THE EFFECTS OF OROGRAPHY ON WIND, CLOUD, AND RAINFALL PATTERNS DURING TYPHOON KETSANA (2009)

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by

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LIST OF ABBREVIATION

AMV	Atmospheric Motion Vector
ASTER GDEM	Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model
CAPE	Convective Available Potential Energy
CIN or CINS	Convective Inhibition
CLC	Cloud Classification
EL or EQLV	Equilibrium Level
EM	East Malaysia
FY-2D	FengYun-2D / Fengyun-2D
LCL or LCLP	Lifted Condensation Level
LFC or LFCV	Level of Free Convection
Li or Lift	Lifted Index
NO	North-Oriented
NOGAPS	Navy Operational Global Atmospheric Prediction System
NWP	Northwest Pacific
PM	Peninsular Malaysia
PRE	Precipitation/ Rainfall Estimation
R	Recurving
SCS	South China Sea
SEA	Southeast Asia
SI	Sweat Index
SM	Straight-Moving
TCs	Tropical Cyclones
TD	Tropical Depression
UTC	Coordinated Universal Time

KESAN OROGRAFI TERHADAP CORAK ANGIN, AWAN, DAN HUJAN SEMASA TAUFAN KETSANA (2009)

ABSTRAK

Kefahaman tentang kesan orografi adalah penting untuk mencegah bencana dan meramal cuaca seperti kejadian siklon tropika (TCs). Pengaruh orografi ke atas TCs masih tidak jelas kerana kerumitan kesan orografi disebabkan oleh kehadiran gunung dan kajian tentang pengaruh ini juga merupakan bidang penyelidikan saintifik yang aktif. Objektif kajian ini adalah untuk menyiasat kesan orografi ke atas curahan hujan, angin dan sistem awan TCs di Malaysia memandangkan kajian ini belum pernah dilakukan di Malaysia. Indochina telah dipertimbangkan kerana ia mengalami pendaratan taufan Ketsana dalam tempoh masa kajian, justeru membolehkan perbandingan kesan langsung and kesan ekor taufan (kesan tidak langsung) itu ke atas kesan orografi.

Teknik penderiaan jauh telah digunakan untuk mengkaji impak TCs. Data satelit Fengyun 2D (FY-2D) digunakan untuk memerhati perkembangan dan struktur taufan Ketsana yang berlaku dari 21 September hingga 4 Oktober 2009. Dalam kajian ini, data penderiaan jauh seperti Model Ketinggian Berdigit Sejagat (Global Digital Elevation Model, GDEM) daripada satelit Advanced Spaceborne Thermal Emission Dan Reflection Radiometer (ASTER), maklumat mengenai angin daripada Navy Operational Global Atmospheric Prediction System (NOGAPS), dan data radiosond telah digunakan bagi menentukan hubungan taufan dengan kesan orografi.

Kajian ini menunjukkan betapa pentingnya kesan orografi kepada peramal cuaca, seperti banjaran gunung yang tinggi dapat mempengaruhi taburan awan, curahan hujan dan juga corak aliran angin semasa musim taufan; tetapi betapa

ketaranya atau jelasnya hubungan antara orografi dan kesan taufan adalah bergantung kepada keamatan sistem taufan itu dan pergerakannya. Berdasarkan kajian ini, kesimpulan berikut dapat dibuat: 1) curahan hujan cenderung pada kawasan pergunungan yang lebih tinggi, 2) arah aliran angin akan berubah apabila bertembung dengan apa-apa sekatan, terutamanya di kawasan teran yang tinggi dan 3) perubahan bentuk corak awan disebabkan oleh gunung yang tinggi dan cenderung untuk bergerak mengikut struktur gunung adalah disebabkan oleh kesan orografi.

Dalam kajian ini, rantau yang paling terjejas disebabkan oleh taufan Ketsana adalah Vietnam di Indochina, Sabah di timur Malaysia (East Malaysia, EM), Kelantan dan Terengganu di Semenanjung Malaysia (Peninsular Malaysia, PM). Perbandingan di antara kawasan kajian menunjukkan bahawa Indochina mempunyai keputusan yang paling ketara bagi kesan orografi terhadap aktiviti taufan, diikuti oleh kesan ekor di EM. Walaupun tidak begitu ketara seperti kawasan kajian yang lain, namun fenomena ini juga ditemui di PM. Teknik sistem penderiaan jauh ini membolehkan siklon tropika untuk diramal, menjelaskan kesannya dan mampu menentukan kawasan bencana.

THE EFFECTS OF OROGRAPHY ON WIND, CLOUD, AND RAINFALL PATTERNS DURING TYPHOON KETSANA (2009)

ABSTRACT

Understanding the orographic effect is crucial for both disaster prevention and weather prediction for events such as tropical cyclones (TCs). Because of the complexity of orographic effects, due to the presence of mountains, the influence of orography on TCs remains unclear and is an active area of scientific research. The objective of this study is to investigate the effects of orography on the rainfall, wind, and cloud systems of the TCs in Malaysia, as this type of study has never been performed in Malaysia. Indochina is taken into consideration because it encountered the landfall of Typhoon Ketsana within the study period, allowing a comparison of the direct impact and the tail-end effect (indirect impact) of the typhoon in terms of wind, cloud, and rainfall on the orographic effects.

Remote sensing techniques have been used to study the impacts of TCs. Using data from the Fengyun 2D (FY-2D) satellite, we observed the development and structure of Typhoon Ketsana, which occurred from September 21 to October 4, 2009. To determine the relationship of the typhoon with the orographic effect, remote sensing techniques such as the Global Digital Elevation Model (GDEM) from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite, wind information from the Navy Operational Global Atmospheric Prediction System (NOGAPS), and radiosonde data were applied in this study.

