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Vertically Integrated Moisture Flux Convergence over Southeast Asia and Its Relation to Rainfall over Thailand

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ABSTRACT

The aims of this research are to study vertically integrated moisture flux convergence (VIMC) over Southeast Asia and to analyse its relationship to rainfall over Thailand during the period 1999 to 2013. Data reanalysed by the National Oceanic and Atmospheric Administration (NOAA) during the period 1999 to 2013 are used in this study. The monthly mean rainfall data are taken from the Global Precipitation Climatology Project (GPCP). Vertically integrated moisture transport (VIMT) is calculated by vertically integrating moisture fluxes of the u and v components. The finite difference method is applied to the vertically integrated moisture flux divergence (VIMD). The results show that VIMD over the Indian Ocean is strong, and the moisture is directed from the Indian Ocean to Thailand by southwest winds that cause strong moisture convergence over Thailand during the rainy season, while moisture in the summer season is a strong divergence. Moisture increases from the South China Sea to Thailand during October to December, causing more moisture convergence over northern and northeastern Thailand. That the relationship between rainfall and VIMC averaged over Thailand from the years 1999 to 2013 is confirmed by large positive correlations. The average from the years 1999 to 2013 over the study area is confirmed by Thailand's rainfall pattern.

Keywords: Moisture transport, moisture flux, rainfall, Southeast Asia, Thailand.

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INTRODUCTION

The Southwest Monsoon and the Northeast Monsoon are related to rainfall over Thailand. The Southwest Monsoon, from May through September, brings a stream of warm moist air from the Indian Ocean towards Thailand, causing more rainfall over the area. The cold and dry air from the anticyclone on the China mainland migrates over Thailand during the Northeast Monsoon, starting in October (Climatological Group, 2015). Thailand had the highest average annual rainfall in 2011 and the lowest average annual rainfall in the year 2005, as presented by the Thai Meteorological Department (2014).

Agriculture in Thailand is highly competitive, diversified and specialised, and its exports are very successful internationally. Agricultural production as a whole accounted for an estimated 9% of Thai GDP and 40% of the population work in agriculture-related jobs (Luedi, 2016). Water is the main factor in agriculture, but the amount of rainfall is uncertain depending on whether it is a drought year or a wet year. This makes it difficult to manage the use of water in Thailand.

This research studied the factors that influence rainfall in Southeast Asia to attend to the predicted rainfall for sufficient water management especially in the drought years and wet years. The period 1999 to 2013 was also studied to determine the trend of rainfall.

Typical anomalous summer rainfall patterns of China were analysed using observational precipitation data (Zhou & Yu, 2005), the NCEP/NCAR and ERA40 reanalysis data related to the vertically integrated atmospheric water vapour transports derived from the Bay of Bengal and the South China Sea. These agreed with Wang and Chen (2012). They showed that mainly, atmospheric water vapour over south-eastern China during summer transported from the Indian Ocean and the tropical western Pacific occurred during the Indian and East Asian Monsoons. Ullah and Gao (2012) presented the convective centres of vertically integrated moisture transport flux over Pakistan and neighbouring regions from the divergent regions of the Arabian Sea and the Bay of Bengal, from which vertically integrated moisture convergence was deep in 1994. Ribeiro et al. (2014) found that winds in low level circulation from the ocean taking more moisture and the change of the wind vectors at high levels of the atmosphere supplied more rainfall in Belém. Trenberth, Fasullo and Mackaro (2011) stated that a better evaluation of the hydrological cycle components was provided by the atmospheric moisture budget, and the results also advised about E - P information. Guo et al. (2017) presented that the tropical cyclones associated with the moisture transport and rainfall over East Asia, and showed the comparison of the contribution of tropical cyclones to the area of water budget with other contributors. Jongaramrungruang, Seo and Ummenhofer (2017) found that convergence mainly due to low-level moisture was strong in the negative Indian Ocean dipole years. Further, He (2015) showed that anomalous northward moisture was taken from the western Pacific to central China, and summer precipitation anomalies were significantly positive over central China.

Other research has found one interesting factor affecting rainfall, namely, moisture transport. Therefore, the aim of this research was to study vertically integrated moisture flux convergence (VIMC) over Southeast Asia and to analyse its relationship to rainfall over Thailand during the period 1999 to 2013. We divided the seasons into three: summer (March-May), the rainy season (June-September) and winter (November-February).

