Estimation of the spatial distribution of maximum PM10 and PM2.5 concentration in Bandung City and surrounding countries using WRF-Chem Model (case study in July and October 2018)

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Abstract. Bandung is one of big cities in Indonesia with high activities on industrial and transportation that will increase the air pollutant emission and causes adversely affect the public health. Based on that matter, monitoring of air pollutant concentration is urgently needed to predict the direction of pollutant dispersion and to analyze which locations are vulnerable to maximum exposure of the pollutant. Field monitoring of air pollutant concentration needs much time and high cost, but modeling could help for this. One of the models that can be used to predict the direction of pollutant distribution is the Weather Research Forecasting/Chemistry (WRF-Chem) model, which is a model that combines meteorological models with air quality models. The output of the WRF-Chem running model on July and October 2018, which has been analyzed visually, showed the dispersion pattern of PM10 and PM2.5 is spread mostly to the west, northwest, and north following the wind direction. According to the output of the WRF-Chem model, Bandung Kulon is the most polluted subdistrict by PM10 and PM2.5 with an exposure frequency of 22 hours (PM10), 24 hours (PM2.5) on July 2018 and 19 Hours (PM10), 14 hours (PM2.5) on October 2018. The correlation value for meteorological parameters is quite high in July 2018 (R = 0.9 for wind speed and R = 0.82 for air temperature). So based on the meteorological factor, WRF-Chem model can be used to predict the direction of pollutant distribution.

Keywords: Bandung, maximum concentration, particulate, pollutant dispersion, WRF-Chem

1. Introduction

Bandung is one of the big cities in Indonesia, which has a high number of activities on industrial and transportation. This condition is supported by the number of tourist destinations, including culinary and fashion tourism, which causes the high level of transportation density in Bandung, especially on weekends. The high level of transportation and industrial activities will increase the air pollutant emission and causes adversely affect public health [1].

Furthermore, the level of air pollution is also influenced by meteorological factors and regional topographical conditions. Bandung City with a basin topography causes the spread of air pollutants in this region to have unique characteristics. These topographical conditions make the air exchange system not ideal for the diffusion and dispersion processes of pollutants. The less ideal process of diffusion and dispersion of pollutants occurred due to the formation of a layer in the city of Bandung which trapped and accumulated on the surface [2].

According to United Nations Environmental Program (UNEP), suspended particulate matter (PM) is the most significant source of air pollution, affecting air pollution levels in major cities in the world.
[3]. Fine particulate can be dangerous to health because they can enter the respiratory system. Even excellent particles below 2.5μm can enter the lungs and cause more severe problems [4].

However, the available data regarding the distribution and concentration of particulates in Bandung city, especially in 2018, is not good enough. The process of monitoring air quality to get the distribution of pollutant concentrations is not cheap and and takes much time, that’s why it requires modeling assistance. One of the models that can be used to predict the direction of pollutant distribution is the Weather Research Forecasting/Chemistry (WRF-Chem) model, which is a model that combines meteorological models with air quality models.

2. Methodology

| No. | Type of data | Data source |
|-----|--------------|-------------|
| 1.  | Global Forecasting System Data (GFS) 0.5° x 0.5° spatial resolution (global meteorology data) | National Oceanic Atmospheric Administration (NOAA) |
| 2.  | Global emission data (EDGAR) | Emission Database for Global Atmospheric Research (EDGAR) |
| 3.  | Bandung City air temperature data in July and October 2018 | National Institute of Aeronautics and Space of Indonesia (LAPAN) Bandung |
| 4.  | Data (speed and direction wind, air temperature, and rainfall) Bandung in July and October 2018 | BMKG online data (Bandung Geophysical Station) |

2.1 Analysis of pollutant dispersion using the WRF-Chem model.

Before running the WRF-Chem model, first, download the Global Forecasting System (GFS) data and EDGARV4 global emissions data from the National Oceanic and Atmospheric Administration (NOAA) website. After downloading the GFS and global emissions data, we can process the running of the WRF-Chem model. The WRF-Chem model consists of 3 main stages, the pre-processing stage using the WRF Preprocessing System (WPS) program, the processing or meteorological analysis, and atmospheric chemistry using Weather Research Forecasting (WRFV3), and post-processing using the ARWpost program.

