Remote Rainfall of Typhoon Khanun (2017): Monsoon Mode and Topographic Mode

YI-HSUAN LIN\textsuperscript{a} AND CHUN-ChIEH WU\textsuperscript{a}

\textsuperscript{a} Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan

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ABSTRACT: Remote rainfall related to tropical cyclones (TCs) can be attributed to interaction between the northeasterly monsoon and TC circulation (hereafter monsoon mode), and topographic blocking and lifting effects (hereafter topographic mode). Typhoon Khanun (2017) is a case in point affected by both modes. The objective of this study is to understand the key factors leading to uncertainty in the TC-induced remote rainfall. Ensemble simulations are conducted, with the ensemble members related to the monsoon mode classified into subtypes based on the geographic location of the precipitation maxima. The results demonstrate that frontogenesis and terrain-induced uplifting are the main mechanisms leading to the heavy precipitation in northeastern Taiwan, while the orographic lifting and the interaction between the TC circulation and the topographically blocked northeasterlies result in the heavy rainfall in southeastern Taiwan. For the topographic mode, at a larger rainfall threshold, strong relation is found between the inflow angle of the TC circulation and the cumulative frequency of the rainfall, while at a smaller rainfall threshold, rainfall cumulative frequency is related to the ensemble track directions. Sensitivity experiments with TC-related moisture reduced (MR) and the terrain of Taiwan removed (TR) show that the average of the 3-day accumulated rainfall is reduced by 40% and more than 90% over the mountainous area in MR and TR, respectively. Overall, this study highlights the fact that multiple mechanisms contribute to remote rainfall processes in Khanun, particularly the orographic forcing, thus providing better insights into the predictability of TC remote rainfall.

KEYWORDS: Frontogenesis/frontolysis; Hurricanes/typhoons; Monsoons; Rainfall; Mountain meteorology

1. Introduction

The heavy rainfall accompanying tropical cyclones (TCs) poses a significant threat to human life. While forecasts of TC tracks have improved in recent decades due to advances in numerical modeling systems and increased amounts of satellite observations (Wu et al. 2007; Chou et al. 2011; Weissmann et al. 2011), quantitative precipitation forecasts (QPF) associated with TCs remain challenging. This is primarily because the precipitation is affected by multiple factors, such as TC structure (Lofat et al. 2004); track (Chang et al. 2013; Wu et al. 2013; Chien and Kuo 2011; Lin et al. 2020); translation speed (Yen et al. 2011); microphysics scheme (Tao et al. 2011) and model resolution (Wu et al. 2002, 2009, 2013). Additionally, producing accurate QPFs is particularly difficult for operational forecast centers in Taiwan due to presence of the complex terrain and complicated interactions between TC circulation and the synoptic systems, such as Asia monsoon systems and upper-level troughs (Wu and Kuo 1999; Yu and Cheng 2008, 2013, 2014; Wu et al. 2009, 2013; Huang and Lin 2014; Chen and Wu 2016; Lin et al. 2020).

TC-related rainfall can be generally categorized into two types: direct and indirect (or remote; Wang et al. 2009). Direct precipitation is mainly caused by the TC eyewall structure or the spiral rainbands, and the pattern of cumulative frequencies of rainfall is identified with the TC track clusters as compared to the best track (Wu et al. 2013). In contrast, indirect precipitation is induced by interactions between the TC and other large-scale systems at a distance from the TC center. The rainfall pattern associated with this remote effect is influenced not only by the TC track, but also by other factors such as the TC circulation/size, strength of the monsoon flow, and their interaction with terrain (Chen and Wu 2016). Wu et al. (2017) investigated the characteristics of extreme hourly rainfall over Taiwan from 2003 to 2012 with 5-yr return period, and found that more than three quarters of the extreme rainfall events are related to typhoons. The extreme precipitation distribution tends to have high correlation with the location of TC center relative to Taiwan when the TCs are within 100 km from Taiwan (i.e., direct effect). However, influence from environmental monsoonal flow and the terrain becomes prominent when TCs are 100 km away from Taiwan (i.e., remote effect; Wu et al. 2017). In the United States, TC remote rainfall events are referred to as predecessor rain events (PRE; Cote 2007; Galarneau et al. 2010), with the criteria being 24-h rainfall rates greater than 100 mm, and the radar reflectivity values within a coherent area of rainfall persisting for at least 6 h at a distinct separation distance from the TC. Heavy precipitation during PREs is often produced by mesoscale convective system at a low-level baroclinic zone, and enhanced through the poleward transported tropical moisture from TCs (Schumacher et al. 2011). The interaction between the upper-level synoptic diabatic divergent outflow and midlatitude jet streak also contribute to enhanced forcing for vertical motion in PREs (Bosart et al. 2012; Moore et al. 2013; Cordeira et al. 2013; Grams and Archambault 2016). In addition, some of the TCs were found to play the role of synoptic convective heating sources over northwestern Pacific, which induces barotropic Rossby wave train (i.e., Pacific–Japan pattern; Nitta 1987). As the Pacific–Japan pattern is established, the west–east pressure gradient between TCs and an anomalous high would intensify,
and therefore enhances low-level warm moisture advection and the remote heavy rainfall over Japan (Kawamura and Ogasawara 2006; Yamada and Kawamura 2007).