This study provides an example of how the orographic effect is important to weather forecasters, as high mountain ranges were able to influence the distribution of the cloud, rainfall and even wind flow patterns during the typhoon season; but

how significant or obvious the relationship between the orography and the typhoon's impacts were depended on the intensity of the typhoon system and its movement. From this study, the following conclusions can be drawn: 1) rainfall tends to be distributed over high mountain regions; 2) wind flow will change its direction upon encountering any restrictions, especially those of high terrain regions; and 3) cloud patterns are deformed by high mountains and tend to flow with the mountains' structure because of the orographic effects.

The regions most affected by Typhoon Ketsana in the study area were Vietnam in Indochina, Sabah in East Malaysia (EM), and Kelantan and Terengganu in Peninsular Malaysia (PM). From the comparison among the study areas, it was found that Indochina had the most significant results for the orographic effects on typhoon activity, followed by the tail effects in EM. This phenomenon was found in PM, although it was not as significant as the other study areas. This remote sensing technique allows tropical cyclones to be forecasted and their impacts to be defined, and it allows disaster zones to be determined.

CHAPTER 1

INTRODUCTION

1.0 Overview

Most natural disasters are caused by weather variations. Three natural disasters common in southeast Asia (SEA) are tropical cyclones (TCs), monsoons and the El Niño-Southern Oscillation (ENSO). These events cause thunderstorms, lightning, flooding and strong winds that affect human life and activities. In recent years, TCs in SEA have destroyed millions of lives and countless properties. These disasters also have more indirect social and economic impacts on SEA countries. Therefore, scientists conduct research into weather forecasting to obtain the most accurate predictions and to reduce the loss of life, property and crops to its lowest rate. At the same time, this research can improve and advance the basis of a physical understanding of cyclones.

The formation of TCs can be divided into seven basins (Neumann and Holland, 1993). Normally, different basins have different names for TC; those generated from the northwest Pacific (NWP), Atlantic, north Indian, and southeast (SE) Indian basins are referred to as typhoons, hurricanes, cyclonic storms and tropical cyclones respectively. The name of a TC depends on the location in which it was generated and its strength. The typhoon, hurricane, tropical storm and cyclonic storm are all, in generic terms, referred to as cyclones. Additionally, TCs can be categorised from 1 to 5 based on a hurricane's intensity at an indicated time, which is known as the Saffir-Simpson Hurricane Wind Scale. Tropical depressions and tropical disturbances are not classified as TCs due to their limited of wind speeds (refer to Appendix Table A.1).

TC is a generic term that includes tropical depression, tropical storm, severe tropical storm and typhoon. A TC is a non-frontal synoptic scale cyclone originating over tropical or sub-tropical waters with organized convection and definite cyclonic surface wind circulation (WMO, 2008a). Typhoons are formed from simple complexes of thunderstorms. However, to achieve typhoon strength, certain necessary requirements must be met, such as 1) originating a few degrees away from the equator to polarward, 2) high relative humidity in the lower and middle troposphere, 3) instability of the troposphere layer, 4) sea surface temperature >26ºC, 5) low and weak vertical wind shear, 6) low-level cyclonic vortices flow and 7) slow variation of monsoon circulation (Krishnamurti, et al., 1985; Chen and Chen, 1995).

Tropical cyclones are able to alter the synoptic scale circulation pattern throughout the entire troposphere, thereby leading to perturbations in the planetary scale circulation pattern, which may have far reaching implications in regions far away from the TC's centres. This phenomenon has a strong influence on the regional rainfall pattern, even in countries that are not directly in the path of these cyclones. The western Pacific, including the NWP ocean and the South China Sea (SCS), is the most active cyclogenesis basin with an average of 27 cyclones per year, almost half of which reach typhoon intensity (Neumann and Holland, 1993). The most active months for cyclogenesis are between August to October (during southwest monsoon period or summer season) (U.S. Naval Maritime Forecast Center/ Joint Typhoon Warning Center Pearl Harbor, 1959-2008). Typhoon tracks in NWP are divided into 3 paths: straight-moving (SM), recurving (R), and north-oriented (NO), as determined using k-means cluster analysis (Elsner and Liu, 2003). However, the SM of the typhoon path is more affected in SEA.

In this basin, Philippines is the most frequent hit by TC and mostly they able to pass through Philippines Island and continue to travel through South China Sea (SCS) toward west or northwest continental region (Indo China or China) when TC having a SM track. Second frequent hit by TC in SEA is Vietnam and occasionally Laos, Cambodia and Thailand. Whereas, TCs which form on North Indian Ocean are frequently dominated at Myanmar and then Thailand (U.S. Naval Maritime Forecast Center/ Joint Typhoon Warning Center Pearl Harbor, 1959-2008).

The direct treatment of TCs is practically nonexistent in the region of Malaysia, but most of the tropical storms that form over the western Pacific ocean and move away from the Sabah shores toward the northwest trigger the tail-end effect of the TCs, including strong wind, heavy rainfall and rough seas in east Malaysia (EM). This is because EM is located between SCS and NWP. Besides that, Peninsular Malaysia (PM) which located at the western SCS also is not directly on the path of these cyclones, but certain impacts have existed during the typhoon season as well. The effect depends on the movement, intensity and position of the TC.

In general, the interior of EM is full of high-terrain regions, including the highest mountain in SEA, Mount Kinabalu, where orographic effects influence the weather conditions. Conversely, the eastern and western coastal regions of PM have different spatial and temporal rainfall patterns because these regions are divided by the Titiwangsa Mountains Range, which is high and long enough to affect low-level atmospheric weather conditions. A sudden, significant change of the weather system in the synoptic scale, such as a tropical cyclone, will modify the basic atmospheric state throughout the entire troposphere. Therefore, regional rainfall rates and distribution patterns vary with the tropical cyclone system. Topography and orography are thought to be able to alter the TC's impact patterns because the terrain is high enough to vary the behaviour of TCs.