The pre-processing using the WPS program consists of 3 stages, which are geogrid, ungrid, and metgrid processes. The geogrid stage is a domain simulation process that includes the layout of latitude, longitude, grid-scale, and terrestrial data interpolation. The ungrid stage is the process of adding GFS data which contains meteorological data. The metgrid stage is the stage of combining the results of the geogrid and ungrid processes. The metgrid stage functions to interpolate meteorological data (from ungrid) into a simulated domain grid arranged at the geogrid stage. The output of the WPS program is the input for meteorological processing in the processing stage. At the processing stage, the initial input of EDGARV4 global emission conditions is entered, which is the basis for estimating the distribution of pollutants. The last stage is the post-processing stage using ARWpost to produce an output file in the form of a .nc file which is converted into .ctl and .dat formats so that it can be analyzed visually and numerically using the GrADS program [5].
| Parameter | Skema Parameter |
|-----------|----------------|
| Microphysics | Lin *et al.* scheme |
| Boundary-Layer scheme | Yonsei University Scheme |
| Longwave radiation | Rapid Radiative Transfer Model (RRTMG) scheme |
| Shortwave radiation | Rapid Radiative Transfer Model (RRTMG) scheme |
| Chem_opt | Regional Acid Deposition Model V.2 (RADM2) chemistry and GOCART aerosols |
| Emiss_opt | GOCART simple emission |
| Photolysis scheme | Madronich photolysis TUV |

### 2.2 Analysis of model visualization result.

The data analyzed was the output data from the WRF-Chem modeling extracted and visualized using the GrADS program. The results of visualization using GrADS are used to perform spatial and temporal analysis. The data visualized in the spatial map is PM$_{10}$ and PM$_{2.5}$ hourly data during the 312 hour modeling period in July and October 2018 to see the distribution of the dispersion of the pollutants in Bandung City. The output value extraction of the model is adjusted to the coordinates of the location of the observation data from Bandung Geophysical Station and LAPAN Bandung. The data extracted is hourly data of PM$_{10}$ and PM$_{2.5}$, which are averaged into hourly diurnal data to see the diurnal fluctuation pattern.

### 2.3 Pollutant concentration analysis.

Analysis of the direction of the dispersion pollutant concentrations was carried out to see which locations are vulnerable to maximum exposure of the pollutant to be used as references and recommendations for regional policies. Pollutant dispersion analysis was continued by analyzing the maximum concentration of each pollutant in areas potentially exposed to the maximum concentration. The maximum concentration in this study is the highest concentration at the same time, spatially at every hour during the modeling period, which is 312 hours. Estimates of areas indicated to have the potential for exposure to maximum pollutant concentrations are based on the number of periods of exposure with a minimum exposure period of once (hour) a day during the modeling period [6, 7].

### 2.4 Comparative analysis of the outputs of the WRF-Chem model

The ability of the WRF-Chem model in predicting meteorological conditions in Bandung can be tested through correlation analysis and significance testing. This analysis was carried out by comparing the output value of the WRF-Chem model that was extracted with the results of the observations from the National Institute of Aeronautics and Space of Indonesia (LAPAN) Bandung City and BMKG online data. The type of data compared is the daily temperature and wind speed data for 312 hours. Comparative analysis was performed by calculating the correlation coefficient value and real test using equations [1] and [2] below [8].

- **Correlation coefficient**

  $$ r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 (y_i - \bar{y})^2}} \quad \ldots \quad [1] $$

  - $r$ = correlation coefficient
  - $x_i$ = model output value
  - $\bar{x}$ = average value output model
  - $y_i$ = observed value
  - $\bar{y}$ = average observed value
• Significance test

\[ t = \frac{r}{\sqrt{1 - r^2}} \quad \ldots \quad [2] \]

- \( n \) = lots of data
- \( r \) = correlation coefficient
- \( t \) table <count, the variable is significant

![Research flow diagram](image)