In previous studies, the interaction between TC circulation and the southwesterly or northeasterly monsoonal flow are shown to be the primary mechanisms for producing remote rainfall in Taiwan (Yu and Cheng 2014; Chen and Wu 2016). The southwesterly monsoonal flow, which prevails in summer, can be strengthened by TC’s outer circulation when TC is about 500 km off the southwest of Taiwan (Lin et al. 2001). With the stronger southwesterly inflow, precipitation is enhanced through a more pronounced orographic lifting in southern Taiwan (Yu and Cheng 2014). During autumn or early winter, the northeasterly monsoonal flow prevails. If a TC passes over the South China Sea, warm and moist air advected northward by TC circulation would converge with dry and cold monsoonal northeasters. The confluence of two air masses of different characteristics is associated with frontogenesis, resulting in lifting and thus triggering heavy rainfall in the vicinity of northeastern Taiwan (Wu et al. 2009; Chen et al. 2013; Chen and Wu 2016). Based on the different controlling factors, Wu et al. (2009) categorized the remote rainfall events in Taiwan during the late TC season (e.g., October and November) into two modes: monsoon mode and topographic mode. The former is associated with the interaction between the northeasterly monsoon and TC circulation, with the low-level convergence found in the vicinity of northeastern Taiwan where the heavy rainfall concentrates. The latter one, or nonmonsoon mode, is not directly related to the northeasterly monsoon, but more associated with the blocking and uplifting effects of the Central Mountain Range, with copious rainfall occurring in eastern or southeastern Taiwan. Note that the two modes are designated based on their relative contributions, and are not exclusive of each other. Series of sensitivity experiments are conducted with the deterministic model in Wu et al. (2009). The results show that several components, such as TC size, monsoon strength, topographic effect, and model resolution, are responsible for the uncertainties in both the rainfall distribution and the accumulated precipitation amount of remote rainfall under the two modes.

Due to the complicated interaction between the TC circulation, monsoonal system, and topography, there are large forecast uncertainties in simulation of TC rainfall (Wu and Kuo 1999; Wu 2001; Wu et al. 2002; Chiao and Lin 2003; Wu et al. 2013; Huang and Lin 2014; Chen and Wu 2016; Lin et al. 2020). To address the predictability challenges, the ensemble systems with multiple models or numerous ensemble numbers have been widely applied to investigate TC-related rainfall issues (Zhang et al. 2010; Fang and Kuo 2013; Wu et al. 2013, Chen and Wu 2016; Zhu et al. 2016; Yue and Meng 2017; Yue et al. 2017). To acquire a better initial vortex condition, Wu et al. (2010) assimilated three observation operators (i.e., TC location, translation speed, and axisymmetric wind profile) in the Weather Research and Forecasting Model (WRF)-based ensemble Kalman filter (EnKF) system. Since the ensemble simulations with more balanced initial field could generate more insightful results compared to deterministic simulations, especially for probabilistic forecasting (Wu 2013), a series of studies related to TC rainfall have been conducted. For direct rainfall events, Wu et al. (2013) investigated the uncertainties in rainfall amount and distribution among all the simulated ensemble members during Typhoon Sinlaku (2009), the result of which suggested that the rainfall patterns of landfalling TCs are highly related to ensemble track variability (i.e., phased locked with terrain; Wu and Kuo 1999); in Yen et al. (2011), the movement of Typhoon Morakot (2009) was controlled by applying EnKF data assimilation with several designated storm locations, and the results show that the maximum accumulated rainfall produced by Morakot was reduced by 33% when the TC translation speed was doubled. For indirect rainfall cases, Chen and Wu (2016) investigated favorable processes for heavy rainfall of Typhoon Megi (2010), and found that there is little relation between track accuracy and rainfall forecast skill.

Since extreme TC remote rainfall attributed to topographic effect and the monsoonal interaction account for only 6.3% and 5.5% of the total TC-type extreme rainfall, respectively (Wu et al. 2017), Typhoon Khanun (2017) is an unusual case with rainfall in Taiwan under both monsoon and topographic modes. Khanun formed to the east of the Philippines, and remained more than 500 km away from Taiwan throughout its lifetime (Fig. 1a). Despite the fact that Khanun did not directly impact Taiwan, heavy rainfall still occurred over the eastern part of Taiwan and the Central Mountain Range (Figs. 1b,c). Note that the heavy rainfall associated with monsoon mode is mainly concentrated in northeastern Taiwan since the fronto-genetical process and the induced vigorous convection typically occur in the vicinity of northeastern Taiwan (Wu et al. 2009; Chen and Wu 2016). However, Khanun features an atypical monsoon mode rainfall pattern, with the precipitation hotspots widely dispersed over eastern Taiwan. Therefore, the objectives of this study are to investigate the mechanisms leading to different rainfall patterns associated with monsoon mode by ensemble simulations, as well as to examine the factors leading to the heavy rainfall under topographic mode, such as the impact of TC tracks, mountain geometry and confluent flow fields. Further sensitivity experiments are also conducted to evaluate the attribution of TC-related moisture and topographic effect to this remote rainfall event. A brief overview of Khanun is provided in section 2. Methodology and experimental designs are described in section 3. Section 4 presents results from the uncertainty analyses and the sensitivity experiments. The summary is provided in section 5.

2. An overview of Typhoon Khanun

Typhoon Khanun formed as a tropical storm on 12 October 2017 to the east of Luzon and made landfall over Santa Ana in northeastern Philippines around 1800 UTC 12 October (Fig. 1a). Intensifying in the South China Sea, Khanun reached its peak intensity with maximum wind speed of 75 kt (1 kt = 0.51 m s⁻¹) and the minimum sea level pressure of 955 hPa. Then the cyclone weakened rapidly under the influence of dry air intrusion and the interaction with land at around 1200 UTC 15 October. Figure 2 shows the synoptic patterns from 1200 UTC 12 October to 1200 UTC 15 October 2017 at 500 and 850 hPa, respectively. At 500 hPa, the midlatitude trough is shallow and far away from Taiwan, which does not significantly...
influence the heavy rainfall of Khanun (Figs. 2a–d); while at lower level (i.e., 850 hPa), the plume of warm moist air is transported northward by the TC circulation, and converges with the prevailing northeasterlies, which provides a baroclinic zone off the northeastern coast of Taiwan (Figs. 2e–h). It is therefore suggested that the remote rainfall in Khanun is more influenced by the lower-tropospheric factors (i.e., 850-hPa moisture flux and thermal structure) than by the mid- to upper-level flow (i.e., 500-hPa geopotential height and vorticity). Similarities of the synoptic-scale configuration between Khanun's remote rainfall event and PREs include moisture fluxes transport from a TC, baroclinic zone and lower-tropospheric frontogenesis. However, an upper-level flow pattern and jet structure are found to play minor roles in Khanun's remote rainfall event as compared to PREs (Bosart et al. 2012; Moore et al. 2013; Cordeira et al. 2013; Grams and Archambault 2016). The surface analysis map with infrared (IR) cloud image obtained from the Central Weather Bureau in Taiwan, along with the wind fields and wind convergence calculated from ERA5 (the fifth major global reanalysis produced by ECMWF; Hersbach et al. 2020) analyses are shown in Fig. 3. During and after the cyclone’s passage over the Philippines, a banded region of clouds and low-level convergence linked to the frontal system was observed separately from the TC circulation over Taiwan, and is hypothesized to have been caused by the interaction between Khanun’s outer circulation and the northeasterly monsoon (Figs. 3a,c). After Khanun moved westward into the South China Sea, the southeasterly outer circulation of TC impinged on eastern Taiwan. The blocking and uplifting effects of the Central Mountain Range likely enhanced torrential rainfall in eastern and southeastern Taiwan (Figs. 3b,d). As a result of these factors, the Cressman analysis (Fig. 1b) shows that Khanun was 700 km away from Taiwan, with no typhoon warnings issued.

