Mechanisms accounting for the repeated occurrence of torrential rainfall over South Thailand in early January 2017

JIN Shuanglong\textsuperscript{a,b} and FU Shenming\textsuperscript{c}

\textsuperscript{a}State Key Laboratory of Operation and Control of Renewable Energy & Storage Systems, China Electric Power Research Institute, Beijing, China; \textsuperscript{b}Electric Power Meteorology State Grid Corporation Joint Laboratory, Beijing, China; \textsuperscript{c}International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

ABSTRACT

Based on CMORPH precipitation estimates and ERA5 reanalysis data, this study investigates the mechanisms accounting for the repeated occurrence of torrential rainfall over South Thailand in early January 2017, which induced the strongest floods over Ko Samui and Ko Phangan in the last almost 30 years. It is found that the maintenance of a northeastward-moving mesoscale vortex that formed southwest of the Indochina Peninsula was the direct reason for the series of torrential rainfall events. Analysis of the vorticity budget illustrates that convergence-related horizontal shrinking was the most favorable factor for the maintenance of the vortex. Tilting was the second most favorable factor, whereas horizontal and vertical transport mainly caused a net export of cyclonic vorticity from the vortex’s three-dimensional range, which was detrimental for its maintenance. Further analysis indicates that tilting and vertical vorticity transport were sensitive to the vortex’s displacement and the enhancement of cyclonic vorticity at lower levels around the vortex, respectively, as the two factors showed completely different effects on the persistence of the vortex during two different stages.

1. Introduction

Thailand is one of the world’s leading exporters of rice (Wangwongchai, Zhao, and Zeng 2005; Chokngamwong and Chiu 2008; Promchote, Wang, and Johnson 2016), and the rice yield of the country is heavily dependent on precipitation. Rainfall over Thailand is affected by both the summer southwest monsoon and the winter northeast monsoon (Matsumoto 1997; Wangwongchai, Zhao, and Zeng 2010). Influenced by the monsoon, under some favorable conditions, torrential rainfall can occur over Thailand and cause severe flooding events, such as the Hat Yai heavy rainfall in late November 2000 (Wangwongchai, Zhao, and Zeng 2005), the Chao Phraya River basin flood during the 2011 summer season (Promchote, Wang, and Johnson 2016), and so on.

Usually, extreme precipitation in Thailand tends to appear in the rainy season (from June to October) (Wangwongchai, Zhao, and Zeng 2010; Promchote, Wang, and Johnson 2016), which is under the influences of the summer monsoon, as the summer monsoon can provide favorable dynamic and thermodynamic conditions for heavy precipitation (Matsumoto 1997; Pillai and Annamalai 2012; Day, Fung, and Risi 2015). In addition, during the cold season in Thailand (from November to February), under the influences of cold surges of the Asian winter monsoon (which can arrive at lower latitudes near the equator), mesoscale vortices can form around the Indochina Peninsula. These mesoscale vortices can induce severe rainfall in Thailand (Zhao and Zeng 2010; Wangwongchai, Zhao, and Zeng 2005).
In this study, a series of cold-season heavy rainfall events that occurred during 2–9 January 2017, over South Thailand, are analyzed. The events resulted in severe flooding that impacted at least 19 provinces, with 750,000 people affected and at least 11 who were killed. During the event, Ko Samui and Ko Phangan experienced their strongest floods in the last almost 30 years, and the observational station at Nakhon Si Thammarat recorded more than 300 mm in just one day (Figure 1).

Thus far, it is unclear why these severe torrential rainfall events happened over Thailand during the cold season. Moreover, the mechanisms accounting for the repeated occurrence of torrential rainfall are still vague. These two scientific questions will be addressed in this study. The remaining part of the paper is structured as follows: the next section shows the dataset and analysis methods used in this study; section 3 provides the main results; and finally, a conclusion is reached in section 4.

2. Data and method

This study used daily 0.25° × 0.25° CMORPH precipitation estimates (Joyce et al. 2004) to analyze the variation of precipitation during the event. In addition, hourly 0.25° × 0.25° ERA5 reanalysis data (Hersbach and Dee 2016) were used for investigating the favorable circulations for the torrential rainfall and for diagnosing the mechanisms accounting for the repeated occurrence of the torrential rainfall events.

