

1 **Investigation of An Extreme Rainfall Event during 8-12 December 2018 over**  
2 **Central Vietnam. Part I: Analysis and Cloud-Resolving Simulation**

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11 **Highlights:**

- 12 • A record-breaking rainfall event over central Vietnam is investigated  
13 • Key factors in this event include the combined effect of northeasterly wind that  
14 originated from northern China, low-level easterly wind blow to central Vietnam  
15 from the northwest Pacific Ocean, southeasterly wind, local topography, and high sea  
16 surface temperature over North West Pacific Ocean and South China Sea.  
17 • A cloud-resolving model is applied to simulated this extreme rainfall event in central  
18 Vietnam, and the results show that the model mostly captured the quantitative rainfall  
19 of this event. These results are very impressive.

## Abstract

An extreme rainfall event occurred from 8 to 12 December 2018 along the coast of central Vietnam. The observed maximum rainfall amount in 72 h was over 900 mm and set a new record, and the associated heavy losses were also significant. The analysis of this event shows some key factors for its occurrence: (1) The interaction between the strong northeasterly winds, blowing from the Yellow Sea into the northern South China Sea (SCS), and easterly winds over the SCS in the lower troposphere (below 700 hPa). This interaction created strong low-level convergence, as the winds continued to blow into central Vietnam against the Truong Son Range, resulting in forced uplift over the coastal plains due to the terrain's barrier effect. Furthermore, the low-level convergence in this event was strong enough, and the air was unstable enough to trigger most of the convection near the shoreline (further inland). As a consequence, heavy rainfall occurred along the coastal zone and coastal sea. (2) The strong easterly wind played an important role in transporting moisture from the western North Pacific across the Philippines and the SCS into central Vietnam. (3) The Truong Son Range also contributed to this event due to its barrier effect. (4) In addition to cumulonimbus, the low-level precipitating clouds such as nimbostratus clouds were also major contributors to rainfall accumulation for the whole event. The analyses of local thermodynamics also indicate that the southward movement of the low-level wind convergence zone caused the southward movement of the main heavy rain band during the event.

The Cloud-Resolving Storm Simulator (CReSS) was employed to simulate this record-breaking event at a grid size of 2.5 km, and evaluated results show the model had good simulated the surface wind as well as captured the southward movement of the low-level wind convergence. The overall rainfall can be captured quite well not only in quantity but also in its spatial distribution (with a Fractions Skill Score  $\approx 0.7$  and Threat Score  $> 0$  at 700 mm for 72 h rainfall). Thus, the CReSS model is shown to be a useful tool for both research and forecasts of heavy rainfall in Vietnam. The model performed better for the rainfall during 9-10 but not as good on 11 December.

45 In the sensitivity test without the terrain, the model had poorly simulated the surface wind, which  
46 led to the model not only did not generate nearly as much rainfall for this event but also did not  
47 capture the spatial distribution of the rainfall. Thus, the test confirms the important role played by  
48 the local topography for the occurrence of this event.

49 Keywords: Extreme rainfall, central Vietnam, cloud-resolving model.

## 50 **1 Introduction**

51 Heavy to extreme rainfalls are natural disasters that often cause deaths, flooding, landslides,  
52 and erosion. Vietnam is one of the most disaster-prone countries in the world with many different  
53 types of natural disasters. In the country, central Vietnam is most affected by natural disasters and  
54 climate change, with frequent occurrences of rainstorms and extreme rainfalls. For example, during  
55 8-12 December 2018, an extreme rainfall event (hereafter abbreviated as the D18 event) occurred  
56 along the coast of central Vietnam. The peak 72-h accumulated rainfall (from 1200 UTC 8 to 1200  
57 UTC 11 Dec) at some stations exceeds 800 mm (Fig. 1d). Among the stations, Da Nang (16.0° N,  
58 108.2° E, cf. Figs. 1a,b) recorded 24-h rainfall amounts greater than 600 mm on 9 December and  
59 over 300 mm the next day. This extreme event resulted in 13 deaths, an estimated 1200 houses  
60 inundated, around 12,000 hectares of crops destroyed, some 160,000 livestock killed and many  
61 other economic losses (Tuoi Tre news, 2018). Furthermore, according to a publication by the  
62 Ministry of Natural Resources and Environment of Vietnam (Tran *et al.*, 2016) regarding climate  
63 change and sea-level rise scenarios, extreme precipitation events will increase in both their  
64 frequency and intensity in the future. Hence, how to improve the ability in the quantitative  
65 precipitation forecast (QPF) of heavy-rainfall events over central Vietnam is very important.

66 Climatologically, the central part of Vietnam is the country's rainiest region and is strongly  
67 affected by heavy to extreme rainfall, with average annual precipitation ranging from 2400 to over  
68 3300 mm (1980–2010, Fig. 1f). The main rainy season in this region is from late fall to early winter

69 (Yokoi and Matsumoto, 2008; Chen *et al.*, 2012). Past studies have shown some main factors that  
70 can lead to heavy rainfall in central Vietnam, such as (1) the combined effect of cold surges that  
71 originate from northern China, (2) tropical depressions, and (3) local topography due to the  
72 topography is characterized by high mountains (< 3000 m), highlands, narrow coastal plain with the  
73 narrowest place less than 100 km in width (east-west), and gradually lowers from the west to the  
74 east (Fig. 1a) (Bui, 2019; Yokoi and Matsumoto, 2008; Chen *et al.*, 2012; Nguyen-Le and  
75 Matsumoto, 2016; van der Linden *et al.*, 2016). According to these studies, a cool, dry continental  
76 surface high pressure system (known as the Siberian high-pressure system) gradually establishes  
77 over the continental East Asia after boreal summer in October–November. This high-pressure  
78 system's intensification and southeastward amplification lead to an episodic southward progression  
79 of cold surge into the tropics. The interaction of this cold surge and preexisting tropical disturbance  
80 over the SCS and the topography in central Vietnam can bring large amounts of rainfall along the  
81 east-central coast through orographic rainfall processes.

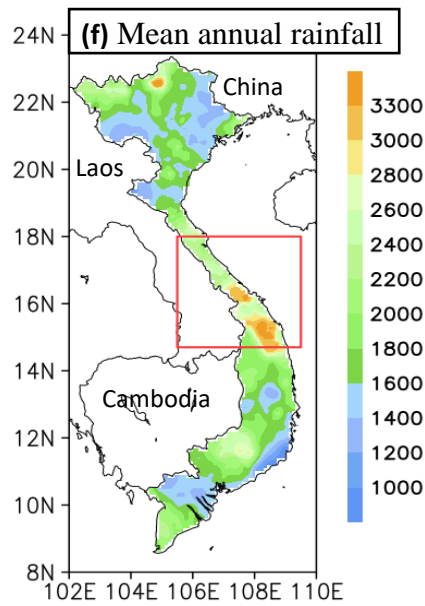
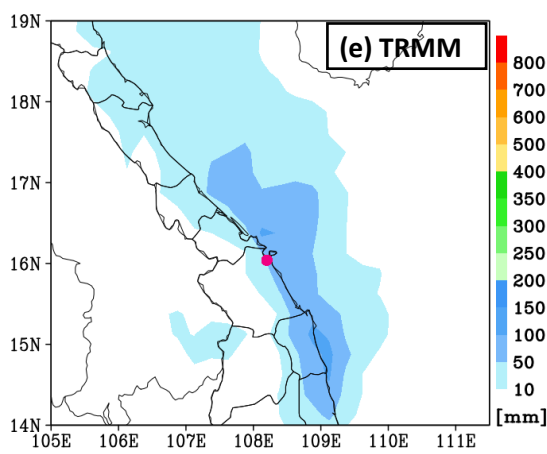
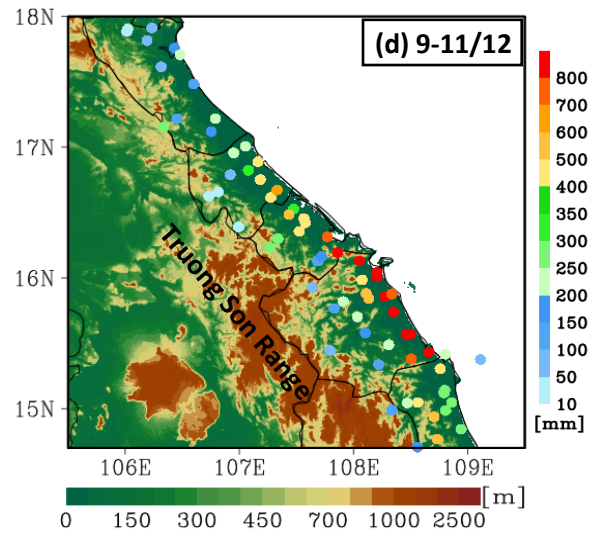
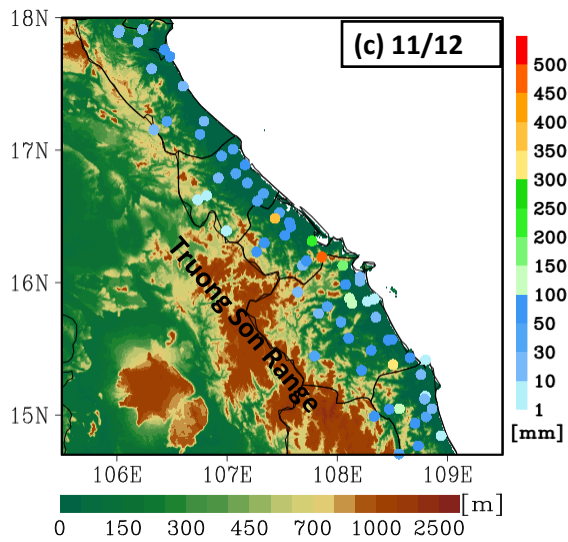
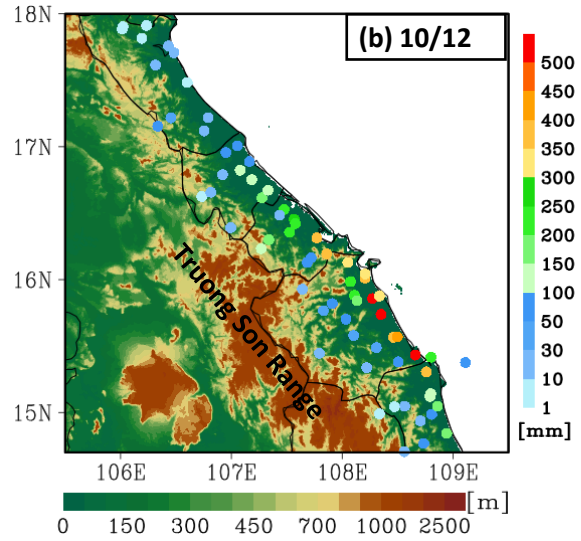
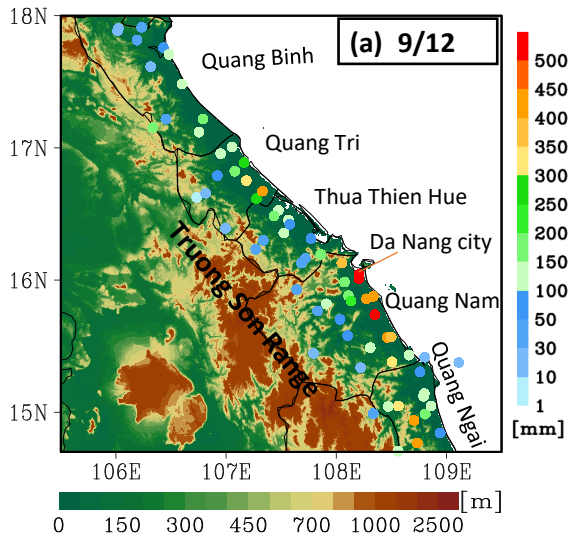
82 In this study, central Vietnam is referred to as the area between 14.7° N and 18° N (Fig. 2a). Its  
83 eastern boundary is the South China Sea (SCS), and the western boundary is the border to Laos,  
84 where the Truong Son Range (also known as the Annamite Range) runs parallel to the coast. The  
85 central Vietnam includes Quang Binh, Quang Tri, Thua Thien Hue, Da Nang city, Quang Nam, and  
86 a part of Quang Ngai province. Most of the population and cities are concentrated along the coastal  
87 plain. By these characteristics of steep topography, when heavy rain occurs, it often leads to  
88 flooding and causes great damages to people and the environment.