3. Model configuration and experimental design

The Advanced Research Weather Research and Forecasting Model [ARW-WRF (version 3.2.1); Skamarock et al. 2008]-based ensemble Kalman filter (EnKF; Evensen 1994, 2003) data assimilation system is used to conduct simulations of Typhoon Khanun (2017). To improve the storm initialization, both the location and the translation speed derived based on the Japan Meteorological Agency (JMA) best track data are assimilated in this study, following the methodology outlined by Wu et al. (2010), which was developed based on the EnKF system of Meng and Zhang (2008a, b). The sizes of the three one-way nested domains are 300 × 130, 490 × 352, and 130 × 229 grid points, with grid spacing of 18, 6, and 2 km, respectively (Fig. 4). The physical parameterization schemes in this study include the Goddard GCE scheme (Tao et al. 1989), the Rapid Radiative Transfer Model (RRTM) for long wave radiation (Mlawer et al. 1997), the Dudhia short-wave scheme for short wave radiation (Dudhia 1989), the Yonsei University (YSU) planetary boundary layer scheme (Hong et al. 2006), and the Kain–Fritsch scheme in the two coarse domains (Kain and Fritsch 1990).

Since the TC rainfall from a series of studies (e.g., Yen et al. 2011; Wu et al. 2013; Chen and Wu 2016) adopting the same ensemble system had been reasonably simulated by using the National Centers for Environmental Prediction (NCEP) Final Analysis (FNL; 1° × 1°), the simulation in this study is initialized at 0000 UTC 12 October 2017 based on the FNL analysis and the optimally interpolated microwave SST (OISST; following Wu et al. 2010) for initial and boundary conditions. The 36 ensemble members are generated by random perturbation in the transformed streamfunction field to guarantee that the initial perturbation fields are in good balance (Zhang et al. 2006). After the 12-h initialization through the EnKF data assimilation with 1-h update cycle, a 3-day ensemble simulation is
FIG. 2. (left) The 500-hPa geopotential height (black solid contours; gpm), wind field (wind barbs; kt), and relative vorticity (shaded; $10^{-5}$ s$^{-1}$) at (a) 1200 UTC 12 Oct, (b) 1200 UTC 13 Oct, (c) 1200 UTC 14 Oct, and (d) 1200 UTC 15 Oct 2017. (right) The 850-hPa geopotential height (black solid contours; gpm), temperature (red dashed contours; °C), wind field (wind barbs; kt), and water vapor flux (shaded; g kg$^{-1}$ m s$^{-1}$) at (e) 1200 UTC 12 Oct, (f) 1200 UTC 13 Oct, (g) 1200 UTC 14 Oct, and (h) 1200 UTC 15 Oct 2017. The locations of Khanun obtained from JMA are indicated by the typhoon symbols.
carried out from 1300 UTC 12 October to 1200 UTC 15 October 2017.

The change of the wind direction from northeasterly to southeasterly off the northeastern coast of Taiwan is a simple indicator that can be used to distinguish between the monsoon mode and topographic mode (Wu et al. 2009). To understand the transition from the monsoon mode to the topographic mode, as well as to indicate whether the rainfall event is associated with either mode, the time-varying low-level (900–1000 hPa) north-easterly moisture fluxes (NE_flux) and the southeasterly moisture fluxes (SE_flux) near northeastern Taiwan (24.2°–26°N, 121.5°–125°E; black rectangle in Fig. 3c) are calculated as follows:

$$\text{NE}_\text{Flux} = \frac{1}{N} \sum_{j=1}^{N} \left( u_j^2 + v_j^2 \right)^{0.5} \times q_j,$$

where $u_j$ and $v_j$ are zonal and meridional velocity (m s$^{-1}$), respectively; and $q_j$ is the specific humidity of the $j$th grid (Pan et al. 2013; Chen et al. 2017). (See Table 1 for a summary of the acronyms and their expansions.) Heavy rainfall associated with the monsoon mode is mainly due to the interaction between TC circulation and the northeast monsoonal system, which frequently occurs in northeastern Taiwan. Therefore, monsoon mode is identified when both fluxes exist, with NE_flux being more dominant, which could correspond to moisture convergence. Meanwhile, a rainfall event is associated with the topographic mode if SE_flux is dominant.

The ground-based rain gauge data from the Central Weather Bureau is used to evaluate whether the time-varying NE_flux and SE_flux near northeastern Taiwan are useful indicators for diagnosing a rainfall event associated with either the monsoon mode or the topographic mode. Only the precipitation in eastern Taiwan (i.e., the parallelogram in Fig. 5a) is taken into account, and further divided into Zones A and B by the boundary between Yilan and Hualien counties (near 24.3°N), which is usually the southern boundary of the