Typhoon activity almost never strikes Malaysia directly because it is located in the equatorial region, making it immune to this natural disaster. Nevertheless, the tail of typhoon can cause sudden changes in the weather condition or even the rainfall rate, as well as its distribution patterns at that period. To study the direct and indirect impacts of the typhoon on orographic effects in Indochina and Malaysia, respectively, reviews of studies conducted in Taiwan are performed because Taiwan experiences many typhoons every year. Therefore, these reports are extensively studied to determine the effect of mountain topography and orographic effects on tropical cyclones. These reports prove that a close relationship between mountain terrains and tropical cyclone activities exists in terms of atmospheric pressure, wind, track path, intensity and precipitation (refer to the literature review in Chapter 2).

By understanding the behaviour of TCs and their interaction with orographic features, weather forecasters are able to make accurate predictions of TC formation, movement direction and landfall location; in order to make public announcements warning people located in the areas that might be affected. The wind, cloud, and rainfall patterns were discussed in term of their temporal and spatial variations during Typhoon Ketsana period. One typhoon event was selected for this study to investigate the effects of orography on wind, cloud, and rainfall patterns because this typhoon has both directly and indirectly impacts for both the nearby and landfall regions. The reasons why only Typhoon Ketsana (2009) was selected for consideration in this study were discussed in the following section.

1.1 Why was Typhoon Ketsana (2009) selected?

Previous studies conducted by Elsner (2003) have shown that typhoon paths from 1945-2002 can be averaged and divided into three track types including 1) SM, 2) R, and 3) NO, as determined using k-mean cluster analysis (Elsner and Liu, 2003). SM typhoons tend to travel in a westerly course, whereas R and NO typhoons tend to move towards higher latitudes. However, NO track will tend to keep the typhoon out to sea or offshore. The average maximum intensity of SM typhoons is less than the other two track types' typhoons, and the average time spent at typhoon intensity is the shortest for SM typhoons because they reach the coast more quickly. However, the SM typhoon event was chosen for study because this typhoon type continually affects and threaten SEA, especially the Philippines and Indochina.

The Joint Typhoon Warning Center (JTWC) announced that there were 30 significant cyclones over the NWP basin from 1 January to 31 December 2009 (Cooper and Falvey, 2009). Among the 30 cyclones, there were 15 typhoons with 5 super typhoons, 8 tropical storms, and 7 tropical depressions. Five tropical cyclones from 1st May to 31st October 2009 were reported have impacted the weather in Malaysia: 4 typhoons (Chan-Hom, Koppu, Ketsana, and Parma) and 1 tropical storm (Saudelor) (MOTIS, 2009c). Based on its track, Ketsana activity is the event of interest in this study because it 1) has an SM track with westerly movement (refer to Figure 1.1), 2) exhibits steady motion, and 3) is relatively close to Malaysia. Figure 1.1 shows the development process and track of Ketsana from the beginning to the end of its life which provided by Joint Warning Typhoon Center (JWTC).

In addition, Typhoon Ketsana was known as one of the top 10 catastrophes of 2009 (Benfield, 2009). The report indicated that the Typhoon Ketsana affected the

Philippines and Vietnam from 26-30 September 2009, damaging or destroying over 7.4 million structures (the highest amount in the world) and killing more than 645 people (the third highest in the world). Furthermore, the typhoon caused 1.03 billion in economic losses (the ninth highest in the world). Even though typhoon Mirinae at the end of October 2009 had similar behaviour to that of Typhoon Ketsana, Mirinae did not have as significant an impact as Ketsana. This phenomenon is another reason why the Ketsana event was chosen as the focus of this study.

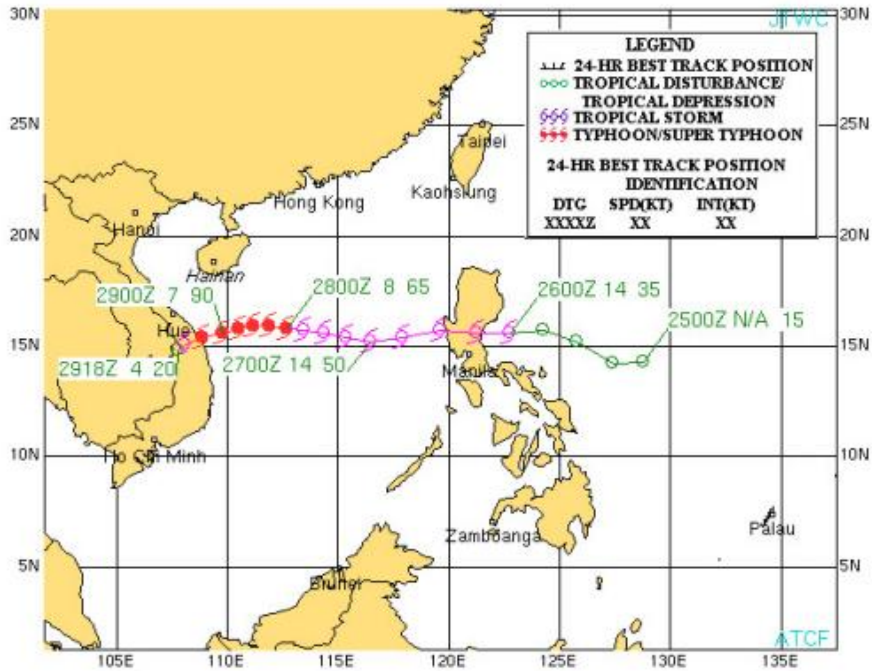

Figure 1.1: The track and stage development of Typhoon Ketsana.*(JWTC)