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93 **Figure 1.** (a) observed 24 h accumulated rainfall (mm, color dots, 1200 – 1200 UTC) and  
94 topography (m, shaded) for 9 Dec. Vertical colorbar for rainfall, and horizontal colorbar for  
95 topography. (b) As in (a), but for 10 Dec. (c) As in (a), but for 11 Dec. (d) As in (a), but for 72 h  
96 accumulated rainfall during 1200 UTC 8–1200 UTC 11 Dec. (e) 72 h accumulated rainfall obtained  
97 by TRMM estimate. The pink dot marks the location of Da Nang station. (f) Mean annual rainfall  
98 distribution (mm) in Vietnam from 1980 to 2010, obtained from the Vietnam Gridded Precipitation  
99 (VnGP) data, and the study area of central Vietnam (red box).

100 Furthermore, according to Wang et al. (2017), Vietnam is impacted by about 4-6 typhoons per  
101 year. Nguyen-Thi *et al.* (2012) investigated the characteristic of tropical cyclone rainfall over  
102 Vietnam in the climatology. Their results show that the tropical cyclone rainfall amount is  
103 concentrated in central Vietnam, peaking between October and November. Takahashi et al. (2009)  
104 performed a long-term simulation for September (from 1966 to 1995) using a high-resolution  
105 model. They found that the observed long-term decrease in September rainfall is due to the  
106 weakening of tropical cyclone activity over the Indochina Peninsula. As for the impacts of El Niño-  
107 Southern Oscillation (ENSO), some studies have examined the linkages between rainfall in  
108 Vietnam and ENSO, and suggested more (less) rainfall during La Niña (El Niño) years. For  
109 example, Yen *et al.* (2010) analyzed the interannual variation of the rainfall in fall over central  
110 Vietnam, and their results indicated a negatively correlated relationship between rainfall in central  
111 Vietnam and the sea surface temperature over the NINO3.4 region. Besides, Vu et al. (2015)  
112 investigated the effects of ENSO on fall rainfall in central Vietnam and concluded that central  
113 Vietnam has more (less) rainfall in La Niña (El Niño) years. Finally, Wu et al. (2012) analyzed the  
114 Madden-Julian Oscillation (MJO) activity from September to November for 30 years (1981-2010)  
115 over Vietnam and showed that the MJO is also an important factor in the formation of extreme  
116 precipitation events in central Vietnam.

117 In recent decades, the Cloud-Resolving Storm Simulator (CReSS) has been widely known due  
118 to its good performance in quantitative precipitation forecasts. This model has been applied to study  
119 tropical cyclones, heavy to extreme rainfall events, and many other convective systems in Japan and

120 Taiwan (e.g., Ohigashi and Tsuboki, 2007; Yamada *et al.*, 2007; Akter and Tsuboki, 2010, 2012;  
121 Wang *et al.*, 2015). Furthermore, the CReSS model has been used to perform routine high-  
122 resolution forecasts at the National Taiwan Normal University (NTNU) and provided to the TTFRI  
123 as a forecast member since 2010. Hence, this study employed the CReSS model to simulate the  
124 D18 event and evaluated its performance

125 From the review above, the important mechanisms for the heavy rainfall in some previous  
126 events over central Vietnam are revealed. However, according to Dr. Hoang Phuc Lam – National  
127 Center for Hydro- Meteorological Forecasting, it can be said that this extreme event has never  
128 happened in the past because the observed rainfall at some places in the Central region has  
129 surpassed the record according to the statistics of rainfall at the end of the main rainy season  
130 (Communist Party of Vietnam Online Newspaper). Furthermore, Figs. 1a,b,c,d and e show that the  
131 main heavy rain band concentrated on the coastal plains and coastal sea while Fig. 1f show the  
132 annual mean rainfall extends into the mountain with their peak amounts over the mountain slopes,  
133 several questions are therefore raised: What mechanisms caused this record-breaking event at such  
134 a magnitude? Was its mechanism similar to those in previous events? Or, it was a different one.  
135 How important was the role played by local terrain in this event? From a forecast perspective, one  
136 related question would be whether a cloud-resolving model is capable of reproducing the D18  
137 event? The answers to these questions will help improve our understanding on the mechanisms that  
138 cause heavy rainfall in central Vietnam, as well as on the predictability of such events in the future.  
139 Hence, the present study was carried out with an aim to answer the above questions. The remainder  
140 of this paper is organized as follows: Section 2 describes the datasets and methodology used in the  
141 study. The analysis and modeling results are presented in Section 3 and 4, respectively. Finally, the  
142 conclusions are given in Section 5.

## 143 **2 Data and Methodology**

### 144 **2.1 Data**

### 145 2.1.1 NCEP GDAS/FNL Global Gridded Analyses and Forecasts

146 The NCEP GDAS/FNL Global Gridded Analyses and Forecasts is provided freely by the  
147 National Centers for Environmental Prediction (NCEP). In this study, this dataset is used as the  
148 initial and boundary conditions (IC/BCs) for the cloud-resolving model (CRM) simulation. The data  
149 are on a  $0.25^\circ \times 0.25^\circ$  latitude-longitude grid with 26 levels extending from the surface to 20 hPa.  
150 The data period is from 0600 UTC 8 December to 0000 UTC 13 December 2018, at 6-h intervals.  
151 Parameters include geopotential height, zonal and meridional wind components, pressure,  
152 temperature, and relative humidity. The dataset and its detailed information are available at  
153 <https://rda.ucar.edu/datasets/ds083.3>.

### 154 2.1.2 The fifth generation ECMWF reanalysis data (ERA5)

155 The ERA5 is the fifth-generation reanalysis dataset, developed by the European Centre for  
156 Medium-range Weather Forecasts (ECMWF) to replace the ERA-Interim reanalysis. We have used  
157 these data to delineate the synoptic weather patterns during the D18 event. The horizontal resolution  
158 of this dataset is  $0.25^\circ \times 0.25^\circ$  latitude-longitude at 22 selected levels from 1000 to 100 hPa and  
159 including the surface. Parameters include zonal and meridional wind components, geopotential  
160 height, specific humidity, relative humidity, temperature, vertical velocity, mean sea level pressure,  
161 and sea surface temperature. The dataset was downloaded from 0000 UTC 8 to 1800 UTC 11  
162 December 2018 at 6-h intervals (Hersbach et al., 2018a,b).

### 163 2.1.3 Observation data

164 The daily observed rainfall data (1200–1200 UTC, i.e., 1900–1900 LST) from 8 to 12  
165 December 2018 at 69 automated gauge stations across central Vietnam are used for case overview  
166 and verification of model results. This dataset is provided by the Mid-central Regional Hydro-  
167 Meteorological Centre, Vietnam.

### 168 2.1.4 Satellite data



169 (a) TRMM (TMPA) rainfall estimates

170 The TRMM multi-satellite precipitation estimates (3B42, version 7, Huffman *et al.*, 2016) are  
171 freely provided by the NASA Goddard Earth Sciences (GES) Data and Information Services Center  
172 (DISC). The horizontal resolution of this dataset (level 3) is  $0.25^\circ \times 0.25^\circ$  latitude-longitude and the  
173 time resolution is every 3 h. In this study, we used this satellite data to verify rainfall distribution  
174 over the coastal sea due to the limitation of the observation station network, we only have the  
175 observation stations inland, as shown in the Figure. 1d and Fig. 1e. This dataset was downloaded  
176 from 1200 UTC 8 to 1200 UTC 11 December 2018 to analyze the D18 event.

177 (b) The Himawari satellite images

178 The color-enhanced infrared imageries are designed mainly for the detection of convective  
179 clouds, including those from the Himawari-8 satellite. The different colours represent different  
180 cloud-top heights. Therefore, we have used these images to discern deep convection in convective  
181 clouds and precipitating clouds based on their characteristics. In this study, the dataset was  
182 downloaded from the Central Weather Bureau website, Taiwan, with a time resolution of 1 h.

#### 183 *2.1.5 Radar data*

184 The column-maximum radar reflectivity data are one indispensable data source to identify  
185 precipitation and verify model results. The reflectivity data (in dBZ) cover a wide range and the  
186 values indicate rainfall intensity (the higher the dBZ, the stronger the intensity of precipitation).  
187 Therefore, we used the column-maximum radar reflectivity data over central Vietnam at 1-h  
188 intervals over 8-11 December 2018 to estimate the rainfall intensity during the D18 event. This  
189 dataset is provided by the Mid-central Regional Hydro-Meteorological Centre of Vietnam.

#### 190 *2.1.6 The Vietnam Gridded Precipitation (VnGP) Dataset.*

191 The VnGP data are derived base on the daily observed data from 481 rain gauges cross  
192 Vietnam. This dataset has a resolution of  $0.1^\circ$  and covers the period of 1980-2010 (Nguyen-Xuan et  
193 al., 2016). In this study, this dataset is used to depict the rainfall climatology in Vietnam.

#### 194 2.1.7 The Oceanic Niño Index (ONI) data

195 The Oceanic Niño Index (ONI) data was made and provided freely by NOAA Climate  
196 Prediction Center (CPC). The ONI data was computed by three month running mean of NOAA  
197 ERSST.V5 SST anomalies in the Niño 3.4 region (5N-5S, 120-170W), based on changing base  
198 period which onsist of multiple centered 30-year base periods. The ONI is the most commonly used  
199 indices to define El Niño and La Niña events. This study used the ONI data for Niño 3.4 region to  
200 define the ENSO phase of 2018. This data is available at:

201 <https://psl.noaa.gov/data/correlation/oni.data>

## 202 2.2 Model description and experiment setup

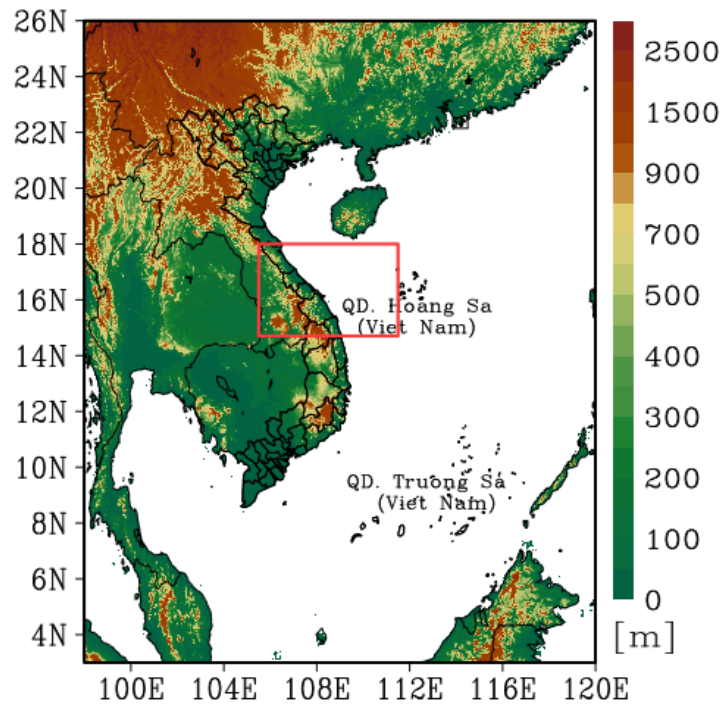
203 The Cloud Resolving Storm Simulator (CReSS, version 3.4.2), developed by Nagoya  
204 University, Japan (Tsuboki and Sakakibara, 2002, 2007) is used for numerical simulation of the  
205 D18 event. This model is a non-hydrostatic and compressible cloud model, designed for simulation  
206 of weather events at high (cloud-resolving) resolution. In the model, the cloud microphysics is  
207 treated explicitly at the user-selected degree of complexity, such as the bulk cold-rain scheme with  
208 six species: vapor, cloud water, cloud ice, rain, snow, and graupel (Lin *et al.*, 1983; Cotton *et al.*,  
209 1986; Murakami, 1990, 1994; Ikawa and Saito, 1991). Other subgrid-scale processes parameterized,  
210 such as turbulent mixing in the planetary boundary layer, as well as physical options for surface  
211 processes, including momentum/energy fluxes, shortwave and longwave radiation are summarized  
212 in Table 1.

