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APPLICATION OF GLOBAL POSITIONING SYSTEM (GPS) DATA FOR ATMOSPHERIC WATER VAPOUR VARIATION IN THAILAND

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วัตถุประสงค์ของการทำวิจัยคือหาการเปลี่ยนแปลงปริมาณไอน้ำในบรรยากาศ สำหรับกำหนดช่วงฤดูมรสุมตะวันตกเฉียงใต้ของประเทศไทย โดยการประยุกต์ใช้ข้อมูลที่ได้จากจีพีเอส พร้อมทั้งใช้ข้อมูลดังกล่าวสมทบกับข้อมูลทางอุตุนิยมวิทยาที่มีอยู่เดิม ในการพิจารณาลักษณะการเคลื่อนที่ของความกดอากาศสูงทางตอนบนของประเทศไทย และการเคลื่อนที่ของไอน้ำตามแนวลมพัดสอบจากอ่าวไทยที่เข้าสู่แผ่นดิน

การใช้งานจีพีเอสในทางอุตุนิยมวิทยา เป็นการประยุกต์ใช้ข้อมูลจีพีเอสแนวใหม่ โดยอาศัยการปรับเปลี่ยน ค่าปรับแก้ค่าคลาดเคลื่อน ของสัญญาณจีพีเอส เนื่องจากปริมาณไอน้ำในชั้นบรรยากาศให้อยู่ในรูปค่าคลาดเคลื่อนแนวดิ่งจากบรรยากาศชื้น (Zenith Wet Delay, ZWD) แล้วนำค่าดังกล่าว มาเปลี่ยนกลับไปเป็นค่าไอน้ำในบรรยากาศรวมเหนือเครื่องจีพีเอส (Integrated Water Vapour, IWV) โดยเลือกใช้ Bernese GPS Software version 4.2 (B-GPS_IWV) เป็นโปรแกรมประมวลผลหลัก ความถูกต้องของการประมวลผลดูได้จากค่าความต่างของผลของการประมวลผลจาก Bernese (B-GPS_IWV) กับผลจากเครื่องมาตรฐาน Water vapour Microwave Radiometer (WMR_IWV) ซึ่งมีค่าประมาณ 1.34 มม และสัมประสิทธิ์สหสัมพัทธ์ซึ่งมีค่า 0.81 สำหรับการนำ B-GPS_IWV มาหาช่วงฤดูมรสุมตะวันตกเฉียงใต้ โดยดูจากค่า B-GPS_IWV ร่วมกับข้อมูลการเปลี่ยนทิศทางของลมและฝนที่ตก พบว่าช่วงเข้าและออกฤดูมรสุมกำหนดได้ด้วยการเปลี่ยนแปลงขึ้นและลงตามลำดับของระดับ B-GPS_IWV ที่สอดคล้องกับช่วงที่ลมมีการเปลี่ยนทิศ จำนวนและความถี่ของฝนที่ตก ส่วนการแผ่กระจายของความกดอากาศสูงกำลังแรงที่พิจารณาจาก B-GPS_IWV พบว่ามีแบบแผนของการลดลงของB-GPS_IWV ก่อนที่ความกดอากาศสูงจะเข้ามาประมาณ 3-5วัน นอกจากนี้ยังพบว่า การกระตุกของข้อมูล B-GPS_IWV ในวันที่มีลมสอบ สามารถอธิบายได้ว่ามีการนำพาความชื้นด้วยลมสอบเข้าสู่แผ่นดิน

ภาควิชา	ธรณีวิทยา	ลายมือชื่อนิสิต....................................
สาขาวิชา	โลกศาสตร์	ลายมือชื่ออาจารย์ที่ปรึกษา....................................
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NITHIWATTHN CHOOSAKUL : APPLICATION OF GLOBAL POSITIONING SYSTEM (GPS) DATA FOR ATMOSPHERIC WATER VAPOUR VARIATION IN THAILAND. THESIS ADVISOR : ASST. PROF. CHALERMCHON SATIRAPOD, Ph.D., THESIS COADVISOR : MISS. BOOSSARASIRI THANA, M.Sc., 62 pp. ISBN 974-53-1707-1.

The purpose of this research is to identify the period of southwest monsoon season in Thailand by using IWV value obtained from GPS together with other meteorological data. In addition, the obtained IWV value are used to study the effect of high pressure area and the transfer of confluence wind in the winter and summer season.

A new application of GPS in Thailand is the GPS-Meteorology. GPS signal propagation delayed by atmospheric water vapour is conversed into the term of zenith wet delay (ZWD), the retrieved ZWD can be transformed to the integrated water vapour (IWV) over that GPS receiver by using Bernese GPS software version 4.2 (B-GPS_IWV). The accuracy of B-GPS_IWV can be measured by the difference between B-GPS_IWV value and the IWV obtained from the Water vapour Microwave Radiometer (MWR_IWV).The result shows that the difference is 1.34 mm and its correlation coefficient is 0.81. The southwest monsoon period can be identified by the relationship of B-GPS_IWV, wind direction change, and rainfall where the onset and withdrawal are represented by the increase and decrease of B-GPS_IWV, respectively. In addition, the passage of high pressure area can be explained by decreasing of B-GPS_IWV in 3-5 days before the high pressure area move down. Moreover, it is found that the occurrent spike of B-GPS_IWV in the day of the dominative confluence wind can be used to explain the transfer of moist air into the land.

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Field of study	Earth Sciences	Advisor's ...Chalermchon Satirapod...
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LIST OF ABBREVIATIONS

C/A-code	: Coarse/Acquisition-code
CSOC	: Consolidation Space Operation Center
DoD	: Department of Defense
DOY	: Day Of Year
ECMWF OA	: European Centre for Medium – Range Weather Forecasts' Operational Analyses
GPS	: Global Positioning System
HOWI	: Hydrologic Onset and Withdrawal Index
IGS	: International GPS Services
IWV	: Integrated Water Vapour
OCS	: Operational Control System
P-code	: Precision-code
PRN	: PseudoRandom Noise
RINEX	: Receiver INdependent EXchange
RH	: Relative Humidity
RAOBs	: Radiosonds
TMD	: Thai Meteorological Department
VIMT	: Vertically Integrated Moisture Transport
WMR	: Water vapour Microwave Radiometer
ZHD	: Zenith Hydrostatic Delay
ZTD	: Zenith Total Delay
ZWD	: Zenith Wet Delay

CHAPTER I
INTRODUCTION

1.1 Statement of Problem

GPS: the Global Positioning System is the navigation system developed by the U. S. Department of Defense (DoD). Whilst this system is fully used by U.S. military, civilian users widely used this system with some limitations of some signals.

The using of GPS by civilian users can be applied for many areas. For example, GPS can be used for the survey, navigation and recreation etc.

The GPS can be applied for meteorology as one of the applications of GPS. The GPS signals, which propagate from GPS satellites to the receivers, are delayed by atmospheric water vapour. Then the signal delay can be observed and retrieved into the term of Integrated Water Vapour (IWV) value above the position of receiver. Consequently, the variation of water vapour can be represented by the IWV obtained from GPS (hereafter referred to as GPS_IWV).

Presently, many countries use the IWV value for meteorological activities such as modeling, monitoring, and weather forecasting. The Ground-based water vapour microwave radiometer [1] and the Ground-based radar [2] are another main instrument that can be estimated the IWV value. However, in Thailand, users are limited by the high cost. Therefore, the increasing of IWV users, GPS application is the best choice for IWV value because GPS instrument is less expensive than the IWV value. Moreover, in case of the usefulness, the GPS permanent stations that install and use for meteorological purpose are also utilized for the position monitoring of crustal deformation studies [3].

However, there are the doubtful points about the use of GPS_IWV concerning whether the one can use and develop for Thai meteorology or not, and what kinds of the activities that the GPS_IWV can be applied. All of these become the main problems of this research.

In order to prove the hypothesis stated that GPS_IWV can be used for the application of meteorology in Thailand, three case studies are introduced to study the possible and simple ways of the use of IWV obtained from GPS. First, the experiment of the use of GPS_IWV for identifying the period of southwest monsoon in the rainy season is considered. This section referred to [4] that the first study of the southwest monsoon in Thailand by using GPS_IWV. The re-analyzing with another element and

GPS software is chosen. Second, the experiment of GPS_IWV for investigating the passage of high pressure area in the winter season is considered. This section referred to **[5]** that the GPS_IWV is increased during the passage of a typhoon, the opposite result with the passage of high pressure area should be displayed. Finally, the experiment of the GPS_IWV for studying the effect of confluence wind in the summer season is investigated. The last section referred to **[6]** that explains the phenomenon of water vapour under the condition of confluence wind, thus the GPS_IWV could make the clear explanation for that phenomenon.

1.2 Objectives

This research aims to identify the period of southwest monsoon season in Thailand by using IWV value obtained from GPS together with other meteorological data. In addition, the obtained IWV value are used to study the effect of high pressure area and the transfer of confluence wind in the winter and summer season.

1.3 Scope of the Investigation

The scope of this research comprises of 5 steps below

1. Literature reviews of related the research topic.
2. Gather the GPS data and meteorological data between year 2001 and 2003 from **CHMI** (Longitude 98.973°N, Latitude 18.771°E Chiang Mai), **BNKK** (Longitude 100.607°N Latitude 13.668°E Bangkok), **PHKT** (Longitude 98.308°N Latitude 8.105°E Phuket), and **SISM** (Longitude 99.862°N, Latitude 17.161°E Sukhothai). All stations are located in Thailand. Another one is microwave radiometer data of the year 2001 from SISM station that also use in this study.
3. Process the GPS data with the Bernese GPS Software version 4.2 and convert data to the GPS_IWV values.
4. Determine the accuracy of the obtained GPS_IWV values.
5. Apply the obtained GPS_IWV values in meteorology.

CHAPTER II

THEORY AND LITERATURE REVIEW

2.1 Meteorological Theory

Meteorological theory can be used to explain the characteristic of atmosphere. Troposphere is the atmospheric layer that has the water vapour. Therefore, the atmospheric processes due to water vapour only occurs in this layer such as rain, snow, fog, cloud formation, Thunderstorms, etc[7].

The meteorological theory that related to the water vapour in the troposphere is described following subsection below.

2.1.1. Temperature at the Tropospheric Layer

Davis et al. **[8]**, reported that the weighted mean temperature (T_m) of the troposphere (unit K) as shown in equation (1)

$$T_m = \frac{\int(\frac{P_v}{T})dz}{\int(\frac{P_v}{T^2})dz}, \qquad \text{.......................... (1)}$$

where is the pressure of water vapour, P_v, [hPa], and T is the temperature of the atmosphere, [K].

With radiosonde sounding, T is directly observed and can be retrieved the T_m values along the path of the sounding which is called as tropospheric temperature profile. Bevis et al. **[9]** suggested that T_m can be approximated by the surface temperature T_s and Liou and Yang **[10]** described the T_m - T_s relationship determined by minimizing the Chi-square error statistic as

$$T_m = aT_s + C, \qquad \text{.......................... (2)}$$

where a is the regression coefficients and C is the constant value.

The accuracy of a and C values depend on the retrieval of T_m and T_s. Tm obtains from the more than ten years data observed by the sounding, and also T_s. Ross and Rosenfeld **[11]** suggested in the study of an accuracy of T_m - T_s relationship method that the T_m values are the site – specific values. They are dependent on the location of station.

2.1.2. The vertical atmospheric pressure

The static fluid pressure is dependent only upon density and depth. Choosing a liquid of standard density like mercury or water allows expressing the pressure in units of height or depth, e.g., mmHg. The mercury barometer is the standard instrument for atmospheric pressure measurement in weather reporting. The decreasing in atmospheric pressure with height can be predicted from the barometric formula (see figure 2.1) **[12,13]**.

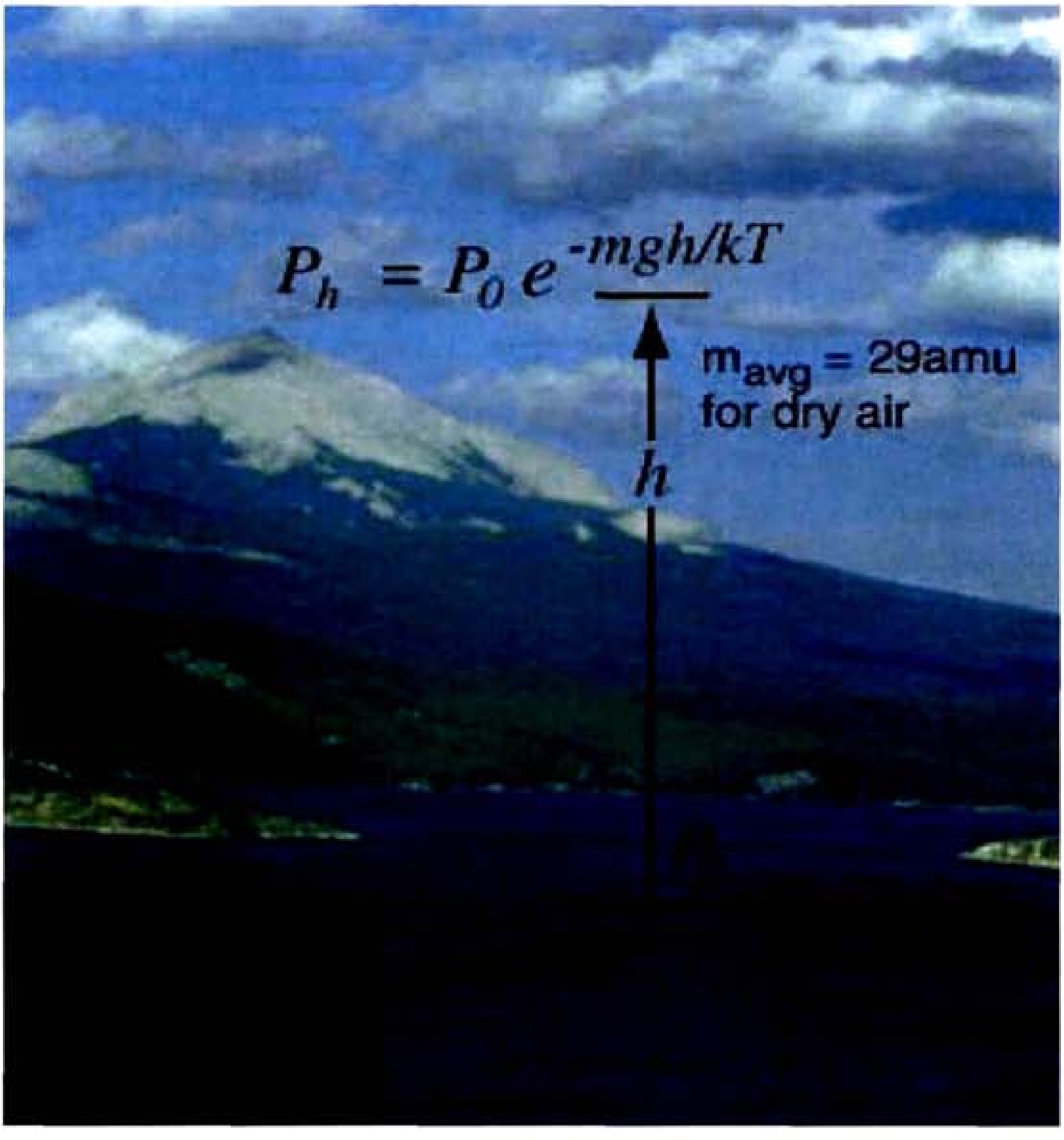

Figure 2.1 The Barometric Formula **[13]**

Figure 2.2 shows that the Barometric Formula, yields as equation (3)

$$P_h = P_0 e^{\frac{-mgh}{kT}} , \qquad \text{......................... (3)}$$

where P_h (unit hPa) is the atmospheric pressure with height h, P_0 (unit hPa) is the atmospheric pressure at mean sea level, m is the mass of molecule and equals to 29 atomic mass unit (amu), g (unit ms^{-2}) is the gravitational acceleration, k is the Boltzmann's constant, and T (unit K) is the mean temperature.

2.1.3. Dry air, Moist air, and Air Masses

Atmosphere consists of two basic components, dry air and moist air [2]. Dry air exists when all the contaminants and water vapour are removed from atmospheric air. By volume, dry air contains about 78 percent nitrogen, 21 percent oxygen, and 1 percent other gases. Moist air is a mixture of dry air and water vapour [14]. The measurement of water vapour in the air is called the mixing ratio. This is due to the fact that it specifies how much water vapour is mixed with the other atmospheric gases. Vapour pressure and mixing ratio are two of more common ways of specifying the water vapour concentration of the air [15].

Air mass is a large body that has similar temperature and moisture properties throughout. The best source regions for air masses are large flat areas where air can be stagnant long enough to be able to take in the characteristics of the surface below. The influence that air masses have on the temperature of a place depends on the location with respect to the source of the air mass and the trajectory of the air mass as it moves from its source region [15].

2.1.4. Wind and Circulation

Wind is defined as the horizontal movement of air relative to the earth surface. Air above hot areas expands and rises. Air from cooler areas then flows into replace the heated air. This process is called circulation. There are three types of wind circulation. Circulation over the entire earth is the general circulation. Smaller-scale circulations that cause day-to-day wind changes are known as synoptic-scale circulations. Winds that occur only in one place are called local winds **[14]**.

For the near-surface wind, the wind speed must be reduced with friction such as mountain, building, tree, etc. Therefore, the air mass movement is also reduced. On the other hand, in the upper atmosphere such as the height at 850 hPa (around 1.5 km above sea level), the air flow from the source area to another place without the frictional influence.**[15]**

The wind and circulation are related to the atmospheric pressure. The movement of air mass is introduced by the difference of the atmospheric pressure. Therefore, the wind is occurred by the flowing of air mass. In general, where air is found to descend, high pressure develops, for example at the subtropical latitudes and again near the poles. Where air is rising, atmospheric pressure is low, as at the equator and in the mid-latitudes where storms or frontal systems develop **[15]**.

2.1.5. Convergence, Divergence and High Pressure Area

In addition to air pressure changes caused by variations of temperature and water vapour content, air pressure can also be influenced by circulation patterns that cause divergence or convergence.

