Early warning of heavy rainfall event using time-lagged ensemble prediction system (case study February 15th 2019)

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Abstract. Convective clouds can be related to the development of intense storms that produce various extreme weather. The development of extreme weather could involve strong nonlinear interactions of many factors in the atmosphere, hence the ability to forecast extreme weather especially heavy rainfall and issued an early warning, becomes very important. BMKG has developed a time-lagged ensemble prediction system by utilizing the initial time difference, which is considered capable of providing data updates more closely to the forecasts final results. This study examines the percentile classification in the ensemble prediction system, to look for an extreme values distribution, then used it as extreme threshold. The extreme threshold was tested in a heavy rain case on February 15th 2019, on D-7, D-3, and D-1 of early warning dissemination. Based on this research, it was found that the use of the 90th and 95th percentile classification method was able to show a signal of extreme events on D-7 and D-3 events with a consistent probability pattern. In the D-1 prediction period, the probability value increases and the average precipitation value exceeds the extreme threshold.

1. Introduction

Numerical weather prediction models are one of the essential data sources used by weather forecasters in making long-term and short-term weather forecasts, including in issuing extreme weather early warnings, so various methods have been developed to maximize the use of numerical models [1, 2]. One of the methods is by using an ensemble prediction system. The ensemble prediction system is a method for predicting the probability distribution of the forecast state caused by model uncertainty [3]. There are several ways to build an ensemble prediction system, one of which is to run a modified initial conditions model, with the aim to produce several possible weather scenarios [2]. Another way is to combine models that have different initial times to predict a particular time, and this initial time difference is considered capable to provide more dense update data on the final forecast results [4]. BMKG has developed an ensemble prediction system since 2018 using the time-lagged ensemble using Integrated Forecasting System (IFS) data [5].

The performance of the time-lagged ensemble shows better skills in making probabilistic forecasts because it is able to capture possible scenarios that will occur over time [6]. Spatially, the time-lagged ensemble also has good skills, because the individual forecasts of each member used to have the same initial condition value as the observation at the initial time [4]. The results of extreme weather prediction
using an ensemble prediction system will be better than a single or deterministic forecast system. However, the bias and extreme threshold values in the ensemble prediction system must be statistically tested to obtain a threshold that meets the requirements in all extreme conditions [7]. Using just one type of model in a time-lagged ensemble has been able to make new predictions with increased accuracy, because this system uses different prediction results with different initiation times (a combination of past predictions and recent predictions) so that it can detect various possibilities that occur from time to time [8]. Figure 1 is an example of a schematic showing the forecast initiation cycle from top to bottom, with a period of 3 hours and a time-lagged ensemble with different initial times (from left to right), the dark color shows the longer lead time and the lighter color shows the lead most recent time. A complete time-lagged ensemble is shown by the inside of the red box in Figure 1, which is the time slices of various initial times.

![Figure 1. Time-lagged ensemble scheme](image)

The theory of extreme values was developed to analyze extreme events and determine the characteristics of changes due to extreme events; using statistics was one of them [10]. Statistical products that can be combined in numerical weather models to predict extreme weather, one of which is the use of quantiles [2,11]. Quantiles that are commonly used are to find the maximum and minimum value of the distribution of the ensemble prediction system, which can express a summary of uncertainty [12]. This statistical method in the ensemble prediction system is considered capable of providing good predictive information for heavy rain events [7]. In some extreme threshold determinations, the distribution used is the 1st, 5th, 10th, 90th, 95th and 99th percentiles. The 90th, 95th, and 99th percentiles are used for extreme thresholds of heavy rain, strong winds, and hot temperatures, while the 1st, 5th, and 10th percentile are used as the threshold for extreme cold temperatures [13].

The evolution of extreme rainfall events in Jakarta, at least experienced a statistically significant increase in the period 1961-2010 [14], so the use of statistical methods is to predict the probability of rain events with heavy and very heavy intensity [11]. This study aims to develop an ensemble prediction system as a data source in providing extreme information, especially heavy rainfall. This research was conducted by examining the percentile classification method in the ensemble prediction system to find the distribution of extreme values in the model members, so that the extreme threshold of rainfall parameters can be found in the heavy rain cases studied. This extreme threshold and probability hopefully can be used as consideration for detecting heavy rainfall events and issuing an early warning of extreme weathers in operational regularly.

