The analysis of skin surface temperature and water vapor on volcanic eruption (case study: Mt. Kelud)

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Abstract. The post-volcanic eruption can be one of main factors in climate variability. The last incident of Kelud eruption had been occurred at 22:50 WIB, 13 February 2014. This paper aims to analyze the climatology of skin surface temperature (SKT), total column water vapor (TCWV), and mixing ratio at 500 mb before eruption from ERA-Interim and the processes before and after eruptions from Weather Research Forecasting (WRF) model simulation. Global Forecast System (GFS) data was used for WRF as initial condition and boundary condition, while ERA-Interim reanalysis dataset was used as a comparison. Bias correction was used to adjust WRF output with ERA-Interim on SKT and TCWV. SKT interval between day and night ranges from 21-23°C (WRF) and 12°C (ERA-Interim). There are 56 SKT WRF and 5 SKT ERA-Interim anomalous day before eruption. TCWV anomalies from WRF have consistent variation with ERA-Interim and there are 2 TCWV anomalies exceed 2 standard deviation. There were no TCWV anomalies detected on ERA-Interim, but were detected on WRF 2 days before and 3 days after eruption above 2 standard deviations. Mixing ratio shows a downward trend before and after the eruption.

Keywords: aerosol, ERA-Interim, mixing ratio, total column water vapor, WRF

1. Introduction

Indonesia is in the Ring of Fire. This area often experiences with earthquakes and volcanic eruptions surrounded by the Pacific Ocean basin. The biggest volcanic eruptions have ever occurred in Indonesia such as Tambora (1815) and Krakatoa (1883). The strength of the eruption of those volcanoes have an impact on changes in regional and global climate conditions [1].

Volcanic Explosivity Index (VEI) is a strength of volcano scale based on pyroclastic material volume that released during the eruption. The relative size of this explosive strength can be used to compare the explosive forces of volcanoes that occurred in the past. The VEI scale is able to provide an analysis of the frequency of volcanic eruptions based on their explosive power levels [2].

Post-volcanic eruptions can be one of main factors for climate variability [1]. Large number of particles and gases which were released from volcanic eruptions enter the atmosphere. The main gases which released from volcanoes are sulfide acid (H₂S) and sulfur dioxide (SO₂). SO₂ and H₂S gases are oxidized to sulfuric acid in the form of gas (H₂SO₄(g)). Sulfuric acid can affect several components of
the global climate system, such as rain, albedo, air temperature, and radiation. Short-wave radiation from sunlight is blocked by sulfate aerosols trapped in the stratosphere, causing a decrease in air temperature in the troposphere. Volcanic halogen compounds which released by volcanoes (e.g. HCl) can be important parameters in changing the composition of ozone in the stratosphere [1]. For example, the Mount Pinatubo eruption in the Philippines in June 1991 caused a maximum decrease in air temperature in the troposphere of 0.4 K [3,4] and an increase in stratospheric temperature of 2-3 K [5]. In addition, a decrease in ozone concentration in the stratosphere can significantly reduce rainfall [6], runoff [7], and sea level [8].

Mount Kelud has erupted seven times since May 22nd, 1991. The last Kelud eruption (VEI 4) was on February 13th, 2014 [9]. SO$_2$ gas by the Kelud eruption reached to 26 km and the volcanic ash spread to 240 km to the west [10]. As a result, around 76,000 people around the Kelud area were evacuated [11].

Various studies on the climate impact after volcanic eruptions have been carried out [12–15]. Timmreck [1] introduced the modeling climatic effects after large explosive volcanic eruptions. The empirical model with surface air temperature parameter was created to detect volcanic eruptions [16]. Studies on skin surface temperature, total column water vapor, SO$_2$, and Dimethyl sulfide parameters were analyzed to detect eruption on 12 volcanoes between 2002-2017, including events in Indonesia such as Kelud (2014), Merapi (2010), and Agung (2017) [17].

This paper aims to analyze the climatology of skin surface temperature, total column water vapor, and mixing ratio at 500 mb before eruptions from ERA-Interim and the processes of those parameters before and after eruptions from WRF model simulation.