Fig. 3. (top) The surface analysis map with IR cloud image obtained from the Central Weather Bureau in Taiwan at (a) 1200 UTC 13 Oct and (b) 0000 UTC 15 Oct 2017. The red circle indicates the location of Taiwan. (bottom) The wind fields (arrows; m s$^{-1}$) and wind convergence (shaded; 10$^{-5}$ s$^{-1}$) averaged from 900 to 1000 hPa calculated from ERA5 at (c) 1200 UTC 13 Oct and (d) 0000 UTC 15 Oct 2017. Black rectangle in (c) is the region where the northeasterly moisture fluxes (NE_flux) and the southeasterly moisture fluxes (SE_flux) are calculated.
confluent region between TC outer circulation and the northeasterlies (Wu et al. 2009; Chen and Wu 2016). Figures 5b and 5c show the time series of rainfall intensity averaged within zones A and B, respectively. The occurrence of maximum rainfall intensity in zones A and B coincides with the monsoon mode of rainfall as defined above (i.e., pink shaded; 1000–1500 UTC 13 October), followed by the decreasing (Fig. 5b) and increasing (Fig. 5c) topographic mode of precipitation, respectively. The result indicates that the heavy rainfall in Khanun associated with monsoon mode is distributed over the eastern region of Taiwan and shows an atypical rainfall pattern compared to other remote rainfall cases [e.g., Typhoon Megi (2010)] with the precipitation maxima occurring mainly in northeastern Taiwan (i.e., zone A).

Several mechanisms leading to TC-related remote rainfall have been discussed in previous studies, especially the topographic effect and the moisture transported from TCs. Schumacher et al. (2011) found that the maximum rainfall amount was reduced by 50% along the low-level baroclinic region when the moisture related to TC Erin (2007) was removed. Wang et al. (2009) suggested the orographic lifting only accounted for 10% of the precipitation in the Songda (2004) case; while in Chen and Wu (2016), 80% of the rainfall was suppressed in Megi (2010) when the model topography was eliminated. To examine the role of terrain and Khanun’s northward moisture transport contributing to remote rainfall, two sensitivity experiments are conducted, one with reduced TC-related moisture (MR), and the other with the terrain of Taiwan removed (TR). The domain settings are the same as the surrounding ocean (Chen and Wu 2016).

4. Simulation results

Figure 6a shows the ensemble tracks of the 36 ensemble members and best track from 1300 UTC 12 October to 1200 UTC 15 October 2017. Most of the ensemble members associated with the monsoon mode are located near the northern Philippines, and north to the best track. However, for the topographic mode, the ensemble tracks of the 36 members show a larger spread, but with the ensemble mean closer to the best track. The simulated TC intensity has a strong bias (at most 15 hPa) for most of the ensemble members during the initial period and monsoon mode; however, the tendency of intensity changes in most of the members of the topographic mode is consistent with the best track (Fig. 6b). To investigate the ensemble variability of rainfall distribution, we calculate the occurrence ratio of rainfall maxima associated with the monsoon mode and topographic mode in zones A and B. In Fig. 6c, the rainfall maxima under monsoon mode occur more frequently in zone A (i.e., yellow box) than in zone B (i.e., blue box), while the rainfall maxima associated with topographic mode are mainly located in zone B (i.e., purple box). The differences are statistically significant at the 95% confidence level. Note that for the follow-up analyses, the two-tailed Student’s t test is applied for statistical significance test between different subgroups.

To quantitatively evaluate the skill of rainfall simulation associated with both the monsoon mode and topographic mode, the equitable threat score (ETS; Schaefer 1990; Black 1994; Chen and Wu 2016) is calculated:

\[
ETS = \frac{(X - C)}{X - C + Y + Z}
\]

where \(X\), \(Y\), \(Z\), and \(C\) are, respectively, hits, false alarms, misses, and the fortuitously correct forecast skill, defined by \(C = (X + Y)(X + Z)/(X + Y + W + Z)\), where \(W\) is the number of correct rejections. The ETS is evaluated based on the Central Weather Bureau rain gauge data over eastern Taiwan (interpolated to 2 km gridded data), with its value which is the averaged value in the region within TC circulation) is defined, where the initial relative humidity over the two outer domains at all horizontal and vertical grid points is reduced to 55% (following Schumacher et al. 2011). In TR, all of the land-associated parameters, such as the land mask, terrain height and background albedo over Taiwan are set to be same as the surrounding ocean (Chen and Wu 2016).

![Figure 4](image-url)
closer to 1 indicating that the rainfall simulations are more consistent with the observations. Results show that unlike landfalling TCs, the remote TCs are found to be insensitive to TC track error in terms of accuracy of their rainfall forecast for all of the rainfall thresholds (Fig. 7). Among all the 36 members and the ensemble mean (i.e., m000), member 35 (m035) has the highest average ETS, calculated with the accumulated rainfall during the entire simulation period (i.e., both monsoon mode and topographic mode). However, the precipitation hotspots in m035 shift from south to north (not shown), with the rainfall patterns totally different from the observation at different time intervals (i.e., location of precipitation maxima shifts from north to south over time in the observation). From calculation of accumulated rainfall during the entire simulation period, we get reasonable accumulated rainfall and high average ETS, yet with incorrect rainfall distribution, indicating the importance of distinguishing between the monsoon mode and topographic mode. We further examine the ETS associated with each mode, and little correlation with track error is found (Figure not shown). It is therefore worthwhile to further investigate the key factors affecting the uncertainty of Khanun’s remote rainfall spatial distribution among the ensemble members associated with both modes.

a. Monsoon mode

To understand the mechanisms leading to these uncertainties in the precipitation spatial distribution, all individual hourly precipitation data associated with the monsoon mode among the ensemble members are gathered together and classified into three types: northeast (NE, which indicates the rainfall hotspots are mainly located near northeastern Taiwan), southeast (SE, which indicates the rainfall hotspots are mainly located near southeastern Taiwan) and both (ALL, which indicates the heavy rainfall is distributed over the eastern region of Taiwan) based on the location of hourly precipitation maxima. Figures 8a and 8b show the corresponding TC locations and minimum sea level pressure. TCs classified as the NE type are located closer to Taiwan; and TC locations of the SE type are relatively farther away; while members of the ALL type are widely dispersed. Three members (m007, m000, and m035) with more prominent precipitation signals and comparable simulated intensity are selected to represent each of the three types (hereafter referred to as NE_07, ALL_00, and SE_35; Figs. 9a–c). The simulated TC tracks and intensity of the three selected members are labeled in Figs. 6a and 6b, and the follow-up analyses on the three groups during their corresponding periods of the maximum rainfall intensity over eastern Taiwan (i.e., 1100, 1500, and 2000 UTC 13 October, respectively) are shown in Fig. 9. The moisture flux divergence, respectively, associated with the three selected members are shown in Figs. 9d–f. To understand whether the TC incident flow is blocked by the considered mountain barrier, the Froude number (Fr = U/Nh, where U is the upstream wind velocity, N is the Brunt–Väisälä frequency, and H is the terrain height) is calculated (Smith 1979; Overland and Bond 1993; Yu and Lin 2017). The mean height of the terrain over eastern Taiwan is about 1500 m, and only the onshore flow (i.e., the incident flow normal to the barrier) is considered. The Brunt–Väisälä frequency is calculated based on model output, with the average static stability over eastern Taiwan estimated at around 1.14 × 10⁻² s⁻¹.