**Figure 1** Research flow diagram.

3. Results and Discussion

3.1 Particulate dispersion pattern (PM\(_{10}\))

The output of WRF-Chem model, which has been analyzed visually, showed that the distribution of PM\(_{10}\) in Bandung City is spread out following the local wind direction. According to Pratama and Sofyan research [9], the wind circulation in Bandung is greatly influenced by local, convective, and temperature gradient factors. This pattern is spread mainly to the west, northwest, and north following the wind direction (Figure 2). The wind direction that is spread mainly to the west, northwest, and north is due to the influence of valley winds and mountain winds from the outskirts of Bandung, which is a mountainous area. During the night and in the morning, the wind blows to the northwest, north and south of Bandung, meanwhile in the afternoon and evening, the wind blows to the west or east of Bandung at most. Based on the results of the model output, the maximum concentration of PM\(_{10}\) in July or October is around the West and Southwest Bandung areas, which are quite close to the Padalarang industrial area in the West Area of Bandung Regency and several toll gates which are the access of in or out to Bandung City. Industrial activities, transportation, and other activities play a significant role in increasing the emission of pollutants into the air, which causes air pollution [10].
3.2 Particulate dispersion pattern (PM$_{2.5}$)

The output of the WRF-Chem model in July and October 2018 (with a modeling period of 312 hours for each month) showed that the particulate (PM$_{2.5}$) has a dispersion pattern that is almost the same as the particulate (PM$_{10}$). PM$_{2.5}$ has almost the same characteristics as PM$_{10}$, only it has a smaller particle size (less than 2.5 microns). The dispersion of PM$_{2.5}$ spread mainly from east to west or south and southeast to north following the wind direction (Figure 3). The wind speed and direction will affect the dispersion of pollutants (the transport process) and determine which direction and how high the pollutant concentration is [11]. According to the output of the WRF-Chem model, west and southwest Bandung areas are the most polluted area by PM$_{10}$ and PM$_{2.5}$.

Based on BPS data [12], Bandung Kulon and Babapak Ciparay subdistricts in the Southwest of Bandung, are the districts with the highest population densities, with 144.89 and 149.61 thousand people. These two subdistricts are also near to the Bandung Regency area, which is the access to come and out of the City and Regency of Bandung (Marga Asih, Katapang, and Soreang). Like PM$_{10}$, the concentration of PM$_{2.5}$ is strongly influenced by the number of inhabitants (population) and the influence of environmental physics, like meteorological factors and geography of the city. The high daily activities of the population such as smoking, transportation activities, industrial activities, and home activities affect the concentration of PM$_{2.5}$ exposed in the air. Besides, meteorological factors, topography, and city climatic conditions such as rainfall, changes in seasons, and wind direction also affect the distribution and density of pollutants in the air [13].

3.3 Analysis of Particulate Concentration (PM$_{10}$) in 312 hours

Overall, PM$_{10}$ concentration in Bandung city is still below the national Ambient Air Quality Standard (BMUA) PM$_{10}$ in 24 hours which is 150 μg / m$^3$ (Figures 4a and 4b). PM$_{10}$ concentration has increased at night and decreased during the day. Increased concentration of PM$_{10}$ at night and early morning occurred due to stable atmospheric conditions so that pollutants tend to be trapped and accumulate on the surface [14]. The highest rates of PM$_{10}$ concentration at Bandung Geophysical Station and PSTAN
LAPAN occurred on the first and second days of the July 2018 modeling period and the twelfth and thirteenth day of the October 2018 modeling period.

3.4 Analysis of Particulate Concentration (PM$_{2.5}$) 312 Hours

The output of the WRF-Chem model analyzed showed that overall PM$_{2.5}$ concentration in Bandung was still below the national Ambient Air Quality Standard (BMUA) PM$_{2.5}$ in 24 hours, which is 65 $\mu$g/m$^3$ (Figures 5a and 5b). Meanwhile, the PM$_{2.5}$ concentration in July and October 2018 had the same diurnal fluctuation pattern as the diurnal fluctuation pattern of PM$_{10}$ concentration increasing at night and decreasing during the day. Based on the simulation results, it was also showed that the PM$_{2.5}$ concentration in Bandung City in July and October 2018 was relatively stable (have not a significant change in concentration) during the modeling period. This conditions may be due to the topographical conditions of Bandung city, which is surrounded by mountains, causing Bandung to have poor air circulation, especially the circulation of air pollutants. The poor air circulation causes pollutants in Bandung to become trapped in the Bandung basin area.