213 To study the D18 event and investigate the role played by the local terrain in this event using  
214 the CReSS model, two experiments were performed using the same model domain setting, physical

215 options, and initial and boundary conditions. Specifically, both experiments using a single domain  
216 at 2.5-km horizontal grid spacing and a (x, y, z) dimension of 912 x 900 x 60 grid points (Table 1,  
217 cf. Figure 2). As introduced in subsection 2.1.1, the NCEP GDAS/FNL Global Gridded Analyses  
218 and Forecasts (0.25° x 0.25°, every 6 h, 26 pressure levels) was used as the IC/BCs of the model.  
219 These experiments were started from 0600 UTC 8 to 0000 UTC 13 December 2018 (for a  
220 simulation length of 114 h).

221 The only different setting between these experiments is at the lower boundary, the real terrain  
222 data at (1/120°) resolution (roughly 0.9 km) was provided for the control simulation (CTRL) while  
223 this was ignored for the sensitivity test without the terrain (NTRN)

224 The main information of these two experiments, including the domain setup and model  
225 configuration, is listed in Table 1.



226 **Figure 2:** The simulation domain of the CReSS model and topography (m) used in this study. The  
227 red box marks the study area.  
228

229 **Table 1.** The basic information of experiments.

<b>Domain and Basic setup</b>	
Model domain	3°–26°N; 98°–120°E
Grid dimension ( $x, y, z$ )	912 × 900 × 60
Grid spacing ( $x, y, z$ )	2.5 km × 2.5 km × 0.5 km*
Projection	Mercator
IC/BCs (including SST)	<i>NCEP GDAS/FNL Global Gridded Analyses and Forecasts</i> (0.25° × 0.25°, every 6 h, 26 pressure levels)
Topography (for CTRL only)	Digital elevation model by JMA at (1/120)° spatial resolution
Simulation length	114 h
Output frequency	1 hour
<b>Model physical setup</b>	
Cloud microphysics	Bulk cold-rain scheme (six species)
PBL parameterization	1.5-order closure with prediction of turbulent kinetic energy (Deardorff, 1980; Tsuboki and Sakakibara, 2007)
Surface processes	Energy and momentum fluxes, shortwave and longwave radiation (Kondo, 1976; Louis et al., 1982; Segami et al., 1989)
Soil model	41 levels, every 5 cm deep to 2 m

230 \* The vertical grid spacing ( $\Delta z$ ) of CReSS is stretched (smallest at bottom) and the averaged value is  
231 given in the parentheses

### 232 **2.3 Verification of model rainfall**

233 In order to verify the model-simulated rainfall, some verification methods are used, including  
234 (1) visual comparison between the model and the observation (from the 69 automated gauges over  
235 the study area), and (2) the objective verification using categorical skill scores at various rainfall  
236 thresholds from the lowest at 0.05 mm up to 900 mm for three-day total. These scores are listed in  
237 Table 2 along with their formulas, perfect value, and worst value, respectively. To apply these  
238 scores at a given threshold, the model and observed value pairs at all verification points (gauge sites  
239 here, N) are first compared and classified to construct a 2 × 2 contingency table (Wilks, 2006). At

240 any given site, if the event takes place (reaching the threshold) in both model and observation, the  
 241 prediction is considered a hit (H). If the event occurs only in observation but not the model, it is a  
 242 miss (M). If the event is predicted in the model but not observed, it is a false alarm (FA). Finally, if  
 243 both model and observation show no event, the outcome is correct rejection (CR). After all the  
 244 points are classified into the above four categories, the scores can be calculated by their  
 245 corresponding formula in Table2.

246 **Table 2.** List of the categorical skill scores and their formulas.

Name of skill score	Formula	Perfect score	Worst score
Bias Score (BS)	$(H+FA)/(H+M)$	1	0 or N - 1
Probability of Detection (POD)	$H/(H+M)$	1	0
False Alarms Ratio (FAR)	$FA/(H+FA)$	0	1
Threat Score (TS)	$H/(H+M+FA)$	1	0

247

248 In addition to the categorical scores, the Similarity Skill Score (SSS, Wang et al., 2022) is also  
 249 applied to evaluate the model rainfall results, as

$$250 \quad SSS = 1 - \frac{\frac{1}{N} \sum_{i=1}^N (F_i - O_i)^2}{\frac{1}{N} \sum_{i=1}^N F_i^2 + \frac{1}{N} \sum_{i=1}^N O_i^2} \quad (1)$$

251

252 where N is the total number of verification points,  $F_i$  is the forecast value, and  $O_i$  is the observed  
 253 value, at the  $i$ th point among N, respectively. SSS is used to measure against the worst the mean  
 254 squared error (MSE) possible. The formula shows that a forecast with perfect skill has a FSS of 1,  
 255 while a score of 0 means zero skill.

### 256 3 Overview of the D18 Event

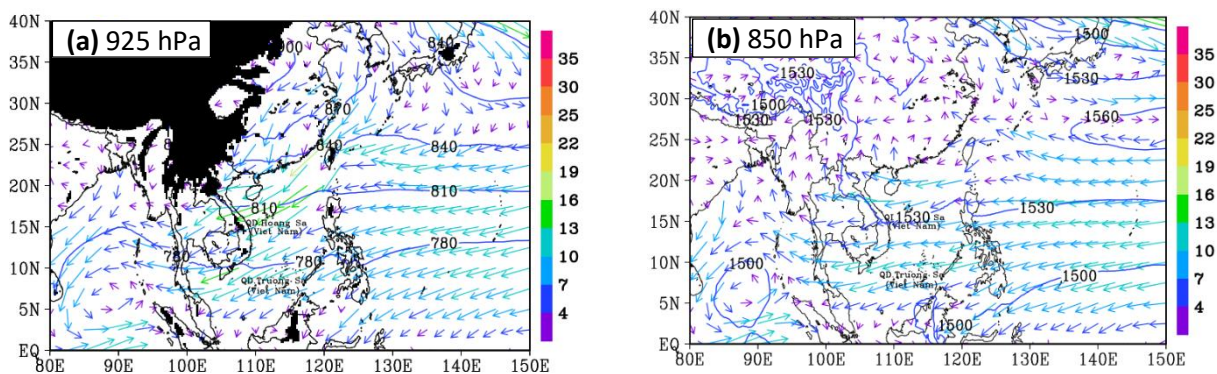
#### 257 3.1 Rainfall and its distribution

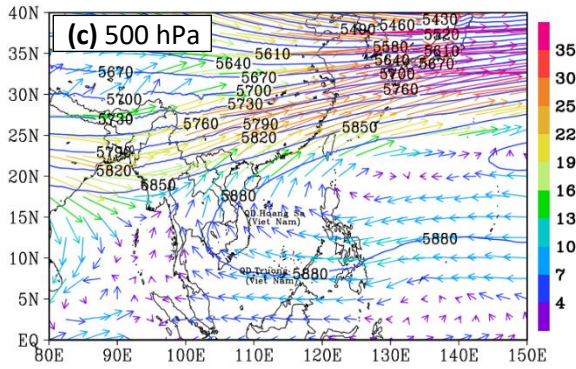
258 The maximum accumulated rainfall was recorded from 9 to 11 December with a peak daily  
 259 rainfall greater than 500 mm and 72-h accumulated rainfall exceeds 800 mm (Figs. 1a-d). Besides,

260 the daily and 72-h rainfalls observed at 69 stations show that the extreme precipitation occurred along  
 261 the eastern coastal plains, on the eastern side of the Truong Son Range. Especially over Quang Nam  
 262 province, where the Truong Son Range reaches its highest of over 2500 m (Figs. 1a-d). In addition,  
 263 satellite products from the Tropical Rainfall Measuring Mission (TRMM) seriously underestimates  
 264 the D18 event (Fig. 1e), but indicates that the rainfall occurred not only in coastal plains but also over  
 265 the nearby ocean.

### 266 3.2 Synoptic conditions

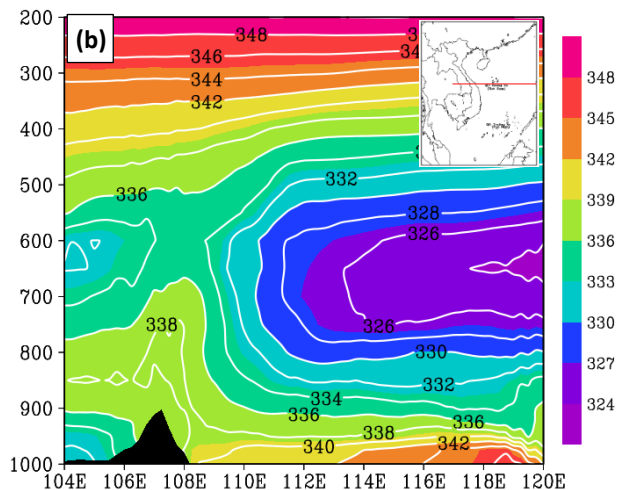
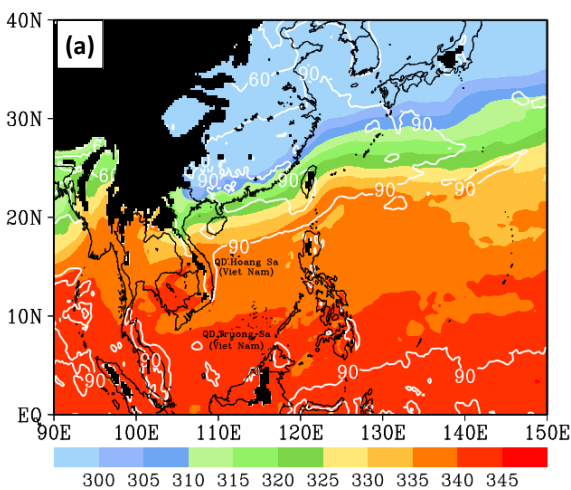
267 During the D18 event, the horizontal winds at 925 hPa (averaged from 0000 UTC 8 to 1800  
 268 UTC 11 December) over central Vietnam and the SCS are characterized by a strong convergent  
 269 zone between the northeasterly winds blowing from northeastern China into northern SCS and  
 270 central Vietnam, and the easterly winds blowing from the western North Pacific (WNP) into the  
 271 SCS (Fig. 3a). The wind speed over northern SCS and central Vietnam is over  $13 \text{ m s}^{-1}$ . At 850  
 272 hPa, horizontal winds are predominantly easterly, with speeds of about  $10\text{--}13 \text{ m s}^{-1}$  (Fig. 3b). At  
 273 500 hPa, central Vietnam is affected by southeasterly winds that originated from the easterly winds  
 274 over the WNP (Fig. 3c). Besides, Figure 3 also indicates that there was no existence of any tropical  
 275 cyclone during the D18 event. Therefore, tropical cyclones or the combined effect of cold surges  
 276 originating from northern China and tropical depressions that have been mentioned as one of the  
 277 patterns that cause heavy rainfall in central Vietnam is not the mechanism of the D18 event.





278 **Figure 3.** (a) The ERA5 averaged horizontal wind vectors ( $\text{m s}^{-1}$ , color for speed) and geopotential  
 279 height (gpm, blue contours, every 30 gpm) at the 925 hPa from 0000 UTC 8 to 1800 UTC 11 Dec  
 280 2018. (b) As in (a), but for the 850 hPa. (c) As in (a), but for the 500 hPa. The blacked areas are  
 281 where the 925-hPa level is below the ground.