2. Methods

This research method utilizes the percentile classification of the model members to find extreme thresholds. The locations used to take extreme threshold samples are at several observation points in the Jakarta and Bogor area (Figure 2). This extreme threshold is then used in the ensemble prediction system in the case of rain. The data uses are:

1) IFS data used in this study were 15 IFS members, which showed the difference in initial time with a spatial resolution of 0.125° x 0.125° in December 2018 to February 2019. One IFS member has an estimated period of 240 hours (10 days) with a temporal resolution of 3 hours.
2) Extreme rainfall data per 3 hours in observed station.
3) Soekarno Hatta Class I Meteorological Station radiosonde data at 00 and 12 UTC.
The function of extreme thresholds are to determine the occurrences probability of an extreme event which is measured based on the overall value distribution [13]. This study only uses the 90th percentile (R90p) and 95th percentile (R95p) classifications which show:

1) The R90p classification is a percentile that is commonly used as the upper limit or the extreme limit of the model on extreme precipitation parameters [13].

2) The R95p classification is when the total rainfall is greater than the 95th percentile and is categorized as very wet days [14,15].

The R90p and R95p classifications were then applied to 15 members of the ensemble prediction system used in cases of selected extreme rain on D-7, D-3, and D-1 before the incident. The 90th percentile and 95th percentile values of the model rainfall distribution are obtained from:

\[
R90 = \frac{90(N + 1)}{100} \quad (2.1) \\
R95 = \frac{95(N + 1)}{100} \quad (2.2)
\]

Where:
N: Total Data

3. Results and Discussion

3.1 Analysis of Heavy Rain Events

The rain event that will be predicted using the ensemble prediction system is heavy rain on February 15th, 2019 occurred around the Bogor area, where rain events were observed at several observation points in the form of stations, rain stations, and automatic stations. The highest daily rain accumulation at the Citeko Meteorological Station reach 87 mm / 24 hours, another location observed for rain accumulation ≥ 50 mm / 24 hours was at the Dramaga Climatology Station with a total of 55.5 mm / 24 hours and both of them are considered in the extreme category [16]. Referring to the research before, if the rainfall in Jakarta and its surrounding areas has an accumulation of 50 mm / 24 hours which can be related to extreme events that lead to flood disasters [14], then this condition is chosen to predict extreme events that can later be one of the parameters considered in issuing an early warning. The rain began to occur around 12 UTC or 19.00 LT in the Citeko Meteorological Station area, while in the Dramaga Climatology Station area, the rain occurred about 60 minutes later, around 13.00 UTC or 20.00 LT. Rain intensities over of 20mm / h at both stations occurred around 16-17 UTC, this indicates that the rain originates from the same convective cloud and is in fairly broad cloud coverage. According to automatic equipment observations and surface observations in both locations, the rain continued until early morning with light to heavy intensity and was accompanied by lightning.

| Table 1. Rain observed by stations on February 15th 2019 |
|--------------------------------------------------------|
| Hour (UTC) | Citeko | Dramaga |
|------------|--------|---------|
| 00         | 0      | 0       |
| 06         | 0      | 0       |
The analysis of lability conditions was used aerial observation of radiosonde, which is only found at Soekarno-Hatta Meteorological Station. However, according to several manuals, the aerial observation network is at least representative of an area of 250 km [17,18] and the research area only covers an area of approximately 100 km, so that the aerial observation at Soekarno-Hatta Meteorological Station is considered representative of the area of heavy rain. Rain occurs starting at 12.00 UTC, which close to the time of the upper air observation. The upper air observation condition is still considered representative enough for the atmospheric lability analysis in this case. The available CAPE value in the atmosphere is 1245 J/kg, and categorized as moderate atmospheric conditions unstable [19]. The potential for congestion or convection is indicated by convective temperature (Tc), the Tc value in this case is 32.1°C and the Tmax value on the surface reaches 32.2°C, so this shows high convective activity due to heating [20]. The Showalter Index (SI) parameter in this case has a value of -0.3, indicating that the atmosphere is in an unstable condition so that the potential for cumulonimbus cloud formation to cause rain is accompanied by thunderstorms with light category [19]. The last index is the K Index (KI), in this case the KI value reaches 29.8, the KI value shows the magnitude of the possibility of convective cloud growth, the greater the KI value, the greater the potential for convective cloud formation. The KI value of 29.9 is equivalent to 40-60% of the potential for convective clouds to occur [20].

