ABSTRACT

CHIAO, SEN. THE DYNAMICS OF OROGRAPHIC PRECIPITATION: A MESOSCALE MODELING PERSPECTIVE. (Under the direction of Dr. Yuh-Lang Lin)

This dissertation is composed of three papers linked by a common theme: to understand the fundamental dynamics of orographic effects on the initiation and maintenance of heavy precipitation. High resolution simulations of various precipitation systems such as midlatitude cyclones and landfalling tropical cyclones are investigated in this research. The Naval Research Laboratory’s Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) is used for simulating tropical storm Rachel (1999) landfalling in southern Taiwan during 6-7 August 1999. The heavy orographic rainfall event that occurred in the Alpine region during 19-21 September 1999 (MAP IOP-2B) is simulated using the PSU/NCAR MM5 model. Both cases are simulated with a 5 km horizontal grid spacing. Validation of the forecast fields against the observations indicates that both COAMPS and MM5 reproduced the synoptic and mesoscale features reasonably well.

The strong orographic lifting of the potentially unstable low-level jet (LLJ) triggered the convective systems in the concave region of the southwest Central Mountain Range (CMR), which produced the first spell of the heavy rainfall episode while tropical storm (TS) Rachel was located in the South China Sea. The second spell of heavy rainfall was attributed to the modification of TS Rachel’s own rainbands by the mountains, and to the strong southwesterly impinging flow. The results indicate that the strong LLJ triggered convective systems in the concave regions. Additionally, density currents, caused by the evaporatively cooled air were
formed on the upslope of the CMR. The low-level convergence propagated upstream over the sea while the southwesterly impinging flow produced new convective cells. The simulation results also suggest that it is important to predict the intensity of the convective structure of the tropical cyclones as they pass through mountain ranges. Therefore, vortex bogusing might be needed for the simulation of precipitation in association with a tropical storm over complex terrain.

The heavy orographic precipitation was concentrated on the upslopes of the Alps, especially in the Lago Maggiore region (i.e., concave topography) during MAP IOP-2B. The results from the fine-scale sensitivity experiments clarified the mechanisms of the westward turning of the impinging southerly low-level jet. The westward turning was caused by mountain blocking, rotation (Coriolis effect) as well as boundary friction effects. The comparison of the real and idealized topography simulations illustrates that precipitation was enhanced near mountain peaks in the real terrain simulation. The 24 h accumulated precipitation was about 50% reduced in the idealized topography simulation. This is explained by the weaker upward motion induced by the smoother, idealized topography. The 1.67 km horizontal grid spacing simulation illustrates that heavy rainfall tended to concentrate in the vicinity of individual mountain peaks. The total amount of rainfall was over-predicted along the windward slopes due to the strong upward motion that occurred on the upslopes.

The orographically-induced moisture flux, a product of low-level horizontal wind velocity, mountain steepness and moisture content, is calculated based on the fine-resolution model output. The regions of positive orographically-induced moisture flux roughly coincide with
the heavy rainfall regions in these two types of precipitation systems. The results suggest that the orographically-induced moisture flux may serve as an index for predicting upslope orographic heavy rainfall. The results in this study illustrate that the timing and distribution of orographic rainfall could be well simulated in high-resolution domains. However, high resolution models tend to over-predict the total amount of rainfall, especially on the windward slopes. It is in part due to the dynamical forcing associated with vertical motion that increases rapidly as grid-spacing decreases and dominates over the microphysical processes over complex topography. This may produce an extreme rainfall amount. The potential instability is a major trigger for deep, moist convection which would result in heavy rainfall. Nevertheless, the release of conditional instability and conditional symmetric instability are not considered to be responsible for causing deep convection in these cases. In addition, these simulation results are consistent with previous studies that have suggested the concave topography, a steep mountain and moist low-level jet are parts of common ingredients in producing heavy orographic rainfall. Information from this study should be beneficial for orographic precipitation modeling and for interpreting and forecasting orographic precipitation.
The Dynamics of Orographic Precipitation:
A Mesoscale Modeling Perspective

by

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CHAPTER 1
INTRODUCTION

1. The role of orographic effects on heavy precipitation

The precipitation forecast over complex orography is one of the most important tasks for mountain meteorology, and is also one of the most difficult and challenging problems for weather forecasting. Naturally, the earth’s terrain is known to cause or modify many types of atmospheric phenomena, such as topographically enhanced rain, torrential rain and flash floods, because terrain can anchor or trigger flow systems in both space and in time, and affect airflow to release its own instability and triggering characteristics. Slight changes in speed, direction, shear, and stability of the incoming flow can lead to sudden reorganization of the airflow and precipitation patterns.

In general, topographic features warrant special considerations in the context of heavy-rainfall and flash-flood forecasting. Virtually all of the record and near-record rainfall and flash-flood events have been linked to distinctive topographic features. These links are manifested from the microscale, mesoscale to synoptic scale. Heavy precipitation can be defined as the heaviest precipitation occurring where the rainfall rate is the highest for the longest time (Doswell et al. 1996). Heavy rainfall can also be defined as rainfalls at the rate of 0.3 inches/hr or more. Striking examples in the U.S. are the Black Hills and Rapid City, South Dakota Flood of 1972 (Maddox et al. 1978); the Big Thompson River, Colorado Flood of 1976 (Maddox et al. 1978; Caracena et al. 1979); the Madison County flood in Virginia Flood of 1995 (Pontrelli et al. 1999); and Fort Collins, Colorado Flood of 1997 (Petersen
et al. 1999). In addition, many floods throughout Asia occurred on the windward slopes of mountain ranges during the Mei-Yu or Baiu season as well as landfalling tropical cyclone events such as the Central Mountain Range (CMR) of Taiwan. CMR is very high, extremely steep, isolated, and surrounded by oceans, it serves almost like a natural laboratory for studying the orographic effects on impinging airflow and weather systems (e.g. Lin 1993; Lin et al. 2001). Mountain ranges such as the Alps act as a strong and permanent modifier of atmospheric circulations on a wide variety of scales. It is evident that the geographical distribution of climate zones and the distribution of precipitation amounts are highly related to orography (e.g., Smith 1979; Binder and Schär 1996; Frei and Schär 1998).

Common themes that emerge from diagnostic studies of heavy rainfall events include the role of topography in lifting the airstream to release its instability, maintaining quasi-stationary storm systems, and in sustaining anomalously large moisture fluxes to storm systems, which caused even more difficulty in the forecasting of orographic precipitation. Thus, more accurate forecasting of the timing, location, and the amount of precipitation in and around complex terrain is a necessary first step toward more reliable and timely forecasts of flash floods and river floods. Systematic studies of observations and numerical simulations are required to understand the structure and formation of the orographic precipitation.

2. Motivations, objectives and methodology

This research is motivated by the fact that orographic precipitation prediction continues to be a difficult problem in numerical weather prediction. Although recent studies have suggested some common ingredients for examining the heavy orographic precipitation (e.g.,
current understanding of dynamics of orographic precipitation systems is deficient when compared to analogous phenomena such as mesoscale convective systems and banded baroclinic precipitation structures. The possible influence of topography in generating heavy orographic precipitation was not easy to be determined in the observational studies, because of the lack of sufficient spatial and temporal resolution over the mountains. A recent field experiment: the Mesoscale Alpine Program (MAP), conducted over the European Alps during the late summer/early autumn of 1999 provided valuable datasets to advance our understanding of the orographic precipitation systems. The goal of this research is to understand the orographic modification of moist airflow as it passes through mountain ranges. In order to compare the orographic effects on different types of precipitation systems, a heavy orographic precipitation event in association with a landfalling tropical storm which passed over the Central Mountain Range (CMR) of Taiwan will also be investigated.

The following scientific questions will be addressed in this research: How is the variation of convective available potential energy associated with orographic precipitation? Does the concave geometry feature favor heavy orographic rainfall? What is the relationship between moist Froude number and the distribution of orographic precipitation? What kinds of instability are responsible for orographic precipitation? Can the orographically induced vertical moisture flux represent the rainfall distribution? Mesoscale numerical simulations and analyses of data collected from field experiments will be the main approach to examine the problems stated above in association with heavy orographic precipitation events. The research will be conducted by comparing high resolution simulation results and available
observational data (i.e. surface, rawinsondes and radar data).

The PSU/NCAR MM5 model (Dudhia 1993) will be used for simulating the orographic rain event of MAP IOP2B. Results from the 5 km domain will be focused in this case study. Sensitivity tests of mountain height and mountain geometry will be carried out in this case, including simulations with modified terrains and different surface friction. Additionally, a 1.67 km grid-spacing simulation will be used to gain further insights of the response of horizontal resolution in the model simulation. The atmospheric component of the NRL’s Coupled Ocean/Atmospheric Mesoscale Prediction System (COAMPS) (Hodur 1997) is adopted for performing the orographic precipitation simulation associated with tropical storm Rachel passing over Taiwan. The purpose of using the COAMPS model is due to its capabilities of sequential data assimilation cycles, that resulted in greatly reduced forecast errors of the tropical storm track. A sensitivity experiment without CMR will be conducted to verify the role of orography on producing heavy rainfall. The primary aims and objectives of this research are:

(1) Performing a series of high-resolution modeling studies to advance fundamental knowledge of orographic precipitation processes over regions of complex terrain, and to document the three-dimensional structure and physical mechanisms of orographic precipitation;

(2) Conducting analyses using the moist Froude number \( (F_w) \), and convective available potential energy (CAPE). Investigating the relation between \( F_w \), CAPE and orographic precipitation distribution;

(3) Investigating the relative importance of atmospheric instabilities for heavy orographic
precipitation events, including potential instability, conditional instability and conditional symmetric instability;

(4) Examining the vertical moisture flux and orographically-induced moisture flux indices in predicting orographic rainfall distribution;

(5) Investigating the role of upstream orographic effects in association with local circulations on the distribution of orographic precipitation; and

(6) Investigating the effect of horizontal resolutions on the generation and distribution of orography precipitation.

The above tasks are conducted to examine heavy orographic precipitation events. The investigations will help understand some of the dynamic processes of orographic precipitation in different types of weather systems as well as in different mountain ranges.

Chapter 2 provides an extensive review of the literature and provides background with regard to the measurement and modeling of orographic precipitation. An orographically-enhanced heavy precipitation event of a landfalling tropical storm is examined in terms of a control simulation and sensitivity test which are given in Chapter 3. Numerical simulations and sensitivity tests of the evolution of meso-γ scale circulations on the formation of heavy orographic rainfall during IOP2B is presented in Chapter 4. Numerical simulations and analyses of the relevant instabilities accompanying the heavy orographic precipitation during MAP IOP2B is presented in Chapter 5. A summary and conclusions from this research are given in Chapter 6.

3. References


CHAPTER 2

A Survey of Orographic Precipitation
ABSTRACT

In this review, some previous studies on orographic precipitation, including observational, theoretical and numerical modeling studies are presented. This includes studies in different mountainous regions around the world.

This literature survey demonstrated that either small hills or high mountains would have great effects when the precipitation systems pass through. The common ingredients method for heavy rainfall and flooding are helpful for providing a guideline for predicting different types of precipitation systems. The results from modeling studies on orographic precipitation amounts and distributions indicate that model initial conditions, physical parameterizations and horizontal resolutions would have great impacts. This review also suggests that the prediction of orographic precipitation could be improved by fine scale modeling with accurate initial conditions and appropriate physical parameterization schemes.

The diagnostic tools which are discussed in this review, include moist Froude number, various moist instabilities, convective available potential energy, and moisture fluxes. These diagnostic approaches could help to understand some mechanisms of orographic precipitation. However, no single approach can determine the formation and distribution of orographic rainfall in the atmosphere.
1. Introduction

Orography significantly modulates the initiation and evolution of precipitation systems, and can promote substantially higher precipitation amounts and greater spatial variability. In spite of numerous studies in the past several decades, the accurate prediction of precipitation in mountainous terrain has remained an elusive goal. Climatologically, orographic forcing causes enhanced precipitation on the windward side due to upslope lifting, and a rain shadow effect to the lee of major topographic barriers due to subsidence. This windward enhancement is especially pronounced during the cool season when large scale precipitation systems interact with orography.

The orographic effects on precipitation varies by location and depends largely on the strength and direction of the flow relative to the terrain. Mountains may directly induce heavy rain through orographic lifting, but also affect heavy rainfall indirectly through the formation of orographically-induced local circulations and the release of instabilities. For instance, the horizontal scale and vertical extent of mountains as well as upstream wind speed and perturbations are all the factors that affect the development of heavy orographic rainfall. Due to the localized nature of many of the orographic effects, the distribution of precipitation near complex terrain is difficult to be characterized based upon the current observational networks or current operational models. Accurate treatment of initial atmospheric conditions, physical parameterizations (e.g., cumulus and cloud microphysics parameterization schemes), and surface characteristics (i.e., vegetation, snow cover, topography and soil type), are extremely important for an accurate prediction of orographic rainfall.
In the last several decades, significant progress has been made in understanding of the effect of topography on airflow and precipitation. Numerous numerical and theoretical studies have documented the response of atmospheric circulation to orography. The purpose of this chapter is to summarize some previous works on orographic effects on mesoscale circulation and precipitation. The primary objectives of this review are to describe different types of precipitation systems over complex terrain in different areas and some diagnostic approaches for analyzing orographic precipitation systems. The advances in understanding of the dynamical mechanisms governing orographic precipitation that have been achieved will also be reviewed. Critical issues that call for further investigations will also be discussed. The review is divided into two main topics. Section 2 will discuss the characterization of the orographic precipitation in different areas in terms of different types of weather systems. Section 3 deals with diagnostic approaches for orographic precipitation. A summary will be given in section 4.

2. Characterization of the orographic precipitation

It is well documented that precipitation systems can be modified as they pass over major mountain ranges that occur in various parts of the world. Important factors regulating orographic precipitation include (1) weather type or season which may produce either stable or convective rain, and (2) the scale of mountains and details of the terrain which may affect the distribution and amount of rainfall. Therefore, we will describe some significant orographic rainfall studies from the past few decades in this section.

Browning et al. (1974) presented a case study showing the three-dimensional structure
and evolution of precipitation upwind, over and downwind of the southern Wales hills during the passage of a wintertime warm sector that gave significant (∼ 30 mm in rainfall totals in 5 hours) and prolonged rainfall. The warm sector was characterized by a fast-moving airstream with potential instability not only at low levels but also in the middle troposphere, in part due to differential thermal advection. The upstream potential instability was found over the ocean in scattered mesoscale precipitation areas, which was embedded in the airstream traveling rapidly at the speed of the winds in the middle troposphere. Once the airstream experienced orographic uplift, fresh outbreaks of midtropospheric convection occurred extensively over the ocean up to 100 km upwind of the hills. Raindrops from these midlevel (Seeder) clouds washed out small droplets within low-level (feeder) clouds which formed over the hills, resulting in even more enhanced precipitation. The maximum of the rainfall totals occurred over the hills. As Browning et al. (1974) reported, this enhancement of orographic rain is consistent with Bergeron’s (1965) seeder-feeder mechanism. The seeder-feeder mechanism may be briefly described as follows. Precipitation from an upper-level precipitating cloud (Seeder) falls through a lower-level orographic stratus cloud (feeder) capping a hill or small mountain. Precipitation droplets or ice particles fall from the higher seeder cloud and collect cloud water as they pass through the lower feeder cloud by collision and coalescence or accretion, thus producing greater precipitation on the hill under the cap cloud than on the nearby flat land. The effectiveness of the process depends on sufficiently strong low-level moist flow to maintain the cloud water content in the orographic feeder cloud and the continuing availability of precipitation particles from the seeder cloud.
Smith (1979) identified three major mechanisms of orographic control of precipitation, based on the horizontal scale of the mountain. First, larger mountains act to enhance rainfall upslope of the mountain, producing a corresponding dry, rain shadow region in the lee. Large scale upslope precipitation occurs where orographically forced ascent brings air to saturation in which raindrops form and fall to the ground after some delay. Secondly, over smaller mountains where rain falling from preexisting higher clouds is intensified by the washout of cloud droplets in dense low clouds maintained by forced uplift of moist low-level air over these hills. This seeder-feeder mechanism (Bergeron 1965) produces a rainfall maximum near the top of hills. The third mechanism is the formation of cumulonimbus clouds over mesoscale mountains within a conditionally unstable airmass, heating produces upslope winds leading to thermals that trigger convective clouds.

Hill and Browning (1981) extended the work of Browning et al. (1974), presenting eight detailed case studies. In these cases, the atmosphere was potentially unstable only in the lowest 2 km. Their results clearly show that over 80% of the rainfall enhancement occurred in the lowest 1.5 km above the hills, again consistent with Bergeron’s mechanism. In virtually all of the cases studied, the maximum precipitation occurred over the top of the hills. One of the important conclusions they reached is that the orographic enhancement is strongly influenced by the low-level wind speed. The largest enhancement of rainfall occurs in association with strong winds and high relative humidity below 2 km. Note that the southern Wales hills have only modest elevations with the maximum height of only 600 m.

Similar studies have been carried out in Japan. Ogura et al. (1985) presented a case
study for a heavy precipitation event that occurred in the northwestern coastal area of Japan. The 5-hour rainfall accumulation was as high as 412 mm locally. They also found that the precipitating mesoscale cloud system stopped traveling and became quasi-stationary during that period. Meanwhile new convective cells formed preferentially and in succession in the area about 50 km off shore and upstream. These clouds traveled eastward downstream and merged with the quasi-stationary precipitating system. They also noted that the timing of the precipitation development coincided with the peak period of the incursion of very moist air associated with the southwesterly low-level jet. Due to the blocking effect in the airstream moving toward the coastal orography, a convergence zone could be formed near the coastline. Watanabe and Ogura (1987) emphasized that surface convergence generated by deflected flow over the land and undeflected flow over the sea was responsible for the heavy rainstorm in Japan. This convergence zone will result in intensifying the precipitation, and the distribution of precipitation may vary, which in turn leads to questions regarding its roles in the orographic rainfall formation processes, especially where the topography is steep near the coast.

Similar phenomena had also been observed around the upslope side of the Central Mountain Range (CMR) of Taiwan. Lin (1993) summarized the possible formation mechanisms of orographic rain over Taiwan, which included (1) upslope orographic rain in a stable atmosphere, (2) orographic rain in a conditionally unstable atmosphere, (3) seeder-feeder cloud mechanism induced orographic rain on small hills, (4) orographic rain induced by convergence of southwesterly flows or a mesoscale convective system downslope, and (5) orographic
rain induced by the low-level jet which served as a conveyor belt of warm and moist air to the upslope of the mountain. Usually the low-level jet is associated with the passage of a front or a tropical cyclone.

The details of terrain surface can have profound effects on convection, no matter whether it is small hills, ridges or mountain ranges. A review of the environmental conditions necessary for different types of orographically-induced or -enhanced precipitation, as well as microphysical aspects of such processes, is given by Banta (1990). He classified the orographic effects on convection into three categories: (1) mechanical lifting to the level of free convection (LFC), (2) thermally generated circulations, and (3) aerodynamic effects, such as blocking, deflection of flow and gravity waves. Indeed, the orographic lifting effects play a very important role, which is more complex than simply lifting the air parcel to saturation on the upstream side. Strong convection can be triggered by orography, yet orographic uplift can destabilize the layer, and convective cells can appear embedded in a more laminar ascending motion (Smith 1979; Houze 1993).

Because isolated mountains and mountain ranges act as obstacles to horizontal flow, airflow impinging upon the orography is typically forced to go over or around the mountains. Usually, such orographic forcing can initiate or enhance precipitation in certain areas. For example, orographically-induced low-level clouds can enhance precipitation falling from clouds aloft in a process known as the seeder-feeder mechanism as mentioned before. In a moist, stable environment, precipitating clouds can be formed due to upslope flow and subsequent condensation. If the air is potentially (convectively) unstable, such upslope flow
can trigger convection, which can occur either on the windward slopes or, in cases of strong blocking by the orography, upstream of the mountains. In the daytime, strong heating on the slopes can cause uplifting, and thus, initiate convection. In addition, convective activity can be triggered by convergence on the lee side by air flowing around an isolated mountain (e.g., Houze 1993).

Extremely heavy orographic precipitation can occur when a tropical cyclone passes over the mountain. Sakakibara and Takeda (1973) presented a case study of heavy precipitation associated with a typhoon and suggested that enhancement of rainfall in the mountainous areas would have been "a result of the addition of many small drops existing in low level clouds to raindrops falling from convective clouds of high top and the capture of the former drops by the latter drops," a process consistent with Bergeron’s mechanism. However, the seeder-feeder mechanism may not be necessary in tropical cyclones due to the very moist environment. Geerts et al. (2000) also found that when Hurricane Georges made landfall on Hispaniola, the topography induced strong low-level ascent which supports a large concentration of cloud water, as a result, this enhances rain formation at low level.

Wu and Kuo (1999) presented the analysis of rainfall distribution associated with Typhoon Herb traversing northern Taiwan. The total accumulated rainfall was about 2000 mm over the 2-day period. They also used a mesoscale model to investigate the rainfall distribution. In their 6.7 km resolution results showed the extremely heavy precipitation over CMR was produced by the steady up-lifting of a deep layer of the moisture laden typhoon circulation over the mountains. They also pointed out that more than 90% of the rainfall over the
CMR and its slopes was produced by the grid-resolvable scale precipitation physics. Recent studies suggest that rainfall occurred over the CMR was strongly controlled by orographic forcing, rather than by the original rainbands associated with the tropical cyclone (e.g., Lin et al. 2002).

Recent studies suggest that prediction of the spatial and temporal distribution of orographic precipitation can be significantly improved with high-resolution mesoscale atmospheric models that adequately capture the orographic influence on the flow. For instance, Colle et al. (1999) verified precipitation forecasts for models of varying resolutions during the cool season in the Pacific Northwest. They evaluated the NCEP/Eta-10 and the Fifth-Generation Pennsylvania State University (PSU)/National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) at 36 and 12 km resolutions. They found that, of the two MM5 resolutions, the 12 km version performed better overall than the 36 km version. However, the 12-km version predicted too much precipitation on steep windward slopes and too little precipitation on the lee slopes. The Eta-10 also under-predicted precipitation to the lee of mountain ranges and over-predicted on the windward slopes. However, much of the Eta-10’s over-prediction occurred further upstream than the MM5. This was attributed to the Eta-10’s lack of horizontal advection of precipitation in the microphysics parameterization scheme and problems caused by excessive blocking. Overall, the 12-km MM5 was found to produce the best forecasts, while the Eta-10 had smaller errors at lower thresholds of precipitation.

Colle et al. (2000) extended the work of Colle et al. (1999), including an additional
run of the MM5 at 4-km resolution. Their results indicated that over areas of complex terrain such as the Pacific Northwest, where the mesoscale flow was highly deterministic and mostly stratiform precipitation type. Their results also showed that although precipitation structures were better resolved at higher resolution, the overall precipitation prediction at 4-km resolution was not noticeably better than at 12-km resolution. In fact, the 4-km version produced too much precipitation on the windward slopes, more so than at 12 km, especially for cases of light precipitation. The results also showed that while errors in the large-scale forecasts were significant contributors to precipitation forecast errors at the coarser resolutions, they were not as important for the 4-km resolution. The results suggested that improving the model’s physical schemes might have the significant impact on improving precipitation forecasts at higher resolutions.

