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Investigation of an extreme rainfall event during 8–12 December 2018 over central Viet Nam – Part 2: An evaluation of predictability using a time-lagged cloud-resolving ensemble system

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Abstract:

This is the second part of a two-part study that investigates an extreme rainfall event that occurred from 8 to 12 December 2018 over central Viet Nam (referred to as the D18 event). In this part, the study aims to evaluate the predictability of the D18 event using a time-lagged cloud-resolving ensemble and a quantitative precipitation forecast system. To do this study, 29 time-lagged (8 days in lead time) high resolution (2.5 km) members were run, with the first members run at 12:00 UTC 3 December 2018, and the last member-run at 12:00 UTC 10 December 2018. Between the first and the last members are multiple members that run every 6-h. The evaluated results reveal that CReSS well predict the rainfall fields at the short-range forecast (less than 3 days) for 10 December (rainiest day). Particularly, results show CReSS has high skills in heavy-rainfall QPFs for the 24-h rainfall of 10 Dec with the SSS scores greater than 0.5 for both the last five members and the last nine members. These good results are due to the model having good predicts of other meteorological variables, such as surface wind fields. However, these prediction skills are reducing at extending lead time (longer than 3 days), and it is challenging to achieve the prediction of QPF for rainfall thresholds greater than 100 mm with lead time longer than 6 days. Besides, the ensemble sensitivity analysis of 24-hour rainfall responds to the initial conditions shows that the 24-hour rainfall is very sensitive with initial conditions, not only at the lower level but also at the upper level. The ensemble-based sensitivity is decreased

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with the increasing lead time. Through the analysis of thermodynamic and moisture sensitivities, it showed that the features of ESA facilitated a better understanding of the sensitivity of a precipitation forecast to the initial conditions, implying that it is meaningful to apply ESA to control initial conditions by work in the future.

1 Introduction

The present study is the second part of a two-part study investigating the extreme rainfall event during 8–12 December 2018 over central Viet Nam (referred to as the D18 event hereafter). D18 event is a record-breaking rainfall event which occurred along the mid-central coast, from Quang Binh to Quang Ngai provinces. The observational data shows that particularly heavy rainfall with the maximum 3-days accumulated rainfall from 12:00 UTC on 8 December to 12:00 UTC on 11 December exceeding 800 mm (Fig. 1f). In which, the rainiest day is 10 December with 24-h observed data exceed 600 mm at some stations (Fig. 4 OBS). This record-breaking rainfall event led to 13 dead, many destructions in the environment, downstream cities, and many other economic losses due to catastrophic flooding and landslides. In part 1 (Wang and Nguyen 2023), we focused on the analysis of the mechanism that caused this event and evaluated the simulation by the Cloud-Resolving Storm Simulator (CReSS; Tsuboki and Sakakibara, 2002, 2007). The analyzed results point out the main factors which led to this event as well as its spatial rainfall distribution. These factors included the combined interaction between the strong northeasterly winds and easterly winds over the South China Sea (SCS) in the lower troposphere (below 700 hPa). The local terrain also played essential role due to its barrier effect. The cloud model's good simulation results in part 1 indicated its promising potential in forecasting this event. Hence, in part 2, the present study focuses on an evaluation of its predictability of the D18 event through a series of time-lagged high resolution ensemble quantitative precipitation forecasts (QPFs) by the CReSS model.

Until now, predicting heavy rainfall events is still challenging to meteorologists and weather forecasters, although great progresses in both computer science and atmospheric science have been made. The prediction of heavy to extreme rainfall is more difficult for

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Viet Nam, where both multi-scale interactions among different weather systems and strong influence by local topography often exist. For example, when D18 event occurred, several operational models were unable to predict this event successfully. Specifically, Fig. 1 shows the predictions for the D18 event by three global models at the National Centers for Environmental Prediction (NCEP), the European Centre for Medium-Range Weather Forecasts (ECMWF), and the Japan Meteorological Agency (JMA), and by one mesoscale regional model, the Weather Research and Forecasting (WRF) model, implemented for operation at the Mid-central regional Hydro-Meteorological center in Da Nang city, Viet Nam. While these models overall made good predictions in the surface wind field, their 72-h accumulated rainfall amounts along the coast of central Viet Nam (less than 250 mm) were much lower than the observation, which exceeded 900 mm (Fig. 1). Therefore, in order to improve the QPFs for heavy rainfall events in Viet Nam, we need to not only understand their mechanisms of occurrence, but also develop better forecasting tools.

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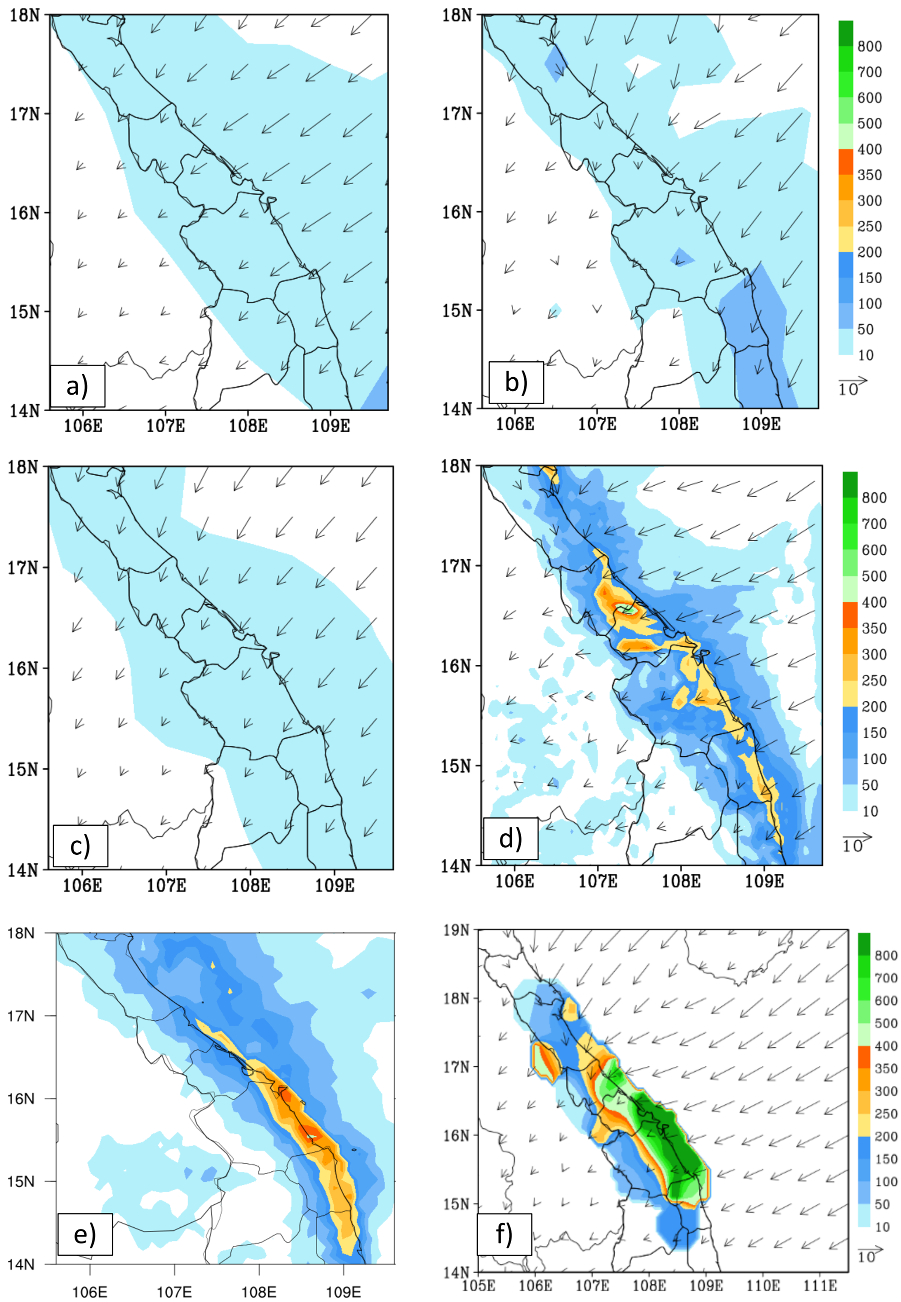

Figure 1. The predicted 72h accumulated rainfall (mm, shaded) and mean surface wind (ms^{-1}, vector) for the period of 12:00 UTC 8 December – 12:00 UTC 11 December 2018

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obtained by (a) NCEP, (b) ECMWF, (c) JMA, (d) WRF, (e) 72h accumulated rainfall obtained by the Global Precipitation Measurement (GPM) estimate (IMERG Final Run product) and (f) 72h observed accumulated rainfall (mm, shaded) and the mean surface wind derived from ERA5 data (ms^{-1}, vector), adapted from Fig. 14c of Wang and Nguyen 2023.

Among several different methods, the present-day weather forecasts depend mainly on numerical weather prediction (NWP) using models, a scientific method that has become indispensable for its ability to simulate weather and produce quantitative results (Fig. 1). However, there is always uncertainty in the numerical forecasts due to the fact that the atmosphere is a chaotic system and tiny errors in the initial state can grow rapidly and lead to large errors in the forecast. Various approximations in numerical methods are also sources of forecast uncertainty. Thus, by generating a range of possible weather conditions in days ahead or into the future, the ensemble forecasting was introduced as an effective method to estimate forecast uncertainty and improve the overall accuracy and usefulness of NWP products. For example, some studies have shown high skill in QPFs for extreme rainfall produced by typhoons in Taiwan using the CReSS model, a cloud-resolving model (CRM), with high resolution and time-lagged approach (Wang et al. 2016; Wang 2015; Wang et al. 2014; Wang et al. 2013). Table 1 of Wang et al. (2016) shows that the high-resolution time-lagged ensemble forecasts provide overall better quality in comparison with both the traditional low-resolution ensemble forecasts and high-resolution deterministic forecasts at a comparable cost in computation. Furthermore, some studies show that the ensemble mean typically has smaller errors than individual members. This error reduction is because the high predictability features that the members agree on are emphasized by the mean, while the low-predictability ones that the members do not agree on are filtered out or dampened (e.g., Leith 1974; Murphy 1988, Surcel et al. 2014).

