The C scores between 5 and 10 are considered to be strongly classifiable, scores between 0 and 5 are moderately classifiable, and scores between 210 and 0 are weakly classifiable storms. Storms with wide convective cores that did not exhibit any leading-line/trailing-stratiform signature at all were designated as unclassifiable storms. We did not attempt to determine whether the storms had symmetric or asymmetric variations on the schematic structure in Fig. 2.14.

The results of the leading-line/trailing-stratiform study are summarized in Table 2.2. In general, the degree to which storms containing wide convective cores resemble the leading-line/trailing-stratiform archetype in southeastern South America is similar to the tendency of the Oklahoma storms studied by Houze et al. (1990) to exhibit this structure. The subdivision of the storms into strongly and weakly classifiable categories was in about the same proportion for the two regions. The storms in the La Plata Basin, east of the Andes, occur under similar conditions to the storms over the U.S. Great Plains, east of the Rocky Mountains (Carlson et al. 1983; Velasco and Fritsch 1987). Additionally, pronounced elongated cells have been observed in numerous storms with wide convective cores in southeastern South America and have also been documented in U.S. Great Plains squall-line systems (Ligda 1956; Houze et al. 1990; Bryan et al. 2007; Marsham et al. 2011). The storms in Switzerland studied by Schiesser et al. (1995) occur under rather different synoptic and topographic conditions, and they exhibited somewhat different characteristics, having no cases in the strongly classifiable category and increasing numbers of less organized systems.

Further comparison to Houze et al. (1990) is presented in Table 2.3, which shows
Table 2.2: Summary of mesoscale organization based on the leading-line/trailing-stratiform archetype from Houze et al. (1990) shown in Figure 2.14. Storms with wide convective cores were rated based on ten characteristics described in Chapter 2.6. The ‘C’ score is the classifiability of the storm. Percentages are based on the total number of storms analyzed in each study.

<table>
<thead>
<tr>
<th>Degree of Organization</th>
<th>Range of Scores</th>
<th>Subtropical South America (Houze et al. 1990)</th>
<th>Oklahoma (Houze et al. 1990)</th>
<th>Switzerland (Schiesser et al. 1995)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly Classifiable</td>
<td>C&gt;5</td>
<td>11 (20%)</td>
<td>14 (22%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Moderately Classifiable</td>
<td>0≤C≤5</td>
<td>30 (54.5%)</td>
<td>18 (28.6%)</td>
<td>12 (21.4%)</td>
</tr>
<tr>
<td>Weakly Classifiable</td>
<td>C&lt;0</td>
<td>7 (12.7%)</td>
<td>10 (15.9%)</td>
<td>18 (32.1%)</td>
</tr>
<tr>
<td>All Classifiable Systems</td>
<td>All C</td>
<td>48 (87.3%)</td>
<td>42 (66.7%)</td>
<td>30 (53.6%)</td>
</tr>
<tr>
<td>All Unclassifiable Systems</td>
<td>—</td>
<td>7 (12.7%)</td>
<td>21 (33.3%)</td>
<td>26 (46.4%)</td>
</tr>
<tr>
<td>Total Number of Storms Analyzed</td>
<td>—</td>
<td>55</td>
<td>63</td>
<td>56</td>
</tr>
<tr>
<td>Degree of Organization</td>
<td>Lightning Flashes</td>
<td>Fatalities</td>
<td>Hail</td>
<td>Tornado</td>
</tr>
<tr>
<td>------------------------</td>
<td>-------------------</td>
<td>------------</td>
<td>------</td>
<td>---------</td>
</tr>
<tr>
<td>Strongly Classifiable</td>
<td>354</td>
<td>1.3</td>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td>Moderately Classifiable</td>
<td>340</td>
<td>0.4</td>
<td>0.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Weakly Classifiable</td>
<td>360</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.3: Average number of severe storm reports per storm with a wide convective core by degree of organization. Storm reports are derived from local media reports in South America and TRMM products. The criteria for each storm report category are described in Table 2.1.
the average number of severe storm reports per event with wide convective cores by degree of organization. The storm report categories of fatalities, hail, tornadoes, heavy/record rain, power outages, strong winds, and total storm reports show a notable preference for strongly classifiable storms. This result differs from that obtained by Houze et al. (1990); the low-C categories in Oklahoma storms contained more severe storm reports in the tornado, hail, strong winds, and heavy/record rain categories.

Lightning flashes, flooding reports, and the number of evacuated people per system are the only storm report categories that do not exhibit a preference for strongly classifiable systems. Lightning and flooding are about equally likely in any of the three storm classifications. All three classifications can produce large numbers of evacuees. The average number of evacuees can be strongly influenced by a single event and is subject to media errors. In contrast to the numbers in Table 2.3, the storms in Oklahoma with strongly classifiable line organization had the highest numbers of lightning reports, with decreasing numbers for less strongly classifiable storms (Table 6 in Houze et al. 1990). However, these numbers may not be strictly comparable since lightning flashes in the South American storms were measured by the TRMM satellite, whereas the lightning reports in the Oklahoma storms were based on visual observations. The more widespread precipitation conditions in strongly classifiable storms may have inhibited visual observations. A larger database of storm reports for South America is probably needed for conclusive comparisons to storms in the United States, as mentioned by Nascimento and Doswell (2005). Nonetheless, substantial differences between line-organized storms in Oklahoma and South America are suggested by Tables 2.2 and 2.3.

2.7 Conclusions

In South America, three distinct categories of storms have been identified from 11 yr of TRMM PR data as storms that contain radar echoes of extreme vertical
or horizontal dimensions. Following Houze et al. (2007), Romatschke et al. (2010), and Romatschke and Houze (2010), these extreme echo structures are called deep convective cores, wide convective cores, and broad stratiform regions. The most frequent types of storms with these extreme echo forms are those containing wide convective cores. Storms containing wide convective cores produce some of the largest volumetric rain amounts. The bigger systems often qualify as MCCs in terms of the size and coldness of their cloud tops seen in infrared satellite imagery. Their rainfall is a relatively even mix of convective and stratiform components. TRMM measurements show that they exhibit frequent lightning flashes. Media reports show that they produce floods, tornadoes, and hail. They have societal impacts in the form of injuries, evacuations, and even fatalities.

The storms containing wide convective cores tend to be largest and most intense in the La Plata Basin and surrounding regions. Because of the importance of this category of storm, we have examined the storms in the La Plata Basin region that contained the 50 largest wide convective core echoes. These especially intense storms tend to occur when baroclinic troughs pass over the southern Andes. The large intense storms in the La Plata Basin region sometimes, but not always, occur in connection with cold fronts embedded in the baroclinic troughs. In either case, intense convection tends to be triggered at the eastern edge of the Andes. They have a strong tendency for their first cells to be generated over the foothills of the Andes or the Sierras de Córdoba range in Argentina. The latter is a favored location, as it lies directly in the path of the climatological SALLJ, which feeds warm, moist, low-level air southward along the edge of the Andes. After the convective cells are triggered over this terrain, they tend to first produce storms with deep convective cores, which are also favored in this region (Romatschke and Houze 2010). They grow into wider systems as the storms move to the east and over the La Plata Basin, where the storms containing wide convective cores are most frequent, and where the storms develop large stratiform regions along with the wide convective cores. Over time, they develop even larger
stratiform regions as they continue eastward toward the Brazilian Highlands and Atlantic Ocean, where Romatschke and Houze (2010) found a maximum occurrence of storms with broad stratiform regions.

The large storms containing wide convective cores in the La Plata Basin region contain elements of both convective and stratiform precipitation (Fig. 2.3). Moreover, they frequently exhibit mesoscale organization, such that they are composed of a leading line of intense convective rain cells followed by a region of stratiform precipitation. The horizontal arrangement of convective and stratiform regions in a mesoscale convective system is an indicator of the internal organization of the system. Therefore, we subjected the storms that the TRMM PR data showed to contain wide convective cores to an analysis of the type carried out by Houze et al. (1990) for Oklahoma rainstorms and Schiesser et al. (1995) for Swiss hailstorms. This exercise revealed that the storms with wide convective cores over southeastern South America were generally similar in mesoscale organization to the Oklahoma rainstorms, but not similar to the Swiss storms. The idea that South American and U.S. mesoscale systems resemble each other has been circulating in the literature for around 30 yr. The present study confirms that notion.

The strongly and moderately classifiable forms of leading-line/trailing-stratiform organization were the dominant organization types in both the southeastern South American storms and the Oklahoma storms, while a relatively small percentage of storms showed no inclination toward this form of organization. The Swiss storms, on the other hand, are much less likely to have a leading-line/trailing-stratiform mesoscale structure. The tendency for the South American storms to be more like the Oklahoma storms is understandable in that both storm regions have mountains lying to the west that channel low-level moist flow poleward, and both regions are located near the equatorward extremity of baroclinic influence, allowing troughs and fronts to often affect the storm organization. In the case of the Oklahoma storms, orographic triggering is not evidently the primary triggering mechanism in the region; the storms
tend to be triggered by some other form of low-level convergence, usually a front or dryline. Well-known exceptions, of course, occur. Topographic features occasionally influence the triggering storms in the central United States (the Palmer Divide in Colorado or the aforementioned Cap Rock escarpment in northwestern Texas). However, close examination of the results of Zipser et al. (2006) reveals that the locations of the deepest convection over the United States do not climatologically cluster around any particular local topographic feature as it does in other regions such as southeastern South America or near the Himalayas (Romatschke et al. 2010; Romatschke and Houze 2010). This observation combined with previous studies suggests that orographic triggering plays a substantially larger role in southeastern South America than in the United States.

One notable difference between the storms in southeastern South America and those over the U.S. Great Plains is that the most mesoscale-organized South American storms produce more hail and tornadoes. We cannot say why this difference exists, but the wind shear profile in the air feeding the South American mesoscale leading-line/trailing-stratiform storms with wide convective cores tended to have counterclockwise shear of the SALLJ lower-level winds, which would favor the development of supercell hailstorms and tornadoes within the leading line of convection. A further comparison of the South American storms containing wide convective cores can be made to storms containing wide convective cores in the western Himalayan region of Pakistan and northwest India. Moist flow from the Arabian Sea feeding the Himalayan systems is overridden by westerlies coming over the mountains to the west, as in the U.S. Great Plains and in southeastern South America. In the Himalayan case, baroclinic forcing plays little if any role, and the triggering of the intense convection occurs when the moist flow encounters lower mountains in front of the main Himalayan range (Houze et al. 2007; Medina et al. 2010). The South American and Himalayan storms are thus both primarily triggered by orographic forcing, which does not seem to be the primary triggering mechanism over the U.S. Great Plains.
The South American and Oklahoma storms are affected by baroclinic forcing, which is absent in the Himalayan storms. Thus, extreme convection in all three regions east of major mountain ranges occurs with different combinations of determining factors. This study leads about as far as one can go with existing data alone in determining the nature of extreme convection in South America. To advance our understanding of these storms requires modeling. Studies such as Skamarock et al. (1994) have examined the Oklahoma type of storms via modeling and led to an explanation of the leading-line/trailing-stratiform structure of those storms. Medina et al. (2010) successfully improved our understanding of Himalayan storms via modeling. Following this path, we are presently undertaking a study using a high-resolution cloud-resolving model to study the storms with wide convective cores in southeastern South America. This work will be reported on in a forthcoming paper (Chapter 7; Rasmussen and Houze 2014).
Chapter 3

SEVERE CONVECTION AND LIGHTNING IN SUBTROPICAL SOUTH AMERICA

Satellite radar and radiometer data show that subtropical South America has the world’s deepest convective storms, robust mesoscale convective systems, and very frequent large hail. We determine severe weather characteristics for the most intense precipitation features seen by satellite in this region. In summer, hail and lightning concentrate over the foothills of western Argentina. Lightning has a nocturnal maximum associated with storms having deep and mesoscale convective echoes. In spring, lightning is maximum to the east in association with storms having mesoscale structure. A tornado alley is over the Pampas, in central Argentina, distant from the maximum hail occurrence, in association with extreme storms. In summer, flash floods occur over the Andes foothills associated with storms having deep convective cores. In spring, slow-rise floods occur over the plains with storms of mesoscale dimension. This characterization of high-impact weather in South America provides crucial information for socioeconomic implications and public safety.

Publication reference:

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3.1 Introduction

Subtropical South America has the deepest convective storms (Zipser et al. 2006) and highest frequency of large hail in the world (Cecil and Blankenship 2012). It is also the location of intense mesoscale convective systems (MCSs) (Romatschke and Houze 2010; Rasmussen and Houze 2011). However, the climatology of severe weather manifested by these storms as hail, tornadoes, and floods have been relatively understudied. This short paper therefore documents the severe weather associated with extreme convective storms in subtropical South America by correlating satellite radar and lightning data with local observations and eyewitness reports of floods, hail, and tornadoes.

TRMM Precipitation Radar (PR) data analysis has revolutionized a number of characteristics of precipitating systems in remote regions of the world that were previously unknown. Subtropical South America is one such region; the lack of a ground-based radar network until recently has limited both the study and understanding of the severe weather that occurs there. TRMM PR observations have led to the realization that intense storms just east of the Andes in subtropical South America are among the most intense anywhere in the world (Zipser et al. 2006) and have shown the different forms of convection that affect the region (Romatschke and Houze 2010; Rasmussen and Houze 2011). These findings raise questions regarding the climatology of severe weather events and socioeconomic impacts associated with these storms. Particularly needed are climatologies of lightning, floods, hail, and tornadoes, the primary elements of weather affecting human activity. This study presents a comprehensive overview of severe weather impacts from the most extreme storms seen by the TRMM satellite in subtropical South America. We examine seasonal and diurnal lightning patterns and compile the spatial distribution of flooding, hail, and tornadoes in subtropical South America. This research provides a basis for future research into the structure and characteristics of the high-impact storms that occur
in subtropical South America.

### 3.2 Data and methodology

The TRMM PR has relatively fine three-dimensional spatial resolution (4-5 km horizontal, 250 m vertical resolution at nadir), and its areal coverage is comprehensive between 36°N and 36°S (Kummerow et al. 1998). In this study, we use sixteen years (1998-2013) of TRMM PR V7 2A25 data (radar reflectivity and rain type; Iguchi et al. 2000; Awaka et al. 1997) over South America in the austral spring through fall seasons. Houze et al. (2007) developed a technique that has been used in multiple studies in subtropical South America (Romatschke and Houze 2010; Rasmussen and Houze 2011; Rasmussen et al. 2013). This method identifies three types of three-dimensional echo objects to facilitate investigation of storms containing extreme structural characteristics: 1) A deep convective core (DCC) is a contiguous volume of convective echo exceeding 40 dBZ and 10 km in height; it indicates the most locally deep and vigorous convection; 2) a wide convective core (WCC) is a contiguous 40 dBZ echo volume \( \geq 1000 \text{ km}^2 \) that indicates the presence of strong convection located within a horizontally sizable area; it suggests strong convective systems organizing onto the mesoscale, as several strong updraft cells are likely located in horizontal proximity to produce a contiguous region of heavy precipitation; and 3) a broad stratiform region (BSR) is a contiguous area of stratiform echo \( \geq 50,000 \text{ km}^2 \); it is typically associated with mature MCSs. Radar echoes that satisfy the criteria for both the DCC and WCC categories are termed deep and wide convective cores (DWCCs). In subtropical South America, the convective categories tend to produce hail, lightning, heavy rain, and tornadoes and the stratiform category is associated with widespread rain and flooding (Rasmussen and Houze 2011). The probability of finding these storm types during the austral summer in South America is analyzed in Romatschke and Houze (2010) and is updated to include probabilities during the spring through fall seasons (Rasmussen et al. 2014c and Chapter 5).
A monthly climatology of lightning rates was calculated from the merged Lightning Imaging Sensor (LIS) and Optical Transient Detector (OTD) dataset (Cecil et al. 2014) from September to May in 1998-2010. In addition, using the LIS orbital data, individual lightning flashes (fl) and the sensor viewing time (observation duration) were identified within the horizontal area projected by each TRMM-identified radar echo defined above and accumulated in a 0.05° x 0.05° grid to estimate the lightning rates from extreme storms. In addition, the raw flash count was scaled by the appropriate detection efficiency, which varies with the time of day (similar to the methodology used in Cecil et al. 2014). Finally, the lightning rate (flashes min⁻¹) was computed as the ratio between the accumulated scaled flash count and viewing time. The maps were then resampled to a coarse grid of 1° x 1° resolution to facilitate a better presentation of the high-resolution data, as has been done in other studies using LIS data (Cecil et al. 2014).

To assess the occurrence of severe storms in subtropical South America, newspaper reports in Argentina and Uruguay are used to compile data in three categories: floods, hail, and tornadoes. The newspapers that provided archived information are as follows: Clarn (www.clarin.com), Diario Los Andes (www.losandes.com.ar), La Nacin (www.lanacion.com.ar), and Ultimas Noticias (www.ultimasnoticias.com.uy). In each of the three storm type categories defined above, the top 100 events were selected based on the following criteria: (1) DCC echo top height, (2) WCC echo size, and (3) BSR echo size. Queries in the above newspaper databases for the top 100 cases of each storm type extending ±1 day of the TRMM overpass time were performed and any articles related to flooding, hail, or tornadoes were identified. Then, each relevant article was examined for specific locations (e.g. town and road descriptions, distances from various cities, landmarks, etc.) to locate each storm report on a map. The resulting spatial distributions of floods, hail, and tornadoes will be presented in Section 3.4.
3.3 Lightning associated with extreme storms in subtropical South America

Assessing the severity of convective storms based on lightning frequency is a topic of great study around the world since lightning is a commonly used proxy for intense and developing storms (Macgorman and Burgess 1994; Lang and Rutledge 2002; Carey et al. 2003). Lightning data from the LIS aboard the TRMM satellite provides a uniform view of the lightning distribution and frequency in the subtropics and tropics. Very few studies have specifically looked at the lightning distribution in subtropical South America, and up to now there has been a distinct lack of analysis of both seasonal and diurnal occurrence of lightning in a region that experiences some of the deepest convection on Earth. This study uses sixteen years of TRMM and LIS data over subtropical South America to assess the seasonal, diurnal, and extreme storm-related lightning patterns.

Figure 3.1 presents a monthly climatology of lightning flash rates in subtropical South America. Lightning activity in the early- to mid-spring season occurs in northeastern Argentina and southwestern Brazil (Fig. 3.1a-c), but in the transition to the summer season (Fig. 3.1d-f), lightning activity moves to the southwest into central Argentina near the Sierras de Córdoba range (between ~30 to 35° S; black outline in Fig. 3.1) and the Andean foothills. Analysis of the spatial distribution of extreme storms with the TRMM PR (Zipser et al. 2006; Romatschke and Houze 2010) has shown that some of the deepest convection in the world occurs in the Andes foothills during the austral summer. This deep convection corresponds in location to the climatological maximum of lightning in Figure 3.1d-f. The lightning distribution in Figure 3.1c-g highlights the role of the Andes foothills in focusing convective initiation, with the Sierras de Córdoba mountains being of particular importance, as was hypothesized in Romatschke and Houze (2010) and Rasmussen and Houze (2011).

To investigate the specific relationship between lightning and specific forms of
Figure 3.1: Monthly lightning climatology from the Lightning Imaging Sensor (LIS) and Optical Transient Detector (OTD) expressed as lightning rates (fl km$^{-2}$ yr$^{-1}$) from September through May in subtropical South America. The thick black line indicates the 0.5 km topography contour on the eastern Andean foothills.
Figure 3.2: Averaged lightning flash rates (fl min$^{-1}$) within TRMM-identified (a-c) deep convective cores and (d-f) wide convective cores showing the seasonal progression lightning associated with extreme storms in South America.
convection in South America, the seasonal patterns of lightning associated with the extreme convective forms defined above are presented in Figure 3.2. Strong similarities between Figures 3.1a-c and 3.2a and d indicate that storms containing both deep and wide convective cores are likely responsible for the maxima of lightning in north-eastern Argentina and southwestern Brazil during the spring season. Additionally, a comparison of Figures 3.1c-f to Figures 3.2b and e indicates that the summer lightning distribution near the foothills of the Andes is associated strongly with both storms containing DCCs and storms containing WCCs. Lightning associated with BSRs is negligible (not shown).

