Identification of atmospheric dynamic condition during heavy rainfall in Banjarnegara Indonesia using WRF-ARW model: case 18 June 2016

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Abstract. The Atmospheric dynamic condition during heavy rainfall on 18 June 2016 in Banjarnegara was examined using the Weather Research and Forecasting (WRF) model. This study calculated hourly atmospheric instability indices and three kind of atmospheric dynamic parameters such as vorticity, vertical velocity, and divergence. Vorticity described cyclonic movements for the cloud growth, vertical velocity described the speed of lift force, and divergence described the existence of air mass encounter in the atmosphere. The final (FNL) data and suitable schemes are applied for the nested domains (27 km, 9 km, 3 km) in model. The result of instability indices is the convection was occurred 1 hour before heavy rain. The result of vorticity is -0.25 x 10⁻³ /s; 0.9 m/s in vertical velocity; and -0.5 x 10⁻³ /s in divergence. From the study, it was also found that the process of cloud development has been seen for 30 minutes to 1 hour before the heavy rain.

1. Introduction
Banjarnegara is a regency in Central Java Province, Indonesia located between 7°12’-7°31’South Latitude (LS) and 109°29’-109°45’50’East Longitude (BT). While for topography, Banjarnegara is dominated by areas with an altitude of 100-500 miles above sea level (msl), which constitutes 37.04% of the total area, while in terms of slope, Banjarnegara is dominated by areas with slopes of more than 15-40%, which amount to 45.04% of the total area [1]. This condition makes it vulnerable to landslides.

Rainfall is one of the factors causing landslides. In this study, atmospheric dynamics which supported heavy rain in Banjarnegara on 18 June 2016 were examined using the Weather Research and Forecasting (WRF) model. The parameters measured are indices of atmospheric instability (LI, KI, CAPE, and TT), vorticity, vertical velocity, and divergence. The index of atmospheric instability is a useful step to detect the potential for bad weather or the potential for convective growth [2]. By observing the atmospheric instability, the tendency of vertical movement of air masses in the atmosphere could be seen. The vertical movement of air masses is an important part of energy transportation and has a profound effect on the hydrological cycle. Without the vertical movement of air masses; the clouds, precipitation, and other atmospheric phenomena will not be formed [3]. There are several instability indices, these are the indices which used in this study (table 1). The information of each indices was resumed in table 2, table 3, table 4, and table 5 [4].
Table 1. Instability indices for severe convective weather forecasting

| Index name                          | Formula                                                                 | References |
|-------------------------------------|------------------------------------------------------------------------|------------|
| Lifted Index (LI)                   | $LI = T_{lp}(\text{fcst surface}) - T_{500}$                          | [5]        |
| K-Index (KI)                        | $KI = T_{850} - T_{500} + D_{850} - (T_{700} - D_{700})$               | [6]        |
| Convevtive Available Potential Energy (CAPE) | $\int_{LFC}^{EL} (\alpha l_p - \alpha) \, dp$ | [7]        |
| Total Totals (TT)                   | $(T_{850} - T_{500}) + (D_{850} - T_{500})$                           | [8]        |

Table 2. The threshold of instability indices LI

| Lifting Index | Definition                                                                 |
|---------------|---------------------------------------------------------------------------|
| $LI < 0$      | Unstable atmosphere (tends to cause significant weather)                  |
| $LI \geq 0$   | Stable atmosphere (tends to cause significant weather is not easy to occur) |
| $1 < LI < 6$  | Conditionally stable atmosphere (causing significant weather is not easy to occur) |
| $-2 < LI < 0$ | Light unstable atmosphere (can cause thunderstorms with lightning to occur) |
| $-6 < LI < -2$| Unstable atmosphere (can cause strong thunderstorms with lightning to occur) |
| $LI < -6$     | Very unstable atmosphere (can cause very strong thunderstorms with lightning to occur) |

Table 3. The threshold of instability indices CAPE

| Nilai CAPE | Definition           |
|------------|----------------------|
| $CAPE < 1000$ | Weak Convective     |
| $1000 \leq CAPE < 2500$ | Medium Convective |
| $CAPE \geq 2500$ | Strong Convective   |