Besides the advantages of ensemble forecasts described above, the ensemble-based sensitivity analysis (ESA) also helps effectively investigate how sensitive the forecast variables are and to what preceding factors. To be more specific, Torn and Hakim (2009)

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used ESA to evaluate how their subject, tropical cyclones (TCs) undergoing extratropical transition, in the prediction respond to a change in the initial condition. In their results, the cyclone minimum sea-level pressure forecasts are determined as strongly sensitive to TC intensity and position at short lead times and equally sensitive to mid-latitude troughs that interacted with the TC at longer lead times. For an extreme rainfall event in northern Taiwan, Wang et al. (2021) performed ESA using the results from 45 forecast members with a grid size of 2.5–5 km to identify contributing factors to heavy rainfall. By normalizing their impacts on rainfall using standard deviation (SD), different factors can be compared quantitatively and on an equal footing. Ranked by their importance, these factors included the position of the surface Mei-yu front and its moving speed (−16.00 mm per 5 km h^{-1}), the position of 700-hPa wind shift line and its speed (+12.59 mm per 0.4° latitude), the moisture amount in the environment near the front (+11.73 mm per 0.92 g kg^{-1} in mixing ratio), timing and location of frontal mesoscale low-pressure disturbance (+11.03 mm per1.38° longitude), and (5) frontal intensity (+9.58 mm per 3 K in equivalent potential temperature difference across 0.5°). Many other studies also used the ESA to study TCs, convective events, or support the development of operational ensemble sensitivity-based techniques to improve probabilistic forecasts (Kerr et al. 2019, Hu and Wu 2020, Coleman and Ancell 2020).

For heavy precipitation over central Viet Nam, Son and Tan (2009) used the Mesoscale Model version 5 (MM5) to investigate the predictability of heavy rainfall events over the southern part of central Viet Nam during the period of 2005 and 2007. Their results showed that MM5 can predict heavy rainfall there and its performance is better for events caused by TCs or TC interactions with the cold air. Toan et al. (2018) assessed the predictability of heavy rainfall events in middle-central Viet Nam due to combined effects of cold air and easterly winds using the WRF model within a forecast range of 2 days. The evaluation indicated that for 24-h lead time, the model performed reasonably well at rainfall thresholds less than 100 mm day^{-1}. For 48-h forecast range, the model performed well only at thresholds below 50 mm day^{-1} and had some skill at 50–100 mm day^{-1}. However, heavy

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rainfall events at thresholds over 100 mm day^{-1} were almost unpredictable by the model. Nhu et al. (2017) also used the WRF model to investigate the role of the topography in central Viet Nam on the occurrence of a heavy rainfall event there in November 1999. In this study, the model well simulated the northeast monsoon circulation, TCs, and the occurrence of heavy rainfall in central Viet Nam. Furthermore, when the topography is removed, the three-day total accumulated rainfall decreased sharply (by approximately 75%) compared to that in the control experiment with the terrain. Hoa Van Vo (2016) examined the predictability of heavy-rainfall events during the wet seasons of 2008–2012 in the middle section and central highlands of Viet Nam using NWP products from several global models, including the Global Forecasting System (GFS) from NCEP, Global Spectral Model (GSM) from JMA, Navy Operational Global Atmospheric Processing System (NOGAPS) from the US Navy, and the Integrated Forecast System (IFS) from ECMWF. Their results indicated that IFS and GSM performed better than GFS and NOGAPS, and IFS was evaluated the best. However, all four global models under-estimated rainfall in extreme events.

The review above suggests that considerable limitations still exist in forecasting heavy rainfall in central Viet Nam, especially using coarser models. It also indicates that a high-resolution time-lagged ensemble approach may offer some advantages in the prediction of extreme rainfall events, such as a better simulation of local weather conditions, a quicker response to changes in forecast uncertainty in real time, and potentially a longer lead time for hazard preparation. Climatologically, the entire Viet Nam lies in the tropical zone (Fig. 2a), where vigorous but less organized convection often develops in response to local conditions, while the region is also prone to the influence and interactions of weather systems spanning a wide range of scales as reviewed. In addition, although central Viet Nam is a small region with the narrowest place only about 80 km in width, it possesses significant topography running in the north-south direction to affect rainfall (Fig. 2a). Hence, a high-resolution CRM with detailed and explicit treatment in cloud microphysics is likely crucial for better QPFs in central Viet Nam. Consequently, the present study used

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the CReSS model to investigate the predictability of the D18 event through a series of time-lagged ensemble predictions. The rest of this paper is organized as follows. Section 2 describes the data, model, and methodology used in the study. The model results are presented and evaluated in Section 3. Finally, conclusions are offered in Section 4.

2 Data and methodology

2.1 Data

2.1.1 The International Grand Global Ensemble retrieval

The International Grand Global Ensemble (TIGGE) retrieval is a key component of The Observing System Research and Predictability Experiment (THORPEX) research program, whose aim is to accelerate the improvements in the accuracy of 1-day to 2-week high-impact weather forecasts. The TIGGE retrieval provides not only deterministic forecast data but also ensemble prediction datasets from major centers, including NCEP of the USA, MetOffice of the United Kingdom (UKMO), ECMWF of the European Union, and JMA of Japan, since 2006. This dataset has been used for a wide range of research studies on predictability and dynamical processes. In this study, we used the global model predictions to analyze the predictability of the D18 event. The variables utilized included total precipitation and surface winds (*u*- and *v*-wind components at 10-m height) from NCEP, ECMWF, and JMA at 6-h intervals during our data period (as shown in Figs. 1a-c) from 12:00 UTC 8 to 12:00 UTC 11 December 2018 (as shown in Figs. 1a-c). The data linked is placed in the “code and data availability” section.

2.1.2 NCEP GFS historical archive

In this study, the NCEP GFS data from the analyses and forecast runs executed every 6 h, at 00:00, 06:00, 12:00, and 18:00 UTC daily, were used to drive the CReSS model predictions. The horizontal resolution of the data is 0.25° × 0.25°, and 26 of vertical levels, and the forecast fields are provided every 3 h from the initial time out to a range of 192 h. The data linked is also placed in the “code and data availability” section.

2.1.3 Observation data

The daily observed rainfall data (12:00–12:00 UTC, i.e., 19:00–19:00 LST) from 8 to 12 December 2018 at 69 automated gauge stations across central Viet Nam is used for case overview and verification of model results. This dataset is provided by the Mid-Central Regional Hydro Meteorological Center, Viet Nam. The spatial distribution of these gauge stations is depicted in figure 2b.

2.1.4 The Global Precipitation Measurement (IMERG Final Run) data

The Global Precipitation Measurement (GPM) is a mission international jointly by the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA), employing an international satellite network for advanced global rain and snow observations. The GPM *IMERG Final Run* is a research-level product which is created by intercalibrate, merging, and interpolating “all” satellite microwave precipitation estimates, along with microwave-calibrated infrared (IR) satellite estimates, analyses from precipitation gauges, and potentially other precipitation estimation methodologies at fine time and space scales. The horizontal resolution of this dataset is $0.1^{o} \times 0.1^{o}$ latitude–longitude and the time resolution is every 30 minute. In this study, we used this satellite data to verify rainfall distribution over the coastal sea due to the limitation of the observation station network, we only have the observation stations inland, as shown in the Fig. 2b. This dataset was downloaded from 12:00 UTC on 8 December to 12:00 UTC on 11 December 2018 to analyze the D18 event as well as the rainiest day of this event (10 December).

2.1.5 The WRF data

The WRF is implemented for operational numerical forecast system at Mid-central regional Hydro- Meteorological center, Viet Nam. In this study, we used this data to analysis the predictability of D18 event using the mesoscale numerical prediction. The download variables include precipitation, the surface U wind component and surface V wind

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component. The lead time is 3 days, starting from 12:00 UTC 8 to 12:00 UTC 11 December 2018 with interval time of 6 hours. The horizontal resolution of this data is 6 km x 6 km.

2.2 Model description and experiment setup

We used the could-resolving model (CReSS). This model had been built and developed by Nagoya University, Japan (Tsuboki and Sakakibara, 2002, 2007). This is a non-hydrostatic and compressible cloud model, designed for simulation of various weather events at high (cloud-resolving) resolution. In the model, the cloud microphysics is treated explicitly at the user-selected degree of complexity, such as the bulk cold-rain scheme with six species: vapor, cloud water, cloud ice, rain, snow, and graupel (Lin et al., 1983; Cotton et al., 1986; Murakami, 1990, 1994; Ikawa and Saito, 1991). Other subgrid-scale processes parameterized, such as turbulent mixing in the planetary boundary layer, as well as physical options for surface processes, including momentum/energy fluxes, shortwave and longwave radiation are summarized in Table 1.

To evaluate of the predictability of the D18 event using an ensemble time-lagged high-resolution system and investigate the ensemble sensitivity of variables for the rainfall, 29 experiments were performed. The first members ran at 12:00 UTC on 3 December 2018, and the last member ran at 12:00 UTC on 10 December 2018. Between the first and the last members are multiple members running every 6-h (for a simulation length of 192 h).