Figure 3.3 shows the diurnal variation of the lightning as a function of distance from the Andes and storm type during austral summer. The maximum occurrence of lightning in storms containing only DCCs (Figure 3.3a), DWCCs (Figure 3.3b), and only WCCs (Figure 3.3c) are all located in the foothills of the Andes around midnight. Romatschke and Houze (2010) and Rasmussen and Houze (2011) concluded that deep convection tends to be triggered over the Andes foothills and the Sierras de Córdoba range in western Argentina. They also concluded that the convection forming in that area starts with storms containing DCCs that move eastward over the plains, as they grow upscale into MCSs containing WCCs and broad stratiform regions. The lightning data in Figure 3.3 show that the lightning occurrence in storms containing DWCCs and WCCs, respectively, is found farther eastward as the systems become more mesoscale in character. Yet, all three categories of storm type retain a maximum of lightning around midnight over the foothills (cf. Figures 3.3a-c over the indicated topography). This indicates that as the systems expand eastward, their deep convective elements related to lightning production continue forming over the terrain as the South American Low-level Jet (SALLJ) continuously brings warm and moist air south from the Amazon into the region, impinging on the foothills and providing a lifting mechanism to break the capping inversion (Rasmussen and Houze 2011). In other words, the continuous formation of new lightning-producing cells over
Figure 3.3: Time-longitude diagrams representing the diurnal progression of averaged lightning rates (fl min$^{-1}$) within TRMM-identified (a) deep convective cores, (b) deep and wide convective cores, and (c) wide convective cores during the austral summer season (DJF). The diagrams are averaged over a meridional band bounded by 36°S to 28°S. Time in UTC and Mean Solar Time (MST) are displayed on the left and right ordinates, respectively. The black contour represents the average topographic relief in the latitude band defined above.
the foothills gives the eastward moving MCSs a back-building aspect. Terrain-locked back-building MCSs have also been observed in southwest Taiwan (Xu et al. 2012); however, in that case the new cells were forming at a distance from the mountain, on the border of a cold pool continually fed by convective cells moving over the mountain. This behavior of the lightning is consistent with studies of the orogenic nature of the extreme convective systems forming in this region that has been described statistically by Romatschke and Houze (2010), in case studies by Rasmussen and Houze (2011), and will be examined via modeling in a forthcoming paper (Rasmussen and Houze 2014; Chapter 7).

3.4 Floods, hail, and tornadoes in subtropical South America

A systematic reporting of severe weather in the region studied here has been lacking until now. However, by compiling newspaper reports of tornadoes, Altinger de Schwarzkopf and Russo (1982) showed that tornadoes occur in central Argentina. Nascimento and Doswell (2005) highlighted the need for improved documentation of thunderstorms and tornadoes in South America. In the absence of such improvement, we have drawn inspiration from Altinger de Schwarzkopf and Russo (1982) and have compiled storm reports for this study from the 100 most extreme storms observed by the TRMM satellite in three storm categories (DCC, WCC, and BSR, as defined in Section 3.2) to provide a seasonal spatial distribution of various types of severe weather impacts including floods, hail, and tornadoes (Figure 3.4). Other sources of disaster information for the region were explored (e.g., DesInventar database, www.desinventar.net), but were not used since such data are scarce and not commonly available for the TRMM era.

Flood reports are distributed throughout the region including Argentina and Uruguay, in both large population centers (e.g. Buenos Aires and Córdoba; labeled in Fig. 3.1i) and the relatively unpopulated La Pampa province in central Argentina (Figure 3.4a; labeled in Fig. 3.1a). Consistent with Figures 3.1, 3.2, and the seasonal
Figure 3.4: Severe storm reports derived from local media sources (newspapers in Argentina and Uruguay) showing the locations of (a) floods, (b) hail, and (c) tornadoes in subtropical South America. Each symbol on all panels represents one report of each type of severe storm impact separated into seasons (red: SON; blue: DJF; green: MAM). The topography is shaded in gray scale.
distribution of TRMM storm probabilities (Romatschke and Houze 2010), heavy rain and flooding tends to occur in central to eastern Argentina and Uruguay in the spring. These floods in the agriculturally rich Pampas region are typically slow-rise floods (Latrubesse and Brea 2009). Figure 3.2d indicates that they are likely produced by storms containing WCCs. Figure 5 of Romatschke and Houze (2010) shows that storms containing BSRs are most likely in this region. Rasmussen et al. (2014c) (Chapter 5) presents a spring-only version of Romatschke and Houze (2010)’s storm type distribution that shows a similar location of BSRs in the Pampas region. Thus, the slow-rise floods in the east are likely associated with storms of extensive mesoscale organization both in their convective structure and their stratiform components. Figure 3.4a shows that during the summer, the flooding shifts northwestward toward the foothills of the Andes in Argentina and Bolivia. News reports indicate that these events are often flash floods. Figure 3.2b and e suggests that they could be associated with storms containing DCCs, WCCs, or both.

Figure 3.4b shows that reports of hail come from a west-east swath across Argentina from the Andes to the Atlantic coast. However, hail reports are highly concentrated in the extreme foothills of the Andes and Sierras de Córdoba, near the cities of Mendoza and Córdoba. Mendoza, located in the foothills of the Andes (32.9°S, 68.9°W; labeled in Fig. 3.1i), is greatly affected by frequent hailstorms with large hail (reported in newspapers as pea to grapefruit sized) that seriously impact the agriculture of this major wine-producing region (Fig. 3.4b). Many wineries in Mendoza have installed anti-hail nets and the Argentinian government subsidizes agricultural hail insurance and funds aircraft cloud-seeding efforts because of frequent large hail in the region (personal communication, Bodega Norton Winery, 2011). Given the known distributions of lightning in the region close to the Andes foothills from Figures 3.1-3.3, frequent hail in the vicinity of the Andes foothills and the Sierras de Córdoba corresponds well to Figure 3.4b and is consistent with the findings of Cecil and Blankenship (2012). Such a concentration of hail near mountains is unlike that
in the United States (Cecil and Blankenship 2012).

Echoing the findings of Altinger de Schwarzkopf and Russo (1982), but specifically looking at the most extreme storms seen by the TRMM PR in 16 years, Figure 3.4c indicates the presence of a South American tornado alley in the central Pampas region. This region is far to the east of where hail is most frequent (Figure 3.4b); perhaps, mountainous terrain presents a boundary condition unfavorable to tornado dynamics (Bosart et al. 2006; Homar et al. 2003). We also note that this region over the plains east of the Andes is where organized MCSs maximize in both frequency of occurrence and maturity (Romatschke and Houze 2010; Rasmussen and Houze 2011; Salio et al. 2007). More specifically, Rasmussen and Houze (2011) found that storms in this region that resembled the leading-line/trailing-stratiform archetype defined by Houze et al. (1990) were more likely to result in tornado reports, but they did not examine the mesoscale organization of storms containing DCCs in their study. Tornado reports shown in Figure 3.4c were associated with storms containing both DCCs and WCCs. Additionally, tornadic storms in the U.S. tend to be supercellular in structure with strong clockwise wind shear (Maddox 1976; Houze 2014) that is also present in subtropical South America (Rasmussen and Houze 2011; counterclockwise shear in the Southern Hemisphere). Thus, the specific characteristics of tornadic storms in subtropical South America need to be more closely examined in a future study to better compare to their more studied U.S. counterparts. However, consistent with known distributions of tornado activity in the U.S., tornadoes are most likely to form where more developed thunderstorms, supercells, and/or mature MCSs are located downstream of the mountain barrier.

### 3.5 Conclusions

The examination of various forms of severe weather in subtropical South America in relation to TRMM Precipitation Radar data shows:
1. The seasonal climatology of lightning in subtropical South America has a maximum in spring and fall over northeastern Argentina and Paraguay in association with storms containing DCCs, WCCs, or both. In summer, the maximum of lightning frequency shifts southwestward to the foothills of the Andes, where it is associated with storms containing DCCs, WCCs, or both. The lightning in this region at this time of year tends to remain over the foothills and Sierras de Córdoba while mesoscale convective systems develop and spread eastward while continuing to build on their western sides as convection continues to generate over the lower mountains.

2. A persistent nocturnal maximum of lightning activity is found over the foothills and Sierras de Córdoba in association with new convection, and with mesoscale systems that may continue to regenerate on their western sides while spreading eastward.

3. Flooding occurs throughout subtropical South America as a result of both flash floods near the foothills and Sierras de Córdoba, where storms with DCCs occur and slow-rise floods in the agriculturally-rich Pampas region, in association with storms containing WCCs. That is, the flash floods occur in the mountains with newly formed very intense and deep convection, whereas the floods over the plains occur in conjunction with mesoscale systems bearing horizontally extensive regions of intense convection and stratiform precipitation.

4. Hail occurs throughout the region, but is highly concentrated in the Andes foothills and Sierras de Córdoba, near Mendoza, in association with storms containing DCCs or WCCs.

5. A South American tornado alley is present in La Pampa region far to the east of the region of maximum hail occurrence. The tornado maximum is located
where more developed and organized thunderstorms, supercells, and MCSs are likely to occur downstream of the Andes Mountains.

The findings from this study provide the basis for future research on severe weather and their impact in subtropical South America. By integrating satellite radar and lightning data with ground-based storm reports to investigate the nature of extreme convective systems in subtropical South America, a greater understanding of these storms, their role in the climate of the region, and their socioeconomic impact on local populations can provide crucial information that could save life and property in this vulnerable region.
Chapter 4

TRMM PRECIPITATION BIAS IN EXTREME STORMS IN SOUTH AMERICA

Deep convective storms in subtropical South America are some of the most intense in the world, and the hydrological cycle plays an important role in both tropical and subtropical South America. Recent studies have suggested that the Tropical Rainfall Measuring Mission (TRMM) precipitation radar algorithm significantly underestimates surface rainfall in deep convection over land. This study investigates the range of the rain bias in storms containing four different types of extreme radar echoes: deep convective cores, deep and wide convective cores, wide convective cores, and broad stratiform regions over South America. Storms with deep convective cores show the greatest underestimation, and the bias is unrelated to their echo top height. The bias in wide convective cores relates to the echo top, indicating that storms with significant mixed phase and ice hydrometeors are similarly affected by assumptions in the TRMM algorithm. The relationship between storm type and rain bias remains similar in both subtropical and tropical regions.

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4.1 Introduction

The precipitation radar (PR) on the Tropical Rainfall Measuring Mission (TRMM) satellite has revolutionized the study of storms in the tropics and subtropics. Analysis of TRMM PR data, however, has led to the recognition that the TRMM PR algorithm tends to underestimate precipitation in regions of intense deep convection over land (Iguchi et al. 2009). Understanding the magnitude of the biases for a variety of precipitating cloud systems over different regions is essential for understanding global precipitation and hydrology.

TRMM observations have led to the realization that intense storms just east of the Andes in southeastern South America, near the western Himalayas, and east of the Rocky Mountains in the U.S. are among the most intense anywhere in the world (Zipser et al. 2006). The most extreme South American mesoscale convective systems (MCSs, Houze 2004) are larger and have more precipitation than in other parts of the world (Velasco and Fritsch 1987; Durkee et al. 2009). Houze et al. (2007), Romatschke and Houze (2010), and Romatschke and Houze (2011) have used TRMM PR data to identify the location and frequency of distinct extreme storm types in both South Asia and South America. Rasmussen and Houze (2011) examined the mesoscale organization and structure of MCSs in subtropical South America and showed that they are structurally similar to the leading line/trailing stratiform archetype identified by Houze et al. (1990) for intense rainstorms in Oklahoma. Using AMSR-E data, Cecil and Blankenship (2012) found that northern Argentina and Paraguay have the highest frequency of significant hailstorms over the globe. This combined evidence points to South America being an important natural laboratory for studying intense convective storms and their hydrological impact.

For a complete perspective of the impact of intense precipitation systems on the hydrologic cycle in South America, it is necessary to assess the contribution from such storms to the climatological rainfall. Indeed, since the convection in South
America is robust and strongly defined in its most intense manifestations, the storms of this region constitute an ideal test bed for determining the TRMM PR bias in intense convection in general. The main question addressed in this study relates to the uncertainties in making the precipitation estimate due to known insufficiencies in the rain estimation algorithm for this type of storm over land regions (Iguchi et al. 2009; Nesbitt et al. 2004). Our study differs from previous work by providing a range of the potential bias in the TRMM PR rain rate estimation, focusing specifically on the most intense convective storms and providing a range of probable errors induced by the algorithm. The results should be extendable to other continental regions that experience intense convection observed by the TRMM satellite, while also highlighting the unique behavior of South American storms.

4.2 Data and Methodology

The TRMM PR is advantageous for studying the climatology of storms because it is not obstructed by topography, as are ground-based radars. The TRMM PR has relatively fine three-dimensional spatial resolution (45 km horizontal, 250 m vertical resolution at nadir), and its areal coverage is comprehensive between 37.5°N and 37.5°S (Kummerow et al. 1998). The TRMM PR database has accumulated for over 14 years (1999–2012). In this study, we use TRMM V7 data from the South American sector (37.5°S–15°N, 100°W–30°W) for the austral spring through fall seasons. Following Houze et al. (2007), four types of three-dimensional echo objects have been identified to facilitate a comparison of precipitation produced by various storm types: (1) deep convective cores (contiguous volume of convective echo exceeding 40 dBZ and ≥ 10 km in height; DCC), indicating severe weather and vigorous convection; (2) wide convective cores (contiguous 40 dBZ echo volume ≥ 1,000 km² horizontally; WCC), indicating intense convective systems organized on the mesoscale; (3) Deep and wide convective cores (cores that fall into both of previous two categories; DWCC); and (4) broad stratiform regions (contiguous area of stratiform echo ≥ 50,000 km²; BSR), typ-
ically associated with mature MCSs. The first three categories produce hail, lightning, heavy rain, and tornadoes in subtropical South America. The last three echo-type categories are associated with widespread rain and flooding (Rasmussen and Houze 2011).

For the purpose of this study, a ‘core’ is defined as the three-dimensional echo object identified by the storm-type algorithm described above, whereas a storm is the contiguous echo with reflectivity values greater than zero within which the cores are embedded. We use two different methods to compute rain rates to investigate the performance of the TRMM PR algorithm in estimating precipitation for each echo type. The first method employs the standard TRMM 2A25 V7 near-surface precipitation data (Iguchi et al. 2009). The second method follows Romatschke and Houze (2011) by using a more traditional $Z-R$ relationship,

$$Z = aR^b \quad (4.1)$$

where $Z$ is equivalent radar reflectivity factor in units of mm$^6$ m$^{-3}$ and $R$ is the rain rate in mm h$^{-1}$) to estimate the precipitation from the TRMM PR attenuation-corrected reflectivity data. The lowest nonzero value of $Z$ is used at each data pixel between the surface and 2.5 km above ground level for each precipitation echo, which is similar to the value used in the TRMM PR algorithm. The parameters $a$ and $b$ are constants depending on rain type (convective, stratiform, or other). We use several reasonable estimates of $a$ and $b$ to obtain a range of estimated rain rates based on radar data. The $Z-R$ method used here has uncertainties and possible biases that are related to the choices of $a$ and $b$. However, these parameters are from the literature and are in no way related to the attenuation-correction method used in the TRMM PR algorithm. The $Z-R$ method is widely used, much simpler, and more transparent than the TRMM PR algorithm. The total volumetric rain rates for each core and storm were calculated using both methods from the footprints of both the core and storm in each relevant overpass. To ensure consistency between the $Z-R$ technique
Table 4.1: List of Z–R Relations tested in South America. For all storm categories, the bias is defined as the average normalized difference in volumetric precipitation amounts (Z–R–TRMM 2A25), expressed as a percentage. The averaged values in each column are from the tropical region (15°N–23.5°S) and subtropical region (23.5°S–37.5°S).

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and the TRMM 2A25 output, the volumetric rain rates for all identified storms were calculated using the 2A25 near-surface reflectivity data. The results of this study were not perceptibly changed.

The underlying premise of this study is that because of the analysis of Iguchi et al. (2009), we expect a priori that the TRMM PR 2A25 algorithm will systematically give lower precipitation rates in the most extreme forms of deep convection over land. The question is how much. In remote regions, rain gauge and ground-based radars are not present in sufficient number to provide a comparison with independent data. Comparison with the rain rates computed from the ensemble of Z-R relations used here is the best available alternative for estimating the possible magnitude of underestimation by TRMM PR in intense convection over land. Table 1 lists multiple physically appropriate values of $a$ and $b$ in the Z-R relationships for the South American region considered here. A combination of Z-R relations from satellite radar algorithms (TRMM PR), operational sources (WSR-88D calibrated values), and those derived from field campaign measurements (MCTEX, TRMM-LBA, and EPIC) was tested for consistency with the Romatschke and Houze (2011) relations. We used the values of $a$ and $b$ in Table 4.1 to calculate rain rate estimates using the Z-R technique in the tropics and subtropics of South America. By using the above-described method for selecting the most extreme convective entities and applying the Z-R to those cases and comparing the Z-R rates with the 2A25 rain rates, we test the degree to which the 2A25 V7 algorithm systematically produces lower rain rates specifically for the most extreme convective entities over land.

4.3 Determination of Bias in TRMM Precipitation Estimates

Table 4.1 shows that of the various Z-R relations, Romatschke and Houze’s (2011) parameters produce a conservative estimate of underestimation. We therefore use it to further illustrate our results. A compilation of the number of intense storms identified in South America (Figure 4.1) shows that over the 14 year climatology,
Figure 4.1: The number of storms identified in each category in South America (37.5°N–15°N, 100°W–30°W) from 1999 to 2012.
Figure 4.2: The normalized difference in volumetric precipitation amounts ($Z-R$ - TRMM 2A25), expressed as a percentage. The percentage indicates the underestimation of the TRMM 2A25 data compared to the $Z-R$ method. Dashed lines indicate precipitation from cores, and solid lines are from the full storm that the core is embedded within.
the storms containing WCCs are the most common during austral spring through autumn. Figure 4.2 shows that the TRMM 2A25 volumetric rain rate averaged over 14 years (1999–2012) is systematically lower than the $Z-R$ estimate. For storms with BSRs, it is 15–20% lower, while storms with DCCs were about 40% lower. Storms with WCCs were 20–30% lower. The relative percentage underestimate is consistent across all months. Table 4.1 provides average September to April values for the various $Z-R$ relationships tested in the tropical and subtropical regions. DCCs are the most relative rain-underestimated storm type regardless of the particular $Z-R$ relationship used. The relative underestimate is larger for storms with DCCs; however, the areas covered by storms containing WCCs and BSRs tend to be larger in area, so these biases are nonetheless significant for their impact on hydrologic estimates in South America.

Figure 4.3 presents comparisons of volumetric rain rates using both precipitation estimation methods. TRMM 2A25 precipitation rates for DCCs and storms containing these echoes consistently exhibit the lowest estimates compared to the $Z-R$ method (Figures 4.3a and 4.3b), consistent with the means presented in Figure 4.2. From Figure 4.3, it not only appears that problems with the TRMM 2A25 algorithm arise from inconsistencies in estimating precipitation for vertically intense deep convection, but other forms of extreme precipitating systems show a systematic bias as well. Similar to Figure 4.2, DCCs show the largest relative bias followed in order by DWCCs, WCCs, and BSRs. Figures 4.3c and 4.3d demonstrate that subtropical South American storms of all types are more intense and produce larger rain rates compared to the tropics, consistent with previous studies investigating extreme storms in South America (Romatschke and Houze 2010; Rasmussen and Houze 2011). However, although the tropical storms tend to be less intense, the relationship between the relative bias in precipitation and storm type remains the same regardless of different climatological regimes and thus could be important for other regions of the world experiencing various types of extreme storms.
Figure 4.3: Volumetric rain rates \( (10^6 \text{ kg s}^{-1}) \) for all echoes identified in South America from the TRMM PR (a) cores and (b) storms. Volumetric rain rates derived from storms in the (c) tropical region \((15\degree N–23.5\degree S)\) and the (d) subtropical region \((23.5\degree S–37.5\degree S)\). In all panels, the black line represents an agreement between the two precipitation methods, and the colored lines indicate the slope of the best fit line for each storm type.
Figure 4.4: Volumetric rain rate ($10^6$ kg s$^{-1}$) comparisons using (a) the 40 dBZ echo top for DCCs and (b) the 40 dBZ echo top for WCCs. In both panels, the color shading represents the height of the echo core in kilometers.
Figure 4.4a illustrates that the precipitation bias in DCCs (40 dBZ echo top height \( \geq 10 \) km) is independent of the maximum height of the 40 dBZ echo and is in fact a systematic bias for this type of convective storm. A similar analysis for the WCCs (Figure 4.4b) shows that the altitude reached by horizontally extensive 40 dBZ cores is proportional to the underestimate of precipitation. The fact that the height of the DCCs is unrelated to the rain bias indicates that the effect of mixed phase and ice hydrometeors complicates the precipitation retrieval and tends to bias the rain estimates for these types of storms. When the echo height of the horizontally contiguous 40 dBZ WCCs are above the 0\(^\circ\)C level (around 4-5 km), the bias in precipitation becomes apparent, again probably in relation to mixed phase hydrometeor effects.

