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CHARACTERISTICS OF MOISTURE TRANSPORT IN ENSO EVENTS IN VIETNAM

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ABSTRACT OF EARTH SCIENCES DISSERTATION

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PREFACE

1. Rationale

Located in the Asian monsoon region, the climate of Vietnam is strongly influenced by the monsoon circulation and the ENSO events. Below-average annual rainfall was observed over Vietnam in El Niño years, due to the strengthen convection in the Eastern Pacific. Whereas, the westward-moving of this convection in La Niña years caused much more rainfall over Vietnam than average. It is indicated that the moisture transport plays an important role in tropical monsoon circulation mechanism as well as affects the weather and climate in Vietnam, especially extreme event such as drought and heavy rain. Therefore, this research titled "**Characteristics of moisture transport in the ENSO events in Vietnam"** is essential.

2. Objectives of research

1) To explore mechanism of the seasonal moisture transport in Vietnam.

2) To determine the relationship between the moisture transport and the ENSO event, especially in ENSO years which heavy rainfall or severe drought occurred in Vietnam.

3) To propose the application of the moisture transport information for monitoring droughts (during El Niño) and heavy rainfall (during La Niña) over Vietnam.

3. Objects and research area

- Objects of research

+ Moisture transport: Total moisture transport, zonal and meridional moisture transport.

+ Circulation component: Zonal and meridional winds, sea

level pressure.

+ The climatic elements and extreme events includes: observed monthly rainfall from meteorological stations in Vietnam, the grid reanalysis data of precipitation, the number of month with drought, the number of month with heavy rainfall.

- Research area

+ Characteristics of moisture transport are evaluated over a region of the Eastern Asia - Western Pacific (40°S-60°N, 40°E-60°W), so called DATTBD (abbreviation in Vietnamese).

+ The circulation and sea level pressure are analysed over the Eastern Asian region (10°S-40°N, 60°E-160°E).

+ The characteristics of climate, the number of drought months and the number of heavy rainfall months are assessed over all climatic regions of Vietnam.

4. The new finding of the research

1) This research determined the moisture source and the moisture distribution in both normal and ENSO condition.

2) This research specified the relationship between the moisture transport and droughts, heavy rain over climatic regions of Vietnam during ENSO events.

3) This research also primarily explained the physical mechanisms for evaluating the relationship between the moisture transport and the autumn rainfall in the Central Vietnam during ENSO period; and the rainfall in May in the Central Highlands during El Niño events.

5. Perspective of the research

1) There are differences in the distribution of the moisture transport between the normal condition and the ENSO condition.

2) There is a relationship between the moisture transport and droughts, heavy rainfall over all climatic regions of Vietnam during ENSO events.

3) The moisture transport is highly correlated to the autumn rainfall in the Central Vietnam during ENSO condition and the precipitation in May in the Central Highlands during El Niño condition.

6. Scientific and practical signification

- The thesis represented the mechanism of the moisture transport at annual and seasonal scale in Vietnam during normal condition and ENSO condition.

- The thesis determined the relationship between the moisture transport and heavy rain during La Niña events, and droughts during El Niño events in Vietnam.

- The thesis initially explained the physical mechanism which caused the decrease of rainfall in autumn over the Central Vietnam during El Niño conditions, and the increase of rainfall during La Niña conditions.

- The results of this dissertation can be used as reference for further study of the relationship between the moisture transport and rainfall, droughts during ENSO events. In addition, these results are also useful for climate prediction which using the moisture transport information for drought assessment during El Niño conditions and heavy rain during La Niña conditions.

7. The structure of the thesis

Chapter 1: Literature reviews

Chapter 2: Data and Methodology

Chapter 3: Distribution of moisture transport under ENSO conditions.

Chapter 4: The relationship between moisture transport and droughts, heavy rain and rain over some regions of Vietnam during ENSO.

Chapter 1: Literature reviews

1.1. Overview of moisture transport

From the mid-1980s, with the advanced improvement in observation technology and the rapid development of computer science, the moisture transport was thoroughly researched all over the world which certainly contributed to the study of atmospheric circulation and climate prediction.Various researches have been conducted with the diversity of the reasearch objects, in different regions and countries which evaluated some aspects of the moisture transport includes:

- The spatial distribution of moisture transport: Zonal, meridional and systhesized transport over various regions, the major moisture transport over the continents.

- The temporal development of the moisture transport over regions (includes monsoon region).

- The relationship between the amount of moisture transport and precipitation, especially with the extreme events such as drought, heavy rainfall over many countries: India in South Asia, China in the East Asia, Canada in the North America, South America, Australia and other continents.