All experiments using a single domain at 2.5 km horizontal grid spacing and a (x, y, z) dimension of 912 x 900 x 60 grid points (Table 1, cf. Figure 2a). As introduced in subsection 2.1.1, the NCEP GDAS/FNL Global Gridded Analyses and Forecasts (0.25° x 0.25°, every 6 h, 26 pressure levels) was used as the IC/BCs of the model.

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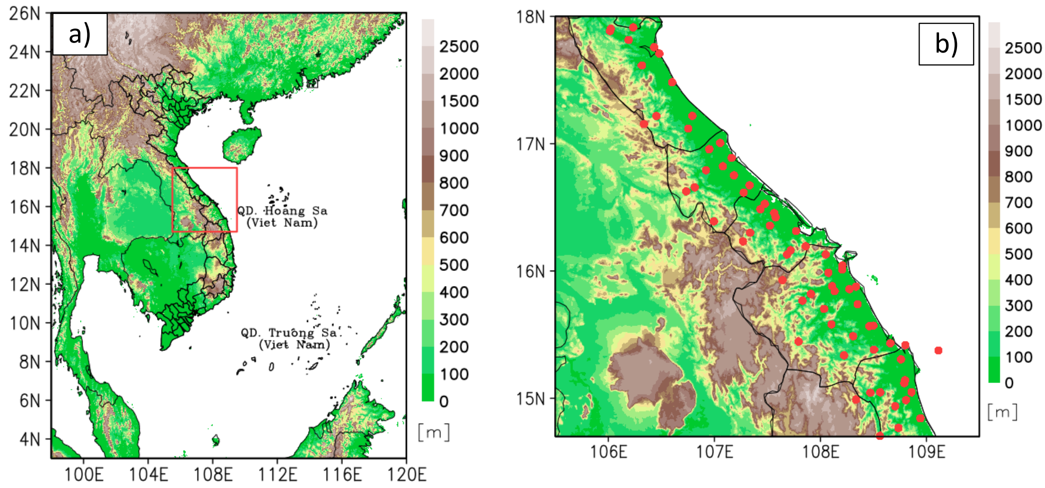

Figure 2. (a) The simulation domain of the CReSS model and topography (m, shaded) used in the study. The red box marks the study area. (b) The distribution of the observation stations (red dots) in the study area.

Table 1. The basic information of experiments.

Domain and Basic setup	
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)	NCEP GDAS/FNL Global Gridded Analyses and Forecasts (0.25° × 0.25°, every 6 h, 26 pressure levels)
Topography (for CTRL only)	Digital elevation model by JMA at (1/120)° spatial resolution

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Simulation length	192 h
Output frequency	1 hour
Model physical setup	
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

* The vertical grid spacing (Δz) of CReSS is stretched (smallest at bottom) and the averaged value is given in the parentheses

2.3 Verification of model rainfall

In order to verify the model-simulated rainfall, some verification methods are used, including (1) visual comparison between the model and the observation (from the 69 automated gauges over the study area), and (2) the objective verification using categorical skill scores at various rainfall thresholds from the lowest at 0.05 mm up to 900 mm for three-day total. These scores are listed in Table 2 along with their formulas, perfect value, and worst value, respectively. To apply these scores at a given threshold, the model and observed value pairs at all verification points (gauge sites here, N) are first compared and classified to construct a 2 × 2 contingency table (Wilks, 2006). At any given site, if the event takes place (reaching the threshold) in both model and observation, the prediction is considered a hit (*H*). If the event occurs only in observation but not the model, it is a miss (*M*). If the event is predicted in the model but not observed, it is a false alarm (*FA*). Finally, if both model and observation show no event, the outcome is correct rejection (*CR*). After all the points are classified into the above four categories, the scores can be calculated by their corresponding formula as:

Bias Score (BS) = (H+FA)/(H+M), (1)

Probability of Detection (POD) = H/(H+M), (2)

False Alarms Ratio (FAR) = FA/(H+FA), (3)

Threat Score (TS) = H/(H+M+FA), (4)

The values of TS, POD, and FAR are all ranged from 0 to 1, and the higher value is the better for TS and POD, and conversely for FAR. For BS, its value can vary from 0 to N−1 and indicate the overestimation (underestimation) of the model for the events.

2.3.1 The Similarity Skill Score

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

$$\mathrm{SSS} = 1 - \frac{\frac{1}{N}\sum_{i=1}^{N}(F_i - O_i)^2}{\frac{1}{N}\sum_{i=1}^{N}F_i^2 + \frac{1}{N}\sum_{i=1}^{N}O_i^2} \qquad (5)$$

where N is the total number of verification points, F_i is the forecast rainfall amount, and O_i is the observed value, at the *i*th point among *N*, respectively. The SSS is a measure against the worst mean squared error (MSE) possible. The formula shows that a forecast with perfect skill has an SSS of 1, while a score of 0 means zero skill (model rainfall does not overlap with the observation anywhere).

2.3.2. The ensemble spread (standard deviation)

The ensemble spread is considered a measure of the difference between the members to the ensemble mean and known as the standard deviation (SD). In other words, the ensemble spread will reflect the diversity of all possible outcomes. Hence, the ensemble spread is

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often applied to predict the magnitude of the forecast error. If small spread indicates high theoretical forecast accuracy, and large spread indicates low theoretical forecast accuracy. Spread is computed by formulated below:

$$\mathrm{SD} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \mu_x)^2}{n-1}} \qquad (6)$$

where x_i is the prediction value of member i, μ_x is the ensemble mean, n is the number of ensemble members.

2.3.3. Ensemble Sensitivity Analysis

As mentioned above, an ensemble forecast is a set of forecasts produced by many separate forecasts with differences in initial conditions, respectively. Moreover, as we know, the numerical weather forecasts are sensitive to small changes in initial conditions and sensitivity analysis is considered a measure to improve forecasts through targeting observations. Hence, this study used the ESA method which is introduced by Ancell and Hakim (2007) to examine how a forecast variable responds to changes in initial conditions. The ensemble sensitivity is computed by the formula:

$$\frac{\partial R}{\partial x_t} = \frac{COV(R, x_t)}{var(x_t)} \qquad (7)$$

Here, the response function *R* is chosen to be the areal-mean 24-h accumulated rainfall in central Viet Nam (15.5°-16.3°N, 107.9°-108.6°E) on the rainiest day, from 12:00 UTC on 9 to 12:00 UTC on 10 December 2018. The starting time of this period, i.e., 12:00 UTC on 9 December, is defined as t_0. Various scalar variables are considered for x_t, while those from 48 h earlier (t_{-48}, or 12:00 UTC on 7 December) to the time of t_0 at 24-h intervals. The *COV* is the covariance of *R* and x_t, and *var* is the variance of x_t, respectively.

As the analysis in part 1, the D18 event is caused by combined effectively between the atmospheric disturbances at lower levels, such as cold surge, easterly wind, and topography, ensemble-based sensitivity analysis (ESA) has been applied for variables at

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surface, near-surface, and mid-tropospheric levels to assess the sensitivity of initial conditions to the predictability of the rainy field. In order to facilitate the comparison among the impacts of different variables, this study normalized ESA results by using the standardized anomaly in the denominator and expressed as the change in R (in mm) in response to an increase in x_t by one SD.

3 Model results

3.1 Time-lagged 24-h QPFs by the CReSS model

In this section, time-lagged forecasts targeted for the 24-h period from 12:00 UTC on 9 to 12:00 UTC on 10 December in the D18 event by the 2.5-km CReSS model are presented and evaluated. This study focuses on this 24-h period because this is the rainiest day with 24-h observed data exceeding 600 mm at some stations (Fig. 3 OBS). Figure 3 shows 25 possible scenarios of 24-h rainfall and average surface winds over the target period produced by the lagged runs every 6 h, with the earliest initial time at 12:00 UTC on 3 December and the latest one at 12:00 UTC on 9 December 2018, respectively. It is immediately clear that several members made a rather good 24-h QPF not only in amounts, but also in rainfall location and spatial distribution. These include most members executed during 8-9 December, and also an impressive member that started at 18:00 UTC on 4 December. In this latter member, a reasonably good QPF was produced at a rather long lead time, almost five days prior to the beginning of the target period (114 h). A common feature among these good members is that they all captured the direction and magnitude of surface winds quite well. On the other hand, most other members did poorly in their QPFs, when executed before 06:00 UTC on 7 December at lead times beyond two days before the target period. In general, they also could not predict the surface winds well enough.