Well-documented problems with near-surface precipitation estimates in deep convective storms over land from the 2A25 algorithm have been partially attributed to errors in the drop size distribution (DSD) parameter (\( \epsilon \)), which tends to negatively bias the \( Z-R \) calculations of rain rate (Iguchi et al. 2009, equation 6). The nondimensional DSD parameter (\( \epsilon \)), which is a by-product of the attenuation correction method, adjusts the vertical profile model (\( \zeta \)) to estimate the effect of DSD variations (Kozu et al. 2009). The values of \( a \) and \( b \) used to estimate \( R \) are related to the values of \( \epsilon \) and \( \zeta \). For high echo tops, the vertical profile model in the algorithm tends to be overestimated because of assumptions used in mixed phase and ice regions (Iguchi et al. 2009), thus leading to an artificially smaller \( a \) parameter in the \( Z-R \) relation and an underestimation of the rainfall rate. The TRMM PR precipitation algorithm currently assumes a particle model that is based on the size and density of a snow particle (Iguchi et al. 2009), which is inappropriate for deep convection over land with significant precipitation ice in the form of graupel and/or hail. This assumption may have a large effect on the near-surface rain rate estimates. The future Global Precipitation Mission (GPM) satellite will have a dual-wavelength precipitation radar, which will entail new algorithm design for better ice particle representation, allowing this bias to be mitigated. However, nearly continuous rain estimation from TRMM
through to GPM will require an understanding of the assumptions in the current algorithms for a smooth transition into the GPM era.

\subsection*{4.4 Conclusions}

Previous studies suggested that the TRMM PR algorithm tends to underestimate precipitation rates of deep convection over land (Iguchi et al. 2009; Kozu et al. 2009) and subtropical South America has some of the deepest convective storms in the world (Zipser et al. 2006). The TRMM PR algorithm exhibits bias in all four extreme echo types considered here when the algorithm rates are compared to a range of conventional \( Z-R \) relations. The bias appears in the monthly-averaged rainfall as a negative difference between the TRMM 2A25 algorithm and the \( Z-R \) method for every echo type. The difference is greatest for storms containing DCCs (up to \( \sim40\% \) underestimate). WCCs and BSRs also have significantly lower estimates (\( \sim25\% \) and \( \sim15\% \), respectively). By calculating the precipitation bias using seven different \( Z-R \) relationships, we find the relation between the storm type and relative precipitation underestimate to be robust in both tropical and subtropical regions. Although the bias for storms containing WCCs and BSRs is less than for DCCs, they are nevertheless likely to produce major hydrologic impacts because of the large areas they cover. The subtropical region tends to have more intense precipitating systems than the tropics, but the relationship between the TRMM PR rain bias and storm type is the same regardless of the climatological regime. Differing from previous studies that only identified deep convection over land as being problematic in TRMM PR precipitation estimates, the current investigation has shown that lower estimates by the algorithm are particularly biased for extreme precipitating systems that contain significant mixed phase and/or frozen hydrometeors.

The regions of South America that experience the most frequent extremely deep convective storms are in the subtropics and not regions that regularly receive large amounts of climatological rainfall (Zipser et al. 2006). Therefore, a significant per-
centage underestimation of the convective precipitation in storms containing DCCs and/or WCCs can greatly affect our perception of the climatology and hydrology of these relatively arid regions. In contrast, but equally important, horizontally intense storms (i.e., those containing WCCs and/or BSRs) frequently occur over the wet Amazon Basin (Romatschke and Houze 2010). These storms are less impacted by the TRMM precipitation bias; however, because they account for so much rain in the largest rainforest in the world, their bias is also of great hydrologic significance. These lessons for South America imply further that for understanding the global distribution of precipitation, it is necessary to examine the biases in precipitation estimates from not only deep convective storms but all systems that extend above the 0°C level that have significant precipitation ice. The results presented here can therefore likely be extended to similar regions around the low-latitude world observed by the TRMM satellite while we await the more advanced radar and algorithms of GPM.
Chapter 5

HYDROLOGICAL IMPACT OF EXTREME STORMS IN SOUTH AMERICA

Publication reference:

5.1 Introduction

Precipitation from thunderstorms, mesoscale convective systems (MCSs), and extreme storms can greatly influence agricultural, socioeconomic, and human conditions around the globe. Before the launch of satellites with spaceborne radars, it was difficult to study the physics and characteristics of storms in remote regions; however, radar observations from the Tropical Rainfall Measuring Mission (TRMM) satellite have revolutionized our ability to observe and analyze storms in these regions. The TRMM satellite was designed to measure the spatial and temporal variation of tropical and subtropical rainfall around the globe with the goal of understanding the factors controlling the precipitation. Furthermore, the satellite’s ability to discern storm structures in three dimensions makes it possible to determine the nature of the storms producing the rainfall. Using these data to study the frequency and intensity patterns of extreme precipitation events in the current climate will help to anticipate changes in these patterns as climate changes occur. In the present climate, extreme
convection tends to form in the vicinity of mountain ranges, and the Andes in subtropical South America help spawn some of the most intense deep convection in the world (Zipser et al. 2006). In general, regions experiencing the most precipitation typically do not coincide with regions known to have frequent deep convection (Zipser et al. 2006). However, mesoscale convective systems (MCSs) can contribute a large fraction of the warm season rainfall due to their large size, long-lived nature, and frequent occurrence in regions downstream of major mountain barriers (Fritsch et al. 1986; Durkee et al. 2009). It therefore seems important to focus on the horizontal as well as the vertical scales of the convective storms producing precipitation.

The intense deep convection in subtropical South America is frequently related to organized MCSs, which are the intense convective systems with the largest horizontal and time scales. MCSs are comprised of an ensemble of convective storms that can produce intense rain rates within contiguously sizable precipitation areas. MCSs typically contain both contiguous zones of intense convective rainfall and adjacent regions of stratiform precipitation. An investigation of the most intense storms in 11 years of TRMM Precipitation Radar (PR) data has shown a tendency for squall line MCSs to initiate and develop east of the Andes with a mesoscale organization similar to storms in the U.S. Great Plains (Rasmussen and Houze 2011). In subtropical South America, however, the topographical influence on the convective initiation and maintenance of the MCSs is unique. Low-level moisture from the Amazon is capped by lee subsidence, as a result of the mechanical displacement of air flowing over the Andes (Rasmussen and Houze 2011; Rasmussen and Houze 2014). The Andes and other mountainous terrain of Argentina focus deep convective initiation in the Argentinian foothills (Romatschke and Houze 2010; Rasmussen and Houze 2011; Rasmussen and Houze 2014). Subsequent to initiation, the convection often evolves into propagating MCSs similar to those seen over the U.S. Great Plains and produces damaging tornadoes, hail and floods across a wide agricultural region (Rasmussen and Houze 2011; Rasmussen et al. 2014). However, the extreme vertical extent of
the Andes tends to keep the South American storms tied to the topography during upscale organization and development longer than those in the U.S. and is related to enhanced lee cyclogenesis, frictional deformation, and wake effects (Rasmussen and Houze 2014). Understanding how both similarities and differences in the cloud populations downstream of major mountain barriers of the world contribute to variations in hydrometeorological conditions will lead to a greater understanding of orographic precipitation processes in general with potential applications for other regions of the world.

The goal of this study is to assess the contribution of precipitation from extreme storms to the climatological precipitation in South America. A quantitative approach will be used to investigate how the most extreme MCSs play a role in the hydrological cycle of the La Plata basin, including an assessment of the influence of the seasonal and diurnal cycle and regional differences. From a hydrological standpoint, empirical knowledge of the precipitation from extreme storms in South America is critical, as the type of runoff and flooding that may occur depends on the specific character of the convective storm and precipitation reaching the surface, and has broad implications for the hydrological cycle in this region. Near the northern foothills of Argentina, landslides and floods are very common during the spring and summer months as well as regions further to the east. The type of hydrologic response likely depends on the type of storm that impacts a region. Systems consisting of deep convective, wide convective, and broad stratiform components produce different hydrologic responses and thus understanding the hydrological implications for each type of event is crucial to hydrologic forecasting efforts in subtropical South America. While many studies have investigated extreme storms and their overall spatial and temporal characteristics within South America, few studies have considered the hydrological impact of the precipitation specifically from storms containing extreme radar echoes. This investigation of how high-impact weather plays a role in the hydrological cycle in the La Plata Basin, including the assessment of the influence of the season and diurnal cycle,
is crucial for understanding the hydrometeorology in subtropical South America with implications for forecasting and human impacts.

5.2 Data and Methodology

The TRMM Precipitation Radar (PR) is advantageous for storm climatology studies because it is not obstructed by topography, as are ground-based radars. In addition, ground-based radars do not exist near many of the Earth’s mountain ranges. The TRMM PR has fine three-dimensional spatial resolution (4–5 km horizontal, 250 m vertical) with a near-uniform global coverage that permits comprehensive analysis between 36°N and 36°S (Kummerow et al. 1998; 2000). This study uses 15 years of TRMM PR data from January 1998 to December 2012, during the austral spring through fall seasons (SONDJFMAM). We focus on the austral spring (SON) and summer (DJF) to specifically address the impact of extreme storms on warm season precipitation. The following TRMM data products are used:

1. 2A23—rain characteristics (Awaka et al. 1997); Rain is separated into three categories: convective, stratiform, and other; all references to convective and stratiform precipitation are based on these classifications

2. 2A25—rainfall rate and profile (Iguchi et al. 2000a, b); provides the attenuation-corrected three-dimensional reflectivity data

These data were processed following the methodology of Houze et al. (2007) and Romatschke et al. (2010). All of the fields were mapped onto a 0.05° by 0.05° latitude-longitude Cartesian grid. We first identify all contiguous three-dimensional echo objects. Each such object is called a ‘storm.’ Each storm may contain embedded features with certain properties that are useful in characterizing the nature of the storm. Such embedded features have been defined and used in previous studies by Houze et al. (2007), Romatschke et al. (2010), Romatschke and Houze (2010),
Rasmussen and Houze (2011), Rasmussen et al. (2013), Zuluaga et al. (2014), and Rasmussen et al. (2014a, b). Embedded features that identify storms with convective and stratiform features of an extreme nature include: 1) deep convective core (40–dBZ echo $\geq 10$ km in maximum height; DCC), which are associated with severe weather and vigorous convection; 2) wide convective core (40–dBZ echo $\geq 1,000$ km$^2$ when projected onto a horizontal plane; WCC), which are normally associated with mesoscale convective systems (MCSs) from an early to middle stage in their life cycle; and 3) broad stratiform region (stratiform echo $\geq 50,000$ km$^2$ when projected onto a horizontal plane; BSR), which are normally associated with mature MCSs. These three extreme storm categories are used to understand the contribution of extreme storms to the hydrological cycle in various regions of South America. For this study, precipitation that is produced by a ‘core’ is defined as the rain falling from an embedded echo of one of the types defined above, whereas the precipitation from a ‘full storm’ is the rain falling from the full storm containing the embedded feature.

Finally, to provide a full perspective of the TRMM data, we define a ‘rain event’ as any contiguous non-zero raining entity $\geq 2$ radar reflectivity pixels. All rain events seen by the TRMM PR are identified and the precipitation produced by these events provide the rainfall climatology data. A similar threshold was used in Romatschke and Houze (2011) to calculate the climatological precipitation in South Asia to reduce errors from ground clutter and other sources. Rain events are different from the extreme storm types defined above and will be used to compare the entire convective population to the extreme storms in this study.

5.2.1 TRMM Precipitation Radar algorithm bias

Previous studies have suggested that the TRMM PR rainfall algorithm tends to underestimate the precipitation from deep convection over land (Iguchi et al. 2009). Chapter 4 investigated the scope of this bias in extreme storms in South America and confirmed that the TRMM PR algorithm tends to underestimate rain in all three
extreme echo types due to insufficiencies in the rain algorithm in capturing the full
characteristics of deep convective storms over land regions. Rasmussen et al. (2013)
showed that lower estimates by the algorithm are particularly biased for extreme
precipitating systems that contain significant mixed phase and frozen hydrometeors.
Regions of South America that experience the most frequent extreme deep convective
cores are in the subtropics and are not regions that regularly receive large amounts of
climatological rainfall, thus an underestimation of the climatological precipitation can
influence the perception of the climatology and hydrologic cycle in South America.

To mitigate the TRMM PR algorithm bias for the exact types of storms studied here, we adopted the methodology of Chapter 4 that uses the $Z-R$ relationship (Equation 5.1),

$$Z = aR^b$$

where $Z$ is equivalent radar reflectivity factor in units of mm$^6$ m$^{-3}$ and $R$ is the
rain rate in mm h$^{-1}$. This relationship is used to estimate precipitation from the
TRMM PR attenuation-corrected reflectivity data. The lowest nonzero value of $Z$ is
used at each data pixel between the surface and 2.5 km above ground level for each
precipitation echo, which is similar to the value used in the TRMM PR algorithm
(Rasmussen et al. 2013). The parameters $a$ and $b$ are constants depending on rain
type (convective, stratiform, or other). As described in Rasmussen et al. (2013) that
tested multiple values for these parameters, our study uses the conservative values
defined in Romatschke and Houze (2011). We use this $Z-R$ method to mitigate the
underestimation of precipitation for the extreme echoes seen by TRMM over land.

### 5.2.2 TRMM Overpass Probability Filter (TOPF)

TRMM PR data are ideal for studying the connection between convection and
precipitation since they provide information on the intensity and distribution of pre-
cipitation, rain type, storm depth, and the height at which snow melts into rain. However, one drawback to using the TRMM PR data is the differential coverage of the satellite as it orbits the tropics and subtropics of the Earth. In order to spatially compare the precipitation contributions pixel-by-pixel, a TRMM overpass probability filter (TOPF) is defined in Equation 5.2.

\[
TOPF = \left( \frac{\text{number of storm pixels}}{\text{number of TRMM pixels}} \right)
\]  

(5.2)

The TOPF accounts for the differential overpass frequency of the TRMM satellite, since the higher latitudes are more frequently observed than the lower latitudes (Negri et al. 2002). To account for this difference, the TOPF is calculated at each pixel in the study region by accounting for the number of times a TRMM-identified extreme storm pixel is present divided by the total number of pixels seen by TRMM. The TOPF is then multiplied by the ratio of the precipitation contributed by a particular type of storm to the total climatological precipitation at each pixel (Equation 5.3).

\[
\text{Adjusted rain contribution} = \left( \frac{\text{rain due to a particular type of storm}}{\text{total rain}} \right) \times TOPF
\]  

(5.3)

The resulting values represent a satellite overpass-corrected field of the rain contribution from each storm type to the total precipitation in the study region. By using this technique, this study will assess how much of the climatological rain is contributed by each extreme storm type in different regions of South America to provide insights into the influence of extreme storm-related precipitation on the hydrologic cycle in various regions of South America.

5.3 Climatological and regional storm characteristics and precipitation

To obtain an overview of the climatological, regional, and hydrological characteristics of the precipitating systems in South America derived from TRMM PR data, we
examine their seasonal, regional, and storm-scale variability. Figure 5.1a shows the regions examined in this study as well as the major rivers in South America. The La Plata Basin in subtropical South America (Fig. 5.1b) is the fifth largest river basin in the world with an area of 3.1 million km$^2$, second only to the Amazon in South America (WWDR3 2009). Transportation via natural waterways in the La Plata Basin is an important part of the regional economy. Several hydroelectric plants provide energy to the region (Berbery and Barros 2002; WWDR3 2009). An understanding of the characteristics of storms producing rain in this very important hydrologic basin will provide guidance for water management and both seasonal and flood forecasting in South America.

### 5.3.1 Precipitation events seen by the TRMM satellite

To better understand the climatological and regional storm characteristics of precipitation in South America, it is important to first investigate all rain events seen by TRMM and the climatological rain they produce. Intense convective systems tend to occur in the austral spring and summer seasons in South America, thus these seasons will be the main focus of the analysis in this study. For an overview of the event frequency and rainfall produced in South America, Figure 5.2 shows the probability of TRMM finding a rain event (defined as any contiguous, non-zero raining entity $\geq 2$ reflectivity pixels; see Section 5.2) during the austral spring season (SON; Fig. 5.2a) and the climatology of precipitation generated by these events (Fig. 5.2b). Although the precipitation maps shown in Fig. 5.2b and throughout this study are created with TRMM orbital data (i.e., instantaneous measurements over an orbital swath), the spatial patterns of rainfall are in agreement with those climatologies of precipitation relying on continuous and merged multi-sensor measurements (e.g., Huffman et al. 2001; Rozante et al. 2010; Liu 2015). In the austral spring, more rain events tend to occur in the tropical Amazon Basin than the subtropics, particularly near the Andes foothills. However, the precipitation climatology for the spring shows a
Figure 5.1: (a) Topographical map of South America showing the Andes mountain range, associated terrain features, and major rivers. Selected regions for this study are outlined in black and labeled. (b) Map of La Plata Basin including topography, major tributaries, and cities [source: Wikimedia Commons].
robust rain maximum in southern Brazil and northeastern Argentina, likely related to frequent MCSs in this region. Rasmussen et al. (2014) (Chapter 3) examined the lightning and severe storm characteristics of storms in the austral spring season and showed that a maxima in lightning and flood storm reports are collocated with the rain maximum seen in Fig. 5.2b, likely related to storms with both deep and wide convective characteristics. However, more rain in the subtropical maximum is produced by fewer overall events than the lower amounts in the tropics produced by more events.

Focusing on the warm season in South America, Figure 5.3 shows the probability of TRMM detecting a rain event and the climatological rainfall in the austral summer season (DJF). The contrast between the tropics and subtropics in the number of TRMM rain events is much greater than for the austral spring (Fig. 5.3a). The Amazon Basin has a large amount of climatological rain contributed by many raining events in the region. However, the subtropics receive substantial rainfall despite how few events occur there compared to the tropics. Similar to the austral spring season (Fig. 5.2), the subtropical rainfall is produced by fewer events than the tropics. Additionally, the subtropical region exhibits a distinct shift in the probability of TRMM rain events and climatological precipitation to the west toward the Andean foothills. A similar shift in extreme storm occurrence and lightning production is shown in Rasmussen et al. (2014) (Chapter 3), consistent with convective initiation and upscale growth into MCSs in subtropical South America (Romatschke and Houze 2010; Rasmussen and Houze 2011; Rasmussen and Houze 2014).

Figure 5.4 presents an overview of the probability of finding the three categories of extreme radar echo structures with the TRMM satellite (defined in Section 5.2) for both the austral spring and summer seasons. Deep convective cores are notably absent in the tropical Amazon (Fig. 5.4a, b). Comparing to Figures 5.2 and 5.3, we conclude that a large amount of precipitation in the Amazon Basin must be contributed by a shallower maritime-like convective population. This result verifies the frequently
Figure 5.2: (a) Geographical distribution of the probability of finding a TRMM rain event (≥ 2 pixels) during the austral spring season (SON) from 1998–2012. (b) Precipitation climatology for all rain events identified in (a). The contour inside the continent represents the 500 m terrain elevation.
Figure 5.3: Same as in Fig. 5.2, but for the austral summer season (DJF months).
made claim that the Amazon region is climatologically similar to a tropical ocean; sometimes this characterization is referred to as the Amazon region being a “green ocean.” This study is an objective verification of that characteristic. Interestingly, the regions with the highest probability of extreme echo occurrence in the subtopics are collocated with the maximum in precipitation in the spring and summer seasons, consistent with the findings of Rasmussen et al. (2014) (Chapter 3) for extreme storm-related lightning and severe storm reports. The amount of climatological precipitation contributed by these extreme storms will be presented in Section 5.4.

Previous studies on subtropical South American convective systems in the austral summer season hypothesize a storm life cycle where convection initiates along the Andean foothills, grows upscale into MCSs while propagating east or northeast and then decays into broad stratiform regions farther east (Romatschke and Houze 2010; Rasmussen and Houze 2011). Given that the storm type distributions of DCCs, WCCs, and BSRs are all located in southern Brazil and northeastern Argentina unlike the summer patterns, a slightly modified storm life cycle likely occurs during the austral spring and should be investigated in a future study.