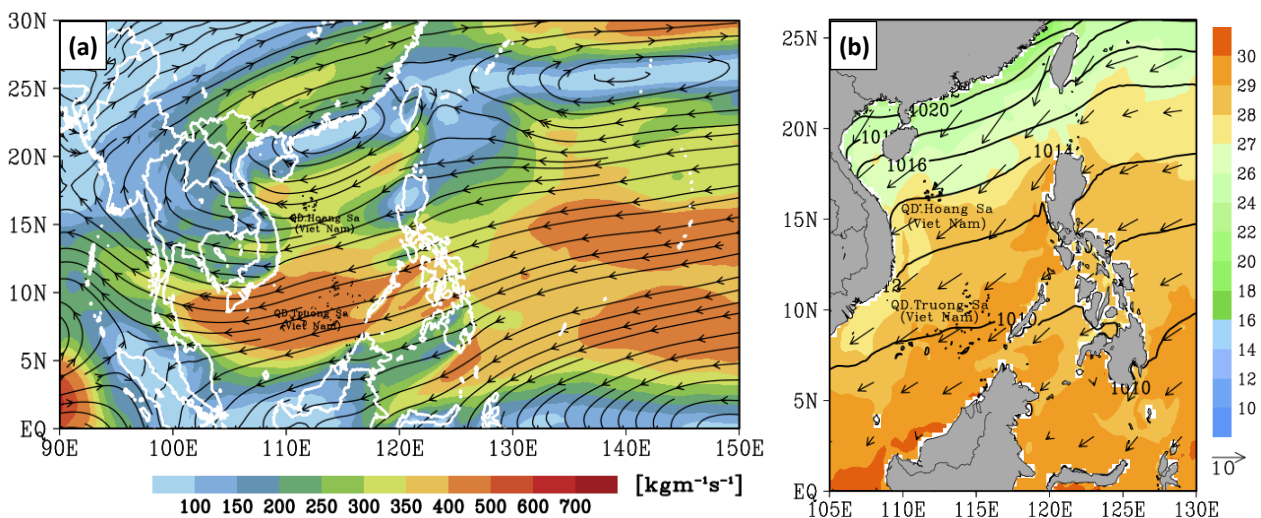
282 From a thermodynamic perspective, the equivalent potential temperature ( $\theta_e$ ) field at 925 hPa  
 283 shows that a warm and moist tropical air mass exist in central and SCS with  $\theta_e$  values greater than  
 284 335 K, and the relative humidity is around 90 % during the D18 event (Fig. 4a). The high moisture  
 285 content combines with a decrease in  $\theta_e$  with altitude, indicating convective instability in the lower  
 286 atmosphere below about 500 hPa (Fig. 4b). Furthermore, the interaction between northeasterly and  
 287 easterly winds seemed to enhance instability in the lower atmosphere.



288

289 **Figure 4.** (a) The ERA5 averaged equivalent potential temperature (K, color), and relative humidity  
 290 (% , white contours, every 30 %) at 925 hPa. The blacked areas are where the 925-hPa level is  
 291 below the ground. (b) the east-west vertical cross-section along 16°N (see insert) of averaged  
 292 equivalent potential temperature ( $\theta_e$ , K, color, every 5 K), from 0000 UTC 8 to 1800 UTC 11 Dec  
 293 2018. The topography is dark shaded.

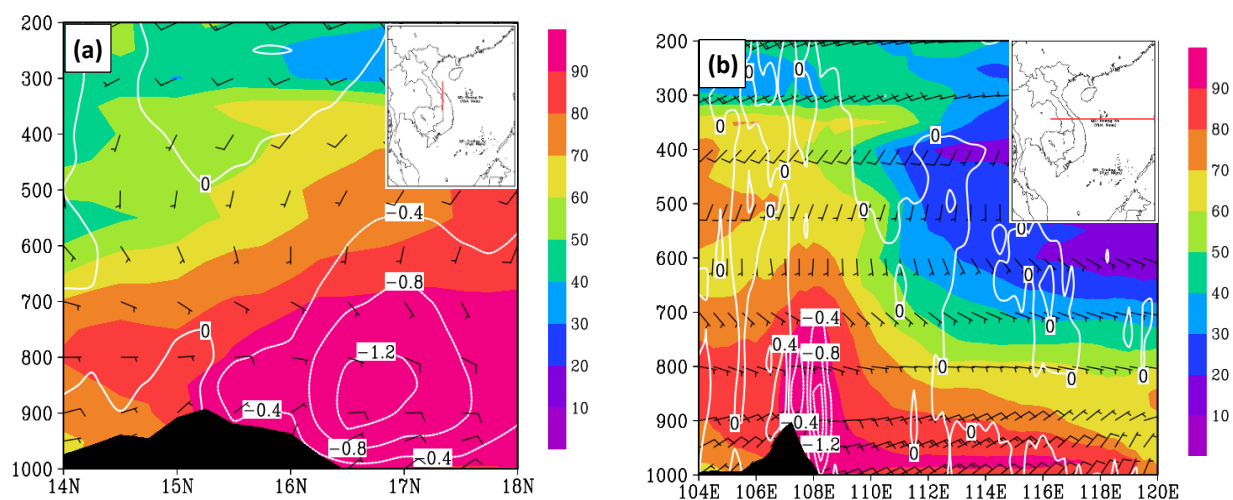
294 The above analysis suggests that the northeasterly, easterly, and southeasterly winds (cf. Figs.  
 295 3a-c) all played an important role in transported unstable air into central Vietnam. Particularly,  
 296 when the strong northeasterly and the easterly winds at low levels and southeasterly wind at upper  
 297 levels blow into central Vietnam, they bring warm, moist, and unstable air into central Vietnam.  
 298 This moisture is transported to central Vietnam by strong moisture flux through the deep column  
 299 from the WNP, across the Philippines and the SCS (Fig. 5a). Furthermore, the high SST of the SCS  
 300 ( $>27^\circ\text{C}$ ) also help to enhance and maintain abundant moisture during this event (Fig. 5b).



301 **Figure 5.** (a) The ERA5 averaged surface–200-hPa vertically integrated moisture flux ( $\text{kg m}^{-1}\text{s}^{-1}$ ).  
 302 (b) the ERA5 averaged SST ( $^\circ\text{C}$ , color), mean sea-level pressure (hPa, isobars, every 2 hPa), and  
 303 horizontal wind vectors at 10-m height ( $\text{m s}^{-1}$ , vector), from 0000 UTC 8 to 1800 UTC 11 Dec  
 304 2018.  
 305

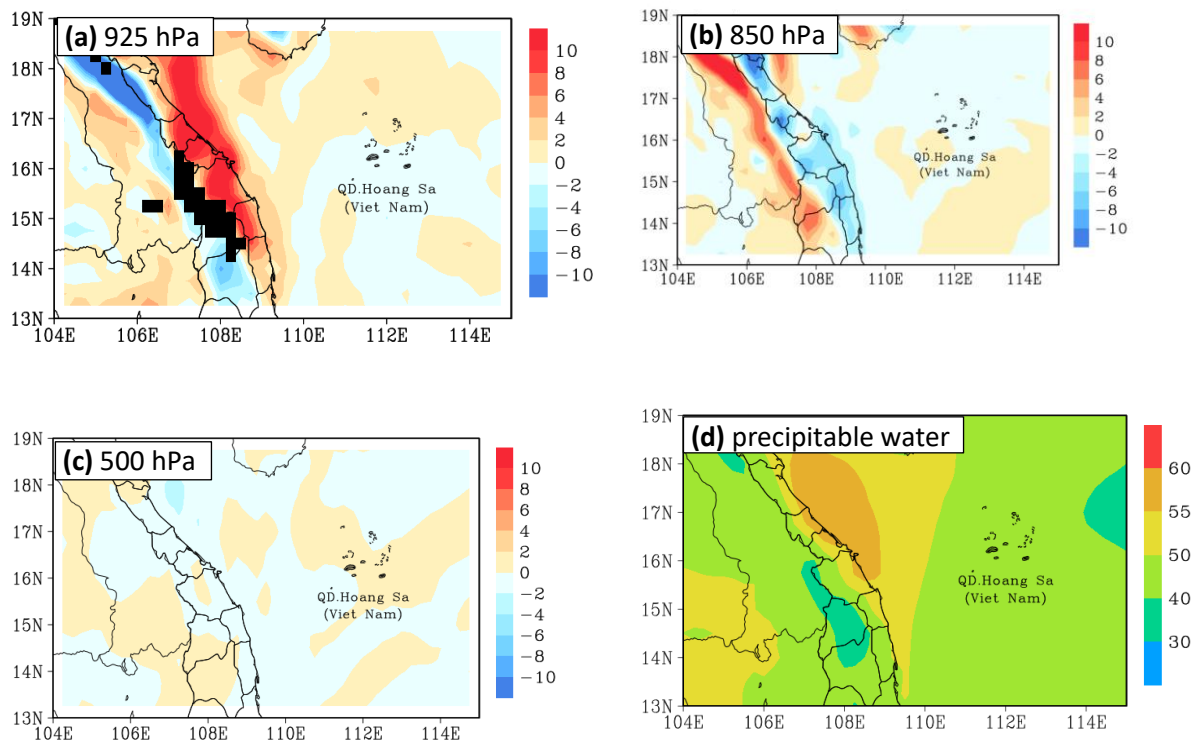


306 Consequently, the atmospheric conditions and local topographic characteristics in interaction  
 307 result in moisture convergence and forced uplift in the lower troposphere during the D18 event.  
 308 This can be seen in Fig. 6, where extensive rising motion occurs in the lower troposphere along  
 309 coastal Vietnam, with a maximum value of  $-1.2 \text{ Pa s}^{-1}$ . Besides, Figs. 6a,b also indicate that the  
 310 strong northeasterly wind along with warm, moist and unstable air is blocked by the Truong Son  
 311 Range. This pattern suggests that the Truong Son Range also played an important role in the  
 312 development of heavy rainfall in central Vietnam in D18. In detail, when the northeasterly and  
 313 easterly winds at low levels blow into central Vietnam and become block by the Truong Son Range,  
 314 which is located along the border of Vietnam and Laos, forced uplift is resulted at the windward  
 315 side, with downward motion over the lee side (in Laos, Fig. 6b). Furthermore, the low-level  
 316 convergence in this event was strong enough (Fig. 3a), and the air was unstable enough (Fig. 4b) to  
 317 trigger most of the convection near the shoreline (further inland, Fig. 6a)



318 **Figure 6.** (a) The ERA5 the south-north vertical cross-section along  $107.5^\circ\text{E}$  (see insert) of  
 319 averaged horizontal wind ( $\text{m s}^{-1}$ , vectors) and vertical motions ( $\text{Pa s}^{-1}$ ; white contours, negative for  
 320 upward motion), and relative humidity (%), shaded), from 0000 UTC 8 to 1800 UTC 11 Dec 2018.  
 321 The topography is dark shaded. (b) As in (a), but for the vertical cross-section along  $16^\circ \text{N}$ .

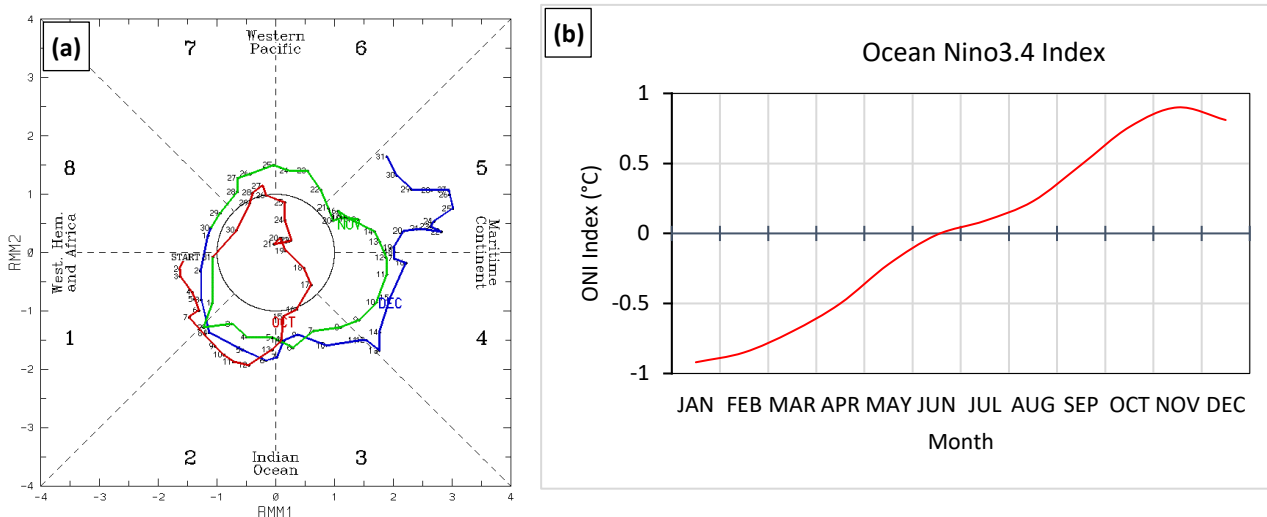
322 As described above, when the strong northeasterly and easterly winds at low levels blow into  
 323 central Vietnam, they bring warm, moist, and unstable air that originated in the WNP and is  
 324 enhanced over the SCS. Then, this air is blocked by the Truong Son Range, which has a height of  
 325 around 2 km, leading to forced convergence and upward motion at low levels and divergence  
 326 further above. These conditions consequently lead to moisture flux convergence of over  $8 \times 10^{-4}$  g  
 327  $\text{kg}^{-1} \text{s}^{-1}$  at 925 hPa (Fig. 7a) and moisture flux divergence at 850 hPa with comparable magnitudes  
 328 (Fig. 7b). This divergence reduces sharply further up toward the middle and upper levels (Fig. 7c).  
 329 These factors create a moist atmosphere with a precipitable water amount (through the deep  
 330 column) exceeding 50 mm during the D18 event (Fig. 7d). The above atmospheric ingredients and  
 331 characteristics in local topography in combination created favorable environmental conditions to  
 332 trigger orographic rainfall. As a consequence, the D18 event happened.