2. Methodology

2.1. Study Area
Mount Kelud (7.93°LS; 112.308°BT) is one of the active strato-type-volcanoes in Indonesia located in the Districts of Kediri, Blitar, Malang, East Java Province. The altitude of Mount Kelud is 1731 m. At the end of 2013, Kelud's activities had increased, but then stabilized. Kelud's activity then increased again so that on 2 February 2014 his status was raised from normal to alert. Kelud’s activity status was increased to Level 4 that occurred on 13 February 2014 21:15 West Indonesia Time (WIB). At 22:50 WIB, the first eruption was happened [28].

The Kelud eruptions value is 4 which is explosive. Volcanic ash from Mount Kelud is spread from the location of the incident to West Java. The impact of the Kelud eruption caused several flight schedules to be delayed, 7 people died, 70 people experienced respiratory infections, damaged agricultural land, and four of five seismic stations were destroyed [9].

The distribution of volcanic ash from the Kelud eruption can be detected from brightness temperatures with satellite images, such as Multi-purpose Transmission Satellite (MTSAT) [10]. The impact of volcanic ash can affect climate conditions as described by Timmreck [1], in addition to damage to building materials and decreasing air quality [29]. Therefore, the five grid sample points (figure 2) located in the north, south, west, east, and around the Mount Kelud crater were selected to see the condition of SKT, TCWV, and mixing ratio at 500 mb before and after the eruption assuming events on WRF and ERA-Interim selected is 13 February 2014 at 15:00 UTC (22:00 WIB). In this paper, we only show the results on fifth grid sample.

2.2. Data
The data used here are 3 hours Global Forecast System (GFS) analysis (0.5° x 0.5°) and ERA-Interim by the European Center for Medium-Range Weather Forecasts (ECMWF) (0.05° x 0.05°) 3 hours of skin surface temperature (SKT), mixing ratio at 500 mb, and total column water vapor (TCWV) parameters. GFS analysis data was selected with the period from 00:00 UTC 14 January 2014 to 00:00 UTC 16 March 2014, while ERA-Interim data from 00:00 UTC 1 January 1984 to 21:00 UTC 15 March 2014.
2.3. Model and Simulations

Advanced Research version of the Weather Research Forecasting Model (ARW, version 4.0.2) was used in this research, including Noah Land Surface Model [18]. Type of topography and land cover were provided as defaults this model. Land cover types was used from MODIS that has 30s (~900 m) grid spacing. Initial condition and boundary condition used here from GFS analysis. Parameterization scheme (table 1) in this study were similar in Stuefer et al. [19]. The domains selected here are four domains. D01 has 15 x 15 grid points with 20 km grid spacing; D02 has 28 x 28 grid points with 6.67 km grid spacing; D03 has 71 x 61 grid points with 2 km grid spacing; D04 has 91 x 91 grid points with 0.67 km grid spacing. Four domains have 35 vertical layers from the ground surface to the pressure level of 50 mb. Parameterization of cumulus was used only in D01. The coverage area can be seen in figure 1.

![Figure 1. WRF domain selection](image)

| Processes                  | Parameterization schemes                      |
|----------------------------|-----------------------------------------------|
| Microphysics               | WRF Single-Moment 5-Class Scheme [20]          |
| Longwave radiation         | Rapid Radiative Transfer Model [21]           |
| Shortwave radiation        | Goddard shortwave radiation scheme [22]       |
| Cumulus parameterization   | Grell-Devenyi [23]                            |
| Planetary boundary layer   | Mellor-Yamada-Janjic [24]                     |

Table 1. WRF model parameterization schemes

Computations were performed during the period from 00:00 UTC 14 January 2014 to 00:00 UTC 16 March 2014. The simulation is divided into two events, before (00:00 UTC 14 January 2014 to 00:00 UTC 14 February 2014) and after eruptions (00:00 UTC 14 February 2014 to 00:00 UTC 16 March 2014).