Table 5.1 shows the overall statistics of the total number of TRMM rain events and TRMM-identified extreme storms (defined in Section 5.2) for the austral spring through fall seasons, and identified in each region defined by the boxes in Fig. 5.1. In general, more storms containing wide convective cores were identified in most regions. However, the ratio of the number of extreme cores to the total TRMM rain events is very low (Table 5.2). The highest percentage of extreme storms to total events are WCCs in the La Plata North and South regions (1.8 and 1.9% respectively) that experience frequent MCSs in the spring and summer seasons. However, ∼2% of the storms in each region likely make up a large fraction of the climatological rain, echoing the discussion of Figures 5.2 and 5.3 above. This type of assessment of how much rain each storm type contributes to will provide crucial information for water management and extreme-storm related flood risks in subtropical South America.
Figure 5.4: Geographical distribution of the probability of finding an event by each extreme type during the austral spring (SON; left column) and summer (DJF; right column) from 1998–2012. This figure is an updated version of Figure 5 from Romatschke and Houze (2010).
### Table 5.1: Number of extreme echo cores in each of the study regions.

<table>
<thead>
<tr>
<th></th>
<th>Sierra de CORDOBA</th>
<th>Foothills</th>
<th>South</th>
<th>North</th>
<th>La Plata</th>
<th>Highlands</th>
<th>Brazilian</th>
<th>Atlantic</th>
<th>Amazon</th>
<th>Plateau</th>
<th>ALI</th>
</tr>
</thead>
<tbody>
<tr>
<td>6,0'47'4</td>
<td>44</td>
<td>112</td>
<td>131</td>
<td>103</td>
<td>1,466</td>
<td>1,477</td>
<td>2,272</td>
<td>772</td>
<td>22</td>
<td>341</td>
<td>346</td>
</tr>
<tr>
<td>71,5'43'6</td>
<td>1'049</td>
<td>620</td>
<td>2,315</td>
<td>888</td>
<td>1,821</td>
<td>1,789</td>
<td>2,315</td>
<td>76</td>
<td>427</td>
<td>346</td>
<td>44</td>
</tr>
<tr>
<td>71,5'15'0</td>
<td>1'019</td>
<td>573</td>
<td>633</td>
<td>403</td>
<td>333</td>
<td>76</td>
<td>427</td>
<td>44</td>
<td>346</td>
<td>44</td>
<td>44</td>
</tr>
</tbody>
</table>

Total Count: 57,150, 715,435, 610,958, 191,789, 50,045, 123,712, 183,614, 64,714
<table>
<thead>
<tr>
<th></th>
<th>Alti Plano</th>
<th>Amazon</th>
<th>Atlantic</th>
<th>Brazilian Highlands</th>
<th>La Plata North</th>
<th>La Plata South</th>
<th>North Foothills</th>
<th>Sierras de Córdoba</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCC</td>
<td>0.6</td>
<td>0.06</td>
<td>0.01</td>
<td>0.3</td>
<td>0.8</td>
<td>0.5</td>
<td>0.05</td>
<td>1.6</td>
</tr>
<tr>
<td>WCC</td>
<td>0.6</td>
<td>0.3</td>
<td>0.3</td>
<td>0.6</td>
<td>1.8</td>
<td>1.9</td>
<td>0.3</td>
<td>1.6</td>
</tr>
<tr>
<td>BSR</td>
<td>0.04</td>
<td>0.08</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.06</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Table 5.2: Ratio of the number of extreme cores to the total TRMM storm counts (%).
5.3.2 Storm-scale precipitation characteristics

In general, larger precipitating systems tend to produce more rainfall (Houze 2014, Chapter 4). For an understanding of how the size of storms containing extreme radar echoes relate to their rain production, a storm-scale analysis is presented in this section.

For each TRMM-identified extreme core, the volumetric rain (kg s$^{-1}$) and storm area (km$^2$) is calculated from only the core footprint and for the full storm containing the core. A ratio of the core to full storm rain amount reveals how much of the total storm rain was contributed by the extreme core. A ratio of the core to full storm areas indicates how large the core is compared to its parent storm. Figure 5.5 presents a comparison of both rain (core volumetric rain ÷ full storm volumetric rain) and area (core area ÷ full storm area) ratios for each region and storm type in this study, expressed in percentages. Both convective storm types (DCC and WCC) and stratiform storm types (BSR) are represented on the same figure with different abscissa values for comparison.

Wide convective core rain and area ratios tend to be smaller than the DCC and BSR categories, likely because they usually represent the development and intensification stage of MCSs that are typically composed of both convective and stratiform precipitation. At an early stage, convection is more rigorous and storms containing DCCs are smaller than the other two categories in all regions (Table 5.3). However, WCCs are larger in area than DCCs, but they contribute less precipitation to their full storm, indicating the presence of stratiform regions with weaker precipitation.

In the case of storms with BSRs, Figure 5.5 shows that they contribute a large proportion of their full storm’s area and precipitation in much greater magnitude than storms with DCCs and WCCs. Storms containing BSRs are the largest storms considered here (Table 5.3) and they contribute a large proportion of their full storm’s area and precipitation (Fig. 5.5). Thus, Figure 5.5 shows that independent of location
Figure 5.5: Comparison of the ratio of storm area (core area ÷ full storm area) to the rain production (core rain ÷ full storm rain) estimated from the TRMM PR data for three storm types, expressed in percentages. Both convective (DCC and WCC) and stratiform (BSR) storm types are represented on the same figure with different scales on the abscissa for comparison.
<table>
<thead>
<tr>
<th></th>
<th>BSR</th>
<th>WCC</th>
<th>DCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>101.126</td>
<td>98.774</td>
<td>40.397</td>
<td>25.049</td>
</tr>
<tr>
<td>112.548</td>
<td>114.625</td>
<td>60.502</td>
<td>46.668</td>
</tr>
<tr>
<td>114.916</td>
<td>105.116</td>
<td>70.411</td>
<td>46.207</td>
</tr>
<tr>
<td>105.116</td>
<td>112.548</td>
<td>68.497</td>
<td>30.117</td>
</tr>
<tr>
<td>96.932</td>
<td>105.116</td>
<td>60.502</td>
<td>30.117</td>
</tr>
<tr>
<td>112.548</td>
<td>114.625</td>
<td>68.497</td>
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<td>114.916</td>
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<tr>
<td>105.116</td>
<td>112.548</td>
<td>68.497</td>
<td>30.117</td>
</tr>
</tbody>
</table>

Table 5.3: Averaged areas of full storms by region (km²).
and storm category, stratiform and convective systems have relatable precipitation and size characteristics in similar proportion regardless of climatological zones or regional characteristics. For all three extreme categories, both the area and precipitation ratio of the core to full storm strongly increases linearly. In regions where the extreme echo cores make up a larger proportion of the full storm area, they will have a greater contribution of rain to the storm total, regardless of the overall size of the storm.

5.4 Rainfall contributions by storms containing extreme radar echo structures

We further investigate the impacts of the precipitation produced by the extreme storms on South America by assessing how much climatological rain is contributed by these storms. Precipitation was calculated from all TRMM rain events (Figs. 5.2b and 5.3b) and from the extreme storms. To accurately present precipitation seen by overpasses of the TRMM satellite, the TOPF filter was applied to the ratio of extreme storm to total rain (Equations 5.2 and 5.3) to account for the differential coverage of the TRMM satellite. Figures 5.6 and 5.7 represent the spatial distribution of the rainfall contribution to the total rain by each extreme storm type during the austral spring and summer seasons.

Although the extreme storm cores make up less than 2% of the total events in all regions, they are capable of producing a significant amount of the total climatological rain in the spring, specifically in the subtropics east of the Andes over the La Plata Basin (Figure 5.6). Overall, WCCs are the strongest contributors to the climatological rainfall in South America (Figure 5.6b). DCCs contribute relatively little total rainfall since they tend to be smaller and shorter-lived storms than WCCs or BSRs. Precipitation from BSRs tends to maximize in southern Brazil, just east of the maximum in WCCs, consistent with the hypothesis that storms grow and decay as they propagate eastward (Romatschke and Houze 2010; Rasmussen and Houze 2011). The
Figure 5.6: Geographical distribution of the rainfall contribution to the total rain by each storm type during the austral spring season (SON). The rainfall contribution was multiplied by TRMM Overpass Filter (TOPF) to account for the differential coverage of the satellite (see Equations 5.2 and 5.3 in Section 5.2). The thick black contour represents the 500 m terrain elevation.
Figure 5.7: Same as in Fig. 5.6, but for the austral summer season (DJF months).
rain contributions from wide cores are of extreme importance to the subtropical spring season, most notably to the La Plata Basin, where the maximum of WCC occurrence and precipitation are collocated (Figs. 5.4b and 5.6b). The storms containing wide convective cores have both very intense rainfall and have organized up to a larger horizontal scale. Thus, they have the double advantage of heavy rain elements and large area.

Echoing the southwestward shift from the spring to summer season storm probability distributions (Figure 5.4), the rain contributions for each storm type also shift southwestward toward the Andean foothills (Figure 5.7). DCCs contribute more rain to the total compared to the spring and the pattern is focused around the Sierras de Córdoba Mountains in Fig. 5.7a suggesting stronger orographic forcing in the summer. Similar to Figure 5.6, WCCs contribute the most climatological rain in the subtropics near central Argentina and Uruguay. This region is important because frequent extreme MCSs occur here (Romatschke and Houze 2010; Rasmussen and Houze 2011; Rasmussen et al. 2014; Rasmussen and Houze 2014). Rasmussen et al. (2014) showed a similar southwestward shift in the occurrence of flooding events in the spring to summer season transition (Figs. 5.6 and 5.7), associated with the same storm types examined in this study. Both flash floods and slow-rise floods have been associated with extreme events producing large amounts of rainfall, thus this study is consistent with the findings of Rasmussen et al. (2014). In both the spring and summer seasons, Figures 5.6 and 5.7 clearly show that the dominant contribution to the total rain is by WCCs in subtropical South America.

Some studies have focused on the North Foothills region labeled in Fig. 5.1. These studies have focused on the narrow maximum of climatological rain along the foothills of the Andes in southeastern Peru and northern Bolivia (Mohr et al. 2014; Garreaud 1999) as seen in Figures 5.2 and 5.3, but Figures 5.6 and 5.7 show no significant precipitation along the North Foothills by extreme storms. This result implies that the maxima of precipitation along the North Foothills must be due to smaller or
weaker non-extreme echoes that likely form from frequent uplift of warm tropical air by the low-level easterly winds consistently impinging on the tropical Andes foothills. A full characterization of the storms in the tropical Andes foothills is beyond the scope of this study and will be explored in future work.

Figure 5.8 shows the accumulated precipitation contributions for each storm type and region in the spring and summer seasons, expressed as percentages. Consistent with Figures 5.6 and 5.7, the contribution from extreme storms to the climatological precipitation is very small in tropical South America compared to the subtropics (Fig. 5.8). Storms with wide convective cores contribute more rain than the other extreme storm categories throughout most of the precipitation regions, which is consistent with higher ratios of WCC events to TRMM rain events in Table 5.2. The variations in contribution by storms with DCCs, WCCs, and BSRs to the total rain in the subtropics support the storm life cycle hypothesis from Romatschke and Houze (2010) and Rasmussen and Houze (2011). Higher percentages from DCCs in the Alti Plano and Sierras de Córdoba regions along the Andes foothills highlights the role of terrain features in convective initiation, as has been recently demonstrated via mesoscale modeling as will be discussed in Chapter 7 and Rasmussen and Houze (2014). Farther east over La Plata Basin, storms with DCCs contribute less rain, while contributions from storms with WCCs to the total rain are $\sim$15–20% higher than in the Sierras de Córdoba region due to upscale growth and intensification of convective systems. Moving farther east where MCSs tend to decay and become more stratiform in nature, contribution by storms with DCCs and WCCs decrease over the Atlantic Ocean. Contributions from storms with BSRs increase from low values near the foothills out to the Atlantic Ocean.

The La Plata Basin South region shows the highest contribution from extreme storms with 43% of the total summer rain falling from storms containing WCCs. Given that the La Plata Basin is the 5th largest river basin in the world, having 43% of warm season rainfall come from an extreme storm type typically associated with
### Figure 5.8: Percentage of the accumulated rainfall contribution from each storm type (indicated by the colors in the legend) to the total accumulated precipitation in each region.

Values on the left represent the contribution from the austral spring season (SON) and the ones in parentheses are from the austral summer season (DJF).

<table>
<thead>
<tr>
<th>Region</th>
<th>SON (%)</th>
<th>DJF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCC</td>
<td>0.8 (0.4)</td>
<td>1.3 (0.1)</td>
</tr>
<tr>
<td>DWCC</td>
<td>1.5 (0.02)</td>
<td>1.2 (0.04)</td>
</tr>
<tr>
<td>WCC</td>
<td>24.7 (17.4)</td>
<td>5.3 (12.8)</td>
</tr>
<tr>
<td>BSR</td>
<td>10.2 (10.4)</td>
<td>6.2 (10.9)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>SON (%)</th>
<th>DJF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCC</td>
<td>1.3 (1.7)</td>
<td>1.6 (2.0)</td>
</tr>
<tr>
<td>DWCC</td>
<td>15.9 (7.9)</td>
<td>9.8 (3.3)</td>
</tr>
<tr>
<td>WCC</td>
<td>32.8 (30.7)</td>
<td>29.5 (37.8)</td>
</tr>
<tr>
<td>BSR</td>
<td>14.6 (13.2)</td>
<td>31.6 (20.3)</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>SON (%)</th>
<th>DJF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCC</td>
<td>6.0 (6.7)</td>
<td>1.7 (1.9)</td>
</tr>
<tr>
<td>DWCC</td>
<td>18.0 (21.6)</td>
<td>19.1 (17.9)</td>
</tr>
<tr>
<td>WCC</td>
<td>31.0 (29.8)</td>
<td>10.0 (43.1)</td>
</tr>
<tr>
<td>BSR</td>
<td>14.4 (7.6)</td>
<td>38.7 (31.7)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>SON (%)</th>
<th>DJF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCC</td>
<td>1.7 (1.9)</td>
<td>0.3 (0.1)</td>
</tr>
<tr>
<td>DWCC</td>
<td>19.1 (17.9)</td>
<td>1.2 (1.0)</td>
</tr>
<tr>
<td>WCC</td>
<td>10.0 (43.1)</td>
<td>6.6 (28.2)</td>
</tr>
<tr>
<td>BSR</td>
<td>38.7 (31.7)</td>
<td>42.3 (33.2)</td>
</tr>
</tbody>
</table>
MCSs demonstrates their considerable role in the hydrologic cycle in subtropical South America. Combining both extreme convective and stratiform elements, ~95% of the total summer rain in the La Plata Basin South region is contributed by all four storm categories studied here. Recall that from Table 5.2, extreme storms in the La Plata Basin South region make up only ~3% of all raining events that occur in this region. This implies that ~3% of all events in the basin are responsible for producing ~70% of the spring precipitation and ~95% of the warm season precipitation in the La Plata Basin South. The importance of understanding the character of storms contributing very large fractions of precipitation to regions with populations susceptible to frequent flooding (Rasmussen et al. 2014) that rely on hydroelectric power and transportation via major waterways is clear. Frequent MCSs in subtropical South America dominate the hydrologic cycle in the region as shown in Figures 5.6-5.8.

Unlike the subtropics, precipitation in tropical South America has a much more maritime nature in proximity to the Amazon Basin. This maritime character does not promote the generation of deep or intense convective systems on a regular basis (Figs. 5.6 and 5.7). Thus, the contribution from storms with extreme embedded features to the total rainfall in the tropics is relatively low compared to the subtropics (Fig. 5.8). Rain contributions in the North Foothills and Amazon regions are surprisingly similar given their proximity to the Andes. While the orographic influence of the Andes in subtropical South America on the rain contributions by convective categories is prominent in Figure 5.8, contributions by all four extreme categories are notably low and similar in the tropical regions (North Foothills and Amazon). One exception is storms containing WCCs in the austral spring season, whose proximity to the Andes affects the magnitude of their rain contribution. However, the relationship to the Andes is much stronger in the subtropics because of the relationship to convective storm initiation and development (Romatschke and Houze 2010; Rasmussen and Houze 2011; Rasmussen et al. 2014; Rasmussen and Houze 2014).
5.5 Seasonal and diurnal precipitation variability

Figure 5.9 shows a monthly time series of the accumulated rain contribution from the three storm types (i.e. storms containing DCCs, WCCs, and BSRs) in the North Foothills and Amazon (Fig. 5.9a) and La Plata South and Sierras de Córdoba (Fig. 5.9b), expressed as percentages. In the tropical regions (Fig. 5.9a), the relative rain contributions from each storm type are relatively similar, suggesting the more maritime-nature of convection in those regions. A separate diurnal analysis for these two regions shows a maritime character as well (not shown). The two subtropical regions (Fig. 5.9b) also exhibit similarities in the storm type rain contribution percentages, with a notable maximum in contributions by storms containing DCCs and WCCs in the austral summer months (DJF). In contrast, BSRs are minimum in the austral summer, likely indicating the presence of fewer frontal systems with associated stratiform echo in subtropical South America during the summer season.

To assess the impact of the diurnal cycle on the rain contributions from extreme storms, time-longitude diagrams representing the diurnal progression of rain contribution are presented in Figure 5.10 during the austral summer season. The data shown in each panel are averaged over a meridional band bounded by 36°S–28°S, which was chosen because it includes the La Plata Basin and Sierras de Córdoba Mountains.

DCC initiation begins at 2pm local time near the Andean foothills, which is consistent with solar heating of the Andes combined with South American low-level Jet (SALLJ) bringing moisture south from the Amazon to provide a favorable environment for deep convection (Romatschke and Houze 2010; Rasmussen and Houze 2011; Rasmussen et al. 2014; Rasmussen and Houze 2014). In Figure 5.10a, the black contours represent the precipitation from DCCs only, indicating the strong tendency for DCCs to appear at the time of initiation of convection in the immediate foothills of the Andes. The eastward-propagating pattern in Figure 5.10a thus indicates how the DCC and WCC echo characterizations relate to each other in a time-sequential
Figure 5.9: Monthly time series of the accumulated rain contribution, expressed as percentages, from storms containing DCCs, WCCs, and BSRs in the (a) North Foothills and Amazon, and (b) La Plata South and Sierras de Córdoba regions.
Figure 5.10: Time-longitude diagrams representing the diurnal progression of the contribution to the total rain climatology from storms containing (a) DCCs, (b) WCCs, and (c) BSRs for the austral summer season (DJF months). The black contour in (a) is the contribution from those events that were classified as DCC only (see text). The diagrams are averaged over a meridional band bounded by 36°S–28°S. The gray line in each plot represents the average topographic relief between 36°S–28°S with a maximum height of 3500 m.
sense. The observed behavior that DCCs form at initiation but then storms grow upscale after initiation to form storms of mesoscale dimension that contain WCCs as they propagate eastward. This behavior is consistent with that hypothesized by Romatschke and Houze (2010) and Rasmussen and Houze (2011) (Chapter 2).

As storms containing DCCs move eastward from the foothills into the plains, growing upscale into intense WCCs, they contribute more climatological precipitation (Fig. 5.10a, b). By late afternoon and early evening, the MCSs are more developed and contain WCCs that are nocturnal, cover large areas on average, and tend to last ~18 hours (Fig. 5.10b). As the convective elements within the WCCs begin to lose their buoyancy at a mature phase, they transition into stratiform precipitation. Figure 5.10c shows that this transition occurs in the early morning and persists through midday. However, a sharp cutoff in the precipitation at the edge of the continent ~50°W indicates that the storms significantly weaken as they move off the coast and over the Atlantic Ocean. Figure 5.10 is consistent with similar studies investigating the diurnal characteristics of MCS-related precipitation over the United States (Trier et al. 2010).

Rasmussen et al. (2014) (Chapter 3) recently found that the diurnal patterns of extreme storm-related lightning exhibit a convective back-building tendency toward the Andes that is not present in Figure 5.10. Thus, while the convective intensity along the Andes foothills remains strong from the early afternoon through the early morning (Figure 3.4 in Chapter 3), the precipitation associated with the eastward-expanding MCSs moves eastward along with the growing systems.