3.5 Diurnal Fluctuation Pattern of Particulate Concentration (PM$_{10}$)

The diurnal fluctuation pattern of PM$_{10}$ concentration from the WRF-Chem model in July and October 2018 at the Bandung Geophysics Station and PSTA LAPAN showed that the particulate concentration increases at night and reaches the maximum value in the early morning then decreases during the day. The maximum concentration pattern occurs around 03.00 - 05.00 WIB with average concentration values of 132.2 $\mu$g/m$^3$ (July) and 128.7 $\mu$g/m$^3$ (October) at Bandung Geophysical Station and 162 $\mu$g/m$^3$.
(July) and 129.9 \mu g/m^3 (October) at the PSTA LAPAN (Picture 6). Generally, pollutant concentrations will increase in the morning and decrease during the day due to the influence of air temperature, radiation, and wind speed. The air temperature and low wind speed in the morning cause the particles in the air to tend to settle to the surface. On the other hand, radiation, air temperature, and wind speed tend to be high during the day, resulting in relatively unstable atmospheric conditions, allowing particles to move or be lifted upward [15]. However, due to the topography of Bandung, which is like a basin and land cover, which is composed of heat-conducting material, the chances of inversion at night, morning, and afternoon (cloudy) in Bandung City are also high. The high chance of inversion causes pollutants to settle and only spread horizontally on the surface following the existing topography [16].

![Figure 6](image)

**Figure 6** Diurnal fluctuation of PM$_{10}$ concentration based on the output model in July and October 2018 at Bandung Geophysical Station and PSTA LAPAN.

The results of the correlation analysis of the meteorological parameters of wind speed and temperature of the model output to the PM$_{10}$ concentration of the model output, show the correlation coefficient value is negative except for the correlation coefficient value of wind speed at the Bandung Geophysics Station in July 2018 which is 0.195 (table 2). A negative correlation indicates that every time the wind speed and air temperature are increase, the PM$_{10}$ concentration in the air will decrease.

**Table 3** Correlation of meteorological parameters (wind speed and air temperature) to PM$_{10}$ concentration based on the output model.

| Location                | July        |          | October       |          |
|-------------------------|-------------|----------|---------------|----------|
|                         | Wind velocity| Air temperature| Wind velocity| Air temperature|
| PSAT LAPAN              | -0.146      | -0.882 * | -0.729 *      | -0.926 * |
| Bandung Geophysical Station | 0.195      | -0.861 * | -0.454 *      | -0.907 * |
3.6 Diurnal Fluctuation Pattern of Particulate Concentration (PM$_{2.5}$)

The maximum concentration pattern of PM$_{2.5}$ in July and October 2018 occurred around 03.00 - 05.00 WIB with an average concentration value of 36.69 $\mu$g/m$^3$ (July) and 37.32 $\mu$g/m$^3$ (October) at Bandung Geophysical Station and 46.78 $\mu$g/m$^3$ (July) and 38.92 $\mu$g/m$^3$ (October) in PSTA LAPAN (Figure 7).

The output of the WRF-Chem model also shows that PM$_{2.5}$ concentration is increasing at night and reaches the maximum value in the early morning then decreases during the day. PM$_{2.5}$ has the same fluctuation pattern as PM$_{10}$ because these two particulates have almost the same characteristics.

![Figure 7: Diurnal fluctuation of PM$_{2.5}$ concentration based on the output model in July and October 2018 at Bandung Geophysical Station and PSTA LAPAN.](image)

Fluctuations in the concentration of PM$_{2.5}$ in the air are strongly influenced by the current meteorological conditions. Generally, particulate concentrations reach their maximum value when the air temperature and wind speed are low. Based on the results of the model output, the correlation coefficient of air temperature and wind speed parameters to the PM$_{2.5}$ concentration shows a negative value at the Bandung Geophysical Station and the LAPAN Observation Station except for the correlation coefficient value of wind speed at the Bandung Geophysical Station in July 2018, which is 0.191 (table 3). A negative coefficient value shows an inversely proportional relationship between air temperature and wind speed to the PM$_{2.5}$ concentration. Increasing air temperature and wind speed will have an impact on reducing PM$_{2.5}$ concentrations.