2.4. Procedure

Parameter of TCWV in WRF must be converted from mixing ratio each vertical layer. The conversion from mixing ratio to TCWV can be seen with the following equation [25]:

\[
W = -\frac{1}{g} \int_{p(x=0)}^{p(z)} dq dp \equiv -\frac{1}{g} \sum_{i=1}^{N} \bar{q}_i \Delta p
\]

\[
\bar{q}_i = \frac{q_i + q_{i-1}}{2}
\]
where $g$ is gravitational acceleration (9.81 m/s$^2$), $q$ is the specific humidity (kg/kg), $p(z)$ is air pressure at height $z$, $p(z = 0)$ is the air pressure on the ground surface, $N$ is the number of heights, and $w$ is the mixing ratio.

WRF output compared with ERA-Interim data from 3 parameters (SKT, TCWV, and mixing ratio). Five samples were selected for analysis to compare between WRF and ERA-Interim. ERA-Interim (only for SKT and TCWV) from 1 January 1984 to 31 December 2013 were averaged climatologically for the specific day and time (for example SKT on 1 January 1984 00:00 UTC, 1 January 1985 00:00 UTC, 1 January 2013 00:00 UTC). ERA-Interim data from 14 January 2014 to 16 March 2014 was used for WRF as comparison. The values of the year with the eruption which exceed 2 standard deviations are then tagged as anomalous. This threshold was used from previous study [17].

Bias correction with delta method (e.g. [26,27]) was used only for SKT and TCWV in this study to adjust WRF output with ERA-Interim:

$$x_{corr,i} = x_{WRF,i} \times \frac{p_{ERA}}{p_{WRF}}$$

3. Results and discussion

3.1. Water vapor

The sensitivity of the Earth's climate to the intensity of solar radiation depends on the water vapor response. Gas emissions produced by volcanoes during eruption are $N_2$, $H_2O$, and $CO_2$ [30] besides $SO_2$ and $H_2S$ which are toxic gases. The oxidation results of $SO_2$ with $H_2S$ can form sulfurous acid gas. For approximately a month, sulfurous acid gas in the air will form sulfate aerosols which have an influence in blocking solar radiation towards the surface. Shortwave radiation from the sun is absorbed by sulfurous acid aerosols and then reflected back into the atmosphere. This results in cooling of the earth's surface, which is a decrease in air temperature and surface temperature [1,30].

Water vapor can be used as an indicator of the preparation phase of volcanic eruptions. An increasing of water vapor concentration in the atmosphere is thought to be increased by the presence of evaporation [17]. Results from WRF output showed consistent variation in the ERA-Interim reanalysis data (figure 3). The indicator of volcanic detection from TCWV can be indicated by anomalies above 2 standard deviations because the evaporation process of lava causes an increasing of water vapor concentration in the atmosphere [17]. Based on research by Piscini et al. suggested that there were no anomalies above 2 standard deviations at TCWV at Mount Kelud. The total column water vapor in the tropics on the
surface is more than in the subtropical region [31]. Cumulus parameterization and PBL selection had an effect on the results obtained from WRF simulations on mixing ratio in the mountain region [32].

Figure 3. TCWV anomaly before (left) and after (right) eruptions on fifth sample after bias correction. The circle shows anomalous day that exceeds 2 standard deviations.

Mixing ratio of an air parcel will be fixed if no moisture is added or removed from an air parcel because the total number of molecules will be constant even though the air parcel expands [33]. Plotting mixing ratio at 500 mb (about 5.5 km) was carried out to see the changes before and after the eruption (figure 4). Throwing volcanic material which reaches 26 km there is the potential for increasing the concentration of water vapor along that altitude. The graph in figure 4 shows a consistent variation of WRF output against ERA-Interim. There was an increase in mixing ratio from 13 February 2014 at 19:00 WIB to 14 February 2014 at 01:00 WIB. However, the graph in figure 4 shows that the linear regression equation shows a decrease before and after the eruption. Increasing the mixing ratio can be caused by increasing water vapor into an air parcel from the surface to a certain height by the condensation process. Water vapor from volcanic eruption emissions can increase the water vapor mass in air parcels in the atmosphere column [34]. The trend declined after the incident on the mixing ratio with a height of 500 mb, one of which could be caused by a chemical reaction between water vapor and SO$_2$ gas by volcanic emissions so that the water vapor concentration in the atmosphere decreases.