- The moisture balance or the moisture transport crossing the boundaries: Western, Eastern, Southern, Northern borders of many areas in South Asia, East Asia and some regions in North America.

In Vietnam, in recent years, many climatic researches have been interested in this important atmospheric circulation element: The atmospheric moisture transport and the relationship between the moisture transport and monsoon as well as rainfall in some areas over Vietnam. The results indicated that the moisture transport is

highly correlated to rainfall in the summer in the Northern and Southern of Vietnam [4], [5], [20].

1.2. Overview of ENSO and its impacts on weather and climate

In recent years, with the advances of coupled atmosphere-ocean model, the development of computer technology over the world, many researches on ENSO events have been conducted including about the physical mechanisms and the operation of ENSO, the indices, characteristics in spatial and temporal distribution of ENSO, the impact of ENSO to the circulation, monsoon, weather, climate and extreme events .

1.3. Chapter summary

In Vietnam, the researches on moisture transport have been carried out since the 2000s in some regions. The monthly spatial moisture transport and the relationship between transport moisture and summer rainfall in the North and South of Vietnam were mentioned. So far, there is not any study or analysis on the seasonal moisture transport mechanism over Vietnam, particularly moisture transport under the ENSO conditions, the relationship between moisture transport and droughts, heavy rain in Vietnam. It is similar to the study about the ENSO events which were started from the 1990s, their principal research objects are the fundamental knowledge of ENSO and the impacts of ENSO to atmospheric circulation, monsoon, weather and climate. Therefore, it is necessary to have further analysis of the following issues:- The spatial distribution of seasonal total moisture transport in the atmospheric layers and in the whole atmospheric column in normal condition and under the ENSO condition.- The relationship between moisture

transport and droughts as well as heavy rainfall during ENSO events.

- In association with the circulation, the moisture and moisture transport have significant impact on rainfall. It is necessary for a deeper investigation for some particular regions such as the Central Vietnam or the Central Highlands.

Chapter 2: Data and Methodology

2.1. Methodology

2.1.1. Atmospheric moisture transport calculation method

The moisture transport characteristics were calculated including total moisture transport, zonal and meridional moisture transport over the entire atmospheric column (1000 - 300 hPa) and on 3 layers of atmosphere (1000-700 hPa, 700-500 hPa and 500-300 hPa).

1) Moisture transport vector on the whole atmospheric column from the surface (Ps=1000 hPa) to 300 hPa level is calculated following the formula below: [42, 44]:

$$\vec{Q} = -\frac{1}{g}\int_{1000}^{300}(\vec{V}q)dp \quad (1)$$

2) Zonal moisture transport (Q_u, kg $m^{-1}s^{-1}$) in the whole atmospheric column from the surface (1000 hPa) to 300 hPa level is calculated following the formula below:

$$Q_u = -\frac{1}{g}\int_{1000}^{300}(uq)dp \quad (2)$$

3) Meridional moisture transport (Q_v, kg $m^{-1}s^{-1}$) over the whole atmospheric column from the surface (1000 hPa) to 300 hPa level is calculated following the formula below:

$$Q_v = -\frac{1}{g}\int_{1000}^{300}(vq)dp \quad (3)$$

4) Total moisture transport in the whole atmospheric column (Q, kg m^{-1} s^{-1}) is calculated by the formula:

$$Q = \sqrt{Q_u^2 + Q_v^2} \quad (4)$$

Where: g- gravitational acceleration (m s^{-2}); *V*- wind vector; u-zonal wind speed (m s^{-1}) and v- meridional wind speed (m s-1); q special humidity (g kg^{-1}); p_s-pressure surface (1000 hPa).

5) Zonal moisture transport in the atmospheric layer from P_1 to P_2 is calculated by the formula:

$$Q_u(p_1, p_2) = -\frac{1}{g}\int_{p_1}^{p_2} u(p)p(p)dp \quad (5)$$

6) Meridional moisture transport on the atmospheric layer from P_1 to P_2 is calculated by the formula:

$$Q_v(p_1, p_2) = -\frac{1}{g}\int_{p_1}^{p_2} v(p)p(p)dp \quad (6)$$

7) Total moisture transport on P_1 to P_2 atmospheric layers

$$Q = \sqrt{Q_u^2 + Q_v^2} \quad (7)$$

In this dissertation, total moisture transport in the entire atmospheric column is calculated using zonal moisture transport (Qu) and meridional moisture transport (Qv) by the continuous integral approximation method with the trapezoidal rule for each layer of the atmosphere, separated by standard isobaric surface 1000, 925, 850, 700, 600, 500, 400, 300hPa. Resultant moisture transport over 3 atmospheric layers: 1) 1000 -700hPa (P_1 = 1000 hPa, P_2 = 700 hPa); 2) 700-500hPa (P_1 = 700 hPa, P_2 = 500 hPa) and 3) 500-300 hPa (P_1 = 500 hPa, P_2 = 300 hPa) is calculated by the zonal and meridional component on the atmospheric layers with the same method as for the whole atmospheric column.