THE STUDY AREA AND DATA USED

The Study Area

Southeast Asia was the designated study area. It is defined by latitude 0°S - 25°N and longitude 85°E - 120°E as shown in Figure 1. The map of Southeast Asia was plotted using the coastline extractor created by Signell (2014).

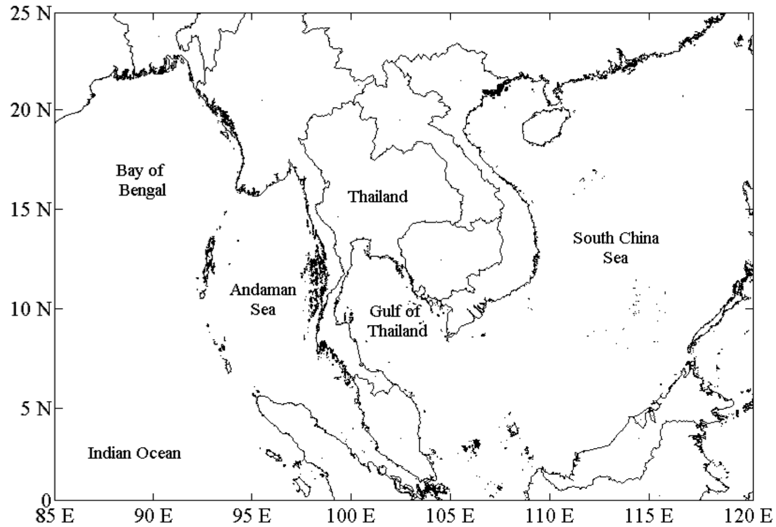

Figure 1. The study area (Signell, 2014)

Data Used

The data taken from the National Oceanic and Atmospheric Administration (NOAA) including the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysed data during the period 1999 to 2013, focussing on the u and v winds, specific humidity at the pressure levels 300 hPa, 400 hPa, 500 hPa, 600 hPa, 700 hPa, 850 hPa, 925 hPa and 1000 hPa and surface pressure at a resolution of 2.5° long × 2.5° lat (Kalnay et al., 1996; The NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, 2014). The monthly mean rainfall data were taken from the Global Precipitation Climatology Project (GPCP) at a resolution of 2.5° long × 2.5° lat during the period 1999 to 2013 (Adler et al., 2003; The NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, 2014). The evaporation minus precipitation (E-P) data were taken from the NCAR at a resolution of 0.7° long × 0.7° lat., which was the monthly mean during the period 1999 to 2013 (National Center for Atmospheric Research Staff, 2014; Trenberth & Fasullo, NCAR, 2014). All the data were interpolated with the computational grid at a resolution of 1° long × 1° lat.

The Moisture Conservation Equation

Water flux and transport information is important for understanding the global hydrological cycle, oceanic dynamics and global climate (Stewart, 2003). The moisture conservation equation in flux form of vertical integration suggested by Trenberth et al. (2011) is

$$\frac{\partial W}{\partial t} = -\nabla \cdot \frac{1}{g} \int_{300}^{p_s} q\mathbf{V} dp + E - P + R, \tag{1}$$

where, q is specific humidity; p is pressure; p_s is surface pressure; $\mathbf{V}$ is wind vector; g is gravitational acceleration; E is evaporation; P is precipitation and R is runoff. The left-hand side of Equation (1) is the change of total precipitable water (W) in column. The right-hand side of Equation (1) is the difference between evaporation and precipitation, vertically integrated moisture flux divergence (VIMD) and runoff (Ullah & Gao, 2012; Mo & Higgins, 1996; Trenberth & Guillemot, 1998).

The tendency term is small for long-term means; this is recommended by Mo and Higgins (1996). So, Equation (1) is now:

$$E - P = \nabla \cdot \frac{1}{g} \int_{300}^{p_s} q\mathbf{V} dp. \tag{2}$$

Equation (2) is the principal balance between E - P and vertically integrated moisture divergence (Trenberth et al., 2011). In this research, E - P is calculated from the NCAR data (National Centre for Atmospheric Research Staff, 2014; Trenberth & Fasullo, NCAR, 2014).