The vorticity budget equation (Kirk 2003; Fu et al. 2015, 2017; Fu, Li, and Ling 2015) was used in this study. Its expression is as follows:

\[
\frac{\partial \zeta}{\partial t} = -\nabla_h \cdot \nabla_h \zeta - \omega \frac{\partial \zeta}{\partial p} + k \left( \frac{\partial \nabla_h}{\partial p} \times \nabla_h \omega \right) - \beta V_{\text{HAV}} V_{\text{AV}} T_{\text{IL}} P_{\text{VA}} + \nabla_h \cdot \nabla_h V_{\text{AV}} T_{\text{IL}} P_{\text{VA}} + \text{RES,}
\]

where STR

Figure 1. The 24-h accumulated precipitation (color shading; units: mm) during the torrential rainfall event in Thailand, where the blue open squares mark the locations of Nakhon Si Thammarat and Pattani.
where $\zeta$ denotes the relative vorticity in the zenith direction, $\mathbf{v} = u\mathbf{i} + v\mathbf{j}$ represents the horizontal wind, and $(\mathbf{i}, \mathbf{j}, \mathbf{k})$ are the unit vectors in the east, north, and zenith direction, respectively. The horizontal gradient operator is written as $\nabla_h = \frac{\partial}{\partial x} \mathbf{i} + \frac{\partial}{\partial y} \mathbf{j}$, $p$ is the pressure, $\omega$ is the vertical velocity under the pressure coordinate, $f$ is the Coriolis parameter, and $\beta = \frac{\partial f}{\partial y}$. The horizontal and vertical advection of vorticity are represented by terms HAV and VAV, respectively. Tilting is denoted by term TIL, the planetary vorticity advection is represented by term PVA, and the stretching effect is denoted by term STR. Term RES stands for the residual effect primarily due to friction, subgrid processes, and calculation errors. The sum of the right-hand side terms except for RES is defined as the total effect (TOT): $\text{TOT} = \text{HAV} + \text{VAV} + \text{TIL} + \text{PVA} + \text{STR}$.

3. Results

3.1. Overview of the event

In early January 2017, from south to north, South Thailand experienced a series of torrential rainfall events. The repeated torrential rainfall events induced severe flooding and urban waterlogging, and caused enormous economic losses and casualties (https://watchers.news/2017/01/06/thailand-flood-january-2017/). The most severe precipitation period (MSPP) mainly appeared from 0000 UTC 4 to 0000 UTC 8 January 2017 (Figure 1), with Ko Samui and Ko Phangan encountering their strongest floods in the last almost 30 years. Severe torrential rainfall also appeared in Nakhon Si Thammarat and Pattani, and according to the CMORPH precipitation estimate (Joyce et al. 2004) the maximum 24-h accumulated precipitation of up to 330 mm appeared around the former on 5 January 2017 (Figure 1(b)) and the maximum 24-h accumulated precipitation of up to 420 mm appeared around the latter on 7 January 2017 (Figure 1(d)).

3.2. Synoptic analyses

As shown in Figure 2(a), during the MSPP, in the upper troposphere, South Thailand was located west of an anticyclone, where the temperature gradient was weak (which means baroclinity was weak in this event) whereas the divergence was intense. Strong upper divergence is favorable for enhancing/maintaining severe ascending motion (Zhao and Zeng 2010; Wangwongchai, Zhao, and Zeng 2005; Gao, Zhou, and Ran 2018). Cross sections along Nakhon Si Thammarat (~100°E) (Figure 2(c)) and Pattani (~101°E) (Figure 2(d)) also confirm the strong upper divergence. However, in the vertical direction, the distribution of divergence was complicated. For Nakhon Si Thammarat, intense convergence associated with the torrential rainfall was mainly located at levels below 800 hPa (~8.5°N) (Figure 2(c)), and the corresponding strong divergence was mainly located in the layer from 850 hPa to 550 hPa. For Pattani, convergence associated with the torrential rainfall (~7°N) was weaker than that of Nakhon Si Thammarat (cf., Figure 2(c,d)), but was located in a much thicker layer (from the surface to 600 hPa). The corresponding divergence was mainly located in the layer from 550 hPa to 150 hPa. In the middle troposphere, South Thailand was controlled by a mesoscale vortex (as shown by the isohypse of 5840 gpm) that was located between an anticyclone over the Philippines (reflected by the anticyclonic wind field) and an anticyclone over the Indian peninsula (Figure 2(b)). The temperature gradient and temperature advection were weak, which means the baroclinity was not obvious.