Moisture transport was calculated on 2,5º x 2,5º grid for DATTBD (40^0S-60^0N, 40^0E-60^0W), for Vietnam and the surrounding regions. Besides, in some cases, moisture transport is calculated for East Asia region which limitted in 10^0S- 40^0N, 60^0E-160^0E.

2.1.2. Moisture transport crossing 4 boundaries over all the climatic regions in Viet Nam.

Monthly moisture transport on the whole atmospheric column in the period 1960-2009 through the boundary of 3 regions in Vietnam including (1) Northern region of Vietnam (BBVN) located in 20^0N-24^0N 102^0E-110^0E; (2) Central region of Vietnam (TBVN) located in 14^0N-20^0N, 102^0E-110^0E and (3) Southern region of Vietnam (NBVN) located in 8^0N-14^0N, 102^0E-110^0E.

2.1.3. Method of identifying the ENSO events

ENSO events are determined according to [4] the following criteria:

A La Niña occurs when there are at least six consecutive months with three month running mean of the SSTA over NINO 3.4 region is less than or equal to -0,5^0C.

An El Niño occurs when there are at least six consecutive months with three month running mean of the SSTA over NINO 3.4 region is greater than or equal to 0,5^0C.

Based on the above criteria, there were 13 El Niño events (109 El Niño months) and 11 La Niña events (168 La Niña months) during period 1960 – 2009.

2.1.4. Determination of heavy rain months and drought months

2.1.4.1 Determining heavy rain months

Over all climatic regions of Vietnam, the month with total rainfall is greater than or equal 450 mm is defined as heavy rain month.

2.1.4.2 Determining drought months

The drought month is the month with total rainfall (Rth) is less than or equal a threshold (R). This threshold is defined as:

For November, December, Januarry, February: R = 10 mm;For March, April, September, October: R = 30 mm;For other months: R = 80 mm.

2.1.5. The relationship between moisture transport and heavy rain, droughts

The relationships between moisture transport and the number of droughts months, the number of heavy rain months over Vietnam climatic regions are analyzed based on the correlation coefficient (r_{xy}) between 2 two variables x and y:

$$r_{xy} = \frac{\sum_t (x_t - \bar{x})(y_t - \bar{y})}{[\sum_t (x_t - \bar{x})^2 \sum_t (y_t - \bar{y})^2]^{\frac{1}{2}}} \quad (8)$$

Where: x- zonal moisture transport, meridional moisture transport; y- The number of drought or heavy rain month of 7 climatic regions of Vietnam

2.2. Data

- The station data: Using monthly rainfall data of 56 meteorological stations in the period 1960-2009 over 7 climatic regions of Vietnam.

- The data of circulation: specific humidity, zonal and meridional wind on isobaric surface levels 1000-300hPa with the resolution of 2,5°x2,5°.

- The wind field from Reanalysis dataset CFSR at 10m, 850hPa; mean sea level pressure with the resolution of 0,5°x0,5° in the period 1980-2007 from NCEP dataset.

- The APHRODITE rainfall dataset on the grid with the resolution of $0{,}25^0$x$0{,}25^0$.

Chapter 3: Distribution of moisture transport under ENSO conditions

3.1 Total moisture transport in ENSO condition.

3.1.1 Total moisture transport in normal conditions.

The South-western moisture transport has magnitude of 150-180 $kgm^{-1}s^{-1}$ on the entire atmospheric column, in which 60-70 $kgm^{-1}s^{-1}$ on layer 1, 58-68 $kgm^{-1}s^{-1}$ on layer 2 and 33-43 $kgm^{-1}s^{-1}$ on layer 3.

The amount of North-eastern moisture transport is 210-240 $kgm^{-1}s^{-1}$ in the entire atmospheric column, in which 90-100 $kgm^{-1}s^{-1}$ on layer 1, 75-85 $kgm^{-1}s^{-1}$ on layer 2 and 45 - 55 $kgm^{-1}s^{-1}$ on layer 3.