The wind vector, $\mathbf{V}$, is defined by $\mathbf{V} = (u, v)$, where u and v are the east-west and north-south components of wind. The vertically integrated moisture transport (VIMT) improved from Fasullo and Webster (2003) and Arias, Fu, Hoyos, Li and Zhou (2011) is calculated by $\int_{300}^{p_s} q\mathbf{V} dp \big/ g$, and the vertically integrated moisture fluxes of u and v components are calculated by $\int_{300}^{p_s} qudp \big/ g$ and $\int_{300}^{p_s} qvdp \big/ g$, respectively.

Specific humidity is small above the 300 hPa level and is not an effect to vertically integrated moisture transport (Fasullo & Webster, 2003). The vertically integrated moisture flux divergence (VIMD) is calculated by

$$\nabla \cdot \frac{1}{g} \int_{300}^{p_s} q\mathbf{V} dp = \frac{\partial \left(\int_{300}^{p_s} qudp \big/ g \right)}{\partial x} + \frac{\partial \left(\int_{300}^{p_s} qvdp \big/ g \right)}{\partial y}. \tag{3}$$

The finite difference method using the central difference scheme is applied in Equation (3), which is a calculation of the monthly mean over Southeast Asia during the period 1999 to 2013. Thus, the VIMD can be approximated by

$$\left(\frac{\partial\left(\int_{300}^{p_s} qudp/g\right)}{\partial x}+\frac{\partial\left(\int_{300}^{p_s} qvdp/g\right)}{\partial y}\right)_{i,j} \approx \frac{\left(\int_{300}^{p_s} qudp/g\right)_{i+1,j}-\left(\int_{300}^{p_s} qudp/g\right)_{i-1,j}}{2\Delta x} + \frac{\left(\int_{300}^{p_s} qvdp/g\right)_{i,j+1}-\left(\int_{300}^{p_s} qvdp/g\right)_{i,j-1}}{2\Delta y}, \quad (4)$$

where, Δx and Δy are the grid spacing along east-west directions and north-south directions, respectively. The no-slip condition is used as the boundary condition in this paper. The specific humidity above pressure level 300 hPa is not an effect in studying vertically integrated moisture transport; this is recommended by Kalnay et al. (1996) and Fasullo and Webster (2003). Thus, the VIMT and VIMD perform from 300 hPa to the surface pressure level.

The vertically integrated moisture flux convergence (VIMC) averaged for Thailand during the period 1999 to 2013 was computed in this study. The VIMC is the negative of VIMD. The correlation between rainfall and VIMC averaged over Thailand was computed by:

$$r=\frac{n\sum_{i=1}^{n} X_iY_i-\sum_{i=1}^{n} X_i\sum_{i=1}^{n} Y_i}{\sqrt{n\sum_{i=1}^{n} X_i^2-\left(\sum_{i=1}^{n} X_i\right)^2}\sqrt{n\sum_{i=1}^{n} Y_i^2-\left(\sum_{i=1}^{n} Y_i\right)^2}}, \quad (5)$$

where, X_i is rainfall averaged for Thailand; Y_i is the VIMC averaged for Thailand; n is the total number of months and i is the indices of the months. The formula for correlation coefficient r in Equation (5) was suggested by Hanke, Wichren and Reitsch (2001).

Absolute error was computed by $|\text{VIMD} - (E - P)|$, where $E - P$ is the difference between evaporation and precipitation and VIMD is the vertically integrated moisture flux divergence over the study area, as suggested by Olver (2008).

RESULTS

Moisture Transport

The VIMT and vertically integrated moisture fluxes of u and v components averaged from the years 1999 to 2013 are shown in Figure 2. In the colour bar, arctic relates to negative VIMT, and purple relates to positive VIMT. The results show that moisture transport appears from the southwest to the east of the study area towards Thailand from the Indian Ocean during the rainy season (June-September). Strong moisture with moisture components from the Indian Ocean towards Thailand is carried by a southwest wind during the Southwest Monsoon associated with the rainy season in Thailand. The moisture transport is strongest (dark purple) in August and the vertically integrated moisture transport over Andaman Sea is strong at this time. This moisture transports from the Indian Ocean towards Thailand, and may bring more rainfall over Thailand. Moreover, strong moisture is in the South China Sea, and the moisture transports flow to the South China Sea during the rainy season. In the summer season (March-May), weak moisture flows from the east to west of the study area.