Around Nakhon Si Thammarat and Pattani, moisture was abundant (the isospecific humidity line of 2 g kg$^{-1}$ reached upward to around 350 hPa), with specific humidity above 16 g kg$^{-1}$ appearing at levels below 900 hPa (Figure 2(c,d)). During the MSPP, moisture transport was strong around South Thailand (Figure 2(e,f)), and strong moisture convergence appeared around Nakhon Si Thammarat and Pattani mainly due to the convergence between the southwesterly moisture transport and southeasterly moisture transport. As shown by Figure 2(e,f), the South China Sea was an important moisture source for the torrential rainfall in this event. From Figure 3, it is obvious that a mesoscale vortex (Orlanski 1975; Cao, Zhou, and Gao 2011; Zhou, Li, and Sun 2014; Fu et al. 2015; Fu, Li, and Ling 2015) maintained strong intensity southwest of the Indochina Peninsula, with torrential rainfall mainly occurring around its northeastern section. Within the northeastern section of the vortex, a strong easterly wind (wind speed maxima were above 15 m s$^{-1}$) appeared (Figure 3), which transported abundant moisture to this region (Figure 2(e,f)). Moreover, strong lower-level convergence appeared around the wind maxima in the strong easterly wind, which contributed to intense ascending motion (Figure 2(c,d)). This vortex was the direct trigger for the torrential rainfall over South Thailand, and the persistence of this vortex was the main reason for the repeated occurrence of torrential rainfall in this region.

3.3. Mechanisms accounting for the maintenance of the vortex

As discussed in the above section, a mesoscale vortex generated southwest of the Indochina Peninsula was the
direct reason for the repeated torrential rainfall over South Thailand. Further analysis indicates that this vortex formed on 2 January 2017, dissipated on 12 January 2017, and mainly followed a northeast track (not shown). The MSPP was also a stage when the vortex reached its maximum intensity in terms of ascending motion (Figure 4(a)) and vorticity (according to the theorem of Green, the integral of vorticity over a horizontal

Figure 2. (a) Time-averaged (from 0000 UTC 4 to 0000 UTC 8 January 2017) divergence (color shading; units: $10^{-6}$ s$^{-1}$), geopotential height (black solid lines; units: gpm), temperature (red lines; units: °C), and wind field (a full bar is 10 m s$^{-1}$) at 200 hPa. (b) Time-averaged (from 0000 UTC 4 to 0000 UTC 8 January 2017) temperature advection (color shading; units: $10^{-5}$ s$^{-1}$), geopotential height (black solid lines; units: gpm), temperature (red lines; units: °C), and wind field (a full bar is 10 m s$^{-1}$) at 500 hPa. (c, d) The divergence (color shading; units: $10^{-5}$ s$^{-1}$), wind (vectors, composed of meridional wind (units: m s$^{-1}$) and 100 × vertical wind (units: cm s$^{-1}$)) and specific humidity (green solid lines; units: g kg$^{-1}$) along 100°E and 101°E, respectively, where the grey shading is terrain. (e, f) Divergence of the integrated (from the surface to 300 hPa) moisture flux (color shading; units: $10^{-5}$ kg s$^{-1}$ m$^{-2}$), integrated (from the surface to 300 hPa) moisture flux (vectors; units: kg s$^{-1}$ m$^{-1}$), and the value of the integrated moisture flux (blue solid lines; units: kg s$^{-1}$ m$^{-1}$). The blue (a, b) and red open squares (e, f) mark the locations of Nakhon Si Thammarat and Pattani.
region equals the velocity circulation along the boundary line of the region. This indicates that a horizontal integral/average of vorticity within the range of a vortex is an effective measurement for this vortex as a whole. As Figure 4(a) shows, during the MSPP, cyclonic vorticity within key regions of the mesoscale vortex (purple dashed boxes in Figure 3) was around $2 \times 10^{-5} \, \text{s}^{-1}$, and changed slightly, which means the vortex maintained its strong intensity and varied slowly. Ascending motion associated with the vortex showed an obvious diurnal variational feature, with stronger ascent appearing around 0600 UTC and 1800 UTC and weaker ascent appearing around 0000 UTC and 1200 UTC. This is generally consistent with the variation of precipitation associated with the vortex (not shown). Moreover, strong lower-level convergence maintained within the vortex range during the MSPP, which tended to enhance when ascending motion intensified (Figure 4(a)).