The South-eastern moisture transport has magnitude of 170-200 $kgm^{-1}s^{-1}$ in the whole atmospheric column, in which 110-120 $kgm^{-1}s^{-1}$ on layer 1, 50-60 $kgm^{-1}s^{-1}$ on layer 2 and only 10-20 $kgm^{-1}s^{-1}$ on layer 3.

Thus, in annual scale, the moisture transport intensity is strongest in North-eastern zone, and then the South-eastern and the weakest is the South-western zone. The moisture transport decreases from layer 1 to layer 2 and from layer 2 to layer 3.

Total moisture transport always changes in the direction and intensity each season.

In the North of Vietnam, the western and southwestern moisture transport is 75-90 $kgm^{-1}s^{-1}$ in the whole atmospheric column, in which 33-38 $kgm^{-1}s^{-1}$ on layer 1, 28-33 $kgm^{-1}s^{-1}$ on layer 2 and 15-20 $kgm^{-1}s^{-1}$ on layer 3.Over the Central of Vietnam, Eastern and North-eastern moisture transport is 45-60 $kgm^{-1}s^{-1}$ in the whole atmospheric column, in which 25-30 $kgm^{-1}s^{-1}$ on layer 1, 10-15 $kgm^{-1}s^{-1}$ on layer 2 and on layer 3.

In the South of Vietnam, eastern and northeastern moisture transport is 45-60 $kgm^{-1}s^{-1}$ in the whole atmospheric column, in which 20-15 $kgm^{-1}s^{-1}$ on layer 1, 15-20 $kgm^{-1}s^{-1}$ on layer 2 and 10-15 $kgm^{-1}s^{-1}$ layer 3.

For the whole year, moisture transport has direction of west and southwest in the North of Vietnam and direction of East and Northeast in the Central and the South of Vietnam. Moisture transport has the strongest intensity in the summer and the weakest intensity in the winter and the spring over Vietnam.

In the whole atmospheric column, moisture transport in Northern Vietnam is stronger than in the Central and Southern Vietnam. In the atmospheric layers, moisture transport is strongest in layer 1 and weakest in layer 3.

3.1.2. Total moisture transport in El Niño conditions

Over DATTBD region, South-western moisture transport has average value of 180-210 kgm-1s-1 in the whole atmospheric column, in which 70-80 $kgm^{-1}s^{-1}$ on layer 1, layer 2 and 40-50 $kgm^{-1}s^{-1}$ on layer 3; North-eastern moisture transport zone has the mean value of 190-220 $kgm^{-1}s^{-1}$ in the whole the atmospheric column, in which, 90-100 $kgm^{-1}s^{-1}$ on layer 1, 60-70 $kgm^{-1}s^{-1}$ on layer 2 and 40-50 $kgm^{-1}s^{-1}$ on layer 3; Southeastern moisture transport zone has the average value of 140-170 $kgm^{-1}s^{-1}$ throughout the atmospheric column, in which, 90-100 $kgm^{-1}s^{-1}$ on layer 1, 30-40 $kgm^{-1}s^{-1}$ on layer 2 and 20-30 $kgm^{-1}s^{-1}$ on layer 3. In Vietnam, on the northern region, direction of total moisture transport is west and southwest with the mean value of 90-120 $kgm^{-1}s^{-1}$ in the whole atmospheric column, in which 50-60 $kgm^{-1}s^{-1}$ on layer 1, 20-30 $kgm^{-1}s^{-1}$ on layer 2 and 20-30

$kgm^{-1}s^{-1}$ on layer 3. On the central area, eastern and northeastern total moisture transport is 20-50 $kgm^{-1}s^{-1}$ in the whole atmospheric column, in which 10-20 $kgm^{-1}s^{-1}$ on layer 1, layer 2 and 0-10 $kgm^{-1}s^{-1}$ on layer 3. On the Southern region, eastern and northeastern total moisture transport is 30-60 $kgm^{-1}s^{-1}$ throughout the atmospheric column, in which 10-20 $kgm^{-1}s^{-1}$ on each layer.