Moisture Convergence and Rainfall

The VIMD and winds averaged from the years 1999 to 2013 are shown in Figure 3. Blue relates to negative VIMD and purple relates to positive VIMD. The VIMC has the opposite sign of VIMD. During the rainy season, the VIMD over the Indian Ocean in September has high positive VIMD (dark purple), which is stronger than in June and July. Moisture direct from the Indian Ocean to Thailand by southwest winds causes strong moisture convergence over Thailand. Moisture convergence over Thailand is strongest in August (dark blue), inducing more rainfall during this period. Moisture convergence is strong over Thailand in May, which is the summer season. A strong divergence over the South China Sea occurs during October through December. Moisture is directed from the South China Sea through the Gulf of Thailand into Thailand during October to December; this causes more moisture convergence over the northern and northeastern parts of Thailand.

Figure 4 a) presents the monthly average values of rainfall and VIMC over Thailand from the years 1999 to 2013. The VIMC over Thailand during the rainy season is high, while during summer and winter it is low; rainfall during summer and winter is low. The relationship between rainfall and VIMC over Thailand from the years 1999 to 2013 has a high positive correlation of 0.8674. The monthly average values of rainfall and VIMC over Thailand in the years 2005 (a dry year) and 2011 (a wet year) are shown in Figure 4 b) and Figure 4 c), respectively. The correlation is highly positive i.e. 0.8938 and 0.8967, respectively. Obviously, VIMC in the year 2005 was smaller than the VIMC in the year 2011 during the rainy season, causing more rainfall in 2011. Figure 4 d) shows the difference of monthly averaged VIMC between the years 2011 and 2005. The difference in VIMC between the years 2011 and 2005 is visibly positive from July to September i.e. the rainy season. It can be inferred that moisture convergence from July to September in the year 2011 was greater than in 2005, and the rainfall in the year 2005 was also less than in 2011. There was a small difference in VIMC between the years 2011 and 2005 in the other months.