Based on the vorticity budget equation, Equation (1), the mechanisms accounting for the maintenance of the vortex were investigated. To represent the whole vortex, all vorticity budget terms were first calculated, and then averaged within key regions of the mesoscale vortex (Figure 3). Before analyses, we evaluated the balance of the vorticity budget equation and the sensitivity of the selections of the key regions. It was found that term TOT accounted for $80.6\% – 93.2\%$ of the local temporal variation of vorticity, which means the balance of the budget equation was good after neglecting term RES. Moreover, sensitivity tests showed the key regions were insensitive to relatively small changes of its range ($\pm 0.5^\circ$ to each boundary line), which implies the key region selection is representative.

The vorticity budget results are illustrated in Figure 4(b) (PVA is not considered as it was much smaller than other terms). It can be seen that, during the MSPP, term TOT remained positive. This means the conditions were overall favorable for the maintenance of the vortex. The convergence-related STR (red line in Figure 4(b)) was the most favorable factor for the maintenance of the vortex.

Figure 3. The 850-hPa stream field (black solid lines), vorticity (color shading; units: $10^{-5} \, \text{s}^{-1}$), and wind with speed above 12 m s$^{-1}$ (a full wind bar represents 10 m s$^{-1}$), where the purple boxes are the key regions of the cyclone, and the red open squares mark the locations of Nakhon Si Thammarat and Pattani.
mesoscale vortex. As convergence before 1200 UTC 6 January 2017 (which was defined as the earlier MSPP) was stronger than the later MSPP (from 1200 UTC 6 January to 0000 UTC 8 January 2017), STR decreased slowly in the later stage. Although tilting (i.e. term TIL) (green line in Figure 4(b)) had changed its effect during the MSPP, overall, it acted as the second most favorable factor for the vortex’s persistence. During the earlier MSPP, TIL was mainly positive, which contributed to the maintenance of the vortex; whereas, in the later MSPP, TIL mainly remained as negative values, which was detrimental to the vortex’s maintenance. The change in the effect of TIL was mainly due to the change in the relative configuration of ascending motion and vertical wind shear as the vortex moved northeastward (not shown). Horizontal transport (i.e. term HAV) (orange line in Figure 4(b)) mainly acted as exporting/importing cyclonic/anticyclonic vorticity from/into the key region, which was a disadvantageous condition for the vortex’s maintenance. Further analysis shows that the import of anticyclonic vorticity through the western section of the northern boundary of the key region and the export of cyclonic vorticity through the southern section of the eastern boundary (Figure 3) were dominant factors for the negative HAV. Similar to that of STR, HAV also showed a stronger intensity in the earlier MSPP than that in the later MSPP. The vertical transport of vorticity (i.e. term VAV) (blue line in Figure 4(b)) was mainly negative (ascending motion transported relatively smaller lower-level cyclonic vorticity upward) in the earlier MSPP, which was detrimental for the maintenance of the vortex. In contrast, it changed to positive (ascending motion transported relatively larger lower-level cyclonic vorticity upward) during the later MSPP, as the lower-level cyclonic vorticity around the vortex enhanced rapidly (not shown) due to intense convergence.