### Table 2. Stability index value observed

| Parameter | Value |
|-----------|-------|
| Tc (°C)   | 32.1  |
| Tmax (°C) | 32.2  |
| CAPE (J)  | 1245  |
| KI        | 29.8  |
| SI        | -0.3  |

#### 3.2 Extreme Threshold Determination

The extreme threshold of the model must be in the same season, because at least the regional atmospheric conditions have in common [9,21]. The extreme threshold in this study was prepared using a scheme adapted from Matsueda and Nakazawa [13], by using 63 points in the study area with a resolution of 0.125° ranging from 106.125° - 107.125° East and 6.0° - 6.75° South. Before looking for model extreme threshold values, it is necessary to know the characteristics of the model through means and standard deviation. This average shows the magnitude of the model uncertainty, while variation is used to show the uncertainty of a random variable [11]. These are used to determine how significant reduction in the skill model is at the prediction time (t).
The model performance looks quite good in this study. The standard deviation value does not deviate too far from the average, at \( t = 12 \) to \( t = 54 \) the average value and standard deviation tend to be the same, indicating that the highest model skill is at that lead time at the DJF period. Entering \( t = 60 \) to \( t = 144 \) the average value of precipitation decreases and the value of variation increases. This shows that the performance of the model starts to decrease, if this standard deviation is higher, then this also shows the high uncertainty of a random variable in the model [3].

After extracting value in each grid in every time step, the 90th percentile value at \( t = 24 \) is around 14.3 mm / 6 hours. Bogor also has the highest threshold value, reaching 14 mm / 6 hours. At \( t = 72 \), the 90th percentile value was around 11.47 mm / 6 hours. Bogor still has the highest extreme threshold of 12.0 mm / 6 hours. At \( t = 168 \), the value is around 11.12 mm / 6 hours. Bogor has an extreme threshold value of 10.8 mm / 6 hours. The 95th percentile value has a higher upper limit than the 90th percentile value. At \( t = 24 \) the highest value is 22.84 mm / 6 hours. Bogor has an extreme threshold between 16.1 - 22.0 mm / 6 hours. At \( t = 72 \), the highest value was 15.64 mm / 6 hours. Bogor has an extreme threshold of 12.1 - 16.0 mm / 6 hours. At \( t = 168 \), the highest value was 18.01 mm / 6 hours. Bogor still has an extremely high threshold of 16.0 mm / 6 hours. The extreme limits at each \( t \) have a consistent pattern, with mountainous areas such as Bogor having a higher threshold than coastal areas such as Northern Jakarta, this shows that the model has a pattern in each region, as evidenced by the fact that each grid has its own threshold value, even though in a nearby location the threshold value has almost the same value [22].

3.3 D-7 Dissemination

Dissemination of early warning information on D-7, meaning that every extreme rain event on the selected date is informed seven days before the event. The prediction for the D-7 event dissemination uses 7 different initial times due to the limited observation period of the IFS data. The scheme of initial time taking in the D-7 dissemination is shown in Figure 4; from this scheme, it is known that each forecast interval is 6 hours intervals. The numbers contained in the box are the forecast time that will be entered into the extreme threshold value at both percentiles; because of the limited processing time and extraction of the threshold value, values that do not have an extreme threshold will be filled with the lowest extreme threshold value at the nearest lead time.

| D+1 00 UTC | D+1 12 UTC | D+2 00 UTC | D+2 12 UTC | D+3 00 UTC | D+3 12 UTC | D+4 00 UTC | D+4 12 UTC | D+5 00 UTC | D+5 12 UTC | D+6 00 UTC | D+6 12 UTC | D+7 00 UTC | D+7 12 UTC |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 12 18 24 30 36 42 48 54 | 60 66 72 78 84 | 108 124 140 156 166 186 204 210 | 216 234 240 | 240 | 252 | 260 | 270 | 280 | 290 | 300 | 310 | 320 | 330 |

**Figure 4.** The schematic on D-7 events and the blue box shows the lead time forecast used in the ensemble prediction system [5].