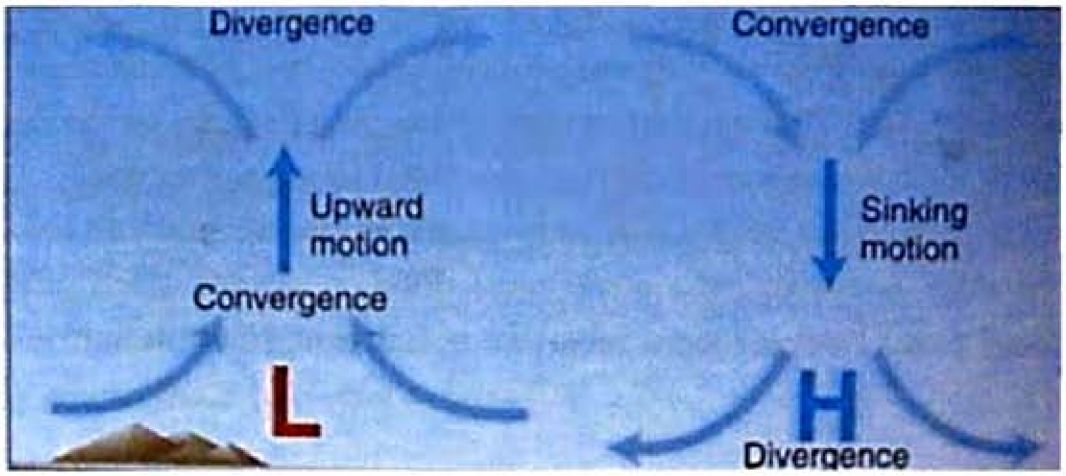

Figure 2.2 A view of air motions in high and low pressure systems **[14]**.

Figure 2.2 shows that if air is converging above and diverging below, it must be sinking. The circulation is in virtually all high pressure cells. If convergence aloft exactly balances divergence below, then the surface air pressure will not change.

However, if the convergence exceeds the divergence, then air is entering the column faster than it is being removed. The surface air pressure must increase as a result, and the high pressure area intensifies. Similarly, if divergence exceeds convergence, more air is leaving the column than entering it. The surface pressure must decrease and weaken [14].

High Pressure Area

The high pressure area is defined by the low-level wind flow pattern within a high pressure cell or the high pressure center. Notice that the air moves around the high in an anticyclonic direction while spiraling away from the high pressure center. [14]

2.1.6. Monsoon

Monsoon is a regional scale wind system that predictably changes direction with the passing of the seasons. The monsoon is occurred by the difference of temperature between the oceans and continents on each season. In the winter season, temperature over the continents is lower than the temperature over the oceans then the air mass over the oceans is uplifted and the cold air mass over the continent flow to supplant it. Consequently, the flowing wind from the continents is occurred. In the summer, temperature over the continents is higher than the temperature over the oceans then the opposite flowing wind of winter season is occurred [7].

Figure 2.3 is shown the monsoon of Asia results from a reversal of the winds between the winter and summer. During winter, dry air flows southward from the Himalayas. When summer arrives, moist air is drawn northward from the equatorial oceans. Surface heating, convergence, and strong orographic effect caused heavy rains over the southern part of the continent [15].

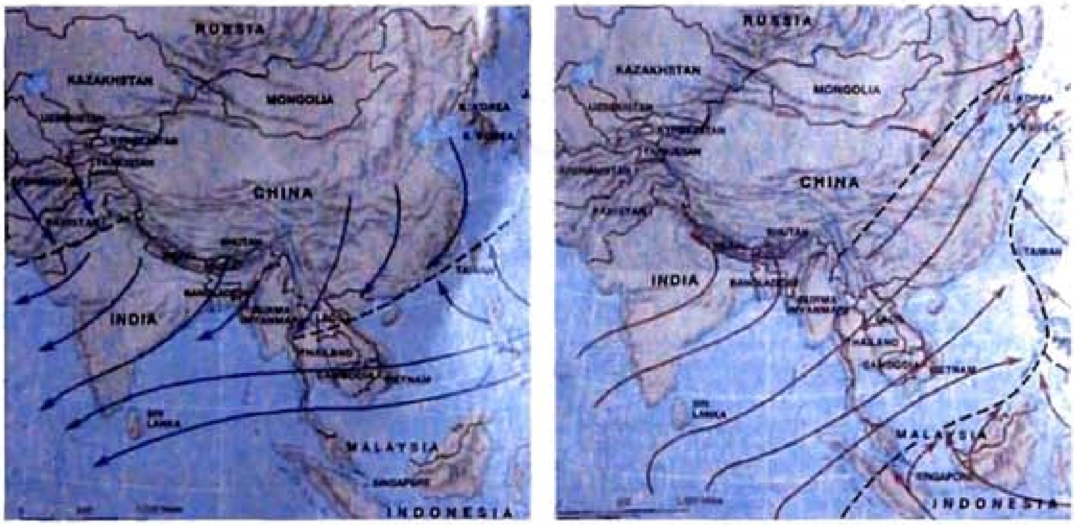

Figure 2.3 The monsoon of Asia. (Left: during winter, Right: during summer)**[15]**

Matsumoto **[16]** investigated the mean onset and withdrawal of summer rainy season over the Indochina Peninsula using the pattern of rainfall data. In Thailand, the effect of southwest monsoon is dominated at onset around early May to mid-May. In case of withdrawal, the post – monsoon rain occurs in late September at the period of the wind field turns to winter time situation.

Kiguchi **[17]** suggested the change of wind direction from northeast direction to southwest direction in early or middle May can be used to be the one of the onset of Asian summer monsoon factor and **[18]** expanded the main summer monsoon of Thailand is in the southwest wind direction. So, it can be called southwest monsoon.

TMD **[19]** suggested the rules on the consideration of southwest monsoon onset and withdrawal of the southern part of Thailand. It is followed below:

- In the any 5 days interval, it must have 3 days of rainfall and more than 5 mm rainfall of each day. Consequently, the total rainfall of those 5 days interval must be 25 mm minimum.
- Using the consideration of the beginning and the end of monsoon season in Thailand together with the consideration of the onset and withdrawal of them.

TMD **[20]** reported the rainy season of Thailand is around mid – May to mid – October normally. It is the same period of southwest wind dominated then the period of rainy season of Thailand is the period of the dominative southwest wind. On the other hand, the dominative northeast wind is occurred around mid – October to mid –

February as the same period of winter season in Thailand. So, the winter season can be represented by the period of the dominative northeast wind.

Lockwood **[21]**, McGregor and Nieuwolt **[22]** expanded the monsoon climates of southern Asia that the season of the northeast monsoon can be divided into two sections. First, it is the winter season around January and February. The last one is hot-weather season around March to May. Another is the season of the southwest monsoon also can be divided into two sections. First, it is the season of general rains around June to September and Matsumoto **[17]** suggested that the pre – monsoon rainfall is around March to May. Final, it is the Post – monsoon season around October to December.

Fasullo and Webster **[23]** investigated the large-scale Indian Monsoon Onset that the hydrologic cycle with the roles of water vapour, clouds, and rainfall can be chosen as a key physical basis for monitoring the monsoon.

To diagnose onset and withdrawal, Vertically Integrated Moisture Transport (VIMT) was used instead of rainfall. Vertically integrated moisture transport is defined as equation (4)

$$VIMT = \int_{surface}^{300hPa} qUdp, \qquad \text{.........................(4)}$$

where p is the precipitation (unit: mm), q is the specific humidity (unit: grams of water vapour per kilogram of air, gkg^{-1}) , and U is the wind vector. Figure 2.4 shows the time series of the annual cycle of VIMT averaged over the regions of particularly rapid VIMT fluctuations during monsoon onset. An index, the Hydrologic Onset and Withdrawal Index (HOWI), is formed from those regions where VIMT variability is pronounced at the beginning and end of the monsoon season. The data based on the satellite sounder data such as humidity and temperature, surface pressure, horizontal wind, and specific humidity are provided to analyse the VIMT.

The HOWI Index is used to track the monsoon hydrology. This index is created by The National Centers for Environmental Prediction– National Center for Atmospheric Research (NCEP–NCAR), U.S.A., Reanalysis project with using the large scale of winds and humidity about 50-yr.

However, the HOWI index is intended to be for regional scale use. It reflects the large-scale hydrologic cycle rather than rainfall at a single point. This study is focused on the local scale where the rainfall data come from the single station.

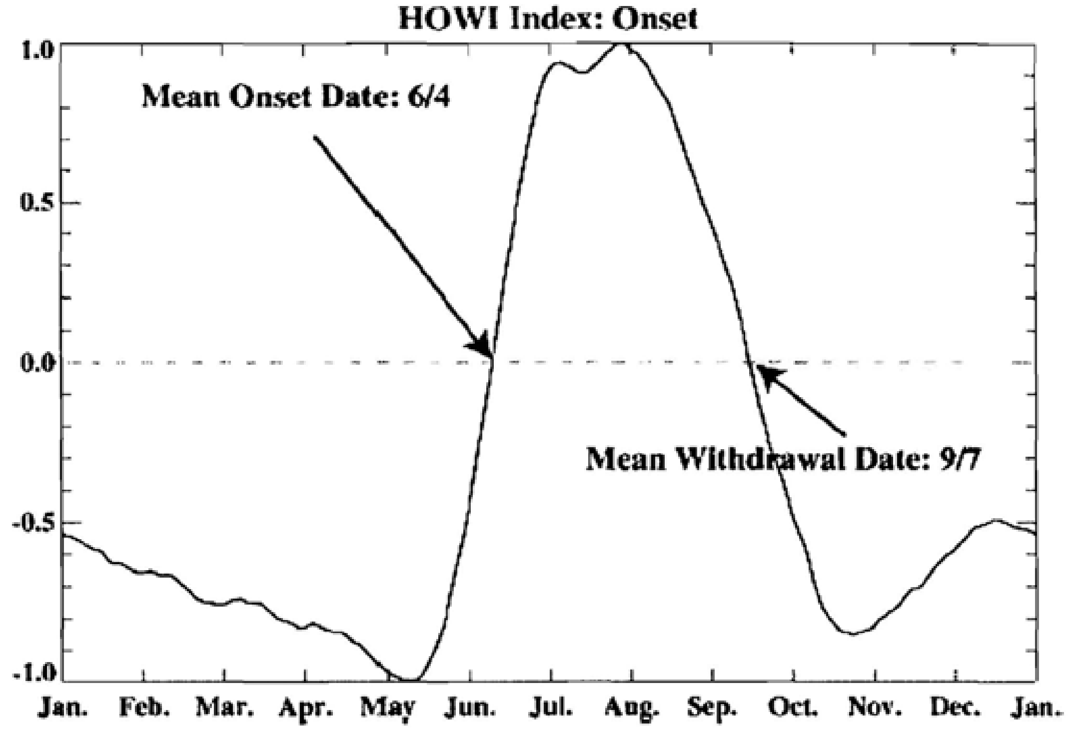

Figure 2.4 Seasonal cycle of the HOWI **[23]**.

2.2 The Water vapour Microwave Radiometer (WMR)

The Water vapour Microwave Radiometer (WMR) receives microwave radiation from the sky at 23.8 GHz (K band) and 31.4 GHz (Ka band). It is a passive system. The two frequencies allow simultaneous determination of integrated liquid water and integrated water vapour along a selected path. The 23.8 GHz frequency was selected to observe the atmospheric water vapour because it is in the reserved frequency band, free from satellite downlink transmissions that could cause erroneous results in the sky observation and this frequency, water vapour are dominated in this channel. In the same way, the 31.4 GHz was selected to observe the cloud liquid in the atmosphere. **[1]**

By calculating sky brightness temperature, the cloud liquid water and integrated water vapour can be obtained.

Chandrasekhar [1] described the radiative transfer equation of the sky brightness temperature at the zenith angle

$$T_b = T_c e^{-\tau(\infty)} + \int_{surface}^{\infty} T(z)\alpha(z) e^{-\tau(z)} dz \qquad \text{..........................(5)}$$

where T_b is the sky brightness temperature (unit: Kelvin), T_c is the cosmic blackbody temperature of outer space (unit: Kelvin), $T(z)$ is the absolute physical air temperature (unit: Kelvin), z is the zenithal spatial position of the emitting air volume (unit: km) and $\alpha(z)$ is the absorption coefficient. This equation can be linearized as

$$T_b = T_c e^{-\tau} + [1 - e^{-\tau}]T_m, \qquad \text{..........................(6)}$$

where the opacity (τ) is defined as equation (7)

$$\tau = \ln\left(\frac{T_m - T_c}{T_m - T_b}\right). \qquad \text{..........................(7)}$$

In non-rainy atmosphere, T_m is the mean temperature along the path from the sky. In order to determine T_m, radiosondes (RAOBs) history data (more than ten years) can be used.

Cloud liquid water and integrated water vapour can be obtained from the linear retrieval equations as

Integrated water vapour = $A_0 + A_1\tau_1 + A_2\tau_2$ .... (8)

Cloud liquid water = $B_0 + B_1\tau_1 + B_2\tau_2$, ... (9)

where A_i is the inversion coefficient of water vapour, B_i is the inversion coefficient of liquid water, τ_1 is the opacity of 23.8 GHz and τ_2 is the opacity of 31.4 GHz .

Elgered [24] found that one algorithm error of the water vapour radiometer is due to errors in the attenuation coefficients. Figure 2.5 shows the effect of water drops forming on the covers of the horn antenna during rain. The error points with covered by boxes for the WMR data have been omitted.

Coster [25] further explained that the errors in the WMR estimation of zenith wet delay (ZWD) might be introduced in the retrieval algorithms, in the absorption models for water vapor emission at the WMR frequencies, and/or in the calibration of the radiometer. It is expected that IWV retrieval biases is 1mm for dry conditions (6.5 mm zenith wet delay) and 2.5 mm of IWV (16-20 mm ZWD) for very humid conditions.

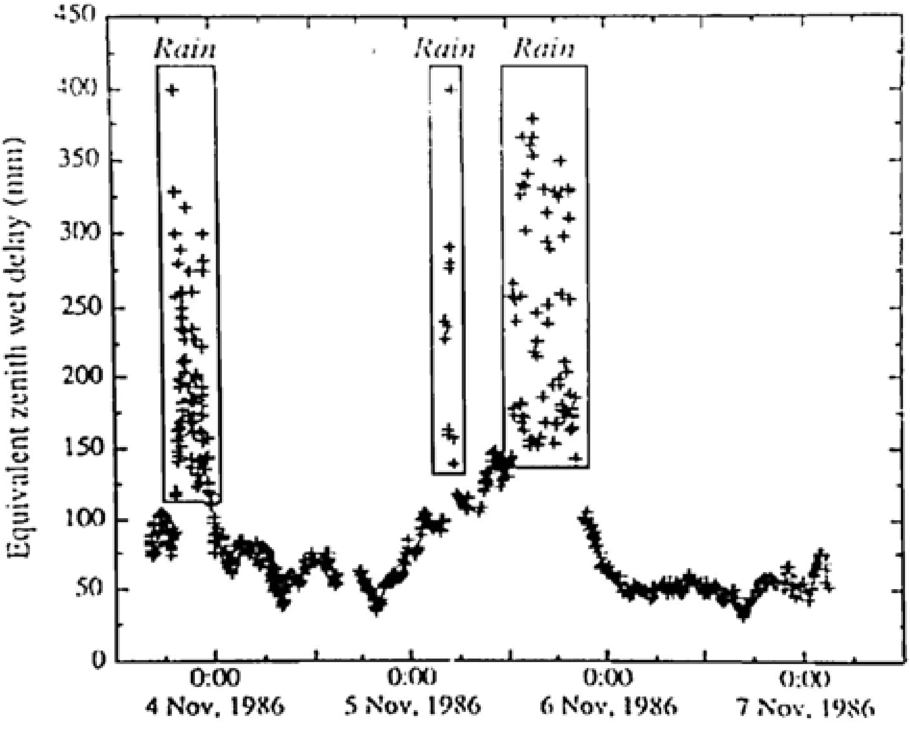

Figure 2.5 The large error points (covered by boxes) from WMR data taken during rain is in this case further increased by water drops forming on the covers of the horn antennas [24].

2.3 Basic concept of GPS

About fifty years ago, the U.S. military developed the positioning system for the navy navigation based on the satellite system as called TRANSIT system. It was the important system for the U.S. military activities. However, the TRANSIT system was not the good system because some problems occurred and low navigation accuracy. The next generation was the Global Positioning System (GPS). It was developed for retrieve all problems in TRANSIT system. This system was higher accuracy than the old one and widely used until now. **[26]**

The GPS consists of three segments; the space segment, the control segment, and the user segment. The following subsections will describe each segment.