333 **Figure 7.** (a) The ERA5 averaged moisture convergence/ divergence ( $\times 10^{-4}$ ,  $\text{g kg}^{-1} \text{s}^{-1}$ , shaded,  
 334 positive for convergence) at the 925 hPa, from 0000 UTC 8 to 1800 UTC 11 Dec 2018. The blacked  
 335 areas are where the 925-hPa level is below the ground. (b) As in (a), but for the 850 hPa. (c) As in

336 (a), but for the 500 hPa. (d) The ERA5 averaged precipitable water between surface and 200 hPa  
 337 (mm), from 0000 UTC 8 to 1800 UTC 11 Dec 2018.

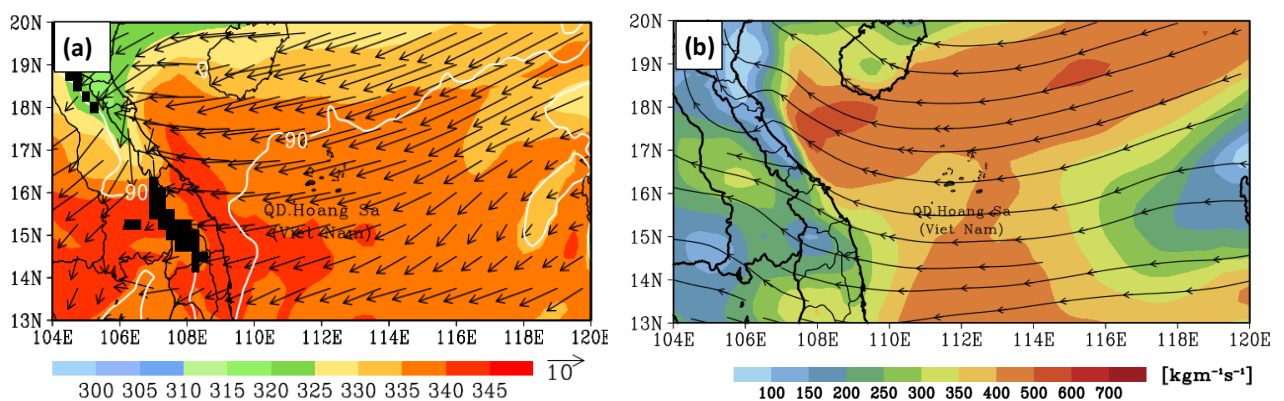
338 Besides investigating the synoptic-scale atmospheric conditions above, this study also verified  
 339 the impact of intraseasonal oscillations in the tropical atmosphere on the D18 event. To be more  
 340 specific, figure 8a reveals that the MJO in Western Pacific was not active in early December 2018  
 341 as well as during the D18 event. Figure 8b indicates that the last three months of 2018 are a fairly  
 342 weak El Niño phase. In addition, previous studies showed that central Vietnam had less rainfall in  
 343 the El Niño years. Therefore, MJO and ENSO are also not the cause and have no impact on the D18  
 344 event.

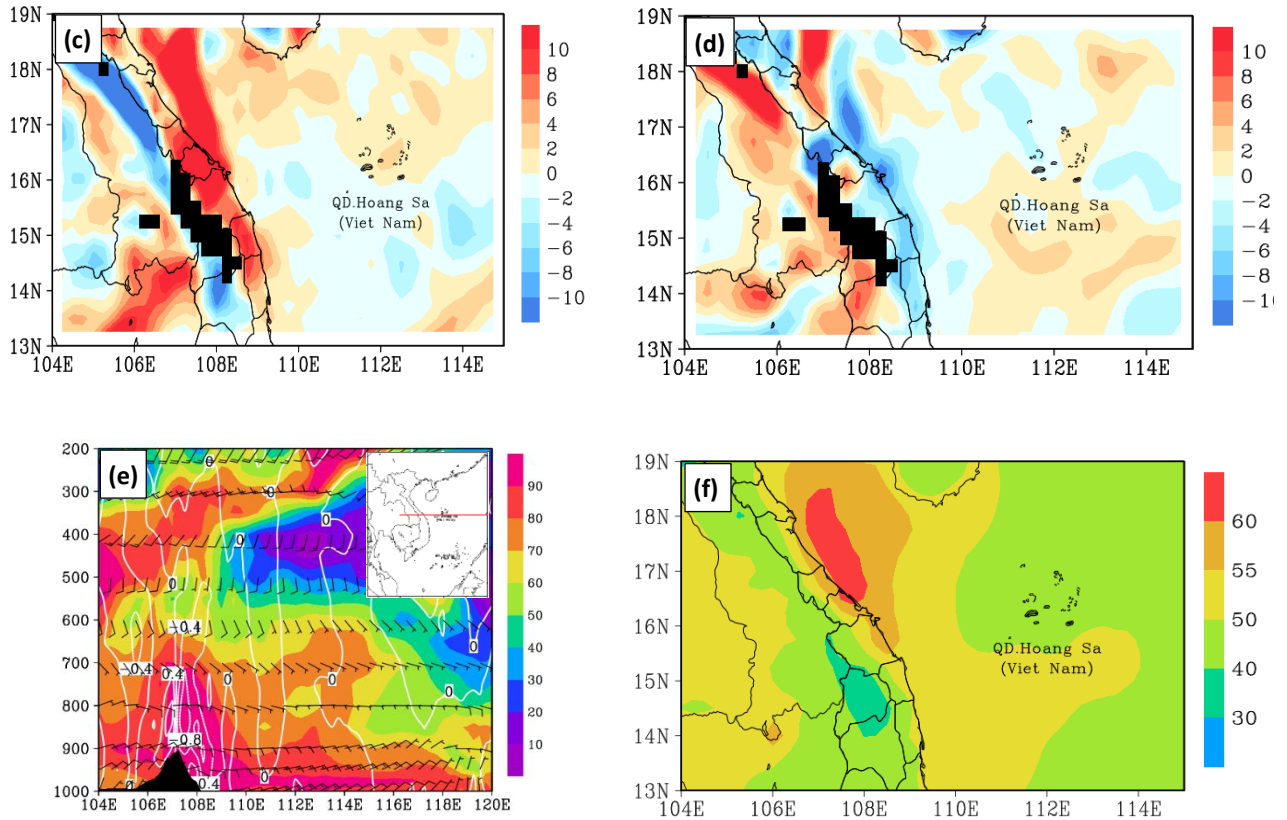


345 **Figure 8.** (a) The Madden-Julian Oscillation (MJO) location and the strength through 8 different  
 346 areas along the equator around the globe. Labelled dots for each day. Red line is for October, Green  
 347 line is for November, Blue line is for December. Source: Commonwealth of Australia 2019, Bureau  
 348 of Meteorology. (b) The Oceanic Niño Index (ONI) of the Niño 3.4 region (5° N-5° S, 120°-170°  
 349 W) for 2018.

### 350 3.3 The local thermodynamic conditions prior the D18 event

351 Figure 9 shows these conditions at 1200 UTC 8 December 2018. At this time, there is a strong  
 352 convergence zone of the low-level northeasterly wind carrying the moisture over the north of the  
 353 study area and near the shoreline (Figs. 9a,b). The northeasterly wind convergence led to a low-level  
 354 moisture convergence both inland and over the coastal sea. This happened as the low-level  
 355 northeasterly wind carrying the moisture blew to central Vietnam and interacted with local  
 356 topography, the low-level northeasterly flow reduced in speed over a wide area (refers to Figs. 6),  
 357 leading to a strong moisture flux convergence at low-level both inland and near the shoreline and  
 358 moisture flux divergence at the upper level (Figs. 9c, d). Due to the convergence of northeasterly  
 359 wind and moisture happened mainly in the north of latitude 16, the rising motion in the south of  
 360 latitude 16 mainly happened at low-level (less than 700 hPa, Fig. 9e) due to blocked by the Truong  
 361 Son range. Furthermore, this process occurred in a warm and unstable atmosphere (refer to Figs. 4),  
 362 making a favourable environmental condition to trigger most of the convection near the shoreline  
 363 instead of over the slopes (further inland) by forced uplift of the terrain. Hence, precipitable water  
 364 between the surface and 200 hPa exceeding 55 mm just formed over the coastal zone of the north of  
 365 the study area (Fig. 9f). Consequently, heavy rainfall only concentrated around the coastal zone.  
 366 These analyses are suitable for satellite and radar data.





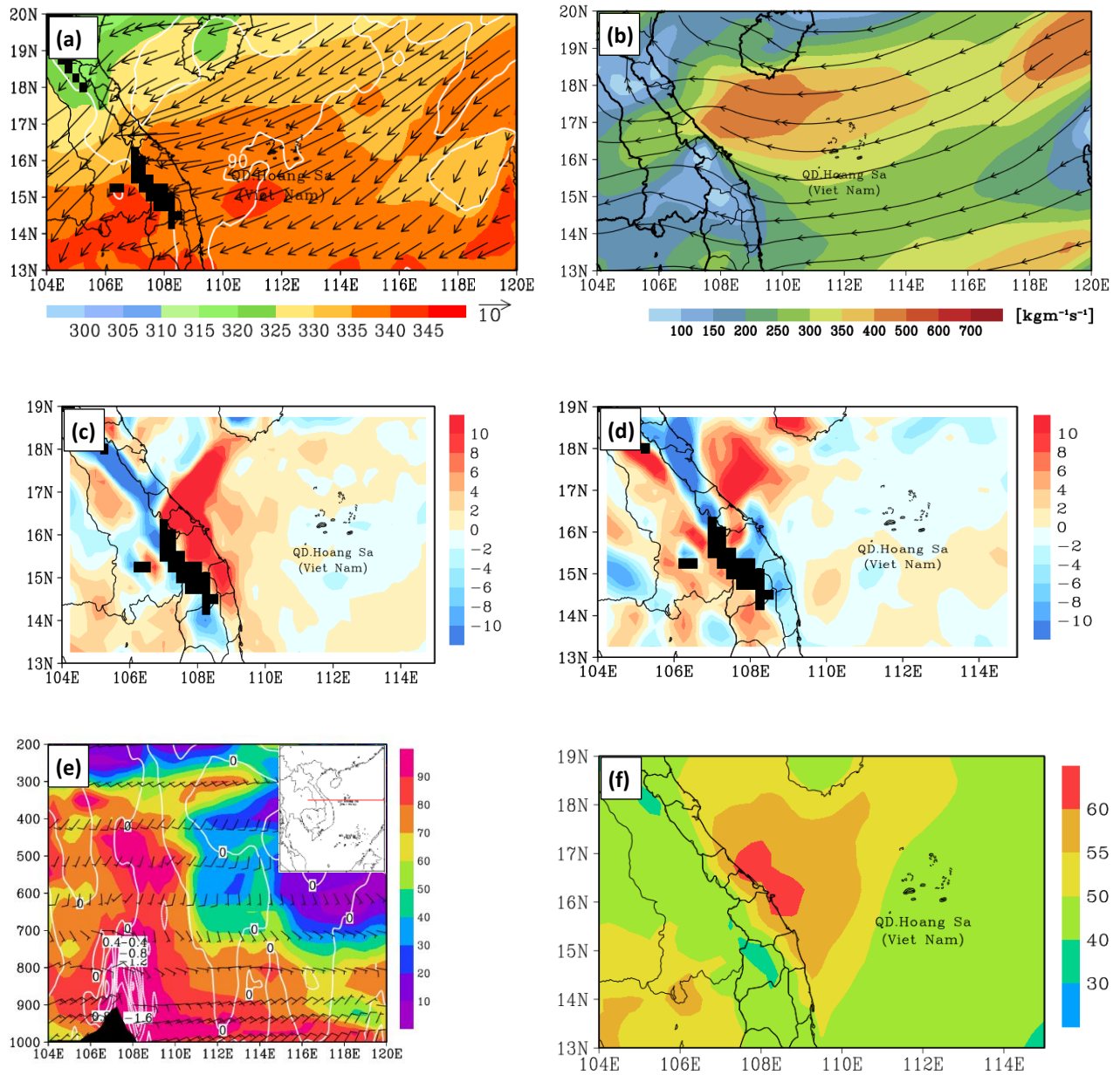
367 **Figure 9.** (a) The ERA5  $\theta_e$  (K, shaded), horizontal winds ( $\text{m s}^{-1}$ , vector), and relative humidity (%),  
 368 white contours, every 30 gpm) at 925 hPa. The blacked areas are where the 925-hPa level is below  
 369 the ground. (b) Surface–200-hPa vertically integrated moisture flux ( $\text{kg m}^{-1} \text{s}^{-1}$ ). (c) East-west  
 370 vertical cross-section along  $16^\circ\text{N}$  (see insert) of vertical motions ( $\text{Pa s}^{-1}$ , white contours), relative  
 371 humidity (%), shaded), and horizontal winds ( $\text{m s}^{-1}$ , vector). The topography is black shaded. (d)  
 372 Precipitable water between surface and 200 hPa (mm). All panels are for 1200 UTC 8 Dec 2018.