A recent field experiment, the Mesoscale Alpine Program (MAP), conducted over the Alpine region in fall 1999 provided valuable datasets to advance our understanding of the orographic precipitation systems (e.g., Bougeault et al. 2001). Some recent studies (e.g., Buzzi and Foschini 2000; Lin et al. 2002) pointed out that orographic precipitation over the Alpine region is generated by different mesoscale atmospheric features associated with the interaction with topography, such as low-level jet, convergence zones, etc. For precipitation to occur, in addition to other factors, such as enough humidity, required temperature structure, sufficient depth of cloud etc., a strong upward motion is essential. In orographic precipitation, the forcing agent was provided by large ranges of hills/mountains blocking the flow of humid air in such a way that vertical (upward) currents of air are produced, the physical processes
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could include condensation, cloud formation/enhancement, precipitation element growth. Direct lifting by orographic forcing usually only produces a small amount of precipitation, but can be the means of enhancing or triggering other mechanisms (e.g. convective activity).

Lin et al. (2001) have suggested nine common ingredients for producing orographic flooding or heavy rainfall, including high precipitation efficiency within an incoming airstream, low-level jet, steep mountain, favorable mountain geometry and confluent flow field, strong synoptically-forced upward motion, high moisture flow upstream, large convective system, slow movement of the convective system and upstream conditionally or potentially unstable airstream. In addition, a low-level flow with high $\theta_e$ tends to be potentially (convectively) unstable, which may trigger orographic convective systems. Although these essential ingredients can serve as a main framework for defining and diagnosing heavy orography precipitation, the relative importance among those common ingredients must be investigated for the orographic precipitation systems in a particular region as well as for variety of different synoptic regimes. Furthermore, it is not clear which types of instabilities are responsible for producing heavy orographic rainfall, i.e., which need to be investigated. We will discuss some necessary conditions or restrictions for defining and diagnosing orographic precipitation in the following section.

3. The diagnostic methods for orographic precipitation

An important objective of this review is to investigate some diagnostic approaches which can be adopted to determine the mechanisms responsible for orographic precipitation features as the weather systems approached the steep topography. The diagnostic methods discussed
herein allow us to understand the relative contributions to the orographic precipitation of different physical/dynamical forcing functions.

3.1 The moist Froude numbers

The moist Froude number ($F_w$) has been proposed to identify different flow regimes, such as an upstream propagating convective system, a quasi-stationary convective system, quasi-stationary and downstream propagating systems by Chu and Lin 2000. It is defined as

$$F_w = \frac{U}{N_w h},$$

(1)

where $U$ is the basic flow speed, $N_w$ is the moist Brunt-Väisälä frequency of the incoming airflow, and $h$ is the mountain height. The moist Brunt-Väisälä frequency may be defined as

$$N_w^2 = \frac{g}{\bar{\theta}_v} \frac{\partial \theta_v}{\partial z},$$

(2)

where $\theta_v$ is the virtual potential temperature, and $\bar{\theta}_v$ is the mean virtual potential temperature in the layer of consideration (Emanuel 1994).

$N_w$ is analogous to $N$, but for a saturated airstream in which negative values lead to buoyant instability from the thermodynamic energy equation (Durran and Klemp 1982). It is useful to investigate the distribution of $F_w$ and its relationship with precipitation. This non-dimensional moist Froude number may help to predict the propagation of the orographic precipitation system. Based on $F_w$, Chu and Lin (2000) identified three moist flow regimes for conditionally unstable flow over a mesoscale mountain: (a) Low $F_w$, convective system over the upslope area. (b) Moderate $F_w$, quasi-stationary convective systems over the upslope and
in the vicinity of the mountain peak. and (c) Large $F_w$, quasi-stationary and downstream propagating convective systems. According to their study, a large $F_w$ (e.g., $F_w \geq 0.5$) does not seem to favor upslope heavy rainfall events. It is a useful parameter to help identify the location, namely upstream, upslope or downslope of the orographic rainfall.

3.2 The moist instabilities

From a synoptic perspective, the adiabatic and frictionless quasi-geostrophic $\omega$ equation (Bluestein 1992) allows for the instantaneous diagnosis of quasi-geostrophic vertical velocity ($\omega$) based on geopotential ($\phi$) and temperature ($T$). The equation can be written:

$$ (\sigma \nabla_p^2 + f^2 \frac{\partial^2}{\partial p^2})\omega = -\frac{R}{P} \nabla_p^2 (-\vec{V}_g \cdot \nabla_p T) + f \frac{\partial}{\partial P} [\vec{V}_g \cdot \nabla_p (\xi_g + f)] $$

where $\omega = \frac{\partial p}{\partial t}$, $\sigma = -\frac{RT}{P} \frac{\partial \theta}{\partial P}$, $f$ is the Coriolis parameter, $\vec{V}_g$ is the geostrophic wind, and $\xi_g$ is the vertical component of the geostrophic relative vorticity. Equation (3) illustrates that the response ($\omega$) to a given forcing is inextricably tied to atmospheric stability ($\sigma$). Thus, the stability of the atmosphere in an area of forcing for vertical motion affects both the location and the intensity of the subsequent vertical motion (assuming quasi-geostrophic flow constraints). If the necessary atmospheric conditions exist, particularly the stability and moisture content of the atmosphere, precipitation may be produced due to the forced orographic uplift of the air. In other words, The stability of the atmosphere determines how the obstacle will affect the flow. Unstable cumulus clouds form when forced lifting releases moist instabilities. Forced lifting of moist air up the slopes of a mountain barrier can lift air directly to its lifting condensation level (LFC) when the LFC is located at some inflow level near or below the mountain summit (e.g., Banta 1990). This will trigger the conditional
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instability, moist convection, and potentially heavy orographic precipitation.

3.2.1 Diagnosis of the potential instability (PI)

A low-level flow with high $\theta_e$ may favor the formation of deep convective systems and result in orographic precipitation. The existence of potential (convective) instability refers to the lifting of a moist atmospheric layer to saturation which becomes buoyantly. In other words, the decrease of $\theta_e$ with height implies a possible existence of the potential instability.

Thus, the potential instability index can be measured by

$$\frac{\partial \theta_e}{\partial z} < 0 \quad (4)$$

For layer with negative $\partial \theta_e/\partial z$, overturning may occur once the layer has been lifted to saturation.

3.2.2 Diagnosis of the Conditional instability (CI)

Because the atmosphere is usually moist but unsaturated (Houze 1993), conditional instability can arise. Conditional instability in the atmosphere represents a temperature profile where the environmental lapse rate ($\Gamma$) is smaller than the dry lapse rate ($\Gamma_d$), but is larger than the moist lapse rate ($\Gamma_m$). For the unsaturated case, the bubble cools faster than the environment, therefore, it sinks (is negatively buoyant), and the atmosphere is considered stable. For the saturated case, the bubble cools slower than the environment. Therefore, it is buoyant, and the atmosphere is considered unstable. So this is called conditional instability because it depends on the conditions of the bubble of air (whether or not it is saturated) to determine whether the atmosphere is stable or unstable. In other words, conditional instability (CI) can be diagnosed by
\[-\frac{\partial T}{\partial Z}\]wet < \[-\frac{\partial T}{\partial Z}\]pel < \[-\frac{\partial T}{\partial Z}\]dry \tag{5}

or

$$\Gamma_m < \Gamma < \Gamma_d \tag{6}$$

It can also be determined by the variation of the saturated equivalent potential temperature with height,

$$\frac{\partial \theta_{es}}{\partial z} < 0, \tag{7}$$

where $\theta_{es}$ is defined by

$$\theta_{es} = \theta(T, p)e^{Lq_{vs}(T,p)/C_pT}, \tag{8}$$

where $q_{vs}(T, p)$ is the saturation mixing ratio, $L$ is the latent heat of condensation, $C_p$ is the specific heat of dry air at constant pressure and $T$ is air temperature.

Because the atmosphere usually contains water vapor but is not saturated, $\theta_{es}$ decreases with height and this state is called conditional instability. In other words, the vertical motions are strong enough to lift the air parcels, under parcel-theory condition, to their level of free convection. This condition needs to be met in order to release the potential energy for convection (Wallace and Hobbs 1977, Emanuel 1994). One can compute $\theta_{es}$ at each level and look for layers where it decreases with height to determine the potential instability. Conditional instability (CI) is developed using a parcel argument (the surrounding atmosphere is invariant), assuming the air is saturated. For sufficiently moist parcels, finite vertical displacements (to LFC) result in the release of buoyant instability.

3.2.3 Diagnosis of the conditional symmetric instability, and absolute instability
Conditional symmetric instability (CSI) is essentially the manifestation of slantwise convection which exists along a slantwise path (Bennetts and Hoskins 1979; Soonk 1992; Schultz and Schumacher 1999). The whole concept of CSI can be viewed as the stability, which is determined, by forcing the parcel both vertically and horizontally. The angle of movement is taken to be in between $\theta_{es}$ and a surface of constant momentum $M_g$. If there exist locations where a parcel travels a slantwise path such that $\theta_{es}$ does not increase and $M_g$ does not decrease, the parcel has encountered conditional symmetric instability and is unstable, both vertically and horizontally along that path. In addition, recent studies suggested that soundings can indicate if the layers of saturated conditional instability exist in advance of squall lines, so call moist-adiabatic unstable layers (e.g., Kain and Fritsch, 1998; Bryan and Fritsch, 2000). Their results identified that the existence of moist absolutely unstable layers (MAULs) were created and maintained as mesoscale convective systems develop. It is also suggested that the moist absolutely unstable layer may help explain the variations in the cellular structure of the convective region of MCSs.

3.3 The convective available potential energy

Convective available potential energy (CAPE) is a quantity to evaluate the convective potential of the atmosphere. In other words, CAPE represents the amount of buoyant energy available to accelerate a parcel vertically, or the amount of work a parcel does on the environment. CAPE is the positive area on a sounding between the parcel’s assumed ascent along a moist adiabatic and the environmental temperature curve from the level of free convection (LFC) to the equilibrium level (EL). The greater the temperature difference
between the warmer parcel and the cooler environment, the greater the CAPE and updraft acceleration to produce strong convection. The larger (smaller) the CAPE is, the stronger (weaker) must be the amount of synoptic and especially mesoscale forced lift to bring the parcel to its LFC. CAPE involves an integration over a depth of the atmosphere and is not as sensitive to specific sounding details.

CAPE can be measured by treating each grid point as a single sounding. It can be defined as

$$CAPE = g \int_{LFC}^{EL} \left( \frac{\theta - \bar{\theta}}{\bar{\theta}} \right) dz,$$

where $\theta$ is the potential temperature of the rising parcel, $\bar{\theta}$ is the potential temperature of the environment, LFC and EL represent the level of free convection and the equilibrium level for the rising parcel, respectively. The distribution of CAPE could imply the potential location of precipitation.

It has been observed that heavy orographic rainfall events are often associated with incoming flow with moderate to large CAPE (e.g., Maddox et al. 1978; Lin et al. 2001). Normally before convection starts, soundings in the environment would possess positive available potential energy. Once convection occurs, CAPE will be released during the condensation process, thus it decreases if the convection continues. In addition, Jordan (1958) pointed out the average hurricane season sounding contains modest CAPE values of 1350 Jkg$^{-1}$ and is characterized by a relatively moist mixed layer and drying above 850 hPa. It has also been found that the highest CAPE value measured in a sounding was through the hurricane’s eye on the previous day when Hurricane Georges made landfall at the Dominican
Republic (Geerts et al. 2000).

3.4 Estimation of the precipitation

The precipitation (P) produced can be approximated by

\[ P = -\int_o^{z_m} \frac{\rho}{\rho_w} \nabla H \cdot (qV) \, dz + E, \]  

(10)

where this approximation equation can be applied for the cumulus convective systems in the tropical region (see Holton 1992), \( E \) represents the evaporation rates, \( Z_m \) is the top of the moist layer, \( q \) and \( V \) are mixing ratio and horizontal velocity. This equation can further be expressed by using the continuity equation

\[ \nabla H \cdot V = -\frac{\partial w}{\partial z}, \]  

(11)

therefore,

\[ P = \frac{\rho \bar{q}}{\rho_w} \int_o^{z_m} \frac{\partial w}{\partial z} \, dz + E \approx \frac{\rho \bar{q}}{\rho_w} [-\nabla H \cdot V] Z_m + E \]  

(12)

\( \bar{q} \) the averaged mixing ratio, \( \rho \) and \( \rho_w \) the air density (\( \sim 1 \text{ kg m}^{-3} \)) and water density (\( \sim 1000 \text{ kg m}^{-3} \)), \( -\nabla H \cdot V \) \( Z_m \) is the total convergence in a column. If we apply the total convergence to the mountain area, then this part can be contributed by orographic and large scale forcing. Thus, if we assume mountain height is \( h \), then the convergence part can be rewritten as

\[ -\int_o^{Z_m} (\nabla H \cdot V) \, dz = -[\int_o^h (\nabla H \cdot V) \, dz + \int_h^{Z_m} (\nabla H \cdot V)\, dz] \]  

(13)

The first term on the right hand side results from the orographic-induced vertical motion, it approaches zero near the ground; while the last term on the right hand side results from
large-scale (synoptic) contribution \((W_l)\), Therefore, Eq. (13) can be further simplified as

\[- \int_0^{Z_m} (\nabla \cdot V) dz \sim V \cdot \nabla H_m + W_l\]

Hence,

\[P \approx \frac{\rho q}{\rho_w} (V \cdot \nabla H_m + W_l) + E \quad (14)\]

This precipitation rate equation will be calculated by using 5 km simulation results in this research. Equation (14) is very similar to the orographic-induced vertical moisture fluxes suggested by Lin et al. (2001). The approach of moisture conservation incorporated with the vertical velocity at terrain level has been developed to study the orographic precipitation (Collier 1975; Bell 1978). The moisture convergence of the orographic rain enhancement over two-dimensional high mountains could be well estimated by assuming that the moisture convergence due to the horizontal wind vector encountering the slope of mountains is proportional to the rain enhancement (e.g., Alpert 1986; Alpert et al. 1994). Sinclair (1994) has shown the precipitation over complex terrain can be estimated based on topographically forced vertical motion. Doswell et al. (1998) suggested the substantial moisture content is necessary for precipitation when rising air is forced by orography. Lin et al. (2001) also suggested that the terrain-induced moisture flux is a combination of some essential ingredients, and can be used to help predict the occurrence and distribution of upslope rainfall, although it needs further improvement for predicting other types of orographic rainfall.

In general, the above listed indices or flow parameters could provide some guidance to estimate the heavy orographic rainfall. However, there is no single method mentioned above that can be used alone for studying the heavy orographic precipitation, each method has its
advantages and disadvantages.

4. Summary and conclusions

A literature survey of some past orographic precipitation studies among different mountainous areas had been performed. Diagnostic tools found in these studies include moist Froude number, conditional instability, potential instability, conditional symmetric instability, convective available potential energy, and precipitation produced. These tools will also be applied in analyzing numerical simulation results presented in later chapters.

The survey reveals that either small hills or high mountains can have significant effects on the formation and distribution of orographic precipitation. Mountains can also induce or enhance precipitation on different types of precipitation systems, such as frontal systems, mesoscale convective systems and tropical cyclones. Nevertheless, due to insufficient model resolution, inappropriate physical parameterizations or lack of better initial conditions, accurate simulation of orographic precipitation continues to be a difficult problem in numerical modeling. The diagnostic methods discussed in this Chapter were designed to help understanding the mechanisms and to improve the forecasting of orographic precipitation. The Froude number can be interpreted as the ratio of natural wavelength of the air to wavelength of the mountain. It, therefore, appears to be attractive to use a non-hydrostatic model with a sufficiently high horizontal resolution to understand the mechanism that contribute to heavy orographic precipitation. However, no single factor could determine orographic precipitation formed in the atmosphere. The basic ingredients proposed by Lin et al. (2001) provide a very useful guideline for examine orographic rainfall events.
The following Chapters of this research will focus on the dynamics that generate heavy precipitation in the presence of high mountains (∼3 km) by modeling various events under different synoptic conditions, and using diagnostic tools. Thus, it is our goal to be able to synthesize the fundamental mechanisms of heavy orographic rainfall.

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CHAPTER 3

Numerical Modeling of Rainfall over Taiwan in Tropical Storm Rachel (1999)
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ABSTRACT

An orographic rainfall event which occurred on 6-7 August 1999 during the passage of Tropical Storm (TS) Rachel over Taiwan is investigated by performing triply-nested, non-hydrostatic numerical simulations using the NRL COAMPS model.

By examining both observational data and numerical model output, we found that this orographic rainfall event may be separated into three distinct stages. During the first stage (00 UTC to 12 UTC August 6), TS Rachel was located in the South China Sea and tracked northeastward to Taiwan. Meanwhile, another TS, Paul, was steered by the subtropical high to the southwest of Japan. During the second stage (12 UTC August 6 to 00 UTC August 7), the southwesterly monsoon current as well as the circulation of TS Rachel over southwest Taiwan strengthened and formed a low-level jet (LLJ) with high equivalent potential temperature when TS Rachel moved closer to Taiwan. Comparing the control and sensitivity (without orography) experiments, we found that the strong LLJ triggered convective systems in the concave region of the southwest Central Mountain Range (CMR), which then produced the first episode of heavy rainfall. The second episode of heavy rainfall which occurred during the third stage (00 UTC to 18 UTC August 7) was attributed to the modification of TS Rachel’s own rainbands by the mountains as well as the strong southwesterly flow impinging on the mountains. The low-level convergence propagated upstream over the sea, and the impinging flow from southwest Taiwan produced new convective cells.

The orographic vertical moisture flux, which is the result of low-level horizontal velocity, mountain steepness, and moisture content, is calculated based on the fine-resolution model...
output. The regions of maximum moisture flux roughly coincide with the heavy rainfall regions over the island during this event, while the regions of the general vertical moisture flux \( wq \) coincide with the heavy rainfall regions over the ocean. Hence, the orographic vertical moisture flux may serve as an index for predicting this type of upslope orographic heavy rainfall. Overall, the model is able to predict the storm track, rainbands, and period of rainfall reasonably well over southern Taiwan, although the maximum rainfall is slightly over-predicted. Nevertheless, the model results also suggest that finer resolution (i.e., less than 5 km) or vortex bogusing might be needed for the simulation of precipitation in association with a tropical storm over complex terrain.
1. Introduction

In this study, we consider a heavy orographic rainfall event associated with the passage of a tropical storm over Taiwan. During early August 1999, tropical storm Rachel made landfall on the southwestern side of the island. Although the Central Mountain Range (CMR) reduced the strength of this tropical storm when it made landfall, it also provided a favorable condition for the moist airstream to be lifted and to release conditional or convective instabilities. The operational numerical guidance of quantitative precipitation forecasts or track at Taiwan’s Central Weather Bureau were not adequate in this case, and thus did not alert the general public of the potential for heavy rainfall. Obviously, the potential orographic enhancement of precipitation of this weather system was not fully foreseen at that time. The main focus of the present work will be on the mechanisms by which the moist airstreams propagate and behave in relation to the orography as well as to the background synoptic flow in which they are embedded.

Chu and Lin (2000) used the moist Froude number, i.e. $F_w = U/N_w h_m$, where $U$ is the basic flow speed near the mountain, $N_w$ is the moist static stability of the incoming airflow, and $h_m$ is the mountain height, to determine the location of orographic rainfall. According to their study, a large $F_w$ ($\geq 0.5$) does not seem to favor upslope heavy rainfall events. On the other hand, it has been demonstrated by other studies (e.g., Lin 1993; Buzzi et al. 1998) that the majority of orographically-induced flash flooding events were associated with a low-level jet (LLJ). In addition, LLJs in the Great Plains of the United States were also found to be important for the rapid transport of heat and moisture from the Gulf region into
areas of convective storms which produce heavy rainfall (e.g., Maddox 1983). In this study, we will also examine the role of a LLJ in a real case simulation.

Lin et al. (2001) proposed nine common ingredients for producing heavy orographic rainfall, which include high precipitation efficiency within the incoming airstream, the presence of a low-level jet, a steep mountain, favorable mountain geometry and confluent flow field, strong synoptically-forced vertical motion, high horizontal moisture flow upstream, a large convective system, slow movement of the convective system, and a conditionally or potentially unstable airstream upstream. In addition, a low-level flow with high $\theta_e$ may induce potential (convective) instability, which favors the formation of orographic precipitation. This type of flow has been observed to exist ahead of fronts or other weather systems, which may serve as a conveyor belt that transports warm and moist air along the upslope side of the terrain (Lin 1993). Therefore, it is very important to understand the various dynamic processes of orographic rainfall. One of our objectives is to examine the common ingredients for heavy orographic rainfall by numerical simulations.

In general, the moisture flux convergence associated with orographic rain enhancement over two-dimensional high mountains could be estimated by assuming that the moisture convergence due to the horizontal wind impinging upon the mountain slope is proportional to the rain (Alpert 1986). Sinclair (1994) has shown that precipitation over complex terrain can be reasonably estimated in a first guess approximation by estimation of the topographically-forced vertical motion. Doswell et al. (1998) suggested that substantial moisture flux convergence is needed when air is forced orographically to rise. Lin et al. (2001) also suggested
that the terrain-induced moisture flux convergence is one of the common ingredients for heavy orographic rainfall, and that it may combine with other common ingredients to produce heavy orographic rainfall. Although the results from previous studies provide some guidance in the estimation of heavy orographic rainfall and have addressed the important role that topography plays in generating heavy precipitation, it is still worthwhile to analyze the temporal and spatial variabilities of orographic precipitation. In addition to the short-comings from model resolution and initial conditions, it appears some additional favorable conditions must co-exist with those previously mentioned in generating orographic precipitation systems. As indicated in Wu and Kuo (1999), the numerical prediction of mesoscale precipitation distribution associated with a typhoon landfalling in Taiwan is a big challenge. Because the rainfall distribution for a typhoon affecting Taiwan is strongly influenced by the orography. It is therefore worthwhile to use a non-hydrostatic model with sufficient horizontal resolution (e.g., grid-spacing less than 5 Km) to better understand the role that orographic vertical moisture flux plays in heavy rainfall events.

2. Description of the Model and Experiment Design

The atmospheric component of the Naval Research Laboratory’s (NRL) Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS, Hodur 1997) is used in this study. The fully compressible, nonhydrostatic governing equations in the terrain-following vertical coordinate (Gal-Chen and Somerville 1975) are solved by using a second-order finite difference scheme. A semi-implicit scheme with time splitting treatment for the acoustic modes enables efficient integration of the fully compressible equations (Klemp and Wilhelmson 1978;
Physical parameterizations include short and longwave radiations (Harshvardhan et al. 1987). The planetary boundary layer and free-atmospheric turbulent mixing and diffusion are parameterized by using a prognostic equation for the turbulent kinetic energy based on the 2.5 level formulation of Therry and Lacarrère (1983). The surface fluxes are computed following Louis’ (1979) formulation and the subgrid-scale moist convective processes are parameterized following Kain and Fritsch (1993). The grid-scale evolution of moist processes are explicitly predicted from microphysical budget equations for cloud water, cloud ice, raindrops, snowflakes, and water vapor (Rutledge and Hobbs 1983; Lin et al. 1983). More detailed information on COAMPS can be found in the Software User’s Manual-Coupled Ocean/Atmosphere Mesoscale Prediction System (Haack 1996).