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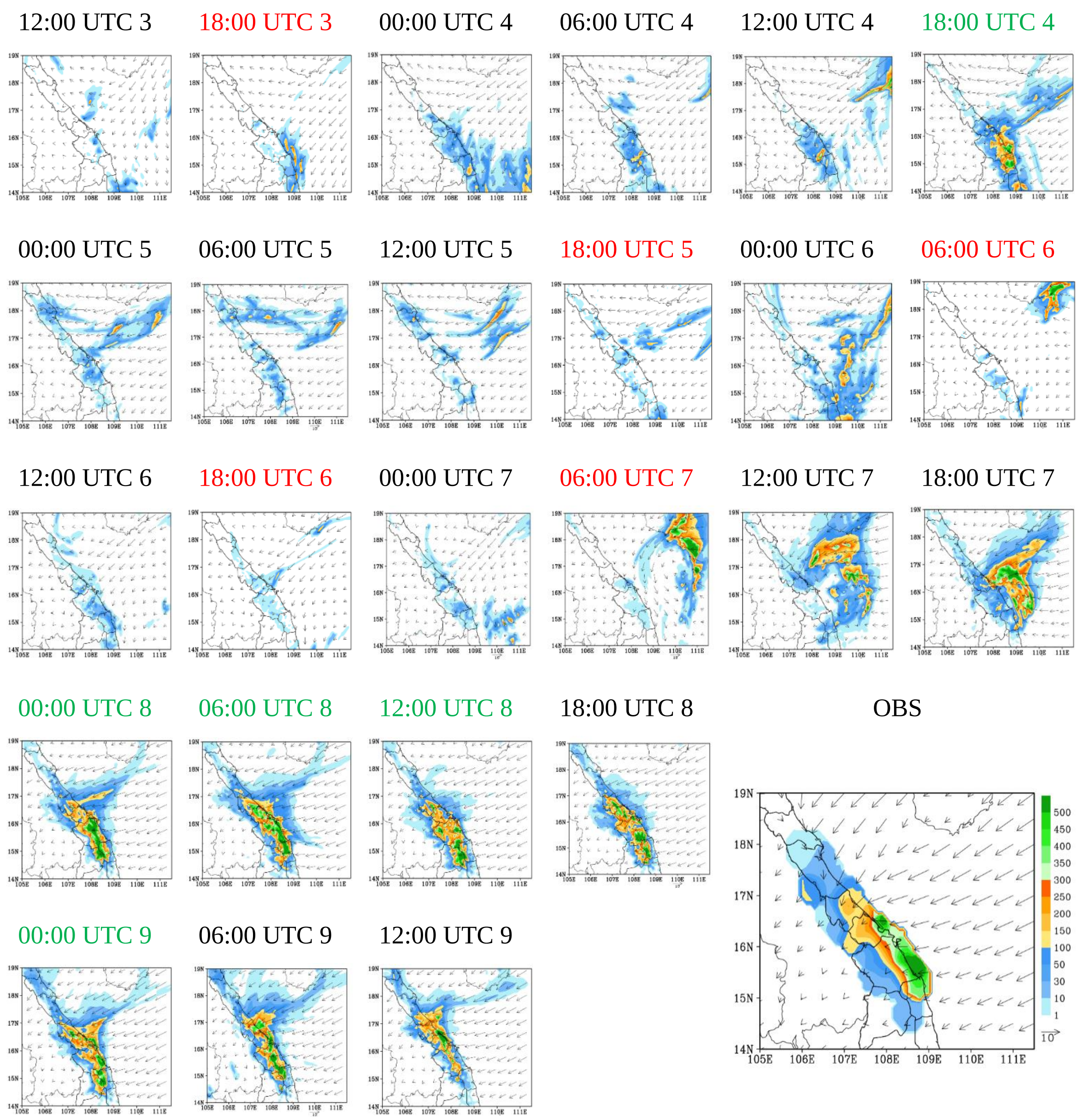

Figure 3. The predicted 24h accumulated rainfall (mm, shaded, scale on the right of panel OBS) and the mean surface horizontal wind (ms^{-1}, vector, reference length at panel OBS) on 10 December 2018 (from 12:00 UTC 9 December to 12:00 UTC 10 December 2018). The green color mark good members and the red color marks bad members. In OBS, 24h

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observed rainfall (mm, shaded) and the surface wind derived from ERA5 data (ms^{-1}, vector), adapted from Fig. 12f of Wang and Nguyen 2023.

The main reason for the significantly different forecast outcomes is elucidated in Fig. 4, which depicts the mean differences in five good members (those with initial times at 18:00 UTC on 4, 00:00, 06:00, and 12:00 UTC on 8, and 00:00 UTC on 9 December) from five bad ones (those ran at 18:00 UTC on 3, 18:00 UTC on 5, 06:00 and 18:00 UTC on 6, and 06:00 UTC on 7 December). In Fig. 4 (good minus bad members), it is clear that the surface easterly winds were much stronger and the relative humidity much higher surrounding central Viet Nam and its upstream areas in the GFS forecast data valid at 12:00 UTC on 9 December (used as BCs in CReSS runs) in the good members than in the bad ones. These factors were identified as crucial for the extreme rainfall in the D18 event in Part 1, and thus the good CReSS members produced much more rainfall in central Viet Nam (Fig. 4b).

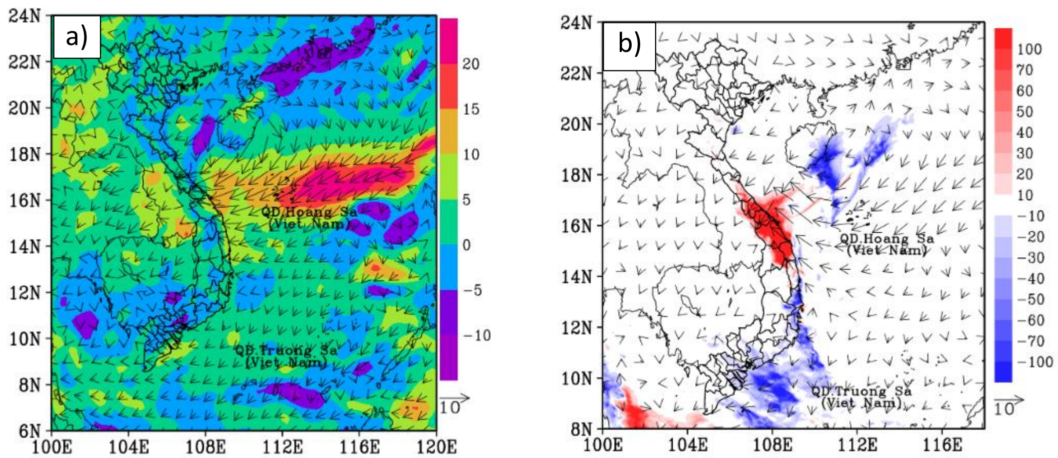

Figure 4. The difference in (a) input data (boundary conditions) and (b) CReSS output between averaged 5 good members (members ran at 18:00 UTC 4, 00:00 UTC 8, 06:00 UTC 8, 12:00 UTC 8, 00:00 UTC 9) and 5 bad members (members ran at 18:00 UTC 3, 18:00 UTC 5, 06:00 UTC 6, 18:00 UTC 6, 06:00 UTC 7). For input data, relative humidity

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(%, shaded) and surface wind (ms^{-1}, vector) at 12:00 UTC December 9 2018. For CReSS output, 24-h accumulated rainfall (mm, shaded) and surface wind (ms^{-1}, vector).

As we know, ensemble weather forecasts are a set of forecasts from multiple members that represent the range of future weather possibilities, and the simplest way to use them is through the ensemble mean (that emphasizes the features that the members agree upon). In order to see how good CReSS can predict the D18 event with the time-lagged strategy, from possible scenarios of 24 hours of rainfall of 10th December that produced by CReSS, This study has grouped scenarios and computed them into different lead times using the range of their initial times. It can be clearly seen in Fig. 5 that the rainfall produced by Fifth 4 and Sixth 4 members is quite similar to observed data, not only rainfall amount but also the locations of significant rainbands and regions that concentrate mainly rainfall. For other subgroup scenarios, the model made the rainfall scenarios much lower than observed rainfall data. In which, third 4 and fourth 4 members are the lowest. It can be relevant to the model that did not predict well the wind fields in every single running at extend ranges (after day 3) as analyzed previous. The rainfall of second 4 members is the highest these subgroup scenarios due to the model having single good-predict at 18:00 UTC on 4 [Fig. 3. (18:00 UTC 4)].

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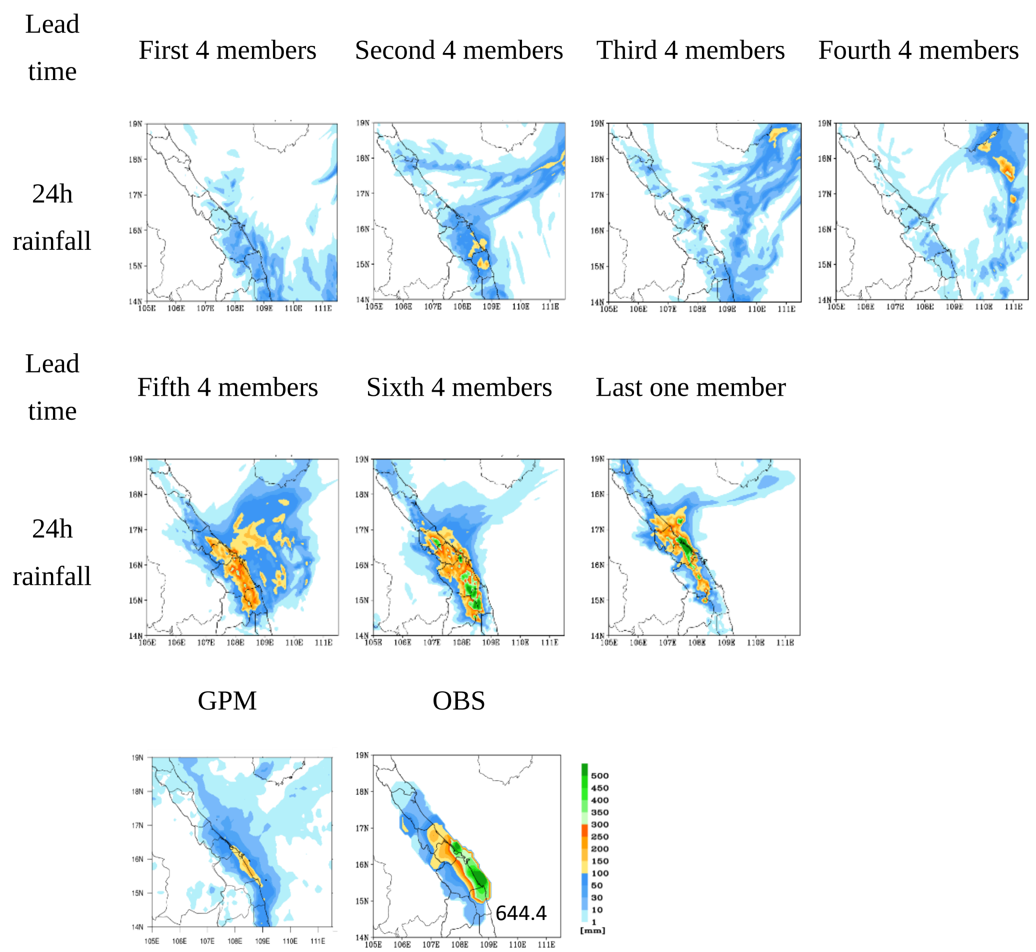

Figure 5. The predicted 24h rainfall by subgroup members, 24h accumulated rainfall by the Global Precipitation Measurement (GPM) estimate (IMERG Final Run product), 24h observed rainfall (mm, peak amount labeled at the lower-right corner) for the period of 12:00 UTC 9 December – 12:00 UTC 10 December 2018 as labelled. The same color bar (lower right) is used for all panels.