373 To be more specific, on satellite imageries from 1200 UTC 8 to 1100 UTC 9 December (Fig.  
 374 S1), a series of deep convective clouds (cumulonimbi, or Cb) first form over northern and central  
 375 Vietnam and Laos on 8 December, with mainly a northeast-southwest to east-west alignment. With  
 376 blackbody temperatures ( $T_B$ ) below  $-42^\circ \text{C}$ , several isolated deep cells also develop near the coast  
 377 over the southern part of the study area after 0200 UTC on 9 December (Fig. S1). Generally, these  
 378 deep Cb clouds tend to move slowly offshore and weaken after a few hours. Meanwhile, the study  
 379 area is also covered by precipitating clouds known as nimbostratus (Ns) that are not as deep, with

380 cloud-top  $T_B$  at  $-20^{\circ}$ - $0^{\circ}$  C and above (Fig. S1). These Ns clouds first form over the northern part of  
381 the study area and then grow and expand southward along the coast, eventually cover the entire  
382 study area on 9 December (Fig. S1). As analyzed above, both deep Cb clouds and the persistent Ns  
383 clouds produced long-lasting rainfall for hours, starting along the coast from 1200 to 1700 UTC 8  
384 December. After that, the rain area extends both inland and over the coastal sea (Fig. S2). The  
385 rainfall intensity is the greatest from 2000 UTC 8 to 0200 UTC 9 December, with a column-  
386 maximum radar reflectivity ( $C_{\max}$ )  $\approx$  40 dBZ (Fig. S2). Afterwards, the rainfall intensity decreases  
387 to some extent but remain at 15-35 dBZ rather steadily (Fig. S2). While the precipitation is not too  
388 intense, it falls persistently over many hours, leading to high 24-h rainfall accumulation at some  
389 locations. Thus, the local thermodynamic conditions seem to maintain for many hours and lead to  
390 the continuous development of precipitating clouds during much of 8 December.

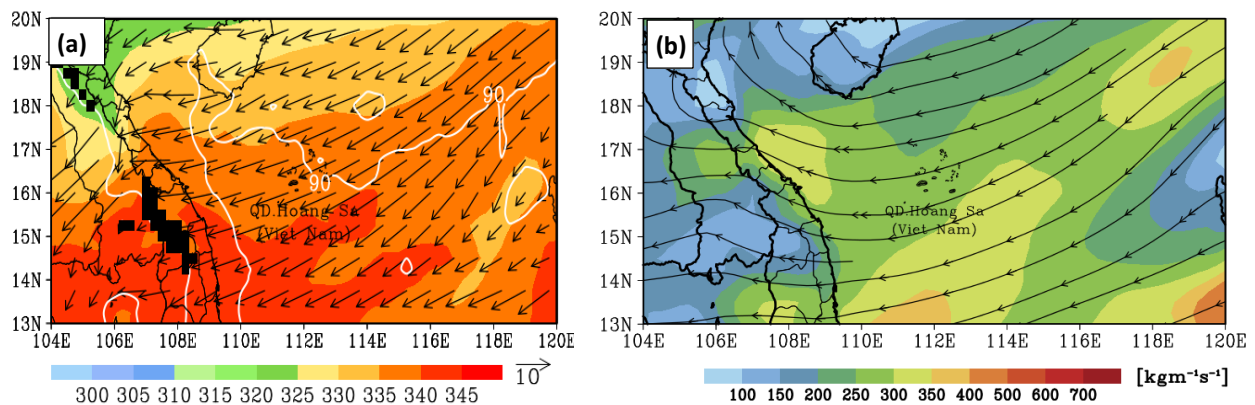
391 At 1200 UTC 9 December, a warm, moist, and unstable atmosphere is still maintained over  
392 central Vietnam and the SCS, with  $\theta_e > 335$  K (Fig. 10a and Figs. 4). However, the strong  
393 convergence of the low-level northeasterly wind carrying the moisture in Ha Tinh and Quang Tri  
394 provinces moved southward to Quang Tri and Quang Nam provinces (Fig. 10a). This moving  
395 dragging along the move of the low-level moisture convergence (Figs. 10c,d). Besides, Fig. 9e  
396 shows that the low-level uplifting motion is stronger than the previous day due to most of the strong  
397 northeasterly wind zone blocked by the Truong Son range. Besides, the southward movement of the  
398 northeasterly wind and moisture convergence zone also led to the southward movement of  
399 precipitable water between the surface and 200 hPa to the coastal zone between Quang Binh and  
400 Quang Tri provinces (Fig. 10f). As a result, the main heavy rainfall also moved southward to this  
401 area. Moreover, these thermodynamic conditions played a role to sustain the development of  
402 precipitating clouds on 9 December. This also coincides with observed satellite and radar data. In  
403 detail, on this day (since 1200 UTC), satellite imageries also show some characteristics of deep  
404 convection over the coastal area (Fig. S3), but the cloud top temperatures, in general, are not as cold

405 as on 8 December. Meanwhile, the lower precipitating Ns clouds cover much of the study area from  
 406 1200 UTC 9 to 0300 UTC 10 December, then gradually disintegrate (Fig. S3). These clouds kept  
 407 producing rainfall for the whole day, with the higher  $C_{\max}$  values ( $\sim 40$  dBZ) and rainfall intensity  
 408 from 1200 UTC 9 to around 0000 UTC 10 December (Fig. S4), mainly over the coastal plain and  
 409 nearby sea. After that, the rain gradually decreases in both intensity and areal coverage.

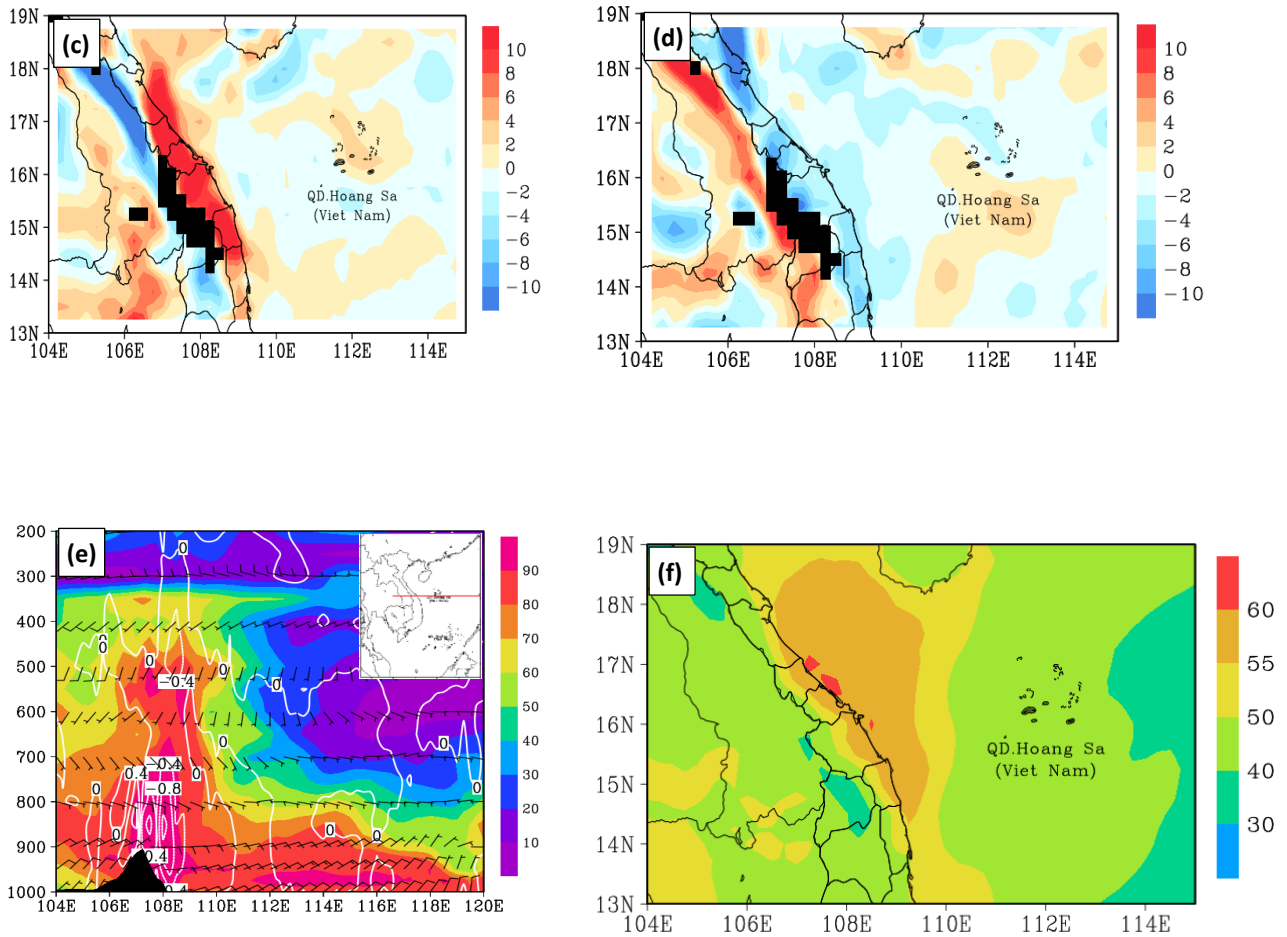


410 **Figure 10.** As in Fig. 9, except for 1200 UTC 9 Dec 2018.

411 At 1200 UTC 10 December, the atmosphere remains very moist with a precipitable water  
 412 amount of 55 mm (Fig. 11d). Some of the local dynamical and thermodynamically parameters,  
 413 however, are reduced from one day earlier and become not as favorable, including the velocity of  
 414 northeasterly wind, the upward motion over central Vietnam (Fig. 11c), moisture flux (Fig. 11b)  
 415 and precipitable water amount (Fig. 11f). Hence, the development of precipitating clouds also  
 416 reduces significantly on this day and mostly exist offshore over the ocean (Fig. S5). Compared to  
 417 the past two days, the development of convective cells is also reduced. Near the coast, only three  
 418 convective cells developed on 10 December, one at 1400 UTC, the second at 2000 UTC, and the  
 419 third one shortly after 2200 UTC. Also, moving eastward and offshore after formation, these  
 420 relatively small cells spend only 1-3 h over land. In general, the environmental conditions become  
 421 less favorable for developing rain clouds after 1200 UTC 10 December. Consequently, there is a  
 422 significant decrease in rainfall, which occurs mainly during 1200-1600 UTC then weaken with time  
 423 (Fig. S6).







424 **Figure 11.** As in Fig. 9, except for 1200 UTC 10 Dec 2018.

425 **4 Model Simulation Results**

426 In this section, the model simulation results are used to investigate the role of topography in  
 427 the development of clouds and rainfall in the D18 event, and the CReSS model is also evaluated for  
 428 its ability to reproduce the event over the study area.