A 48-hour simulation, starting at 00 UTC 6 August 1999, utilized the incremental update data assimilation procedure that enabled mesoscale circulations to be retained in the analysis increment fields. The initial fields were created from multivariate optimum interpolation (MVOI) analyses of the surface, upper-air sounding, aircraft, and satellite data that were quality controlled and blended with 1° resolution first-guess fields (Barker 1992) from the U.S. Navy Operational Global Analysis and Prediction System (NOGAPS; Hogan et al. 1991). Time dependent lateral boundary conditions made use of NOGAPS forecast fields (Davies 1976).

The computational domain for the present study was configured on a Lambert conformal projection with three horizontally nested domains encompassing of 91 x 101, 151 x 151 and
133 x 133 grid points, respectively. The grid-point spacings of these computational meshes were 45 km, 15 km and 5 km, respectively. The horizontal area extends from the northwest Pacific, westward to China, and includes Taiwan and parts of western China (Fig. 1a). A total of 30 vertical levels were used, in which 11 levels were distributed in the lowest 2.0 km in order to sufficiently resolve the planetary boundary layer. The model contains the 1-km resolution terrain data that is mapped to the COAMPS model grid resolution to better account for the mesoscale effects of topography. The terrain data for the third (i.e. finest) grid mesh of $\Delta x = 5$ km is shown in Fig. 1b. The model topography data is representative of the complex local topographic features, with several mountain peaks to the north and middle of the CMR higher than 3800 m, and a concave geometry located in the southwestern part of Taiwan.


3.1 Overview of the synoptic conditions

Tropical Storm (TS) Rachel formed in the monsoon trough of the South China Sea, approximately 260 km southeast of Hong Kong on August 5, 1999. The Joint Typhoon Warning Center (JTWC) issued the first warning on TS Rachel at 09 UTC August 6. The storm had reached its maximum intensity of 35 kts ($\sim 17 \text{ m s}^{-1}$) 3 hours later. By August 6, the surface analysis at 00 UTC indicated that Tropical Storm Rachel (996 hPa) was located at (21.0N, 117.9E) in the South China Sea (Fig. 2a). Associated with this tropical storm was a southwesterly wind, which brought moist air in to impinge on the Central Mountain
Range (CMR). Meanwhile, TS Paul (990 hPa) was located at 27.9N, 133.2E, moving around the Pacific subtropical high. At 00 UTC August 7, the surface analysis indicated that TS Rachel would move over Taiwan in the next 24 hours, and TS Paul had already skimmed the southwest coast of Kyushu Island (Fig. 2b). Fig. 3a shows the best tracks of TS Rachel and TS Paul, indicating that TS Rachel tracked northeastward to Taiwan, and made landfall around 06 UTC August 7. The fine scale (i.e. 5 km) simulation results indicated that TS Rachel filled when it crossed over the CMR (Fig. 3b).

Figure 4 represents the 500 hPa wind and geopotential height fields, which were analyzed by NOGAPS, valid at 12 UTC August 6 and 12 UTC August 7, respectively. TS Rachel and TS Paul were both embedded in the southwesterly monsoon trough during 12 UTC August 6 (Fig. 4a). At this time the subtropical ridge was located around 38N and TS Paul moved under the combined influence of the mid-level southwest monsoon flow and the mid-level flow on the southwest periphery of the subtropical high. TS Rachel was embedded in the monsoon trough, and steered by the weak flow near the western periphery of the southwesterly monsoon surge. Fig. 4b shows the wind and geopotential height fields at 12 UTC August 7. TS Rachel and TS Paul maintained separate cyclonic circulations, in spite of the fact that they are embedded in the same large-scale circulation. The same situation was also found at 850 hPa (not shown). As shown in Figs. 4a and 4b, these two tropical storms were influenced by the subtropical high and southwesterly monsoon current. The relative positions of TS Rachel and TS Paul as shown in Figs. 3a and 4 suggest that there might have been some Fujiwhara interaction. However, the binary interactions of the tropical storms
are not our main focus in this study. Readers are referred to Fujiwhara (1921), Dong and Neumann (1983), Chang (1986) and Lander (1995) for more detailed discussion about the Fujiwhara effect. Although TS Rachel was still over the South China sea, heavy precipitation was recorded over southern Taiwan during this stage.

In general, from 12 UTC August 6 to 00 UTC August 7, the primary importance of TS Paul was to anchor the southwest monsoon well north and east of TS Rachel. This imposed a northeastward steering flow on TS Rachel, allowing it to cross the central mountain range of Taiwan. Besides, the interaction of the southwest monsoon flow and the southeastward flow on the southwestern periphery of the subtropical high are sufficient to impose the observed cyclonic motion of the two storms. From 00 UTC August 7 to 00 UTC August 8, TS Paul’s motion was likely due to the combination of the effects of the mid-level steering imposed by both the monsoon flow and the flow on the southwestern periphery of the subtropical high. The weakening and dissipation of TS Paul would cause the monsoon trough to retreat to the south towards TS Rachel. Subsequently, the subtropical easterlies would spread southward. This interaction would cause Rachel to move from a northwestward to a northward to a westward track. It appears that Rachel dissipated before acquiring the westward track. TS Rachel brought considerable rainfall to Taiwan in its approach and passage.

3.2 Mesoscale conditions

The center of TS Rachel on 18 UTC August 6 was shown in GMS infrared (IR) imagery (Fig. 5a). TS Rachel is somewhat irregular and represents the entire circulation. Imagery also indicates that TS Rachel was embedded in the broad southwesterly flow upstream before
landfall. As TS Rachel approached southern Taiwan, the southwesterly flow that impinged on the CMR became more apparent. Fig. 5b shows the IR imagery at 06 UTC August 7. Although the center was not clearly shown in the satellite imagery at this time, it was located around the southwest coast of Taiwan. The center was covered with a mesoscale precipitation shield, which covered the mountainous terrain of southwest and central Taiwan. A comparison of the evening and morning infrared satellite images (Fig. 5) shows some dramatic changes in the cloud top structure. The 18 UTC image shows that TS Rachel has a relatively symmetric cloud system center. At 06 UTC, from the satellite image, TS Paul was losing most of its deep convection. It is also evident that new strong convection was initiated around the CMR during the time TS Rachel made landfall. Subsequently, TS Rachel became disorganized and filled over the CMR.

Since the strong southwesterly flow and the outer circulation of TS Rachel had reached the southern part of Taiwan, the orographic rainfall was observed before TS Rachel made landfall, or between 12 UTC August 6 to 00 UTC August 7. Fig. 6a displays the 3-h accumulated precipitation from 15 UTC to 18 UTC August 6. Significant rainfall (~60mm) had been recorded at the southern tip of Taiwan. Apparently, the precipitation was due to the orographic forcing, in which the steep terrain in the southern tip of Taiwan affected the impinging flow, rather than from the rainbands of TS Rachel. This is evident in the satellite imagery (Fig. 5a), indicating that the rainfall on southern Taiwan during this particular time was not directly associated with Rachel’s moist processes. Fig. 6b shows the 3-h accumulated precipitation from 18 UTC to 21 UTC August 6, and orographic rainfall could
still be found along the windward side of southern Taiwan. Notice that due to the movement of TS Rachel, the distribution of the rainfall area had moved further north. From 21 UTC August 6 to 00 UTC August 7, the accumulated precipitation was found broadly over the southern part of Taiwan (not shown). While the maximum rainfall area was still around the southern tip of Taiwan, the total amount of rainfall had diminished to 40 mm during this time period.

Precipitation was assumed to be enhanced when TS Rachel moved inland, where a continuously moist flow was forced to rise over elevated terrain. This was the second rainfall episode which occurred during 00 UTC to 06 UTC August 7. Fig. 6c shows the 3-h accumulated precipitation during TS Rachel’s landfall period (00 UTC to 03 UTC 7 August). Precipitation was found at the slope of a concave area as well as the coastal region of southern Taiwan. More than 50 mm had been recorded within 3 hours. The peak amount of rainfall area was located around Yuh-You (22.59N, 120.42E, station height: 1518 m). During 03 UTC to 06 UTC August 7, TS Rachel gradually filled as it approached Taiwan (as illustrated in Fig. 3b). Fig. 6d shows the distribution of the 3-h accumulated precipitation. Apparently, the total precipitation increased while TS Rachel moved toward Taiwan. In addition, the heavy precipitation area was still located around southern Taiwan and the west coast of central Taiwan, while no significant rainfall fell on the east side of the CMR before and during TS Rachel’s landfall. It will be shown later that the convection of TS Rachel was enhanced by strong vertical motion induced by the mountains. It is worthwhile to note that during this period that TS Rachel was moving inland, the precipitation could be
found not only on the windward slope of the concave area (see Fig. 1b), but also along the coastal area. However, there was no upslope wind over the west coastal area. This implies that some other moist processes were in progress. We hypothesize that these new convective systems along the west coastal area were induced by the vertical moisture flux associated with convergence of the incoming airstream. The evolution of the precipitation distribution is given in the next section.

4. Results of Numerical Experiments

4.1 Fine-Scale Simulation of Orographic Rainfall

It is well recognized that increasing model resolution with proper initial conditions for the simulation of orographic rain events will significantly improve the rainfall prediction (e.g. Cacaiamani et al. 2000). In other words, high resolution simulations can offer better insight and understanding of the physical processes and mechanisms of orographic precipitation. For this reason, we shall limit our discussion to only the fine-scale simulation (5 km), and focus on a comparison between the 5-km resolution simulation results and observations.

As discussed in the previous section, due to the strength of the impinging southwesterly flow during the second stage, heavy orographic rainfall was observed from 12 UTC August 6 to 00 UTC August 7. Fig. 7a shows the numerically simulated 3-h accumulated precipitation distribution from 15 UTC to 18 UTC on August 6. The results indicated that most of the precipitation was located in southern Taiwan, especially in and around the southern tip area. Some convective cells can be found over the open ocean. Although the amount of simulated precipitation was higher than what the rain gauges actually recorded, the simulated rainfall
distribution pattern is relatively consistent with the observed rainfall distribution (Fig. 6a). From 18 UTC to 21 UTC August 6, precipitation was still occurring along the southern tip area, since the strength of the impinging southwesterly flow increased as TS Rachel approached, and subsequently the rainfall patterns were shifted to the east side of southern Taiwan (Fig. 7b). Compared with the observed (Fig. 6b), the model reproduced the location of rainfall over the southern CMR. The orographic rainfall was still simulated from 21 UTC to 00 UTC August 7, as a broad precipitation shield around the tip of southern Taiwan and the rainfall distribution was about the same as 3 hours before (not shown). It appears that the mountains played an important role in triggering and redistributing the precipitation, even though TS Rachel had not yet made landfall during this stage.

During 00 UTC to 03 UTC August 7, most of the simulated precipitation was located in southern Taiwan, especially in the concave region of the CMR (Fig. 7c). Although the simulation was not able to capture the observed local rainfall over the middle of west coast, the simulated precipitation amount over southern Taiwan (∼ 90 mm) may be somewhat higher than that observed (∼ 60 mm) (Fig. 6c). As indicated in the infrared satellite imagery (Fig. 5b), the circulation of TS Rachel was not well-organized when it moved closer to the CMR. As shown in Fig. 7d, rainfall could still be found over southern Taiwan from 03 UTC to 06 UTC, and some local convective cells were found over the northern and central parts of Taiwan. Compared with observational analysis (Fig. 6d), besides missing the local rainfall over the west coast and overpredicting the rainfall over southern Taiwan, the model roughly captures the pattern of heavy precipitation over southern Taiwan. In summary,
from 00 UTC to 06 UTC August 7, the simulation results demonstrated that the heavy rainfall area was found along the slopes of the concave area as well as the southern tip of Taiwan. Although the model did not adequately simulate the local rainfall amount over the middle west coast, it was able to simulate the location of the heavy precipitation region over southern Taiwan during this period, and the total amount of rainfall was over-predicted by about 70 mm (~ 30%).

In order to isolate the role of orography in this heavy precipitation event, we performed a sensitivity simulation without orography for comparison. Fig. 8a shows the 3-h accumulated rainfall distribution from 15 UTC to 18 UTC August 6 with heavy rain located around the south and southeast coast of Taiwan. From 18 UTC to 21 UTC August 6, a large portion of the rain was over the ocean to the southeast of Taiwan (Fig. 8b). During 00 UTC to 03 UTC August 7 (Fig. 8c), simulated precipitation was over southern Taiwan, and the maximum rainfall located over the ocean. Three hours later, heavy rainfall still can be found over southern Taiwan (Fig. 8d). However, as TS Rachel moved over the ocean, heavy rainfall was mainly associated with the southwesterly low-level flow during this period.

Comparing the control simulation (Fig. 7) with the sensitivity simulation (Fig. 8), the similarity of the results illustrated in Figs. 7a and 8a suggests that the rainfall amounts and distribution were more a result of the large-scale circulation than from the orography. The differences between Figs. 7b and 8b do suggest that the orography near the southern end of Taiwan may have had some influence on the circulation of TS Rachel in the 18 - 21 UTC time frame. In Figs. 7c and 8c, the results indicate that rainfall was more abundant over
Taiwan in the experiment without topography. It is clear that the presence of the topography changed the distribution of TS Rachel’s precipitation significantly during the landfall period. In addition, the simulation results indicate that the rainfall patterns seemed to start initially at the windward slope of the CMR and subsequently propagate to the coast. In other words, the complex topography could induce convection by convergence and organize the localized convective cells. Nevertheless, some other conditions for inducing heavy orographic rainfall must have also been present, in order to produce heavy orographic rainfall. We will discuss these conditions in the following section.

4.2 Some common ingredients for orographic rainfall

In this section we will examine some of the common ingredients that have been proposed by Lin et al. (2001) to explain heavy orographic rainfall for this particular event. The role of a steep mountain as well as favorable mountain geometry will be examined by using the fine-scale simulation results. In addition, the strong southwesterly low-level jet, the presence of a high moisture flow upstream and a conditionally or potentially unstable upstream airflow will also be discussed.

As discussed in the previous section, the COAMPS model performed reasonably well in predicting the distribution of heavy rainfall over the southern CMR during different time periods. After comparing the control simulation and the sensitivity simulation (without orography), it is clear that the steep mountain is an important ingredient in this case. In particular, it has an approximated steepness value of 0.033 in the southern CMR (i.e., $h_m/L_x$, where $h_m$ ($\sim 3$ km) is the average mountain height, and $L_x$ ($\sim 90$ km) is the width
of southern Taiwan. As indicated in Fig. 1b, the concave geometry of the CMR is located around (22.8N, 120.5E), where the most significant precipitation was observed to occur. As suggested in Lin et al. (2001), the mountain concave geometry and LLJ will give a large value of $V_H \cdot \nabla h$, which then results in heavy precipitation in the concave area. Similar phenomena have also been observed in the Lago Maggiore region over the southern Alps (e.g. Schneidereit and Schär 2000). Orographic rainfall over southern Alpine slopes often starts from the Lago Maggiore region when a moist LLJ flows from the Mediterranean. Another clear example of orographic rainfall enhancement produced by the interaction of the Mediterranean LLJ with the concave geometry occurs in the Valencia region in eastern Spain (see Romero et al. 2000).

Fig. 9 shows the horizontal wind vectors and velocities at 850 hPa during the orographic rainfall period. The southwesterly flow dominated the flow field at 21 UTC August 6 (Fig. 9a) with the direction of the impinging wind was nearly perpendicular to the southern part of the CMR. The strong low-level wind ($\sim 18$ m s$^{-1}$) was located around the southern tip of Taiwan. The upward motion also existed over the foothills of the CMR, and as a result, heavy orographic precipitation was also recorded there. Three hours later, as TS Rachel moved much closer to southern Taiwan, the wind speed at the concave region was enhanced by the combination of the southwesterly monsoon and the outer circulation component of TS Rachel, which served as a low-level jet (Fig. 9b). The upward motion cells were found along the foothills of the southern CMR and over the open ocean. These strong upward motion cells illustrated orographically-induced vertical motion as well as the vertical motion
associated with TS Rachel, which were consistent with the change of convection seen in satellite imagery (Fig. 5b). Fig. 9c shows the wind field at 03 UTC August 7. Since TS Rachel moved closer to Taiwan at this time, a strong continuous flow coming from the southwest with wind speeds in excess of 15 m s$^{-1}$ located on the lee side of the CMR was produced. The upward vertical velocity field along the coast was oriented in the southwest-northeast direction as TS Rachel continued its northeastward track. At the same time, there was upward motion over northern Taiwan. The region of strong upward motion was well organized in southern Taiwan as TS Rachel moved inland, and the rainfall over southern Taiwan peaked by 06 UTC August 7 (Fig. 9d). These upward motions also demonstrate that grid-explicit convection was produced in the model (e.g., Kain and Fritsch 1998).

Convergence of the flow also formed along the coastline of southwest Taiwan when TS Rachel moved closer to the island. On 03 UTC August 7, a convergence zone formed in the concave region where the most significant rainfall was observed. The offshore divergence was associated with the winds redirected by the concave regions (not shown). The area of strong upward motion at 850 hPa (Fig. 9) was correlated with zones of near surface horizontal wind convergence. In contrast, the horizontal wind field and upward motion at 850 hPa in the sensitivity experiment without orography suggested that TS Rachel moved faster and made landfall on 03 UTC August 7 (Fig. 10a). Three hours later, TS Rachel had existed Taiwan and moved over the ocean (Fig. 10b). Some convective cells were embedded in Rachel’s circulation as well as in southwesterly flow when TS Rachel was moving over Taiwan. In comparing the results of the control and sensitivity experiments, while the large-
scale circulation had some contribution to the rainfall, it is evident that the increased near surface convergence and upward motion over the concave region of southwestern Taiwan played a role in intensifying the precipitation of TS Rachel as it made landfall (cf. Figs. 7 and 8). In other words, the favorable mountain geometry (i.e., concave area) is another ingredient to enhance orographic rainfall.

In order to identify the flow over or flow around (and blocking) regime of the LLJ impinging on southern Taiwan, we have also calculated the moist Froude number \( F_w = U/N_w h_m \). The \( F_w \) upstream of the concave region for this case is about 0.34 \( (U = 10.0 \text{ m s}^{-1}, N_w = 0.0098 \text{ s}^{-1}, h_m = 3000\text{m}) \), which demonstrated the impinging flow was blocked by the CMR. This flow condition may also be identified as the regime with upstream-propagating convective systems (e.g. Chu and Lin 2000; Chen and Lin 2001). Because of the blocking effects of the southern CMR, the southwesterly winds were split into two components. As indicated in Figs. 9c and 9d, the southwesterly flow on the windward side was significantly redirected northwest into the concave region, while the other component of the impinging southwesterly flow moved around the southern end of Taiwan. Strong upward motions were simulated over the foothills of the CMR throughout the entire period of heavy orographic rainfall (Fig. 9). Apparently, the blocking effects of the CMR would enhance the vertical motion while TS Rachel moved inland. Comparing the simulated rainfall distributions (Fig. 7) with the wind fields (Fig. 9), it appears that the orographic rainfall was affected by the strong southwesterly LLJ and the convergence near the concave region. Thus, we can conclude that the strong southwesterly low-level jet is another ingredient for producing heavy
orographic rainfall.

During the second stage (12 UTC August 6 to 00 UTC August 7), the impinging southwesterly flow was very moist since it came from the ocean. The $\theta_e$ distributions at 850 hPa at 21 UTC 6 August and 03 UTC 7 August (Figs. 11a and 11b) indicate that the impinging southwesterly flow was very moist over southern Taiwan with high $\theta_e$ ($\geq 335$ K). The orographic rain started to occur when the moist tongue moved toward the southwestern CMR (as illustrated in Fig. 6b). When TS Rachel moved closer to the island, a more significant change of $\theta_e$ could be found in the concave region and southern CMR, which was colocated with the heavy rainfall area during that time (Fig. 11b). An area of high $\theta_e$ was also found in northeastern Taiwan (Fig. 11b). However, the impinging flow only existed over northeastern Taiwan and the precipitation was not as heavy as that in southwestern Taiwan. The results suggest that the high moisture airstream is one of the ingredients for producing heavy orographic rainfall.

In order to understand the generation mechanisms of orographic rainfall associated with this event, we use the fine resolution data generated by the model to examine the orographic precipitation efficiency formula proposed by Lin et al. (2001). Based on their Eq. (8), the total precipitation produced ($P$) may be estimated by

$$P = \frac{\rho}{\rho_w} E \left( V_H \cdot \nabla h + w_s \right) q L_s / c_s$$

where $V_H \cdot \nabla h$ is directly related to the orographically-induced vertical motion (Doswell et al. 1998; Lin et al. 2001), $w_s$ the synoptically forced vertical motion, $q$ the mixing ratio, $\rho$ and $\rho_w$ the air density ($\sim 1$ kg m$^{-3}$) and water density ($\sim 1000$ kg m$^{-3}$), $c_s$ the propagation
speed of the convective system and $L_s$ the horizontal scale of the convective system. The precipitation efficiency ($E$) is defined as the ratio of the precipitated water mass to the mass of water vapor inflow (Fankhauser 1988; Doswell et al. 1996). $E$ is not easy to calculate or estimate since it is far more sensitive to the parameterization of cloud microphysics, and the values are ambiguous due to repeated ascent and descent at the convective scale. $L_s$ and $c_s$ may be estimated, however, they are too sensitive to be taken into account in Eq. (1). Therefore, the precipitation produced ($P$) is roughly proportional to orographically-induced vertical motion and synoptically-induced vertical motion multiplied by the mixing ratio. We will calculate these two terms individually for this particular case. Although the synoptically-forced vertical motion may not be significant in our particular case, the vertical moisture flux associated with it could contribute to the precipitation when the convective system is over a flat area such as the open ocean.

The evolution of the orographically induced moisture flux, i.e. $(V_H \cdot \nabla h)q$ at 850 hPa is shown in Figs. 12 a-d for 18 UTC and 21 UTC on August 6, and 03 UTC and 06 UTC on August 7. As mentioned in previous sections, these four times represent the heavy precipitation period induced by orographic effects during the landfall of TS Rachel. Note that $V$ and $q$ vary strongly in time and space, which in turn, causes the vertical moisture flux to vary strongly, also. Therefore, we chose the 850 hPa level to calculate the orographically-induced moisture flux, since the 850 hPa level is less affected by boundary layer processes.

When the southwesterly flow impinges on the mountains, the vertical moisture flux is positive (negative) on the windward (lee) side (Fig. 12a). At 21 UTC August 6 (Fig. 12b),
the high positive value of this vertical moisture flux was still located in southern Taiwan. It can be seen that high vertical moisture flux regions were located along the southwest coast of the island. This result is consistent with the observed (Figs. 6a and 6b) and simulated (Figs. 7a and 7b) heavy orographic rainfall areas. When TS Rachel moved closer to Taiwan, the impinging flow tended to be shifted by the concave region of the CMR. Hence, the terrain-induced vertical moisture flux was more vigorous in southern Taiwan at 03 UTC August 7 (Fig. 12c). This result also suggests that the precipitation over the southern coast of Taiwan was induced by the vertical moisture flux that was associated with flow convergence. The same situation can be found at 06 UTC August 7 (Fig. 12d). As indicated in both the observations (Fig. 6d) and the simulations (Fig. 7d), the high precipitation regions were located on the slope of the the southern CMR during that time.