2.3.1. Space segment

The space segment is the part of satellite and signal of GPS. The GPS satellites have the orbits with an altitude of about 20,200 km above the earth surface. Figure 2.6 shows the satellites orbits, 24-satellites are operated and 4-satellites are reserved. By this reason, all locations on the earth surface are covered by GPS satellite signals. The satellite signal consists of two fundamental frequencies, L1 = 1575.42 MHz and L2 = 1227.60 MHz respectively. **[26]**

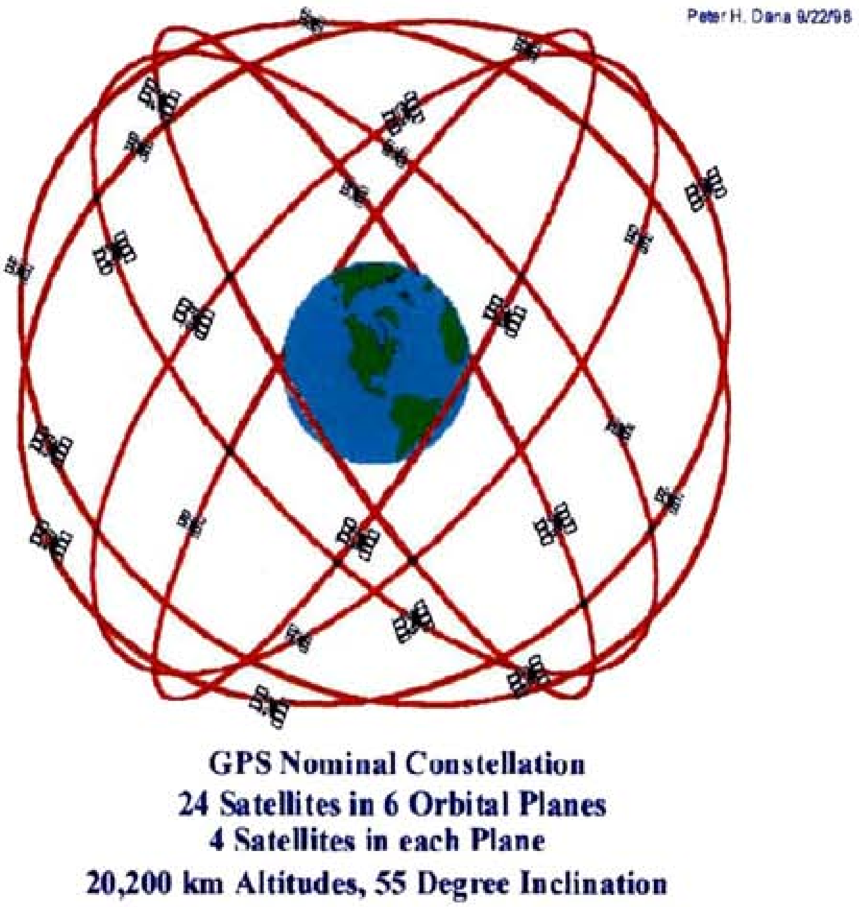

Figure 2.6 GPS Satellites Orbits **[27]**

Each frequency of L1 and L2 is modulated by the several codes that called pseudorandom noise (PRN) code. The PRN code has 2 types; C/A-code (Coarse/Acquisition-code) and P-code (Precision-code)

The P-code, which has the wavelength 30m, is modulated on both L1 and L2. It can be used by U.S. military only. For C/A-code, which has the wavelength 300m, it is modulated only on L1 and it is available for civilian users.

2.3.2. Control segment

The control segment consists of 3 parts. First part is the master control station. It is located at the Consolidation Space Operation Center (CSOC), Colorado Spring, Colorado. The function of this station is the calculation of the satellite orbit and clock parameters for upload to the GPS satellites. The second part is the monitor stations that have the function for sending the necessary data of GPS satellite to the master control station for calculating all parameters. There are five monitor stations located around the world. Their locations are in; Hawaii, Colorado Springs, Ascension Island, Diego Garcia, and Kwajilein Island. The final part is ground control stations that are located at Ascension Island, Diego Garcia, and Kwajilein Island. These stations have the direct communication links to the satellites. **[26]**

2.3.3. User segment

The user segments are GPS receivers and users. GPS receivers can be described by a term of the receiver types. For example, the C/A-code receiver is the receiver that measures this C/A-code, and also the P-code receiver is the receiver that measures the P-code. For the users, the U.S. military can use all signals while the civilian users can use this system with the limitation of the signal use. **[26]**

Today, the GPS is widely used by civilian users compared to military users. The accuracy of GPS data is used to identify the "level of usage". For example, the navigation of the car on the road requires only the standard GPS data **[28]** but the high accuracy of GPS data is applied for crustal deformation studies **[3]**, etc.

In order to obtain the high accuracy GPS positioning, the reduction of the error source is considered. The biases in the GPS consist of three groups; the satellites group, the signal group, and the receiver group, respectively. First, the satellite error source involves the Clock bias and Orbital errors. Second, the signal propagation error source consists of Ionospheric refraction, Tropospheric refraction, and Multipath. Finally, the receiver error source consists of Antenna phase center variation and Clock bias. **[26]**

For the propagation errors, they are the refraction of the signal propagation through the atmosphere. Therefore, two atmospheric layers, Ionosphere and Troposphere, are related to this refraction. The result of signal refraction is the signal spends time for propagating to the receiver as called the propagation delay. **[9]**

The delay by the Ionospheric layer can be removed by using the comparison of the propagational difference of both frequencies (L1 and L2) **[29]**. In case of the delay by the tropospheric layer (hereafter referred to as tropospheric propagation delay), water vapour in this layer is the mainly cause to the delay. However, the standard model or mathematical method is used to remove this delay. **[9]**

2.3.4. Tropospheric propagation delay

Physics of the tropospheric propagation delay is defined by equation (10)

$$\Delta L = \int_L (n-1)\,ds, \qquad \text{......................... (10)}$$

where n is the refractive index along the path L.**[26]** In general, n should be adjusted into the term of refractivity N. **[9]** It is shown as equation (11)

$$N = 10^6 (n-1). \qquad \text{......................... (11)}$$

So that Equation (10) becomes equation (12) **[26]**

$$\Delta L = 10^{-6} \int_L N ds . \qquad \text{......................... (12)}$$

In 1969 Hopfield showed that the refractivity N can be derived into 2 components. These components consist of dry and wet component that is showed as equation (13) **[9,26]** :

$$N = N_d + N_w, \qquad \text{......................... (13)}$$

where the dry part results from the dry atmosphere and the wet part from the water vapour. Then, equation (12) becomes equation (14)

$$\Delta L = 10^{-6}\int_L N_d dS + 10^{-6}\int_L N_w dS. \qquad \text{......................... (14)}$$

2.4 GPS for Meteorological purposes

According to Saastamoinen **[26]** and following to equation (14), ΔL can be partitioned into a large quantity which depends only on surface pressure, so-called the "hydrostatic delay" (dry delay) and a smaller quantity which is a function of water vapour distribution, so-called "wet delay". Elgered **[24]** found that the dry and wet delays which along the zenith angle can be called in sequences that the Zenith Hydrostatic Delay (ZHD) and Zenith Wet Delay (ZWD), and the term of ZHD can be calculated using the equation (14)

$$\Delta L_h = ZHD = (2.2779 \pm 0.0024)\frac{P_s}{f(\lambda, H)}, \qquad \text{......................... (15)}$$

where P_s is the surface pressure (hPa) and *f(λ, H)* is defined as equation (16)

$$f(\lambda, H) = (1 - 0.00266\cos 2\lambda - 0.00028H) \qquad \text{......................... (16)}$$

where $f(\lambda, H)$ is a factor close to unity that accounts for the variation in gravitational acceleration, with latitude *(λ)* and height *(H)* in kilometers.

Bevis **[9]** concluded that the ΔL along the zenith angle, so-called the Zenith Total Delay (ZTD), comprises of 2 part, ZHD and a ZWD respectively. Thus, ZTD can be represented as

$$\text{ZTD} = \text{ZHD} + \text{ZWD}. \qquad \text{......................... (17)}$$

The term ZWD depends upon the vertical distribution of water vapour and can be directly related to the Integrated Water Vapour (IWV) using equation (18)

$$IWV \times \rho_{H_2O} = \kappa \times ZWD \qquad \text{.........................(18)}$$

with a proportional coefficient κ yielded from equation (19)

$$\frac{1}{\kappa} = 10^{-6}\left(\frac{c_1}{T_m} + c_2\right)R_V, \qquad \text{.........................(19)}$$

where c_1 = (3.776 ± 0.030) 10^5 K^2hPa^{-1} and c_2 = (17 ± 10) $KhPa^{-1}$, R_V is the specific gas constant for water vapour (461.45 J kg^{-1} K^{-1}) and ρ_{H_2O} is the density of water (1000 kg m^{-3}). T_m is the weighted mean temperature which obtained from equations (6) and (7).

In order to investigate the accuracy of the Integrated Water Vapour obtained from GPS data, the ground – based Water vapour Microwave radiometer can be used for comparisons since it provides the Integrated Water Vapour. Most results of the comparison were shown good relationships in Europe and America regions. For example, in Italy **[30]**, the bias of the comparison is around 4 mm. In U.S. **[9]**, the bias is around 2 to 6 mm. Also in the region of Asia, for example, the bias is less than 2 mm in Japan **[31]**, Taiwan around 3 mm **[10]**, Thailand, around 6 mm **[32]**.

2.4.1. Some of the use of GPS in Meteorological Studies

During 1998 - 2000 Takiguchi and Kato delineated the Asian monsoon onset based on the observation of water vapour by using GPS in Thailand. In a comparison of the IWV estimated from radiosonde data (Sonde_IWV) and the IWV estimated from GPS data (GPS_IWV), the trends of both GPS_IWV and Sonde_IWV are rapid increase of water vapour is around May. It is represented to onset of the monsoon. The differences between GPS_IWV and Sonde_IWV were eminent. About 8.7 mm is the RMS of the difference between both of them. However, the RMS of the difference is about 5 mm when removed some unreliable radiosonde data and made a linear correction to Sonde_IWV. In order to judge the onset of the monsoon, a correlation between the GPS-IWV rapid increment and rainfall of Bangkok and Chiang Mai was investigated. It is shows the strong correlation between both of them [4].

Hageman and Bengtsson [33] shown that the success of the global scale-comparison of IWV from GPS by using ZTD data from the GPS global network and IWV from European Centre for Medium – Range Weather Forecasts' Operational Analyses (ECMWF OA). The IWV simulated from GPS is the quality control as well as GPS and pressure stations. The good agreement of the comparison between both of them illustrates the GPS_IWV can validated for OA of IWV. The erroneous values in the GPS_IWV come from the ZTD measurements, the surface pressure measurements, and the estimation of integrate mean temperature from the OA, are induced to the analysis error. The comparison shows the small bias and standard deviation of most GPS stations for the both of summer and winter months. On the other hand, the winter months in some regions shows the large dry systematic bias which is the ECMWF OA_IWV lower than the GPS_IWV. In this case, the effect of humidity for winter season dominated.

CHAPTER III
EXPERIMENT

3.1 Equipment

For this study, GPS and microwave radiometer are used as primary source of data. The information about these instruments is detailed below.

3.1.1 GPS

The 4 GPS permanent stations are shown in table 3.1, occupied by dual-frequency GPS receivers (Ashtech Z-Xtreme for CHMI, BNKK and PHKT provided by Institute of Observational Research for Global Change (IORGC) and Japan Agency for Marine – Earth Science and Technology (JAMSTEC), Japan since 1998 and Trimble 4000SSE Geodetic System Surveyor for SISM station that provided by the GEWEX Asian Monsoon Experiment – Tropics project (GAME – T), Japan since 1997). In order to investigate the atmospheric water vapour, data were collected in static mode for 24 hours at 30-second data rate. Figure 3.1 shows the 4 GPS permanent stations' locations used in this study (white circle).

Table 3.1 GPS permanent stations in Thailand [34]

GPS Station Name	Location	Longitude (°N)	Latitude (°E)	Height at MSL (m)	Data Format	Data sampling
CHMI	Chiang Mai	98.973	18.771	290	Ashtech	30 sec.
BNKK	Bangkok	100.607	13.668	0	Ashtech	30 sec.
PHKT	Phuket	98.308	8.105	10	Ashtech	30 sec.
SISM	Sukhothai	99.862	17.161	50	Trimble	30 sec.

Figure 3.1 The locations of GPS permanent stations (modified) **[35]**.

3.1.2 Water vapour Microwave Radiometer (WMR)

The Radiomatrics WVR – 1100 portable water vapour radiometer (see Figure 3.2) was used to collect water vapour microwave radiometer data (WMR_IWV) with high accuracy. In Thailand, there is only one WMR which is located at SISM provided by the GEWEX Asian Monsoon Experiment – Tropics project (GAME – T) since 1997. Table 3.2 shows the characteristics of the microwave radiometer (WVR-1100). The 24-hr observation at the zenith angle is selected to collect the data **[1]**.

Table 3.2 Characteristics of the Water vapour Microwave Radiometer, model: WVR-1100. [1]

Specifications	**Value**
Operating frequencies:	23.8-31.4 GHz
Angular coverage:	All Sky
Power requirement:	120 watts maximum
Accuracy:	0.30 K
Resolution:	0.25 K
Radiometric range:	0 K to 700 K
Output:	RS232 at 1200 baud
Dimensions:	50X28X76 cm.
Weight:	21 kg with azimuth steering mount
Pointing slew rate:	3 degree/sec, azimuth greater than 90 degree/sec, elevation

Figure 3.2 The Water vapour Microwave Radiometer WVR 1100 Model (WMR)

3.2 Data Acquisition

All of GPS and WMR data were collected in static mode. This study used three years data set (2001 to 2003) from each instrument (see Table 3.3). The meteorological data such as surface temperature, surface pressure, wind speed and other meteorological data are used together with GPS data. These meteorological data are provided by Thai Meteorological Department (TMD).

Table 3.3 The data set of each instrument.

Instrument	Station	Data Type/Format
GPS	CHMI	RAW GPS data/Ashtech
	BNKK	RAW GPS data/Ashtech
	PHKT	RAW GPS data/Ashtech
	SISM	RAW GPS data/Trimble
WMR	SISM	RAW WMR data/WMR .los file

3.3 Data Processing

The primary data obtained from each instrument were not directly used. It must be selected or converted before analysis. The raw GPS data was converted into the term of GPS_IWV whilst the raw WMR data was converted into the term of WMR_IWV and also the raw meteorological data was selected and prepared. The detail how to obtain these data above is shown in the following subsections.

3.3.1 Preparation of GPS_IWV data

The RAW GPS data were converted into the Receiver INdependent EXchange (RINEX) format. After that, they were processed by the Bernese software version 4.2 [36]. The main characteristics are:

- use of International GPS Service (IGS) precise ephemeris.
- apply Saastamoinen a-priori troposphere model.
- ambiguity float solutions using the ionosphere-free linear combination (L3).
- estimation of 1 ZTD per hour and station using "dry Niell" mapping function.

A ZWD data from Bernese software was subsequently derived by subtracting ZHD from the ZTD. Finally, ZWD has been converted to the estimate of the GPS_IWV. Figure 3.3 shows the example GPS_IWV of each station without the erroneous subtraction and filtering.

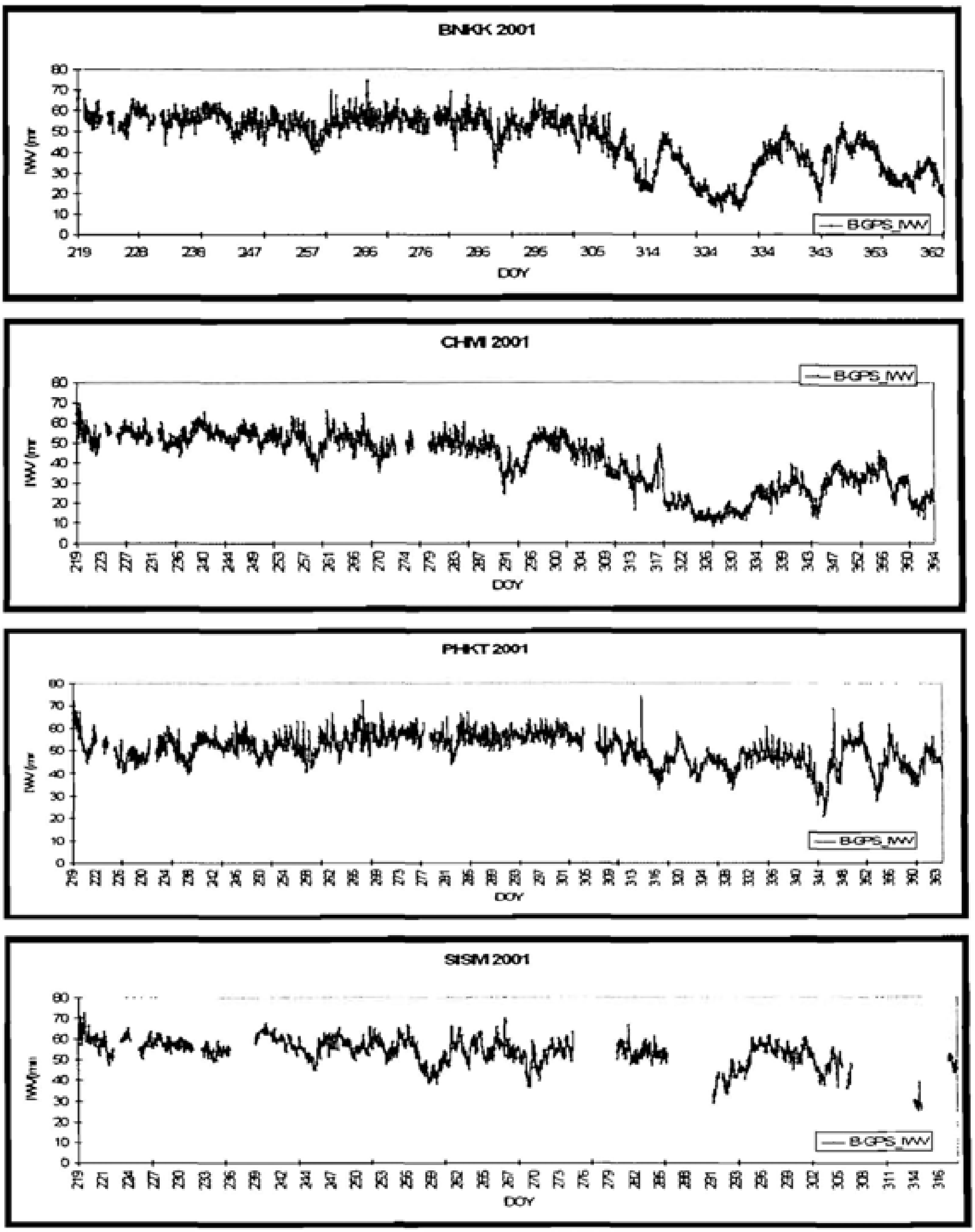

Figure 3.3 the GPS_IWV data

3.3.2 Preparation of WMR_IWV data

The RAW WMR data were directly converted into WMR_IWV data because the instrument firmware automatically created a final data format. (See the Appendix B for the selection of WMR_IWV data). Figure 3.4 shows the example of WMR_IWV data without erroneous subtraction and filtering.