The World Health Organization Regional Office for the Western Pacific had reported that Ketsana, bearing maximum centre winds of 85 kph and gusty winds up to 120 kph, hit Luzon Island on 26 September 2009. Ketsana left large areas inundated with floods and caused extensive damage to property in the northern regions of the Philippines. Ketsana then continued to travel westerly towards Indochina via the SCS. Ketsana developed to typhoon stage before making landfall in Vietnam on 29 September with maximum centre winds of 118-149 kph. After the area of landfall, the area most affected by floods and gusty wind included Thanh Hoa, Nghe An, Ha Tinh, Quang Tri, Hue, Da Nang, Quang Nam, and Quang Hgai (all provinces of the central coastal regions). Ketsana hit southern Laos on 29 September 2009, bringing heavy rains and strong winds to the provinces of Xekong and Attepeu and causing heavy flooding in the regions. At the same time, Ketsana brought heavy floods and caused severe damage to the infrastructure and agriculture of Cambodia.

TC can have far reaching implications in regions far away from the TC's centres. Therefore, during the Ketsana period Malaysia also reported impacts due to Ketsana's activity. The east Malaysian report indicated that strong winds caused severe damage to hundreds of houses, electric poles and trees, as well as telecommunication towers in west Sabah on the night of 27 September 2009 (MOTIS, 2009b). The report mention that the strong winds of the tail-end effect of Ketsana were felt in west Sabah when the storm was located at 15.8°N and 114.2°E, approximately 1146 km away from the northwest of Kota Kinabalu, with wind speeds of 150 km/hr and a minimum pressure of 960 hPa. The Malaysian Meteorological Department (MMD) also reported that thunderstorms and hail occurred in few regions of the state of Pahang, including Bera and Jerantut, in the evening and night of 28 September 2009 (MOTIS, 2009a). These effects caused severe damage to numerous houses in Pahang.

Typhoon Ketsana was the only case chosen in this study because besides the above statements, this study case can be a reference case for the study of interaction between orography and for all SM typhoons in the future. Therefore, this study intends to focus on the quantitative than qualitative study. Thus multi-parameters will be applied in this study. The information and results from this study may provide general but comprehensive ideas for the scientists who intending to do simulation study.

1.2 Orography overview

Orography refers to the study of the formation and relief of mountains or other elevated terrain (Naik, 2011). The study of orography is essential because it plays a crucial role in determining the climate of various regions in the world and for meteorologists to forecast the local weather. Orography can play a major role in the type, amount, intensity and duration of precipitation events. Researchers have discovered that barrier width, slope steepness and updraft speed are the major contributors to the optimal amount and intensity of orographic precipitation. Computer model simulations for these factors showed that narrow barriers and steeper slopes produced stronger updraft speeds which, in turn, enhanced orographic precipitation.

The orographic effect is the way mountains and other elevated terrain alter the prevailing weather conditions in a particular region. This effect can also refer to an atmospheric disturbance that is caused by, or relating to, the existence of mountains or other high terrain. Two examples are as follows: 1) Orographic lift causes an air mass to rise up into the mountains. Adiabatic cooling develops during the rising process, but the temperature decreases with altitude, eventually resulting in condensation when the relative humidity reaches 100 percent. Triggering, cloud formation (referred to as an orographic cloud) and resulting in precipitation (referred to as orographic precipitation/rainfall). 2) The windward side of a mountain normally experiences heavy rainfall, while the leeward side is dry and warm. The mountain is unlike to have a high rainfall rate (or called as rain shadow) within 25 km of the leeward side because all of the moisture in the clouds is drained out by orographic rainfall (Whiteman, 2000). The drastic difference between the windward and leeward sides of a mountain is the experience of the orographic effect.

Furthermore, the orographic effect may cause mountain waves due to air flow passing over a mountain or mountain range (Woodson, 1969). A large mountain wave is an elusive and dangerous phenomenon that can form in the lee of a mountain with smooth laminar flow as a twisting, writhing, swirling mass of air known simply as the "rotor." The rotor wind is the most dangerous wind of the mountain wave. The structure of the barrier and the strength of the wind determine the amplitude and type of the wave. Turbulence can be expected in varying degrees and is particularly severe in the lower levels; however, the turbulence can extend to the tropopause to a lesser degree.

The tropopause is the layer that separates the troposphere and the stratosphere. The troposphere is the lowest layer of the Earth's atmosphere. The troposphere starts at the Earth's surface and extends to a height of 7 to 20 km above sea level, containing approximately 80% of the total mass of the atmosphere. Almost all weather occurs within this layer. Air temperature decreases from the ground level upward. Air pressure and density are also lower at high altitudes. Nearly all of the water vapour and dust particles in the atmosphere are in the troposphere; therefore, most clouds are found in this layer.

The top of a thunderstorm can reach the tropopause, due to updrafts in the storm and form anvil clouds in which the environmental air is warmer than the cloudy air in the storm, thereby causing the cloudy air to stop rising. The top of a tropical cyclone will also only reach the tropopause. Therefore, this study of tropical cyclones will focus on variations in the weather within the troposphere and the impact of the cyclonic activity on the orography in this layer. The bottom of the troposphere, which is close to the surface of the Earth, is referred to as the "Planetary Boundary Layer". Areas of the Earth's surface with complex or uneven topography (mountains, forests) cause erratic, jumbled behaviour in the winds in this boundary layer. In smoother areas (over water or ice), the winds are smoother. The winds above this boundary layer experience few effects from the surface.