Fig. 13a shows the vertical moisture flux by using model-predicted vertical motion multiplied by the mixing ratio \((wq)\) at 03 UTC 7 August at 850 hPa. Compared with Fig. 12c, the general vertical moisture flux did represent that portion of the precipitation over the ocean, as can be seen from the high values of moisture flux located along the coast of Taiwan. Similar results can also be found at 06 UTC August 7 (Fig. 13b). At this time, large positive values of general vertical moisture flux were located in southern Taiwan with a narrow band that stretched in from the ocean, and which is associated with a rainband of TS Rachel. Based on this study, we may conclude that the positive area of orographically-induced vertical moisture flux could be used to help forecast areas of potential heavy rainfall over the windward mountain area. The orographic vertical moisture flux proposed by Lin et
al. (2001) can provide weather forecasters with additional information for forecasting heavy orographic rainfall.

Another important process is the triggering of potential instability by the orography. The decrease of $\theta_e$ with height implies the possible existence of a potentially unstable layer. The high $\theta_e$ flow has been observed to exist ahead of a front or other weather systems which may serve as a conveyor belt that transports warm and moist air to the upslope (e.g., Harrold 1973; Lin 1993). The model sounding near the slopes of southern Taiwan (22.6N, 120.3E) on 12 UTC August 6 (Fig. 14a) indicated the lifting condensation layer (LCL) was 0.4 km and the level of free convection (LFC) was lower than 1.0 km. The convective available potential energy (CAPE) was about 818 J kg$^{-1}$ during this time. It appears that the impinging LLJ ($\sim$ 10 m s$^{-1}$) can be elevated up to the LFC and produce heavy rainfall. In fact, the depth ($\Delta \eta$) due to orographic lifting can be roughly estimated by assuming $\Delta \eta = w \Delta t$, where $w \approx U (\partial h/\partial x)$. If $U \approx 10 ms^{-1}$, and $\partial h/\partial x \approx 0.033$, the impinging air will be lifted up to LFC after one hour. At 00 UTC August 7, as TS Rachel moved closer to southern Taiwan, the model sounding becomes almost completely saturated (Fig. 14b). It suggests that latent heat has been released, and the CAPE has been consumed, and heavy rainfall produced. Notice that the vertical sounding at 12 UTC August 6 (Fig. 14a) indicates that the low-level flow is potentially unstable since $\partial \theta_e/\partial z < 0$.

In order to gain further insight into the potential instability during the heavy orographic rain associated with TS Rachel’s landfall, we analyzed the vertical cross-section of $\theta_e$ from (21.8N, 119.5E) southwest to (24.0N, 122.3E) northeast (see Fig. 1b). The $\theta_e$ and cloud
water \((q_c)\) on the vertical cross-section through the concave region (Fig. 15) indicate intense updrafts and heavy orographic rainfall which occurred when TS Rachel moved inland. Fig. 15a indicates that the potentially unstable layer \((\partial \theta_e/\partial z < 0)\) existed upstream of the CMR, and that the regions of high \(q_c\) formed upstream and over the top of the mountain, which indicates that convection was forced by orographic blocking at about 21 UTC August 6. At 00 UTC August 7 (Fig. 15b), the \(\theta_e\) and \(q_c\) fields indicate that the moist convection formed upstream of CMR. Additionally, density currents were formed on the upslope of the CMR caused by the evaporatively cooled air (low equivalent potential temperature). In fact, the density currents can be treated as outflow boundaries which were produced by the convective cold pools (Fig. 15b).

At 03 UTC August 7, when TS Rachel moved closer to southern Taiwan (Fig. 15c), a strong enhancement of the \(\theta_e\) contrast in the lower troposphere existed upstream of the CMR. This contrast of \(\theta_e\) is associated with the impinging southwesterly flow and Rachel’s outer circulation. As a result, two strong potentially unstable layers existed upstream of the CMR (Fig. 15c). Three hours later (Fig. 15d), when TS Rachel made landfall, the \(\theta_e\) cross-section indicates a deep potentially unstable layer over the southwest slope of the CMR. During 00 UTC to 06 UTC August 7 (Figs. 15c and 15d), new convection formed upstream from southern Taiwan. Apparently, the outflow boundaries forced the low-level convergence to propagate upstream over the ocean, and the impinging flow from the southwest triggered new convection.

Fig. 16 presents the vertical velocity on cross section AA’, which helps identify the
depth and intensity of the updraft rooted over the sloping orography. Specifically, Fig. 16a shows that a strong and deep updraft occurred upstream and upslope of the CMR on 03 UTC August 7. It is clear that the orographically-induced upward motion occurred as flow impinged on the mountains, while the upstream updraft was part of the circulation of TS Rachel. Three hours later (Fig. 16b), when TS Rachel moved over Taiwan, intense and deep vertical motion occurred over the mountains. It appears that the potentially unstable layer over the ocean was due to the vertical motion embedded in the circulation of TS Rachel, and the potentially unstable layer in mountainous areas was caused by the impinging LLJ associated with orographically-induced vertical motion. In addition, these results may help to explain the changes that were found in the cloud top structure in satellite imagery (Fig. 5b). The potentially unstable regions were colocated with those of the heavy rainfall (Figs. 7c and 7d) as well as the high values of vertical moisture fluxes (Figs. 12 and 13). The location of heavy precipitation was also colocated with the strongly unstable regions. As shown in Fig. 15, some unstable layers existed near the surface both on the windward side and lee side. However, no significant rainfall was predicted over the lee side, due to the fact that potential instability could not be released under the conditions of air descent induced by the orography. We conclude that the upward motion induced by the orography and TS Rachel was able to release the potential instability which could trigger the strong convection, and produce orographic precipitation.

5. Discussion and Conclusions

In this study, numerical experiments were performed to investigate the observed synoptic
and mesoscale environments and examine some common ingredients for orographic rain when tropical storm Rachel passed over Taiwan. The numerical experiments were conducted using a coupled ocean/atmosphere numerical weather prediction model (COAMPS). Based on a recent study of some common ingredients for orographic rainfall (Lin et al., 2001), we have investigated the evolution of heavy orographic rain to better understand the mechanisms responsible for orographic precipitation.

It was shown that this landfalling tropical storm event could be divided into three distinct stages. From 0000 to 1200 UTC August 6, TS Rachel was embedded in the monsoon trough of the South China Sea, and moved northeastward toward Taiwan. Meanwhile TS Paul was steered by the subtropical high to the northwest. During the second stage, from 1200 UTC August 6 to 0000 UTC August 7, the steering flow in the mid-troposphere accompanying the subtropical high and the southwesterly monsoon current caused the mid-tropospheric circulation of TS Paul and TS Rachel to interact with each other, which resulted in counterclockwise rotation of these two storms. In the final stage (0000 UTC to 1800 UTC August 7), orographic rainfall was triggered by the continuous strong southwesterly low-level jet impinging on the Central Mountain Range (CMR) of Taiwan. This strong low-level jet was a combination of TS Rachel’s direct circulation and the southwesterly monsoon.

During the second stage, the impinging southwesterly flow strengthened and formed a low-level jet (LLJ) with high $\theta_e$ due to the approach of TS Rachel toward Taiwan. The heavy precipitation was caused mainly by orographic lifting. Heavy rainfall was still observed between 00 UTC and 06 UTC August 7 while TS Rachel made landfall. This second episode
of heavy rainfall was also caused by the combined effects of orographic forcing and TS Rachel’s rainbands, in which the strong orographic lifting of the LLJ triggered convective systems in the concave region of the southwest CMR. Based on the numerical results, the simulation of the large scale environment of the two tropical storms helped the model to predict the location of the orographic precipitation. However, the observed precipitation over the western slope of the CMR could not be reasonably simulated, and the model slightly over-estimated the total amount of precipitation. This discrepancy between observation and simulation could have been caused by the complex topography which may not be able to be resolved in a 5 km resolution grid-spacing domain, especially over the southwest CMR. This grid spacing results in about 4 grid points along the concave region. In addition, the model was not able to reproduce the intensity and convective structure of TS Rachel. Subsequently, the circulation of TS Rachel weakened as it came closer to southern Taiwan, which downplayed the impinging flow from the west. As a result, the precipitation over the western slope of the CMR could not be reasonably simulated. Even though TS Rachel is a weak tropical cyclone, it appears that vortex bogusing is needed at the initial stage in order to get a better result. On the other hand, the complex topography could play a role in disorganizing the sub-grid scale convection, resulting in the model over predicting the total amount of precipitation. However, the model results provide good insight into the dynamics of moist convective systems over complex orography, and the period of the orographic precipitation was predicted reasonably well.

The sensitivity simulation without orography helped to better gauge the role of the terrain
during the heavy rainfall period. We found that the large-scale circulation made more of a
contribution to the rainfall amounts and distribution over southern Taiwan before Rachel
made landfall. The heavy rainfall was closely related to the complex topography when TS
Rachel moved inland, and the low-level impinging flow was dramatically changed by the
slope as well as the concave area of southwestern Taiwan. We also examined the horizontal
distribution of $\theta_e$ as well as the vertical cross-section of $\theta_e$ and $q_e$. The results indicate
that high $\theta_e$ as well as unstable layers can be found on both the windward and lee sides of
the topography, however, the heavy orographic rainfall existed only on the windward side
(concave area). The results also suggest that the southwesterly LLJ in association with high
$\theta_e$ airstream supplies moist air and helps establish the potentially unstable layer; combined
with the orographic blocking effects as well as strong upward motion from TS Rachel which
produced the heavy orographic rainfall.

By examining the orographically-induced vertical moisture flux and general vertical mois-
ture flux, we found that the rainfall distribution over the mountains was roughly consistent
with the orographically-induced vertical moisture flux distribution. Hence, the orographic
vertical moisture flux may serve as an index for predicting the potential threat area of up-
sloping heavy orographic rainfall, while the general vertical moisture flux could predict the
rainfall distribution better over a flat surface. In addition, the mountain geometry (concave
area) could help to enhance confluent flow and organize localized convective cells. Sub-
sequently, outflow boundaries are produced by the convective cold pools, which force the
convective systems to propagate upstream over the sea, and the impinging flow from the
southwest develops new convection.

The results shown in this study are a first step to better understand the factors that produce heavy orographic rainfall, which may provide guidance for improving orographic rainfall forecasts. Although some other potential factors might still be embedded in orographic rainfall events, the results of this case study provided useful information. The high sensitivity of the orographic precipitation to the common ingredients found by Lin et al. (2001) and in this study suggests some subtle, complex relations between complex terrain and vertical moisture flux that require further study. More validation of modeling results against rainfall measurements is needed.
6. References


Lin, Y.-L., 1993: Orographic effects on airflow and mesoscale weather systems over Taiwan.  


Figure 1: (a) COAMPS model computational domain. The grid increments for the three nested meshes are 45km (D1), 15km (D2) and 5km (D3), respectively. (b) Terrain (contour interval 500 m) used for the 5-km resolution grids. The solid line AA’ represents the orientation of the x-z cross sections in subsequent analyses.
Figure 1: Cont’d
Figure 2a: Surface analysis charts over East Asia valid at 00 UTC 6 August 1999 (From Japan Meteorological Agency).
Figure 2b: Surface analysis charts over East Asia valid at 00 UTC 7 August 1999 (From Japan Meteorological Agency).
Figure 3: (a) Best tracks of TS Rachel and TS Paul and (b) The simulated time evolution of TS Rachel’s minimum low pressure (hPa). The times for (b) start from 12 UTC 6 August and end at 00 UTC 8 August 1999.
Figure 4: NOGAPS analysis of 500 hPa wind vector (m/s) and geopotential height (m) on (a) 12 UTC 6 August and (b) 12 UTC 7 August 1999.
Figure 5: GMS-5 visible satellite images at (a) 18 UTC 6 August, and (b) 06 UTC 7 August 1999.
Figure 6: Analysis of the observed 3-hr total accumulated rainfall (contour interval 10 mm) over Taiwan area valid at (a) 15-18 UTC, (b) 18-21 UTC 6 August 1999, (c) 00-03 UTC, (d) 03-06 UTC 7 August 1999.
Figure 6: Cont’d
Figure 7: 5km resolution grid forecast 3-h total accumulated (contour interval 10 mm) rainfall over Taiwan area valid at (a) 15-18 UTC, (b) 18-21 UTC 6 August, (c) 00-03 UTC, (d) 03-06 UTC 7 August 1999.
Figure 7: Cont’d
Figure 8: 5km resolution grid without orography forecast 3-h total accumulated (contour interval 10 mm) rainfall over Taiwan area valid at (a) 15-18 UTC, (b) 18-21 UTC 6 August, (c) 00-03 UTC, (d) 03-06 UTC 7 August 1999.
Figure 8: Cont'd
Figure 9: The simulated 850 hPa wind field and vertical velocity (contour interval 10 cm s$^{-1}$) for 5km resolution grid valid at (a) 21 UTC 6 August, (b) 00 UTC 7 August, (c) 03 UTC 7 August, and (d) 06 UTC 7 August 1999.
Figure 9: Cont'd
Figure 10: The 850 hPa wind field and vertical velocity (contour interval 10 cm s\(^{-1}\)) for 5km resolution grid simulation without orography valid at (a) 03 UTC 7 August, and (b) 06 UTC 7 August 1999.
Figure 11: The simulated equivalent potential temperatures ($\theta_e$) at 850 hPa at (a) 21 UTC 6 August, and (b) 03 UTC 7 August 1999. Areas with $\theta_e$ greater than 335K are shaded.
Figure 12: Topographically induced vertical moisture flux (contour interval 0.5 gkg\(^{-1}\)m s\(^{-1}\)) at 850 hPa at (a) 18 UTC 6 August, (b) 21 UTC 6 August, (c) 03 UTC 7 August, and (d) 06 UTC 7 August 1999.
Figure 12: Cont’d.
Figure 13: Total vertical moisture flux (contour interval 0.5 g kg$^{-1}$ m s$^{-1}$) at 850 hPa at (a) 03 UTC 7 August and (b) 06 UTC 7 August 1999.
Figure 14: Skew T-log P charts from model; located at 22.6N, 120.3E, at (a) 12 UTC 6 August, and (b) 00 UTC 7 August 1999.
Figure 15: X-Z cross-section of equivalent potential temperature ($\theta_e$) (contour interval 2°K) and cloud water ($q_c$) from (21.8N, 119.5E) to (24.0N, 122.3E) (SW → NE) valid at (a) 21 UTC 6 August, (b) 00 UTC 7 August, (c) 03 UTC 7 August, and (d) 06 UTC 7 August 1999. The cross section AA’ is depicted in Fig. 1b. Areas with $q_c$ greater than 0.02 g kg$^{-1}$ are shaded.
Figure 16: X-Z cross-section of vertical velocity (contour interval 0.3 m s\(^{-1}\)) from (21.8N, 119.5E) to (24.0N, 122.3E) (SW → NE) valid at (a) 03 UTC 7 August, and (b) 06 UTC 7 August 1999. The cross section AA’ is depicted in Fig. 1b.
CHAPTER 4

Numerical Study of Formation Mechanisms of Heavy Rainfall during MAP IOP-2B. Part I: Orographically-induced Circulations
This Chapter investigates the local circulation associated with a heavy orographic rainfall event during 19-21 September 1999 (MAP IOP-2B). This event was simulated with a 5 km horizontal grid spacing using the Penn State/NCAR MM5 model. The MM5 simulation reproduced the basic features such as the timing and location of the deep trough and the associated precipitation evolution, though the total amount of precipitation is slightly higher than that measured by rain-gauge (∼30% in 24 hours). The near surface flow was dominated by an easterly jet originally from the Adriatic Sea and a southerly jet from the Gulf of Genoa. A significant westward turning occurred when the southerly flow approached the south side of the Alps. This deflection was caused by boundary friction, rotation as well as mountain blocking effects. Flow was generally from the south above the surface. Precipitation was mainly concentrated on the windward slopes, especially near the Lago Maggiore region.

Sensitivity experiments have been conducted to investigate the effects of upstream orography, western flank of the Alps, rotation, boundary layer friction, idealized mountain geometry, and horizontal resolution. The results indicate that precipitation distribution and amount over the southern upslopes of the Alps were not directly related to either coastal Apennines mountains or the west flank of the Alps. The effect of rotation was essential to make the westward turning of the southerly flow. The boundary layer friction appears to reduce the total amount and alter the distribution of rainfall by means of weakening the wind near the surface. Although the rainfall distribution over the southern Alpine slopes was very similar to the control simulation in both arc-shaped and elongated bar-shaped idealized
topography, the total precipitation was reduced as much as 50% in comparison with the control simulation with realistic topography. This is explained by the weaker upward motion induced by smoother, idealized topography. The 1.67 km horizontal grid spacing simulation indicates that heavy rainfall tended to concentrate in the vicinity of individual mountain peaks. The total amount of rainfall was over-predicted along the windward slopes due to the strong upward motion that occurred on the upslopes. The results imply the dynamical forcing associated with vertical motion, which increases rapidly as resolution increases. Thus, the rainfall over-prediction problem might be caused by the inaccurate or unrealistic microphysical processes over complex topography.
1. Introduction

A heavy orographic rainfall event occurred on 19-20 September 1999 during the Mesoscale Alpine Programme (MAP; Bougeault et al. 2001) Intensive Observing Period (IOP) 2B when a deep trough propagated eastward through Alps. The 24 h accumulated rainfall exceeded 250 mm locally. The heavy rain was concentrated on the windward slopes of the Alps, and in the Lago Maggiore Target Area (LMTA). Similar synoptic conditions and amounts of precipitation comparable to this event were recorded in the Piedmont flood event in November 1994, in which the southerly low-level jet, associated with the deep trough, picked up moisture from the sea and advected it into the southern slopes of the Alps (e.g., Buzzi et al. 1998; Buzzi and Foschini 2000). A detailed description of IOP-2B event was presented by Lin et al. (2002), and Asencio et al. (2003). Synthesis of the papers describing orographic rainfall events observed during MAP indicates that orographic rainfall over Alpine regions occurs under a variety of conditions (e.g. Bougeault et al. 2001; Houze et al. 2000; Smull et al. 2000; Steiner et al. 2000). Additionally, one piece of evidence suggesting that orographically-induced circulations may play a role in heavy rainfall events is that the precipitation climatology over the Alps is not uniformly distributed but instead is distributed along the Alpine foothills and the shielding of the inner-Alpine valleys (e.g. Frei and Schär 1998). Although many studies have demonstrated how the airstream moves past terrain features and what synoptic scale conditions are favorable for orographic rainfall, it is important to understand the precise mechanisms that lead to the formation, distribution, and persistence over many hours of this type of orographic precipitation. This study was
stimulated by the fact that the precipitation was concentrated over the windward slopes around the Lago Maggiore region with long duration in this heavy precipitation event.

Recent research (Buzzi and Foschini 2000) pointed out that orographic precipitation is generated by different mesoscale features associated with the interaction with topography, such as a moist low-level jet (LLJ) and convergence zones. As a matter of fact, the orographic rainfall over the southern Alpine slopes often starts in the Lago Maggiore region when a moist LLJ flows from the Mediterranean. The strong influence of the Alps on the flow has also been demonstrated in the numerical work of Chen and Lin (2001). They concluded that a relatively large amount of rainfall can be produced over the upwind slope under the presence of an impinging LLJ. In addition, idealized experiments by Rotunno and Ferretti (2001) show that in the 1994 Piedmont heavy rainfall event, the western moist part of the airstream (saturated) flows over the mountains, while the eastern drier branch (unsaturated) is deflected westward around the obstacle. Thus, a convergence of air is produced between the airstreams, and heavy precipitation is produced. The influence of terrain on the flow and precipitation has also been demonstrated in the idealized simulation by Schneidereit and Schär (2000). They conjectured that the Coriolis effect and a pronounced moist low-level jet provided a suitable environment for heavy condensation and precipitation. In addition, Lin et al. (2002) also found that a vortex was produced near the Lago Maggiore area due to the interaction of the LLJ and the concave geometry of the Alps. However, the impact of this closed local circulation on orographic rainfall is still not clear, and deserves further study.
A previous numerical study by Buzzi et al. (1998) has revealed that orographic rainfall would be strongly reduced as the heights of upstream mountains (i.e., Ligurian Apennines) and western flank of the Alps (i.e. French Alps) were reduced. They concluded that the lack of the orographic lifting would change the condensation as resulting in reduced orographic precipitation. Stein (2002) also pointed out that if the surrounding mountains are removed (i.e., Alps alone), the accumulated rain is less than 4 mm in a 12-hour simulation. It is worth noting that simulations in Buzzi et al. (1998) and Stein (2002) were conducted with rather coarse 30 and 10 km resolutions, respectively. It appears that local circulations as well as the rainfall distributions in either the upstream mountains or western flank of the Alps are quite complicated and deserve further study. In this Chapter I will focus on fine scale simulations to understand the effects of the Ligurian Apennines and French Alps on local circulation as well as rainfall distribution. In addition, I will use simulation with idealized topography (i.e., arc-shaped and elongated bar-shaped) to investigate effects of topographic features on the formation of rainfall.

The IOP-2B case provides an excellent opportunity to investigate how the orographic effects on moist flows can lead to heavy precipitation. This study is aimed to advance fundamental knowledge of the interaction between orographically-induced local circulations and precipitation processes over the Alpine mountain ranges. The purpose of this study is to validate the mesoscale model performance on precipitation forecasts over the regions of complex topography. The analysis is based on the data collected from the MAP project, which includes special sounding ascents, surface data, radar observations, and rain-gauge obser-
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vations. Fine resolution simulation (i.e., 5 km) results will be used as a diagnostic tool to create a mesoscale dataset describing the initiation and subsequent orographic precipitation. The numerical model and experiment design are described in section 2. A general description of the spatial structure and temporal evolution of precipitation during MAP IOP-2B using the observed precipitation dataset and radar imagery are discussed in section 3. The verification of the control simulation results is presented in Section 4, while the sensitivity tests are discussed in section 5. Section 6 presents the conclusions.

2. Model description and experiments design

Numerical simulations were performed by using the PSU/NCAR MM5 model (Dudhia 1993; Grell et al. 1994). Three nested domains were constructed with the grid spacing of 45 km, 15 km, and 5 km horizontal resolutions, respectively. The corresponding numbers of grid points are $91 \times 85$, $121 \times 121$, and $121 \times 121$. The model top is located at the 50 hPa level. Time steps of 90, 30 and 10 s were used in these nested grid simulations, respectively. The 45 km resolution domain covered Europe and the 5 km domain was concentrated in northern Italy (Fig. 1a). Several options are available in the model for parameterization schemes of physical processes. The planetary boundary layer (PBL) scheme used in this study is the Blackadar high-resolution PBL scheme (Zhang and Anthes 1982). The atmospheric radiation scheme, described by Dudhia (1989), accounts for longwave and shortwave transfers and interactions with the atmosphere, clouds, and the surface. Precipitation is produced from both grid-scale condensation and convection. Grid-scale precipitation is determined from an explicit moisture scheme that includes graupel of Lin et al. (1983).
The Kain-Fritsch (Kain and Fritsch 1993) scheme was adopted for the cumulus parameterization. Klemp and Durran’s (1983) upper-radiative boundary condition was applied in order to prevent gravity waves from being reflected off from the model top. In the control experiment (CTRL, see Table 1 for a list of numerical experiments), the model contains 1-km resolution terrain data that are mapped to the MM5 model grid resolution to better account for the mesoscale effects of topography. The terrain data for the third (i.e., finest) grid mesh of $\Delta x = 5$ km is shown in Fig. 1b. The model topography data is representative of the complex local topographic features, with several mountain peaks of the Alps higher than 3500 m.