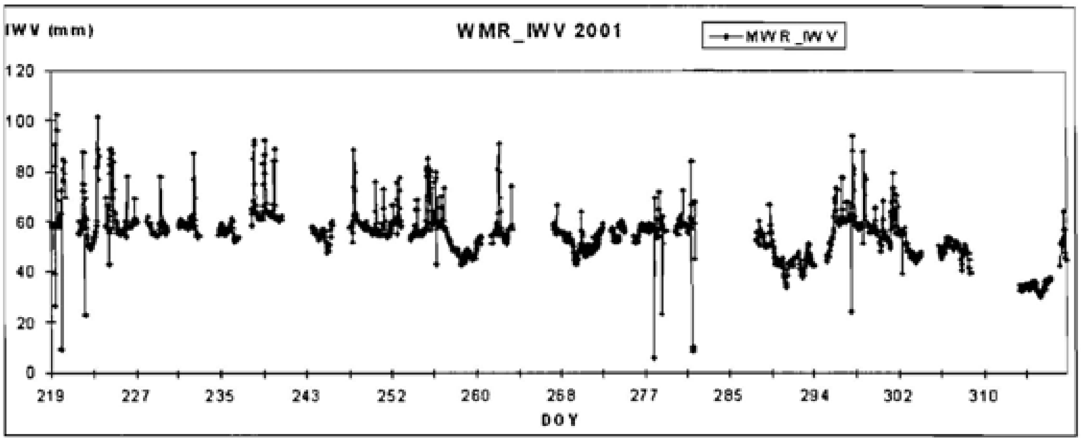

Figure 3.4 The WMR_IWV data

3.3.3 Preparation of Meteorological data

Mean temperature (Tm) and surface pressure (Ps) are the meteorological data that were selected and prepared. These datasets will be used to estimate the IWV value.

3.3.3.1 The vertically integrated mean temperature (T_m)

T_m can be approximated by the surface temperature (T_s) using the T_m - T_s linear relationship. The ten years T_m and T_s observed at each GPS station were used to determine the correlation (see Appendix A) **[37,38]**.

The T_m - T_s relationship derived from ten years of data show small correlation coefficient and hence the T_m - T_s relationship will not be used to compute the IWV value. The global π value (0.15) is adopted for calculation of IWV value. Figure 3.5 shows an example of T_s that used to determine the T_m - T_s relationship.

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‖+E Station: BANGKOK METROPOLIS

January 1990

Dry bulb temperature (Celsius) +F

I+‖

Dey	0100	0200	0300	0400	0500	0600	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400	Mean
1	26.0	25.8	25.5	25.5	25.0	24.6	24.0	25.5	28.1	29.5	30.4	31.3	32.2	32.5	32.6	32.2	31.5	28.6	27.5	27.0	26.5	26.5	26.3	26.3	28.0
2	26.2	26.0	25.8	25.5	25.5	25.5	24.7	25.5	27.2	27.6	28.7	29.7	31.2	31.8	32.0	31.3	30.3	28.8	27.5	27.1	27.0	26.7	26.5	26.3	27.7
3	26.2	26.2	26.1	26.1	26.0	26.0	25.5	25.8	27.1	28.7	29.5	29.7	31.4	31.1	32.2	32.0	31.3	28.8	27.7	27.2	26.7	26.5	26.3	26.3	27.9
4	25.8	25.2	25.0	24.5	24.2	24.1	24.0	24.5	26.0	27.0	29.2	30.6	32.1	32.5	32.5	32.5	32.3	30.2	28.4	27.1	27.7	27.5	26.7	25.7	27.7
5	25.4	25.2	25.0	24.5	24.0	23.8	23.6	24.3	26.7	29.2	30.5	33.0	33.5	33.6	32.1	30.3	30.0	29.2	27.5	26.5	25.6	26.7	26.7	26.5	27.6
6	26.1	25.9	25.7	25.2	24.9	24.1	23.7	24.7	27.3	29.6	30.5	32.0	32.6	34.0	34.5	34.1	33.5	32.5	29.4	28.3	27.6	27.2	27.0	26.7	28.6
7	26.7	26.2	25.8	25.6	25.4	25.0	24.5	25.0	26.5	28.4	29.9	30.7	31.5	32.5	32.4	32.3	31.9	29.9	28.3	27.2	27.0	27.0	27.0	26.5	28.1
8	25.4	25.1	24.9	24.4	23.8	23.3	23.6	24.0	26.5	29.3	31.0	32.1	32.7	33.0	33.3	33.0	32.2	30.4	27.9	27.0	26.5	25.2	25.1	25.0	27.7
9	24.0	23.8	23.1	23.0	22.5	22.2	21.7	22.2	25.5	28.5	31.0	32.1	33.0	33.5	32.4	31.8	31.0	29.6	28.1	26.8	26.1	26.6	26.2	26.2	27.1
10	26.0	25.9	25.7	25.7	25.1	24.8	24.4	24.5	26.8	26.7	30.0	30.7	31.5	31.6	32.1	31.6	31.3	29.5	28.4	27.5	27.2	27.0	26.8	27.0	27.9
11	26.6	26.4	26.2	26.0	25.9	25.8	25.0	25.4	27.0	28.5	30.1	31.5	31.9	32.4	32.5	32.0	31.3	29.7	28.3	27.5	27.4	27.2	27.0	26.7	28.3
12	26.6	26.5	26.1	25.7	25.4	24.8	25.0	25.2	27.2	29.0	30.6	31.6	32.8	33.1	33.0	33.1	31.4	29.4	28.4	28.1	27.7	27.4	27.1	27.0	28.4
13	27.0	26.7	26.3	25.5	25.0	25.0	25.5	26.4	28.1	29.2	31.1	33.0	32.5	32.2	32.3	32.8	31.5	29.5	28.6	28.1	27.9	27.5	27.5	27.0	28.6
14	27.0	27.0	26.8	26.4	26.0	25.8	25.2	26.0	28.1	30.0	31.7	31.5	31.6	31.8	31.1	30.2	30.0	28.5	27.5	27.2	27.0	27.0	26.8	26.7	28.2
15	26.5	26.4	26.1	25.9	25.4	25.2	24.7	25.5	26.5	29.5	30.3	31.1	31.5	32.0	32.5	32.5	31.7	29.7	28.3	27.7	27.5	27.3	27.0	26.8	28.2
16	26.6	26.4	26.5	26.3	26.2	25.8	25.2	26.2	27.6	29.1	30.3	31.8	32.4	32.5	32.2	32.0	31.4	29.5	28.6	28.1	27.9	27.7	27.5	27.4	28.6
17	27.3	27.0	27.0	26.8	26.7	26.3	26.0	26.5	28.0	28.4	29.1	30.0	30.4	30.8	31.5	30.6	30.3	28.5	27.7	27.5	27.4	27.2	27.0	27.0	28.1
18	27.0	26.8	26.6	26.4	26.2	25.9	26.3	26.7	28.0	29.8	31.0	32.0	31.7	31.6	31.5	31.3	30.0	28.0	27.5	27.5	27.3	27.2	27.0	27.0	28.3
19	26.9	26.6	26.3	26.0	25.8	24.0	23.0	24.0	26.6	28.6	30.0	31.4	32.1	32.3	32.0	31.4	31.0	28.8	27.2	27.0	26.8	26.7	26.3	26.3	27.8
20	26.5	26.4	25.9	25.5	25.2	24.6	25.0	25.3	26.5	27.8	29.5	30.5	32.1	32.6	32.8	32.6	31.8	30.9	29.0	28.5	27.9	26.3	26.2	26.4	28.2
21	26.2	26.3	26.0	25.8	25.3	25.0	24.7	25.5	27.3	28.5	29.5	30.6	31.3	32.4	32.7	32.3	31.5	30.2	28.5	27.8	27.0	26.2	26.0	25.1	28.0
22	24.6	24.1	23.7	23.3	23.1	23.3	23.4	23.5	26.5	28.5	30.0	31.4	32.0	33.0	33.1	33.0	32.8	30.8	29.2	27.6	27.8	27.5	26.0	25.2	27.6
23	24.4	24.1	23.8	23.6	23.4	22.9	22.5	24.1	27.3	29.0	30.1	31.1	31.8	32.5	33.0	32.9	32.3	31.1	28.8	28.7	28.0	27.3	26.5	26.0	27.7
24	25.7	25.5	24.7	24.0	23.0	22.5	22.2	22.5	23.5	25.5	27.1	29.0	29.6	31.3	31.2	31.5	30.8	29.2	27.6	26.6	25.1	24.3	23.6	23.0	26.2
25	22.8	22.2	22.3	22.5	22.6	21.8	21.8	23.0	25.5	27.5	29.1	30.2	30.6	32.1	32.3	32.0	31.6	30.0	28.3	26.7	26.7	26.5	26.0	25.0	26.6
26	24.8	24.2	23.9	23.8	23.0	22.7	23.0	23.2	25.4	26.2	27.1	29.1	30.2	30.5	31.2	31.0	30.3	29.3	28.0	27.3	27.0	26.2	25.7	24.3	26.6
27	23.2	22.4	22.0	21.4	20.7	20.9	20.5	21.9	24.2	26.9	27.6	29.9	30.5	31.1	31.5	31.9	31.3	29.7	28.0	26.7	25.6	25.0	24.6	24.3	25.9
28	24.0	23.3	22.5	22.0	21.5	21.0	21.7	23.2	26.3	28.1	29.4	29.9	31.1	32.1	32.8	33.0	32.1	30.6	27.4	25.9	25.4	25.2	25.4	23.7	26.6

Figure 3.5 The raw T_s data.

3.3.3.2 The surface pressure at the level of GPS station height (P_s)

All of pressure data from TMD are the mean sea level pressure data. In the order to use it at the height of each GPS station, the pressure data were retrieved by the Barometric Formula as equation (10). Figure 3.6 shows an example of P_s data that will use to convert the GPS_IWV value.

Psราย1 ชมกรุงเทพ00_01 - WordPad

File Edit View Insert Format Help

+E Station: BANGKOK METROPOLIS

January 2000
MSL. Pressure (Hpa) +F

▮+1¶

Day	0100	0200	0300	0400	0500	0600	0700	0800	0900	1000	1100
1	1.1	1.0	.9	.9	.9	1.0	1.0	1.1	1.1	1.2	1.1
2	1.0	.9	.9	.9	.9	.9	1.0	1.1	1.1	1.2	1.2
3	1.0	.9	.9	.8	.9	.9	1.0	1.0	1.1	1.1	1.1
4	.9	.8	.8	.8	.8	.8	.9	1.0	1.1	1.1	1.1
5	1.0	1.0	.9	.9	.9	.9	1.0	1.0	1.1	1.1	1.1
6	1.0	1.0	.9	.8	.9	.9	.9	1.1	1.1	1.2	1.1
7	1.0	1.0	.9	.9	.9	.9	1.0	1.1	1.1	1.1	1.1
8	1.1	1.0	1.0	.9	.9	1.0	1.0	1.1	1.2	1.2	1.2
9	1.0	1.0	1.0	.9	.9	1.0	1.1	1.1	1.1	1.2	1.2
10	1.0	.9	.8	.8	.8	.9	.9	1.0	1.1	1.1	1.1
11	.9	.9	.9	.8	.9	.9	1.0	1.1	1.1	1.1	1.1
12	.9	.9	.8	.8	.8	.9	.9	1.0	1.2	1.2	1.1
13	.9	.8	.8	.8	.8	.8	.9	1.0	1.1	1.1	1.0
14	.8	.8	.8	.7	.7	.8	.8	.9	1.0	1.0	1.0
15	.8	.7	.7	.7	.7	.8	.9	1.0	1.1	1.1	1.1
16	1.0	.9	.9	.9	.9	1.0	1.1	1.1	1.2	1.2	1.2
17	1.0	.9	.8	.8	.9	.9	1.0	1.1	1.2	1.2	1.2
18	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.2	1.3	1.3	1.3
19	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.2	1.3	1.3	1.3
20	1.2	1.2	1.2	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.3
21	1.4	1.3	1.3	1.3	1.3	1.4	1.5	1.6	1.7	1.6	1.6
22	1.4	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.5	1.5	1.5
23	1.2	1.2	1.1	1.1	1.1	1.2	1.2	1.3	1.4	1.4	1.4
24	1.1	1.1	1.0	1.0	1.0	1.1	1.2	1.2	1.3	1.4	1.3
25	1.1	1.1	1.0	1.0	1.0	1.1	1.1	1.3	1.3	1.4	1.4

Figure 3.6 The raw P_s data

3.4 The test of data accuracy

The GPS data was brought to process by the Bernese software version 4.2. The ZTD is the result from this process. After that, by using equation (15), (17), and (18), the IWV can be estimated. (hereafter referred to as B-GPS_IWV)

To test the B-GPS_IWV data accuracy, the WMR_IWV data was used to compare with B-GPS_IWV because the WMR is the main observational instrument on IWV value and also the WMR_IWV itself is the high accuracy data. The trend of this comparison, the different value of them, and the correlation coefficient were investigated.

The accuracy of the B-GPS_IWV is shown in Figure 3.7. Figure 3.7 shows the comparison between the B-GPS_IWV (Gray line) and the WMR_IWV (Green line) from day 219 to day 318 of year 2001, where Y-axis is IWV (mm) and X-axis is the day of year (DOY). The B-GPS_IWV shows good compatibility with the WMR_IWV. Most of B-GPS_IWV values are overlapped by the WMR_IWV, the average different value of them is 1.34 mm and the correlation coefficient is 0.81.

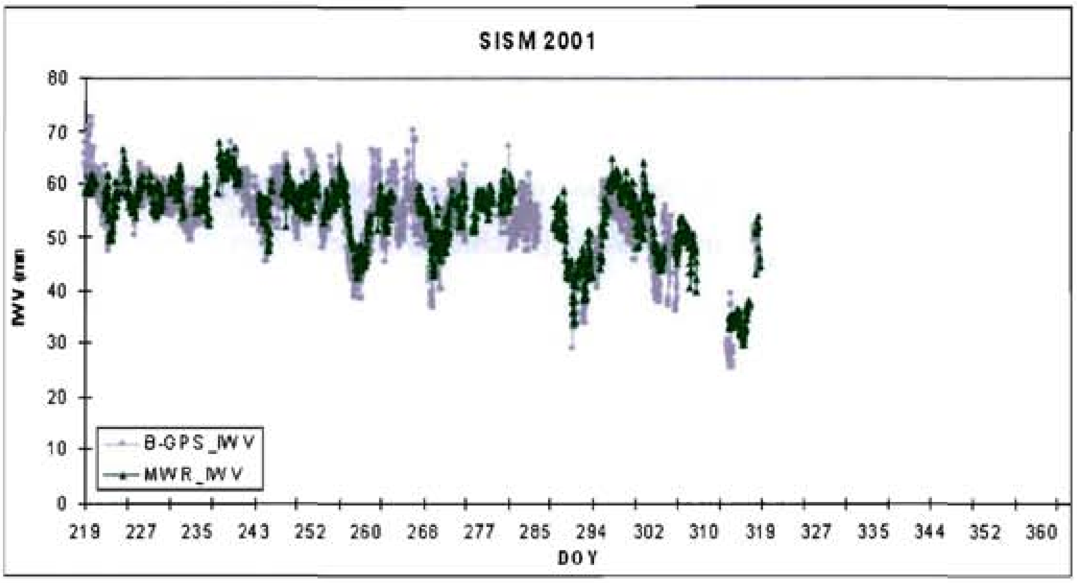

Figure 3.7 Comparison of the B-GPS_IWV (Gray Line) and WMR_IWV (Green Line) of SISM station in year 2001.

CHAPTER IV
RESULTS AND DISCUSSION

The results of this research are separated into 3 sections. The details are shown below.

4.1 Identification of the period of Southwest Monsoon of Thailand

This section is the use of IWV to identify the southwest monsoon period of the rainy season of Thailand. The B-GPS_IWV data was chosen together with wind direction and rain fall data to consider the relation of them during the transition period. The consideration was divided into two cases, onset and withdrawal. The period of southwest monsoon was obtained by combination of both cases.

Generally, water vapour always varies in the troposphere. Therefore, the IWV are also varied. Figure 4.1 shows the variation of IWV (Pink line) together with the daily wind direction observed at 0700 local time (Blue points) and the daily rainfall (Green bars) of year 2002 of BNKK (Top), CHMI (Middle), and PHKT (Bottom). Primary-Y-axis is IWV (mm), Secondary-Y-axis consists of wind direction (degree) and rainfall (mm), and X-axis is DOY.

In Figure 4.1, at BNKK and CHMI station, the IWV is around 30 mm in the beginning of the year and 50 mm in the middle of the year. The IWV slightly decreases in later part of the year. On the other hand, the IWV value at the PHKT station remains unchanged throughout the year. This may be the fact that the PHKT station is located on the Island surrounded by the ocean. Therefore, the air mass over the station is the moist air from the ocean. Consequently, the IWV value remains in the high level all the year.

From the IWV data above, the consideration can be divided into two parts. The first one is the period between February and June for the southwest monsoon onset. Another period is between August and December for the southwest monsoon withdrawal. The details of each part are shown below.