3.1.3 Total moisture transport in La Niña conditions

Over DATTBD region, the South-western moisture transport zone has average value of 140-170 $kgm^{-1}s^{-1}$ in the whole atmospheric column, in which 60-70 $kgm^{-1}s^{-1}$ on layer 1, 50-60 on the layer 2 and 30-44 $kgm^{-1}s^{-1}$ on layer 3; the North-eastern moisture transport zone has the mean value of 240-270 $kgm^{-1}s^{-1}$ in the whole the atmospheric column, in which, 120-130 $kgm^{-1}s^{-1}$ on layer 1, 70-80 $kgm^{-1}s^{-1}$ on layer 2 and 50-60 $kgm^{-1}s^{-1}$ on layer 3; average value of Southeastern moisture transport zone is 140-170 $kgmm^{-1}s^{-1}$ in the whole atmospheric column, in which, 90-100 $kgm^{-1}s^{-1}$ on layer 1, 40-50 $kgm^{-1}s^{-1}$ on layer 2 and 10-20 $kgm^{-1}s^{-1}$ on layer 3.

In Vietnam, the characteristic of total moisture transport in 11 La Niña events are: In the northern area, total moisture transport has direction of west and southwest with the average value of 50-80 $kgm^{-1}s^{-1}$ in the whole atmospheric column, in which 20-30 $kgm^{-1}s^{-1}$ on layer 1, layer 2 and 10-20 $kgm^{-1}s^{-1}$ on layer 3; On the central of Vietnam, direction of total moisture transport is east and northeast with the mean intensity of 50 -80 $kgm^{-1}s^{-1}$ in the whole atmospheric column, in which 30-40 $kgm^{-1}s^{-1}$ on layer 1 and 10-20 $kgm^{-1}s^{-1}$ on layer 2 and layer 3; On the Southern region, total moisture transport has direction of east and northeast with the average value of 70-100

$kgm^{-1}s^{-1}$ in the whole atmospheric column, in which 30-60 $kgm^{-1}s^{-1}$ on layer 1, 20-30 $kgm^{-1}s^{-1}$ on layer 2 and on layer 3.

3.2. Total moisture transport in each ENSO event

3.2.1. Total moisture transport in the entire atmospheric column in each of El Niño events

Over the DATTBD region, the intensity of each moisture transport zone (Southwest, Northeast, Southeast) are very different in El Niño events. However, in general, they varied around the mean intensity of 13 El Niño events.

Dominant direction of moisture transport in each region (North, Central, South) in El Niño events is the mean direction of moisture transport in 13 El Niño events.

Based on the direction of moisture transport over Vietnam, the El Niño events can be divided into 3 categories:

Category 1: Moisture transport has direction of north-east in the Northern and South-western in the Central and the South of Vietnam;Category 2: Moisture transport has south-western direction in all over 3 regions: North, Central and South;Category 3: Moisture transport has direction of northeast in all three regions: North, Central and South.

3.2.2. Total transport in the entire atmospheric column in each La Niña event.

Intensity of each moisture transport zones (Southwest, Northeast, Southeast) are very different among La Niña events, however, in general, they varied around the mean intensity of 11 La Niña events.Dominant direction of moisture transport in each region

(North, Central, and South) during La Niña is the mean direction of the moisture transport in 11 La Niña events.

Under La Niña conditions, the north-eastern moisture transport is enhanced. Besides, 2 La Niña - type 3 events with North-eastern moisture transport over all 3 regions occur.

Chapter 4: The relationship between moisture transport and droughts, heavy rain and rain over some region in Vietnam under ENSO conditions

4.1. Moisture transport crossing the boundaries over some regions in Vietnam

On the northern area, moisture source provided for rainy season in BBVN in the early and middle of summer (V-VIII) is mainly from the west and south, in the end summer (IX, X) is from the east.

On the central of Vietnam, moisture resource provided for rainy months including IX, X, XI is mainly from the East Sea through the eastern boundary.

On the Southern region, moisture source provided for rainy season in the early and mid summer is mainly through the western and southern boundary and mainly through the eastern boundary in the end of summer.

4.2. The relationship between moisture transport and droughts under El Niño condition in Vietnam

4.2.1. The effects of El Niño on droughts in Vietnam

Impacts of El Niño on droughts in Vietnam is considered by analysis the sign of anomaly drought index over 7 climate regions in 13 El Niño events in the period 1960 - 2009. The analysis results indicate that El Niño contribute to the increase in droughts. However, the impacts of El Niño on droughts are very different between the North and the South. Its impact is very significant in the south of Vietnam meanwhile it is quite weak in the North, except the North Central region.

4.2.2. The relationship between moisture transport and droughts in Vietnam

The relationship between moisture transport and the number of droughts months under El Niño events is considered by using correlation coefficient between zonal, meridional moisture transport and the number of droughts months (STH) over 7 areas including: BBVN, TBVN, NBVN, TGTQ, XĐ-ĐNA, BĐ in 13 El Niño events.