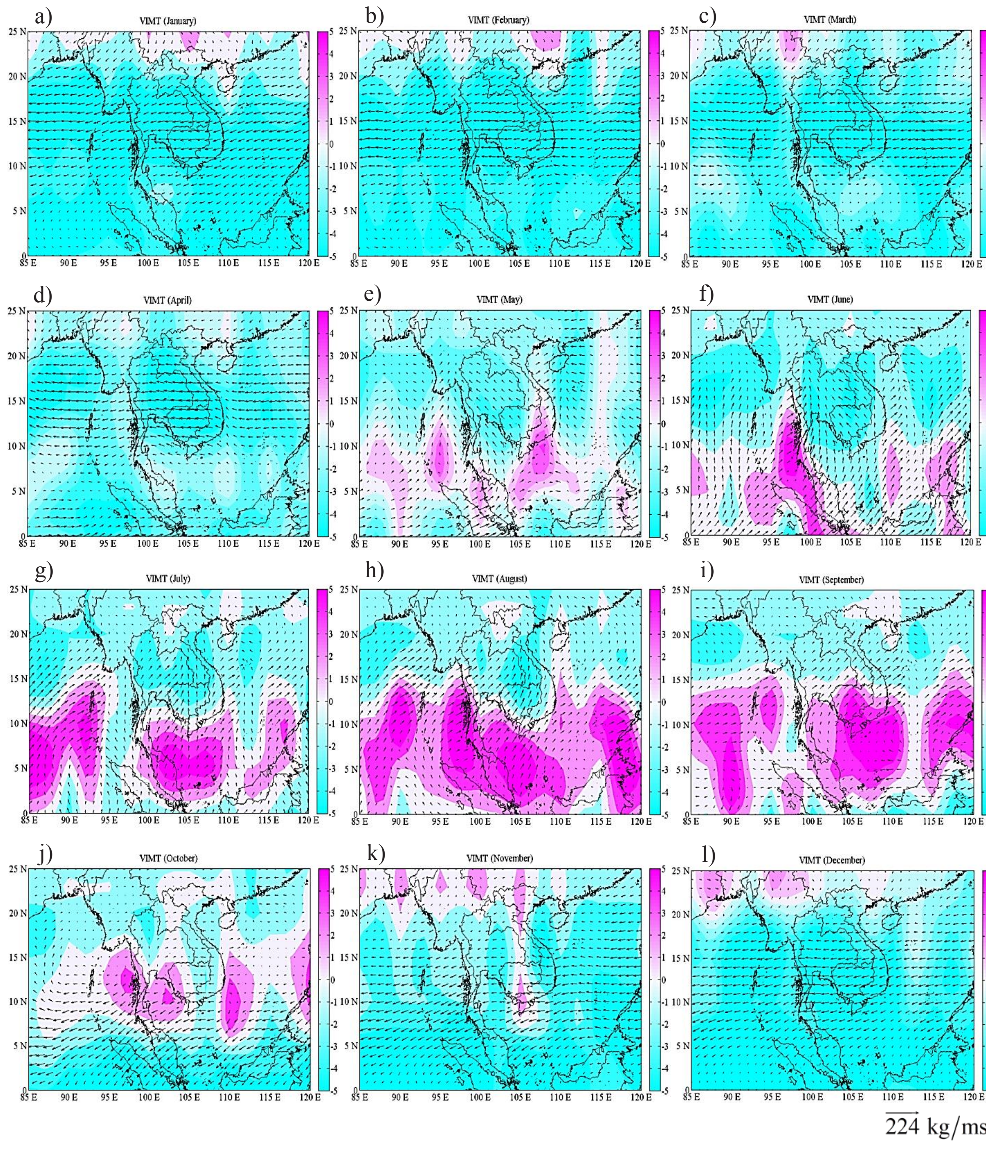

Figure 2. VIMT (kg/ms) shown as colour bars and vertically integrated moisture fluxes of u and v components averaged from the years 1999 to 2013 shown as vector during a) January, b) February, c) March, d) April, e) May, f) June, g) July, h) August, i) September, j) October, k) November and l) December