Wind decreases in velocity near the surface due to surface roughness; therefore wind velocity profiles are quite different for different terrain types (Brown and DeKay, 2001). In the continental region, rough, irregular ground, and man-made obstructions cause a slowing of the air near the surface and a reduction of wind velocity (Oke, 1988; Crawley and Dillon, 1993). Over a city or over rough terrain, the wind gradient effect could cause a reduction of 40% to 50% of the geostrophic wind speed; conversely, over open water or ice, the reduction may be only 20% to 30% (Thompson, 1998; Harrison and Chemistry, 1999).

Complex topographies, especially mountains, can have a significant influence on the air that flows over and around them. The various weather conditions we experience, on average, in only the lowest ten kilometres deep of the troposphere. For example, a hill with 500 m elevation (about five percent of the troposphere) will still exert quite an influence on the air around and above it (Inness, 2008). If the mountains are high enough, they effectively dam to the air in the troposphere and lead to completely different weather conditions on either side of the range. Thus, this study is more interested in the orographic effects when interacting with a tropical cyclone on the entire tropospheric column in the study area.

1.3 Introduction of remote sensing

Remote sensing is a technique that is used to acquire information about an object, target or phenomenon without making physical contact with the object. In modern usage, the term generally refers to the use of aerial sensor technologies to detect and classify objects on Earth (on the surface and in the atmosphere or oceans) by means of propagated signals (e.g., electromagnetic radiation emitted from aircraft, satellites or radiosondes). Electromagnetic energy includes light, heat and radio waves. The goal of remote sensing is to understand the relationships between these measurements and the nature and distribution of events within the atmosphere or on the Earth's surface (Mather and Koch 2004). This approach was used for Earth observation in this study, especially the typhoon development process, the weather conditions during the typhoon development period and the topographic structure of the Earth.

The common remote sensing tool use in such study is satellite data, as satellites provide valuable cloud photographs of areas where there are no ground-based observations. Before weather satellites were used, severe storms such as typhoons and hurricanes often went undetected until they moved dangerously near inhabited areas. Today, satellites spot these storms while they are still far out in the ocean and track them accurately. There are two primary types of weather satellites in use for cloud observation: geostationary or geosynchronous satellites and polar-orbiting satellites.

Geostationary satellites orbit the equator at the same rate (or angular speed) as the Earth spins, remaining nearly 36000 km above a fixed spot on the Earth's surface. This positioning allows continuous monitoring of a specific region. These satellites also represent a real-time system because they can transmit the photographs to the receiving system on the ground as soon as the camera takes the picture. Continuous cloud photographs can be displayed by a time-lapse movie sequence to show the cloud movement, dissipation, or development associated with weather fronts and storms. Wind directions and speeds at various levels can also be determined by monitoring the sequence cloud movement.

Polar-orbiting satellites are closely parallel to the Earth's meridian lines. These satellites pass over the north and south polar regions during each revolution, at an altitude of approximately 850 km. As the Earth rotates to the east beneath the satellite, each pass monitors an area to the west of the previous pass. Eventually, the satellite covers the entire Earth. These satellites provide better resolution and more detailed photographic information about objects or targets, such as violent storms and cloud systems, than geostationary satellites.

The radiosonde is another remote sensing tool used in this study. With the radiosonde technique, a weather balloon is released from the ground surface to the upper troposphere to measure various atmospheric parameters along the troposphere and transmit them to a fixed receiver by a radio wave frequency. The radiosonde provides a two-dimensional vertical profile of temperature, dew point, and winds that cover a relatively small area, such as mesoscale regions. Computer programs then automatically calculate data from the sounding number to meteorological indexes, which can aid the forecaster in determining the likelihood of small-scale weather phenomena, such as thunderstorms, tornados, and wind shear.

1.4 Problem statement

Malaysia is located in the most active cyclogenesis basin (the Western Pacific, including the NWP Ocean and the SCS). The tail effects of typhoon occasionally affect regions in Malaysia, especially with heavy rainfall and strong winds. Studies have been performed on the impacts of typhoons in Malaysia as follows: 1) The impact of a TC at different locations on rainfall in Malaysia was studied using 57 years of data (Regional Specialized Meteorological Centre (RSMC) – Tokyo and rainfall data from the same period from selected principal meteorological stations in Malaysia) from 1951 to 2007, using probability computation of the statistics (Ariffin and Moten, 2009); 2) the impact of a TC at different locations on the rainfall in PM was studied using 27 years of data (Joint Typhoon Warning Centre (JTWC) and daily rainfall data from the same period from selected principal meteorological station in Malaysia) from 1981 to 2007 using probability computation of the statistics (Ariffin and Moten, 2010); 3) an MTSAT – 1R geostationary satellite was used to identify rain cloud clusters and rainfall chart data from meteorological stations in Malaysia to identify TCs that have affected/impacted Malaysian weather (MOTIS, 2009c); 4) rainfall distribution patterns due to the tail-end effects of typhoons was studied using an FY-2C geostationary satellite and weather radar echoes (MOTIS, 2009a); 5) wind strength was determined using wind speed charts from a few selected meteorological stations in EM (MOTIS, 2009b).

In brief, previous studies and reports on the tail-end effects of typhoons on Malaysia have not considered the orographic effects that may affect the impacts of rainfall and wind patterns distributed throughout Malaysia. However, many studies of orographic effects on typhoons have indicated that complex mountain structures play a crucial role in rainfall and wind flow patterns. Therefore, it is necessary take orographic effects into consideration. Understanding the characteristics of the mountains in Malaysia is essential to improving the forecasting of flash floods and strong winds, which are natural disasters that constantly influence the life activities of Malaysians. Such sources as FY-2D, ASTER GDEM, radiosonde, and Navy Operational Global Atmospheric Prediction System (NOGAPS) will be applied and used to determine the relationship of the tail-end effects of the typhoon on the orographic effects in Malaysia. Additionally, this study considers the way Malaysians face these impacts and which parts of the country are most affected when the tail end of a typhoon travels to Malaysia.