5.6 Hydrological synthesis

The hydrologic cycle related to convective storms in South America has been previously investigated in studies that use merged satellite data, radiosondes, ground-based rain gauges, or reanalysis data to assess their contribution to the climatological rainfall (Berbery and Barros 2002; Durkee et al. 2009; Romatschke and Houze 2013;
Viale and Garreaud 2014). However, these previous studies did not precisely identify the nature of the convective clouds producing the precipitation, whereas the present study determines quantitatively the amount that originates from storms with specific types of vertical and horizontal structures (DCCs, WCCs, and BSRs). This method has accounted for all of the precipitation seen by the TRMM satellite over South America, providing a rigorous calculation of the impact of the more extreme types of storms on the hydrologic cycle in the region. From the discussions in Sections 5.4-5.5, extreme convective storms have the greatest impact on the La Plata Basin in South America. Given that the La Plata Basin produces $\sim 70\%$ of the Gross National Product for countries within the basin (Mechoso et al. 2001; WWDR3 2009), major rivers in the basin supply $\sim 80\%$ of the electricity to the region through hydroelectric power, and it is the fifth largest river basin in the world, an understanding of the storms that contribute 70-95\% of the rainfall associated with convective storms in the region (Fig. 5.8) is extremely important. Changes in the timing, frequency, location, or intensity of the MCSs that contribute large fractions of precipitation to the region can critically affect the hydrometeorology of the La Plata Basin that depends on these types of storm systems for agricultural irrigation, hydroelectric power, and human consumption.

Table 5.4 compares the relative impact of extreme storm precipitation in the tropics and subtropics during the austral spring and summer seasons. Although tropical South America has a higher number of events and more climatological rain, the relative impact of total extreme storm precipitation on the hydrologic cycle of the Amazon is a factor of 2–3 lower than the subtropics. The most notable differences in extreme storm rain contribution are with storms containing DWCCs, WCCs, and BSRs. These storm types are associated with storms organizing on the mesoscale, which occurs more frequently in subtropical than tropical South America (Romatschke and Houze 2010; Rasmussen and Houze 2011). Strong moisture advection from the Amazon Basin via the SALLJ provides the necessary low-level instability required for
<table>
<thead>
<tr>
<th>Storm type</th>
<th>Tropics (%)</th>
<th>Subtropics (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep convective full storms</td>
<td>1.4 / 0.5</td>
<td>1.6 / 1.9</td>
</tr>
<tr>
<td>Deep and wide convective full storms</td>
<td>2.3 / 0.5</td>
<td>11.2 / 9.8</td>
</tr>
<tr>
<td>Wide convective full storms</td>
<td>24.5 / 13.8</td>
<td>34.5 / 33.2</td>
</tr>
<tr>
<td>Broad stratiform full storms</td>
<td>9.5 / 10.4</td>
<td>38.4 / 26.9</td>
</tr>
<tr>
<td>Total rain contribution</td>
<td>39.1 / 25.2</td>
<td>85.7 / 83.5</td>
</tr>
</tbody>
</table>

Table 5.4: Climatological rain contribution in the tropics and subtropics of South America (full storm precipitation ÷ total precipitation) in the austral spring and summer seasons (represented as SON / DJF), expressed in percentages.

the convective initiation in the foothills of the Andes (Rasmussen and Houze 2014). Additionally, the extreme vertical extent of the Andes results in strong lee cyclogenesis associated with the frictional deformation of baroclinic waves passing over the southern Andes, which sets up a strong N–S pressure gradient accelerating the SALLJ and moisture flux into the region (Rasmussen and Houze 2014). Convective initiation along the immediate foothills and Sierras de Córdoba Mountains in the summer season and subsequent upscale growth into MCSs provides the storm life cycle that matches the hydrological analysis presented in this study.

Assessing the contribution to the climatological precipitation from MCSs in the United States showed that between 30–70% of the warm season rainfall comes from mesoscale convective weather systems (Fritsch et al. 1986). Durkee et al. (2009) estimated that between 30–50% of the rainfall in subtropical South America comes from MCSs using merged satellite precipitation data. However, consistent with the findings of Fritsch et al. (1986) in the U.S., this study shows that extreme storm types associated with MCSs contribute a much greater fraction of the climatological rainfall in subtropical South America. This similarity in MCS rainfall contribution is consistent with the findings of Rasmussen and Houze (2011), who recognized a
similarity between the mesoscale organization of MCSs in South America and the
U.S. Thus, the results from this study are consistent with other rain contribution
estimates from the U.S. (Fritsch et al. 1986) that also experiences frequent MCSs.

A further comparison to the precipitation in the U.S. is presented in Figure 5.11,
which shows the diurnal cycle of the climatological precipitation from all TRMM
rain events averaged in the same region as Figure 5.10 (36°S–28°S). Figures 5.10
and 5.11 show relatively similar diurnal patterns at similar longitudes showing the
strong influence of frequent MCSs in subtropical South America. Compared to the
diurnal cycle of precipitation in the U.S. presented in Trier et al. (2010), heavy
rain rates occur much closer to the large mountain barrier than in the U.S. and the
movement of precipitation seems to be slower in general. The midnight to early
morning nocturnal maximum in precipitation intensity is also observed in the U.S.,
although it tends to occur farther downstream of the mountain barrier compared to
South America (Trier et al. 2010). In addition, Figure 5.11 shows that most of the
rainfall associated with these events is concentrated along the Andes foothills and
persists for multiple hours rather than propagating rapidly eastward after initiation
[Figs. 1 and 2 from Trier et al. (2010)]. Thus, although the relative contribution
from MCSs to the warm season precipitation is similar in amount in the U.S. and
subtropical South America, the tendency of the intense storms to remain close to the
mountains in South America indicates different processes at work to maintain the
storms and control their propagation.
Figure 5.11: Time-longitude diagram representing the diurnal progression of the rain rate climatology from all events (≥ 2 pixels) during the austral summer season. The diagram is averaged over a meridional band bounded by 36°S–28°S. The grey line represents the average topographic relief between 36°S–28°S with a maximum height of 3500 m.
Chapter 6

SATELLITE VALIDATION OF MICROPHYSICS PARAMETERIZATIONS IN REMOTE REGIONS

Publication reference:

6.1 Introduction

Satellite observations have vastly improved our understanding of weather phenomena around the world since the 1960’s. The first precipitation radar in space aboard the Tropical Rain Measurement Mission (TRMM) satellite that was launched in 1997 marked the beginning of a new era of scientific discovery. The TRMM Precipitation Radar (PR) has enabled detailed analysis of three-dimensional storm structures around the low-latitude regions of the globe (Zipser et al. 2006, Houze et al. 2007, Romatschke and Houze 2010, Zuluaga et al. 2014, and many others). Studies investigating the nature of precipitating systems in remote regions without access to ground-based or in situ data are particularly noteworthy since in some cases, precipitating systems in those regions were viewed with radar technology for the first time with the TRMM PR. Given that 16 years of high-resolution three-dimensional radar information is available within the TRMM domain, this data should be used in a variety of applications. However, an understanding of the characteristics of storms occurring in remote regions of the world must be obtained before mesoscale modeling
efforts can be fruitful.

In recent years, high-resolution mesoscale modeling tools have become freely available to researchers around the world. While extensive testing and validation of these models have occurred in the United States and elsewhere with access to adequate validation observations, evaluating the performance and quality of the model data in remote regions of the globe without sufficient ground-based or in situ data is a challenging issue that limits the utility of mesoscale modeling tools in those regions. To provide a framework for evaluating modeling data in remote regions without access to sufficient validation information, we present here a method to use information from the TRMM and geostationary satellites to evaluate the three-dimensional structures of modeled precipitating systems in the tropical and subtropical regions of the world. While the TRMM satellite currently observes tropical and subtropical regions, the recently launched Global Precipitation Measurement (GPM) satellite will provide high-resolution data throughout the midlatitudes and tropics and will continue to revolutionize our view of precipitating systems around the world. A mesoscale models ability to reproduce observed precipitating systems is crucial to the application of the modeling results as a poor simulation can be misleading and unrepresentative of the true nature of the phenomenon. Satellite validation of mesoscale models in remote regions of the world is necessary to ensure that the simulated systems are realistic and can lead to insight into the storm formation and dynamics in places never before possible without detailed in situ or ground-based information.

From a modeling perspective, accurately representing the three-dimensional structures of convective storms in numerical models is extremely challenging and has been an important topic of research in the mesoscale modeling community for many years (Riehl and Malkus 1958, Simpson and Wiggert 1969, Klemp and Wilhelmson 1978, Rotunno et al. 1988, Fovell and Ogura 1988, and others). The structural characteristics of a convective system are highly dependent on the horizontal and vertical distribution of precipitating and non-precipitating hydrometeors; thus the microphysical
parameterizations of hydrometeors are very important in mesoscale modeling. Fovell and Ogura (1988) showed that by including ice microphysics in model simulations of mid-latitude squall lines, the storm structure was more realistic compared to simulations without ice, especially in the trailing stratiform region. The improved storm representation was primarily attributed to the rearward transport of low-density snow. However, the inclusion of hail hydrometeors negatively impacted the storm structure as the hail depleted the snow field, which was crucial to developing stratiform precipitation in their simulations. Limitations of microphysical schemes have until recently made it difficult to accurately reproduce the observed cloud and precipitation structures in model simulations of a variety of storm types that occur in different climatic regimes. The performance of microphysics schemes available in the Weather and Research Forecasting (WRF) model have been extensively tested for idealized and real case studies in the United States with sufficient validation data (Bryan and Morrison 2012, Morrison and Milbrandt 2011, Liu et al. 2011, Dawson et al. 2010, etc.). However, the impact of using different microphysics schemes on model-simulated precipitating systems has been limited in remote regions of the world because of a lack of reliable surface and upper air observations that sample those systems. Powell et al. (2012) investigated the performance of six microphysics schemes in simulating non-precipitating anvil clouds of mesoscale squall line systems in west Africa and found that single moment schemes (WSM6 and GCE) best reproduced the non-precipitating anvil reflectivity structure. In their study, ground validation with an ARM/DOE W-band radar enabled precise analysis of the vertical structure of the simulated cloud structures. However, due to the attenuation of the radar beam in the precipitating regions of the storm, they focused on the non-precipitating anvils in the storms and did not compare the performance of the schemes in the precipitating region. The results from Powell et al. (2012) stand in contrast to the general result that double moment schemes more accurately reproduce the vertical structures of the precipitating regions of mesoscale convective systems (Morrison et al. 2009, Morrison and Milbrandt 2011,
Bryan and Morrison 2012). The need to evaluate the model parameterizations used in different regions, seasons, and phenomena is clear, even in remote regions without access to adequate validation information.

Seemingly insignificant differences in the parameterizations of various hydrometeor species can greatly influence the resulting storm structure and dynamics of simulated storms. A variety of simple to complex microphysics schemes are currently available in mesoscale modeling frameworks, and the choice of scheme may depend on the application (e.g. numerical weather prediction, mesoscale modeling, and regional climate simulations). This study will investigate the performance of multiple microphysics schemes that are commonly used in the WRF model with the explicit purpose of simulating and reproducing observed TRMM Precipitation Radar (PR) data in subtropical South America, a region without access to adequate validation information. Extreme convection tends to form in the vicinity of mountain ranges, and the Andes in subtropical South America help spawn some of the most intense convection in the world (Zipser et al. 2006). These and other extreme convective storms in subtropical South America have not been extensively studied because of the historical lack of specialized observational platforms, infrastructure, and the remote nature of the region. The synoptic environment and mechanisms leading to extreme convection and mesoscale convective systems (MCSs) in subtropical South America have been examined in recent literature, and they have some similarities to those found in other regions of the world, including the United States (Carlson et al. 1983, Velasco and Fritsch 1987, Romatschke and Houze 2010, Rasmussen and Houze 2011, Rasmussen and Houze 2014). However, the role of the topography in convective initiation is a unique aspect of the extreme storms in subtropical South America that is not well represented in the United States where most of the mesoscale modeling validation efforts have occurred.

An investigation of the most intense storms in 11 years of TRMM PR data has shown a tendency for squall lines to initiate and develop in subtropical South Amer-
ica (Rasmussen and Houze 2011). The measurements from the TRMM satellite analyzed by Rasmussen and Houze (2011) provide an opportunity to compare the observed storms to their simulation by high-resolution modeling. Producing a simulated mesoscale system that closely resembles the storm structure identified by the TRMM PR, as well as the overall shape and character of the storm shown in the GOES satellite data, allows inference of the microphysical and dynamical characteristics of these extreme storms in addition to ensuring that the simulated storms are consistent with the available observations. The objective of this study is to employ a microphysics ensemble approach to produce multiple realizations of a TRMM-observed MCS in subtropical South America with various microphysics schemes to identify the most important processes in producing the observed three-dimensional storm structure that will facilitate future research and model validation efforts in remote regions of the world.

### 6.2 Model architecture and experimental design

The NCAR Advanced Research Weather Research and Forecasting (ARW-WRF) model version 3.2 (Skamarock et al. 2008) was used to simulate a case study detailed in Rasmussen and Houze (2011) (Figure 6.1). The model is a compressible, non-hydrostatic, three-dimensional mesoscale model and was initialized with GFS data at 00 UTC 27 December 2003 and run for 24 hours using a triple-nested domain of 27, 9, and 3 km (Figure 6.2). All of the domains used two-way nesting and each simulation had 34 uneven vertical levels with maximum resolution in the boundary layer. A summary of the experimental setup is shown in Table 6.1.

The simulations were conducted using five state-of-the-art microphysical schemes that form an ensemble test bed to investigate the role of the hydrometeor representation on the overall structure of the simulated MCSs. The simulations were run using identical input conditions and parameters for the different schemes. Table 6.2 shows the key properties and options used for the microphysics ensemble study. The
Figure 6.1: Storm that was identified by the TRMM PR as containing a wide convective core at 1002 UTC 27 Dec 2003. (a) Reflectivity from the TRMM PR in dBZ at 4 km overlaid on the GOES infrared satellite brightness temperature (K). The white lines indicate the TRMM PR swath and the red line indicates the location of the vertical cross section. The thick black contour outlines the 0.5-km topography. (b) Vertical cross section taken along the red line in (a) of the TRMM PR data. Reproduced from Rasmussen and Houze (2011) (Chapter 2).
### Table 6.1: WRF model setup

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<th>Scheme</th>
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<td>Rapid Radiative Transfer Model</td>
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</tr>
<tr>
<td>Shortwave radiation</td>
<td>Dudhia</td>
<td>Dudhia (1989)</td>
</tr>
<tr>
<td>Cumulus convection</td>
<td>Kain-Fritsch, none in Domain 3</td>
<td>Kain and Fritsch (1993)</td>
</tr>
<tr>
<td>Surface layer</td>
<td>Monin-Obukhov</td>
<td>—</td>
</tr>
<tr>
<td>Land surface</td>
<td>Noah Land Surface Model</td>
<td>Chen and Dudhia (2001)</td>
</tr>
<tr>
<td>Planetary boundary layer</td>
<td>Yonsei University (YSU) PBL</td>
<td>Hong et al. (2006)</td>
</tr>
</tbody>
</table>

An ensemble consisted of two single-moment schemes and three multi-moment schemes. Single-moment schemes predict the mixing ratios of hydrometeor mass and make assumptions about particle concentrations, while double moment schemes predict both mass mixing ratios and number concentrations.

Eleven years of TRMM PR data (Kummerow et al. 1998; Iguchi et al. 2000) were analyzed and separated into two convective storm types using a methodology developed by Houze et al. (2007). An algorithm identified contiguous three-dimensional echo structures from the TRMM PR data that had deep convective cores (40-dBZ echo $\geq 10$ km in maximum height; DCC) and wide convective cores (40-dBZ echo $\geq 1000$ km$^2$ when projected onto a horizontal plane; WCC). The case used for the simulations in this study on 27 December 2003 (detailed in Rasmussen and Houze 2011) contained both types of TRMM-identified echo cores (15,000 km$^2$ WCC, 16 km DCC). Synoptic analysis showed that at the time of the TRMM PR overpass, there was a baroclinic system passing over the southern Andes. The storm was located in a region of strong surface convergence, a sharp temperature and moisture gradient, and exhibited a leading-line/trailing-stratiform radar-echo structure in the TRMM PR data (Figure 6.1).
Figure 6.2: Domains used in the WRF simulations, centered over Argentina and the Sierras de Córdoba mountains (shown in the dashed black line). Topography is indicated in the grayscale shading. All simulations used the following domain setup: (1) Outer domain with a 27-km horizontal resolution and 209 x 184 grid points, (2) nested domain with a 9-km horizontal resolution with 374 x 341 grid points, and (3) inner domain with a 3-km horizontal resolution and 614 x 563 grid points.
<table>
<thead>
<tr>
<th>Microphysics Scheme</th>
<th>Description</th>
<th>Reference</th>
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<tr>
<td>WDM6</td>
<td>Double moment, 6-class scheme with graupel</td>
<td>Lim and Hong (2010)</td>
</tr>
<tr>
<td>Goddard (GCE)</td>
<td>Single moment, 6-class scheme with graupel, hail/graupel option</td>
<td>Tao and Simpson (1993)</td>
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<td>Milbrandt</td>
<td>Double moment, 7-class scheme with separate hail and graupel</td>
<td>Milbrandt and Yau (2005)</td>
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<tr>
<td>Morrison</td>
<td>Double moment, 6-class scheme with graupel, hail option</td>
<td>Morrison et al. (2005)</td>
</tr>
<tr>
<td>Thompson</td>
<td>6-class scheme with graupel, double moment for cloud ice</td>
<td>Thompson et al. (2008)</td>
</tr>
</tbody>
</table>

Table 6.2: Microphysics scheme descriptions

### 6.3 Satellite validation of model simulations

#### 6.3.1 Cloud shield comparison and precipitation hydrometeors

In this study, outgoing longwave radiation (OLR; W m$^{-2}$) is used as a proxy for the temperature and height of the upper-level cloud shield in deep convective systems as was shown to be a reasonable approximation for deep convection in Gutzler and Wood (1990). The lowest minimum and highest domain-averaged OLR values are from the WDM6 and GCE simulations (Table 6.3) and the cloud shields have intense deep convection while appearing less spatially coherent in comparison to the GOES IR data (Figure 6.3). Additionally, the lowest domain-averaged OLR values are from the Milbrandt and Morrison schemes (Table 6.3) and their cloud shields are to be too large in horizontal extent compared to the GOES IR data (Figure 6.3f). The Thompson scheme OLR cloud shield strongly resembles the GOES IR data in size,
shape, and placement relative to the topography.

Specific metrics comparing the ensemble members in Table 6.3 differentiates various aspects of the nature of the precipitation hydrometeors in each simulation. The domain-averaged and maximum rain rates (mm hr\(^{-1}\)) and the total accumulated precipitation (mm) for the microphysics ensemble members (Table 6.3) show that the GCE scheme has the highest values in all three categories. The GCE maximum rain rate is more than twice as high as the other schemes aside from the Thompson scheme. Additionally, the GCE domain-averaged rain rate is considerably higher than the others, but the total accumulated precipitation is not significantly larger. Additional analysis of the graupel mixing ratios (not shown) reveals that the GCE simulation converted a much larger amount of rain water into graupel than other schemes. The GCE scheme is known to convert too much rain water into precipitation ice that appears in these simulations as well. Thus, the GCE scheme is producing convective cells that are too strong, consistent with Figure 6.3, and the precipitation is raining out of the system too quickly, which can ultimately affect the lifetime, organization, and storm structure of the resulting MCS.

Further analysis represented in Table 6.3 indicates that the Thompson scheme has significantly more snow hydrometeors than the other schemes. However, Thompson et al. (2008) states that the snow and cloud ice categories overlap in their scheme since a size threshold (200 µm) is used for growth of snow by vapor deposition, which allows for small ice crystals to coexist with larger more rapidly falling snow hydrometeors. The Thompson scheme also uses a more sophisticated representation of snow than other schemes by allowing for non-spherical particles following the Cox (1988) modeling study and an observationally derived snow number density function from Field et al. (2005). This procedure likely allows the concentration of snow hydrometeors in the Thompson scheme to better represent the particle size distribution of snow and cannot be directly compared to the other schemes. Bulk microphysics schemes (WSM6, WDM6, GCE, Morrison, Milbrandt, etc.) typically assume a spherical snow
Table 6.3: OLR and precipitation hydrometeors

<table>
<thead>
<tr>
<th></th>
<th>MinOLR (W m$^{-2}$)</th>
<th>MeanOLR (W m$^{-2}$)</th>
<th>Total accum.precip. (mm)</th>
<th>Max rainrate (mm hr$^{-1}$)</th>
<th>Mean rainrate (mm hr$^{-1}$)</th>
<th>Mean MR (10$^{-3}$ g kg$^{-1}$)</th>
<th>Mean supercooled water (10$^{-6}$ g kg$^{-1}$)</th>
<th>Scheme</th>
<th>WDM6</th>
<th>Milbrandt</th>
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<td>2.1</td>
<td>2.2</td>
<td>118.2</td>
<td>2.87.679.34</td>
<td>2.867.934</td>
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<td>3.45</td>
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<td>1.9</td>
<td>3.669.49</td>
<td>116.3</td>
<td>3.669.49</td>
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<td>1.9</td>
<td>3.669.49</td>
<td>116.3</td>
<td>3.669.49</td>
<td>3.669.49</td>
<td>62.6</td>
<td>62.6</td>
<td>62.6</td>
<td>62.6</td>
</tr>
</tbody>
</table>
Figure 6.3: Cloud shield comparisons for the simulations using different microphysics schemes. Panels (a)-(e) show the outgoing longwave radiation (OLR; W m$^{-2}$) at the peak of storm development in each simulation. The labels indicate which microphysics scheme was used in each panel. The observed GOES infrared cloud shield, represented as brightness temperatures (Tb; K), is shown in (f).
shape with constant bulk density and an exponential shape for the snow size distribution even though observational studies rarely agree with this assumption (Westbrook et al. 2004, Brandes et al. 2007, Mitchell and Heymsfeld 2005, Field et al. 2005).