Besides the evaluation on time-lagged results using batches of fixed number of successive runs (every 4 members) as presented above, this study also grouped the members using different ensemble sizes based on their behavior in order to better assess the temporal evolution of forecast uncertainty and event predictability as the lead time shortened.

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Particularly, this study divided the 25 members into several subgroups as shown in Fig. 6, including the first eight members (those executed during 12:00 UTC 3 – 06:00 UTC 5 December), the middle eight members (run between 12:00 UTC 5 and 06:00 UTC 7 December), the last nine members (12:00 UTC 7–12:00 UTC 9 December), and the last five members (12:00 UTC 8–12:00 UTC 9 December), respectively. In other words, the last five members were those executed within 0-24 h (1 day) prior to the beginning of the target period, and so on. In Fig. 6, it is clear that both the ensemble means from the last five and the last nine members compare quite favorable to the observation, not only in the accumulated amount but also in spatial distribution of rainfall. This indicates that the model could produce QPFs at fairly good quality and rather consistently since the time as early as roughly 48 h prior to the commencement of the rainfall event (also Fig. 3). These two sub-ensemble groups within the short range gave much better quality in QPFs than the other sub-groups executed before them at longer lead times, including the first eight, middle eight, and all 25 members. In terms of skill scores, for example, the mean QPF by the last five members have TS = 0.4, POD = 0.8, FB = 1.5, and FAR = 0.5 at 100 mm (per 24 h), while the last nine members give similar scores of TS = 0.5, POD = 0.8, FB = 1.4, and FAR = 0.5 (Figs. 7a-d), respectively. On the contrary, the mean QPFs from both the middle eight and first eight members only yield zero scores in TS, POD, and FB with no skill in FAR at 100 mm, obviously due to not enough rainfall in central Viet Nam in most of their members. At 200 mm (per 24 h), similarly, the last five members (TS = 0.2, POD = 0.4, FB = 1.4, and FAR = 0.7) and the last nine members (TS = 0.3, POD = 0.5, FB = 1.2, and FAR = 0.6) again produce much better scores in QPFs, compared to no skill in all four scores in QPFs from the middle eight, first eight, and all 25 members (Fig. 8a-d). In SSS, the mean from the last nine members exhibits the highest score (0.64), the middle eight members have the lowest score (0.04), and the mean from all 25 members is 0.43 (Fig. 7e).

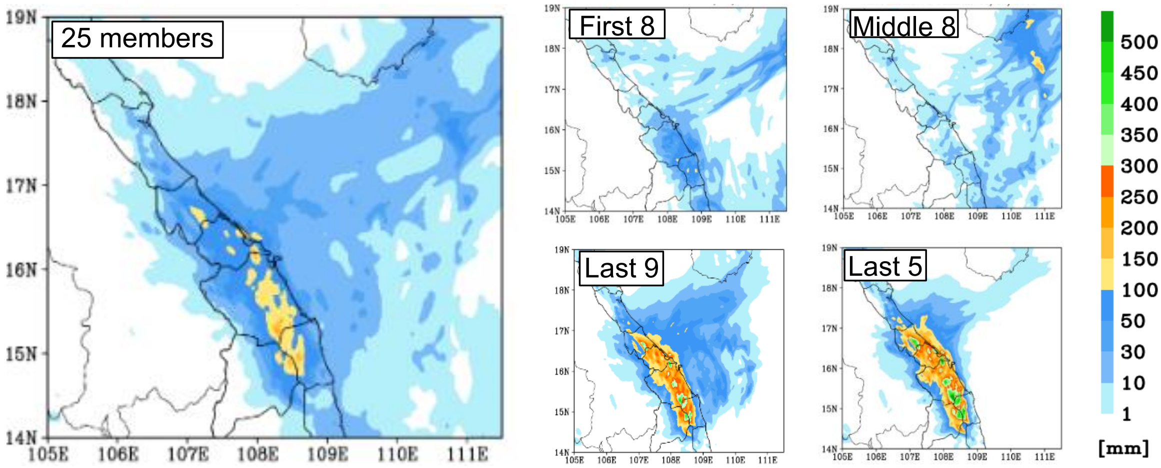

Figure 6. Ensemble mean rainfall (shaded, scale on the right) from all 25 time-lagged members, executed every 6 h from 12:00 UTC 3 December to 12:00 UTC 9 December, for the 24h period from 12:00 UTC 9 December to 12:00 UTC 10 December.

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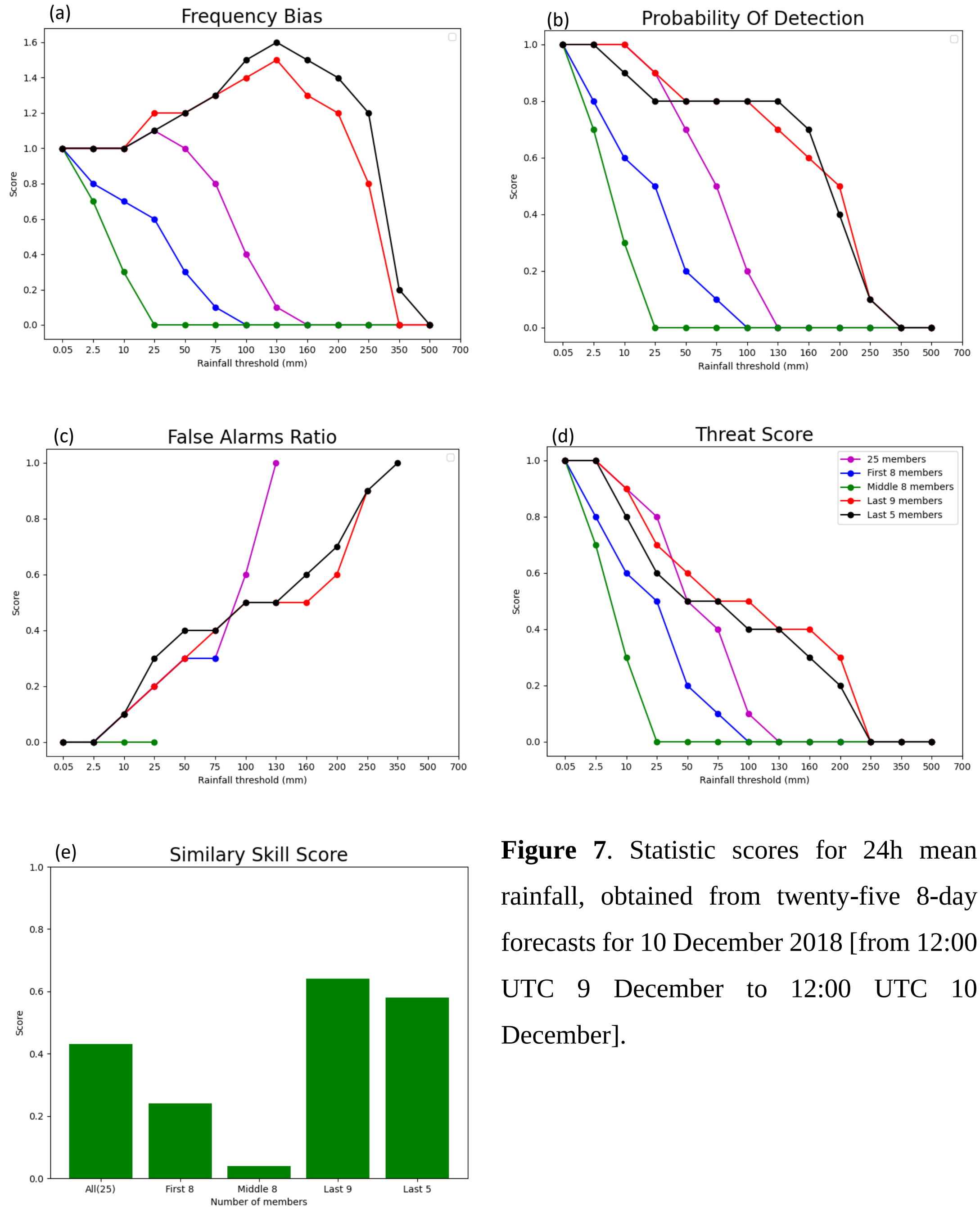

Figure 7. Statistic scores for 24h mean rainfall, obtained from twenty-five 8-day forecasts for 10 December 2018 [from 12:00 UTC 9 December to 12:00 UTC 10 December].