1.5 Scope of study

This study examines the interaction between typhoon activity and orographic effects over countries in SEA but only focus on Indochina and Malaysia (Peninsular Malaysia and East Malaysia), with a specific focus on Typhoon Ketsana in 2009. Only remote sensing techniques are used, such as FY-2D (for rainfall, cloud, and wind data), ASTER GDEM (elevation data), Radiosonde (upper-air data), and NOGAPS (wind information), to implement the study objectives because a typhoon is a synoptic system that is generated over the ocean. If information cannot be obtained from the ocean itself, remote sensing techniques are essential for typhoon study.

1.6 Objectives of the study

i) To study the direct impacts of Typhoon Ketsana on orographic effects in Indochina and identify which parts of Indochina was most affected.

ii) To study the impact of tail-end effect of Typhoon Ketsana on the orographic effects in Malaysia and identify which parts of Malaysia was most affected.

iii) To examine the differences between the effects of the direct (landfall) and indirect (tail-end effects) impacts of Typhoon Ketsana on orographic effects and identify the trends of their impacts in the synoptic scale.

1.7 Novelty of this study

Studying the tail-end effect or indirect impact of the typhoon on orographic effects is new to Malaysia. A comparison of the direct and indirect impacts of typhoons on orographic effects is implemented in Indochina and Malaysia. Furthermore, this study uses various sources, such as ASTER GDEM, FY-2D geostationary satellite products, NOGAPS, and radiosonde data to determine the effects of orography on wind, cloud, and rainfall patterns during the typhoon period in synoptic scale. These sources of data have infrequently been applied to Malaysia, and the integration of these four types of data to study the orographic effects on the tail-end effects of typhoons has not been performed by other researchers.

1.8 Outline of the thesis

This dissertation consists of six chapters, which are described in brief as follows:

Chapter 1 provides an overview of this study. Additionally, this chapter presents a brief background of TCs and the typhoon case study. A brief definition is provided for orographic effects and troposphere characteristics. A statement of the problem, scope of study, originality, and objectives of this study are also presented.

Chapter 2 provides an overview of the literature and of related work on the activity of TCs on orographic effects, including explanations of how these studies are related to this study. Potential data sources for TC variations on orographic effects are mentioned in this chapter. For example, geostationary and orbiting satellite and radiosonde data have been used to study similar cases or to facilitate specific study purposes that may be related to orographic studies.

Chapter 3 describes the study area and methodology in detail. This chapter presents the tools used in this study and their application, as well as the data sources and their features. This chapter discusses the research procedures and all techniques and methods applied for data processing.

Chapter 4 includes the analysis of all the obtained results and consists of four sources including Fengyun-2D (wind flow, rainfall and cloud classification), ASTER GDEM (topography elevation), radiosonde (weather conditions), and NOGAPS (wind flow) for three different study areas respectively. In the Typhoon Ketsana period, four of these sources of data are evaluated and their relationship on orographic effects was discussed.

Chapter 5 provides comparisons of the three different study areas. This chapter first discusses the weather conditions based on the radiosonde data and subsequently describes the results of the effects of orography on wind, cloud, and rainfall patterns during Typhoon Ketsana (2009) obtained from the Fengyun-2D satellite products and the NOGAPS products. Finally, conclusions and suggestions for future research are presented in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapter discusses studies about orographic effects on tropical cyclones by other scientists, including some of their study methods and results and how their studies relate to this study.

2.1 Study cases for tropical cyclones affected by orography

The Earth's complex mesoscale mountain ranges have led to many difficulties in weather prediction. A basic understanding of these effects can be helpful for investigating and precisely evaluating the synoptic and mesoscale weather variation. Thus, to understand the studies of orographic effects on TC system variation (in terms of clouds, rainfall, and airflow), it is necessary to understand the mechanisms of orographic rainfall. Orographic rainfall is a central part of the interaction between the land surface and the atmosphere, and it provides vital water resources for humans and is important for natural ecosystems. Nevertheless, orographic rainfall can have disadvantages in the form of natural hazards such as flash floods and landslides triggered by heavy rainfall on shorter timescales in mountainous regions (Fernando, et al., 1979; Caine, 1980).

Several researchers have conducted extensive studies on the mechanisms of orographic rainfall (Smith, 1979; Houze, 1993). They have widely and clearly stated that orographic rainfall must be linked with airflow and cloud dynamics in the atmosphere and with the topography on the ground surface. Smith (1979) studied the influence of mountains on the atmosphere, and he suggested the following: 1) wind tends to move around rather than over mountains; 2) air that has climbed the mountain runs down the leeward side, causing severe downslope winds; and 3) heavy orographic rainfall occurs on windward slopes. Orographic rain may be generated by closely spaced convection triggered by orographic lifting. The majority of precipitation tends to increase with height. The spatial variation of rainfall can be explained by the influence of topography (Wilson and Atwater, 1972). Basically, precipitation was greater on the hills, but with the maximum shifted toward the upwind slopes.

Several typhoons cases have been discussed by Li (1963), he stated that surface pressure varied with the mountain range when a typhoon passed through. At 0900 UTC 22 July 1962, Typhoon Kate was located at the southern tip of Taiwan, while the northern part experienced easterly winds and the pressure differed across different regions of the mountains (Li, 1963). The typhoon then moved towards the north and shifted to the northwest region of the island at 2200 UTC 22 July. At 0600 UTC 23 July, the entire island was exposed to westerly winds. A distinct pressure difference was found both times. Li (1963) believed that the westerly wind on the island had been slowed by the orographically induced high pressure and decreased Coriolis force, which allowed the wind to accelerate in or towards the centre of the lower part of the mountain.