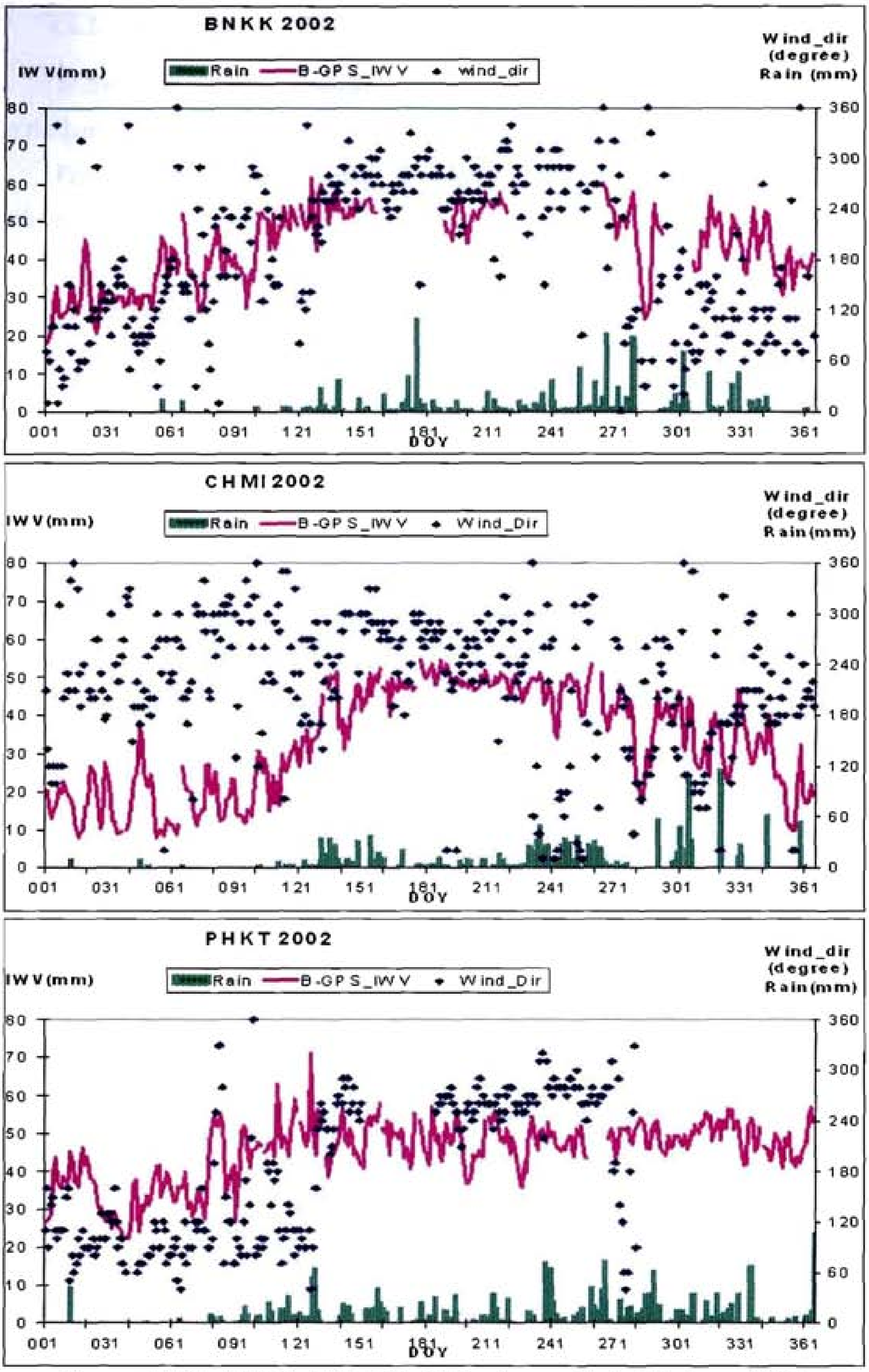

Figure 4.1 The B-GPS_IWV, Wind Direction and Rainfall of year 2002.

Top: BNKK station. Middle: CHMI station. Bottom: PHKT station.

4.1.1. The onset

In the onset period, the southwest wind brings the moist air from the ocean into the land and it is the cause of the rainfall [16].

From the reason that expended in chapter II (section 2.1.6), the onset of the southwest monsoon can be identified by two factors as:

- the change of wind direction to the southwest direction.
- the increase of rainfall.

According to the use of B-GPS_IWV together with the conditions above, the southwest monsoon onset period should start around day 138 (See Figure 4.2). Figure 4.2 shows the variation of B-GPS_IWV (pink line), wind direction (blue points), and rainfall (green bars) of day 30 to day 200 of year 2002. The details of the consideration are shown below.

- The wind direction data of PHKT station was used to consider the change of wind direction because it was clearly seen on this station. Thus, the change of wind direction was around day 130.
- All stations have the rainfall during day 120-140 and the first continuous - 3 days rainfall is around day 125 to day 130.
- The level change of B-GPS_IWV from "low to high" level and the extension at high level.
- At BNKK station, B-GPS_IWV completely changed its level from low level (about 30 mm) to high level (about 50 mm) around day 127. Similarly at CHMI station, B-GPS_IWV completely changed its level around day 149. Therefore, the average was around day 138.

According to the Annual report of the year 2002 by TMD, the onset of southwest monsoon was around early May [40]. Then, the B-GPS_IWV was suitable used to identify the precise day of the onset.

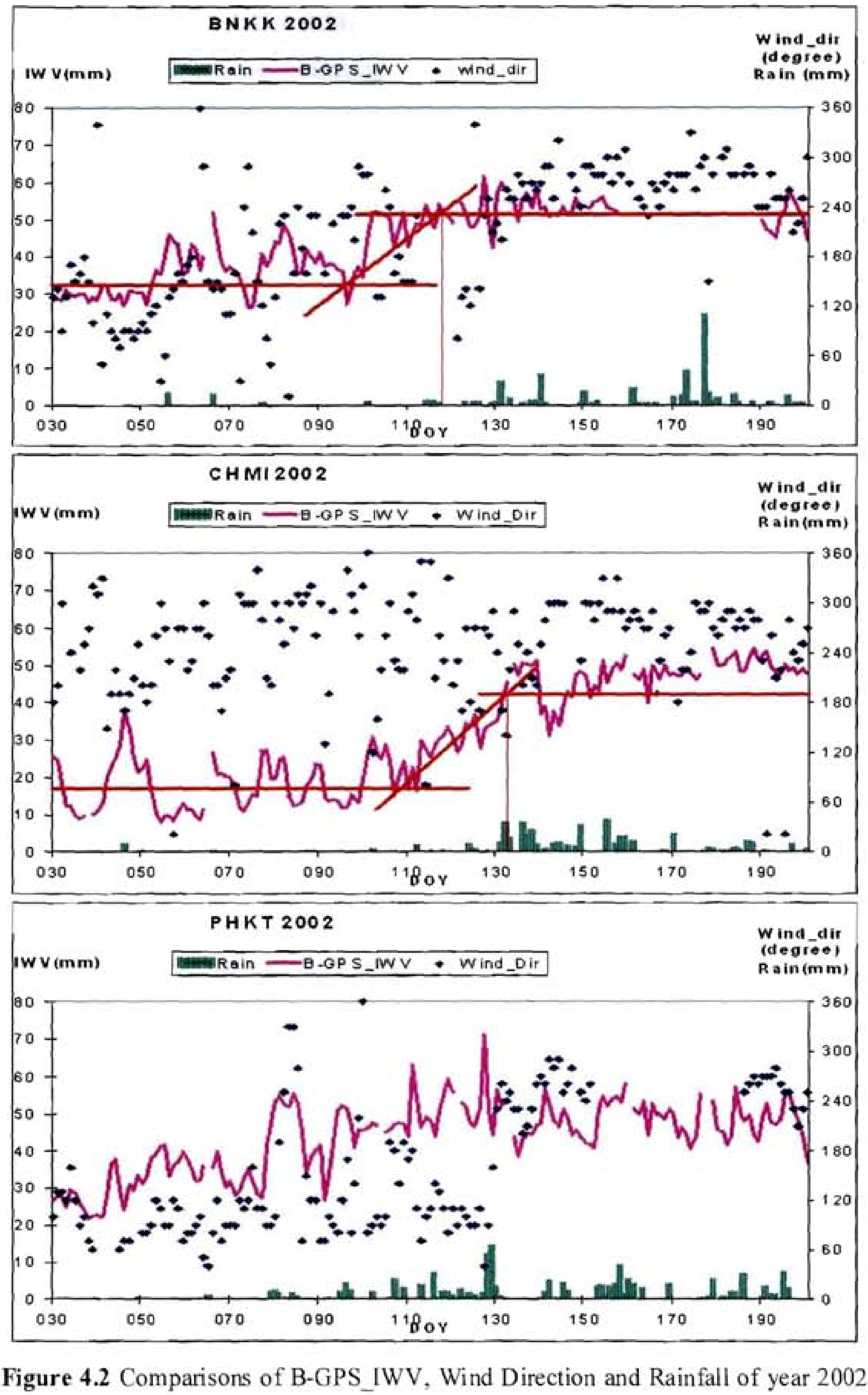

Figure 4.2 Comparisons of B-GPS_IWV, Wind Direction and Rainfall of year 2002 (Onset). Top: BNKK station. Middle: CHMI station. Bottom: PHKT station.

In addition, another method which could be used as a guide-line for determining the onset is the average-lines of B-GPS_IWV (red line). The average line is applied from the average value of B-GPS_IWV of each level which is the start and the end point of IWV data of each level are considered by the condition rule of onset and withdrawal, respectively, and the cross point can be identified by creating the line of join between the high level – average line and low level – average line over the transition period. In Figure 4.2, the cross point at the high level of the average line was around day 119 at BNKK and around 132 at CHMI. In fact, this method was not guaranteed in its accuracy because the personal error was dominated.

4.1.2. The Withdrawal

In the withdrawal period, most of the wind is northeast wind. The cold and dry air flow from the main land China reduces the water vapour in the atmosphere [15]. Consequently, the rainfall and the IWV are decreased and also with the reason that expended in chapter II (section 2.1.6), the factors of the withdrawal of the southwest monsoon can be shown below.

- the change of wind direction from the southwest direction.
- the decrease of rainfall.

According to the use of B-GPS_IWV together with the conditions above, the withdrawal period should start around day 328 (see Figure 4.3). Figure 4.3 shows the variation of B-GPS_IWV (Pink line), wind direction (Blue points), and rainfall (Green bars) of day 218 – 365 of the year 2001. The details of the consideration are shown below.

- The change of wind direction from southwest to northeast and southeast directions of PHKT station is around day 296
- The rainfall decreases around the period between day 290 and 320 for all stations.
- The change level of B-GPS_IWV from “high to low” level and the extension at low level.

- At the BNKK station, B-GPS_IWV completely changed its level from high to low level around day 329. Similarly to CHMT station, B-GPS_IWV completely changed its level around day 327. Therefore, the average was around day 328.

Referring to the annual report of year 2001 from TMD, the withdrawal of southwest monsoon was around late November [39]. Then, the precise day of withdrawal can be identify by using B-GPS_IWV.

Furthermore, the average-lines method can also be used as a guide-line for determining the withdrawal as same as the onset. In Figure 4.3, the cross point at low level were around day 316 at BNKK station and around day 318 at CHMI station.

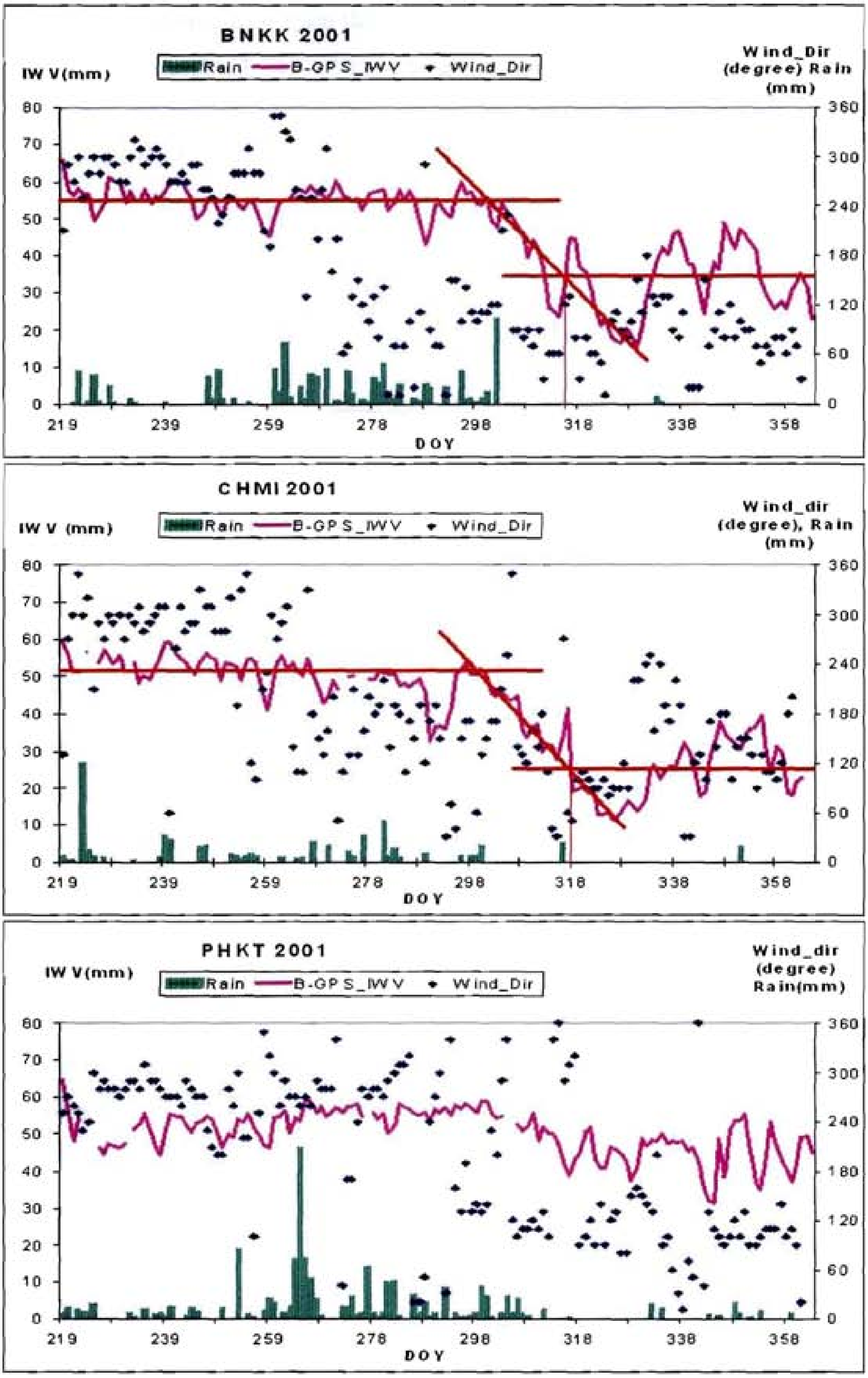

Figure 4.3 Comparisons of B-GPS_IWV, Wind Direction and Rainfall of year 2001 (withdrawal). Top: BNKK station. Middle: CHMI station. Bottom: PHKT station.

With the information from the onset and withdrawal, the period of southwest monsoon can be identified. Table 4.1 shows the period of southwest monsoon for year 2001 to 2003. It is seen from table 4.1 that the period of southwest monsoon in Thailand is around 6 months with the onset around day 138 (May) and the withdrawal around day 320 (November)

Table 4.1 Summary of results of the investigation of Southwest Monsoon period base on B-GPS_IWV data.

Year	Onset	withdrawal
2001	-	Day 328
2002	Day 138	Day 302
2003	-	Day 330
Mean	Day 138	Day 320

According to the change of B-GPS_IWV level at "low-to-high" and "high-to-low" for onset and withdrawal, respectively, this change can be called as the transition period. In order to explain the transitions period, the slope of the level change of B-GPS_IWV can be chosen.

In this research, the method which obtained the transition period slope cannot be done because the B-GPS_IWV dataset does not support (the DOY cannot be used for slope calculation). In the present knowledge, we do not have any methods or the other data for the DOY conversion into the suitable value. The future research, we will have to find the way how to convert the DOY for the transition period slope consideration.

4.2 Consideration of the passage of high pressure area

This section is the use of B-GPS_IWV to prove the possibility in Thai meteorological use. The use of B-GPS_IWV was divided into two terms for the explanation of winter season in Thailand. First, The B-GPS_IWV was used to consider its phenomenon of each station for explaining the winter seasonal behavior.

Second, the consideration of B-GPS_IWV during the passage of high pressure area was used to explain the influence of high pressure area. In this study, the B-GPS_IWV was used together with pressure data and Synoptic Map.

Generally, the winter season of Thailand is around November to February [6].The weather is cold and dry because the cold and dry air mass flowing from the main land China to Thailand. However, the characteristic of cold air is also different due to the location of each region.

In case of high pressure area move down to Thailand, the weather under this condition is cold and dry air [18]. Then, it is the cause to the decrease of water vapour content in the atmosphere as shows in Figure 4.4.

Figure 4.4 shows the comparison between B-GPS_IWV (Black line) and the surface pressure (Gray line) of BNKK (Top) and CHMI (Bottom) in the period of winter season, where primary-Y-axis is IWV (mm), secondary-Y-axis is surface pressure (hPa), and X-axis is DOY. In Figure 4.4, the B-GPS_IWV at both BNKK and CHMI stations change its level from about 60 to 10 mm, around day 325. It is clearly illustrated from the B-GPS_IWV to the influence of dry air in the winter season of Thailand.

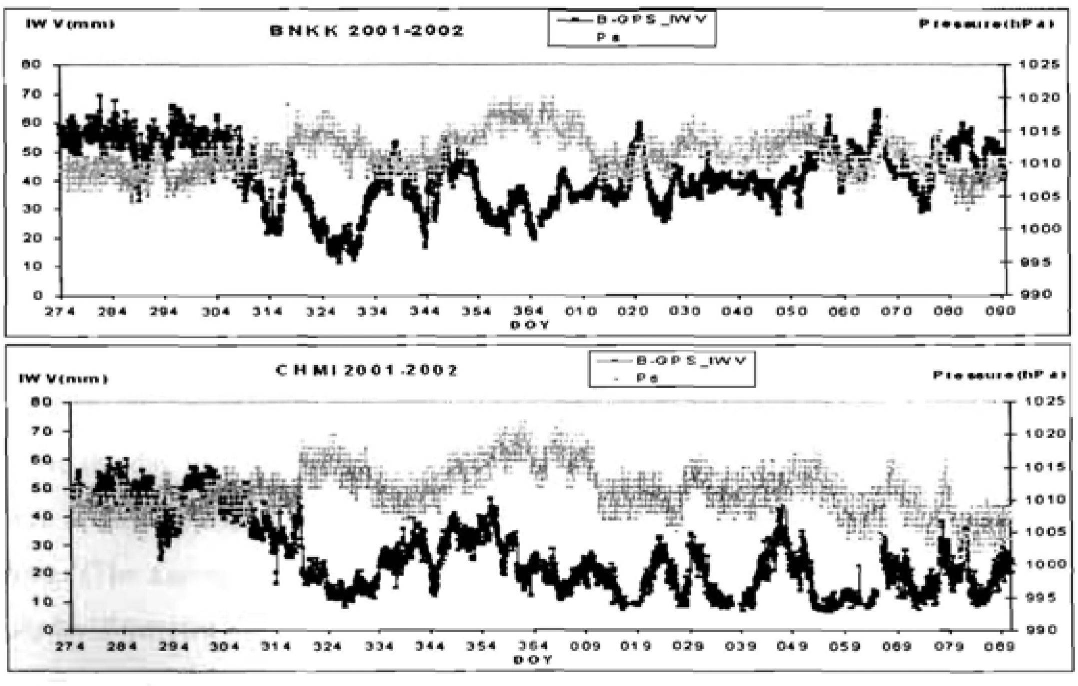

Figure 4.4 Comparison of B-GPS_IWV (Black color) and Surface Pressure (Gray color) of Year 2001 to 2002. Top: BNKK station. Bottom: CHMI station.