6.3.2 Three-dimensional storm structure comparison to TRMM PR data

While it is important for the model to produce realistic precipitation characteristics, it is imperative to produce that precipitation for the correct physical reasons. The microphysical processes producing precipitation are highly sensitive to the temperature and therefore altitude. It is therefore challenging for a model to produce the correct physical processes at every altitude, and if successful in doing so, the model is most likely producing the precipitation for physically correct reasons. We therefore attach great importance to determining how well the model reproduces both the vertical and horizontal structures of the storms in comparison to the vertical structures seen in the TRMM PR as it is our only vertical observation in this region.

Each microphysical scheme employed in this study produces hydrometeor size distributions and conversion processes differently. Figure 6.4 shows the simulated horizontal and vertical structures for each simulation (WDM6 not shown, similar to GCE results). All microphysics schemes tested for this case clearly show a leading line of convection (Figures 6.4a, c, e, g) with a connection to the Sierras de Córdoba Mountains resembling the TRMM PR data (Figure 6.1a). The vertical cross sections (Figures 6.4b, d, f, g) illustrate the ability of the model, with different microphysical schemes, to reproduce the vertical structure observed by the TRMM PR. The GCE scheme shows a region of large values of rainwater mixing ratios near the convective line consistent with the notion of raining out too quickly, likely at the expense of producing stratiform precipitation (Figure 6.4b and Table 6.3). The Milbrandt scheme (Figure 6.4d) shows a weak trailing stratiform region and large concentrations of graupel. The Morrison scheme (Figure 6.4f) indicates weak stratiform precipitation reaching the surface trailing the leading line of convection, which resembles the
TRMM PR data. However, relatively low values of rainwater mixing ratio and the absence of a clearly defined leading line of convection differs from the TRMM data. The Thompson scheme notably reproduces the vertical structure observed by the TRMM PR shown in Figure 6.4h. A clear leading line of intense convection with high rainwater mixing ratios directly beneath the highest concentrations of graupel is consistent with known hydrometeor distributions in MCSs (Biggerstaff and Houze 1991, Braun and Houze 1995). Additionally, a robust region of trailing stratiform precipitation is observed with the slight suggestion of a secondary maximum in the stratiform region as described by Houze et al. (1990) and Biggerstaff and Houze (1991), which is also present in the TRMM PR data (Figure 6.1b).

The Thompson scheme was originally developed to simulate aircraft icing incidents, thus an accurate representation of supercooled water was of utmost importance to the development of their scheme (personal communication, Roy Rasmussen). From Table 6.3, the supercooled water concentrations from the Thompson scheme are in the middle of the range of values and this seems to play a role in the development of stratiform precipitation in combination with a realistic snow distribution in the simulated MCS. Too much supercooled water can produce enhanced riming and aggregation that leads to greater fallout of large particles possibly to the detriment of the storm structure, which echoes the findings of Fovell and Ogura (1988). On the other hand, low values of supercooled water can restrict the vapor deposition process and growth of frozen hydrometeors, which also would limit the development of robust stratiform regions. Small particles coexisting with larger ones in physically realistic proportions seems to be important in reproducing both convective and stratiform elements in mesoscale modeling scenarios (Fovell and Ogura 1988) and has been a topic of study for the last ∼25 years. A ‘Goldilocks’ amount of supercooled water and a realistic snow representation appears to be an ideal combination in microphysics parameterizations to represent both convective and stratiform regions well.

This investigation of the performance of various microphysics representations in
Figure 6.4: Horizontal and vertical cross-sections for each of the microphysics ensemble members. Panels (a), (c), (e), (g), and (i) show the horizontal maximum reflectivity (dBZ) at the peak of storm development in each simulation. The labels indicate which microphysics scheme was used in each panel. Panels (b), (d), (f), (h), and (j) are the corresponding cross-sections from their horizontal representation along the red line in panels (a), (c), (e), (g), and (i). The color shading represents the rainwater mixing ratio (g kg$^{-1}$). The green contour represents the snow mixing ratio at 0.15 g kg$^{-1}$. The black contours represent the graupel mixing ratios at 0.15 (outer) and 2.5 (inner) g kg$^{-1}$. The blue contour represents the cloud ice mixing ratio at $5 \times 10^{-2}$ g kg$^{-1}$. The magenta dashed line represents the 0°C level.
Figure 6.4: Continuation of Figure 6.4
the WRF model for use in future studies has illuminated key physical processes that lead to the production of a robust MCS structure in a remote region without adequate ground-based measurements. A similar analysis of the performance of various modeling scenarios and other types of parameterizations in remote regions of the world can be compared to a variety of satellite measurements to ensure consistency and accuracy of the resulting simulations.

6.4 Conclusions

A representative case that was observed by the TRMM PR in subtropical South America has been simulated using a high-resolution mesoscale model to illustrate the utility of validating model results with satellite data in remote regions of the world. High-resolution mesoscale models are now freely available and widely used in a variety of applications including case study analysis, numerical weather prediction, and regional climate modeling. However, when such studies occur in regions of the globe without access to adequate ground-based data to assess the quality of the resulting simulations, the results are limited by the understanding of the phenomena, and performance of the model and its parameterizations in that region. Satellite data of various types that cover remote regions of the world can potentially fill the gap in observations that limits the utility of mesoscale modeling simulations. This study presents a method to use both TRMM PR data and geosynchronous infrared data to identify the best simulation among an ensemble of microphysics scheme tests. However, many other methods and satellites can be used depending on the application and goals of the studies using mesoscale models.

Given that previous studies demonstrated that convection in this region is among the most intense anywhere in the world (Zipser et al. 2006) and the historical lack of observational and ground-based data from this region, modeling studies present a unique opportunity to investigate these intense storms and compare the simulations to available satellite data. The three-dimensional representation of hydrometeor dis-
tributions greatly affects the models ability to reproduce observed stratiform regions in MCSs (Fovell and Ogura 1988, Morrison et al. 2009, Morrison and Milbrandt 2011, Bryan and Morrison 2012) Thus, this study used an ensemble approach to investigate the performance of various microphysics schemes in reproducing the three-dimensional MCS structure in subtropical South America seen by the TRMM satellite.

For an MCS in subtropical South America, the representation of snow hydrometeors and the amount of supercooled water in the simulation played an important role in generating stratiform precipitation as demonstrated by the Thompson scheme. By allowing a size threshold to enable small ice crystals to coexist with larger frozen hydrometeors, incorporating non-spherical snow particles, and using an observationally derived snow number density function, the Thompson scheme adequately simulated an MCS in this remote region. However, the manifestation of the various parameterizations in different regions, climate zones, and types of weather patterns will greatly differ, thus detailed testing and validation compared to satellite data should be performed in each remote region of interest. The framework for model validation in remote regions is relevant for a wide range of model parameterizations in various regions of the world.

Seemingly small differences in the representation of various hydrometeor species can substantially affect the resulting simulations of convective systems in a variety of climatic regimes, seasons, and regions of the world. Subtropical South America has been identified as having among the most intense deep convective storms in the world and frequently has MCSs in the austral spring and summer seasons. Understanding the convective processes and storm dynamics in this and other remote regions of the world require mesoscale modeling efforts. However, these efforts must adequately capture the structure and characteristics observed by the TRMM PR and other satellite data to eventually be able to learn about the lifecycle, convective initiation, and dynamics of precipitating systems. The GPM era will provide crucial data in remote regions from the mid-latitudes through tropics and the implications for mesoscale
model validation is an exciting prospect that will be explored in future work.
Chapter 7

CONVECTIVE INITIATION IN THE VICINITY OF THE SUBTROPICAL ANDES

Publication reference:

7.1 Introduction

Convective clouds and mid-latitude frontal systems are vital to both hydrologic and energy cycles on Earth. As the global climate changes, patterns of severe weather are likely to shift. In order to eventually include all types of storms in numerical forecasts, general circulation models, and climate projections, the physical mechanisms and specific details involving convection initiation, propagation, lifecycle, topographical effects, environmental influences, and hydrometeorological impacts from such storms need to be more fully understood. Around the globe, topography on every major continent influences the distribution of precipitation, cloud occurrence and type, climate regimes, convective storms, floods, high-impact weather, hydrometeorology, and much more.

Before the launch of satellites with spaceborne radars, it was difficult to study the physics and characteristics of storms in remote regions; however, radar observations from the Tropical Rainfall Measuring Mission (TRMM) satellite have revolutionized the ability to observe storms in these regions. In the present climate, extreme convect-
tion tends to form in the vicinity of mountain ranges, and the Andes in subtropical South America help spawn some of the most intense deep convection in the world (Zipser et al. 2006). Extreme deep convection is also located over the plains east of the Rocky Mountains in the United States, near the western Himalayas in South Asia, and the Sahel regions west of the Ethiopian highlands in Africa. This type of convection typically occurs near a mountain range, which is indicative of the orogenic nature of storms in these locations. Over the United States Great Plains region, a moist low-level flow originating from the Gulf of Mexico is typically capped by warm and dry air flowing off the Mexican Plateau and the Rocky Mountains from convective diabatic heating in the monsoon. This capping inversion inhibits the release of instability over large areas, while enhancing the intensity of convective outbreaks in narrowly focused regions (Carlson et al. 1983).

Velasco and Fritsch (1987), Zipser et al. (2006), and others have pointed out that a topographically-guided low-level jet bringing moist air poleward affects the occurrence of intense convection east of the Andes in South America, in a manner similar to processes east of the Rocky Mountains in the U.S. Severe convection in the U.S. and Andes regions, however, is released differently. Low-level moisture from the Amazon is capped by lee subsidence, as a result of the mechanical displacement of air flowing over the Andes (Rasmussen and Houze 2011). Convective initiation typically occurs as the moist northerly low-level flow encounters small foothills and a secondary mountain range east of the main Andes barrier (Romatschke and Houze 2010; Rasmussen and Houze 2011), whereas other features such as frontal or dry line convergence, gust front propagation off terrain, or mountain-plains solenoidal circulations are primary triggering mechanisms in the United States. On average, South American cloud shields associated with MCSs are 60% larger than those over the United States (Velasco and Fritsch 1987), the convection is deeper (Zipser et al. 2006), and they have larger and longer-lived precipitation areas than those over the United States or Africa (Durkee et al. 2009). In the subtropics, precipitation from
extreme storms seen by the TRMM satellite contributes ~95% of the climatological warm season rain in the La Plata Basin (Rasmussen et al. 2014c).

Rasmussen and Houze (2011) used eleven years of TRMM Precipitation Radar (PR) data to show a tendency for squall lines to initiate and develop east of the Andes with a mesoscale organization similar to storms in the U.S. Great Plains. In subtropical South America, however, the topographical influence on the convective initiation and maintenance of the MCSs is unique. The Andes and other mountainous terrain of Argentina focus deep convective initiation in the Argentinian foothills (Romatschke and Houze 2010; Rasmussen and Houze 2011). The MCSs developing after initiation produce damaging tornadoes, hail and floods across a wide agricultural region (Rasmussen and Houze 2011; Rasmussen et al. 2014b).

Cecil (2009, 2011) used TRMM Microwave Imager (TMI) data to objectively identify hailstorms using ice scattering as a proxy and found southeastern South America to be a likely region of large hail production. More recently, Cecil and Blankenship (2012) found that northern Argentina and Paraguay have the highest frequency of significant hail (≥ 1 inch diameter) using AMSR-E data globally. Extreme convective storms over subtropical South America are also associated with significant crop damage and a large number of fatalities, flooding events, and tornadoes (Altinger de Schwarzkopf and Russo 1982; Nascimento and Marcelino 2005; Rasmussen and Houze 2011; Matsudo and Salio 2011; Rasmussen et al. 2014b). Thus, subtropical South America is an important, albeit understudied natural laboratory and socioeconomic venue for investigating the climatological factors controlling severe weather and MCSs along a major mountain range.

Idealized modeling can be used to diagnose specific convective processes and/or terrain impacts. For example, Smolarkiewicz and Rotunno (1990) performed idealized simulations of the flow around obstacles of varying β (across-stream length/along-stream length) dimensions and found that for larger values of β, the resulting lee vortices became larger and were located further downstream of the barrier. However,
in the current study, realistic topography is necessary to understand the subtle influences that both small and large terrain features have on the convective initiation and upscale growth of MCSs. In order to test how various terrain features influence the convection, modeling experiments were conducted with a variety of terrain configurations.

### 7.2 Model experimental design

Fifteen years of V7 TRMM PR data (Iguchi et al. 2000; Iguchi et al. 2009) were analyzed using a methodology developed by Houze et al. (2007). An algorithm identified contiguous three-dimensional echo structures from the TRMM PR data and categorizes them according to whether they contain deep convective cores (40-dBZ echo \( \geq 10 \) km in maximum height; DCC), wide convective cores (40-dBZ echo \( \geq 1000 \) km\(^2\) when projected onto a horizontal plane; WCC)), and/or broad stratiform regions (stratiform echo \( \geq 50,000 \) km\(^2\); BSR). DCCs represent vigorous developing convection and WCCs indicate convection that has organized on the mesoscale. Figure 7.1 shows the probability of finding one of these three types of echo features.

The NCAR Advanced Research Weather Research and Forecasting (ARW-WRF) model version 3.4.1 (Skamarock et al. 2008) was used to simulate a representative convective system discussed in Rasmussen and Houze (2011). The ARW-WRF model is a compressible, non-hydrostatic, three-dimensional mesoscale model. The model was initialized with GFS data at 00 UTC 26 December 2003 and run for 48 hours using a triple-nested domain of 27, 9, and 3 km (Figure 7.2). All of the domains used two-way nesting and each simulation had 40 uneven vertical levels with maximum resolution in the boundary layer. A microphysics ensemble study was first performed to assess which microphysics scheme best captured the TRMM PR data in three-dimensional space (Chapter 6). In terms of reproducing the TRMM PR data, the Thompson microphysics scheme best captured the mesoscale structure of the simulated MCSs. A summary of the model architecture and experimental setup used in all
Figure 7.1: Probability of finding (a) deep convective cores, (b) wide convective cores, and (c) broad stratiform regions in the austral summer season (DJF) from TRMM precipitation radar data (Updated from Romatschke and Houze 2010 and reproduced from Rasmussen et al. 2014c).
Table 7.1: WRF model setup

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<th>Physical process</th>
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<th>Reference</th>
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<td>Shortwave radiation</td>
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<td>Planetary boundary layer</td>
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<td>Hong et al. (2006)</td>
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simulations is shown in Table 7.1. The model simulations were conducted using six different terrain configurations (Figure 7.3) to investigate how changes in the Andes topography and related terrain features influence the convective initiation, intensity, spatial distribution, and character of the simulated convective systems. The WRF simulations were run using identical input conditions and parameters for the different terrain configurations detailed in Table 7.2.

The case simulated here contains both types of TRMM-identified echo cores (15,000 km² WCC, 16 km DCC). Synoptic analysis shows that at the time of the TRMM PR overpass, there was a baroclinic system passing over the southern Andes. The storm was located in a region of strong surface convergence, a sharp temperature and moisture gradient, and exhibited a leading-line/trailing-stratiform radar echo structure in the TRMM PR data (Rasmussen and Houze 2011).

As described in Section 7.4.2, a storm-tracking algorithm was developed for this study. At each time of the simulation, grid boxes that contained values within a certain threshold were identified. The latitude and longitude coordinates of those grid boxes were then averaged to get a domain-scale average of where those values were located. This technique is different from traditional storm-tracking algorithms because this study is concerned with cloud populations and not necessarily individual
Figure 7.2: Domains used in the WRF simulations, centered over Argentina and the Sierras de Córdoba mountains. Topography is indicated in the grayscale shading. All simulations used the following domain setup: (1) Outer domain with a 27-km horizontal resolution and 209 x 184 grid points, (2) nested domain with a 9-km horizontal resolution with 374 x 341 grid points, and (3) inner domain with a 3-km horizontal resolution and 614 x 563 grid points. The region outlined in the dashed red line represents the SALLJ region used for averaging in Tables 7.3 and 7.4.
Figure 7.3: Topography used for the WRF terrain modification simulations: (a) Control experiment, no modifications (CTRL), (b) Sierras de Córdoba (SC) mountains removed from the CTRL topography (CTRL_TM), (c) CTRL terrain reduced by 50% (HANDES), (d) SC mountains removed from the HANDES topography (HANDES_TM), (e) CTRL terrain increased by 20% south of 26.5°S (BSANDES), and (f) SC mountains removed from the BSANDES topography (BSANDES_TM).
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<tr>
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<td>Sierras de Córdoba mountains removed only</td>
</tr>
<tr>
<td>HANDES</td>
<td>50% reduction in CTRL terrain</td>
</tr>
<tr>
<td>HANDES_TM</td>
<td>HANDES without the Sierras de Córdoba mountains</td>
</tr>
<tr>
<td>BSANDES</td>
<td>20% increase in CTRL terrain south of 26.5°S</td>
</tr>
<tr>
<td>BSANDES_TM</td>
<td>BSANDES without the Sierras de Córdoba mountains</td>
</tr>
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</table>

Table 7.2: WRF terrain modification experiment summary

storm movement.

7.3 Synoptic evolution of convective storm environments

Synoptic analysis showed that at the time of the occurrence of the MCS simulated here, there was a baroclinic system passing over the southern Andes. The storm was located in a synoptic-scale region of strong surface convergence, a sharp temperature and moisture gradient, and exhibited a leading-line/trailing-stratiform radar-echo structure in the TRMM PR data (Rasmussen and Houze 2011; Chapter 2). To obtain an understanding of the occurrence of synoptic-scale patterns related to convective storm initiation and development, time-lagged composites associated with TRMM-identified WCCs in subtropical South America are presented in this section. Figure 7.4 shows a time-lagged sequence of composite 850-hPa (color contours) and 500-hPa (gray contours) geopotential height anomalies relative to the occurrence of a TRMM-identified WCC (labeled Day 0) in the La Plata Basin (-28 to -17°S; -61 to -54°W). Frequent incursions of cold air into the subtropics of South America are sometimes related to convective storm outbreaks (Garreaud and Wallace 1998). In particular relation to the occurrence of WCCs, the low-level pressure field exhibits significant frictional deformation while traversing the central to southern Andes (Fig.
7.4a-c). The Andes have an average altitude of \( \sim 4-5 \) km, but the average height decreases to the south. The mid-latitude synoptic features at low-levels traverse the mountains and experience significant frictional effects consistent with similar situations in other regions of the world influenced by large mountain ranges (e.g. The Rocky Mountains, East Asian Mountains, southern Alberta, and the European Alps; Chung 1977; Smith 1988). The deformation of the low-level pressure field slows down the movement of the wave and allows the upper-level low to catch up, forming the canonical lee cyclogenesis scenario that is frequently observed in the lee of the Rocky Mountains and other major mountain ranges (Smith 1986; Smith 1988). Some prior studies have documented the lee cyclogenesis effect east of the Andes (Chung 1977; Gan and Rao 1994), but Figure 7.4 establishes a specific connection between lee cyclogenesis and storms containing WCCs that typically manifest as MCSs with significant precipitation and severe weather (Rasmussen et al. 2014b-c).

The deepest 850-hPa low in the composite maps is observed in concert with the occurrence of storms containing WCCs (Figure 7.4d). Deep lee cyclogenesis occurs primarily from the atmospheric dynamics related to the westward-tilted upper- and low-level pressure anomalies (Palmén and Newton 1969). As air traverses a mountain range, a potential vorticity (PV) anomaly is formed on the lee side of the range related to the compression and stretching of vorticity by the lower boundary. Low-level lee cyclone development is the response to this PV anomaly, represented by the pressure pattern sequence in Figure 7.4. This situation is often associated with a strong baroclinic environment, supporting convergence with focused moisture and temperature gradients in the lee of the Andes, which was noted in Rasmussen and Houze (2011) for two case studies in this region.