In addition to the studies by Li (1963) in Taiwan, many other examples of orographic pressure disturbances exist in daily sea level charts constructed and archived by various national weather services. There are a few significant study cases in specific regions that are consistent with orographic disturbances to pressure, especially at Mt. Pico Duarte (3087 m), Hispaniola; Mt. Maromokotro (2876 m), Madagascar; Galdhøpiggen (2469 m), Norway; the Snowy Mountains of Australia

(2228 m); Mt. Pico Turquino (2005 m), Cuba; and Mt. Cerro de Punta (1328 m), Puerto Rico. Bender (1987) studied the relationship of topography and typhoon features in regions such as the Taiwan area, a few regions in the Caribbean (including the islands of Cuba, Hispaniola and Puerto Rico), and in the northern Philippine island of Luzon (Bender, et al., 1984). According to Bender's observations, storm features such as track deviation and decay are affected by mountainous areas. After making landfall, surface pressure can decrease rapidly, and an upper level vortex might detach from the original low surface pressure of the storm and eventually couple with a secondary vortex due to the high mountain ranges. In addition, tropical cyclones are weakened when dry air is advected from the mountain region into the storm area, and this situation may be enhanced when the vertical axis of the storm system is forced to tilt at the same time. To investigate storm positions, surface, upper air or satellite observations are necessary because they can define the warm core of the storm system or areas of intense precipitation, upper and lower circulation centres, and surface pressure centres displaced from one another.

Furthermore, Taiwan extended its studies of topographic or orographic effects to tropical cyclones cases. These studies all found a close relationship between mountain terrains and tropical cyclone activities in terms of pressure, wind, track path and precipitation. For examples, previous studies (Brand, et al., 1974; Chang and Madala, 1982; Bender, et al., 1984; Bender, et al., 1987; Yeh and Elsberry, 1993a; Yeh and Elsberry 1993b) have shown significant changes in intensity, structure and tracking when typhoons are close to an island or a continental region. The terrain-typhoon interaction causes the track of the typhoon to deflect and sometimes become discontinuous; at the same time, the magnitude of the wind is reduced when the typhoon approaches any related mountain range due to the friction effect and the restriction of wind movement. Landfall location may also be affected by the complexity of mountain ranges. The above studies and experiments proved that the orographic effect must be considered if a tropical cyclone is approaching a continental region because the complexity of the orographic effect may influence the activity of the cyclone.

Recently, the single Doppler radar technique was used to study the structure and evolution of the intense tropical cyclone Dina on 22 January 2002 (Frank, et al., 2004). By using ground-based Doppler radar, Frank found that location changes and the intensity of the maximum winds, as well as a veering of Dina's track path, were caused by high mountain ranges impacting the cyclonic winds. Additionally, wind profiler radar has been used to study typhoon-orography interactions in Taiwan. Although this method has limitations regarding its coverage of large regions, it is still successful in identifying the significant relationship between complex mountain ranges and wind structure and precipitation (Pan, et al., 2008). Pan examined this issue and discovered that wind deflection is due to a blocking effect by the topography of the continental region at lower altitudes (Pan, et al., 2010).Different tropical cyclones have different characteristics in term of wind structure, so when they encounter these barriers on different islands, the airflow of the tropical cyclone will shift from its original path and may change direction based on the terrain's structure.

Typhoon-orography interaction studies have been conducted by many researchers in terms of pressure, intensity and track variation. The geophysical fluid dynamics laboratory (GFDL) hurricane prediction system has been used to evaluate the relationship of topography with typhoon activity (Wu, 2001). By his simulation model of Typhoon Gladys (1994) on Taiwan's terrain, Wu found that the translation speed of Gladys was decelerated and deviated southward as it approached Taiwan and that it accelerated northwestward while passing Taiwan. This phenomenon indicates that the characteristics of typhoons are different over open sea and continental regions. The Central Mountain Range (CMR) in Taiwan also plays an important role in the varied behaviour of typhoons. The evolution of the low pressure centre and vorticity of the storm is more complex over the CMR than over the ocean. In addition, different typhoons with different initial vortex strengths can result in different track patterns, leading to completely different typhoon-orography interactions.

After analysing the dataset of National Center for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) from December to March for the years 1996 to 2005, Smith found that orography plays a key role in rainfall distribution patterns (Smith II, et al., 2006) and that the track of cyclones directly affected the patterns of precipitation distribution over the Sierra Nevada mountain range in California. Smith's result is similar to that of Wu (2001), even if study area was different. The topography-typhoon relationship has been studied using a modified moist ageostrophic Q vector and data from a Weather Research and Forecasting (WRF) model simulation (Yue, 2009). Other studies determined that topographic lifting affected the formation of rainfall during typhoon Haitang (2005), whereas the rainfall amounts were forced by the topographic friction effect (Yue, 2009). In brief, typhoon rainfall may be modified and enhanced by topographic effects.

In addition, to understand the dynamics of orographic rainfall associated with Supertyphoon Bilis (2000) over the CMR of Taiwan, a simulation by Penn State/NCAR Mesoscale Model Version 5 (MM5) was used (Witcraft, et al., 2005). Air was forced up the CMR as the typhoon came close to the coastal regions of Taiwan, and heavy rainfall was inevitable. However, the results of moisture flux (wq) showed that a large portion of the rainfall over mountain regions was caused by orographically-induced vertical motions and convergence. In the Bilis period, the model sounding was quite moist and conditionally unstable, but there was in fact a deep layer. After comparing the sounding results of the eastern and western sides of the CMR, the air flow was found to be modified by the CMR at the western side.