| Location               | July Wind velocity | July Air temperature | October Wind velocity | October Air temperature |
|------------------------|--------------------|----------------------|-----------------------|-------------------------|
| PSAT LAPAN Bandung     | -0.151             | -0.879 *             | -0.729 *              | -0.934 *                |
| Geophysical Station    | 0.191              | -0.861 *             | -0.452 *              | -0.917 *                |
3.7 Correlation Analysis of WRF-Chem Model Output to Observational Data

The results of the correlation analysis of the meteorological parameters (wind speed and air temperature) from the model output to the observational data at the Bandung Geophysical Station and the LAPAN Observation Station, showed a pretty excellent and significant correlation value at $\alpha = 0.05$ in July. The correlation coefficient values of air temperature at the LAPAN Observation Station in July and October were 0.82 and 0.05, while at the Bandung Geophysical Station were 0.6 and 0.38 (Table 5). The value of the wind speed correlation coefficient at Bandung Geophysical Station in July and October 2018 is 0.9 and 0.45 (Table 5).

Table 5 Correlation of the meteorological parameters (wind speed and air temperature) from the model output to the observational data (significant at $\alpha = 0.05$).

| Location                  | July |          | October |          |
|---------------------------|------|----------|----------|----------|
|                           | Wind velocity | Air temperature | Wind velocity | Air temperature |
| PSAT LAPAN Bandung Geophysical Station | - | 0.82 * | - | 0.05 |
| Geophysical Station      | 0.9 * | 0.6 * | 0.45 | 0.38 |

3.8 Estimates Areas Vulnerable Exposed to Maximum Concentrations of $PM_{10}$ and $PM_{2.5}$

According to the output of the model, almost all districts in Bandung City have the potential to be exposed to the maximum concentration of $PM_{10}$ and $PM_{2.5}$. The model results showed that in July 2018, 24 subdistricts had the potential to be exposed to the maximum concentration of $PM_{10}$ and 26 subdistricts that had the potential to be exposed to the maximum concentration of $PM_{2.5}$ with different frequencies. Meanwhile, in October 2018, 23 subdistricts had the potential to be exposed to the maximum concentration of $PM_{10}$, and 18 subdistricts that have the potential to be exposed to the maximum Bandung Kulon and Babakan Ciparay are the most polluted subdistrict by $PM_{10}$ and $PM_{2.5}$, either in July or October 2018 concentration of $PM_{2.5}$ with different frequencies (Table 5).

Model simulation results showed that Bandung Kulon and Babakan Ciparay are the most polluted subdistrict by $PM_{10}$ and $PM_{2.5}$, either in July or October 2018. The frequency of exposure $PM_{10}$ maximum concentrations in Bandung Kulon and Babakan Ciparay subdistricts during the running model period in July are 22 hours and 19 hours. During the running model period in October are 19 hours and 9 hours (Table 5). The highest maximum $PM_{10}$ concentration during the running model period in July in the districts of Bandung Kulon and Babakan Ciparay reached 545 $\mu g/m^3$ in both subdistricts, while in the October running model period it reached 458 $\mu g/m^3$ in both subdistricts. This value exceeds Ambient Air Quality Standards (BMUA) $PM_{10}$ in 24 hours which is 150 $\mu g/m^3$.

The frequency of exposure of maximum $PM_{2.5}$ concentrations in Bandung Kulon and Babakan Ciparay during the running model period in July is 24 hours and 19 hours, while during the running model period in October are 17 hours and 8 hours (Table 5). The highest maximum $PM_{2.5}$ concentration during the running model period in July in Bandung Kulon and Babakan Ciparay reached 191 $\mu g/m^2$ in both subdistricts, while during the running model period in October, it reached 209 $\mu g/m^2$ in both areas. This value exceeds Ambient Air Quality Standards (BMUA) $PM_{2.5}$ in 24 hours which is 65 $\mu g/m^3$.

Overall, $PM_{10}$ and $PM_{2.5}$ concentrations in Bandung City is still below the National Ambient Air Quality Standard (BMUA). However, based on the results of the running model for 312 hours at two different months, there were several times when the concentration of the two pollutants exceeded the national BMUA value. High concentrations of $PM_{10}$ and $PM_{2.5}$ at certain times can be caused by high social activity at or before that time. High concentrations can affect public health. Therefore, an intense effort to monitor the air quality is needed in some areas which prone to the exposure of maximum concentrations as a form of control so that the concentration of pollutants in the air is still below the national BMUA value. Intense observation and information on air quality in areas that vulnerable to
exposure to maximum concentrations are also needed so that people can be more careful in their outdoor activities.