Table 4. The threshold of instability indices KI

| K Index | Definition                                                                 |
|---------|---------------------------------------------------------------------------|
| $< 15$  | 0% chance of potential thunderstorm                                      |
| $15 - 20$ | 20% chance of a potential thunderstorm                                   |
| $21 - 25$ | 20 - 40% chance of a potential thunderstorm                              |
| $26 - 30$ | 40 - 60% chance of a potential thunderstorm                              |
| $31 - 35$ | 60 - 80% chance of a potential thunderstorm                              |
| $36 - 40$ | 80 - 90% chance of a potential thunderstorm                              |
| $> 40$  | 100% chance of a potential thunderstorm                                  |

Table 5. The threshold of instability indices TT

| Total Totals Index | Definition                                                                 |
|--------------------|---------------------------------------------------------------------------|
| $ITT < 50$         | Weakly convective, the potential for small thunderstorms to grow          |
| $50 - 55$          | Moderate Convective, the potential for moderate thunderstorm growth       |
| $ITT > 55$         | Strongly convective, the potential for large thunderstorms to grow        |

Vertical motion and vertical velocity information play an important role in the influence of cloud formation, rain, and sunny conditions. Based on the research in Ambon (Indonesia), when there are cumulonimbus clouds, the vertical velocity of the air is negative which indicates there is an uplifting of the air mass. Negative vorticity values also cause cyclonic air movement and trigger the formation of cumulonimbus clouds. While the air divergence condition vertically shows a value that tends to be positive, namely compressing air masses plays less role [9]. This study aims to obtain the value of hourly atmospheric instability indices (LI, KI, TT, CAPE), vorticity, vertical velocity, and divergence. This study use model WRF-ARW because there is not a meteorological station in Banjarnegara.
2. Methods

2.1 Numerical Model

The final analysis (FNL) data which used in this study is the data of 12 hours before the day of the landslide. This is to implement spin up. The function of spin up is to avoid the process of convection that is not realistic [10]. The data which used are the final analysis data (FNL) from 17 June (12 UTC) to 19 June (00 UTC). This data is processed in the WRF-ARW 3.8.1 model, an open source model, version 3.8.1 released in August 2016 [11]. As for the data processing as shown in figure 1 and table 6. This arrangement is based on the scheme parameterization research had been done by the STMKG lecturer team [12].

The next step is displaying atmospheric instability data (LI, KL, CAPE, and TT), vorticity, vertical velocity, and divergence in a Grid Analysis and Display System (GrADS). GrADS is an application that is used to visualize the results of global numerical model outputs and satellite data in the NetCDF format in a more interactive and simplified picture system.

![Figure 1. The domain in WRF-ARW 3.8.1](image)

| Settings                  | Domain 1 | Domain 2 | Domain 3 |
|---------------------------|----------|----------|----------|
| Resolution                | 27 km    | 9 km     | 3 km     |
| Microphysics Scheme       | WSM-3    | WSM-3    | WSM-3    |
| Cumulus Scheme            | Kain-Fritsch | Kain-Fritsch | Kain-Fritsch |

2.2 Observational Data

The data used in this study is rainfall data from the Automatic Rain Gauge (ARG) Waduk Mrica because this study needs hourly temporal scale rainrate data around the landslide location (table 7). Then this data is processed into hourly rainfall graphs and compared with graphs of instability indices, vorticity, vertical velocity, and divergence output from WRF-ARW.
Table 7. Rain rate which was recorded by ARG Waduk Mrica Banjarnegara

| Jam (UTC) | Rain rate (mm/hour) | Category       |
|-----------|---------------------|----------------|
| 1         | -                   | -              |
| 2         | -                   | -              |
| 3         | -                   | -              |
| 4         | -                   | -              |
| 5         | -                   | -              |
| 6         | -                   | -              |
| 7         | 1,8                 | Slight Rain    |
| 8         | 15,2                | Heavy Rain     |
| 9         | 1,6                 | Slight Rain    |
| 10        | -                   | -              |
| 11        | 31                  | Heavy Rain     |
| 12        | 29,4                | Heavy Rain     |
| 13        | 14,2                | Heavy Rain     |
| 14        | 2,8                 | Slight Rain    |
| 15        | 6,6                 | Moderate Rain  |
| 16        | 2,2                 | Slight Rain    |
| 17        | -                   | -              |
| 18        | -                   | -              |
| Total     | 104.8               |                |

3. Results and Discussion

Table 7 shows that light to heavy rainfall from noon to night is one of the factors causing landslides on June 18, 2016. According to rainfall data from that ARG, rain occurred from 07 to 16 UTC, which is equivalent to 14.00 until 23:00 LT. The atmospheric instability indices is a good measure in indicating the existence of bad weather [2], then this section will explain WRF-ARW model output (per hour) in representing conditions atmospheric stability at the landslide location (Grumbul Gunung Duwur, Gumelem Kulon Village).