In addition to the presence of lee cyclogenesis, a clear relationship between the South American Low-level Jet (SALLJ) strength and the lee cyclone is observed in Figure 7.5. Three days prior to the occurrence of a WCC in the La Plata Basin, the meridional wind strength related to the SALLJ (colored contours in Figure 7.5) is
Figure 7.4: Time-lagged climatological composite maps for days on which the TRMM PR showed storms containing wide convective cores over the La Plata South region (-28 to -17°S; -61 to -54°W) for (a) Day -3, (b) Day -2, (c) Day -1, (d) Day 0, (e) Day +1, and (f) Day +2. 850- and 500-hPa geopotential height anomalies (m) are represented by color and gray contours (dashed contours represent negative values), respectively.
Figure 7.5: Same as Figure 7.4, but for 850-hPa meridional wind anomalies (m s$^{-1}$) represented by the colored contours. Black composite horizontal 850-hPa wind vectors are shown for comparison.
only slightly higher than normal. However, in the two subsequent days prior to the WCC occurrence, the strength of the SALLJ becomes notably stronger (\(\sim\) twice as large as the climatological wind speed), that likely contributed to stronger moisture and warm temperature advection from the Amazon basin to the north. Given that a strong cyclone was developing in the lee of the Andes concurrently, this implies that the notable N–S pressure gradient along the eastern foothills of the Andes helped to strengthen the SALLJ through down-gradient suction effects, which also increased the available moisture and therefore the low-level instability required for extreme convective storms in the region. The meridional wind anomalies show that on the day when a storm containing a WCC is present in the La Plata Basin, the deep lee cyclone results in strong southerly flow along the Andes foothills that creates a strong zone of convergence that provides continued forcing for the longer-lived MCSs to develop and grow upscale.

The relationship between an enhanced SALLJ and convective storm occurrence was previously noted by Salio et al. (2007), but a full analysis of the mechanisms producing this change were not explicitly examined in their study. The robust signals in the composite maps (Figures 7.4 and 7.5) show that these two effects act in concert to provide a favorable environment for widespread and strong convection in subtropical South America. This observationally derived hypothesis will be tested in the numerical modeling experiments presented in the next section.

### 7.4 Convective initiation with various terrain configurations

To further probe the relationship between convective initiation and the Andes, terrain modification experiments were performed as described in Section 7.3. The six different terrain configurations used in the WRF simulations are summarized in Table 7.2 and these simulation names will be used throughout the rest of the manuscript. Three main types of modifications were conducted, including reducing and increasing the height of the Andes Mountains, and removing the secondary mountain range
east of the Andes (Sierras de Córdoba Mountains). The resulting suite of numerical experiments enables an analysis of the impact of both large and small-scale variations in topography in generating and organizing convective storms in the lee of the Andes.

In order to provide confidence in the simulations, Figure 7.6 shows a comparison of the GOES infrared satellite data and CTRL simulation outgoing longwave radiation (OLR; $W \, m^{-2}$) at key times in mesoscale storm development. In this study, OLR is used as a proxy for the temperature and height of the upper-level cloud shield in deep convective systems as was shown to be a reasonable approximation for deep convection in Gutzler and Wood (1990). At an early stage associated with convective initiation (Fig. 7.6a and c), the observed and modeled storms occur in a similar location on the eastern foothills of the Sierras de Córdoba Mountains at a similar time, providing confidence in the model representation of this process. Similarly, when the convective system has become more organized and grown upscale into a mature MCS feature (Fig. 7.6b and d), both the GOES-IR and model OLR fields show a deep circular cloud shield that is attached to the northeastern edge of the Sierras de Córdoba Mountains. Given that the CTRL simulation resembles the data obtained from the GOES-IR, the terrain modification experiments will provide a reasonable test of how various configurations of orography impact the resulting convective storms initiation, upscale growth, and development.

### 7.4.1 Lee cyclogenesis and the strength of the SALLJ

The occurrence of extreme convective storms in subtropical South America is often related to mid-latitude synoptic pressure systems passing over the southern Andes, as shown in Figures 7.4-7.5 and other studies (Garreaud and Wallace 1998; Romatschke and Houze 2010; Rasmussen and Houze 2011). Convective initiation typically occurs ahead of a cold frontal passage in the presence of strong northerly moisture flux from the Amazon Basin. As described in Section 7.3, time-lagged composites of pressure anomalies in reanalysis data shows a robust signature of lee cyclogenesis leading up to
Figure 7.6: Comparisons of the GOES infrared satellite data to the WRF CTRL simulations at an earlier initiation phase and a later mature phase of the storm life cycle. The panels show the following: (a) GOES IR brightness temperatures (K) at 2045 UTC on 26 December 2003, (b) Same as (a) but at 1045 UTC on 27 December 2003, (c) WRF CTRL simulation outgoing longwave radiation (OLR; W m\(^{-2}\)) at 20 UTC on 26 December 2003, and (d) Same as (c) but at 10 UTC on 27 December 2003. The thick black outline in all panels represents the 0.5 km topography for reference.
the occurrence of a storm containing a WCC. In this section, we test the hypothesis that the presence of a taller mountain range creates more deformation of the flow pattern as low-level synoptic features traverse the range, leading to a deeper lee cyclone. Figure 7.7 presents 850-hPa geopotential height difference maps compared to the CTRL simulation for each of the five terrain modification experiments. The most robust result is presented in the reduced Andes runs (Fig. 7.7b and c) wherein the lower mountain range produces a weaker lee cyclone compared to the CTRL case. Also notable is that this reduction is largest in the immediate foothills of the Andes, indicating the role of the terrain in the dynamical production of lee cyclogenesis as has been shown in many previous studies (Kasahara 1966; Smith 1984; Smith 1986). In contrast, when the southern Andes are increased in height (Fig. 7.7d and e), the lee cyclone appears to deepen, which is consistent with terrain-related lee cyclogenesis. Again, the enhancement of the lee cyclone is observed relatively close to the Andes Mountains, showing the role of the mountains and related flow deformation effects contributing to lee cyclogenesis.

Table 7.3 presents the averaged pressure perturbations from the initial time to the end time for all six terrain modification experiments in the SALLJ region shown in Figure 7.2. In the HANDES runs, the pressure perturbations are significantly lower in magnitude than the CTRL or BSANDES runs, echoing the patterns in Figure 7.7. In contrast, the BSANDES runs are slightly larger in magnitude than the CTRL runs, indicating the role of the higher southern Andes in producing a stronger lee cyclone. Thus, the model results appear to confirm the notion that a taller mountain range tends to produce deeper lee cyclogenesis associated with greater flow deformation along higher terrain, consistent with Figure 7.4. In other words, the higher the mountain range, the more difficult it is for synoptic disturbances to traverse the barrier and deeper lee cyclogenesis results.

To further investigate the behavior and strength of the SALLJ related to convective storms in this region, an analysis of the averaged meridional wind perturbations
Figure 7.7: Difference maps of 850-hPa geopotential height (m) from the terrain modification runs compared to the CTRL run at 7 UTC on 27 December 2003: (a) CTRL_TM - CTRL, (b) HANDES - CTRL, (c) HANDES_TM - CTRL, (d) BSANDES - CTRL, and (e) BSANDES_TM - CTRL. The 0.5-km topography in the CTRL run is outlined in black for reference.
Table 7.3: Time-averaged pressure perturbations from T=0 in each terrain modification simulation in the SALLJ region shown in Figure 7.2.

<table>
<thead>
<tr>
<th>Run</th>
<th>700-hPa lee pressure</th>
<th>850-hPa lee pressure</th>
<th>950-hPa lee pressure</th>
<th>SALLJ lee pressure (surface to 600 hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>-318.8</td>
<td>-371.2</td>
<td>-409.2</td>
<td>-377.8</td>
</tr>
<tr>
<td>CTRL_TM</td>
<td>-319.1</td>
<td>-371.6</td>
<td>-409.7</td>
<td>-378.1</td>
</tr>
<tr>
<td>HANDES</td>
<td>-194.4</td>
<td>-223.1</td>
<td>-242.5</td>
<td>-225.8</td>
</tr>
<tr>
<td>HANDES_TM</td>
<td>-194.8</td>
<td>-223.6</td>
<td>-243.2</td>
<td>-226.4</td>
</tr>
<tr>
<td>BSANDES</td>
<td>-321.5</td>
<td>-374.5</td>
<td>-413.0</td>
<td>-382.5</td>
</tr>
<tr>
<td>BSANDES_TM</td>
<td>-322.4</td>
<td>-375.9</td>
<td>-414.6</td>
<td>-381.1</td>
</tr>
</tbody>
</table>

is presented in Table 7.4 from the SALLJ region shown in Figure 7.2. The HANDES runs show a significant decrease in northerly wind strength, with positive values representing a faster-moving storm due to the presence of southerly flow in the SALLJ region as will be shown in Section 7.4.2 below. The lower mountains produce less flow deformation on the lower levels of the atmosphere and thus the synoptic systems traverse the mountains faster than the higher terrain runs. In addition, a weaker lee cyclone results in a weaker N–S pressure gradient force and therefore a weaker SALLJ. Thus, it seems that the combination of enhanced flow deformation leading to deeper lee cyclogenesis and a stronger N–S pressure gradient force are intimately related with the height and characteristics of the mountain barrier that control the response in the lee and help modulate the convective storm environment and the resulting storm lifecycle development in South America.
Table 7.4: Time-averaged meridional wind perturbations (m s\(^{-1}\)) from T=0 in each terrain modification simulation in the SALLJ region shown in Figure 7.2.
7.4.2 Convective initiation and storm development

Given that the synoptic-scale impacts of various terrain configurations produce significantly different results related to lee cyclogenesis and the strength of the SALLJ as shown in Section 7.4.1, an investigation of how various terrain configurations modify convective storm initiation and growth is presented in this section. Identifying the orographic controls on convective initiation and development near the Andes can be extended to other mountain ranges of the world for a greater understanding of global orographic impacts.

Figure 7.6 shows that at an early initiation time in the model simulations, the CTRL run resembles the observational GOES IR data in both temporal and spatial perspectives. Figures 7.8 and 7.9 present outgoing longwave radiation (OLR) difference plots compared to the CTRL run for each of the terrain modification experiments to determine the impact on convective storm initiation and development with varying topography. When the Andes Mountains are unchanged, but the Sierras de Córdoba mountains are removed (CTRL_TM; Fig. 7.8a), convective initiation appears to be weaker and more widespread than the simulation with the Sierras de Córdobas. Romatschke and Houze (2010) and Rasmussen and Houze (2011) hypothesized that this particular mountain range plays a strong role in both initiating and focusing convective initiation that is seen in Fig. 7.8a. However, in the evolution of the convective system in the CTRL_TM run, a storm system nevertheless occurs, but the overall convective storm intensity is less as will be discussed in Section 7.5.

The largest difference in convective initiation is observed in the 50% reduced Andes runs (HANDES; Fig. 7.8b and c). As is clearly seen in Figs. 7.8b and c, convective initiation occurs in a widespread band that extends north into Paraguay and northern Argentina that is not observed in the CTRL run. Rasmussen and Houze (2011) hypothesized that lee subsidence from the midlevel westerlies traversing the Andes Mountains provides a capping inversion of warm and dry air between ~20-
Figure 7.8: Difference maps of outgoing longwave radiation (OLR; \( \text{W m}^{-2} \)) from the terrain modification runs minus the CTRL run at 16 UTC on 26 December 2003: (a) CTRL_TM - CTRL, (b) HANDES - CTRL, (c) HANDES_TM - CTRL, (d) BSANDES - CTRL, and (e) BSANDES_TM - CTRL. The 0.5-km topography in the CTRL run is outlined in black for reference.
30°S, preventing low-level instability from releasing until it reaches the Sierras de Córdoba Mountains to the south. Rasmussen and Houze (2011) and Rasmussen et al. (2014b) discuss the role of the Sierras de Córdoba Mountains in focusing deep convection by providing an orographic lifting mechanism for the low-level unstable air to break through the capping inversion aloft. When the Andes Mountains are reduced to half their height in this study (Figs. 7.8b and c), convectively unstable air is more readily released with the lower mountain range. This is most likely due to a weaker capping inversion that cannot prevent the widespread release of convective instability compared to a taller mountain range. The thermodynamic considerations of convective available potential energy (CAPE) and convective inhibition (CIN) for the various terrain experiments are examined in Section 7.7 to address and confirm this notion. Increasing the southern Andes height by 20% shifts the convective initiation to the south (Figs. 7.8d and e), likely in response to the deeper lee cyclone and associated southward location of the region of convergence as noted in Section 7.3.

Corresponding to a mature phase of the convective storm life cycle shown in Figures 7.6b and d, OLR difference plots for the terrain modification experiments are presented in Figure 7.9 to gain insight into the role of terrain variations in upscale convective growth. Slight differences in the CTRL_TM from the CTRL run (Fig. 7.9a) indicate a slight northeastward shift in the mature convective system that could be related to the absence of the secondary mountain range that has been linked to both back-building and focusing convection (Romatschke and Houze 2010; Rasmussen and Houze 2011; Rasmussen et al. 2014b). However, the CTRL_TM storm location is relatively similar to the CTRL run, indicating that the presence of the Sierras de Córdoba do not tie the convective storms to the terrain in a general sense. Stronger orographic controls are observed in the simulations with 50% reduced Andes terrain (Figs. 7.9b, c). With the reduced Andes, the mature systems are located much farther east than the CTRL run, reminiscent of the typical MCS life cycle in the U.S. with a lower N–S mountain barrier. Weaker lee cyclogenesis and SALLJ strength
Figure 7.9: Same as Figure 7.8, but for 8 UTC on 27 December 2003.
combine to produce an environment that favors convective systems that propagate downstream from the mountain barrier more rapidly than for similar systems downstream of higher mountains. This clear difference between the MCSs observed in the lee of the Rockies and Andes is specifically related to the height of the barrier and the related synoptic and mesoscale dynamics that occur in response to large orographic barriers. Faster movement indicates weaker frictional deformation by lower mountains that enables more rapidly moving synoptic patterns in general. Increasing the southern Andes by 20% results in a southwestward shift of the convective systems (Figs. 7.9d, e), demonstrating an inverse relationship to Figs. 9b and c indicating the robust orographic control on MCSs in this region. Thus, as was demonstrated in Figures 7.5-7.9, reducing and increasing the Andes Mountains produces opposite results that indicate the strong role of the orography in modulating the resulting convective storm environments and storm development in subtropical South America. These results represent a case-study insight into the convective processes in the lee of the Andes, however further investigation into the generality of these findings should be conducted in future research.

To further investigate the relationship between orographic height and convective initiation, Figure 7.10 shows the results of a storm-tracking algorithm that identifies the average location of intense values of reflectivity and cloud top temperatures (description in Section 7.2). For simplicity, only the CTRL and HANDES runs are presented. Identifying regions with particularly intense reflectivity (dBZ) or cloud top temperature values is a commonly used technique in research around the world on convective storms seen by satellites (e.g., Zipser et al. 2006; Houze et al. 2007; Romatschke and Houze 2010; Yuan and Houze 2010; Romatschke et al. 2011; Zuluaga et al. 2013; Barnes and Houze 2013; Rasmussen et al. 2013; Zuluaga and Houze 2014; Zuluaga et al. 2014; Rasmussen et al. 2014a-c). For the analysis in Figure 7.10a, the reflectivity threshold was increased to 45 dBZ to capture the evolution of particularly intense storms. The reduced Andes simulation tended to have aver-
Figure 7.10: Storm track of averaged (a) model reflectivity ≥ 45 dBZ and (b) OLR ≤ 90 W m⁻². In each panel, the terrain modification experiment averages are represented by thick solid lines as shown in the legend. Averaged topography from 25 - 35°S for reference are shown in thin colored lines with the scale axis on the right side of the figure. The symbols represent the following: star – initial hour, circle – intermediate hour, square – end hour. The small numbers next to each symbol indicate the hour of the simulation.
age reflectivity $\geq 45$ dBZ farther north compared to the regular Andes terrain (Fig. 7.10a). Additionally, the HANDES storm track shows a more rapid northeastward movement of intense convective elements compared to the CTRL, which is consistent with the discussion above related to Figures 7.8 and 7.9. Comparisons between the storm tracks of the CTRL and HANDES terrain modification simulations with OLR values $\leq 90$ W m$^{-2}$ (Fig. 7.10b) also indicate a faster northeastward movement in the HANDES storm. However, the role of the barrier height in producing deep cold cloud tops closer to the mountain front is apparent in Figure 7.10b. With a lower Andes height, the HANDES storm track originates $\sim 2^\circ$ longitude east compared to the CTRL storm track. A larger mountain barrier creates stronger lee cyclogenesis, increased low-level jet magnitude, and down-gradient E–W suction as shown in this study in Figures 7.4, 7.5, and 7.7.

Additionally, lee vortices rotating toward the foothills of the mountain barrier in response to a strong low-pressure system, as was previously demonstrated in idealized simulations and for flow around the island of Hawaii (Hunt and Snyder 1980; Smolarkiewicz et al. 1988; Smolarkiewicz and Rotunno 1990; Rasmussen et al. 1989), are also observed near the southern Andes (Figs. 7.5d and e). Flow deformation related to lee cyclogenesis around the southern Andes produces an anticyclonic lee vortice as demonstrated in the above idealized and observational studies. However, the excessive height of the Andes precludes the formation of the northern cyclonic vortex as shown in studies using an idealized circular mountain or island terrain. Typically, the convergence of the lee vortice pair combined with the advection back toward the terrain feature and subsequent rising motion on the terrain produces weak precipitation, which is ideal for growing crops that require persistent light to moderate precipitation (e.g., coffee agriculture in Kona, HI in the lee of Mauna Kea and Mauna Loa; Rasmussen et al. 1989). However, in subtropical South America, the SALLJ provides convergence on the northern edge of the southern vortice and a similar return flow into the Sierras de Córdoba occurs in conjunction with baroclinic systems passing
over the southern Andes. This effect is seen in Figure 7.10b, with the CTRL pattern originating much closer to the foothills.

Thus, a large-scale wake low is formed in the lee of the Andes and processes important in smaller-scale flow around islands are also important downstream of the subtropical Andes. This effect likely contributes to the back-building or serial upstream propagating aspect of South American storms (Anabor et al. 2008; Rasmussen et al. 2014b), while the larger-scale convective systems themselves propagate to the east or northeast. Additionally, the frequent occurrence of deep and wide convective systems near the eastern foothills of the Andes has been noted in previous studies (Zipser et al. 2006; Romatschke and Houze 2010; Rasmussen and Houze 2011), in contrast to the known distributions of MCSs in the U.S. far downstream of the Rockies. However, the reasons for this difference are not well understood in the literature. By varying the topography in this study, a better understanding of why this difference exists provides a step forward in our study of global orographic precipitation and the physical processes leading to intense storms near major mountain ranges.

Examining the domain-scale effect of varying the topography and intensity of the resulting storms, Figure 7.11 presents storm intensity information for the duration of each terrain modification simulation. During the period of convective initiation in each simulation (between hours \( \sim 12-20 \)), the 40 dBZ echo tops were higher on average in the CTRL and BSANDES runs, which both include the Sierras de Córdoba mountains (Fig. 7.11a), indicating their role in focusing deep convection hypothesized in previous studies (Romatschke and Houze 2010; Rasmussen and Houze 2011). In contrast, the CTRL_TM and BSANDES_TM simulations without the Sierras de Córdoba produced notably lower echo tops, indicating a decrease in overall convective intensity in the absence of this secondary mountain range. Interestingly, this effect is not observed with the reduced Andes runs (HANDES), suggesting that the different dynamical effects also led to a different mode of convective initiation compared to the full or increased Andes runs. The HANDES runs both showed larger individual in-
Figure 7.11: Echo-top analysis calculated during the entire duration of the WRF simulations for each terrain modification scenario showing (a) the 40-dBZ echo-top mean (km) and (b) 40-dBZ echo-top $\geq 10$ km counts.
stances of 40 dBZ echo-tops exceeding 10 km (Fig. 7.11b), consistent with the larger zone of convective initiation extending much farther east and north compared to the CTRL run (Figs. 7.8b and c). With a lower mountain barrier and a weaker capping version, convection is able to break out at numerous locations instead of the strongly orographically forced and focused convective initiation with the full Andes. Thus, the lower Andes result in more instances of convective initiation, but the storms overall were weaker than the full Andes storms likely because of the differential build-up of convective instability.