Table 6 Areas potentially exposed to the maximum concentrations of PM$_{10}$ and PM$_{2.5}$ based on the WRF-Chem output.

| Region (subdistrict) | Total exposures (hours) over 312 hour |
|----------------------|--------------------------------------|
|                      | July 2018 |          | October 2018 |
|                      | PM$_{10}$ | PM$_{2.5}$ | PM$_{10}$ | PM$_{2.5}$ |
| Bandung Kulon        | 22        | 24        | 19        | 17        |
| Babakan Ciparay      | 19        | 19        | 9         | 8         |
| Bojongloa Kaler      | 17        | 13        | 2         | 5         |
| Bojongloa Kidul      | 16        | 12        | 4         | 8         |
| Astanaanyar          | 15        | 9         | -         | -         |
| Regol                | 10        | 8         | 1         | -         |
| Lengkong             | 8         | 5         | -         | -         |
| Bandung Kidul        | 5         | 3         | 3         | 4         |
| Stone Fruit          | 8         | 5         | 3         | 2         |
| Rancasari            | 6         | 6         | 5         | 3         |
| Gedebage             | 5         | 7         | 5         | 1         |
| Cibiru               | 1         | 3         | 6         | 3         |
| Panyileukan          | 3         | 2         | 3         | 2         |
| Ujungberung          | -         | -         | 3         | 1         |
| Cinambo              | 5         | 6         | 1         | -         |
| Arcamanic            | 6         | 4         | -         | -         |
| Antapani             | 4         | 3         | -         | -         |
| Mandalajati          | -         | -         | 1         | 1         |
| Kiaracondong         | 6         | 4         | -         | -         |
| Batununggal          | 6         | 3         | -         | -         |
| Bandung wells        | 5         | 3         | -         | -         |
| Andir                | 10        | 8         | 2         | 1         |
| Cicendo              | 10        | 8         | 4         | 2         |
| Bandung Wetan        | 1         | 1         | 1         | -         |
| Cibeunying Kidul     | -         | -         | 1         | 1         |
| Cibeunying Kaler     | -         | -         | 1         | -         |
| Small hole           | 1         | 1         | 2         | -         |
| Sukajadi             | 1         | 1         | 1         | 1         |
| Sukasari             | -         | 1         | 6         | 1         |
| Cidadap              | -         | 1         | 2         | 1         |

4. Conclusion

The results of the WRF-Chem model, which were visually analyzed, show that the PM$_{10}$ and PM$_{2.5}$ dispersion patterns in Bandung City are dominantly distributed to the west, northwest and north following the wind pattern. Meanwhile, pollutant sources are dominated by outside the city of Bandung or areas with high population activity. The results of running the model during the modeling period in July and October 2018 (with a modeling period of 312 hours for each month) showed that in July 2018, 24 subdistricts had the potential to be exposed to the maximum concentration of PM$_{10}$ and 26 subdistricts that could potentially be exposed to the maximum concentration of PM$_{2.5}$. Meanwhile, in October 2018, 23 subdistricts have the potential to be exposed to the maximum concentration of PM$_{10}$ and 18 subdistricts that have the potential to be exposed to the maximum concentration of PM$_{2.5}$. The highest maximum PM$_{10}$ concentration during the running model period in July 2018 at Bandung Kulon and
Babakan Ciparay subdistrict reached 545 µg/m³ in both areas, while during the running model period in October 2018 reached 458 µg/m³ in both areas. The highest maximum PM₂.₅ concentration during the running model period in July at Bandung Kulon and Babakan Ciparay subdistrict reached 191 µg/m³ in both areas, while during the running model period in October 2018 reached 209 µg/m³ in both areas. Based on that matter, Bandung Kulon and Babakan Ciparay are the most polluted subdistrict by PM₁₀ and PM₂.₅, either in July or October 2018. The correlation value for meteorological parameters is quite high, especially in July 2018 (R = 0.9 for wind speed and R = 0.82 for air temperature). So based on the meteorological factor, WRF-Chem model can be used to predict the direction of pollutant distribution.

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