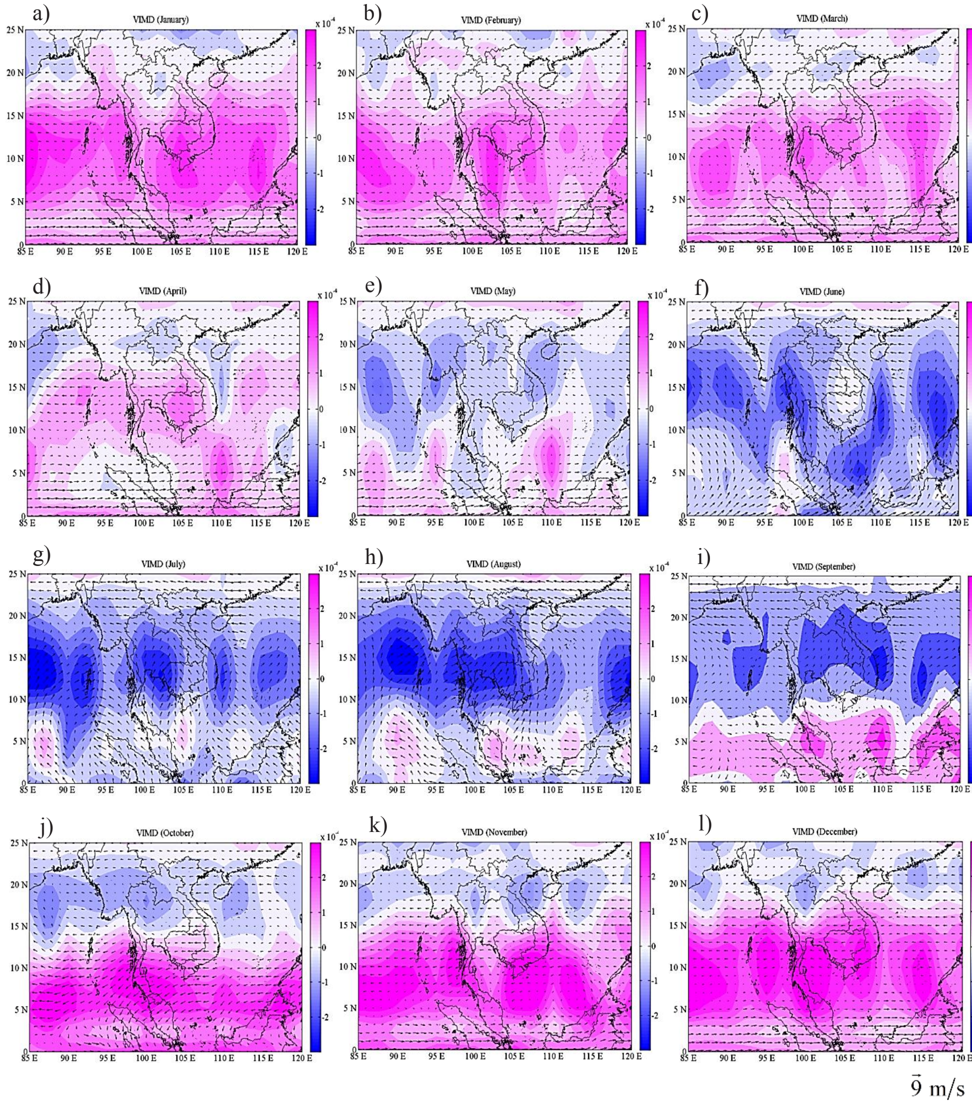

Figure 3. VIMD (kg/m^{2}s) shown as colour bars and winds averaged from the years 1999 to 2013 shown as vector during a) January, b) February, c) March, d) April, e) May, f) June, g) July, h) August, i) September, j) October, k) November and l) December

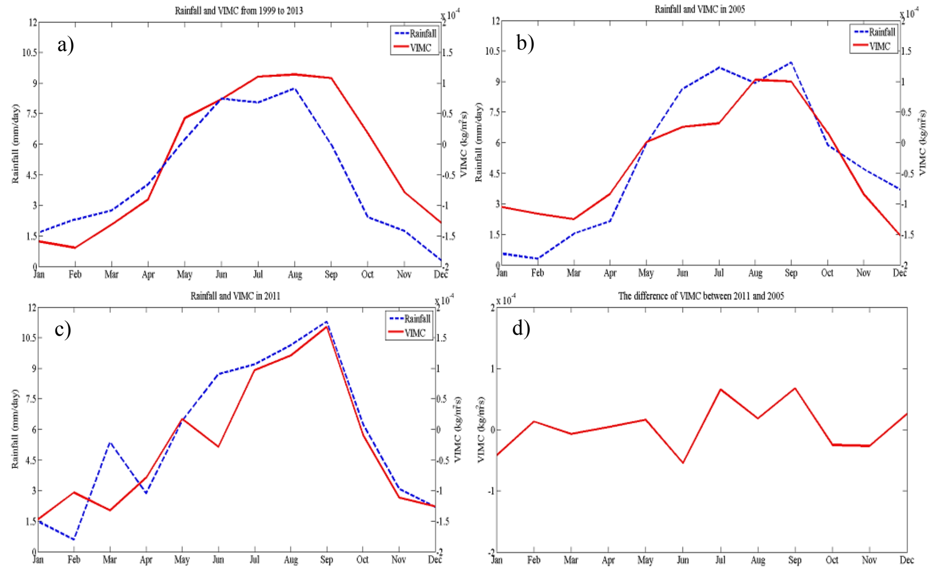

Figure 4. The monthly average values of rainfall and VIMC over Thailand a) from the years 1999 to 2013, b) in the year 2005 (dry year) and c) in the year 2011 (wet year); and d) the difference in monthly averaged VIMC between the years 2011 and 2005

Model Comparison with *E* - *P*

The *E* - *P* values averaged from the years 1999 to 2013 over the study area are shown in Figure 5. The *E* - *P* data were taken from the National Center for Atmospheric Research Staff (2014) and Trenberth and Fasullo, NCAR (2014). The *E* - *P* values were negative over the study area during May to October and highly negative over Thailand during the rainy season. It can be inferred that there was more precipitation than evaporation, causing more precipitation during the rainy season of Thailand. However, *E* - *P* values during January, February, March, April, November and December were positive over northern, northeastern, central and eastern parts of Thailand. The results show that there was more evaporation than precipitation; this corresponds to less precipitation during those periods over Thailand. Absolute error was employed in the evaluation study to find the absolute value of the difference between the calculated and actual values. If absolute error is very small, it can be said that *E* - *P* can be estimated by VIMD. In this study, the absolute error of *E* - *P* and VIMD are shown in Table 1. The small difference between *E* - *P* and VIMD infers that VIMD can be used to estimate *E* - *P*. The *E* - *P* value is the quantity that indicates the amount of water.