The correlation between STH and Q_u and Q_V is quite weak over 5 climatic regions including TB, DB, DBBB, TN and NB. In contrast, the correlation coefficient between STH over the BTB, NTB and Qu, Q_V is remarkable.

4.3. The relationship between moisture transport and heavy rain in La Niña events in Vietnam

4.3.1. Effects of La Niña on heavy rains in Vietnam

According to the calculations of the capability of occurring heavy rain under normal conditions and La Niña conditions, it is indicated that heavy rainfall occurs in 4/7 climatic regions and 33/56 stations under La Nina condition.

4.3.2. The relationship between moisture transport and heavy rain in Vietnam

The relationship between moisture transport and the number of heavy rainfall months under La Nina events is considered by using correlation coefficient between zonal, meridional moisture transport and the number of heavy rainfall months (STML) over 7 climatic regions in 11 La Niña events.

The results show that most correlation coefficients between STML on 7 climatic regions of Vietnam and Q_u is positive. The

correlation is quite high on TB, ĐB regions, moderate on BTB, NTB regions and quite low on DBBB, TN, NB regions. Most correlation coefficient between STML and Q_V is positive. It is quite high on the TB, NE regions, moderate on the BTB, NTB, TN and relatively low on DBBB, NB regions.

4.4. Applying the moisture transport information to research the influence of ENSO on rainfall over specific area

The effects of ENSO on rainfall in the Central of Vietnam are conducted by using rainfall observation from 13 coastal stations (12^0N-19^0N) and Aphrodite data in the period 1980-2007.

The ENSO autumns are determined based on Oceanic Nino index over the Nino3.4 region (ONI) of NOAA. In the period 1980-2007, there were 9 El Niño and 10 La Niña autumns [35].

4.4.1. Effects of ENSO on rainfall in Central of Vietnam in the autumn, the role of moisture transport

4.4.1.1. Distribution of total rainfall in the autumn over Central of Vietnam

Total rainfall in the autumn (IX, X, XI) in the Central of Vietnam ranges from 800 to 2400mm. There are four heavy rainfall center whose total rainfall are over 1600 mm including: Ky Anh (1740mm), Hue (1887mm), Tra My (2429mm) and Ba To (2094mm).

4.4.1.2. Effects of El Niño

Under the El Niño conditions, total rainfall autumn in the Central of Vietnam decrease from -15 to -25%. The highest decrease is -30.3% (Nha Trang), the lowest is -3.9% (Dong Ha) and the average is 18.3%.

The confidence level of the dependence of decrease in autumn rainfall on El Niño condition is verified by t-Test in which rainfall data of 9 El Niño autumn and 9 autumn in normal condition are employed to compare with climatology. The results are indicated that the difference of rainfall in El Niño and climatology has the confidence of 95%.

The decrease in autumn rainfall over the Central of Vietnam in the El Niño conditions relates to the formation of an anticyclonic wind anomaly vector over the East Sea. This anticyclonic formed due to the North East monsoon is weaker than the climatology leading to the shortage of moisture source from the Pacific to the East Sea and the Central of Vietnam.

4.4.1.3. Effects of La Niña

The rainfall in autumn over the Central of Vietnam increase around 10.1% under the influence of La Niña condition. The increase in autumn rainfall in La Niña conditions due to the following reasons: (1) North East monsoon at lever 10m and 850hPa are stronger than climatology leading to the formation of a cyclonic wind anomaly vector in the middle of East Sea. This cyclone provides much more moisture for rainfall in the Central of Vietnam; (2) There are 2 strengthen sources of moisture provided for rainfall in the Central of Vietnam including a source from outside the Pacific to the East Sea and another moisture source from lower latitudes.

The figure 4.1 illustrates the factors controlling the autumn rainfall in the Central of Vietnam during ENSO conditions. The differences between El Niño and La Niña are: (1) the North East monsoon is weaker during El Niño conditions compared to La Niña

conditions; (2) the secondary moisture source over the southern region of the East Sea is absent during in El Niño conditions (Figure 4.1a) and (3) Under El Niño conditions, there is an anticyclonic wind anomaly over the East Sea, meanwhile there is a cyclonic wind anomaly there during La Niña (Figure 4.1b).