In order to examine the relative roles of upstream topography on the formation of orographic precipitation over the Lago Maggiore region, we conducted several experiments in an attempt to isolate their effects on local circulations as well as the formation of orographic precipitation. To test the effect of upstream mountains, we performed a simulation without the Ligurian Apennines and mountains of Corsica and Sardinia topography (NAPN) on 15 km and 5 km domains, while keeping everything else identical to the CTRL. This topographic feature is very similar to the arc-shaped barrier-like obstacle of the Alps. The upstream topography includes Apennines, and mountains on Corsica and Sardinia. In addition to the NAPN, in order to better gauge the initiation of orographic rainfall, we carried out an experiment in which the Maritime Alps (i.e., French Alps) were set to be flat from 43N to 45N, while keeping everything identical to the NAPN. Thus, the mountain was very similar to an east-west elongated ridge. This experiment is denoted by NWAP. In order to
test the friction effects, another experiment (NFRC) with free slip lower boundary was also conducted. In addition, we also conduct two idealized terrain simulations, and a 1.67 km horizontal grid spacing simulation. Detailed discussions about these sensitivity experiments will be presented in Section 5.

All the simulations used the same initial and lateral boundary conditions, which are generated from the NCAR/NCEP Reanalysis (Kalnay et al. 1996) with $2.5^\circ \times 2.5^\circ$ resolution. The first-guess fields interpolated from the re-analysis are then enhanced by the blending in of the rawinsonde, surface observational data using the Cressman (1959) analysis technique to introduce mesoscale features. Time-dependent lateral boundary conditions are provided at 12-h intervals. A total of 46 unequally spaced levels in the vertical with the lowest model level beginning approximately 20 m above ground are used. Forty-eight hour simulations were run from 0000 UTC 19 to 0000 UTC 21 September 1999. Our discussions are based on the results of the 5-km grid domain.

3. Observed local circulation and rainfall

In this section, a description of the observed mesoscale evolution of IOP-2B is presented, followed by an examination of the low-level local circulation induced by the Alps, and the spacial and temporal distribution of precipitation. The analysis is based on conventional data, visible satellite imagery, and high resolution networks of Alpine countries’ rain-gauge datasets, including Italy, Austria, and Switzerland. Theses datasets and daily analyses are available at the MAP Data Center (e.g. Frei 1995; Frei and Häller 2001). While all the available observations were used, a limited number of observations are analyzed and
presented here. The synoptic environment for IOP-2B was presented in Lin et al. (2002). In addition, Houze et al. (2000) and Rotunno and Ferretti (2002) have analyzed the orographic rainfall associated with IOP-2B. However, their studies focused on the later development stage of IOP-2B. This study will concentrate instead on mesoscale aspects of the orographic precipitation.

IOP-2B took place during 19-21 September 1999 when a trough swept into northern Italy and heavy rain was concentrated on the windward (southern) slopes of the Alps and in the Lago Maggiore region. During the IOP, a south-southwesterly low-level jet (LLJ) was accompanied by the eastward moving deep trough, which impinged on the Alps (see Lin et al. 2002). This LLJ serves as an ingredient for heavy orographic rainfall (Lin et al. 2001). Figure 2 shows a visible satellite image from MeteoSat-6 rapid scan data at 0900 UTC 20 September. The imagery indicates a large area of clouds south of the Alps in a wide band extending from the central Mediterranean northward through northern Italy and the Alps. The scenario suggests that a large scale ascent was associated with the trough at that time, and consisted largely of a mesoscale precipitation shield that covered the south side of the Alps as well as the Lago Maggiore region. The 500 hPa height field from ECMWF 0.5 degree analyses data and 850 hPa radiosonde observations from 1800 UTC 19 to 1200 UTC 20 September at 6 hr intervals are presented in Figs. 3a-d. During this period, the low-level flow is mainly from south or southwest. The low-level wind increased when the trough moved into northern Italy. European Centre for Medium-Range Weather Forecasts (ECMWF) 0.5 degree analyses also indicated that the a moist flow into the south side of
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the Alps at the 2 km level was generally from the south to southwest throughout the entire period of precipitation (Rotunno and Ferretti 2002).

The rainfall event in IOP-2B started with light rain around 1500 UTC 19 September, intensified during the night, and became more convective around 1000 UTC 20 September, especially on the southern slopes of the Alps. Doppler radar observations during this time period showed the presence of a precipitation shield located near the windward slopes of the Alps as well as in the Lago Maggiore region (e.g., Houze et al. 2000). Figures 4a-d show the Monte Lema (46.04N, 8.83E; 1625 m) radar-derived precipitation rate from 0000 to 0900 UTC 20 September at the 3-h interval. Rectangular plots at the top and right side of each figure show maximum reflectivity in vertical cross-sections running west to east and south to north, respectively (e.g., Joss et al. 1998). At 0000 UTC 20 September (Fig. 4a), the maximum precipitation rates in LMTA exceeded 15 mm h$^{-1}$. The precipitation was weaker in the vicinity of the radar site. Three hours later (Fig. 4b), the area of heavy precipitation extended to the upslope of the Alps as the southeasterly wind flowed continuously onto the upslope of the Alps. The time sequence shows that the maximum precipitation rate increased beginning around 0600 UTC 20 September (Fig. 4c), and the precipitation area began to migrate eastward as the trough propagated eastward. At 0900 UTC 20 September, the intense precipitation was characterized along the southern slopes of the Alps as the trough moved over this region (Fig. 4d). There are major persistent and intense precipitation rates greater than 10 mm h$^{-1}$ occurring up against the south-facing slopes of the Alps in the Lago Maggiore region that last approximately 12 h. It also indicates that local convection systems
occurred in the Monte Lema area (Fig. 1b) during that time.

The Cressman (1959) objective analysis approach has been used in dealing with hourly high resolution networks of rain-gauge data in this study. Figure 5 shows the time sequence of 6 h accumulated analyzed rainfall during 1200 UTC 19 to 1200 UTC 20 September. Beginning in the late afternoon of 19 September (local time), light rain initiated along the steep southward-facing slopes of the Maritime Alps and the southeastward-facing slopes of Alps in between 45N and 46N, i.e. the concave topography area (Fig. 5a). From 1800 UTC 19 to 0000 UTC 20 September (Fig. 5b), the rain was located generally over the similar location as in Fig. 5a, but at a heavier rate. Some light rain was also recorded around the Piedmont area. Total rainfall amount was increased and the rainfall concentrated on the windward slopes from 0000 UTC to 0600 UTC 20 (Fig. 5c). As illustrated in Fig. 5c, some peak values of rainfall of 20 mm h\(^{-1}\) were observed over the Lago Maggiore region, Maritime Alps and the Po Valley. In the afternoon (local time) of 20 September (i.e., 0600 to 1200 UTC 20), the precipitation area broadened on the windward slopes of the eastern side of the Alps and moved toward the east along with the trough (Fig. 5d). Light rain was still observed in the Lago Maggiore area at 1800 UTC 20 September. Note that due to the rainfall period over the south side of the Alps as well as the Lago Maggiore area, the 24 h accumulated rain had exceeded 200 mm.

In summary, the moist south to southwesterly flow associated with the trough/low pressure system producing heavy rainfall over the windward slope. The rain over the upslope of the Alps was started around the concave area, and then migrated eastward along with the
movement of the trough. The heavy rain over the Lago Maggiore area lasted approximately from 1500 UTC 19 to 0000 UTC 21 September 1999. It appears that the concave topography and a moist south to southwesterly low-level jet are essential ingredients for producing heavy orographic precipitation.

4. Evolution of orographic precipitation associated with the control simulation

Since this study is aimed to investigate the local circulations as well as the orographic effects on the rainfall distribution, the discussion will limit to only the fine-scale simulation (i.e., 5 km domain), and focus on a comparison between the fine scale simulation results and observations. The 5 km resolution simulation started at 0600 UTC 19 September 1999, which was about 12 hours prior to the formation of heavy rainfall over the south side of Alps. This allows the pre-rainfall environment to be examined.

4.1 Fine-scale simulation of orographic rainfall

The observed (Fig. 6a) and model simulated (Fig. 6b) wind profiles at Lonate (45.57N, 8.72E) from 1200 UTC 19 to 1200 UTC 20 September 1999 compare reasonably well. Although the winds at lower levels were slightly deflected to be more southeasterly, the model was able to capture the timing of trough passage at this station around 0600 UTC 20 September. In addition, the winds computed from the dual-Doppler radar data around 0900 UTC 20 September indicated the flow into the Lago Maggiore region at the 2 km level was generally from the south, and the flow turned to the left as it approached the barrier (Fig. 7a). As the wind turned to be more southeasterly, it flowed nearly perpendicular to the southwest-northeast oriented mountains on the western side of the Lago Maggiore region. The model
was able to capture this low-level south to southeasterly flow, as well as the cyclonic turning near the Lago Maggiore region. The model-calculated radar reflectivities (∼ 40 dBZ) were also consistent with those observed by the dual-Doppler radars (Fig. 7b).

Figure 8 shows the horizontal evolution of the simulated wind and convergence at 1000 hPa for a portion of the 5 km resolution domain from 1800 UTC 19 to 1200 UTC 20 September at 6 h intervals. At 1800 UTC 19 September (Fig. 8a), a convergence zone was formed along the foothills on the western side of the Lago Maggiore area (i.e., concave area) in association with a weak southeasterly flow from the Adriatic Sea. The convergence zone was consistent with the observed rainfall area (Fig. 5a). By 0000 UTC 20 September (Fig. 8b), a clear easterly jet had developed along the south side of the Alps, which is often referred to as a barrier jet. This barrier jet was formed by the westward turning of the low-level southeasterly flow. This westward turning might be caused by the orographic blocking, Coriolis deflection and boundary layer friction. The formation of this barrier jet will be further discussed in Section 5. The convergence zone persisted near the concave area throughout this period. At 0600 UTC 20 September, the convergence had intensified along the southern slopes of the Alps (Fig. 8c), which was caused by the intensified low-level southeasterly flow from the Ligurian sea and the barrier jet. By 1200 UTC 20 September (Fig. 8d), there were several significant convergence zones along the mountain slopes, even though the trough has moved to the east. These convergence zones were consistent with the observed rainfall distribution at that time (Fig. 5d). A noteworthy feature is that a convergence zone existed over the upslopes near the concave area throughout this period.
The model-simulated wind field, 850 hPa $\theta_e$ field, and rainfall distributions from 1200 UTC 19 to 1200 UTC 20 September 1999 at 6-h intervals are presented in Fig. 9. Comparison of the simulated and observed winds at 1800 UTC 19 September (Fig. 9a and 3a) shows that the model has replicated the southerly flow along the Gulf of Genoa, and clearly shows the westward turning of the southerly flow near the south side of the Alps. Also, a high $\theta_e$ ($\sim 324$ K) zone existed near the coastal area. The 6-h rainfall distribution was consistent with the observed analysis (Figs. 9a and 5a). Areas of light to moderate precipitation extended from the Maritime Alps to the western side of the Lago Maggiore area. During the next 6 h, the simulated rainfall is very similar to the observed analysis (Figs. 9b and 5b). The southerly flow had intensified in association with a moist tongue impinging on the south side of the Alps at this time. The southerly flow near the foothills of the Alps as well as the Lago Maggiore area was deflected to the west. As mentioned earlier, this westward turning was caused by the mountain blocking as determined from sensitivity simulations to be presented later. Also, the 850 hPa wind field (Fig. 9a) differed from that at 1000 hPa (Fig. 8b) due to the boundary layer forcing. More discussion of this phenomena in a sensitivity experiment with no boundary layer friction will be presented later. By 0600 UTC 20 September, the trough has reached northern Italy, which resulted in strong wind speed and higher $\theta_e$ over the Po River basin (e.g., 850 hPa). The simulated heavy rainfall occurred along the windward side of the Maritime Alps and the Ligurian Apennines mountains, as well as the Lago Maggiore area (Fig. 9c). Compared with the observed rainfall during this period (Fig. 5c), the rainfall was over-predicted around the coastal areas and over the
southern Alpine slopes by the model, but under-predicted at the southern tip of the Maritime Alps. In addition, the simulated wind shift around the Gulf of Genoa and Ligurian Sea is more than what was observed (Fig. 5c). This may be due, in part, to the strong surface fluxes over the Ligurian Sea in the numerical model.

By 1200 UTC 20 September, the synoptic analysis indicates that the trough moved to the eastern side of the Alps (not shown). As revealed by the 5-km domain, the southwesterly low-level jet associated with the trough has also approached the same location (Fig. 9d). Also, a broad area of high $\theta_e (\sim 328$ K) in association with this trough existed around the Po Valley. The simulated rainfall distribution was generally consistent with observations (Figs. 4d and 5d). Also, some heavy rainfall spots existed along the windward upslopes, similar to those produced by small to moderate convective cells embedded in the broad-scale precipitation layer over the windward slopes (Houze 2000). The rainfall distribution also indicates that the low-level convergence is very effective in forcing the moist air upward and producing heavy precipitation. However, the rainfall was over-predicted at the western side of the Lago Maggiore region (i.e., the concave area) and the coastal areas. These misplacements might be caused by the treatment of the model microphysical processes over complex topography (Grell et al. 2001) or the cumulus parameterization at the mesoscale. Sensitivity tests by partially removing the orography in an area around the upstream mountains (i.e., Apennines mountains), western flank of the Alps (i.e., French Alps), and a finer resolution simulations will be performed to further investigate this issue in the next section. Overall, the MM5 captured many of the salient features of this event, although the total amount of simulated
precipitation is slightly higher (∼30% in 24-h) than observed. The similarity between simulated and observed precipitation in terms of pattern and timing, suggests that the model has represented the physical processes, which are responsible for producing the precipitation, reasonably well.

To further document the evolving vertical structure of the simulated trough as it passed over northern Italy, Fig. 10 shows a cross section (AA’) from northwest to southeast direction. At 1800 UTC 19 September (Fig. 10a), the $\theta_e$ gradients were strong (particularly near the surface). There was a band of strong (∼35 dBZ) convective echoes over the mountain upslope, which is consistent with observations as well as the convergence zone. As the trough approached, precipitation intensity in this zone increased vertically. It appears that strong upward motion on the windward slopes realized that potential instability ($\partial\theta_e/\partial z < 0$). An area of convection had increased to 40 dBZ over the lower windward slope during the past 6 h (Fig. 10b). By 0600 UTC 20 September, convection increased significantly over the windward slope. The simulated radar reflectivities clearly indicate the appearance of a strong convective echo as the trough moved over northern Italy (Fig. 10c). It is likely due to the orographically-induced upward motion and the synoptic lifting (Lin et al. 2002), triggered strong convection in potentially unstable layer. The simulated strong convective motion is consistent with the observed analyses by S-Pol radar (see Median and Houze 2002). By 1200 UTC 20 September (Fig. 10d), the convection weakened as the trough moved to the eastern side of the Alps. The convective reflectivity structure over the mountain peaks still existed at this time.
4.2 Moisture flux calculations

The precipitation over terrain can be reasonably estimated in a first guess approximation by estimating the topographically-forced vertical moisture flux (e.g., Alpert 1986; Sinclair 1994; Doswell et al. 1998). As developed by Lin et al. (2001), the simplest flux model for orographic rain is given by

$$ P = \left( \frac{\rho}{\rho_w} \right) E (V_H \cdot \nabla h + w_{env}) q \frac{L_s}{c_s} $$

as shown in Chapter 3, Eq (1). For simplicity, it is assumed that $E = 1$. Figure 11 shows the vertical moisture flux using model calculation at the 2 km level. By 0600 UTC 20 September (Fig. 11a), positive $wq$ was located on the windward slopes. The maximum was about 1.0 g kg$^{-1}$ cm s$^{-1}$ at the western side of the Lago Maggiore area. Subsequently, a broad-area of large $wq$ is located on the upslopes of the Alps and Ligurian Apennines mountains during the next 6 hours (Fig. 11b). In order to understand the contribution by orographically-induced upward motion, the orographically-induced vertical moisture flux was also calculated from the model output (i.e., $(V_H \cdot \nabla h)q$). Figures 12a and 12b shows the orographically-induced moisture flux at 0600 UTC and 1200 UTC 20 September, respectively. It appears that the strong positive region existed on the steep slopes. Although they were very similar to $wq$ (cf. Fig. 11), the orographic induced moisture flux showed a more detailed structure around each individual mountain peak. In general, Figs. 11 and 12 show a reasonably good comparison between the model-simulated moisture flux and orographically-induced moisture flux with the observed precipitation (Fig. 5).

5. Sensitivity experiments

An important objective of this study is to find out the dynamical and physical pro-
cesses which are responsible for producing heavy orographic precipitation. The sensitivity simulations conducted in this study are designed to isolate effects on local circulations and orographic precipitation due to the Ligurian Apennines mountains, western flank of the Alps (i.e., French Alps), Coriolis force (rotational effects), boundary layer (BL), and small-scale features of the topography. Characteristics of these experiments are summarized in Table 1. The topography features of sensitivity experiments are shown in Fig. 13.

5.1 Effects of surface friction

While it is widely recognized that the boundary layer can have important effects on flow over topography (e.g. Richard et al. 1989; Olafsson and Bougeault 1997; Braun et al. 1999; Peng et al. 2001), few studies address the friction effects on the local circulations in terms of the flow deflection and rainfall distribution. Therefore, an experiment with a free slip lower boundary condition has been conducted. This experiment is the same as the CTRL, except the lower boundary condition is set to no friction (NFRC) and no planetary boundary layer fluxes (i.e., friction velocity, $U_* = 0$). When we turned off the boundary layer processes, we deactivated not only the surface friction effects but also thermal effects from the surface layer. Therefore, the boundary condition for the NFRC case is basically free-slip, thermally insulated. However, the flow is not inviscid, because subgrid horizontal and vertical eddy diffusivities are allowed in the model (Chen et al. 1997). Figure 14 shows the 850 hPa wind fields, $\theta_e$ and accumulated rainfall at 6-h intervals. As can be seen in Fig. 14a, valid at 1800 UTC 19 September, the absence of surface friction on the 6-h accumulated rainfall and wind field at 850 hPa are similar to the CTRL run (Fig. 9a). However, a low-level easterly jet
is shown in the difference of NFRC-CTRL (Fig. 15a). By 0000 UTC 20 September (Fig. 14b), the flow at 850 hPa shows the westward turning of the southerly flow in the Po Valley (see Fig. 1b). It was nearly perpendicular to the windward slope on the western side of Lago Maggiore area. Nevertheless, the wind fields at 1000 hPa indicate a southerly flow of $\sim 20\ \text{ms}^{-1}$ approaching the barrier and no westward turning occurred near the Alps or in the Po Valley, except a slightly deflection occurred near the Lago Maggiore area (not shown). The 1000 hPa wind difference of NFRC-CTRL also indicated that strong southwesterly wind existed in the Po Valley (Fig. 15b). Apparently, the lack of surface friction enhanced the magnitude of flow near the surface at this time. In other words, the surface friction acts to decelerate the inertial-advective component of the wind.

By 0600 UTC 20 September, broad-scale precipitation fell on the windward slopes as well as in the Po Valley in Exp. NFRC (Fig. 14c). In addition, a significant downslope wind ($\sim 30\ \text{ms}^{-1}$) was simulated over the lee side of the Alps. The difference (NFRC-CTRL) of accumulated rainfall is shown in Fig. 15c. The rainfall over the Po Valley, compared to the CTRL run, was partly the result of the lower level convergence due to the lack of surface friction (not shown). At 1200 UTC 20 September (Fig. 14d), the strong southerly flow of $\sim 25\ \text{m s}^{-1}$ associated with the eastward movement of the trough was one of the main features. A zone of substantial low-level convergence occurred in the Po Valley (not shown). The major difference in cases NFRC and CTRL is that there was a zone of rainfall extending from the Po Valley southeastward, which was associated with a convergence zone. This convergence zone was caused by the decreased westward turning of the wind in the NFRC
case. The 6-h accumulated rainfall in the NFRC run at this time is as much as 70 mm higher than the CTRL run in the Po Valley (Fig. 15d). However, the accumulated rainfall over the windward slopes of the Alps in NFRC is about 30 mm lower than the CTRL run (not shown). As anticipated, the wind field difference of (NFRC - CTRL) over the upslopes reveal that wind speeds were stronger in NFRC case. This indicates that the southerly flow in the NFRC case fell more in the regime of flow over the terrain barrier than that of flow around the terrain barrier (Smith and Grønås 1993; Schneidereit and Schär 2000). Thus, the accumulated precipitation is lower over the upslopes in NFRC than CTRL from the period of 0600 UTC to 1200 UTC 20 September 1999.

Fig. 16 shows a series cross-sections (AA'; see Fig. 1a) to illustrate how the equivalent potential temperatures, wind and radar reflectivity structures evolved during the passage of the trough when there was no surface friction. By 0600 UTC 20 September, as the trough moved to the northern Italy (Fig. 16a), the vertical reflectivity structure shows convection (∼35 dBZ) extending up to 3 km along the windward slopes. In contrast to the CTRL case, the convective echo structure appears to be much weaker in the NFRC case. Meanwhile, the equivalent potential temperature gradients were relatively weak (Fig. 10c). By 1200 UTC 20 September (Fig. 16b), the convection was strengthened, but not as deep as in the CTRL case 6 h earlier (Fig. 10c). It appears that the convection was more shallow due to the lack of surface friction in terms of thermal mixing effects. In summary, without surface friction, there was less westward deflection of the low-level wind. In other words, the Coriolis effect was changed implicitly by changing friction as inertial-advective flow was strengthened.
Consequently, more flow over the mountains and the upslope convection is more shallow.

5.2 Effects of the upstream and concave topography

To test the effects of upstream mountains on the precipitation, a simulation (NAPN) without upstream topography (i.e., Ligurian Apennines Mountains) was performed on 15 km and 5 km resolution domains, while keeping everything else identical to the control experiment. Figure 13a shows the topography on the 5 km resolution domain.

From 1800 UTC 19 to 0000 UTC 20 September, there was less westward deflection of the flow at 850 hPa in the NAPN case compared to the CTRL case (not shown). The flow near the Lago Maggiore area was about 10 to 15 ms\(^{-1}\), and the 6-h accumulated rainfall distribution was also similar to the CTRL case (not shown). From 0600 to 1200 UTC 20 September (Fig. 17), strong convergence zones occurred around the Lago Maggiore area in association with the southeasterly low-level jet (\(\sim 15\) ms\(^{-1}\)). The strong low-level convergence zone was generally consistent with the precipitation over the upslopes of the Alps (Figs. 17c and d). In addition, the distribution of the \(\theta_e\) gradients were still similar to those in the CTRL (Figs. 9c and d). In general, the simulated evolution of the local circulation is qualitatively similar to the CTRL (Figs. 8, and 9). However, a feature worthy of note is that a broad-scale area of rainfall (\(\sim 20\) mm in 6 h) fell on the Po Valley, which was caused by the absence of upstream mountain blocking (Figs. 17c and d). Evidence supporting this result was that in the CTRL case the precipitation on the windward slopes of the Ligurian Apennines mountains was due to the coastal blocking, which results in the shallow convection along the windward slopes. In addition, this coastal blocking also suggested a rain shadow effect which resulted from
downslope wind as the southerly flow developed over the crest of the Ligurian Apennines mountains. The rain shadow effect has also been found over California’s coastal mountains (Ralph et al. 2002). In general, the rainfall distribution on the windward slopes of the south side of the Alps was not directly related to the Ligurian Apennines mountains. The widespread rain in the Po Valley in the NAPN case corroborated the conclusions of Stein (2002), but in his case, relatively coarse model resolution (10 km) was used.