429 Figure 12 presents the daily averaged surface horizontal winds and daily rainfall in CTRL and  
 430 NTRN for each of the three days from 9 to 11 December 2018. In CTRL, the model has well  
 431 simulated the surface wind. As a result, the model produced a maximum 24-h rainfall of around 400  
 432 mm on 9 December (Fig. 12a), roughly comparable in magnitude to the observation (Fig. 12c).  
 433 While one should bear in mind that the limited number of rain gauges have a smaller coverage area  
 434 and cannot resolve the detailed distribution of rainfall (cf. Fig. 1a), the model rainfall in CTRL is

435 slightly more offshore north of 16° N but more inland near 16° N, thus is not as abundant along the  
436 coast compared to the observation. In other words, model rainfall has some location errors but the  
437 magnitude is comparable by visual inspection.

438 An objective and more quantitative verification of model rainfall can be provided by the threat  
439 score (TS) computed at the rain-gauge sites, which shows that the model has high score at low  
440 thresholds of  $\leq 10$  mm (per 24 h) but gradually decreases toward higher thresholds (Fig. 13a, red  
441 curve). In particular, the TS is about 0.5 at 25-50 mm, below 0.2 above 160 mm, and about 0.1 at  
442 350 mm. Eventually, the TS drops to zero at 500 mm, which is not too far from the observed peak  
443 rainfall of over 500 mm (at Da Nang, cf. Fig. 1a). The bias score (BS) confirms that the model does  
444 not produce enough rainfall over the coastal plains, as its value drops from about 1.0 at 0.05 mm to  
445 below 0.4 at and above 250 mm. As another objective measure of overall quality of prediction, the -  
446 Similarity skill score (SSS) is about 0.5 for 9 December. Overall, the model appears to produce too  
447 much rainfall offshore north of 16° N and not enough rainfall along the coast, and this might be to  
448 some extent linked to its surface wind coming more from the east-northeast, compared to northeast  
449 in the ERA5 analysis (Figs. 12a,c), leading to somewhat different locations of low-level  
450 convergence of wind and moisture.

451

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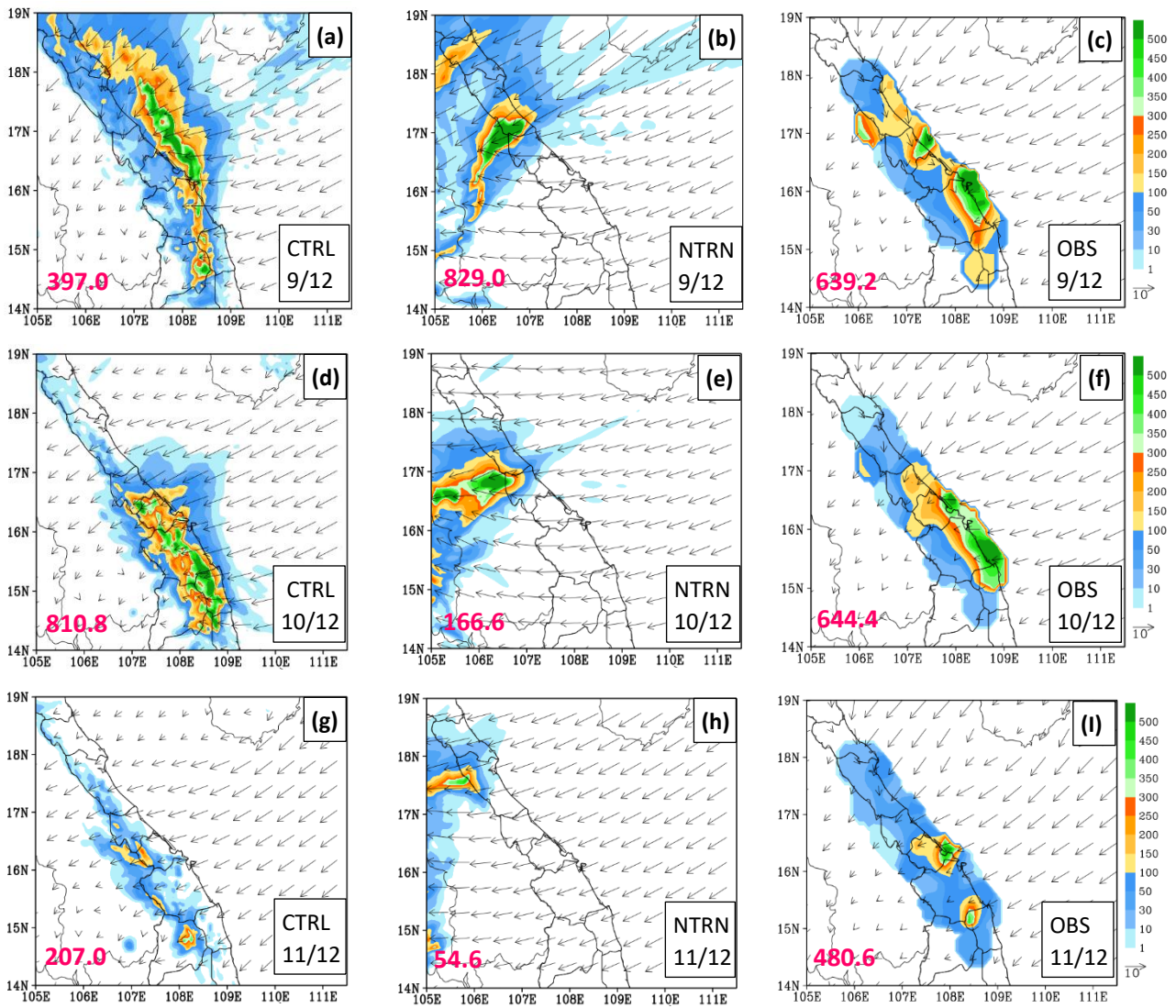
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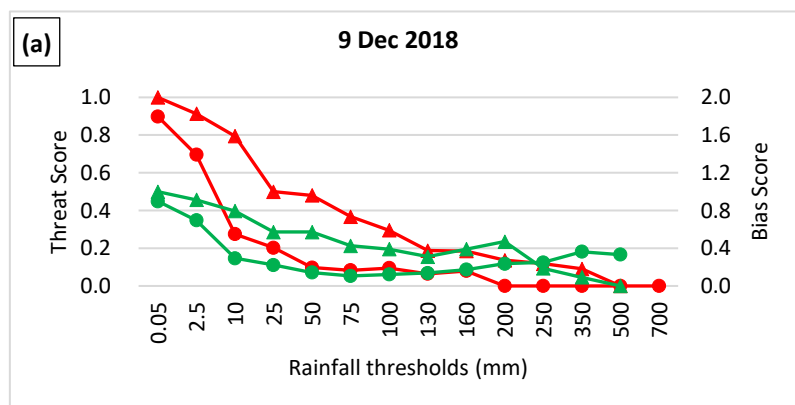
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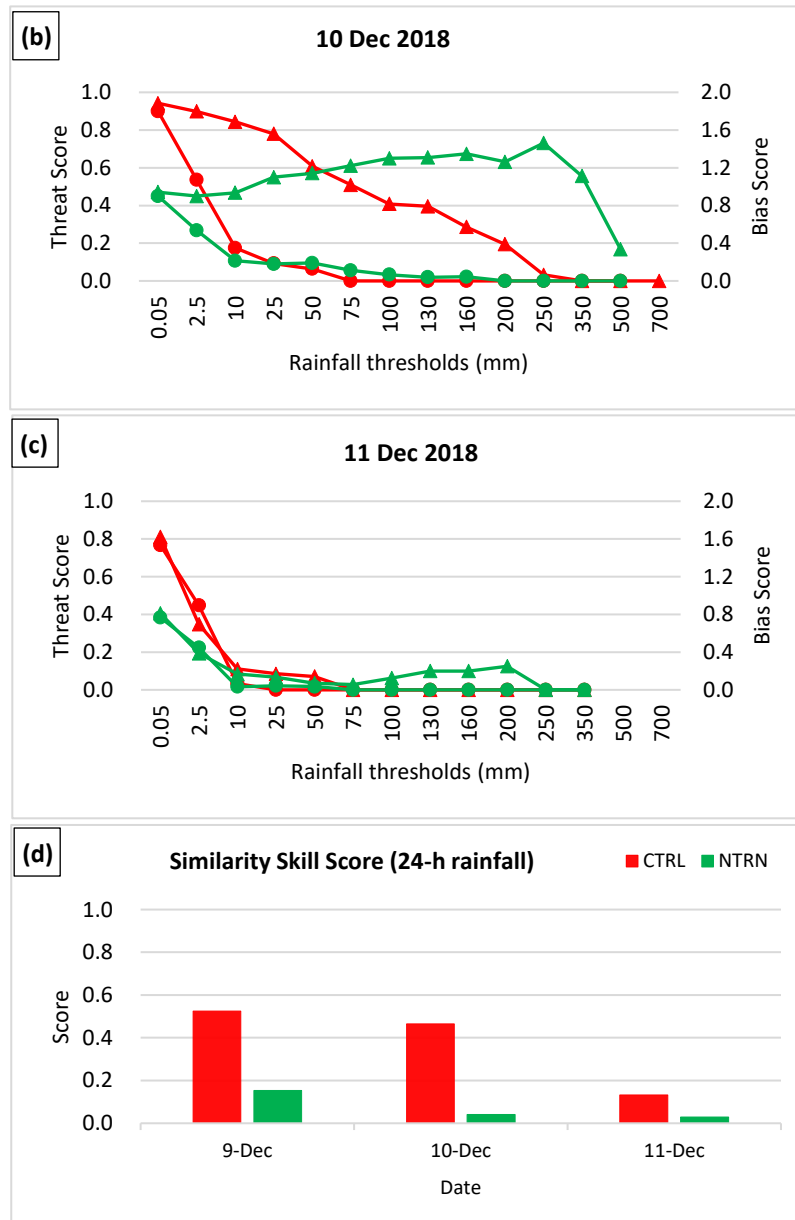
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458 **Figure 12.** Simulated daily-mean surface horizontal wind vectors ( $\text{m s}^{-1}$ , reference length at right  
 459 column) and 24-h accumulated rainfall (mm, color) in CTRL (left column) and NTRN (middle  
 460 column), and the observed rainfall at gauge sites (OBS), overlaid with the daily-mean surface wind  
 461 vectors derived from the ERA5 data (right column). From top to down are: (a-c) 9 Dec, (d-f) 10  
 462 Dec, and (g-i) 11 Dec 2018. The pink number at the lower left indicates the maximum value of 24-h  
 463 rainfall.





464 **Figure 13.** (a)-(c) The threat scores (red) and bias scores (green) of 24-h accumulated rainfall for  
 465 the CTRL (curve with triangles) and NTRN (curve with dots) experiments for the three days of 9-11  
 466 Dec 2018. (d) Fractions skill scores of 24-h accumulated rainfall for the two experiments.

467 For 10 December, while similar differences in prevailing surface winds still exist between  
 468 model simulation and ERA5 data, the model captured the southward movement of the northeasterly  
 469 wind. Therefore, the model had well captured the southward movement of the main heavy rainfall.  
 470 The rainfall location has improved with better agreement with the observation (Figs. 12d,f), but in

471 general slightly more inland and not right on the coast. Both over 600 mm, the observed and  
472 simulated peak daily rainfall values are again comparable. Due to the improvement in spatial  
473 pattern, the TSs exhibit higher values than those for the previous day across low to middle  
474 thresholds (up to 200 mm) but reduce to zero at 250 mm (Fig. 13b), while the SSS (near 0.46) is  
475 only slightly reduced (Fig. 13d). In agreement with the better TS values, the BS remains between  
476 0.8 and about 1.4 from low thresholds up to 350 mm, and drops to about 0.35 at 500 mm (Fig. 13b).