7.4.3 Thermodynamic implications of terrain modifications

From the discussion in sections 7.4.2 and 7.4.3, it is apparent that thermodynamic understanding is crucial to fully parse the relationship between varying terrain and the resulting convective storms. This section specifically addresses the hypothesis from Rasmussen and Houze (2011) who showed that when storms with WCCs occurred in subtropical South America, lee subsidence related to the mechanical uplift and descent of the mid-level westerlies traversing the Andes was present in a broad zone between 20–35°S. Figure 7.12 shows two west-to-east cross-sections prior to the first instance of convective initiation in this region (Fig. 7.12a) and at a later time when a mature thunderstorm has formed in the lee of the Andes (Fig. 7.12b). Associated with stronger winds traversing the Andes, mid-level dry air advection is clear in both panels that forms a capping inversion to prevent low-level unstable air from releasing, supporting the hypothesis from Rasmussen and Houze (2011). In contrast to the typical situation in the U.S. Great Plains, where strong thermodynamic boundaries exist partially due to diurnal heating on the elevated Mexican Plateau that commonly produces a capping inversion preventing convective initiation (Carlson et al. 1983), South America seems to have more mechanically forced thermodynamic boundaries. Convection commonly initiates along drylines in the Great Plains of the U.S. that have been shown to be diurnally varying (Sun and Wu 1992), unlike the stationary
foothills that initiate and focus convection in subtropical South America (Romatschke and Houze 2010; Rasmussen and Houze 2011; Rasmussen et al. 2014b).

A common way to understand the thermodynamic environment related to convective initiation is to examine the convective available potential energy (CAPE) and convective inhibition (CIN), which indicates the amount of air parcel instability and the strength of the capping inversion, respectively. Time-averaged values of CAPE and CIN for each terrain modification experiment were calculated in the SALLJ region indicated in Figure 7.2. A strong relationship between the strength of the CAPE and CIN and the height of the mountains is revealed in Figure 7.13. The higher Andes had greater CAPE and CIN values compared to the reduced Andes values. A weaker capping inversion (lower CIN) resulted in more widespread convective initiation, but weaker storms (lower CAPE) in the HANDES runs (Figs. 7.8b-c and 7.11). With a taller barrier, both CIN and CAPE increased, making topographic initiation more important since the unstable air has a larger cap to overcome. Probing this effect in other regions of the world with significant mountain barriers can provide a better understanding of global orographic precipitating systems.

7.5 Conceptual model for convective initiation

A synthesis of the results presented in this study form a conceptual model for convective initiation in subtropical South America (Figure 7.14). Warm and moist low-level air advected from the Amazon Basin via the SALLJ is capped by mid- to upper-level dry air subsidence from the westerlies traversing the Andes Mountains. Leading up to the occurrence of extreme convective storms east of the Andes, the strength of the SALLJ and lee cyclone increase in response to synoptic baroclinic waves passing over the southern Andes. Lee cyclogenesis induces a N–S pressure gradient that helps bring air from the SALLJ into the foothills of the Andes instead of its climatological position to the east. Frictional deformation of the low- to mid-level flow around the southern Andes, where the height is decreased compared to its
Figure 7.12: Vertical cross-sections at 30°S with shaded contours of relative humidity (%), black contours of equivalent potential temperature, and white circulation vectors (m s\(^{-1}\)) at hours (a) 14 and (b) 22 of the simulation. Both panels are from the CTRL simulation with no topography modifications.
Figure 7.13: Summary of the relationship between convective available potential energy (CAPE), convective inhibition (CIN), and the WRF terrain experiments. Averaged CAPE and CIN values from hours 12-36 of each simulation are shown in blue and red circles, respectively.
tropical height, allows for the formation of a southerly wake flow reminiscent of lee vortices downstream of isolated islands. The area where the mid-level wake flow and the SALLJ converge is collocated with the Sierras de Córdoba, forming the optimal region for convective initiation in this region. Thus, while the Sierras de Córdoba help focus and initiation convective storms, they happen to be in an ideal location to intersect converging air from various sources as shown in Figure 7.14. A more complete understanding of the relationship between the terrain in subtropical South America and the extreme convective storms that occur there have been realized by probing the orographic controls that modulate convective initiation.

7.6 Conclusions

Numerical simulations using various terrain configurations conducted with the NCAR WRF model extend the satellite observational analysis of extreme convective storms in subtropical South America and provide an objective evaluation of storm initiation, development mechanisms, orographic controls, and storm-related thermodynamic characteristics. Modeling results from this study confirm that a capping inversion in the lee of the Andes is important in preventing premature convective initiation, as was hypothesized by Rasmussen and Houze (2011). Sensitivity studies removing and/or reducing various topographic features demonstrate the strong influence of the terrain on the initiation and upscale growth of the subsequent MCSs. The extreme vertical extent of the Andes tends to keep the South American MCSs tied to the topography during upscale organization and development longer than those in the U.S., related to enhanced lee cyclogenesis, flow deformation, and wake effects from a taller mountain range. Identifying common features and differences between the mechanisms producing extreme convection near major mountain ranges of the world is an essential step toward a general understanding of orographic precipitation on a global scale.

To better understand the role of larger-scale synoptic features on the initiation and
Figure 7.14: Conceptual model representing the key ingredients for convective initiation in the lee of the subtropical Andes. Blue arrows and text represent low-level flow, purple arrows and text represent mid-level flow, and red arrows and text represent mid- to upper-level flow. The region highlighted in orange represents the optimal region for convective initiation. Composite surface winds (m s$^{-1}$) for days when a wide convective core is located in the La Plata Basin regions are represented in black vectors.
development of convective storms in subtropical South America, time-lagged composite synoptic maps related to WCC occurrence in the La Plata Basin showed that the Andes have a significant influence on the synoptic patterns related to extreme storm occurrence. Leading up to the occurrence of storms containing wide convective cores, mid-latitude synoptic waves moving over the southern Andes experience significant frictional deformation from the tall mountains resulting in strong lee cyclogenesis in subtropical South America. Strong north-south pressure gradients associated with the deep lee cyclone encourage down-gradient northerly advection of warm and moist air from the Amazon via the South American Low-Level Jet (SALLJ). The strength of the SALLJ increases leading up to the occurrence of a wide convective core due to pressure-gradient suction from the strengthening lee cyclone.

Terrain modification experiments using a mesoscale model provided an objective test of the orographic controls on synoptic-scale disturbances that are related to the occurrence of storms containing wide convective cores. The results from the modeling experiments provide a greater understanding of the role of the Andes in modulating the synoptic environment leading to extreme convective storms. Lee cyclogenesis downstream of the Andes that was identified in the time-lagged synoptic composites was confirmed in the model simulations. A 50% reduction in the height of the Andes resulted in a weaker lee cyclone magnitude, weaker (N–S) pressure gradients, and decreased SALLJ strength. In contrast, a 20% increase in the height of the southern Andes Mountains, which essentially moved the slope to lower heights farther south, strengthened the lee cyclone and the associated N–S pressure gradient force that acted to increased the magnitude of the SALLJ. This increased northerly SALLJ magnitude advected more warm and moist air south to fuel the intense convective storms. Thus, an inverse relationship between the strength of both the lee cyclone and SALLJ and the height of the Andes is established, showing the profound role of the high mountains in establishing the convective storm environment that results in some of the most extreme storms on Earth.
The terrain modification experiments resulted in the following mesoscale conclusions:

1. A 50% reduction in the Andes Mountains resulted in convective initiation being more widespread throughout in a N–S band (extending north to Paraguay) east of the Andes. This effect is hypothesized to occur as a result of a weaker capping inversion from the lower mountains that are unable to prevent convective initiation compared to higher mountain ranges.

2. A mature MCS simulated with the 50% reduced Andes shows that the entire convective system propagated faster to the east, reminiscent of MCSs in the United States. This effect is hypothesized to occur because the flow deformation along the Andes is less with a lower mountain range so the low-level cyclone traverses the Andes faster than in higher terrain configurations. Additionally, the weaker lee cyclone has a weaker E–W pressure gradient force with weaker westward suction toward the mountain that typically provides a back-building aspect to the convective systems with the full Andes terrain.

3. Increasing the southern Andes height results in a southward shift in the convergence zone that shifts both convective initiation and the mature MCS south. The increased terrain where the Andes typically become less steep increases the flow deformation of low-level synoptic disturbances.

4. Averaged 40-dBZ echo top values throughout each terrain modification simulation shows that the presence of the Sierras de Córdoba mountains results in more intense storms for high mountain ranges. This partially confirms the hypothesis that this secondary mountain range tends to focus convective initiation in a narrow region particularly for high mountain ranges, as this effect was not present in the 50% reduced Andes run.
5. A time-series of the number of instances of 40-dBZ occurrence \( \geq 10 \) km in altitude showed that the 50% reduced Andes runs had more counts than other terrain modification simulations. However, according to the mean 40-dBZ echo top values, the storms simulated with the reduced Andes were weaker overall. The weaker capping inversion resulted in more instances of convective initiation, but generally weaker storms, likely because the convective instability was spread over more storm entities and released at many locations in the lee of the Andes.

6. Average maximum convective available potential energy (CAPE; indicating convective instability) and convective inhibition (CIN; strength of the capping inversion) values for each terrain modification simulation shows that the reduced Andes runs generally had less convective instability and a weaker capping inversion, while increased Andes runs had both stronger CAPE and CIN values. This perspective is entirely consistent with conclusion points above, demonstrating the profound influence of orography on the resulting convective systems.

This study has advanced our knowledge and understanding of the role of mountain front orography in the initiation and maintenance of extreme storms and an improved overall perception of the processes leading to high-impact weather and their simulation near major mountain ranges in subtropical South America. By nature, the study and investigation of high-impact and severe weather has wide reaching socioeconomic implications. A greater understanding of the formation mechanisms, patterns of development and organization, and severe weather impacts, including hail, flash floods and tornadoes, resulting from such storms can provide forecasters and the general public with crucial information to save life and property. In order to eventually forecast all types of storms and their effects via numerical weather prediction, general circulation, and climate models, such an integrated understanding is vital and this study provides a step in that direction. Argentine storms and MCSs have provided a unique opportunity for the integrated study of high-impact weather and mesoscale
modeling, including the orographic controls on convective initiation and storm life cycle near the Andes, and the synoptic and mesoscale influence on storm mechanisms. This research has resulted in an original conceptual model for convective storm environments leading to convective initiation in subtropical South America.
Chapter 8

DISSERTATION CONCLUSIONS

The objective of this dissertation is to gain a greater understanding of the physical processes, hydrologic implications, orographic controls, and human impacts of the most intense convective storms that occur near the Andes in subtropical South America. The TRMM satellite has shown that subtropical South America experiences the deepest convective storms in the world (Zipser et al. 2006), yet it is the most understudied region in the world experiencing such storms. On average, South American MCC cloud shields are 60% larger than those over the United States (Velasco and Fritsch 1987), the convection is deeper (Zipser et al. 2006), they have larger precipitation areas than those over the United States or Africa (Durkee et al. 2009), and they contribute up to $\sim95\%$ of the warm season rain in the La Plata Basin (Rasmussen et al. 2014c). Subtropical South America also has the highest frequency of large hail in the world (Cecil and Blankenship 2012), which severely impacts the wine agriculture in the Andean foothills (Rasmussen et al. 2014b). Other severe weather impacts including tornadoes and floods (Rasmussen et al. 2014b) also occur in this region.

Prior to the work presented in this dissertation, the mesoscale structure, hydrological impacts, orographic controls, severe storm impacts, and many more aspects of these storms were unknown. The primary mechanisms for deep convective initiation were relatively unknown and no conceptual model existed for these extreme storms. The research in this dissertation presents a comprehensive examination of the extreme convective storms that occur near the Andes in subtropical South America and has provided new insights into these convective systems including, but not limited to the following:
1. Seasonal and regional characterization of extreme storms seen by the TRMM Precipitation Radar.

2. Hypothesis that lee subsidence provides a dry and warm capping inversion that helps prevents the release of low-level unstable air advected into the subtropics by the South American Low-level Jet (SALLJ).

3. The degree of mesoscale organization of storms with extreme horizontal dimension are similar to the leading-line/trailing-stratiform archetype commonly observed in the United States.

4. The seasonal climatology of lightning in subtropical South America has a maximum in spring and fall over northeastern Argentina and Paraguay in association with storms containing deep convective cores, wide convective cores, or both. In summer, the maximum of lightning frequency shifts southwestward to the foothills of the Andes, where it is associated with storms containing deep convective cores, wide convective cores, or both. The lightning in this region at this time of year tends to remain over the foothills and Sierras de Córdoba while mesoscale convective systems develop and spread eastward while continuing to build on their western sides as convection continues to generate over the lower mountains.

5. A persistent nocturnal maximum of lightning activity is found over the foothills and Sierras de Córdoba in association with new convection, and with mesoscale systems that may continue to regenerate on their western sides while spreading eastward.

6. Flooding occurs throughout subtropical South America as a result of both flash floods near the foothills and Sierras de Córdoba, where storms with deep convective cores occur and slow-rise floods in the agriculturally rich Pampas
region, in association with storms containing wide convective cores. That is, the flash floods occur in the mountains with newly formed very intense and deep convection, whereas the floods over the plains occur in conjunction with mesoscale systems bearing horizontally extensive regions of intense convection and stratiform precipitation.

7. Hail occurs throughout the region, but is highly concentrated in the Andes foothills and Sierras de Córdoba, near Mendoza, in association with storms containing deep convective cores or wide convective cores.

8. A South American tornado alley is present in La Pampa region far to the east of the region of maximum hail occurrence. The tornado maximum is located where more developed and organized thunderstorms, supercells, and mesoscale convective systems are likely to occur downstream of the Andes Mountains.

9. The TRMM PR rain rate algorithm tends to underestimate precipitation from all three types of extreme storms over land partially due to errors in the drop size distribution assumptions.

10. Lower estimates by the TRMM PR rain rate algorithm are particularly biased for extreme precipitating systems that contain significant mixed phase and/or frozen hydrometeors.

11. Subtropical South America tends to have more intense precipitating systems than tropical South America, but the relationship between the TRMM PR rain bias and storm type is the same regardless of the climatological regime.

12. Deep convective cores contribute the least amount of climatological rain near the foothills given their smaller size and typically short-lived nature. Wide convective cores contribute a large fraction of the climatological rain in the La Plata
Basin as they are typically associated with growing and mature mesoscale convective systems that are large in area and tend to be long-lived systems. Broad stratiform regions contribute a significant amount of climatological rain with decaying mesoscale convective systems with widespread and long-lived stratiform precipitation.

13. In the La Plata Basin, storms containing wide convective cores contribute \(\sim 44\%\) of the total warm season rain. The accumulated contribution from storms containing deep convective cores, wide convective cores, and broad stratiform regions is \(\sim 95\%\) of the total warm season precipitation in La Plata Basin.

14. Diurnal time-longitude analysis of the rain contribution by these three types of extreme storms supports the life cycle hypothesis; convective initiation in the late afternoon near the foothills of the Andes that grows upscale to form nocturnal mesoscale convective systems that begin to expand eastward, and then finally decay into broad stratiform regions farther east.

15. Mesoscale model microphysics parameterizations vary in their ability to adequately simulate a mesoscale convective system with robust convective and stratiform components. Schemes with more realistic representations of snow particles combined with a ‘Goldilocks’ amount of supercooled water best reproduced the horizontal and vertical structures seen by the TRMM PR.

16. Time-lagged composite synoptic maps related to wide convective core occurrence in the La Plata Basin indicate the following:

   (a) Leading up to the occurrence of storms containing wide convective cores, mid-latitude synoptic waves moving over the southern Andes experience significant frictional deformation from the tall mountains resulting in strong lee cyclogenesis in subtropical South America.
(b) Strong N–S pressure gradients associated with the deep lee cyclone encourage down-gradient northerly advection of warm and moist air from the Amazon via the South American Low-Level Jet.

(c) The strength of the South American Low-Level Jet increases leading up to the occurrence of a wide convective core due to pressure-gradient suction from the strengthening lee cyclone.

17. Terrain modification experiments using a mesoscale model resulted in the following synoptic conclusions:

(a) Lee cyclogenesis downstream of the Andes that was identified in the time-lagged synoptic composites was confirmed in the model simulations.

(b) A 50% reduction in the height of the Andes resulted in a weaker lee cyclone magnitude, weaker (N–S) pressure gradients, and decreased SALLJ strength.

(c) In contrast, a 20% increase in the height of the southern Andes Mountains, which essentially moved the slope to lower heights farther south, strengthened the lee cyclone and the associated N–S pressure gradient force that acted to increased the magnitude of the SALLJ. This increased northerly SALLJ magnitude advected more warm and moist air south to fuel the intense convective storms.

18. Terrain modification experiments using a mesoscale model resulted in the following mesoscale conclusions:

(a) A 50% reduction in the Andes Mountains resulted in more widespread convective the initiation in a N–S band (extending north to Paraguay) east of the Andes Mountains. This effect is hypothesized to occur as a result
of a weaker capping inversion from the lower mountains that are unable to prevent convective initiation compared to higher mountain ranges.

(b) A mature MCS simulated with the 50% reduced Andes shows that the entire convective system propagated faster to the east, reminiscent of mesoscale convective systems in the United States. This effect is hypothesized to occur because the frictional deformation along the Andes is less with a lower mountain range so the low-level cyclone traverses the Andes faster than in higher terrain configurations. Additionally, the weaker lee cyclone has a weaker E–W pressure gradient force with weaker westward suction toward the mountain that typically provides a back-building aspect to the convective systems with the full Andes terrain.

(c) Increasing the southern Andes height results in a southward shift in the convergence zone that shifts both convective initiation and the mature mesoscale convective system south. The increased terrain where the Andes typically become less steep increases the frictional deformation of low-level synoptic disturbances.

(d) Averaged 40-dBZ echo top values throughout each terrain modification simulation shows that the presence of the Sierras de Córdoba mountains results in more intense storms for high mountain ranges. This partially confirms the hypothesis that this secondary mountain range tends to focus convective initiation in a narrow region particularly for high mountain ranges, as this effect was not present in the 50% reduced Andes run.

(e) A time-series of the number of instances of 40-dBZ occurrence ≥ 10 km in altitude showed that the 50% reduced Andes runs had more counts than other terrain modification simulations. However, according to the mean 40-dBZ echo top values, the storms simulated with the reduced Andes were weaker overall. The weaker capping inversion resulted in more instances
of convective initiation, but generally weaker storms, likely because the
convective instability was spread over more storm entities and released at
many locations in the lee of the Andes.

(f) Average maximum convective available potential energy (CAPE; indicat-
ing convective instability) and convective inhibition (CIN; strength of the
capping inversion) values for each terrain modification simulation shows
that the reduced Andes runs generally had less convective instability and
a weaker capping inversion, while increased Andes runs had both stronger
CAPE and CIN values. This perspective is entirely consistent with con-
clusion points above, demonstrating the profound influence of orography
on the resulting convective systems.

19. From this research, the first conceptual model for convective storm environ-
ments leading to convective initiation was developed for subtropical South Amer-
ica.

The cumulative impact of the research presented in this dissertation provides an
analysis of the extreme and unique nature of convective systems in subtropical South
America. The storms in this region remain understudied but efforts to conduct a
major field campaign in central Argentina is currently underway. This dissertation
provides a basis on which future work in this region can build. This study has resulted
in a conceptual model presented herein that is the first one for this region and as such
will be modified and updated as more detailed ground-based and in situ data are
available.

This dissertation has advanced our knowledge and understanding of (1) the role
of major mountain range topography in the initiation and maintenance of extreme
storms, (2) hydrometeorological and severe weather impacts from such storms, and
(3) improved overall perception of the processes leading to high-impact weather and
their simulation near major mountain ranges. By nature, the study and investigation
of high-impact and severe weather has wide reaching socioeconomic implications. A greater understanding of the formation mechanisms, patterns of development and organization, and severe weather impacts, including hail, flash floods and tornadoes, resulting from such storms can provide forecasters and the general public with crucial information to save life and property. In order to eventually forecast all types of storms and their effects via numerical weather prediction, general circulation, and climate models, such an integrated understanding is vital and this dissertation provides a step in that direction. The need for integrated and cross-discipline research in a shifting climate is essential for mitigating storm impacts, continued improvement of forecast skill, and a greater understanding of the weather-climate interaction. Argentine storms and MCSs have provided a unique opportunity for the integrated study of the full scope of high-impact weather and regional climate, including the hydrometeorology of precipitation, physical understanding of storm mechanisms, and human impacts.


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