In NE_07, a region of significant convergence is observed off the northeastern coast of Taiwan; however, an alongshore northeasterly on eastern coast of Taiwan is parallel to the eastern terrain (Fig. 9d), which is not related to topographic lifting. In ALL_00, the moisture flux convergence off the northeastern coast is weaker; however, the prevailing onshore flow off the eastern coast (~18 m s⁻¹; Fig. 9e) yield a Froude number greater than 1, which means the orographically generated precipitation results from forced upslope lifting. For SE_35, the onshore wind speed is weaker (~12 m s⁻¹; Fig. 9f), and a distinct moisture flux convergence is found over the confluent region between the TC circulation and the northeasterly off the southeastern coast of Taiwan compared to NE_07 and ALL_00. To examine the mechanism of the seaward extent convective band and the formation of the near-shore northeasterly, the Rossby radius of deformation with the mountain height replaced by the inertial height scale is calculated:
FIG. 6. (a) The simulated tracks and (b) the simulated TC intensity (hPa) from the ensemble members. Lines colored in gray, pink, and green represent before-monsoon mode, monsoon mode, and topographic mode, respectively. The black, purple, red, and blue thick lines represent the best track provided by JMA, selected member of NE_07, ALL_00, and SE_35, respectively. The typhoon
where \( U \) is upstream wind velocity, and \( f \) is the Coriolis parameter \((f = 23.5 \times 10^{-5} \text{ s}^{-1}; \text{Overland and Bond 1995; Yu and Lin 2017})\), yielding a \( L_R \) of 206 km. Taking the average half-width of the Central Mountain Range into consideration (~40 km), the upstream blocking would occur about 160 km away from the coastline, in line with the convergence zone offshore in SE_35.

To further examine whether the frontogenesis exists in the convergent region, the scalar form of frontogenesis (Petterssen 1936; Keyser et al. 1986) is calculated, but with potential temperature replaced by equivalent potential temperature to make the region of convective instability more consistent with the observed rainfall maxima in East Asia (Chen and Chang 1980; Ninomiya 1984; Chen et al. 2000; Zhou et al. 2004; Yamada et al. 2007; Chen and Wu 2016). The low-level frontogenesis resulting from the confluence of two different air masses not only occurs off the northeastern coast of Taiwan in these three selected members, especially in NE_07 and SE_35 (Figs. 10a,c), but are also located in the vicinity of the southeastern coast of Taiwan in SE_35. The divergence and deformation terms in the scalar form of Petterssen frontogenesis are of comparable contribution in both NE_07 and SE_35. However, their maxima do not occur at the same spots (not shown). Figures 10d and 10e show the cross sections along the maximum frontogenesis area indicated in Figs. 10a and 10c, respectively. The peak value of the modified frontogenesis is located near 900 hPa for NE_07, accompanied by large horizontal gradient of equivalent potential temperature, as well as the ascending warm moist flows (Fig. 10d). As for SE_35, frontogenesis in the northern region (near 25.2°N) is slightly weaker compared to that in NE_07, while in the southern region (near 23.2°N), two peaks of the frontogenesis are found near 550 and 950 hPa, respectively (Fig. 10e). Interestingly, there is a region between the two frontogenous areas in SE_35, where the northerlies are shallower and weaker, and the warm air is lifted above the cold sectors (Fig. 10e). The warm moist flows are transported northward, and ascend again upon interacting with the other stronger northerlies, which corresponds to the northern part of the frontogenesis.

Since the strong frontogenesis is mainly located offshore, it is of interest to investigate the mechanisms leading to the heavy precipitation over land. In Wu et al. (2009), the remote rainfall distribution remains the same when the monsoon strength is reduced. In Chen and Wu (2016), frontogenesis in the adjacent seas is essential for rainfall over ocean, but is not highly related to the heavy rainfall over land. Therefore, we focus on the prevailing winds over eastern Taiwan and its upstream area, rather than the strength of frontogenesis over sea in the follow-up analyses. Figures 11a–c show the vertical cross sections of horizontal divergence, vertical motion, the equivalent potential temperature, the relative humidity above 99% (following Chen and Wu 2016), and the hourly rainfall along 24.6°N and from 121.4° to 121.9°E (labeled in Figs. 9a–c, line A–A’). In NE_07, high vertical velocity is observed on the
upwind slope of the terrain, where heavy hourly precipitation occurs. In ALL_00, weaker upward motion and reduced rainfall are observed despite the high environmental humidity and the decreased equivalent potential temperature with height, indicating that heavy precipitation in this case is primarily driven by the dynamic process (i.e., orographic lifting) as opposed to the thermodynamic process (i.e., convective instability). In the meantime, vertical cross sections along 23.5°N (labeled in Figs. 9a–c, line B–B′) are shown in Figs. 11d–f. The hourly rainfall accumulation in ALL_00 is comparable to that in SE_35; however, the upward motion and convergence on the windward side of the mountain in ALL_00 is much more significant than in SE_35.