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However, as indicated by the SD, the spreads in rainfall scenarios in both ensembles from the last five and nine members are quite large (Fig. 8). Thus, while the lagged members can produce a wide range of possible rainfall scenarios for the D18 event, which is the main purpose of an ensemble as reviewed (Section 1), the members often cannot agree on the precise locations of heavy rainfall. Given the small scale of local convection during the event, this result is perhaps anticipated. On the other hand, the maxima in spread are >160 mm in Fig. 8 among the last nine members, and reasonable in magnitude compared to the peak amounts of about 400 mm in the ensemble mean. In any case, Figs. 7 and 8 indicate that the predictability of the D18 event changed considerably with time, and the 2.5-km CReSS has a good skill in QPFs inside the short range (≤ 72 h). However, it is difficult to predict the event successfully at longer lead times.

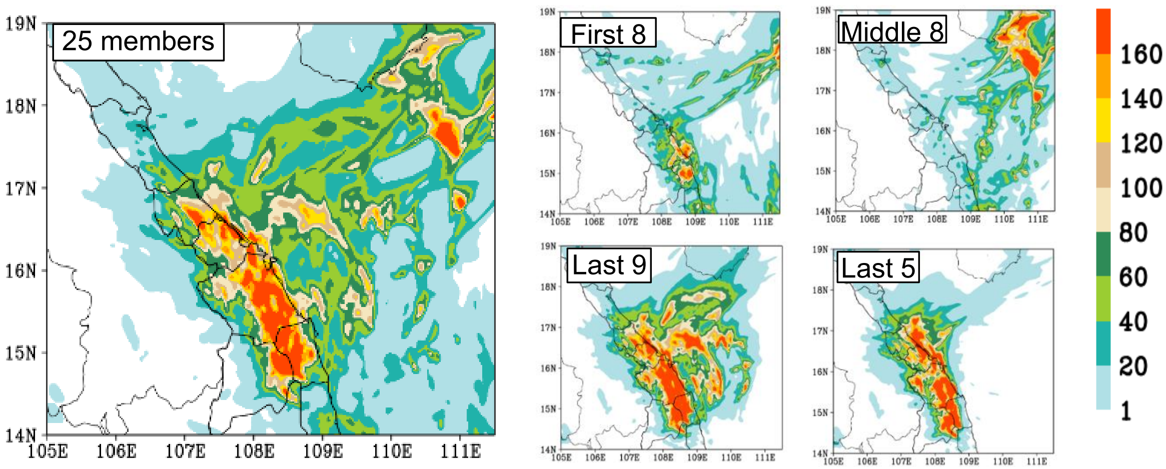

Figure 8. The spread (shaded, scale on the right) from all 25 time-lagged members, executed every 6 h from 12:00 UTC 3 December to 12:00 UTC 9 December, for the 24h period from 12:00 UTC 9 December to 12:00 UTC 10 December.

The probability information derived from the sub-ensemble groups at four different rainfall thresholds from 100 to 450 mm is shown in Fig. 9, in which the increase in heavy-rainfall probability in central Viet Nam and thus the predictability of the event with time is also

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evident. From the first eight members executed at the longest range (≥ 102 h prior to rainfall accumulation), there is only a 10-25% chance in parts of central Viet Nam to receive at least 100 mm of rainfall (from 12:00 UTC 9 to 12:00 UTC 10 December). The probability is even lower from the middle eight members (run between 54-96 h prior to target period), as their SSS is the lowest among all sub-ensemble groups and only a couple of the runs could reach 100 mm anywhere inland in central Viet Nam. As the lead time shortens to inside the short range, the probabilities to have ≥ 100 mm of rainfall increase dramatically, to roughly 70-80 % in the last nine members and further to over 80-90% in the last five members. Due to the contribution from later members, about 20-40% of all 25 members can reach 100 mm inland. Toward higher thresholds, the probabilities decrease in Fig. 9 as expected, so are the areal sizes actually reaching those thresholds (red contours). At the highest value of 450 mm, the ensembles in general show less than about 20% and 30% chances for its occurrence from the last five and last nine members, respectively, and the high probability areas are also slightly more inland than the observed one.

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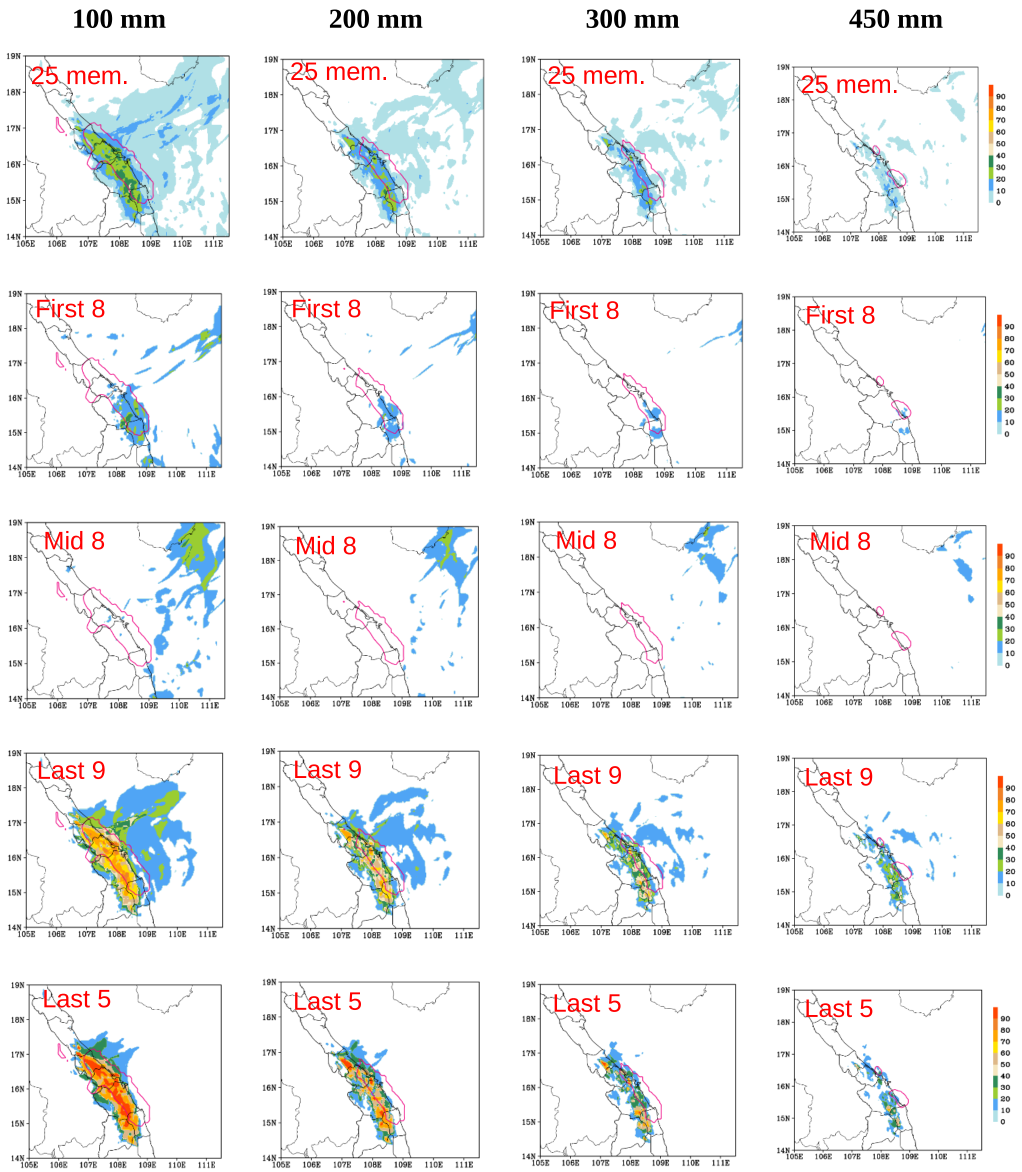

Figure 9. Probability distribution (%; shaded, scale on the right) from all 25 time-lagged members, executed every 6 h from 12:00 UTC 3 December to 12:00 UTC 9 December, reaching thresholds of 100, 200, 300, and 450 mm, for the 24h period from 12:00 UTC 9 December to 12:00 UTC 10 December. The observed areas at the same thresholds are

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depicted by the pink contours. For each picture, red labeled at the top-left corner show the number of members grouped to calculate the probability distribution.

3.2 Ensemble-based sensitivity analysis

The results in part 3.1 above reveal that the CReSS model with a horizontal resolution of 2.5 km had well QPF predicted the rainiest day of the event while other models can't capture it. Therefore, this part was made rely on this good performance. Figure 10 shows the sensitivity of mean 24-h total rainfall inside the green box in central Viet Nam (*R*) to zonal (*u*) and meridional (*v*) wind components and water vapor mixing ratio (q_v) at the altitude of 100 meters, and the ensemble mean are also plotted. It is clear that the sensitivity of rainfall to these variables is lower at longer forecast ranges and becomes higher at shorter lead times. Specifically, from two days before (t_{-48}) to the starting time of the accumulation period (t_0), the sensitivity of rainfall to *u*-wind over the SCS and along the coast of central Viet Nam turned more negative, indicating heavier rainfall associated with stronger easterly winds ($u < 0$) near the surface, especially in areas immediately upstream at t_0. The rainfall's sensitivity to *v*-wind leading to t_0, on the other hand, exhibited a dipole structure, with negative values to the north-northwest and positive values to the south-southeast across central Viet Nam and the upstream ocean. This structure indicates a stronger confluence in northeasterly winds over the region in rainier members, consistent with the results in Part 1. In Figs. 10d-f, the increase in *v*-wind just south of central Viet Nam is particularly evident, from –10 mm (per SD) at t_{-48} to over +70 mm (per SD) at t_0. Thus, the precipitation amount in the D18 event in central Viet Nam is highly sensitive to the northeasterly winds in short range forecasts. In contrast, compared to the winds, the rainfall was less sensitive to the water vapor amount as shown in Figs. 10g-i.