Thus, the characteristic of the cold air for each location can be explained by using B-GPS_IWV. At the BNKK station after day 325, the B-GPS_IWV slightly increases from around 10 mm to 40 mm during the winter period. On the other hand, it seems that the B-GPS_IWV is in "stable state" around 10 mm with some variational occurrence at CHMI station.

The B-GPS_IWV shows different characteristic due to the location of each station. The BNKK station is located closer to the Gulf of Thailand than CHMI station and the moist air is easily transferred to the BNKK station. Therefore, the slightly increment characteristic is shown at BNKK station whilst the more stable characteristic is presented with the lack of water vapour supply at CHMI station.

The passage of high pressure area can be explained by the B-GPS_IWV. This leads to another application of B-GPS_IWV. According to the studies of the GPS_IWV during the passage of a Typhoon by Yuei et al. [5], the GPS_IWV was increased by a lot of water vapour from the passage of Typhoon. Then, the oppositional result of their studies is illustrated when the passage of high pressure area event is occurred. For example, the B-GPS_IWV had been decreasing for 5 days before the high pressure area moved down to Thailand area in day 323. (See Figure 4.4 for the B-GPS_IWV and Figure 4.5 – 4.9 for the Synoptic map [42] with the passage of high pressure area of day 323, the isobar 1012 hPa line was covered the BNKK station)

The same phenomenon was found again when the high pressure area moved down to BNKK station between day 343 and 357, the decremental B-GPS_IWV was occurred around 4 days before day 343 and around 5 days before day 357, respectively.

Furthermore, the slopes of the decremental B-GPS_IWV of the day span before the day that high pressure area move down such as the day 323, 343, and 357 were around -0.19, -0.19, and -0.16, respectively. These slopes are about the same value. (The average value is -0.18) Therefore, the passage of the high pressure area may be illustrated by the slope value is around -0.18.

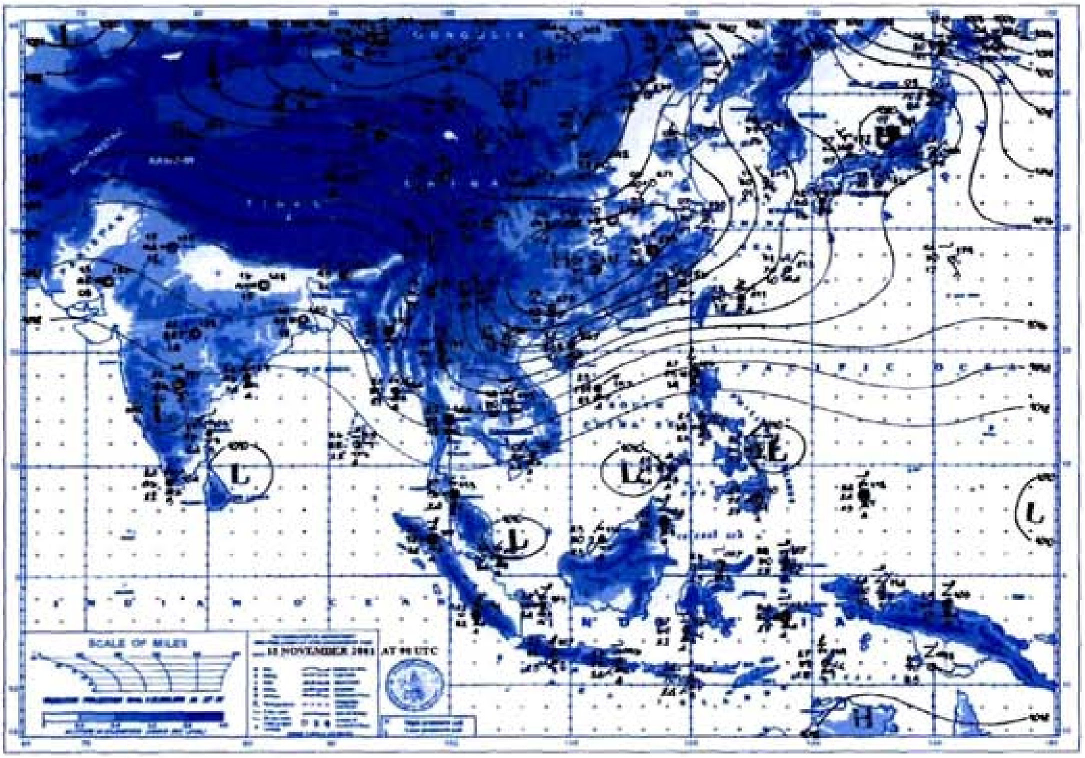

Figure 4.5 The Synoptic Map day 319, year 2001[42]

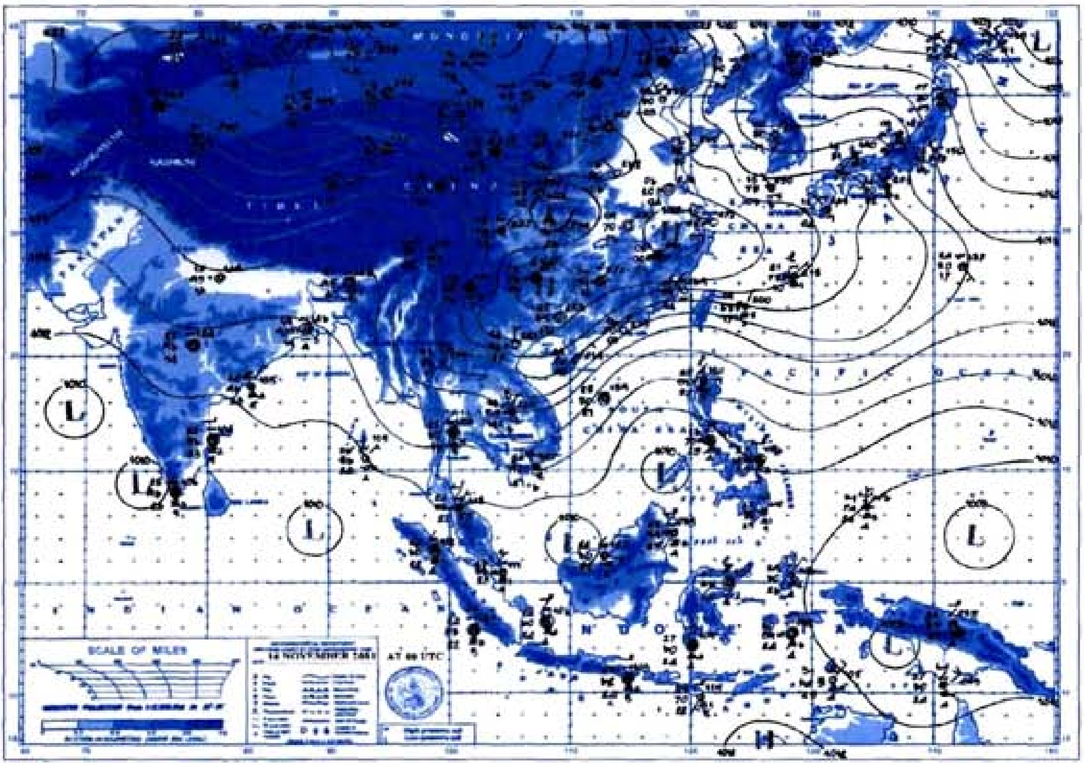

Figure 4.6 The Synoptic Map day 320, year 2001[42]

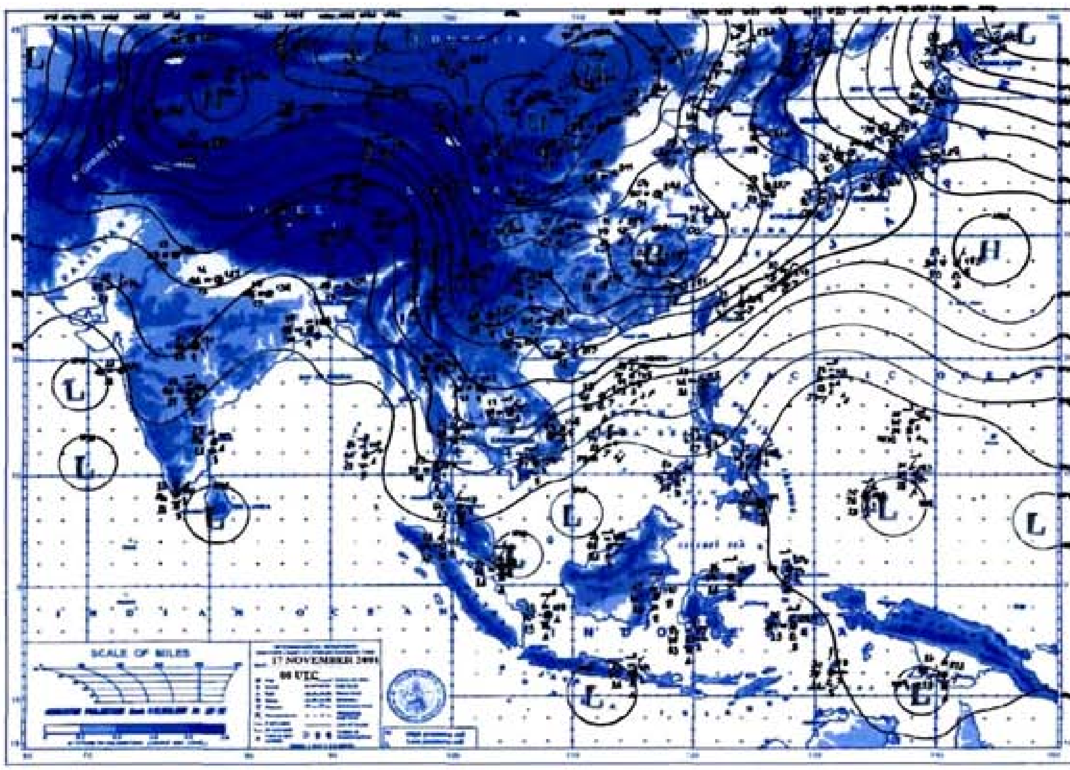

Figure 4.7 The Synoptic Map day 321, year 2001[**42**]

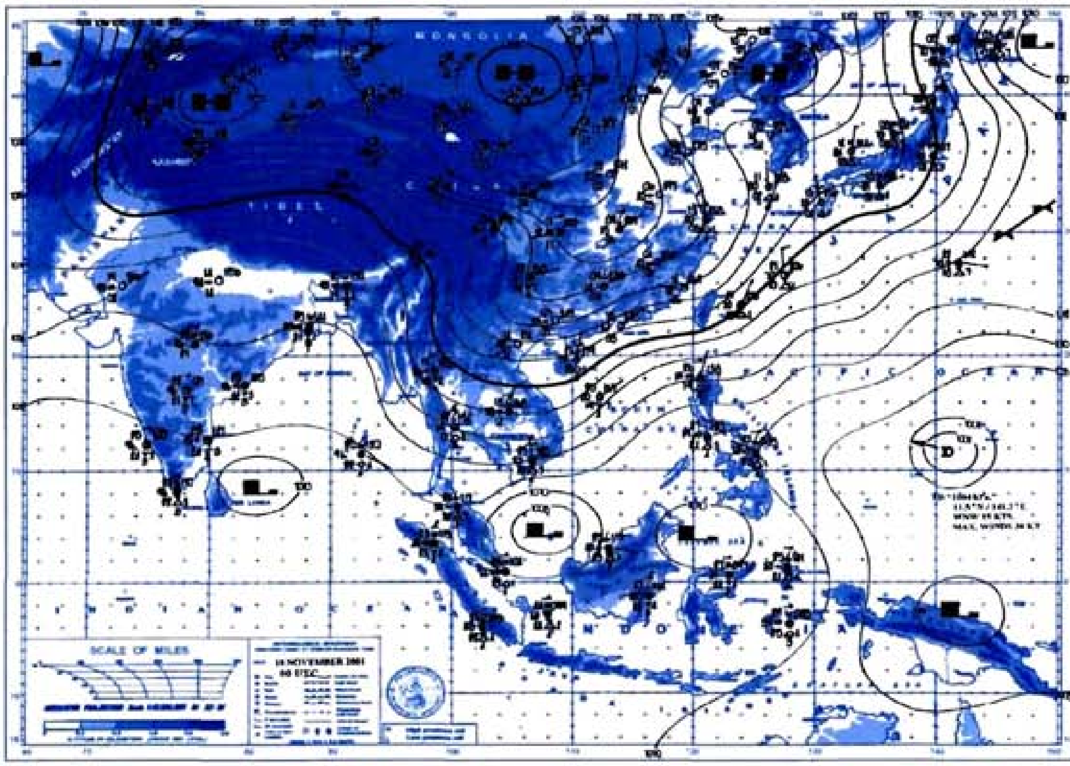

Figure 4.8 The Synoptic Map day 322, year 2001[**42**]

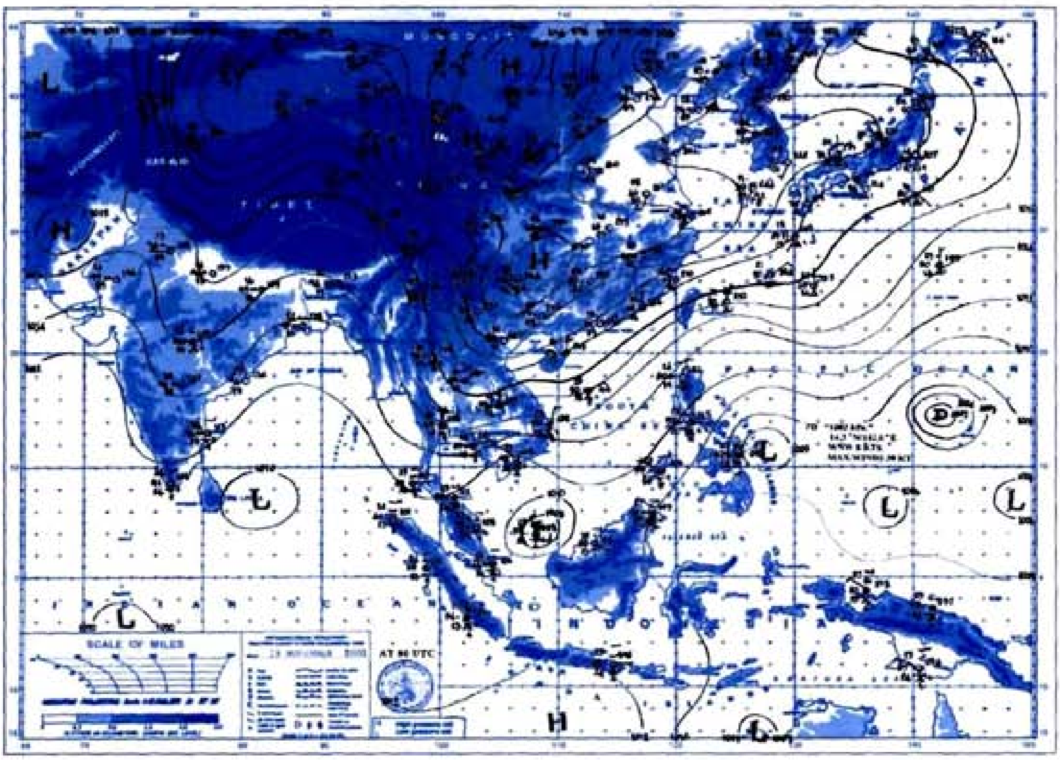

Figure 4.9 The Synoptic Map day 323, year 2001**[42]**

4.3 Consideration of the confluence wind from the Gulf of Thailand into the land

This section is the use of B-GPS_IWV together with wind direction, wind speed, and the Synoptic Map to consider the confluence wind. The inner-relation of the data for one station and the relation among the stations were investigated.

The air mass over some areas can be transferred to the other areas by the wind. Therefore, the moist air from the ocean can be transferred into the land **[15]**. In Thailand, the wind that flows from the Gulf of Thailand into the land is in the south-to-east direction range, namely "the confluence wind from the Gulf of Thailand" **[6]**.

Referring to the Bureau of Royal Rain-making and Agricultural Aviation (BRRAA), the confluence wind dominates around January to April and the most appearance is in March. This wind may cause the heavy rain or the hailstone if the combination between high pressure area and confluence wind is occurred **[6]**.

The air over the land which is saturated by moist air is influenced by the confluence wind. Thus, it can be explained by a spike of B-GPS_IWV appearing in the days of the dominative confluence wind. Figure 4.10 illustrates the B-GPS_IWV spike of BNKK and CHMI station of year 2003, where left-Y-axis consists of IWV in mm (Blue line) and wind speed in km per hour (Black bars), right-Y-axis is wind direction in degree (Orange points), and X-axis is DOY.

For example, the day of the dominative confluence wind was day 80. (See Figure 4.11, the Synoptic Map day 080, year 2003 [44] and Figure 4.12, the UPPER WIND at 600 METERS of the same day [45]) The spike at BNKK station is 52.83 mm with the wind direction was 180 degrees and wind speed was 8 km per hour. At the same day in CHMI station, the spike also occurred with the maximum peak 27.62 mm, wind direction was 320 degrees, and wind speed was 3 km per hour.