Chen (2007) studied the features and mechanisms of sea surface wind fields around Taiwan Island during typhoon periods by QuikSCAT remote sensing data from 1999 to 2005 (Chen, et al., 2007). They stated that terrain can affect wind field formation and cause interesting phenomena, such as strong wind (> 10 m/s) appearing earlier in Taiwan Strait, leeward trough formation and “corner flow” to the flanks and downstream of the tips of the CMR, respectively. However, they emphasised that the location and scope of the “corner flow” and leeward trough will always change along the different typhoon tracks.

Mountains play an important role in bringing heavy rainfall by blocking and convecting warm, moist air to the tops of the mountains (Tanaka, et al., 2008). In the worst case, the orographic effect will cause flooding over the region in the low plain area due to the longer period of rainfall. Cheung (2008) also suggested that the orographic effect is one of the important factors causing variation in rainfall intensity and the distribution of rainfall patterns (Cheung, et al., 2008). The rainfall distribution patterns of the approaching tropical cyclone will be modified by the mountain range to a certain degree. The above studies were related to the case of the landfall of the tropical cyclone or very near the continental region.

Recently, scientists in different countries have studied the rainfall accumulation and distribution patterns of tropical cyclones when associated with orographic effects. The high mountain range not only causes the track to deflect from its origin path but will also change the typhoon intensity, structure and rainfall patterns (Huang and Wu, 2011). Although Colón-Pagán (2009) studied the orographic effects on rainfall induced by the passage of tropical cyclones over mountainous islands (with a focus on landfall but not the tail effects), he found that the rainfall is at a maximum in the higher mountain regions (Colón-Pagán, 2009).

2.2 Potential data and techniques which suitable for the study of the effect of tropical cyclone on orography.

2.2.1 Skew-T

McCaul (1991) found certain characteristics of soundings associated with supercell storms in tropical cyclones, such as relatively shallow buoyancy and very strong low-level shear. By using radiosonde data, a Skew-T diagram can indicate the level of instability in the atmosphere and can assess the potential for outbreaks of severe weather (McCaul, 1991). McCaul's (1991) study was continued by (Davies, 2006a; Davies, 2006b), who indicated that low-level thermodynamic parameters, such as the lifting condensation level (LCL) and the level of free convection (LFC), are crucial in TC events because the heights of LCL and LFC are generally quite low during TC periods, which means these parameters reflect the very moist and humid low-level conditions present in TCs. Meanwhile, the level of cloud formation and the thickness of the clouds can also be estimated from this diagram. The wind variation with altitude can be viewed by the vertical profile of the atmosphere. By using the multi-parameters of the sounding data, the development of storms can be predicted by investigating the unstable environment (Suzuki, et al., 1999).

In mesoscale analysis, Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) play important roles in severe weather outbreaks. CAPE is used to estimate the potential overall instability in the troposphere, whereas CIN acts in opposition to CAPE (Naetaert, 2010). CIN is the amount of energy needed to initiate convection. Thus, Naetaert (2010) used these features to illustrate mesoscale weather conditions. This sounding information shows the atmospheric condition as storms were approaching. He also used hodographs to predict the storm motion because strong winds at various levels of the atmosphere may represent the overall development of severe weather. He indicated that this technique shows that a storm's motion coincides with the actual motion of storms during the day. The above variables of sounding data were applied in the case of a tornado outbreak in the southeastern United States moving into the Ohio Valley on April 7, 2006; a severe weather outbreak at the eastern portion of the southern plains into the lower Mississippi Valley on March 10, 2010; and severe weather potential in the northern plains (northern Wyoming, north central Nebraska, and western central South Dakota) on June 17, 2007.

In 2011, Chang and Lin (2011) used a Skew-T diagram to illustrate the atmospheric conditions during typhoon Krosa (2007). They interpreted the sounding data at 0000 UTC 6 October 2007 at Hualien and Green Island. At Hualien, they found the following: 1) significant subsidence warming and drying between the near surface layer and at 3000 m; and 2) the wind directions were northerly with speeds of 15-20 m/s at the layer between the inversion top (800 m) and 300 m, and southwesterly with speeds of 5-10 m/s below the inversion layer (Chang and Lin, 2011). The Green Island sounding station also showed similar characteristics of subsidence warming and drying, but with moister conditions. Both sounding stations recorded a maximum $T - T_d$ (environment temperature – dew point temperature) of approximately 10°C near the inversion top (800 m for Hualien and 600 m for Green Island), indicating an extension of the warming and drying throughout the eastern coast and offshore area.

2.2.2 Hodograph

Hodographs have been discussed by Doswell (1991) for the forecasting of severe thunderstorms. He explained that hodographs are helpful in monitoring and predicting severe weather. Not only can hodographs help us forecast thunderstorms quickly, but this technique can also identify potential supercell thunderstorms. He emphasised that the wind information plotted in hodographs is more useful than that of the Skew-T diagram because hodographs can easily visualise the effect of changing wind speeds (length of the vector along the angle) and direction (angle of the vector) with height, especially atmospheric convection (Doswell, 1991). In his review, he point out that a clockwise rotation (rightward moving wind) of a hodograph favours the cyclonic, while a counterclockwise rotation (leftward moving wind) favours the anticyclonic (both of these cyclones occur in the Northern Hemisphere).

On 25 February 2004, the most intense rainfall since 1979 occurred in San Francisco County. The rain gauge recorded 1.56 inches in 30 minutes and 1.90 inches