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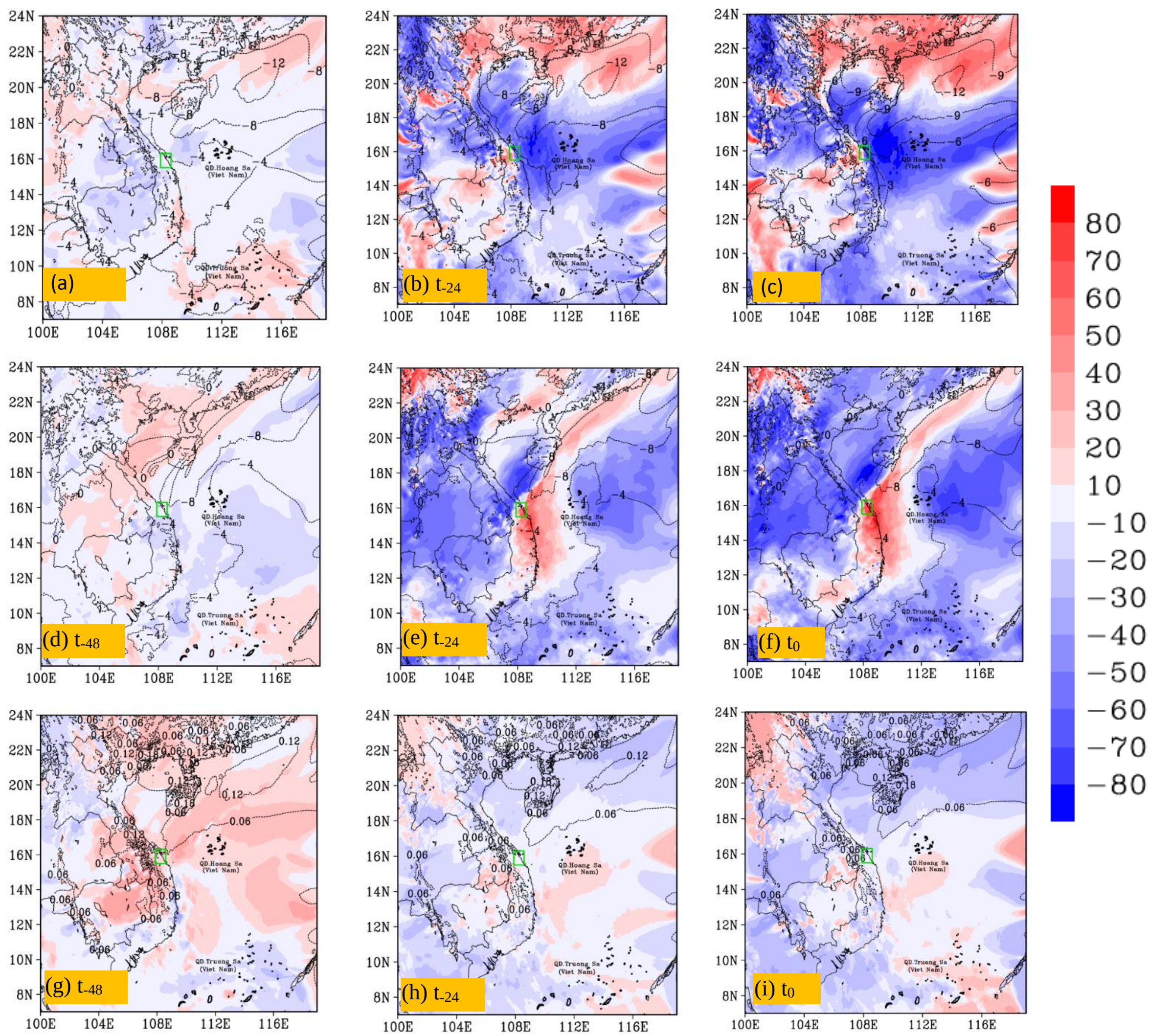

Figure 10. The sensitivity (mm, per SD, color, scale on the right) of areal-mean 24h accumulated rainfall in central Viet Nam starting from t_0 (i.e., R, averaging area depicted in green box) to surface wind components (ms^{-1}, shaded) and the ensemble mean (contours, every 4 ms^{-1}) and to surface water vapor mixing ratio (r, g kg^{-1}) and its ensemble mean (contours, every 0.06 g kg^{-1}) at different times at 24h intervals from (a) t_{-48} to (f) t_0. The time of t_0 is 12:00 UTC 9 December 2018. In which, (a), (b), (c) for the zonal wind

component. (d), (e), (f) for the meridional wind component, and (g), (h), (i) for surface water vapor mixing ratio.

Slightly higher at 1476 m (near 850 hPa), where easterly flow prevailed during the D18 event (see Fig. 3b in Part 1), the sensitivity of rainfall to winds exhibits similar spatial patterns (Figs. 11a-f) to those at the altitude of 100 meters, with stronger easterly winds and larger confluence in association with heavier rainfall. On the other hand, note that the rainfall becomes more sensitive to mixing ratio in central Viet Nam at this level (Figs. 11g-i), especially at shorter lead times, compared to its insensitivity to surface moisture amount. Presumably, this positive correlation is due to upward transport of moisture, as the ascending motion in convective clouds could become larger at this level.

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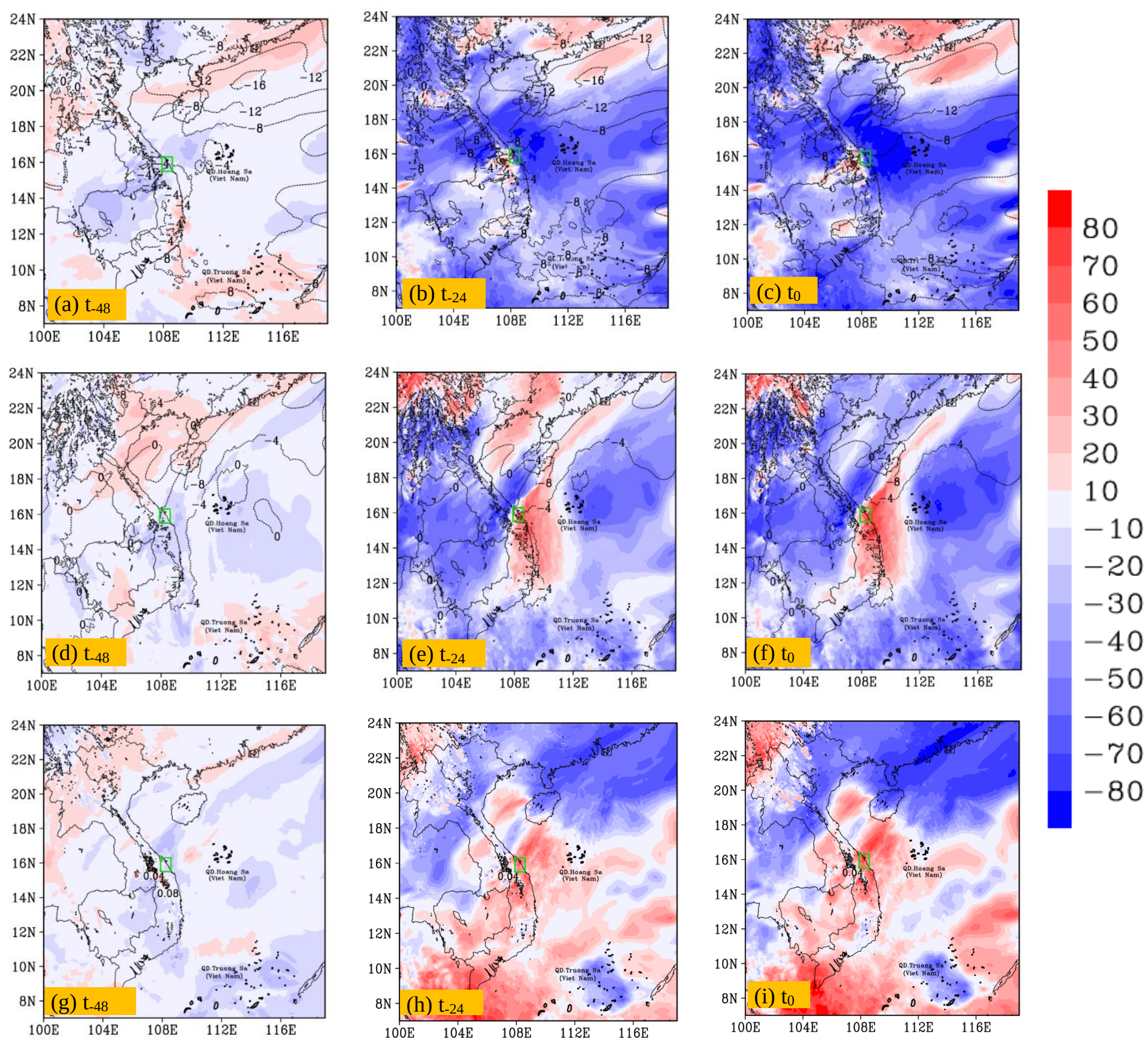

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520 **Figure 11**. The sensitivity (mm, per SD, color, scale on the right) of 24h accumulated
521 rainfall in central Viet Nam starting from t_0 (i.e., R, averaging area depicted in green box)
522 to the wind components (ms^{-1}, shaded) and the ensemble mean (contours, every 4 ms^{-1})
523 and to water vapor mixing ratio (r, g kg^{-1}) and its ensemble mean (contours, every 0.06 g
524 kg^{-1}) at attitude of 1476 m and at different times at 24h intervals from (a) t_{-48} to (f) t_0. The
525 time of t_0 is 12:00 UTC 9 December 2018. In which, (a), (b), (c) for the zonal wind

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component. (d), (e), (f) for the meridional wind component, and (g), (h), (i) for water vapor mixing ratio.