To further assess the role of topographically induced upward motion, \( W_f = \mathbf{u} \cdot \nabla h \) (where \( \mathbf{u} \) is the horizontal wind vector at the lowest model level, and \( h \) is the terrain height; Lin et al. 2001; Wu et al. 2002) is also calculated. From the time evolution of the vertical velocity and the topographically induced vertical motion, the area-averaged \( W_f \) accounts for more than 65% of the averaged vertical velocity \( W \) among the three selective members in northeastern Taiwan (averaged over 24.1°–24.6°N, 121.4°–121.7°E; Fig. 12a), indicating that orographic lifting also plays an important role in northeastern Taiwan. However, in southeastern Taiwan (averaged over 23°–24°N, 121.2°–121.3°E), \( W_f \) in SE_35 is smaller and even negative, indicating that terrain plays a minor role in inducing the vertical motion (Fig. 12b).

Since the orographic lifting shows little effect on the torrential precipitation in SE_35, it is of interest to understand the mechanisms leading to the corresponding heavy rainfall, as well as to identify the source of the moisture in southeastern Taiwan in ALL_00 and SE_35, respectively. Figures 13a and 13b show 6-h backward air parcel trajectories for ALL_00 and SE_35. Trajectory analyses are conducted by the Read/Interpolate/Plot (RIP; Stoelinga 2009) program (version 4), with 25 air parcels released at the model level (eta coordinate) of 0.969 in the rainfall region over eastern Taiwan. Beginning at 1500 and 2000 UTC 13 October 2017 (based on the corresponding timing of the maximum rainfall intensity) in ALL_00 and SE_35, respectively, all of the 25 air parcels can be categorized into two groups based on ratios of the parcel altitudes at the backward positions to their initial release points. In the first group, the parcel altitudes during the backward period is close to those at the release points, indicating that the parcels are advected inland. Those air parcels in the advection group are further divided into high-level and low-level subgroups according to the average parcel altitude of 500 m. On the contrary, the second group of air parcels have much lower altitudes during the backward period than at the release points, which indicates that the air parcels are influenced by orographic lifting (figure not shown). In Figs. 13a and 13b, air parcels released in northern Taiwan are advected inland from the frontogenesis area by the northeasterly wind (refer to Fig. 10), while the orographic lifting is dominant in central eastern Taiwan in ALL_00 (Fig. 13a). In contrast, in SE_35, advection plays a critical role especially at the corresponding locations of precipitation maxima. The confluent flows between the seaward extent of the topographically blocked northeasterly and the southeasterly moisture-laden flow associated with the outer circulation of Khanun provide a moisture-laden environment (Fig. 13b). The plume of warm moist air is lifted, as well as the precipitation generated offshore. The elongated convective bands parallel to the shoreline with embedded precipitation systems are advected inland, leading to the subsequent heavy rainfall over southeastern Taiwan. Maps showing the evolution of simulated hourly precipitation for three selected members are shown in Fig. 14 to support the arguments above. In all, rainfall systems advected onshore from the frontogenesis region, as well as orographic lifting are the main mechanisms inducing heavy rainfall over northeastern Taiwan for all three of the ALL, SE and NE types. However, different mechanisms contribute to the heavy rainfall over eastern and southeastern Taiwan. The orographic lifting plays a critical role in the ALL type (Figs. 14d–f), while rainfall systems advected from the frontogenesis region attributed to the confluence of topographically blocked northeasterly and TC outer circulation are responsible for the SE type (Figs. 14g–i).

b. Topographic mode

After Khanun moves westward into the South China Sea, the southeasterly flow becomes the prevailing wind over
FIG. 9. The average rainfall intensity (mm h$^{-1}$) over the period of monsoon mode for (a) NE_07, (b) ALL_00, and (c) SE_35. The black lines represent the locations of cross sections in Fig. 11. (d)–(f) As in (a)–(c), respectively, but for the snapshots of moisture flux divergence (associated with the three selected members during their corresponding period of the highest rainfall rate, i.e., 1100, 1500, 2000 UTC 13 Oct, respectively) averaged from 900 to 1000 hPa (shaded; $10^{-5}$ s$^{-1}$), and horizontal wind at 925 hPa (wind barbs; kt).
eastern Taiwan and its upstream area. At this time, the northeasterly monsoonal flow shifts to the north, and the impingement of Khanun’s circulation on the Central Mountain Range becomes the main mechanism for producing heavy rainfall over eastern Taiwan, which is referred to as the topographic mode. Since the topographic mode is mainly related to the orographic effect, it is of interest to investigate whether the precipitation associated with remote rainfall cases is also phase-locked with the terrain as in the landfalling TCs (Wu and Kuo 1999; Wu et al. 2013). Within the topographic mode, three ensemble members with their centers too close to Taiwan are excluded, and the remaining TC tracks are divided into three groups based on their locations compared with the best track (as the north–south boundary for division between groups A and B (northern) from C (southern), and 118°E [as the division line between groups A (earlier stage) and B (later stage)] (Fig. 15a). The averaged zonal wind \((U)\), and meridional wind \((V)\) are calculated over the region off the eastern coast of Taiwan (22.8°–24.2°N, 121.6°–123°E; Fig. 15a) during the entire simulation period under the topographic mode. The magnitude of \(U\) component is found to peak at the lowest model level, before gradually decreasing to the minimum level of 800 hPa (Fig. 15c). The “reverse shear” type of wind profile (i.e., the shear vector is opposite to the wind direction and away from the mountains) can likely provide a favorable environmental condition and enhance the already strong orographic precipitation (Colle 2004; Yu and Cheng 2014). In contrast, only minimal variation is observed in the average meridional wind above 700 hPa (not shown). Besides, the ratio of the zonal and meridional velocity (i.e., \(U/V\); RUV) is calculated to represent the inflow angle. A larger RUV magnitude represents an inflow with larger easterly component, which is more favorable for the uplifting effects of the Central Mountain Range. The inflow angles are further derived from the mean RUV values, with the average inflow angle below 900 hPa of group A being approximately 55°, followed by groups C and B with the angles of 30° and 20°, respectively (Fig. 15d). Considering the larger incident angles and thus the impact of terrain, Froude number analysis for the topographic mode is also conducted. In Fig. 15e, the favorable mountain geometry and confluent flow fields correspond to a Froude number at lower level greater than 1 in most members of group A, while the Froude numbers in groups B and C are smaller. Note that since the effective Brunt–Väisälä frequency is lower when the air is saturated (Durran and Klemp 1982), the flows with Froude number greater than 1 would be located at higher altitudes than those shown in Fig. 15e.