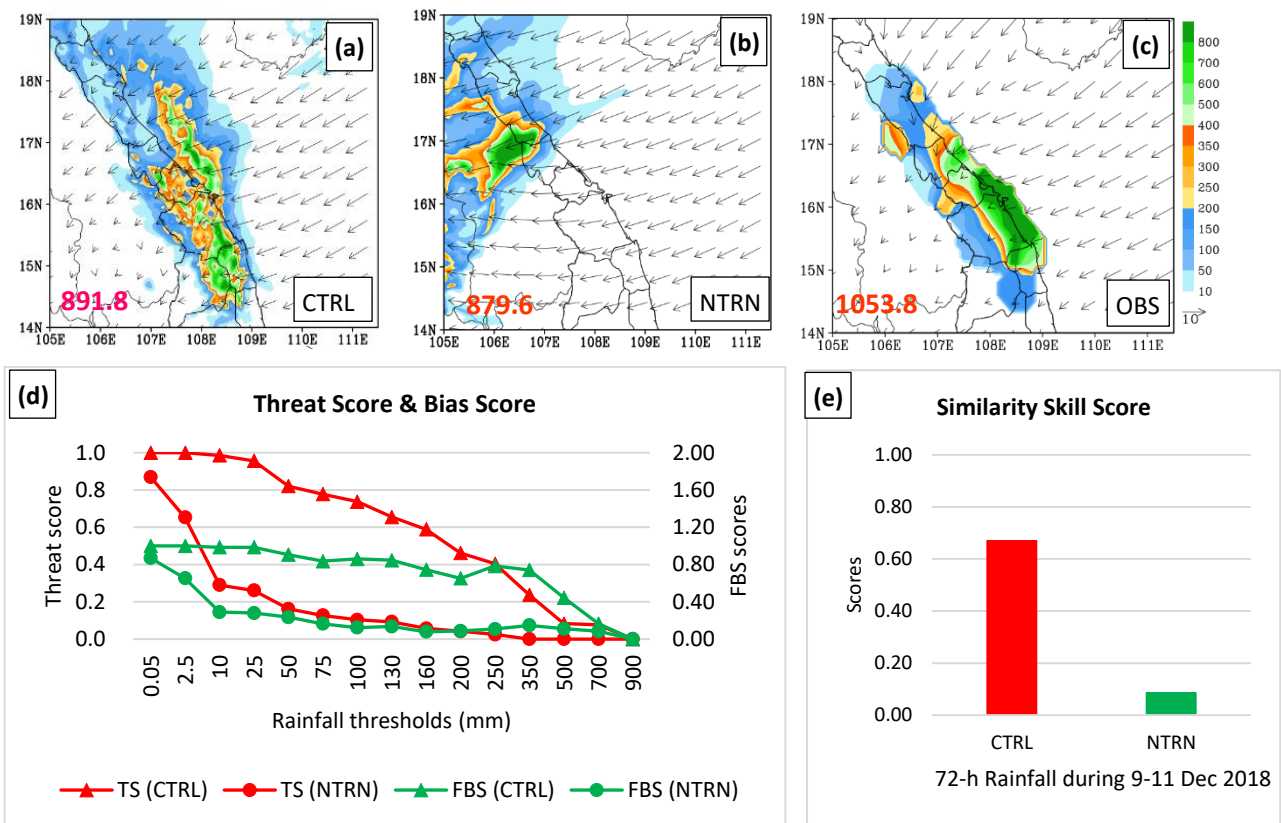
477 For 11 December, the model does not simulate well the rainfall field, as its rainfall is displaced  
478 toward the Truong Son Range (and the border to Laos), instead of over the coastal plain as observed  
479 (Figs. 12g,i). The spatial coverage of model rainfall is smaller and the peak amount (~200 mm) also  
480 lower compared to the rain-gauge data, while the surface wind appears weaker than the ERA5 data  
481 as well. While the observed peak amount became lower as the D18 event was coming to an end, the  
482 TSs also decrease rapid with threshold, and are close to 0.1 at just 10 mm and become zero at and  
483 above 70 mm (Fig. 13c). Consistent with the inadequate amount over land, the BSs also decrease  
484 rapidly with thresholds, from about 0.8 at 0.05 mm to below 0.3 over 100-200 mm. For this day, the  
485 SSS is only about 0.14 and significantly lower than the values for 9 and 10 December (Fig. 13d).  
486 Likely also related to the weaker surface winds in the model, the less-than-ideal results of rainfall  
487 may be also affected by the longer range of integration, at 66-90 h, for 11 December.

488 To test the impact of topography in the D18 event, the NTRN experiment was carried out.  
489 Without the terrain, the model had not good simulated the surface wind. Consequences, the rainfall  
490 as simulated by CReSS would be displaced much more inland from the coastal region for all three  
491 days of 9-11 December (Figs. 12b,e,h), and more importantly, the pattern would no longer be  
492 elongated and parallel to the coast, even though the peak amounts are similar to the observation.  
493 Thus, the topography was fundamental in determining the basic rainfall area and pattern in the D18  
494 event. With incorrect distributions, the TS values (Fig. 13, green curves) are much lower and drop  
495 to below 0.2 at thresholds above 10-25 mm for all three days. The thresholds at which the TSs

496 decrease to zero are 200, 75, and 25, respectively for the three days, and much lower than those in  
497 the CTRL, especially for 9 and 10 December. The BS values in the NTRN also tend to be lower  
498 than those in the CTRL, sometimes much lower, reflecting its incorrect location and thus little  
499 rainfall at gauge sites with rainfall in reality. The SSS values are also much lower, with values near  
500 0.16, 0.04, and 0.04 for the three days. Without the topography, the surface wind pattern near the  
501 coast and over land would be much stronger and very different, due to the lack of its blocking and  
502 uplifting effects, and also the associated thermodynamic effects.

503 For the D18 event as a whole, the three-day total rainfall distribution produced by the model  
504 compares quite favorably with the observation in both quantity and spatial pattern (Figs. 14a,c),  
505 with generally minor displacement errors more toward inland at around 15°-16° N. Despite these  
506 errors, the spatial distribution of rainfall in the model corresponds well to the zone of low-level  
507 moisture convergence in the ERA5 analysis (Fig. 7a). In agreement with visual assessment, the TSs  
508 of the 72-h QPFs are quite high across even heavy-rainfall thresholds: around 0.8 at 100 mm (per 72  
509 h), close to 0.5 at 200 mm, above 0.2 at 350 mm, and 0.1 at 700 mm, with an overall SSS  $\approx$  0.7  
510 (Figs. 14d,e). As shown, the rainfall fields for individual days in D18 are very different without the  
511 topography in NTRN, and the same is true for the whole event (Fig. 14b). The TSs also indicate a  
512 much lower skill in QPF, with TS below 0.2 at  $\geq$  50 mm (per 72 h) and TS = 0 at  $\geq$  350 mm, BS  
513 below 0.35 at  $\geq$  10 mm, and also an overall SSS of less than 0.1 (Figs. 14d,e). The results in Figs.  
514 12 and 14 also indicate a significant wind-blocking effect by the Truong Son Range. In CTRL, the  
515 surface northeasterly winds commonly exceed 10 m s<sup>-1</sup> in speed over the SCS, but are reduced  
516 significantly (and even to near-zero speed) near the Annamite Range (and in Laos). On the contrary,  
517 there is no reduction in speed as the winds blow across central Vietnam in NTRN, without the  
518 blocking effect of the topography.

519



520 **Figure 14.** (a)-(c) As in Figs. 11a-c, except for three-day averaged surface horizontal wind vectors  
 521 and 72-h accumulated rainfall over 9-11 Dec 2018. (d), (e) As in Figs. 12c,d, except for TSs and  
 522 FSSs of the 72-h accumulated rainfall over 9-11 Dec 2018.

523 **5 Conclusion**

524 In this study, the extreme precipitation event that occurred on 8-12 December 2018 along the  
 525 coast of central Vietnam is analyzed, and the simulation results by a CRM (the CReSS model) is  
 526 evaluated. The major findings are summarized below.

527 Analysis on the D18 event has revealed several key factors which led to this record-breaking  
 528 rainfall event: First, for all four days from 8 to 11 December, the strong northeasterly winds in the  
 529 lower troposphere blew from the Yellow Sea into the SCS, and interacted with strong low-level  
 530 easterly winds (below 700 hPa) over the SCS. This interaction strengthened the upstream easterly to  
 531 northeasterly winds and generated strong low-level convergence, as the winds blew into central  
 532 Vietnam and were blocked by the Truong Son Range, the low-level northeasterly flow reduced in

533 speed and led to moisture flux convergence and rising motion along the coast of Vietnam  
534 persistently. Consequently, heavy rainfall was produced along the coast of central Vietnam. Second,  
535 the strong easterly winds played an important role in transporting moisture from the WNP, across  
536 the Philippines and the SCS, into central Vietnam. Third, the Truong Son Range also played an  
537 important role in this event due to its barrier effect. Finally, the high SST of the SCS ( $>27^{\circ}$  C) also  
538 acted to help replenishing the moisture in this event. This above mechanism in the D18 event is  
539 different from those documented in previous studies. Particularly, according to previous studies, the  
540 heavy and extreme rainfall events are usually due to the multi-interaction between the northeasterly  
541 wind and preexisting tropical disturbance over the SCS and local topography or tropical cyclone or  
542 impacts by ENSO or MJO. However, these factors have not appeared during the D18 event.  
543 Therefore, we suggest that the interaction of the northeasterly and easterly winds in the moist,  
544 unstable atmospheric and local topography can also lead to heavy precipitation events along the  
545 central coastal plains of Vietnam. Another interesting finding of this study is that even though short  
546 periods of heavy rainfall from deep convection also contributed, the extreme rainfall of the D18  
547 event was mainly from the persistent rain from nimbostratus clouds (Ns) that do not possess a high  
548 reflectivity or a very cold cloud top.

549 One of the features of the D18 event is that the main heavy rain band moved from the north to  
550 south of the study area during the event. The analysis of the local thermodynamic reveals the  
551 movement of the convergence northeasterly wind zone in the north of the study area from north to  
552 south. This movement dragged along the movement of the convergent moisture zone. The movement  
553 of convergent moisture zone results in precipitation water column moving from north to south.  
554 Consequently, the main heavy rain band moved from north to south.

555 The evaluation of model simulation results at a grid size of 2.5 km indicates the following. In the  
556 CTRL, the model has well simulated the surface wind as well as captured the wind convergence's  
557 southward movement. Therefore, the CReSS model has reproduced this event's rainfall field quite



558 well, for both daily and three-day accumulations, but with some displacement errors. In terms of  
559 objective verification skill scores, in particular, CReSS displays high skills at heavy-rainfall  
560 thresholds for both daily rainfall ( $TS \geq 0.1$  at 200-350 mm and  $FSS \approx 0.5$  for 9 and 10 December)  
561 and 72-h total ( $TS \approx 0.1$  at 700 mm and  $FSS \approx 0.7$ ). However, the rainfall simulation is less ideal for  
562 11 December ( $TS$  drops to zero at thresholds  $\geq 75$  mm), which had less rainfall and is at a longer  
563 range (than the previous two days). Besides, the model also captured the southward movement of the  
564 main heavy rain band during the event, as seen in the observed data. In the sensitivity test of NTRN  
565 where the topography is removed, the model has poorly simulated the surface wind and did not  
566 capture the southward movement of the wind convergence zone. This led to the model produced a  
567 different rainfall pattern not along the coast as observed (and in CTRL), thus confirming the important  
568 role by the Truong Son Range in this event. In addition, the evaluation of simulation results also  
569 shows that the CReSS model has well simulated the surface winds, both in their direction and  
570 magnitude.

571 Generally, these results enhanced our knowledge about the mechanisms which cause the heavy  
572 rainfall in central Vietnam, as well as explained features of the D18 event. The above result also  
573 shows the promising capacity of the CReSS model for research and forecast of heavy rainfall in  
574 Vietnam. In a follow-up paper, a set of high-resolution time-lagged ensemble prediction is performed  
575 using the CReSS model, and the predictability of the D18 event will be evaluated.

#### 576 **Code and data availability**

577 The CReSS model used in this study and its user's guide are available at the model website at  
578 [http://www.rain.hyarc.nagoyau.ac.jp/~tsuboki/cress\\_html/index\\_cress\\_eng.html](http://www.rain.hyarc.nagoyau.ac.jp/~tsuboki/cress_html/index_cress_eng.html).

#### 579 **Author contribution**

580 Duc Van Nguyen prepared datasets, executed the model experiments, performed analysis, and  
581 prepared the first draft of the manuscript. Chung-Chieh Wang provided the funding, guidance and  
582 suggestions during the study, and participated in the revision of the manuscript.

### 583 **Competing interests**

584 The authors declare that they have no conflict of interest.

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588 Service (C3S) Climate Data Store (CDS) [https://www.ecmwf.int/en/forecasts/datasets/  
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