At the upper level of 5424 m (near 500 hPa), it is seen that from t_{-48} to t_0, dipole structures developed in the sensitivity patterns to both *u* and *v* winds (Figs. 12a-f). To *u* winds, positive sensitivity up to about +70 mm (per SD) existed to the south and negative sensitivity up to −70 mm (per SD) to the north of central Viet Nam. Meanwhile, positive sensitivity to *v*-wind appeared to the north and east with negative sensitivity to the south and west of the rainfall area. While the prevailing winds at 500 hPa were southeasterly over southern Viet Nam and southwesterly over northern Viet Nam during D18 (thus with anticyclonic curvature, see Fig. 3c in Part 1), the above sensitivity patterns, apparent at t_{-24} already, corresponded to stronger diffluence/divergence and a weaker anticyclone aloft to favor more rainfall. To q_v, positive sensitivity signals up to +70 mm (per SD) also appeared over the rainfall area at t_{-24} and t_0 (Figs. 12h,i), and the reason is similar to those near 850 hPa in Fig. 11.

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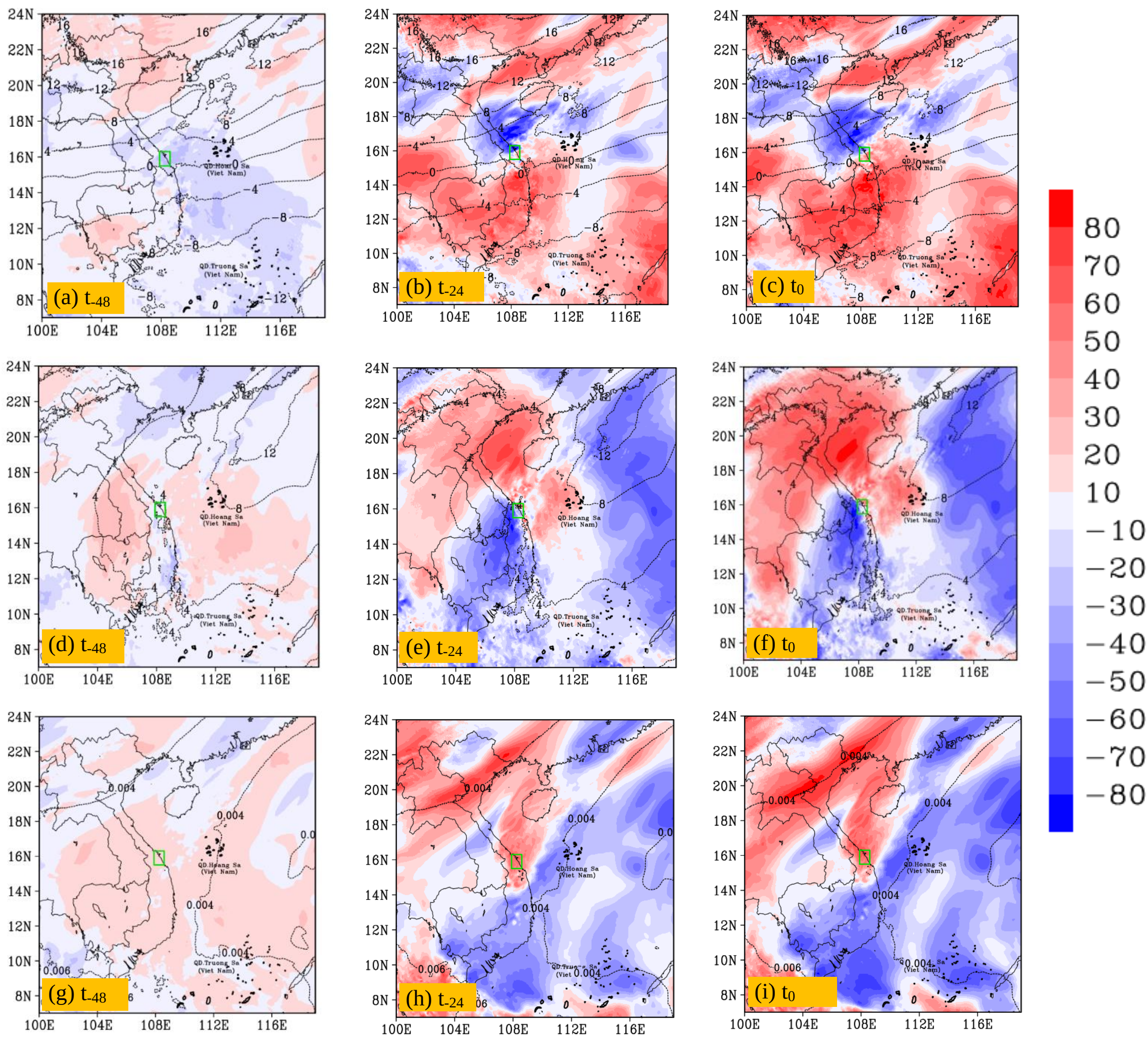

546 **Figure 12**. The sensitivity (mm, per SD, color, scale on the right) of 24h accumulated
547 rainfall in central Viet Nam starting from t_0 (i.e., R, averaging area depicted in green box)
548 to the wind components (ms^{-1}, shaded) and the ensemble mean (contours, every 4 ms^{-1})
549 and to water vapor mixing ratio (r, g kg^{-1}) and its ensemble mean (contours, every 0.06 g
550 kg^{-1}) at attitude of 5424 m and at different times at 24h intervals from (a) t_{-48} to (f) t_0. The
551 time of t_0 is 12:00 UTC 9 December 2018. In which, (a), (b), (c) for the zonal wind

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component. (d), (e), (f) for the meridional wind component, and (g), (h), (i) for water vapor mixing ratio.

4 Conclusion

As high resolution is required in numerical models to predict heavy rainfall more successfully, the present work utilizes a time-lagged high-resolution ensemble forecast system and evaluates how well the D18 event (during 9-12 December 2018) in central Viet Nam can be predicted in advance before its occurrence. Using the CReSS model with a grid size of 2.5 km (912 × 900 in dimension with 60 vertical levels), ensemble forecasts were produced with a total of 29 time-lagged runs at 6-h intervals, each out to a forecast range of 192 h (eight days). Our evaluation results in predictability indicate that the 2.5-km system predicted the rainfall fields on 10 December during the event fairly well, including both the amount and spatial distribution, within the short range at lead times of day 1, 2, and 3. More specifically, the SSS of QPFs at these three ranges are about 0.4, 0.6, and 0.7, respectively, with fairly consistent results among successive runs that indicate a reasonable predictability, despite some spread and disagreement on the precise locations of heavy rainfall. The above good results are due to the model's capability to better predict the conditions in the lower troposphere such as the wind fields.

At lead times longer than three days, however, the predictability of the event is lowered due to a higher level of forecast uncertainty, and the quality of QPFs drops with significant under-prediction. Nevertheless, good QPFs are still possible occasionally. At lead time beyond six days, it is challenging to achieve a good QPF at thresholds greater than 100 mm even with a high-resolution model. This is presumably linked to the rapid evolution of atmospheric conditions surrounding Viet Nam in a tropical environment. In the present study, a CRM is applied to forecast extreme rainfall in central Viet Nam for the first time. Although still with certain limitations, our results do indicate hope to predict such events successfully beforehand, at least within the short range. Therefore, based on the present work, more studies on the predictability of extreme rainfall in Viet Nam are recommended in the near future.

The present study also performed an ensemble sensitivity analysis to identify the important factors that influenced the 24-h rainfall amount in central Viet Nam in the D18 event. The result shows that the rainfall is most sensitive to the wind conditions in the lower troposphere leading to the event, with more rain associated with stronger northeasterly to easterly winds and their confluence. In addition, the rainfall also shows some sensitivity to the moisture amount and winds further aloft at the upper levels. In the ESA, the finer-scale features (convection) are also seen to link to synoptic conditions in their background, implying that it is meaningful to apply ESA to control the perturbations in initial fields.

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Code and data availability. The CReSS model used in this study and its user's guide are available at the model website at http://www.rain.hyarc.nagoya-u.ac.jp/~tsuboki/cress_html/src_cress/CReSS2223_users_guide_eng.pdf (last access: 6 July 2023; Tsuboki and Sakakibara, 2007). The TIGGE data and its information are available at https://confluence.ecmwf.int/display/TIGGE/TIGGE+archive. The NCEP GFS dataset and its description are available at https://rda.ucar.edu/datasets/ds084.1/.

Author contributions. **Duc Van Nguyen** prepared datasets, executed the model experiments, performed the analysis, and prepared the first draft of the manuscript. **Chung-Chieh Wang** also prepared the first draft and provided the funding, guidance and suggestions during the study, and they participated in the revision of the manuscript. **Kien Ba Truong** provided the funding and participated revising of the manuscript. **Thang Van Vu**, **Pham Thi Thanh Nga**, and **Pi-Yu Chuang** also participated in the revision of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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