As discussed above, the model tends to over-predict the precipitation around the concave area as well as in the Lago Maggiore area in the CTRL case. Although it was partly due to the model-simulated low-level confluence in that area, the results also imply the western flank of the Alps (i.e., concave area) could play a role resulting in the enhancement or redistribution of rainfall. Thus, in order to better gauge the concave topography effects on the initiation and redistribution of orographic rainfall, we carried out an experiment in which the western flank of the Alps was set to be flat (approximately from 43N to 45N), while keeping everything identical to the NAPN. The modified mountain was very similar to an elongated barrier-like obstacle (Fig. 13b). This experiment is referred to as the NWAP. From 1800 UTC 19 to 0600 UTC 20 September, the wind field at 850 hPa was generally from the south. As shown in Fig. 18a, valid at 0600 UTC 20 September, the near-surface flow indicated a significant terrain-parallel barrier jet of $\sim 10 \text{ ms}^{-1}$ from the Adriatic Sea. The low-level convergence was still along the Lago Maggiore area and the windward slopes. The westward turning of the impinging southerly flow ($\sim 20 \text{ ms}^{-1}$) at 850 hPa occurred adjacent to the windward slopes of the Alps (Fig. 18c). A high $\theta_e (> 324 \text{ K})$ zone was also present.
along the mountains. The precipitation distributions appear to be correlated with the slopes of the modified mountains (i.e., the left end of the Alps). The maximum rainfall is located near the slopes of the Lago Maggiore area immediately aligned with the barrier jet.

By 1200 UTC 20 September (Figs. 18b and d), a clear cyclonic vortex existed along the left end of the modified mountains, where strong convergence was formed by the westerly and southeasterly flows. The model simulated a low pressure center at that area (not shown). Heavy rain was still concentrated on the windward slopes around the left end of the Alps. The 6-h simulated accumulated rainfall (∼160 mm) was about 30 mm higher than NAPN and CTRL near the Lago Maggiore area from 0600 to 1200 UTC 20 September. The strong $\theta_e$ gradients were along the leading edge of westerly flow at this time (Fig. 18d). In addition, a narrow band of precipitation for the last 6 h (>70 mm) fell across the region in association with the trough that moved eastward to its present position. The precipitation amounts appear to be correlated with the steepest slopes at the left end of the mountains as well as the low pressure center. In comparison with the CTRL and NAPN cases (see Figs. 9 and 17), precipitation along the Lago Maggiore area remained strong. This result suggests that the French Alps do not play a significant role in the formation of heavy rainfall near the Lago Maggiore area. This is consistent with the results of Buzzi et al. (1998) for the role of orography in 1994 Piedmont flood case. In addition, the results also suggest that the type of flow regime (blocked or unblocked) is apparent at the lower levels. These results again support the common ingredients concept of Lin et al. (2001) for heavy orographic rainfall.

5.3 Effects of small-scale topography features
Although the upstream mountains and concave topography effects have been examined, it is still worthwhile to investigate how the detail topography features such as the individual mountain peaks affect the total amount and distribution of precipitation. As discussed in the control simulation, the strong convective echo structures exist around the mountain peaks. This is partly due to the fact that localized convergence (windward slope) or divergence (lee slope) occurs in individual mountain peaks. The simplified representations of the Alps used in this study are identical to orography described by Schneidereit and Schär (2000). Rotunno and Ferretti (2001) also adopted the same setting of idealized orography to investigate the 1994 Piedmont flood event. They concluded that the rainfall simulation using idealized topography was quantitatively and qualitatively similar to their real terrain simulation in the 10 km resolution domain. In order to understand the effects of individual mountain peaks in terms of orographic rainfall, we intend to use the same orography setting in the 5-km resolution domain to examine the evolution of mountain-induced local circulations as well as the rainfall distribution in MAP IOP-2B. The idealized arc-sharped obstacle (Fig. 13c) and elongated barrier-like obstacle (Fig. 13d), are referred to as AALP and BALP, respectively. The mountain height used in these experiments is 2.5 km. Otherwise the experiments are the same as the control simulation case discussed above.

Unlike the real topography simulations, the accumulated rainfall was less than 10 mm from 1200 UTC 19 to 0000 UTC 20 September (not shown). The southerly flow at 850 hPa was much lower (~10 m s\(^{-1}\)) than the CTRL case during that time (not shown). From 0600 to 1200 UTC 20 September (Figs. 19a and b), compared with NAPN case (Figs. 17a
and b) the results clearly demonstrate that the low-level barrier jet ($\sim 10 \text{ ms}^{-1}$) was from the Adriatic Sea. This low-level barrier jet turned south as it impinged on the upslopes of the western flank of barrier (i.e., concave region). It appears the southward deflection of this barrier jet is due to the orographic blocking. This southward turning is similar to IOP 8 as discussed by Bousquet and Smull (2002). In addition, the low-level convergence zone was formed adjacent to the concave region, which was in connection with the precipitation around this area. The simulated 850 hPa wind field, equivalent potential temperatures, and the 6-h accumulated rainfall at 0600 and 1200 UTC 20 are shown in Figs. 19c and d, respectively. The equivalent potential temperature gradients were very similar to the NAPN and CTRL cases. The southerly flow was decelerated and deflected to the west as it approached the barrier. The results also indicated that the south or southwesterly flow was not substantially blocked by the barrier. The maximum accumulated rainfall ($\sim 20 \text{ mm}$) was along the upslopes of the western flank of the barrier from 0000 UTC to 0600 UTC 20 September (Fig. 19c). While the trough moved eastward (Fig. 19d), the maximum accumulated rainfall ($> 70 \text{ mm}$) associated with the concave region occurred during 0600 UTC to 1200 UTC 20 September.

In general, the flow pattern was very similar to the NAPN and CTRL cases, except the magnitude of the total amount of rainfall and wind speed, which were much weaker in the AALP case. Rainfall was mainly concentrated in the concave region. The 6-h accumulated rainfall was about 50% less than the NAPN case. This was partly due to the smoother terrain feature in which the upward motion induced by the barrier was about $\sim 0.6 \text{ ms}^{-1}$ at 1200
UTC 20 September (not shown). The comparison of CTRL, NAPN and AALP suggests that complex topography features could enhance the precipitation through the localized convection in terms of the low-level convergence or divergence.

As discussed in the NWAP case, the French Alps did not play a major role in contributing heavy rainfall around the Lago Maggiore area during this event. Apparently, the small-scale concave feature near the Lago Maggiore area may enhance the rainfall. Figure 20 shows the experiment results with a barrier-like obstacle. From 0600 UTC to 1200 UTC 20 September (Figs. 20a and b), the wind field and convergence at 1000 hPa were very similar to the AALP cases (Figs. 19a and b). The results also indicated a westerly flow associated with the trough that moved over northern Italy on 1200 UTC 20 September (Fig. 20b), which was consistent with the NWAP run (Fig. 18b). The easterly jet combined with the south or southwesterly moist flow were the major features during the initiation of orographic rainfall around 0600 UTC 20 (Fig. 20c). During the next 6 hours (Fig. 20d), a similar banded precipitation occurred in association with the low-level westerly flow that moved into the domain as in the NWAP case. The major rainfall during this period fell on the left end of the barrier, which was consistent with the NWAP case. However, the total amount of rainfall was much less than in the NWAP case. The simulated accumulated rainfall in this case was higher (\(\sim 20 \text{ mm}\)) than the AAPL run during 0000 UTC to 1200 UTC 20 September 1999.

The results from the BALP case demonstrate that small scale concave topography along the Lago Maggiore area could enhance the orographic rainfall. This is in part due to the orographic lifting which is more significant in the real topography cases near the Lago Mag-
giore area. This experiment again evidenced that the French Alps served as an obstacle which could block the trough moving eastward. Based on the AALP and BALP simulations, the accumulated rainfall in idealized topography was much less than the real topography simulations. Our simulation results were inconsistent with the conclusion made by Rotunno and Ferretti (2001). The lower precipitation amounts in these two idealized topography simulations were partly the result of the smoother topography (i.e., decreased roughness length) that reduced the strength of orographic uplift, and partly due to the simplicity of the barrier, including the mountain height and width. Apparently, a smoother topography would reduce the occurrence of localized convection as well as orographic precipitation. The effects of the model resolution and topography resolution on the local circulation as well as the precipitation differences will be further investigated later in this section.

5.4 Effects of rotation

As mentioned in the beginning of this section, the combined effects of rotation (Coriolis effect) and low-level orographic blocking force the southerly or southeasterly flow to turn westward, producing convergence between the low-level easterly jet and the southerly jet in the general vicinity of the Lago Maggiore area. The primary effect of rotational dominance is the leftward-deflection of the split flow when the conditions of $H > U/N$ and $L \sim U/f$ exist, where $H$ the height of obstacle, $U$ the constant flow and $N$ static stability, and $L$ the mountain width (e.g., Peng et al. 2001). In this case, $H \sim 3.5$ km, $U \sim 20$ m/s, $L \sim 200$ km, $f \sim 10^{-4}$s$^{-1}$, and $N \sim 6.0 \times 10^{-3}$ s$^{-1}$, which was in the nonlinear regime (i.e., rotating; see Rotunno and Ferretti 2001). Although the deflection of flow by the Coriolis effect (i.e., near
mountains) is well known, it is worthwhile to re-examine this effect on the formation of the easterly jet as well as the precipitation distribution in this case. The Coriolis parameter was set to be half of the original, Exp. HCOR (Table 1). Other parameters in this experiment are set as in the control simulation case discussed above.

Figure 21 shows the wind field and $\theta_e$ at the 850 hPa level and accumulated rainfall at 6-h intervals. At 0600 UTC 20 September (Fig. 21a), the south or southwesterly flow was the main feature. However, the flow field with stronger westerly component differed dramatically as compared with the control experiment. In addition, a feature worthy of note was that the rainfall almost disappeared. A similar behavior was also present during the next 6 hours (Fig. 21b). This was because the trough was under-developed due to the effects on the variation of the wind field which was caused by the weak of Coriolis effects. As a result, the convection was poorly produced in northern Italy due to differences in the convergence. These results suggested that the westward deflection of the southerly flow was partly due to Coriolis effects.

5.5 Effects of horizontal resolution

In order to study the effect of horizontal grid resolution on the orographic rainfall prediction, the sensitivity experiment was conducted with a horizontal grid size of 1.67 km (FALP). The initial condition was generated by one-way interpolating from the simulation results of the 5 km resolution domain. The number of horizontal grid points was $271 \times 271$. The 1-km resolution topography dataset was also used in this simulation. All other parameters in this experiment were identical to those in the CTRL except explicit cloud physics were used to
In the FALP experiment at 1800 UTC 19 September (Fig. 22a), a broad area of light precipitation developed along the French Alps. The simulated radar reflectivity along the cross section BB’ indicated that convective echoes developed around the upslopes (Fig. 23a). The $\theta_e$ gradients and wind field were similar to those in the CTRL. As a result, from the decrease in horizontal grid length (increase in horizontal resolution), there was enhanced precipitation along the upslopes as compared to the CTRL (Fig. 9a). By 0000 UTC 20 (Fig. 22b), heavy rainfall was concentrated near the Lago Maggiore area (> 90 mm in 6 hours). It was nearly 30 mm higher than the observed (Fig. 5b). Also, a narrow band of precipitation became aligned with the moist southerly low-level jet. Nevertheless, comparing of Figs. 9b and 22b, a most striking difference was the broad precipitation along the upslopes of the coastal Apennines mountains in the CTRL, which was not that significant in this finer resolution experiment. This was partly due to the topographic feature change in the coastal Apennines mountains. Figure 23b shows a strong convective echo (> 40 dBZ) structure over the first peak of the mountain range, where the impinging flow was approximately perpendicular to the upslopes. During the next 6 hours (Fig. 22c), a noteworthy feature was that the model did reproduce the southerly low-level jet in the Gulf of Genoa as compared to the ECMWF reanalysis (not shown), which was not well-simulated in the CTRL run (Fig. 9c). However, the accumulated rainfall was over-predicted on the windward slopes of the Alps as well as the Maritime Alps. The rainfall was around 50% increased as compared to the CTRL. A similar result was presented by Richard et al. (2002), in that the total
precipitation was about 30% over-estimated in their 2 km resolution MM5 simulations. The cross section along the Lago Maggiore area showed that the upward motion ($> 3.2 \text{ ms}^{-1}$) was about twice as strong as than the CTRL (not shown). As can be seen in Fig. 23c, a strong convective echo maximum appeared just upslope of the major rainfall cells over the terrain. The results suggested that vertical motion was further enhanced by the fine resolution topography (i.e., steeper mountain slopes). The results also suggested that strong convective cells developed around each individual mountain peak. Caracena et al. (1979) proposed this idea to explain the low-altitude echo maximum in the orographic convective storm that produced the Big Thompson flood in the Rocky Mountains in 1976. In addition, Smith (1979) suggested that the convective cells can make the precipitation process faster and more efficient in broad-scale upslope flow. These small to moderate convective cells were associated with a deeper moisture layer which affected the whole Alpine barrier. In other words, more moisture flow reached saturation over the windward slope than was deflected away from the barrier before condensation occurred.

At 1200 UTC 20 September (Fig. 22d), the windward slopes of the Alps were covered by broad-scale precipitation in FALP. Some heavy rainfall spots were concentrated on the western side of the Lago Maggiore area. The location of these heavy rainfall spots compared well with the rain accumulation as determined by S-Pol radar where amounts of over 275 mm were seen over specific peaks (see Fig. 25 in Houze 1999). As shown in Fig. 23d, the simulated radar reflectivity had increased in areal coverage and intensity ($> 45 \text{ dBZ}$) primarily because of the trough in association with the strong southerly low-level jet. Also,
the convective echo was narrower in the presence of the mountains. Noticed that there was not much rain generated on the coastal Apennines mountains during the entire heavy rainfall period. This was consistent with the observed rainfall analyses (Fig. 5). However, the model over-predicted the rainfall on the windward slopes of the Alps. In contrast, the CTRL did a reasonable prediction of the rainfall amounts and distribution on the windward slopes and in the Lago Maggiore area, but over-predicted the same over the coastal Apennines mountains. A comparison of the time evolution of the hourly precipitation from the rain gauges over the 15 km, 5 km, and 1.67 km resolution domains at Cimetta (46.2N, 8.8E, station height: 1672 m) is shown in Fig. 24. The station is located in the Lago Maggiore area (as illustrated in Fig. 22a). Clearly, the increase in resolution has drastically changed the precipitation patterns and magnitudes, and leads to an increase in precipitation, especially over the mountains. The results imply that the vertical motion increases rapidly as resolution increases, transitioning from less-than to greater-than particle fall speeds and allowing more variety of microphysical processes over complex topography. This may produce an extreme amount of precipitation. Colle et al. (2000) also demonstrated a similar result in their 4 km domain simulation over the Pacific Northwest. This rainfall over-prediction problem might be caused by the inaccurate or unrealistic parameterized of the microphysical processes over the steep mountains. Our results also suggest that improving the model’s physical schemes might have the most significant impact on improving precipitation forecasts at higher resolutions, especially over the complex mountain areas.

6. Summary and discussion
This Chapter constitutes an important extension of the previous work by Lin et al. (2002), in which the synoptic and mesoscale environmental conditions were exploited to describe the evolution of a heavy orographic rainfall event in northern Italy during 19-21 September 1999 (MAP IOP2B). During this event, the orographic precipitation was found to intensify rapidly as the deep trough approached the Alps. The goal of this study described here has been to use high-resolution mesoscale model simulations to investigate the local circulation and determine the responsible mechanisms for the heavy orographic precipitation.

This event was simulated with the Penn State/NCAR MM5 model at 5 km resolution. Many of the major aspects of the precipitation event of IOP-2B were realistically reproduced, including the timing and location of rainfall. The moist flow into northern Italy at 850 hPa was generally from the south in association with high $\theta_e$ throughout the entire period of precipitation. The impinging moist flow was not substantially blocked by the barrier but rather easily flowed over the Alps. Most of the precipitation was found on the windward slopes in this event. The model results show good correspondence with major features in the observations. The near surface flow (e.g., 1000 hPa) was characterized by a southerly jet from the Gulf of Genoa and an easterly jet from the Adriatic Sea. These two flows impinged on the steep mountains near the Lago Maggiore region, which led to the development of strong convection along the steep mountain slopes. The westward deflection of the southerly flow occurred as it approached the barriers. The results are clearly shown in the 1000 hPa level. Two notable weaknesses of the control simulation were that: 1) the model’s overestimate of the low-level southerly flow magnitude near the Gulf of Genoa when the trough moved in
this area during 0600 UTC 20 September, and 2) the 6-h accumulated rainfall was higher than was observed by as much as 30%, especially when the deep trough passed over the Lago Maggiore region. In spite of that, by examining the orographically-induced vertical moisture flux and general vertical moisture flux, we found that the rainfall distribution over the mountains was roughly consistent with the orographically induced vertical moisture flux distribution. Convection enhanced by orographic lifting plays an important role in such a heavy rainfall event, so forecasting the occurrence of deep convection is a critical part of any orographic precipitation event.

The control simulation and sensitivity experiments serve to illustrate the complex interrelationships among local circulation, complex topography, and precipitation distribution in northern Italy. The experiment without boundary layer friction (NFRC) reveals an important role of friction processes in the deflection of impinging southerly flow. In addition, more precipitation was produced in the lack of boundary layer friction condition, which was partly caused by the strong surface convergence. However, the convection was shallower due to the lack of boundary layer thermal fluxes. Our sensitivity test on the role of the Ligurian Apennines mountains (NAPN) illustrated that the total amount and distribution of precipitation over the south side of the Alps were not directly affected by the upstream mountains. However, this sensitivity experiment revealed a rain shadow effect resulting from downslope wind as the southerly wind flowed over the crest of the coastal Apennines mountains. The sensitivity experiment on the existence of the French Alps (NWAP) indicates precipitation was concentrated along the steep slopes at the left end as well as the Lago Maggiore region.
of the mountains. A narrow banded precipitation maximum was formed when the trough swept into northern Italy. This rainband was caused by the low-level convergence. Overall, the rainfall distribution over the Lago Maggiore region as well as the south side of the Alps did not have a significant change in either the absence of upstream mountains or the western flank of the Alps. The southerly flow at 850 hPa toward the Alps was moist and strong. A significant westward turning occurred at the near surface level (i.e., 1000 hPa) before the flow impinged on the barriers. Broad-scale precipitation fell on the Po Valley and the Piedmont areas in both experiments (i.e., NAPN and NWAP). Apparently, it is because of the lack of mountain blocking.

The idealized topography experiments (i.e., arc-shaped; AALP, and elongated bar-shaped obstacle; BALP) indicate that accumulated rainfall was significantly reduced by as much as 50% in comparison with real topography experiments. It was in part due to the smooth topographic surfaces (i.e., decreased roughness length) and less steeper slopes which drastically reduced the terrain-induced upward motion. In addition, the mountain height was 2.5 km which could also reduced the orographic rainfall. Apparently, the complex topography with individual mountain peaks contributed to the overall orographic rainfall. The results again supported the ingredient concept of the heavy orographic rainfall (Lin et al. 2001). The sensitivity experiment on the Coriolis effects clearly showed that the unblocked rotation is a necessary condition for the westward deflection of the southerly impinging flow for this case. The high-resolution experiment ($\triangle x = 1.67$ km; FALP) illustrates that significant convective structure extended up to 7 km in the upslope regions. The results suggest that more intense
convection is allowed to develop in the finer resolution domain, which resulted in extremely heavy rainfall in the complex mountain areas, especially over the steeper upslopes. A comparison of precipitation from the observed analyses as well as the 15 km, 5 km, and 1.67 km domain simulations clearly illustrate that the increase in model resolution as well as the terrain resolution have drastically changed the precipitation patterns and magnitudes and leads to an increase in precipitation.

In general, this study illustrates that the topographically-induced local circulation contributes to the formation and subsequent maintenance of a heavy orographic precipitation event in association with a deep trough approaching northern Italy. The fine scale simulations reveal many important features of the local circulation which includes flow deflection resulting from orographic blocking. In conclusion, the spatial and temporal distribution of orographic rainfall are reasonably simulated in the 5 km domain, however, the qualitatively-evaluated orographic precipitation forecasts over complex topography still need to improve. To understand the interrelationships among the horizontal grid spacing, topographic resolution, microphysical schemes, better turbulence closure schemes as well as better initial data are the keys to improve orographic precipitation forecasts.

7. References


and regional conditions for the rainfall over Lago Maggiore target area during MAP IOP2B. *Quart. J. Roy. Meteor. Soc.*, special MAP issue, accepted.


Smull, B., O. Bousquet, and M. Steiner, 2000: Contrasting stratification and mesoscale


Table 1: Summary of numerical experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Topography</th>
<th>Condition</th>
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<tr>
<td>CTRL</td>
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<td>—</td>
</tr>
<tr>
<td>NFRC</td>
<td>Real</td>
<td>No friction</td>
</tr>
<tr>
<td>NAPN</td>
<td>No Ligurian Apennines</td>
<td>—</td>
</tr>
<tr>
<td>NWAP</td>
<td>No French Alps</td>
<td>—</td>
</tr>
<tr>
<td>AALP</td>
<td>Idealize mountain (arc-shaped)</td>
<td>—</td>
</tr>
<tr>
<td>BALP</td>
<td>Idealize mountain (bar-shaped)</td>
<td>—</td>
</tr>
<tr>
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</tr>
<tr>
<td>FALP</td>
<td>Real</td>
<td>$\Delta x = 1.67 km$</td>
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</table>

Figure 1: (a) Domains for numerical simulations used in this study. The grid increments for the three nested meshes are 45km, 15km and 5km, respectively. (b) Terrain (every 500m) used for the 5-km domain CTRL. The solid line AA’ represents the orientation of the x-z cross-section in subsequent analyses. Triangle ($\triangle$) and circle (○) represent the Monte Lema radar and wind profiler at Lonate.
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Figure 3: Cont’d.
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CHAPTER 5

Numerical Study of Formation Mechanisms of Heavy Rainfall during MAP IOP-2B. Part II: The Relevance of Instabilities
ABSTRACT

A study of the relevant instabilities in heavy orographic rainfall is carried out by performing high-resolution, triply nested numerical experiments of the MAP IOP-2B case. Comparison of the model simulations, which use 5 km horizontal resolution, with mesoscale observation indicates that the fine scale structure of southerly low-level jets and rainfall distribution are adequately simulated, although slight wind direction and total rainfall amount errors occur.