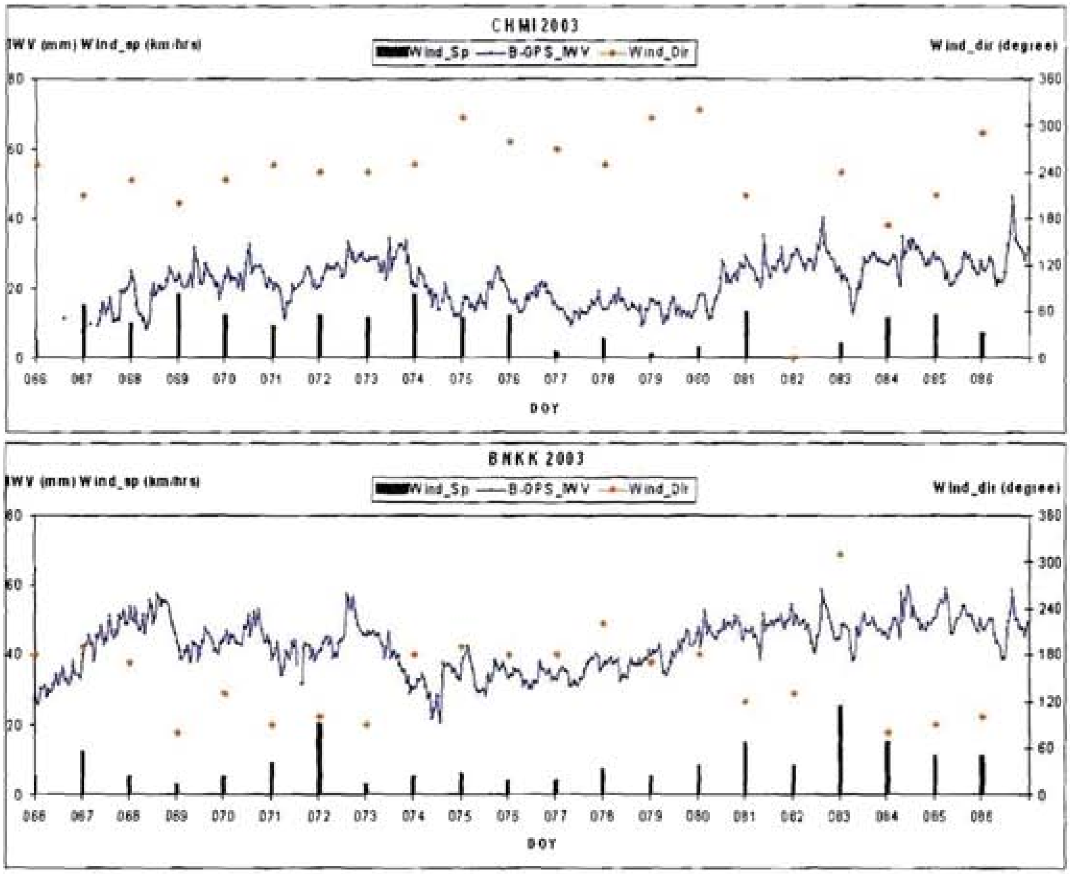

Figure 4.10 Comparisons of B-GPS_IWV, Wind Direction and Wind Speed. Top: CHMI station. Bottom: BNKK station

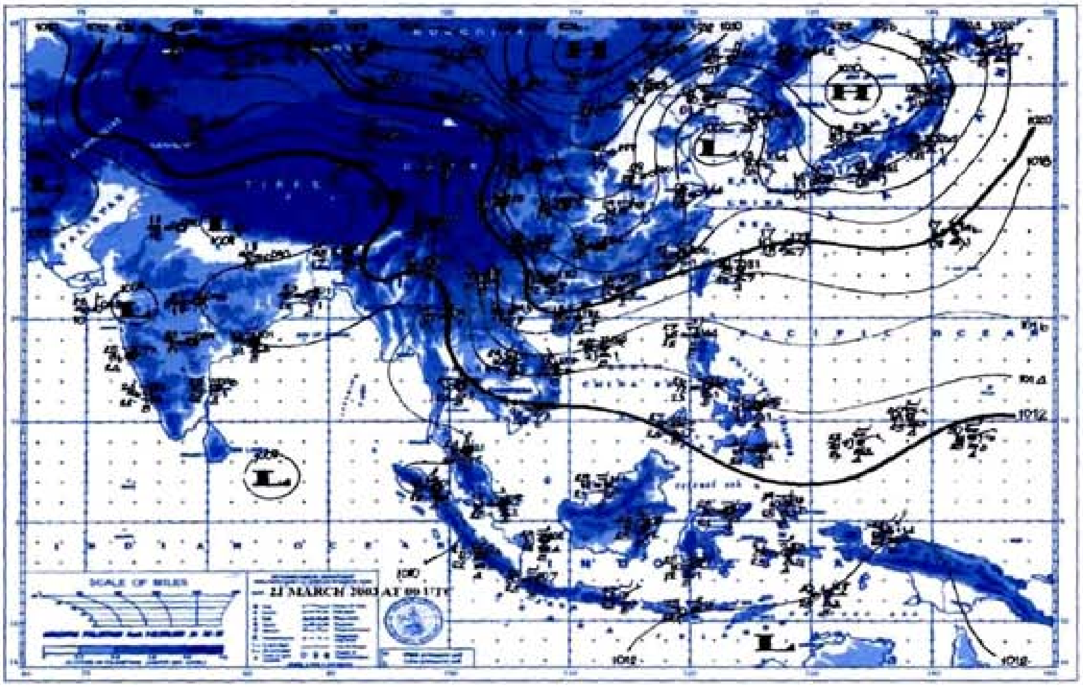

Figure 4.11 The Synoptic Map day 080, year 2003 **[44]**

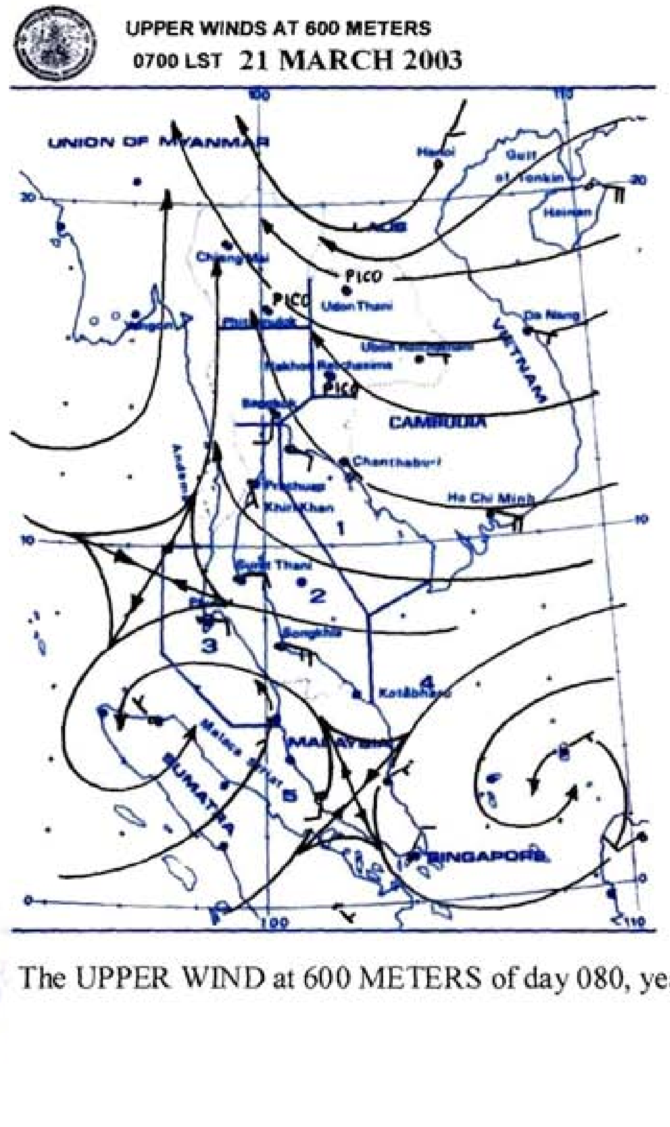

Figure 4.12 The UPPER WIND at 600 METERS of day 080, year 2003 [45]

Other days that the confluence wind dominates are shown in table 4.2. It is shown that the wind direction range was around 100 – 180 degrees at BNKK station and around 200 – 300 degrees at CHMI station. In this case, it can illustrate that the wind from the Gulf of Thailand flows to CHMI by passing though the BNKK station. However, the wind speed does not seem to the close relationship with the other information. This may be due to the unreliable wind seed data which is obtained only one time per day.

Table 4.2 The days of year 2003 that the effect of confluence wind occurred.

	BNKK				CHMI			
	Wind		Min.	Max.	Wind		Min.	Max.
DOY	Direction (degree)	Speed (km/hrs)	IWV (mm)	peak (mm)	Direction (degree)	Speed (km/hrs)	IWV (mm)	peak (mm)
069	80	3	37.75	47.72	200	18	16.81	31.40
072	100	20	38.99	57.49	240	12	20.73	33.08
073	90	3	28.91	46.51	240	11	21.51	34.38
080	180	8	44.22	52.83	320	3	11.15	27.62
086	100	11	38.81	58.48	290	7	21.14	45.83

From reasons above, the phenomenon of the occurrent spike for both stations can be used to explain the transfer of moist air by confluence wind from the Gulf of Thailand.

CHAPTER V
CONCLUSIONS AND SUGGESTIONS

GPS can be applied to many fields of studies. The one of the GPS applications is the conversion of "the geodetic noise" to "the meteorological signals" for the use of meteorological field **[9]**.

The IWV is the value obtained from GPS which is the same value obtained from the WMR instrument. The accuracy of GPS_IWV is to be equivalent to the WMR_IWV because the results of their comparison show a good agreement, but the advantage of GPS is a low cost instrument.

For the use of GPS-meteorology in Thailand, it is clearly seen from the three case studies that the results introduce the good possibility and suitability to fully use in Thailand. The first one illustrates the next step of the study on southwest monsoon period in Thailand. The precise days of the monsoon that are indicated by using GPS_IWV respond to the success of the water budget management. The second one can display the difference of winter season of each Thailand area and the effect of high pressure area. Thus, it will provide that the GPS_IWV can be used as the one of fundamental data for meteorology. The last one shows the good way to develop the monitoring system because the GPS_IWV can be used to identify the transferential characteristic of the moist air. It may be useful to the BRRAA for rain-making activity.

This research uses the history dataset only 3 consecutive years. Therefore, the results will be more significance if we have more the dataset. Moreover, this research only used GPS data from 4 permanent stations. Then, they cannot represent an entire Thailand area. If there are more GPS permanent stations in the future, these GPS data will be vary useful for meteorological studies.

In comparing of GPS and WMR, it is found that the advantage of GPS is less expensive than WMR and it can be used for many applications in the same time (e.g. for meteorological and geodetical purpose) but the disadvantage of GPS is the method to obtain IWV data is difficult than WMR.

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APPENDICES

Appendix A

The Mean Temperature Tm

APPENDIX A

The Mean Temperature Tm

For each station *Tm* can be obtained by the *Tm-Ts* relationship can be determined by minimizing the Chi-square error statistic as

$$Tm = aTs + C \qquad \text{.........................} (2)$$

The Tm-Ts relationship equations for each station are given by

BNKK T_m = 041 T_s + 142.73 with correlation coefficient 0.41 ...... (A-1)

CHMI T_m = 0.35 T_s + 159.36 with correlation coefficient 0.76 ...... (A-2)

PHKT T_m = 0.48 T_s + 121.27 with correlation coefficient 0.56 ...... (A-3)

Yuei and Yang [14] suggested that the correlation coefficient should be 0.85. Therefore, all of equations cannot be used.

By this reason, Bevis et al. [10] showed the proportional coefficient κ per ρ_{H_2O} is the density of water was about 0.15 in general. Then, equation (18) becomes to equation (A1)

$$IWV = \pi \times ZWD \qquad \text{.........................} (A1)$$

where π is about 0.15

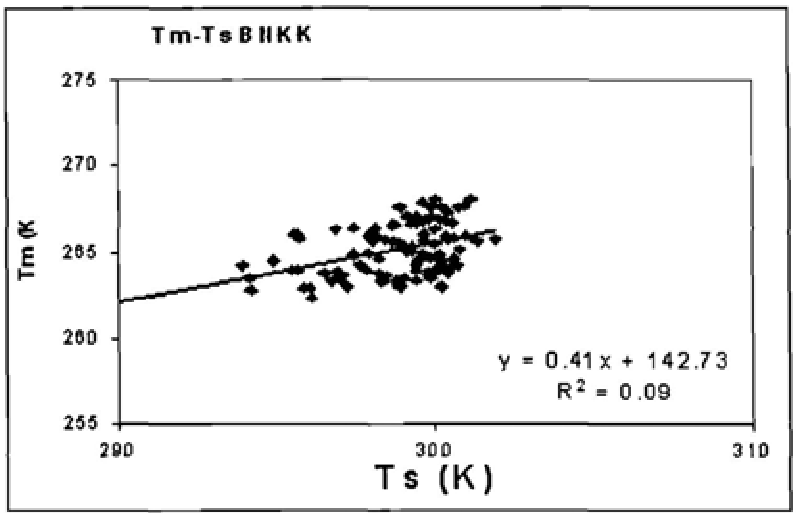

Figure A-1 The relationship between *Tm* and *Ts* and Its regression coefficient of BNKK station.

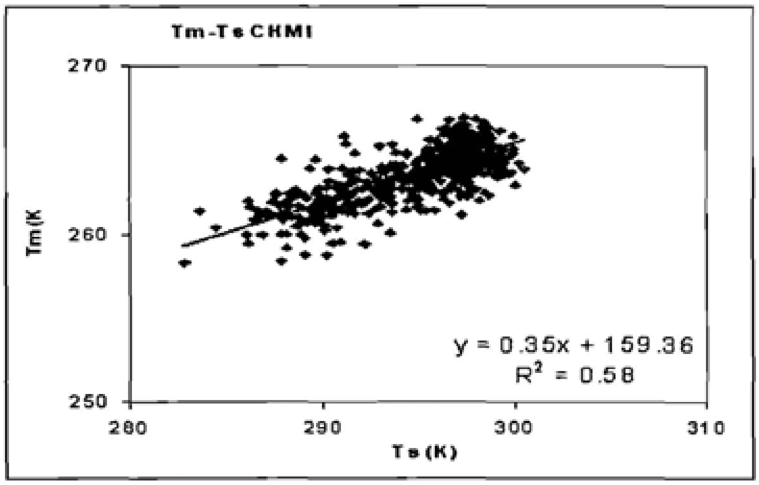

Figure A-2 The relationship between *Tm* and *Ts* and Its regression coefficient of CHMI station.

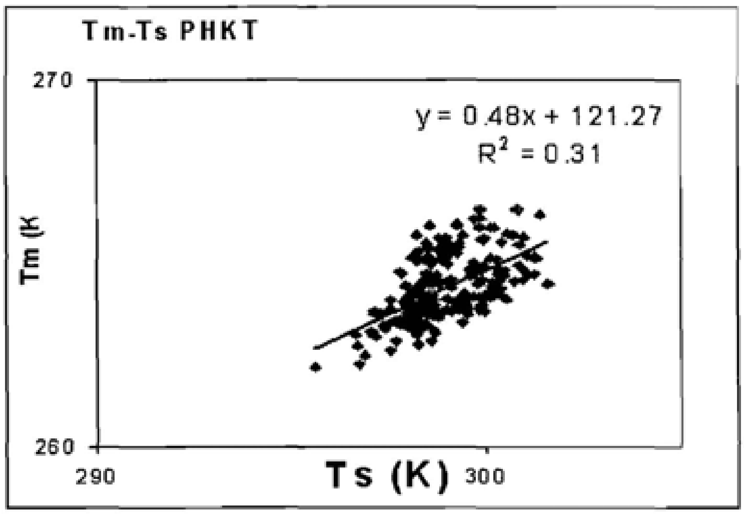

Figure A-3 The relationship between *Tm* and *Ts* and Its regression coefficient of PHKT station.

Appendix B

On the accuracy of WMR data

APPENDIX B

On the accuracy of WMR data

According to the WMR instrument was automatically created the WMR_IWV, generally this data can be immediately used. However, several errors were combined inside this data.

Elgered et al. **[24]**, found the one of error was the algorithm error due to liquid water or the presence raindrops. In the rainy day condition, the raindrops on the horn antennas was made the error of WMR_IWV data when the signal was over- scattered by the liquid water drops before go to the sensor. Then, it is clearly seen why the peak of data was occurred under the condition of rainy day.

In order to remove the error data with a condition of rainy day, the double-standard deviation (2SD) was chosen. The SD value calculated from the real WMR_IWV and then the RAW data with over the 2SD was eliminated.

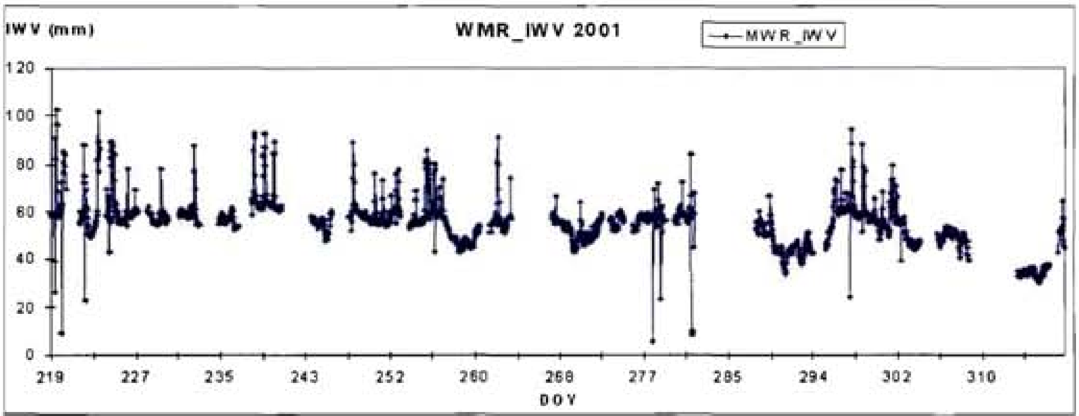

Figure B-1 The WMR_IWV with non-eliminated by the 2SD value.