Threshold values used were extracted around the location of heavy rain events, whereas around 6.5° – 6.625° south and 106.625° – 106.75° east. The value entered in the prediction is the smallest value of all the points. The case is on February 15th, 2019. If the D-7 early warning is disseminated, then the dissemination will be carried out on February 8th, 2019. The data used are only three days from February 8th, 2019, there are February 8th (00 and 12 UTC), February 7th (00 and 12 UTC), February 6th (00 and 12 UTC), and February 5th (00 UTC), so the total ensemble members used are 6. The use of values in the 90th and 95th percentile focuses on locations around the occurrence of extreme rain only, so that the threshold used is considered representative of the location around the extreme rainfall event.

The result of the ensemble mean for precipitation per 6 hours shows that the predicted average rainfall in the Bogor area ranges from 2.5 - 5 mm / 6 hours at 12 UTC, while the observation results show...
that the extreme precipitation at these hours reaches 86.7 mm / 6 hours in the station area. The probability of extreme events on D-7 using the 90th percentile threshold in this case shows a pretty good percentage value for the area of extreme events, where the rain starts the percentage value reaches 20%, according to Linden [23], 20% in D-7 extreme event could be a signal of an occurrence of extreme rainfall. Based on PDF distribution for random variables on the 90th percentile, a probability close to 25% has indicated that there is a possibility or an extreme signal. Meanwhile, the 95th percentile prediction of the same case showed quite good results, almost in all locations that were used as verification of the probability of the occurrence of 10-20%. The use of time-lagged ensemble in probability prediction will indeed reduce unrealistic model variations, for rain variables, especially extreme rain, the time-lagged ensemble is not good enough to show the actual probability, but at least extreme signals can be detected on D-7 [2,7].

Figure 5. The results of the ensemble mean and the probability of occurrence using the extreme threshold P90 and P95 on the D-7 event dissemination on February 8th 2019

3.4 D-3 Dissemination

D-3 dissemination of early warning information, meaning that every extreme rain event on the selected date is informed again by updating the data 3 days before the incident. Predictions on the D-3 dissemination of events have used 14 different initial times, thus capturing more model uncertainties and minimizing variations. The scheme for taking the initial time of the D-3 dissemination is shown in Figure 4 above; from this scheme, it is known that each forecast time with an interval of 6 hours. The numbers contained in the box are the forecast time which will be entered in the extreme threshold values at both percentiles; due to limited processing time and extracting the extreme threshold, the values which do not have an extreme threshold will definitely be filled with the lowest extreme threshold value at the lead time closest, and then the accuracy of the prediction results will be analyzed. The threshold in the case was as same as the threshold on D-7; only different forecast times will be calculated to produce new predictions.

Figure 6. The results of the ensemble mean and the probability of occurrence using the extreme threshold P90 and P95 on the D-3 event dissemination on February 12th 2019

The threshold used in the case on February 15th 2019 are in Table 4.10, and if D-3 is disseminated, an early warning information will be given on February 12th, 2019. The data used are data on February
6th to February 12th 2019 (00 and 12 UTC), so it has 14 ensemble members. The ensemble means results, in the D-3 prediction have a more consistent pattern, which shows an increase in average amount of precipitation in all locations of extreme rain events with a total accumulation of 6 hours reaching 6-15 mm. Although the center of highest precipitation accumulation still does not indicate a sufficiently precise location, in general, the amount of rainfall has increased. The probability result on D-3 has an increasing percentage, reaching 40% in the Citeko Meteorological Station and Dramaga Climatology Station. The locations shown in the D-3 prediction are quite consistent and expand following the ensemble mean average precipitation yield pattern. The use of the 90 and 95 percentile thresholds in this case has a fairly consistent pattern, which shows an increase in the percentage value and the corresponding location. D-3 prediction in several previous studies, the use of the 90, 95, and 99 percentiles can always pick up extreme signals even with a probability level of only 40% [23].