The control simulation results suggest that the areas conducive to potential instability and conditional instability are similar when the impinging airstream is near saturation. The results also indicate that the conditional symmetric instability is not responsible for initiating the deep convection in this case. The parcel trajectory analysis from the control simulation indicates that ascent is very strong near the surface, which could be induced by the convergence in the concave region. The parcel trajectories suggest that layer lifting (potential instability) is a major feature in triggering deep, moist convection resulting in heavy rainfall. The results from the sensitivity experiment with 50% reduced mixing ratio indicate that the atmospheric moisture content significantly affect the westward turning of impinging southerly flows. It is found that a low-level cyclonic circulation is formed adjacent to the Piedmont area. Comparison of the simulated soundings from both control and sensitivity experiments indicate that the convective available potential energy values are higher in the sensitivity simulation. However, the level of free convection (LFC) is also much higher in the sensitivity simulation, which implies that more energy is needed to lift air
streams up to this level. Thus, the total amount of rainfall is much less than in the control simulation as well as the observations. Most of the rainfall in the sensitivity experiment is concentrated over the western flank of the Alps. In addition, the results from the sensitivity experiment also demonstrate that conditional instability does not play a significant role in the initiation of the convection. The comparison of control and sensitivity simulations also indicates that moisture content is an essential ingredient for heavy orographic rainfall.
1. Introduction

As discussed before, a heavy orographic rainfall event occurred on 19-20 September 1999 (IOP-2B) when a deep trough propagated through the Alps, with a maximum 24 h rainfall exceeding 250 mm. The heavy rain was concentrated on the windward (southern) slopes of the Alps, especially in the Lago Maggiore Target Area (LMTA). Similar synoptic conditions and amounts of precipitation comparable to this event were recorded in the Piedmont flood event in November 1994 (see Buzzi et al. 1998). The synoptic and mesoscale environments associated with IOP-2B were presented by Lin et al. (2001). The research interest in this heavy precipitation event was stimulated by the fact that deep moist convection was triggered by conditionally and/or potentially unstable impinging airflow, which resulted in heavy orographic precipitation concentrations over the windward slopes as well as in the concave region (i.e., LMTA). As pointed out by Lin et al. (2001), the conditionally or potentially unstable flow is one of the common ingredients conducive to heavy orographic rainfall. Therefore, this study is intended to investigate the role of moist instabilities in triggering the deep convection resulting in heavy orographic precipitation.

Browning et al. (1974) presented a case study showing the three-dimensional structure and evolution of precipitation upwind, over and downwind of the southern Wales hills during the passage of a wintertime warm sector that gave moderate (~ 30 mm in 8 hours) and prolonged rainfall. The warm sector was characterized by a fast-moving airstream with potential instability, not only at low levels, but also in the middle troposphere. Hill and Browning (1981) extended the work of Browning et al. (1974), presenting eight detailed case
studies. In these cases, the atmosphere was potentially unstable in the lowest 2 km. Their results clearly show that over 80% of the rainfall enhancement occurred in the lowest 1.5 km above the hills. It is consistent with Bergeron’s seeder-feeder mechanism (Bergeron, 1965). In virtually all of the cases they studied, the maximum precipitation occurred over the hills. One of the conclusions they stated is that the orographic enhancement is strongly influenced by the low-level wind speed. The largest enhancement of rainfall occurs in association with strong winds and high moisture content below 2 km. Note that the southern Wales hills have only modest elevations (maximum height only 600 m). Additionally, in the Big Thompson flash flood event (Maddox et al. 1978; Caracena et al. 1979), although the relative elevation of the Rocky Mountains in the area under discussion is generally less than 1000 m, the orographic lifting released the convective instability which provided the necessary destabilization to trigger convection and result in flash flood. The convective available potential energy was about 2526 J Kg\(^{-1}\) in this case, which also implies the conditional instability is likely involved in this case. Similar high values of CAPE were observed in the orographic flash flood event at Rapid City, South Dakota in 1972 (e.g., CAPE \(\sim 2180\) J Kg\(^{-1}\)). Some high values of CAPE were also observed in the flash flood events in east Asia (see Lin et al. 2001).

As mentioned above, IOP-2B had similar synoptic conditions as the Piedmont flood event in 1994. Meteorological analysis of the Piedmont case by Doswell et al. (1998) and Romero et al. (1998) indicate that the flooding event was mainly orographically-generated with convection playing an important role only in the coastal zone. Numerical studies of this
case by Ferretti et al. (2000) suggested that the deep convection was initiated within the conditionally unstable air existing over the Mediterranean, which resulted in large amounts of rainfall. In a recent study, Lin et al. (2001) examined the orographic rainfall cases in different regions, and suggested that a conditionally or potentially unstable upstream airflow was one of the common ingredients for producing heavy orographic rainfall. Houze et al. (2000) reported that IOP-2B was a case with a low-level warm, moist and potentially unstable airstream. Lin et al. (2002) examined the influence of synoptic and mesoscale environments of IOP-2B, and suggested that low-level flow over the southern Alpine slope tends to release the potential instability. The studies of rainfall in California’s coastal mountains also pointed out that the presence of potential instability laminae in the warm sector below ∼ 4km mean sea level (see Neiman et al. 2002; Ralph et al. 2002). Nevertheless, Rotunno and Ferretti (2002) suggested that due to the effect of the Alps on the westward passage of the moist tongue in IOP-2B, heavy rain is produced in association with strong conditional instability. In addition to the potential and conditional instabilities mentioned above, as noted by Buzzi and Alberoni (1992), the slantwise convection in an area of strong vertical shear suggested the symmetric instability could be one of the factors that have determined the spatial organization of the convection with frontal passage associated with thunderstorm development over the northern Italy.

From these studies, the unstable airstreams appear to be significantly related to the dynamics of moist convection which would result in heavy orographic precipitation events. However, the diagnostic approach to assessing instabilities requires a clear explanation, and
there is also a need to investigate the importance of the type of instability or multiple type of instabilities that trigger moist convection and result in heavy orographic precipitation. The purpose of this Chapter is to investigate the relevance of instabilities responsible for the convective initiation which would result in heavy rainfall. Various types of instabilities, such as potential (convective) instability, conditional instability and conditional symmetric instability will be examined and verified using model results. In addition, the relationship of convective available potential energy to convective development, as well as the common ingredients for heavy precipitation, as suggested by Lin et al. (2001), will also be examined.

This study is organized as follow: A general description of the mesoscale conditions and observational analyses of precipitation from raingauges can be found in Chapter 4. Additional discussion of the radiosonde observation is addressed in Section 2. Simulation and analysis are discussed in Section 3, which includes the numerical model setup and experiment design, verification of the control simulation results, a short overview of atmospheric instabilities as well as the discussion of the modeling results. Sensitivity tests will also be discussed in Section 3. Section 4 presents the conclusion and discussion.

2. Mesoscale overview

IOP-2B was characterized by a deep trough which moved rapidly over the region of northern Italy during the period of 19-21 September 1999. The region of northern Italy is illustrated in Fig. 1b. It was observed that a cloud system with apparent embedded convective elements swept across northern Italy in association with this trough. Heavy rain was concentrated on the windward slopes of Maritime Alps as well as in the Lago Maggiore
area. The accumulated precipitation during the entire period in the Lago Maggiore area as well as in northern Italy ranged from 100 to 300 mm (see Houze et al. 2000). The detailed synoptic and mesoscale conditions during IOP-2B have been investigated by Lin et al. (2002). The detailed discussion of mesoscale features associated with heavy orographic rainfall can be found in Chapter 4.

Figure 2 shows the European Center for Medium-Range Weather Forecast (ECMWF) 0.5 degree resolution analyses of equivalent potential temperature ($\theta_e$) and winds at 850 hPa. The moist flow into the Lago Maggiore area was generally from the south, and then turned southeasterly near the foothills of the Alps. The averaged wind speed is about 10 ms$^{-1}$ at 18 UTC 19 September 1999 (Fig. 2a). High $\theta_e$ ($\sim$ 327 K) existed in the Piedmont area (as illustrated in Fig. 1b). Six hours later (Fig. 2b), the low-level southerly flow intensified as the trough approached northern Italy. Subsequently, by 06 UTC 20 September (Fig. 2c), the low-level jets ($\sim$ 20 ms$^{-1}$) with high $\theta_e$ were formed in a narrow tongue around the Gulf of Genoa. During the subsequent hours (Fig. 2d), the moist tongue and low-level jets moved eastward in association with the trough. In general, the moist flow into the LMTA at the lower levels was generally from the south. The southerly low-level flow intensified and transported moisture toward the Lago Maggiore as well as the Po Valley throughout the period of precipitation. Also, the moist flow turned cyclonically as it approached the barrier. Notice that the wind turned to a more southeasterly direction when approaching the foothills. It flowed nearly perpendicular to the southwest-northeast oriented mountains on the western side of the Lago Maggiore area. This flow persisted for many hours, and the
maxima of rainfall occurred where this flow encountered specific mountain peaks.

The objectively analyzed 6-h accumulated precipitation maps over northern Italy from 1200 UTC 19 September to 1200 UTC 20 September 1999 can be found in Fig. 5 of Chapter 4. The 850 hPa wind field and $\theta_e$ analysis (Fig. 2c) suggest that the precipitation was supported by moist southerly flows in this region. It appeared that the orographic lifting may have enhanced the precipitation as the southerly flows impinged on the steep terrain in the Maritime Alps and the south side of the Alps. Meanwhile, the rainfall area had moved eastward, as the trough approached northern Italy. The total amount of rainfall had reached more than 60 mm surrounding the Lago Maggiore area during 0000 UTC to 0600 UTC 20 September. In addition, a moderate accumulated rainfall was still observed over the upslope of the Maritime Alps and Apennines. Evidently, the localized heavy precipitation could be induced by orographic blocking effects.

Most of the heavy rain fell out over the upslopes during the trough passage over the south side of the Alps. The total precipitation increased around the eastern side of the Lago Maggiore area while the trough moved eastward. In addition, some individual heavy rain spots were found close to the upslope of the Lago Maggiore area. The results are consistent with the S-Pol radar observations which indicated that small to moderate convective cells were embedded in the broad-scale precipitation layer over the windward slopes of the Lago Maggiore area (see Houze 2001). Smith (1979) also pointed out that the convective cells can enhance the precipitation process making it faster to develop and more efficient in areas of broad-scale upslope flow. These small to moderate convective cells were associated with
moist layers which would affect the entire Alpine barrier. In other words, the moist flow was condensed over the windward slope rather than turned away from the barrier. The results discussed above indicate that the genesis of convective cells needs an initiating mechanism to release the energy repeatedly in the same area, which implies that the convection over the Lago Maggiore area as well as the south side of the Alps might be triggered by moist instabilities. We will discuss the moist instabilities in Section 3b.

The environmental conditions along the upstream of the south side of the Alps are well represented by the sounding at 0000 UTC 20 September at Cagliari (LCAG; 39.25N, 9.05E), which is near the southern end of Sardinia (see Fig. 1a). As indicated in Fig. 3a, the southerly flow is significant in the lower layer up to 2.0 km. Above this layer, warm advection is apparent as the wind veers from southerly to southwesterly. This sounding also indicates a layer convective available potential energy (CAPE) of 2826 J kg$^{-1}$ for a surface parcel, and high humidity resulting in 48 mm of precipitable water. This very high CAPE value suggests the strong convective potential environment and highly conditionally unstable atmospheric conditions. In addition, the lifted index (LI = -7.0), total total index (TT = 46), K index (KI = 26), and low level of free convection (LFC = 2.5 km) all imply the high possibility of strong convective systems formation. By 1200 UTC 20 September, as shown in Fig. 3b, the sounding at the same station shows the flow near the surface was from the northeast and CAPE had been consumed as this trough moved into the south side of the Alps and the Lago Maggiore area. As a result, the heaviest precipitation occurred in northern Italy from 0000 UTC to 1200 UTC 20 September.
Chapter 5

The sequential soundings at Milan (45.43N, 9.27E) indicate that CAPE values are 180 and 291 J kg\(^{-1}\) at 0000 UTC and 1200 UTC 20 September, as shown in Figs. 4a and 4b, respectively. Noteworthy features in the Milan soundings are that a near moist neutral condition existed from the surface up to 5.0 km, and the near surface layer was dominated by strong low-level easterly flows during that time. CAPE values are small at this station, because the moist impinging flow in the Po Valley has been modified by the orography. Thus, it cannot truly represent the conditions for heavy orographic rainfall. The CAPE values of the soundings also indicate that heaviest precipitation is rarely correlated with high CAPE. The model results of CAPE distribution in northern Italy will be discussed in the next section.

Although CAPE values may vary with the time of the day and the location as indicated in Cagliari and Milan soundings, the characteristics of these sequential soundings suggest that moist convection over the south side of the Alps would develop rapidly while the trough approached this area. It appears that the orography could lift air up to the LFC resulting in heavy orographic rainfall over the windward slope of the Alps. Additionally, the moist Froude number, i.e. \(F_w = U/N_w h_m\) (\(U\) is the upstream flow speed perpendicular to the terrain, \(N_w\) is the moist static stability from surface to 850 hPa, and \(h_m\) is the height of the mountain, see Chu and Lin 2000), calculated from the Milan sounding at 1200 UTC 19 September is about 0.97 (\(U = 15.0\) m s\(^{-1}\), \(N_w = 0.00524\) s\(^{-1}\), \(h_m = 3000\) m), which suggests the impinging flow was not essentially blocked by the barrier.

The features discussed above lead us to hypothesize that, in this case, moist instabilities
have been realized and resulted in moist convection, which occurs during 1200 UTC 19 to 1200 UTC 20. Therefore, the potential (convective), conditional or conditional symmetric instabilities may play a role in this heavy precipitation event. The numerical experiments and the sensitivity tests on the relevant instabilities during this event are given in the next section.

3. Simulations and Analysis

3.1 The model

The detailed numerical model configuration can be found in Chapter 4. The 45 km resolution domain covered Europe and the 5 km domain concentrated on the northern Italy (Fig. 1a). A 30-second topographic dataset was interpolated to the 5-km domain grid in order to better resolve the Alps (as illustrated in Fig. 1b).

3.2 The control simulation

A detailed description and discussion of simulated precipitation as well as the 850 hPa wind field can be found in Chapter 4. As evidenced from the analyses of observed soundings, convective available potential energy (CAPE) values were small near the heavy rainfall area, such as Milan. The model result for 1800 UTC 19 September shows only small CAPE ($\sim 50 - 250 \text{ Jkg}^{-1}$) in the Lago Maggiore and Po Valley areas (Fig. 5a). By 0000 UTC 20 September (Fig. 5b), CAPE values were small in the Lago Maggiore area, but concentrated in the Ligurian Sea. This result suggests that the development of the convective systems took place along the southern Alpine slopes. As heavy precipitation concentrated on the windward slopes of the Alps, the CAPE was reduced ($\sim 50 - 100 \text{ JKg}^{-1}$) in the same area.
(Fig. 5c) on 0600 UTC 20 September. Six hours later (Fig. 5d), there was not much CAPE left on the eastern side of the Alps because the trough had propagated eastward; instead, modest CAPE was replenished over the Piedmont region as well as over the Ligurian Sea. As revealed in the 6-h accumulated precipitation patterns, much of the heaviest precipitation over the upslope of the south side of the Alps is devoid of any significant CAPE. The model-simulated CAPE values and spatial distribution are comparable to those calculated from observed soundings. It indicates that the CAPE has been consumed as the air parcels were lifted in the region where the precipitation was produced.

3.3 Assessing instabilities

As indicated by radar data, the moist convection over the Lago Maggiore area had a rapid development from 0000 to 1200 UTC 20 September when the trough passed through northern Italy (see Chapter 4). Considerable clouds had developed during this period. The onset of convection depends on whether the moist airstream had been lifted to the lifting condensation level (LCL) or not. The moist instabilities appear to be responsible for the development of convection which resulted in heavy precipitation.

The use of moist instabilities for assessing deep convective events has been elaborately reviewed by Schultz and Schumacher (1999). Briefly speaking, the necessary condition for the potential instability (PI; layer lifting) results from lifting an initially stable, unsaturated layer to saturation. In other words, the equivalent potential temperature decreases with height, \( \frac{\partial \theta_e}{\partial z} < 0 \).

Conditional instability (CI) can be diagnosed through an examination of lapse rates of
saturated equivalent potential temperature ($\theta_{es}$). Thus, we may look for the layer in which $\theta_{es}$ decreases with height ($\partial \theta_{es}/\partial z < 0$). For sufficiently moist air parcels, finite vertical displacements to the LFC will result in the release of buoyant instability. This can be quantified by the CAPE of an upstream sounding. Conditional symmetric instability (CSI) exists locally at each height where the environmental lapse rate along an absolute angular momentum ($M_g$) surface lies between the moist and dry adiabatic lapse rates, where the $M_g$ surfaces slope less steeply than $\theta_{es}$ surface (i.e. conditionally unstable along a $M_g$ surface), or $\frac{\partial \theta_{es}}{\partial z} |_{M_g} < 0$.

To document the evolving structure in unstable layers, several vertical cross sections along the AA' axis (cross-section location is shown in Fig. 1b) were constructed from the model output. Figure 6a shows upward motion and $\theta_e$ distribution at 1800 UTC 19 September, which was the time when light rain started over the Alpine upslopes. A tongue of high $\theta_e$ in the lower layers was pushing northward into the Po Valley from the Gulf of Genoa. This moist tongue rises over the southern slopes of the Alps. PI exists in between 1.0 km to 3.0 km along the upstream of southern Alpine slopes where the high-$\theta_e$ air is underneath and lower-$\theta_e$ air is flowing above; clouds had also developed covering the entire area (Fig. 6c). On 0600 UTC 20 September the elevated maximum upward motion was associated with the high-$\theta_e$ flow (Fig. 6b) that was producing heavy rainfall in the Lago Maggiore area. Strong upward motion extending from the surface to 8 km was fixed to the upslopes of the Alps during this time. A time sequence indicated that this upward motion was already rooted to the upslopes of barriers through time (not shown). PI occurs in the middle layer, as
shown in Fig. 6d and was very similar to Fig. 6c. However, high-$\theta_e$ airstreams had flowed into the Lago Maggiore area and Po Valley in association with the movement of the trough. A noteworthy feature is that the upward motion was in phase with locally upslope high-$\theta_e$ airstreams (Figs. 6a and 6b). This feature is consistent with the convective growing stage as proposed by Lin et al. (1998). As a result, rain occurred over the upslope of the southern Alpine slopes during that time. Notice that $\theta_e$ can be considered as a tracer in a moist airstream when there is no strong mixing process. Thus, the results as shown in Fig. 6 also imply that the air easily ascended the mountain slopes and that orographic lifting and condensation were easily achieved, which released the PI and resulted in heavy orographic rainfall.

Figure 7 was constructed in a similar way as Fig. 6, except using the saturation equivalent potential temperature ($\theta_{es}$) to represent regions of CI. Notice that the saturation equivalent potential temperature is the equivalent potential temperature the air would have if it were saturated with water at the same pressure and temperature. Thus, when the air is not saturated, $\theta_{es}$ is not conserved, but when the air is saturated, $\theta_{es} = \theta_e$ and both are conserved. On 1800 UTC 19 September (Fig. 7a), the higher-$\theta_{es}$ was associated with southerly flows covering the upstream of the southern Alps. However, the $\theta_{es}$ is relatively lower around the windward slope of the Alps during this time. The $\theta_{es}$ increased after the trough moved into northern Italy (Fig. 7b). The areas conducive to CI on a N-S cross section are shown in Fig. 7c, where a band of airstream with possible CI stretched along the upstream of the southern Alpine slopes. During the following 12 hours, the distribution of CI (Figs. 7d) was still very
similar to PI. Although the depth of CI seems larger than PI, there is little change in time in CI and PI versus the location of cloud boundaries. As inferred above from Figs. 6 and 7, the PI and CI might co-exist upstream of the southern Alpine when the environment is near saturated.

Figure 8 shows $M_g-\theta_{es}$ relationship (e.g., Snook 1992), which was constructed to investigate the possible existence of conditional symmetric instability (CSI) for this event. On 1800 UTC 19 September (Fig. 8a), the slopes of the $M_g$ surface were much steeper than the $\theta_{es}$ surface, which indicates that CSI was barely evident. Over the next 12 hours, the $M_g-\theta_{es}$ diagram (Fig. 8b) indicates that the $M_g$ surface was even steeper than the $\theta_{es}$ surface compared to that at 1800 UTC 19 September. It was unlikely that slantwise convection occurred under these conditions. In other words, the slantwise convection was not found for this heavy rainfall event. In addition, there is a lack of banded precipitation distribution, which suggested that CSI did not play a significant role in the formation of convective systems. The results also suggested that the release of PI or CI would dominate the release of CSI (Nicosia and Grumm 1999).

Although the air near the surface was conditionally unstable because $\theta_{es}$ decreased with height (Figs. 7a and 7b), it was potentially stable because $\theta_e$ increased with height (Figs. 6a and 6b). This situation illustrates the importance of distinguishing the difference between $\theta_e$ and $\theta_{es}$ and the relationship in assessing moist instabilities. As shown in Figs. 6c, 6d, 7c, and 7d the distributions of PI and CI regions are very similar. Therefore, in order to investigate whether parcel (CI) or layer lifting (PI) plays the major role in initiating the
moist convection, a set of model-derived forward parcel trajectories is used to examine the three-dimensional airflow along the Lago Maggiore area during the heavy orographic rainfall period.

Figures 9a and 9b present the paths of parcels released from 0.5 km up to 3.0 km with 0.5 km vertical interval at 1200 UTC 19 September, about the beginning of the precipitation. The trajectory calculation is based on wind field (i.e., $u, v$ and $w$), and the time step is 600 seconds. The time increment between data files of the trajectory is one hour. The paths taken by the parcels depend greatly upon their initial positions. Parcels A-F moved in a south to north direction and over the Alps. Above 1.0 km, it appears layer lifting occurs from parcel B to F as they approach the upslope of mountains. The ascent is also detached or displaced from the upslope zone near the mountain. The result also indicates that the ascent below 1.0 km is very strong. In other words, surface convergence must vary dramatically around the terrain in association with orographic lifting. This result might reflect a complex pattern of surface ridging and troughing in between various terrain features within an unstable or convective surface layer. In contrast, parcels A'-F' originate at the same height (1.0 km) with 25 km horizontal intervals (Figs. 9c and d). The parcels gradually ascend above the upslopes of Alps. A noteworthy feature is that parcels over the upslope regions were affected by orographically-forced ascent which demonstrated variability in parcel movement processes. The parcel redistribution features are very similar to that described by Smith (2002). The above result suggests that the moist instability was caused by layer lifting, instead of parcel lifting. This implies that the PI might play a more significant role than the
3.4 Sensitivity tests on mixing ratio

In order to investigate the role of conditional instability on triggering convection, we conducted a sensitivity experiment which is identical to the control experiment except that the water vapor mixing ratio is reduced by half in the model initial conditions. Therefore, it would reduce the possibility for the air to become saturated by reducing the water vapor mixing ratio. Here we hypothesize that convective available potential energy and conditional instability would be downplayed due the lack of moisture. Thus, we might be able to distinguish the roles played by different instabilities.

The evolution of the lower-tropospheric wind associated with the trough is depicted by the model-simulated 850 hPa equivalent potential temperature $\theta_e$ and wind field from the 5 km domain, shown in Fig. 10. On 1800 UTC 19 September, a zone of lower $\theta_e$ was present in the Po Valley and along the coast (Fig. 10a). The trough was located farther to the west at this time, outside of the third domain. A low-level southeasterly wind of $\sim 10$ ms$^{-1}$ was present in the Gulf of Genoa. Figure 11 shows the accumulated rainfall at 6-h intervals. By 0600 UTC 20 September, the light rain had started (Fig. 11a). Subsequently, a broad precipitation shield was over the western side of the Alps from 0600 to 1200 UTC 20 September (Fig. 11b). Compared with the control simulation (cf. Figs. 9c and 9d in Chapter 4), accumulated rainfall was reduced as much as 50%. Apparently, this was due to the low humidity. The vertical cross section of equivalent potential temperature for 18 UTC 19 September (Fig. 12a) constructed along the AA’ cross section (see Fig. 1b) suggested that
the strong gradient of $\theta_e$ persisted offshore, immediately upstream of the coastal mountains near the Ligurian Sea. Meanwhile, weak upward motion also existed over the upslope of the Alps. As indicated in Fig. 12c, the cloud base was about 4.5 km at 1800 UTC 19 September. Compared with the control simulation (Fig. 9c in Chapter 4), the result implied that the high LCL might exist during this time period. In addition, weak signatures of PI were apparent in the lower levels (Fig. 12c) due to the weak $\theta_e$ contrast in the lower levels (cf. Fig. 12a). In contrast, a deep layer of possible CI existed during this time (Fig. 13a). However, no deep convection occurred in northern Italy. The total precipitation was weak during this time period (not shown). Apparently, in spite of that, CI is more probable than PI, which does not imply that moist convection would occur in this region.