On the instability indices, each index has varying values. Following are the indices from 00 to 18 UTC: LI from -5 to 1, CAPE from 0 to 2048 J/kg, KI from 33 to 39, and TT from 41 to 45. More detailed discussion hourly indices will be separated to 2 distribution, they are: rainy noon period (7 to 9 UTC) and rainy night period (11 to 16 UTC). Comparison charts of rain rate and indices can be seen in figure 2.

In figure 2, it can be seen that the maximum instability of atmosphere occurred in the rainy noon period: in 2 hours before the 6 UTC (for LI and CAPE) and during the rain (for TT and KI). Following are the respective indices sequentially: -5 to 0 for LI, 2048 to 169 J/kg for CAPE, 39 to 33 for KI, and 43 to 41 for TT. Those indices value indicate the weak to moderate convectivity exsistance. As for the rainy noon period of the day, the indices are less representative in describing the conditions of heavy rainy conditions. This is indicated by LI values between 1 to -1, CAPE between 0 to 337 J/kg, KI between 33 to 35, and TT between 41 and 43. The cause of model’s less representative in describing night convectivity still need to be studied.
Based on the research in Ambon (Indonesia) [9], when there are cumulonimbus clouds, the vertical velocity of the air is negative which indicates there is an uplifting of the air mass. Negative vorticity values also cause cyclonic air movement and trigger the formation of cumulonimbus clouds. While the air divergence condition vertically shows a value that tends to be positive, namely compressing air masses plays less role.

This section will explain the parameters of vorticity, divergence, and vertical velocity during landslides on June 18, 2016. The following is the explanation. From figure 3, it can be seen that between 06 and 09 UTC the vorticity parameter shows a value of $-1.5 \times 10^{-3}$ to $-0.3 \times 10^{-3}$ from the 900 mb to 200 mb layer. This shows the presence of clouds. Convection causes rain between 06 and 09 UTC according to figure 2, but in the rainy night period, the value of vorticity obtained is not significant. This is indicated by the value 0 /s.

From figure 4, it can be seen that between 06 and 09 UTC the divergence parameter shows the value of $-2.5 \times 10^{-3}$ to $-0.5 \times 10^{-3}$ from the 900 mb to 750 mb layer. This shows the growth of convective clouds causing rain between 06 to 09 UTC in accordance with figure 2 a, while supporting figure 3. However, in the rainy night period, the divergence value shows the value of $-0.5 \times 10^{-3}$ (11 to 11:30 UTC) and 0 /s (11:30 to 16 UTC). When taken with a vorticity value at the same time, the factor is recognized.

From figure 5, it can be seen that between 06 and 09 UTC the vertical vorticity parameter shows a value of $0.5 \text{ m/s}$ to $5 \text{ m/s}$. This also shows the growth of clouds. Convection causes rain between 06 and 09 UTC. This is in accordance with the definition of literature which explains the phase of climate change will be updated by updraft. During the night rain period (11 to 16 UTC), the vertical velocity values are 0 m /s.
From comparing with figure 2a, the results show that the parameters of vorticity, divergence, and vertical velocity cannot represent atmospheric conditions when it rains between 11 and 16 UTC. It still need more study to know the reason of this result (the inability of the model to properly simulate parameters at night).

Figure 3. Vorticity during heavy rain that triggered landslides on June 18, 2016

Figure 4. Divergence during heavy rain that triggered landslides on June 18, 2016
4. Conclusions

From the study that has been done, it can be concluded that instability index shows that the activity is already effective 1-2 hours before heavy rain. The value of LI, CAPE, KI, and TT per hour are -2 to 1; 0 to 756 J/kg; 33 to 39; and 41 to 45, respectively. The condition of the atmosphere during the formation of cumulonimbus had been seen 30 minutes until 1 hour before heavy rain occurred. This is signified by the vorticity of the dynamic atmosphere of the Banjarnegara, it is known that the formation of cumulonimbus clusters has been seen 30 minutes to 1 hour before heavy rain occurs. This is indicated by vorticity of -0.3 x 10⁻³ /s to -1.5 x 10⁻³ /s, divergence of -0.5 x 10⁻³ to -2.5 x 10⁻³ /s, and vertical velocity of 0.5 m/s to 5 m/s. Each parameter fluctuates according to the stage of cloud development being undertaken (the phase of growing, maturing, or dissipation).

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