Figure 4. Mixing ratio at 500 mb before (left) and after (right) eruptions on fifth sample
3.2. Skin surface temperature

Skin surface temperature has an influence on topography, type of land cover [35], and diurnal and seasonal variations [36]. Between WRF and ERA-Interim show almost the same value during the day, while their values are wide different at night. The magnitude interval of skin surface temperature between the time of day and night in the area around Mount Kelud ranges from 21 - 23°C according to WRF output, while 12°C according to the ERA-Interim on the five grid samples. The analysis conducted by Piscini [17], the time seen in the SKT parameter is 12:00 UTC because it avoids the presence of solar radiation factors. At that time, it will be easy to see the changes before an eruption.

The SKT values above 2 standard deviations are thought to be the activity of the Kelud mountain [17]. The thickness of the cone near the volcano can affect skin surface temperature. This is caused by the process when the magma coming out around the volcanic cone that can increase the surface temperature for a moment [17]. The results obtained from figure 5 are SKT ERA-Interim anomalies from 13 November 2013 to 13 February 2014. SKT anomalies detected on 11 December 2013 (64 days before eruption) and 12 February 2014 (3 hours before eruption) at 19:00 WIB. In addition, there are SKT anomalies which are also above 2 standard deviations on 11 December 2013 at 22:00 - 04:00 WIB. This result is different from the study by Piscini et al that there are SKT anomalies above 2 times the standard deviation on 25 November 2013 (68 days before the event) at 12:00 UTC. This is due to the determination of climatology years (1979 – 2013) and resolution grid of the ERA-Interim used is 0.0625° x 0.0625°. In addition, Piscini et al [17] use the Climatological Analysis for seismic Precursor Identification (CAPRI) algorithm that averaging the grid which covers around the mountain and remove the trend due to climate change from the ERA-Interim. In this study, the grid covering the Mt. Kelud area was not averaged and only took one grid as a sample. Figure 6 shows the presence of SKT anomalous on WRF and ERA-Interim before and after the eruptions. SKT ERA-Interim anomalous days before the eruption occurred on 12 February at 16:00 and 19:00, while when after the incident occurred at 7:00 2 March 2014. The results of the summary from figure 6 show in table 2. There are 92 SKT anomalous days, each of which is 46 during the day (07:00 - 16:00) and at night (19:00 - 04:00). A total of 56 SKT anomalies were detected before the eruption, while the rest were after eruptions.

Figure 5. SKT anomaly from ERA-Interim on fifth sample 90 days before eruption (13 November 2013 – 13 February 2014). The circle shows anomalous day that exceeds 2 standard deviations.
The problem of the WRF model is at the height of a region which can cause errors in the simulation results. A 600 meter of grid resolution for D04 on WRF is enough to represent the area around the mountain, while the resolution on the ERA-Interim of 0.05° (5 km) is not enough to describe the mountain region with an altitude less than 2000 meters above sea level. Zhang [37] showed the magnitude of surface temperature in mountainous regions with a height of less than 2000 m with an error of 3°C at night with the highest resolution domain of the model (1.11 km). The choice of PBL parameterization can also cause errors in simulation of the WRF model. The PBL parameterization scheme chosen in this study was Mellor-Yamada-Janjic as a comparison to the study of Zhang have a small error value for surface temperature.

4. Conclusions

ERA-Interim shows the characteristics of surface parameters (SKT and TCWV) climatologically and mixing ratio at 500 mb, while WRF shows the processes of SKT, TCWV on the ground surface, and
mixing ratio at 500 mb. Mixing ratio showed a downward trend before and after the eruption from fifth samples. There were no TCWV anomalies that exceed 2 standard deviations detected on ERA-Interim, but were detected on WRF 2 days before eruption and 3 days after eruption. SKT anomalies that exceed 2 standard deviations were detected on ERA-Interim on day 64 at 19:00 - 04:00 and day 1 at 19:00 before the eruption. After bias correction on WRF, there are 56 SKT anomalous before eruption and 36 SKT anomalous after eruption.

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