Figure 4. (a) The key-region-averaged vertical motion (red solid line; units: $10^{-2}$ Pa s$^{-1}$), divergence (blue solid line; units: $10^{-6}$ s$^{-1}$), and vorticity (black solid line; units: $10^{-5}$ s$^{-1}$). (b) The key-region-averaged STR (red solid line; units: $10^{-10}$ s$^{-2}$), VAV (blue solid line; units: $10^{-10}$ s$^{-2}$), TIL (green solid line; units: $10^{-10}$ s$^{-2}$), HAV (orange solid line; units: $10^{-10}$ s$^{-2}$), and TOT (black solid line; units: $10^{-10}$ s$^{-2}$). See section 2, Equation (1), for definitions of the budget terms.
(Figure 2(a)), which contributed to the vortex’s maintenance. Overall, VAV was the second most detrimental factor for the vortex’s persistence.

4. Conclusion

In this study, based on CMORPH precipitation estimates and ERA5 reanalysis data, the mechanisms accounting for the repeated occurrence of torrential rainfall over South Thailand in early January 2017, which caused the strongest floods over Ko Samui and Ko Phangan in the last almost 30 years, were analyzed. It was found that a long-lived northeastward-moving mesoscale vortex that formed southwest of the Indochina Peninsula was the direct trigger for the series of torrential rainfall events. During the rainfall, baroclinity was weak, as reflected by the unobvious temperature gradient and weak temperature advection. This is very different from the torrential rainfall associated with mesoscale vortices over the Yangtze River Basin (Fu et al. 2015, 2017). Moisture for the repeated torrential rainfall was abundant, with the South China Sea acting as a main moisture source.

Maintenance of the mesoscale vortex was a necessary condition for the repeated occurrence of torrential rainfall over South Thailand. Analysis of the vorticity budget illustrated that the convergence-related horizontal shrinking (STR) was the most favorable factor for the maintenance of the vortex. Tilting was the second most favorable factor, although it only contributed to the vortex’s maintenance during the earlier MSPP. Horizontal transport acted as the most detrimental factor for the persistence of the vortex. This was mainly due to the import of anticyclonic vorticity through the western section of the northern boundary of the vortex’s key region and the export of cyclonic vorticity through the southern section of the eastern boundary. Overall, vertical transport of vorticity was unfavorable for the vortex’s maintenance, particularly during the earlier MSPP. However, during the later MSPP, it changed to a favorable factor. The changes in the effects of tilting and vertical transport were mainly due to the movement of the vortex and the rapid enhancement of cyclonic vorticity at lower levels around the vortex, respectively.

Wangwongchai, Zhao, and Zeng (2005) found one important reason for the torrential rainfall in the cold season of Thailand in the form of the cold surges of the Asian winter monsoon that originate from Siberia. However, in this study, we found that a mesoscale vortex that formed in the lower-latitude regions near the Indochina Peninsula was enough for inducing torrential precipitation over Thailand in the cold season (without the influences from cold surges). The lower-latitude mesoscale vortex differs from those mesoscale vortices over the Yangtze River Basin, as it is much weaker in baroclinity. For a more complete understanding of torrential rainfall events in the cold season of Thailand, more cases should be investigated and compared in the future.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was supported by the National Key R&D Program of China [grant number 2018YFC1507400], the National Natural Science Foundation of China [grant numbers 41861144015 and 41775046], and the Youth Innovation Promotion Association, Chinese Academy of Sciences.

References

Cao, J., Y. S. Zhou, and S. T. Gao. 2011. “A Brief Report of Graphic Explanations for Generalized Potential Temperature in the Non-uniformly Saturated Atmosphere.” Atmospheric and Oceanic Science Letters 4: 162–167. doi:10.1080/16742834.2011.11446923.

Chokngamwong, R., and L. S. Chiu. 2008. “Thailand Daily Rainfall and Comparison with TRMM Products.” Journal of Hydrometeorology 9: 256–266. doi:10.1175/2007JHM876.1.

Day, J. A., I. Fung, and C. Risi. 2015. “Coupling of South and East Asian Monsoon Precipitation in July–August.” Journal of Climate 28: 4330–4356. doi:10.1175/JCLI-D-14-00393.1.