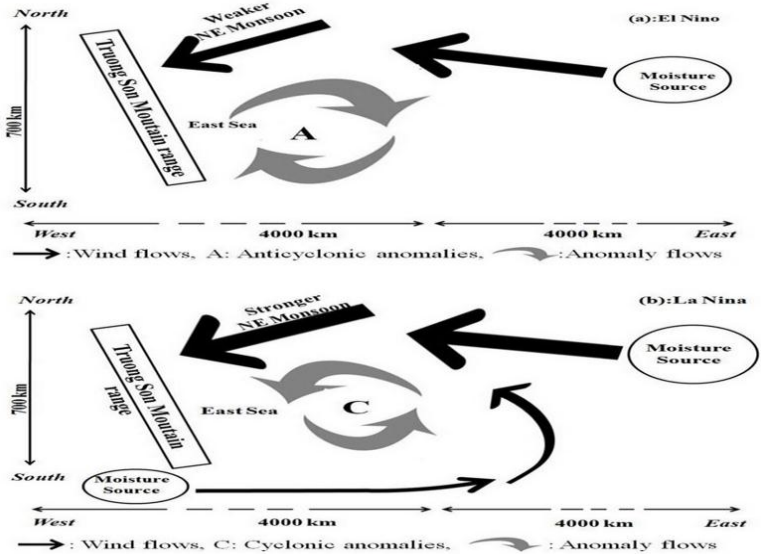

Fig. 4.1. *Schematic diagrams of atmospheric circulations for (a) El Niño, and (b) La Niña conditions. Wind flows are indicated by thick dark arrows. Wind anomalies are indicated by gray arrows.*

4.4.2. Effects of El Niño on the decrease in rainfall in May over Central Highlands, the role of moisture transport

Under the impacts of El Niño, the total rainfall in May over the Central Highlands region decrease in almost stations (11/12 Stations). The decrease ranges from 10 to 25%. The highest decrease

value is 30.9% (Buon Ho) and the lowest is 3.1% (A Yun Pa), except Lien Khuong station where rainfall increases 10%.

The reduction of rainfall in May in the Central Highlands during El Niño conditions is related to a cyclonic wind anomaly over the Bay of Bengal. This cyclone appears due to the weakening of the southwest monsoon circulation compared to the average of many years. In addition, the large moisture source providing for rain of the Central Highlands in the south of the Bay of Bengal is lower than the average of many years**.**

Conclusions and recommendations

1. Conclusions

According to the results of the research on the moisture transport characteristics over the DATTBD region and Vietnam as well as the relationship between the moisture transport and rainfall, heavy rain and droughts in Vietnam during the ENSO, it can be concluded as follows:

1) For the moisture transport over DATTBD region and Vietnam during normal conditions

- There are always three main moisture transport zones with different values between seasons in the DATTBD region including (1) the South-western moisture transport zone in the middle latitude regions; (2) the North-eastern moisture transport zone in tropical-equatorial-western Pacific; (3) the South-eastern moisture transport zone in the southern hemisphere. Annually, total moisture transport is strongest in the Northeastern zone and weaker in the Southeastern zone and weakest in the southwestern zone. The moisture transport also decreases gradually from layer 1 to 2 and from 2 to layer 3.

- In Vietnam, the direction of moisture transport in the winter

and spring is West and Southwest in the North. Its direction in the Central and the South is East and Northeast. In the summer, the direction of moisture transport is West and Southwest in all regions over Vietnam; in contrast, in the autumn the direction is East and Northeast. Annually, the direction of moisture transport in the North of Vietnam is Southwest and its direction in the Central and the South of Vietnam is East and Northeast. The intensity of moisture transport is strongest in the summer and weakest in the winter or spring. On the entire atmospheric column, in annual scale, the intensity of moisture transport in the North of Vietnam is stronger than in the Central and South of Vietnam. In the atmospheric layers, moisture transport is strongest in layer 1 and weakest in layer 3.

2) For the moisture transport in DATTBD and Vietnam during ENSO conditions.

- Over the DATTBD region, during El Niño conditions, Southwestern moisture transport zone is enhanced while both North-eastern and South-eastern moisture transport zone is weaker. In contrast, during La Niña conditions, the South-western moisture transport zone is weaker while Northeastern zone is stronger.

- In Vietnam, during El Niño conditions, Western and Southwestern moisture transport in the north of Vietnam is enhanced while the intensity of Eastern and Northeastern moisture transport in the Central and the South decreases. In contrast, under La Niña conditions, the intensity of Western and Southwestern moisture transport in the north declines whereas the intensity of Eastern and Northeastern moisture transport in the Central and the South increases.

3) For the distribution of total moisture transport under ENSO conditions and the effects on droughts and heavy rain.

- The distribution of total moisture transport in each of El Niño (La Niña) events has similar as well as different features in comparison with distribution of average moisture transport of 13 El Niño events (11 La Niña events). Notably, under the El Niño conditions, there are 5 El Niño events type 2 whose direction is Southwest, while during La Niña conditions, 2 La Niña events type 3 appear whose direction is Northeast.