High correlation coefficients (greater than 0.99) between each parameter in Figs. 15c–e are found, thus the averaged inflow angle is adopted to understand the correlation between
variability in the accumulated rainfall and the flow fields. The Spearman’s rank correlation coefficients between the 24-h cumulative frequency of the total rainfall (Wu et al. 2002) and the inflow angles associated with the topographic mode are calculated. Figure 15b shows that the cumulative frequency of rainfall with higher precipitation thresholds (e.g., above 250 mm in 24 h) is correlated with the inflow angle of the TC circulation, indicating that the inflow angle of the southeasterly flow plays an important role in Khanun’s remote effect on heavy rainfall associated with the topographic mode over eastern Taiwan. In contrast, the cumulative frequency of rainfall with smaller precipitation thresholds (e.g., below 250 mm in 24 h) shows little correlation with the inflow angle (i.e., the Spearman’s rank correlation coefficients are less than 0.4). Furthermore, it is of interest to investigate the factors leading to the cumulative frequency bifurcation in group B at smaller rainfall thresholds (Fig. 15b). Figure 16a shows the ratio of cumulative frequency of 24-h accumulated rainfall between groups B and A. The $\alpha$ angle is shown and described in Figs. 16b and 16c as the angle between the track direction and the horizontal line. Members with westward tracks (averaged $\alpha$ equal to 15°; Fig. 16b) exhibit less rainfall in the latter stage (group B) than in the earlier stage (group A; blue lines in Fig. 16a); while members with northwestward tracks (average $\alpha$ equal to 30°; Fig. 16c) show the cumulative rainfalls in group B closer to that in group A (pink lines in Fig. 16a). The
differences of the averaged $\alpha$ between Figs. 16b and 16c are statistically significant at the 95% confidence level. In summary, heavy rainfalls associated with the topographic mode are similar to those in the landfalling TCs (e.g., Wu et al. 2013), indicating importance of the phase-locking effect with terrain, as well as that of mountain geometry and confluent flow fields.

c. Sensitivity to TC initial moisture and terrain of Taiwan

Since the moisture transport and the topographic effect are two of the main mechanisms leading to the remote heavy rainfall in Khanun, it is of interest to quantify the importance and attribution of the TC initial moisture and the terrain of Taiwan to the uncertainties of TC remote rainfall. Two sensitivity experiments, MR and TR are conducted to elaborate on this issue. In simulations with the initial moisture reduced, the heavy rainfall associated with the monsoon mode is delayed, and the precipitation under topographic mode is less continuous than that in CTRL (figure not shown), leading to a 40% (roughly 200 mm) reduction of the 3-day accumulated rainfall totals in domain 2 (with grid resolution of 6 km) not only in the area where the TC-related moisture in the initial field is removed, but also over mountainous areas in eastern Taiwan.

![Time series of vertical velocity (W; solid lines; m s$^{-1}$) and the topography-induced vertical motion (Wf; dashed lines; m s$^{-1}$) averaged over (a) 24.1°–24.6°N, 121.4°–121.7°E and (b) 23°–24°N, 121.2°–121.3°E. Lines colored in red, blue, and purple represent ALL_00, SE_35, and NE_07, respectively.](image)

FIG. 12. Time series of vertical velocity ($W$; solid lines; m s$^{-1}$) and the topography-induced vertical motion ($W_f$; dashed lines; m s$^{-1}$) averaged over (a) 24.1°–24.6°N, 121.4°–121.7°E and (b) 23°–24°N, 121.2°–121.3°E. Lines colored in red, blue, and purple represent ALL_00, SE_35, and NE_07, respectively.

![Twenty-five 6-h backward air parcel trajectories beginning at model level of 0.9690 for (a) ALL_00 and (b) SE_35; overlaid on the 6-h accumulated rainfall (green shaded; mm), water vapor mixing ratio below 900 hPa (gray shaded; g kg$^{-1}$), and the horizontal wind at 925 hPa (wind barbs; kt). Lines colored in bright blue, orange, and dark blue represent low-level advection, uplifting, and high-level advection, respectively. The dots over eastern Taiwan represent the initial release points.](image)

FIG. 13. Twenty-five 6-h backward air parcel trajectories beginning at model level of 0.9690 for (a) ALL_00 and (b) SE_35; overlaid on the 6-h accumulated rainfall (green shaded; mm), water vapor mixing ratio below 900 hPa (gray shaded; g kg$^{-1}$), and the horizontal wind at 925 hPa (wind barbs; kt). Lines colored in bright blue, orange, and dark blue represent low-level advection, uplifting, and high-level advection, respectively. The dots over eastern Taiwan represent the initial release points.
In TR, without topography, the moisture is no longer retained on the upslope side of the Central Mountain Range. Rainfall reduction over the flattened Taiwan is much more significant than that in MR, in which the maximum rainfall observed in mountainous areas is reduced by more than 90% (roughly 450 mm; Fig. 17b). In addition, without the blocking by the terrain, the confluent region of the northeastlies and TC outer circulation shifts to the northwestern coast of Taiwan (i.e., no monsoon mode exists in northeastern Taiwan), leading to the enhancement of rainfall offshore and over western Taiwan. In summary, the results of these experiments suggest that the remote effect of Khanun on the heavy rainfall over eastern Taiwan is primarily caused by orographic lifting, which is inconsistent with the remote rainfall event associated with Pacific–Japan pattern (e.g., The moisture transported by Typhoon Songda plays a critical role in Wang et al. 2009).