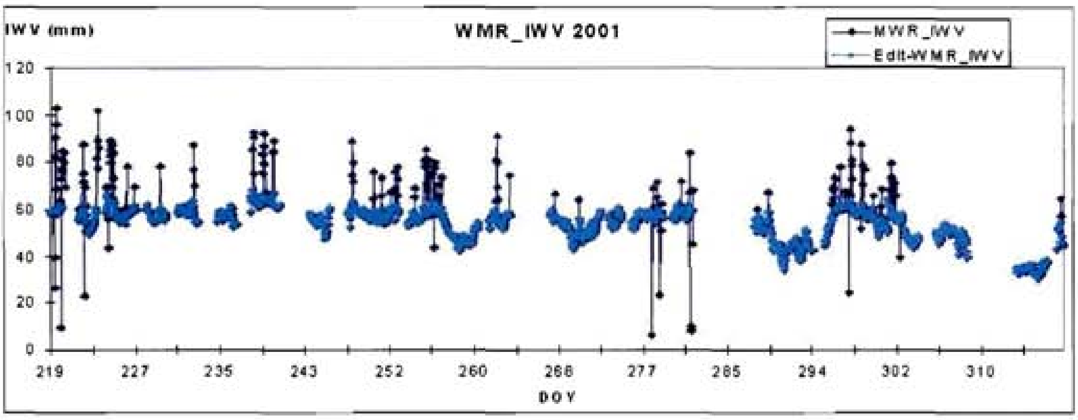

Figure B-2 The comparison between WMR_IWV data with eliminated by 2SD value and the RAW-WMR_IWV data.

Figure B-1 shows that the error peaks of WMR_IWV data in the rainy day with non-eliminated by 2SD value of year 2001 and the SD of this data was about 9.14 and the mean value about 50.69 mm.

When filtered by the 2SD values, the new WMR_IWV data was smooth than the old one. The new SD was about 7.02 and the mean value was about 49.68 mm.

Appendix C

The B-GPS_IWV data

APPENDIX C

The B-GPS_IWV data

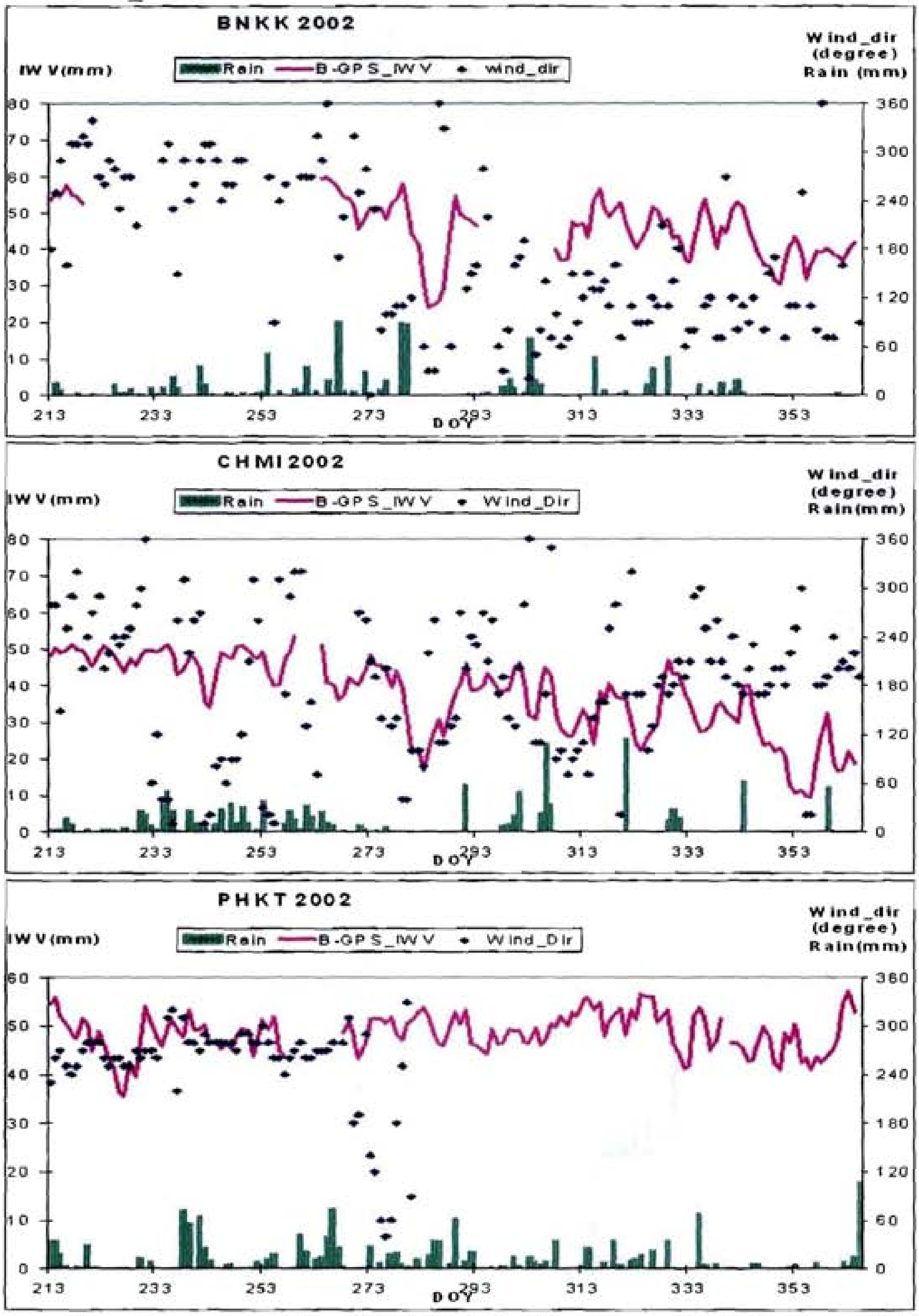

Figure C-1 Comparisons of B-GPS_IWV, Wind Direction and Rainfall of year 2002. (Withdrawal)Top: BNKK station. Middle: CHMI station. Bottom: PHKT station.

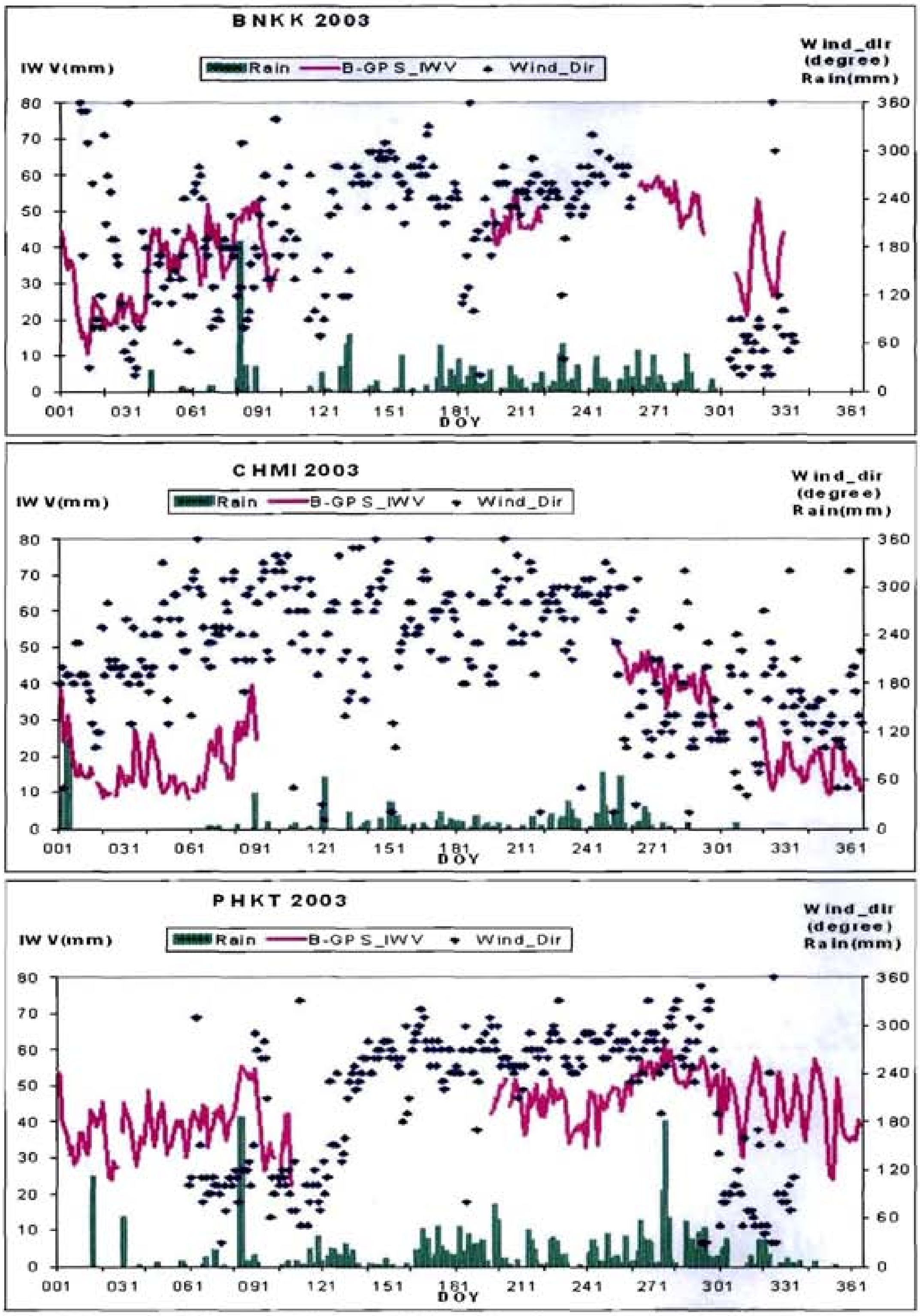

Figure C-2 The B-GPS_IWV, Wind Direction and Rainfall of year 2003.

Top: BNKK station. Middle: CHMI station. Bottom: PHKT station.

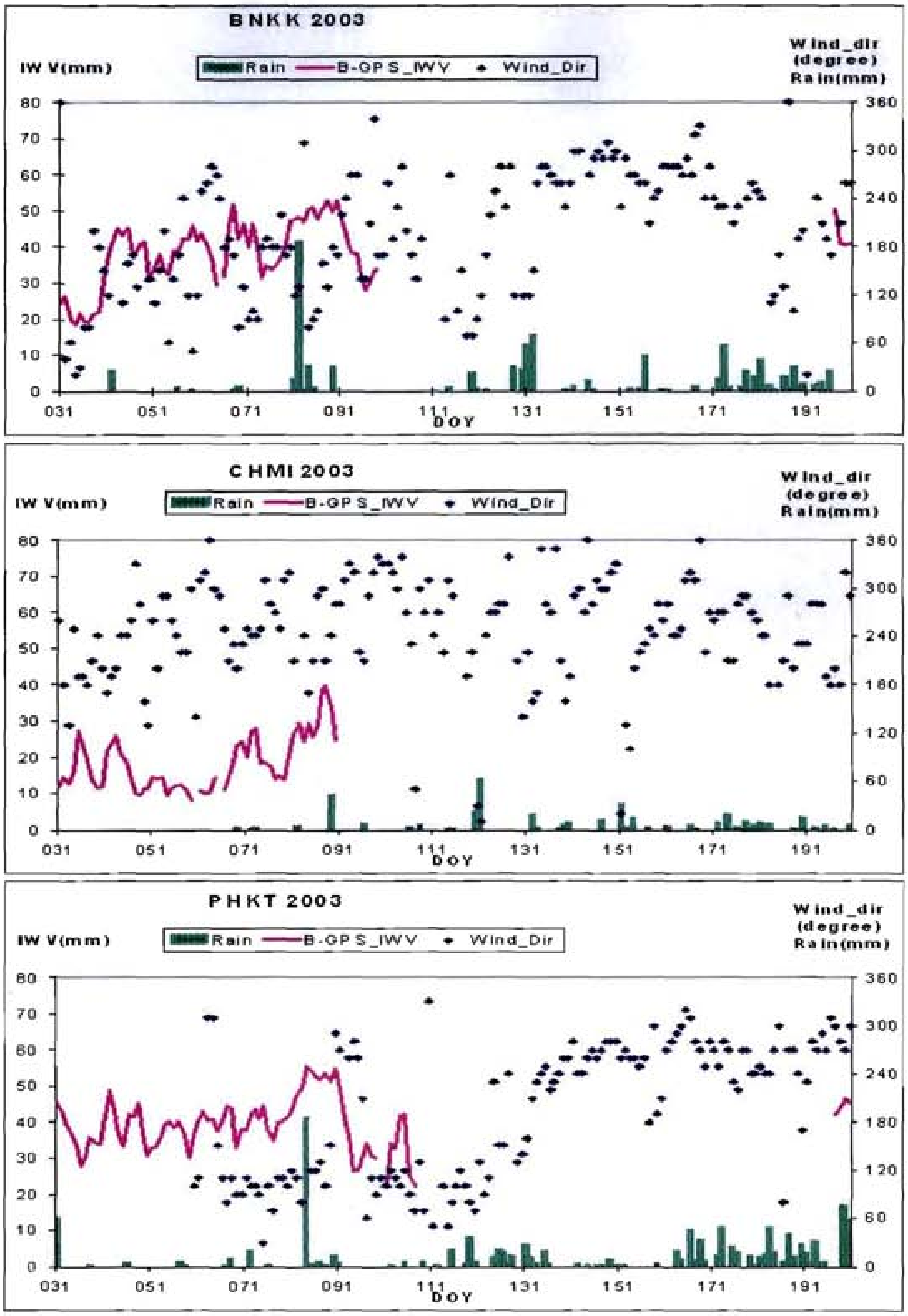

Figure C-3 Comparisons of B-GPS_IWV, Wind Direction and Rainfall of year 2003. (Onset)Top: BNKK station. Middle: CHMI station. Bottom: PHKT station.

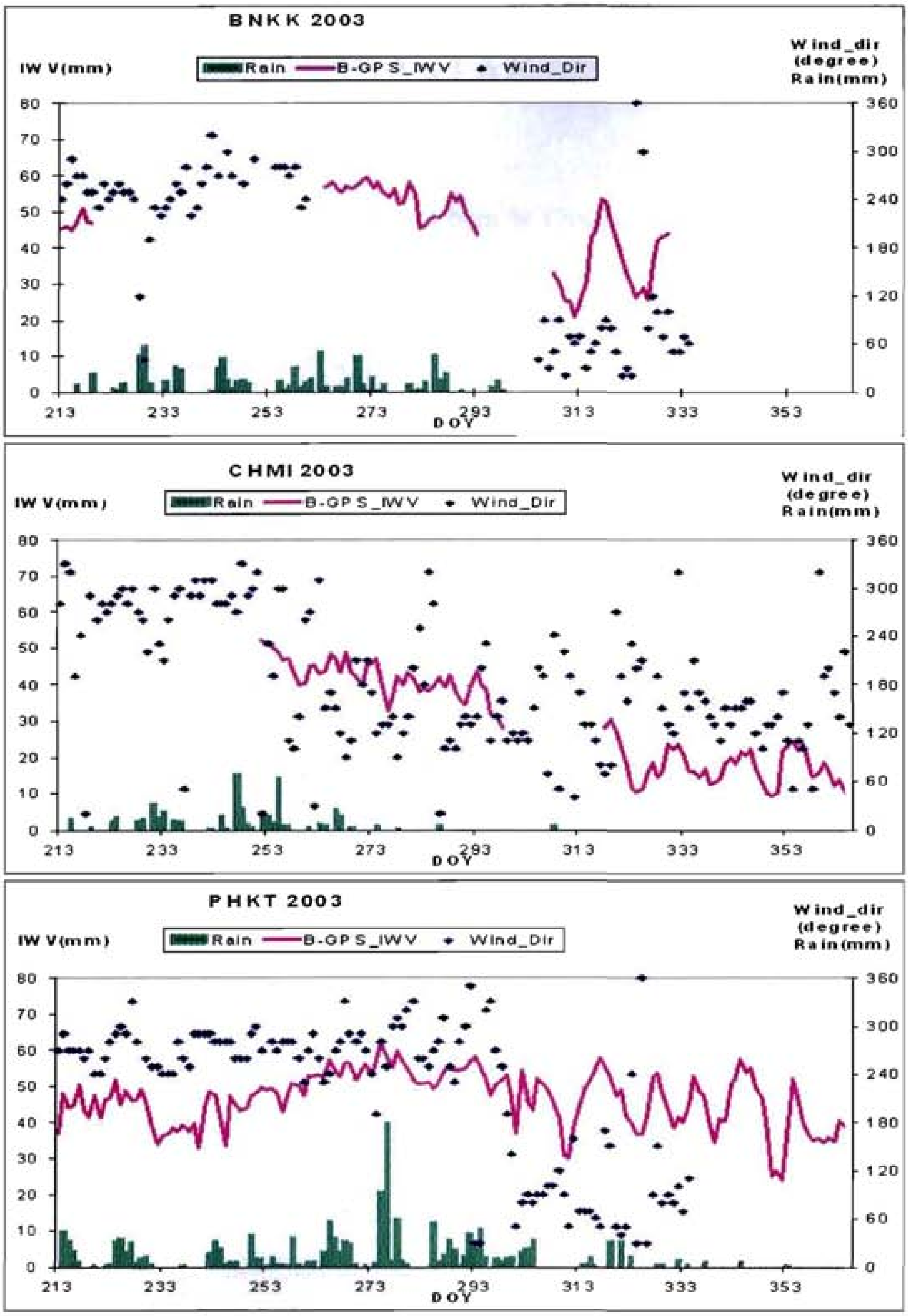

Figure C-4 Comparisons of B-GPS_IWV, Wind Direction and Rainfall of year 2003. (Withdrawal)Top: BNKK station. Middle: CHMI station. Bottom: PHKT station

VITAE

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