- During El Niño conditions because of the enhancement of Western and Southwestern moisture transport, the number of droughts months in the Northern climatic regions decreases while those of Southern climatic areas rises significantly. Under La Niña conditions, due to strengthening of Eastern and Northeastern moisture transport, the number of heavy rain months in the southern climatic regions highly increases whereas those of Northern climates only increase a little.

4) For the relationship between moisture transport and rainfall in some specific regions under ENSO conditions.

- The decrease in autumn rainfall in the Central of Vietnam during El Niño conditions is caused by the following reasons: Northeast monsoon is weaker than the average of many years; there is only a source of moisture from East Sea to study area which is lower than climatology; there is an anticyclonic wind anomaly over East Sea that lead to the decrease in moisture over the Central of Vietnam.

- The reasons why autumn rainfall increase in the Central of

Vietnam under La Niña conditions are: the Northeast monsoon is stronger than climatology; there are two sources of moisture which are provided for rainfall in this region and the main moisture source in the East Sea is higher than climatology; A cyclonic wind anomaly exists over East Sea that makes a moisture enhancement to the Central Region of Vietnam.

- The reduction of rainfall in May in the Central Highlands during El Niño conditions is caused by the weakening of the Southwest monsoon circulation over the Bengal Bay compared to climatology. Besides, a cyclonic wind anomaly over Gulf of Bengal reduces moisture sources from the south of Bengal Bay to the study area.

5) The appication of moisture transport information

- Moisture transport information can be applied to assess droughts under El Niño conditions and heavy rainfall under La Niña conditions over some specific areas.

- The decline of moisture over East Sea during El Niño conditions in the autumn is an important factor causing droughts in Central of Vietnam. Typically, El Niño event in 1997-1998 caused droughts in October and November in 1997. In contrast, the increase of moisture in the East Sea during the autumn is an element causing the increase of rainfall in the Central of Vietnam, for instance, La Niña events 1998-2001 leads to heavy rain in November 1999.

2. Recommendations

1) In the basis of the achieved results, further research can be recommended as follows:Continue to study the relationship between moisture transport and the number of droughts months as well as

heavy rain months over the climatic regions of Vietnam in order to determine the moisture transport information to server for heavy rainfall and droughts forecast in Vietnam.

2) Continue to study about moisture balance, moisture convergence and divergence over some the regions of Vietnam based on high resolution data sets (0,5x0,5°) to explain the physical mechanisms of relations between moisture transport and rainfall in Vietnam

3) Continue to research about moisture transport and rainfall in different El Niño events as well as La Niña events (formation, development, decay and disintegration) to clarify the relationship between moisture transport and rainfall over some specific areas.

List of author's publications related to the thesis

1. **Thang Van Vu**, Hieu Trong Nguyen, Thang Van Nguyen, Hiep Van Nguyen, Huong Thi Thanh Pham and Lan Thi Nguyen (2015), *Effects of ENSO on Autumn Rainfall in Central Vietnam*. *Advances in Meteorology*, Vol 2015, Article ID 264373, 12 pages.

2. **Vu Van Thang**, Hoang Duc Cuong, Nguyen Van Thang, Nguyen Trong Hieu, Hiep Van Nguyen, (2014), *Reduction of May Rainfall in El Niño at the Central Highlands and the role of mosture transport. Journal of Hydrometeorology,* No 644, pp. 1-4.

3. **Vu Van Thang,** Nguyen Van Thang, Nguyen Trong Hieu (2014), *Moisture transport across four boundary in the Vietnam. Journal of Hydrometeorology,* No 646, pp. 1-4.

4. **Vu Van Thang,** Nguyen Van Thang, Nguyen Trong Hieu, Huong Thi Thanh Pham (2012), *Charateristics of moisture transport in Vietnam period El Niño.* Conference Report of the 15th, Scientific and Technical Publisher vol.I, pp. 93-99.

5. **Vu Van Thang,** Nguyen Van Thang, Nguyen Trong Hieu (2013), *Distribution of standard deviation of moisture transport over Vietnam during El Niño.* Conference Report of the 16th, Scientific and Technical Publisher vol.I, pp. 49-54.

6. **Vu Van Thang,** Nguyen Van Thang, Nguyen Trong Hieu (2015), *Effects of La Niña to heavy rainfall in Vietnam*. Conference Report of the 18th, Vietnam Publishing House of Natural Resources, Environment and Catorgraphy (NARENCA), pp. 32-37.