By 0000 UTC 20 September (Fig. 10b), a higher $\theta_e$ zone existed along the coastal Apennines mountains. The low-level southerly flow ($\sim 15$ m s$^{-1}$) entered the eastern fringe of the domain from the Adriatic Sea and was partly blocked from passing over the crest, as indicated by a marked deceleration adjacent to the barrier. Consequently, the southerly flow became southeasterly near the Lago Maggiore area. The wind speed was $\sim 5 - 10$ m s$^{-1}$ at this time. The total rainfall from 1200 UTC 19 to 0000 UTC 20 September was less than 10 mm (not shown). By 0600 UTC 20 September (Fig. 10c), a significant $\theta_e$ gradient with low-level southeasterly flow ($\sim 15$ m s$^{-1}$) was present along the Po Valley and coastal Apennines mountains. The low-level southeasterly flows from the Gulf of Genoa have penetrated into Lago Maggiore. A shallow layer of high $\theta_e$ air was located about 1.5 km above the surface, and the upward motion had started over the upslopes of the Alps (Fig. 12b). Note that
the upward motion was again in phase with the slope of $\theta_e$ surfaces as simulated in the control simulation (cf. Fig. 6b). Meanwhile, a shallow PI region existed in accordance with the southeasterly impinging flows (Fig. 12d). CI also had a very similar structure as PI (Fig. 13b) during this time. Deep clouds formed over the Alps and Apennines mountains, which suggested that the convection had been triggered by the instabilities. The southerly flows over the eastern side of the Po Valley were still deflected to become easterly in part of mountain blocking and friction effects (Fig. 10c).

The low-level flow intensified at 1200 UTC 20 September as the simulated trough approached northern Italy. A high $\theta_e$ tongue associated with the strong southeasterly flows (locally exceeding 25 m s$^{-1}$) had entered the Piedmont area and the western side of the Lago Maggiore area (Fig. 10d). It is noticeable that the nearly perpendicular southeasterly impinging flow on slopes of the western side of the Alps decelerated and turned parallel to the terrain. Subsequently, a low-level cyclonic circulation formed between the Piedmont and the lee side of the Maritime Alps. This low-level cyclonic circulation might enhance the local precipitation over the Maritime Alps (Fig. 11b).

Comparison of upstream soundings (at 42.9N, 94.43E, near the northern tip of Corsica) from the control and sensitivity experiments are shown in Figs. 14 and 15. At 0000 UTC 20 September, the simulated upstream soundings from the control experiment yielded a CAPE for the surface parcel of 214 J Kg$^{-1}$, a convective inhibition (CIN) of 69 J Kg$^{-1}$, and a LFC of 804 hPa (Fig. 14a). Conversely, as shown in Fig. 15a, the sounding in the sensitivity experiment produced a CAPE of 243 J Kg$^{-1}$, and the LFC of 664 hPa. However, CIN
(344 J Kg$^{-1}$) was about 5 times higher than in the control simulation. This implied that the convective motion was not easy to archive. By 1200 UTC 20 September, the values of CAPE from the control simulation did not vary too much ($\sim$ 232 J Kg$^{-1}$), and CIN was 146 J Kg$^{-1}$ (Fig. 14b). At the same time, the sensitivity experiment sounding (Fig. 15b) yielded a CAPE of 717 J Kg$^{-1}$, a CIN of 217 J Kg$^{-1}$, and LFC of 690 hPa. Besides, a noteworthy feature in the sensitivity experiment sounding was a rapid saturation near the surface. It implied that surface fluxes from the ocean were vigorous. In other words, the layer near the surface picked up the moisture immediately from the ocean surface. The sensitivity experiment results suggest that in spite of the existence of a deep layer of CI along the south side of the Alps as well as the existence of moderate CAPE throughout the time period, the conditional instability was never realized in the form of heavy rainfall in the Lago Maggiore area. This is because the LFC is much higher and CIN is much larger than in the control experiment, which downplayed the occurrence of deep convection. Therefore, total precipitation was reduced significantly in the sensitivity experiment.

In general, the results indicate that when the LFC exists at a higher altitude, the air parcels may not be sufficiently lifted by the synoptical flow over the slope, even though the upstream CAPE values are larger. Subsequently, precipitation was concentrated over the western part of the Alps from 0000 to 1200 UTC 20 September. The total amount of rainfall for this sensitivity experiment was much less than the control simulation as well as the observed. Thus, we may conclude that conditional instability is difficult to be realized under these conditions. Therefore the rainfall is greatly reduced. The results from the
sensitivity test also demonstrate that low-level south or southeasterly flow is more easily deflected westward without the convection over the Alps. It suggests that the distribution of the horizontal gradient of moisture can be very important on the distribution of rainfall (Rotunno and Ferretti 2001). Additionally, the presence of the sensitivity experiment results can explain that moisture content is an essential ingredient for heavy rainfall (see Lin et al. 2001).

4. Conclusion and discussion

A case study of an intense precipitation event (19-21 September 1999; IOP-2B) that affected northern Italy, mainly the Lago Maggiore region, was investigated using fine scale simulations. The motivation for studying this heavy orographic precipitation event is defined by the need to understand the role of moist instabilities on triggering convection that resulted in heavy rainfall. The numerical experiments were constructed by 45/15/5 km nesting domains with 48-hour integrations on a relatively coarse domain and 36-hour integrations on 15 and 5 km domains, respectively. The investigation is focused on the 5 km domain from 1200 UTC 19 to 1200 UTC 20 September since the strong convection and heavy rainfall occurred in this time period.

Comparison of the control numerical experiment and observations demonstrate that the heavy orographic rainfall event was simulated reasonably well. Although the wind direction was slightly deflected to southeasterly and stronger at 0600 UTC 20 September and the total amount of rainfall was higher (∼ 60 mm in 24 hours), the model results provide a spatially and temporally rich set of data from which to diagnose the moist instabilities. It
was shown that the low-level flow impinging on the Alps from the southerly or southeasterly direction was moist from the surface up through $\sim 3$km. The impinging southerly low-level flow over the Lago Maggiore region was not substantially blocked by the barrier but rather traversed the Alps. Subsequently, most of the precipitation was concentrated at the windward slopes near the Lago Maggiore region. The heavy orographic rainfall was enhanced by the deep convection in association with strong orographic lifting. The upward motion was in phase with the increase of equivalent of potential temperature over the upslopes, indicating growing deep convection (Lin et al. 1998). Meanwhile, the westward turning of the impinging southerly low-level flow was due to the orographic blocking, Coriolis deflection and boundary layer friction. Diagnosis of potential instability (PI), conditional instability (CI) and conditional symmetric instability (CSI) from the control simulation indicate that PI and CI co-exist in initiating deep convection. However, CSI was not an essential element in this case. The parcel trajectories reveal that layer lifting occurred from 1.0 to 3.0 km, while below 1.0 km the ascent was very strong. The results suggest that PI played an important role in triggering moist convection in this case.

To further investigate the role of PI and CI in triggering convection, a sensitivity experiment was conducted with a 50% reduction of the water vapor mixing ratio in the model initial condition. The results demonstrate a significant westward turning of low-level south-southeasterly flows from 1800 UTC 19 to 1200 UTC 20 September. In addition, precipitation was concentrated on the western flank of the Alps. The westward turning of low-level south or southeasterly flow was very similar to MAP IOP-8 (see Lin et al. 2001). A noteworthy
feature was a low-level cyclonic circulation that formed in between the Piedmont and Maritime Alps. This low-level cyclonic circulation seemed to enhance the precipitation over the upslopes of the western flank of the Alps. The total amount of 24 h accumulated rainfall was much less than the control simulation. The cross-section of CI and PI were also constructed in this sensitivity experiment. The results indicate that the depth of CI was much larger than PI at 1800 UTC 19 September. By 0600 UTC 20 September, CI and PI had a very similar structure. Nevertheless, the upstream soundings from the sensitivity experiment on 0000 UTC and 1200 UTC 20 September indicated a rapid saturation near the surface, which could be caused by moisture flux from the ocean surface (i.e., the Gulf of Genoa). In addition, it is worthwhile to note that the soundings also showed moderate CAPE in these two time periods. However, the LFC was much higher, and CIN was much larger than in the control simulation. These results suggest that even though CAPE increased, the LFC was so high that convective available potential energy was not released, due to insufficient mechanical lifting. Thus, the rainfall was much less than in the control simulation as well as the observational analyses. It should be pointed out that to distinguish between the roles of PI or CI could be misleading if one only uses the cross-section diagram of PI and CI (e.g., Figs. 6, 7, 12 and 13). The soundings yield CAPE, CIN and LFC which also reveal valuable information to identify the potential for moist convection as well as the heavy rainfall areas. In addition, the sensitivity experiment also provides the evidence that moisture is an essential ingredient conducive to heavy rainfall (Lin et al. 2001). Therefore, we can conclude that the potential instability plays a major role in triggering the deep, moist convection, yet
the orographic lifting effect, and moisture content are also very important to produce heavy orographic rainfall.

The study here is a first step to investigate the relevance of instabilities in triggering moist convection resulting in heavy orographic rainfall based on a real-data simulation. Further study involving more complete sensitivity tests on high convective available potential energy environments and soundings with the moist absolute instability condition, is needed.

5. References


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Chapter 5


Figure 1: (a) Domains for numerical simulations used in this study. The grid increments for the three nested meshes are 45km, 15km and 5km, respectively. LIMM and LCGA denote the surface station at Milan and Cagliari. (b) Terrain (every 500m) used for the 5-km resolution grids. The solid line AA' represents the orientation of the x-z cross-section in subsequent analyses.
Figure 1: Cont’d
Figure 2: 850 hPa equivalent potential temperature and wind fields from ECMWF analysis at (a) 18 UTC 19, (b) 00 UTC 20, (c) 06 UTC 20, and (d) 12 UTC 20 September 1999.
Figure 3: Upstream soundings at Cagliari (LCGA; 39.25N, 9.05E) at (a) 00 UTC 20, and (b) 12 UTC 20 September 1999.
Figure 4: Soundings at Milan (LIMM; 45.43N, 9.27E) at (a) 00 UTC 20, and (b) 12 UTC 20 September 1999.
Figure 5: Simulated convective available potential energy at (a) 18 UTC 19, (b) 00 UTC 20, (c) 06 UTC 20, and (d) 12 UTC 20 September 1999. The contour interval is 50 Jkg$^{-1}$.
Figure 6: Cross sections AA’ of Fig. 1b showing upward motion (shaded) and equivalent potential temperature (every 1 K) for (a) and (b). Potential instability (PI) (shaded), cloud regions (dotted lines for $q_v > 0.001 \text{ g kg}^{-1}$), and total circulation (vectors) in the cross section from 5 km control simulation domain for (c) and (d). Left panels are for 1800 UTC 19 September 1999, while right panels are for 0600 UTC 20 September 1999.
Figure 7: Same as Figure 6, but for saturation equivalent potential temperature in (a) and (b), conditional instability (shaded) in (c) and (d).
Figure 8: Cross section AA’ of Fig. 1b showing the saturation equivalent potential temperature (thick lines), and absolute angular momentum surface (thin lines) at (a) 1800 UTC 19, and (b) 0600 UTC 20 September 1999. Contour intervals are 1 K and 2 m s\(^{-1}\).
Figure 9: Parcel trajectories on north-south direction (AA’) in (a) starting from 0.5 km to 1.5 km, and (b) starting from 2.0 km to 3.0 km, with 0.5 km interval. (c) and (d) at 1.0 km height, with 250 km interval, respectively. The time intervals are denoted in (a).
Figure 10: Simulated 850 hPa winds (one full barb = 10 ms\(^{-1}\)) and equivalent potential temperature from the 5 km sensitivity simulation domain ending at (a) 18 UTC 19, (b) 00 UTC 20, (c) 06 UTC 20, and (d) 12 UTC 20 September 1999.
Figure 11: Simulated 6-h accumulated precipitation (shaded) from the 5 km sensitivity simulation domain ending at (a) 06 UTC 20, and (b) 12 UTC 20 September 1999.
Figure 12: Cross sections AA’ of Fig. 1b upward motion (shaded) and equivalent potential temperature (every 1 K) for (a) and (c) at 18 UTC 19. Potential instability (PI) (shaded), cloud regions (dotted lines for $q_v > 0.001$ g kg$^{-1}$), and total circulation (vectors) in the cross section from 5 km sensitivity simulation domain for (b) and (d) at 06 UTC 20 September 1999.
Figure 13: Same as Fig. 12, but for conditional instability (shaded) in (a) 18 UTC 19, and (b) 06 UTC 20 September 1999.
Figure 14: Simulated upstream soundings at 42.9N, 9.43E (near the northern tip of Corsica) from 5 km control simulation domain at (a) 00 UTC 20, and (b) 12 UTC 20 September 1999.
Figure 15: Simulated upstream soundings at 42.9N, 9.43E in Corsica from 5 km sensitivity simulation domain at (a) 00 UTC 20, and (b) 12 UTC 20 September 1999.
CHAPTER 6
SUMMARY AND CONCLUSIONS

Two well-documented heavy rainfall events occurred on 6-7 August 1999 in southern Taiwan and on 19-21 September 1999 over the European Alps during the Mesoscale Alpine Program (MAP). These events have been investigated with state-of-art mesoscale numerical models. The Naval Research Laboratory’s Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) is used for simulating Tropical Storm Rachel’s (1999) landfalling in southern Taiwan. The heavy orographic rainfall event that occurred in the Alpine region is simulated using the PSU/NCAR MM5 model. Both cases are simulated with a 5 km horizontal resolution domain. Validation of the forecast fields against the observations indicates that both COAMPS and MM5 reproduced the synoptic and mesoscale features reasonably well, providing invaluable high-resolution datasets to evaluate the mesoscale model performance of orographic rainfall predictions, and to advance our fundamental knowledge of orographic precipitation processes over the the complex mountain ranges.

A survey of the literature on orographic precipitation including observational, theoretical and numerical studies of various weather systems was presented. These diagnostic approaches are provided in this study to advance our understanding of the dynamics of orographic precipitation. The basic theories, assumptions and limitations of each approach has been documented. These diagnostic methods include moist Froude number, moist instabilities, convective available potential energy and a moisture flux model. In addition, this study constitutes an important extension of the common ingredients concept from a
mesoscale modeling perspective. The common ingredients concept (Lin et al. 2001) on the behavior of orographic rain or flooding has been used to examine orographic rainfall events. These ingredients include: (1) high precipitation efficiency within the incoming airstream; (2) the presence of a moist, moderate to intense low-level jet; (3) a steep mountain to release the instability; (4) favorable mountain geometry and confluent flow field; (5) strong environmentally-forced upward motion; (6) the presence of high moisture upstream; (7) a preexisting large-scale convective system; (8) slow (impeded of retarded) movement of the convective system; and (9) a conditionally or potentially unstable upstream airflow.

The model results illustrate that heavy orographic rainfall associated with the landfalling Tropical Storm (TS) Rachel could be divided into two distinct rainfall episodes. The comparison of the control and sensitivity (without topography) simulations helped to better gauge the role of the terrain during the heavy rainfall period. As the results indicate, the large-scale circulation had more of a contribution to the rainfall amount and distribution over southern Taiwan before Rachel made landfall, which was the first rainfall episode. From 0000 to 1800 UTC 7 August 1999, the strong orographic lifting of the potentially unstable southwesterly low-level jet (LLJ) triggered the convective systems in the concave region of the southwest Central Mountain Range (CMR), which produced heavy orographic rainfall. This second episode of heavy rainfall was caused by the combined effects of orographic forcing and TS Rachel’s rainbands. The horizontal distribution of $\theta_e$ and the vertical cross-section of $\theta_e$ and $q_c$ have shown that high $\theta_e$ as well as unstable layers existed on both the windward and lee sides of the topography, however, the heavy orographic rainfall existed only on the windward
side (concave area). The results suggest that a southwesterly LLJ in association with high \( \theta_e \) airstream supplied moist air and helped establish the potentially unstable layer; which, when combined with the orographic blocking effects as well as strong upward motion from TS Rachel, produced heavy orographic rainfall. By examining the orographically-induced vertical moisture flux and general vertical moisture flux, the results show that the rainfall distribution over the mountains was roughly consistent with the orographically-induced vertical moisture flux distribution, while the general vertical moisture flux could predict the rainfall distribution better over a flat surface. Besides, the concave topography could help to enhance confluent flow and organize localized convective cells. Subsequently, outflow boundaries were produced by the convective cold pools, which forced the convective systems to propagate upstream over the sea as well as the impinging flow from the southwest to develop new convection.

It is worthwhile to point out that the observed precipitation over the western slope of the CMR could not be reasonably simulated, and the model slightly over-estimated the total amount of precipitation. This discrepancy between observations and simulations could have been caused by the complex topography which was not resolved in a 5 km resolution domain, especially over the southwest CMR. This grid spacing results in about 4 grid points along the concave region. The model was not able to reproduce the intensity and convective structure of TS Rachel. Subsequently, the circulation of TS Rachel weakened as it came closer to southern Taiwan, which downplayed the impinging flow from the west. As a result, the precipitation over the western slope of the CMR could not be adequately simulated. The
results suggest that vortex bogusing is needed at the initial stage in order to get a better simulation, even though TS Rachel is a weak tropical system. Also, the complex topography could play a role in disorganizing the sub-grid scale convection, resulting in the model’s over-predicting the total amount of precipitation. Overall, the model results provide good insights into the dynamics of moist convective systems over complex orography. In addition, the period of the orographic precipitation were simulated reasonably well. The results could also be used as a case study to demonstrate the importance of correctly simulating the convective structure of a tropical cyclone in quantitative precipitation forecasts.

A heavy orographic rainfall event occurred on 19-20 September 1999 during the MAP (Mesoscale Alpine Program) IOP-2B when a deep trough propagated eastward through the Alps. The MM5 model results show that many of its noticeable aspects were realistically reproduced, including the timing and location of the deep trough and the associated precipitation evolution, though the total amount of precipitation was significantly higher ($\sim 30\%$) than observed rain-gauge analyzed. The moist flow in northern Italy at 850 hPa was generally from the south in association with high $\theta_e$ throughout the entire period of precipitation. The impinging moist flow was not substantially blocked by the barrier but rather flowed over the Alps. The westward deflection of the southerly low-level flow occurred as it approached the barriers. The flow deflection was caused by mountain blocking, rotation (Coriolis effect) as well as boundary friction effects. Precipitation was mainly concentrated on the windward slopes, especially in the Lago Maggiore area.

The sensitivity experiments serve to illustrate the complex interrelationships among local
circulation, complex topography, and precipitation distribution in northern Italy. The experiment without boundary layer friction (NFRC) reveals an important role of the frictional processes in the deflection of impinging southerly flow. A sensitivity test on the existence of the Ligurian Apennines mountains (NAPN) illustrates that the total amount and distribution of precipitation over the windward slopes of the Alps were not directly affected by the upstream mountains. However, this experiment reveals a rain shadow effect resulting from downslope wind accompanying the southerly flow over the crest of the coastal Apennines mountains. The sensitivity experiment on the removal of the French Alps (NWAP) indicates precipitation was concentrated along the steep slopes at the left end as well as the Lago Maggiore area of the mountains. A narrow band of precipitation was formed when the trough swept into northern Italy. The idealized topography experiments, including arc-shaped (AALP) and elongated bar-shaped obstacles (BALP), indicated that the total amount of rainfall was significantly reduced as much as 50% in comparison with real topography experiments. It was, in part, due to the smooth topography surface and less steeper slopes, which drastically reduced the terrain-induced upward motion. The high-resolution experiment with a 1.67 km resolution domain (FALP) illustrates that significant convective structure extended up to 7 km above the upslope regions. The results suggest that more intense convection would develop in the finer resolution domain, which would result in extremely heavy rainfall in the complex mountain areas, especially over the steeper upslope regions. In addition, the parcel trajectories and moist instabilities analyses from the model output demonstrates that the potential instability (i.e., layer lifting) played a significant
role in initiating deep, moist convection which then resulted in heavy orographic rainfall. However the conditional instability and conditional symmetric instability were not essential elements in this heavy orographic rainfall event. The convective available potential energy (CAPE) values of the soundings also indicate that heaviest precipitation is rarely correlated with high CAPE.

Orography significantly affected these two precipitation systems as they passed over major mountain ranges. The common features of these heavy rainfall events were the outflow aloft (e.g., Lin et al. 2002), and orographically-induced uplifting which produced and enhanced precipitation. Yet, the low-level convergence produced by the impinging low-level jet as well as the barrier jet produced even more precipitation over the concave topography area. The barrier jet in IOP-2B was formed ahead of the southern Alpine slopes by the westward deflection of the southerly low-level jet. The Rossby number \( R_o \) in the concave topography region in MAP IOP-2B is about 2, i.e., \( R_o = U/fL \), where \( U \sim 20 \text{ m s}^{-1} \), \( f \sim 10^{-4} \text{ s}^{-1} \) and \( L \sim 100 \text{ km} \) as estimated from Fig. 1b in Chapter 4. However, the Rossby number is larger than 10, i.e., \( U \sim 15 \text{ m s}^{-1} \), \( f \sim 5.8 \times 10^{-5} \text{ s}^{-1} \), and \( L \sim 20 \text{ km} \) as estimated from Fig. 1b in Chapter 3, in Taiwan’s case. Thus, the rotational effect played a more important role in producing the low-level flow convergence at the concave region of the Alps during IOP-2B resulting in additional orographic rainfall. The rotational effects can be investigated more rigorously by performing idealized numerical simulations, which will be considered in future studies.

Through numerical experiments and data analyses, the fine-scale simulation results re-
veal insights into the important factors that control orographic precipitation. Although these cases were simulated in two different mesoscale models, both mesoscale models demonstrate the capability of accurately simulating orographic rainfall cases. However, the quantitative orographic precipitation forecasts over complex topography still need to be improved. To understand the interrelationships among the horizontal grid spacing, topography resolution and microphysical schemes is the key to improve orographic precipitation forecasts. The results shown in this study are the first step to better understand the factors essential for producing heavy orographic rainfall, which potentially could provide guidance to improve flash floods and other precipitation forecasts in mountainous terrain. More accurate forecasting of the amount of precipitation in and around complex terrain is a necessary first step toward more reliable and timely operational real-time forecasts of heavy precipitation and flash floods. The results of this study would not only lead to better utilization of current numerical models by forecasters, but also provide some guidance for improving quantitative orographic precipitation forecasts in numerical models. These objectives are directly related to the quantitative-precipitation forecasting focus of the U.S. Weather Research Program.

References