5. Summary

In this study, an ARW-WRF-based EnKF data assimilation system is used to conduct simulations of remote rainfall associated with Typhoon Khanun (2017), which is an unusual case with heavy precipitation attributed to both interaction between the northeasterly monsoon and TC circulation (i.e., monsoon mode), and blocking and uplifting effects of the Central Mountain Range in Taiwan (i.e., topographic mode). Time-varying northeasterly and southeasterly moisture fluxes...
near northeastern Taiwan are used to determine whether the rainfall event is associated with the monsoon mode or the topographic mode. The results show that, in contrast to typical remote rainfall cases, the precipitation hotspots in Khanun under monsoon mode are not concentrated in the northeastern regions but are distributed over eastern Taiwan. Based on different controlling factors contributing to the two modes, three major issues are investigated individually in this study to achieve the below objectives: 1) to understand the key factors resulting in the uncertainty of TC-induced remote rainfall patterns associated with monsoon mode; 2) to examine whether the precipitation associated with remote rainfall cases under topographic mode is also phase locked with the terrain as in the landfalling TCs; and 3) to quantify the attribution of the TC-related moisture and the terrain of Taiwan to remote rainfall events.

The ensemble members are divided into three types: northeast (NE), southeast (SE) and both (ALL) based on the location of precipitation maxima under the monsoon mode. Frontogenesis, vertical cross sections of horizontal divergence, vertical motion, and equivalent potential temperature along terrain, as well as the backward trajectories, are analyzed on the three selected members (i.e., NE_07, ALL_00, SE_35). In northeastern Taiwan, the confluence of the cold dry northeasterlies and the warm moist air transported by TC outer circulation creates a frontogenetical region offshore. With the onshore northeasterlies, the moist-laden flows are advected inland and ascend along the terrain. The topographically induced vertical motion accounts for more than 65% of the averaged vertical velocity among the three selective members, resulting in the heavy rainfall over northeastern Taiwan. However, in eastern and southeastern Taiwan, orographic lifting is the main mechanism for ALL_00 (with Froude number greater than 1); while for SE_35, the Rossby radius of deformation yields the upstream blocking occurring 160 km away from the coastline. The southeasterly moist flows transported by Khanun ascend

**FIG. 15.** (a) The best track from JMA (black) and simulated tracks. (b) The cumulative frequency of 24-h accumulated rainfall (mm) and Spearman’s rank correlation coefficient between the averaged inflow angles and the cumulative frequency of 24-h accumulated rainfall (red line with red circles). (c) The vertical profiles of the averaged zonal wind (m s⁻¹). (d) The inflow angle (°), associated with the topographic mode. (e) The averaged Froude number calculated over the region off the eastern coast of Taiwan [22.8°–24.2°N, 121.6°–23°E; green rectangle in (a)] during the entire simulation period of the topographic mode. Lines colored in green, yellow, and blue represent groups A, B, and C, respectively.
over the topographically blocked northeasterly, and thus generating the precipitation offshore. With the convective bands embedded in rainfall systems being advected inland, the heavy rainfall occurs over southeastern Taiwan.

For the topographic mode, the reverse-shear type of wind profile (i.e., the shear vector is opposite to the wind direction and away from the mountains) is found under 800 hPa, which provides a favorable environmental condition for the enhanced orographic precipitation. The cumulative frequency of the rainfall with smaller precipitation thresholds (e.g., below 250 mm in 24 h) shows little correlation with the inflow angle, but is related to the ensemble track directions. In contrast, the cumulative frequency of the rainfall with higher precipitation thresholds is highly correlated with the inflow angle of the TC circulation. In other words, the upstream flow with higher impinging angle (e.g., 55°) leads to the favorable orographic lifting and confluent flow field (large $V_H \cdot \nabla h$), and therefore provides favorable conditions for heavy rainfall. The Froude number analysis is also conducted, with the results showing that members with higher impinging angles tend to have larger Froude numbers, and thus ascend and produce more rainfall associated with the topographic mode, which is similar to landfalling TCs.

Analyses from the sensitivity experiments show that the 3-day accumulated rainfall total in domain 2 (with grid resolution of 6 km) is reduced by roughly 200 (40%) and 450 mm (90%) in the moisture-reduced (MR) and the terrain-removed (TR) experiments, respectively. With the reduced TC-related moisture, the heavy rainfall is delayed under the monsoon mode and less continuous under the topographic mode; while without the blocking by the terrain, the frontalogenesis region shifts to the northwestern coast of Taiwan, indicating that the rainfall under monsoon mode would no longer occur in northeastern Taiwan. These results indicate that the terrain of Taiwan plays a crucial role in enhancing the remote orographic heavy rainfall. Without the blocking and uplifting effects on the windward side of the Central Mountain Range, heavy rainfall is not observed even if environmental conditions are favorable.

In summary, this study provides a new and simple method to distinguish remote rainfalls of the monsoon mode from those of the topographic mode, identifies different mechanisms leading to different rainfall patterns under monsoon mode, examines the characteristics of precipitation associated with topographic mode, as well as investigates the major process involved in this remote rainfall event. Four key findings are
presented: 1) the remote rainfall event in Khanun is mainly influenced by the lower-tropospheric patterns instead of the upper-level synoptic systems (different from one of the mechanisms leading to the PREs, e.g., Moore et al. 2013); 2) heavy rainfall over eastern Taiwan associated with the monsoon mode in Khanun is not only attributed to the interaction between the northeasterly monsoon and Khanun’s outer circulation, but also to the orographic lifting, topographic blocking, and rainfall systems advection [putting forward a new argument compared to Chen and Wu (2016)]; 3) remote rainfall associated with the topographic mode is similar to that of landfalling TC cases, which highlights the importance of the mountain geometry and confluent flow fields; and 4) in Khanun, multiple mechanisms contribute to remote rainfall processes, particularly the orographic forcing [inconsistent with the findings shown in Wang et al. (2009)].

Two of the caveats to note are the lack of verification for the exact rainfall amounts, as well as uncertainty in the robustness of these results owing to the limited sample sizes. Due to the complicated interaction of the TC–monsoon–terrain system, one should be wary of the source of errors that may compromise predictability of these contributing factors. Furthermore, future work would be investigating the criteria of which the topographic lifting becomes the main mechanism of heavy rainfall. Sensitivity experiments with different model resolutions and different sizes of TC circulation would form basis for another interesting research. The physical insights in this study are aimed to improve understanding of the likelihood of such high-impact but easily underestimated heavy rainfall cases associated with remote typhoons in real-time forecasting.

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