Fu, S.-M., W.-L. Li, and J. Ling. 2015. “On the Evolution of a Long-lived Mesoscale Vortex over the Yangtze River Basin: Geometric Features and Interactions among Systems of Different Scales.” Journal of Geophysical Research: Atmospheres 120: 11,889–11,917. doi:10.1002/2014JD021523.

Fu, S.-M., W.-L. Li, J.-H. Sun, J.-P. Zhang, and Y.-C. Zhang. 2015. “Universal Evolution Mechanisms and Energy Conversion Characteristics of Long-lived Mesoscale Vortices over the Sichuan Basin.” Atmospheric Science Letters 16: 127–134. doi:10.1002/asl.2015.16.issue-2.

Fu, S.-M., J.-H. Sun, Y.-L. Luo, and Y.-C. Zhang. 2017. “Formation of Long-lived Summertime Mesoscale Vortices over Central East China: Semi-idealized Simulations Based on a 14-year Vortex Statistic.” Journal of the Atmospheric Sciences 74: 3955–3979. doi:10.1175/JAS-D-16-0328.1.

Gao, S. T., Y. S. Zhou, and L. K. Ran. 2018. “A Review on the Formation Mechanisms and Forecast Methods for Torrential Rain in China.” Chinese Journal of Atmospheric Sciences 42: 833–846.

Hersbach, H., and D. Dee. 2016. “ERA5 Reanalysis Is in Production.” ECMWF Newsletter, No. 147, ECMWF, Reading, United Kingdom, 7. www.ecmwf.int/sites/default/files/elibrary/2016/16299-newsletter-no147-spring-2016.pdf.

Joyce, R. J., J. E. Janowiak, P. A. Arkin, and P. Xie. 2004. “CMORPH: A Method that Produces Global Precipitation Estimates from Passive Microwave and Infrared Data at High Spatial and Temporal Resolution.” Journal of
Kirk, J. R. 2003. “Comparing the Dynamical Development of Two Mesoscale Convective Vortices.” *Monthly Weather Review* 131: 862–890. doi:10.1175/1520-0493(2003)131<0862:CTDDOT>2.0.CO;2.

Matsumoto, J. 1997. “Seasonal Transition of Summer Rainy Season over Indochina and Adjacent Monsoon Region.” *Advances in Atmospheric Sciences* 14: 231–245. doi:10.1007/s00376-997-0022-0.

Orlanski, I. 1975. “A Rational Subdivision of Scales for Atmospheric Processes.” *Bulletin of the American Meteorological Society* 56: 527–530.

Pillai, P. A., and H. Annamalai. 2012. “Moist Dynamics of Severe Monsoons over South Asia: Role of the Tropical SST.” *Journal of the Atmospheric Sciences* 69: 97–115. doi:10.1175/JAS-D-11-056.1.

Promchote, P., S.-Y. S. Wang, and P. G. Johnson. 2016. “The 2011 Great Flood in Thailand: Climate Diagnostics and Implications from Climate Change.” *Journal of Climate* 29: 367–379. doi:10.1175/JCLI-D-15-0310.1.

Wangwongchai, A., S.-X. Zhao, and Q.-C. Zeng. 2005. “A Case Study on A Strong Tropical Disturbance and Record Heavy Rainfall in Hat Yai, Thailand during the Winter Monsoon.” *Advances in Atmospheric Sciences* 22: 436–450. doi:10.1007/BF02918757.

Wangwongchai, A., S.-X. Zhao, and Q.-C. Zeng. 2010. “An Analysis of Typhoon Chanthu in June 2004 with Focus on the Impact on Thailand.” *Advances in Atmospheric Sciences* 22: 436–450. doi:10.1007/BF02918757.

Zhao, S. X., and Q.-C. Zeng. 2010. “A Study of East Asia Strong Cold Wave — Surge Crossing Equator and Influencing the Development of Tropical Cyclone and Heavy Rainfall in the Southern Hemisphere.” *Climatic and Environmental Research* 10: 507–526.

Zhou, Y. S., N. Li, and M. S. Sun. 2014. “Application of Generalized Ertel-Rossby Invariant to the Heavy Rainfall Case on 21 Jul 2012 in Beijing.” *Climatic and Environmental Research* 19: 303–310.