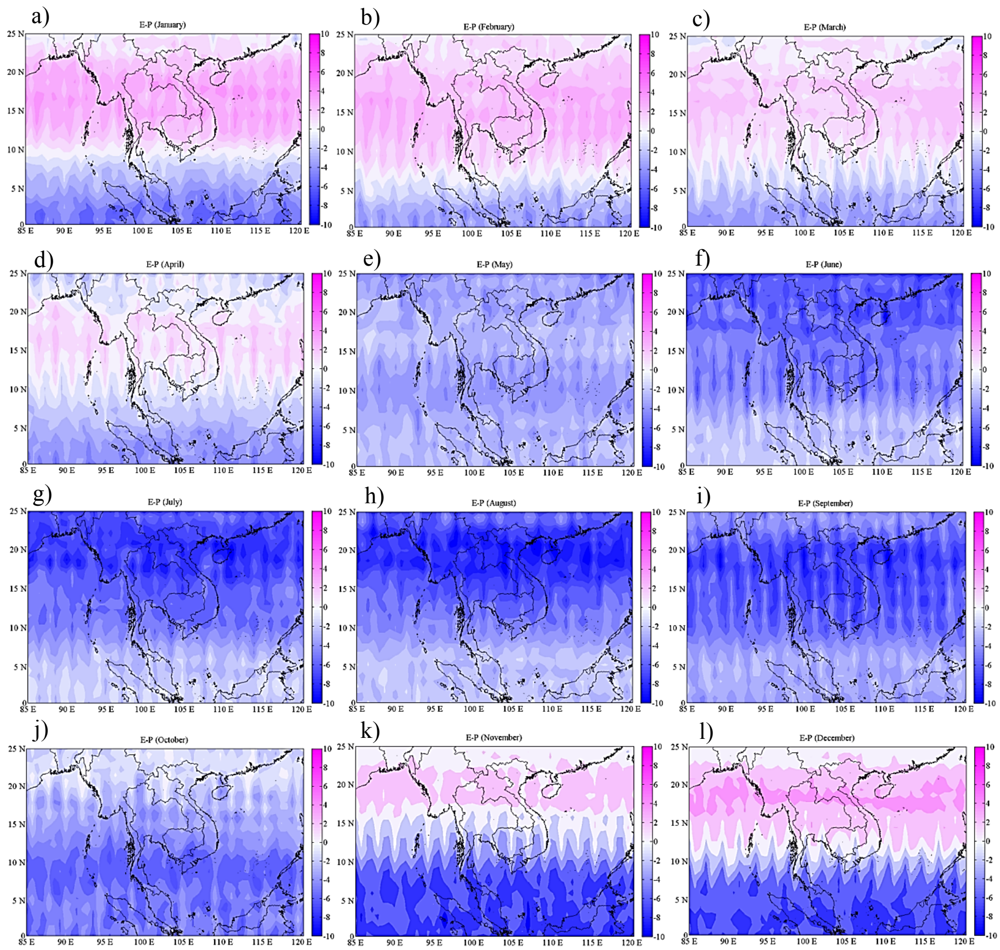

Figure 5. E - P taken from NCAR (National Center for Atmospheric Research Staff, 2014; Trenberth & Fasullo, NCAR, 2014) averaged from the years 1999 to 2013 (mm/day) during a) January, b) February, c) March, d) April, e) May, f) June, g) July, h) August, i) September, j) October, k) November and l) December

Table 1
Absolute error (kg/m^{2}s) between   and VIMD averaged from the years 1999 to 2013

Month	Absolute Error	Month	Absolute Error
January	0.000118	July	0.000010
February	0.000096	August	0.000009
March	0.000091	September	0.000065
April	0.000071	October	0.000141
May	0.000042	November	0.000147
June	0.000012	December	0.000146

CONCLUSION

In this analysis it can be summarised that moisture transport appears during the rainy season from southwest to east of the study area with southwest winds towards Thailand from the Indian Ocean. The strong moisture transports from the Indian Ocean towards Thailand may bring more rainfall over Thailand, and a weak moisture flow in the summer season occurs from west to east of the study area, causing less rainfall than during the rainy season. The VIMD over the Indian Ocean is strong. The moisture directs from the Indian Ocean to Thailand by a southwest wind, causing strong moisture convergence over Thailand during the rainy season. Moisture is directed from the South China Sea to Thailand during October to December, causing more moisture convergence over the northern and northeastern part of Thailand. The relationship between rainfall and VIMC averaged over Thailand from the years 1999 to 2013 is confirmed by large positive correlations. The difference in VIMC between the years 2011 and 2005 during the rainy season had positive values, and it can be inferred that the moisture convergence in the year 2011 was more than in 2005 during the rainy season, while rainfall in the year 2011 was greayer than in 2005. The small difference between E - P and VIMD inferred that VIMD can be used to estimate E - P.

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