3.5 D-1 Dissemination

Dissemination of early warning information on D-1, meaning that every extreme rain event on the selected date is informed again by updating the data 1 day before the incident. Predictions on the D-1 dissemination of events have also used 14 different initial times, thus capturing more model uncertainties and minimizing variations. The scheme of initial time taking in the D-1 dissemination is shown in Figure 4 above; from this scheme, it is known that each forecast time with an interval of 6 hours. The numbers contained in the box are the forecast time that will be entered into the extreme threshold value at both percentiles; because of the limited processing time and extraction of the extreme threshold, values that do not have an extreme threshold will be filled with the lowest extreme threshold value at the nearest lead time, then the accuracy of the prediction results will be analyzed. The threshold in each case is basically the same as the threshold on D-7; only different forecast times will be calculated to produce new predictions.

D-1 early warning dissemination will be submitted on February 14th 2019. The data used are data on February 8th to February 14th 2019 (00 and 12 UTC), so it has 14 ensemble members. The ensemble means results in the D-1 prediction have the same pattern as D-3, which shows an increase in average amount of precipitation in all locations of extreme rain events with a total accumulation of 6 hours reaching 20 mm. The center of the highest precipitation accumulation has shown a reasonably precise location in the Citeko Meteorological Station area. The probability result on D-1 has an increasing percentage, reaching 80% in the Citeko Meteorological Station and Dramaga Climatology Station. The locations shown in the D-1 prediction are very consistent and conical to follow the ensemble mean pattern yield. The use of the 90th and 95th percentile thresholds have a relatively good pattern of prediction D-7 to D-1, showing an increase in the percentage value and the corresponding location. Prediction of the D-1 shows the percentage reaches 75% and the skill model is good and quite representative to be used to predict extreme events at that location [7]

4. Discussion

Figure 7. The results of the ensemble mean and the probability of occurrence using the extreme threshold P90 and P95 on the D-1 event dissemination on February 14th 2019
The rain that occurred in the mountainous region of Bogor on February 15th 2019 showed a more consistent pattern. In this case, the probability value at D-7 reaches 20% in the Dramaga area, even though the average precipitation does not reach the minimum threshold. In the second prediction period, namely D-3 the probability value reaches 40% at both locations and the average precipitation value reaches the extreme threshold, even exceeds the extreme threshold. Consistent prediction results are still shown up to D-1 prediction of extreme events. The probability value even reaches 90% and the average precipitation value reaches 20 mm / 6 hours which indicates that this extreme rain event is more likely to happen. The use of 95th in this case also shows an almost consistent pattern, an extreme signal is found in the D-7 prediction with an event probability value reaching 20%, at D-3 the probability increases to 40%. The average precipitation value exceeds the 95th percentile threshold relatively high on the D-3 which reaches 16 mm / 6 hours. The following prediction is that the D-1 probability value reaches 80% and the average precipitation value reaches 20 mm / 6 hours even though it has not reached the 95th percentile threshold which reaches 22 mm / 6 hours. However, the average precipitation reaches 20 mm / 6 hours. This number shows that the ensemble prediction system using either the 90th percentile or the 95th percentile in mountainous areas shows quite good results, because every numerical model has considered orographic patterns and atmospheric dynamics patterns from time to time globally [24]. In this study, it is known that the prediction patterns in mountainous areas show a consistent pattern, because the precipitation pattern in mountainous areas is more modified by orography [25]. In this case, the ensemble prediction system is considered successful in detecting the event 168 hours before the event.

5. Conclusion
The ensemble prediction system used to detect extreme rain events is quite capable of showing extreme signals with a probability value of D-7 of 20% with a 90th percentile value of 8-10 mm / 6 hours in the study area. The probability threshold value reaches 40%. In the D-1 prediction period, the probability value increases to above 75% and the average precipitation value exceed the extreme threshold i.e., 4-14 mm / 6 hours. The use of 95th percentile classification method in the ensemble prediction system is also considered good in predicting heavy rain events in the Bogor area on February 15th 2019. Signals of extreme events have been able to be detected up to 168 hours before the incident. The closer to the event, the prediction pattern shows consistent results as with the 90th percentile, with an increase in the mean amount of precipitation and a probability value of up to 60%.

6. Suggestion
This research can be developed using more extended data series to determine more representative extreme threshold at each point and also more cases to increase the accuracy value also the skill model. It should be noted that for very extreme cases, low probabilities may be encountered at various predicted periods, so low probabilities cannot simply be ignored when other factors such as wind or average amount of precipitation have shown signs of extremes.

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