Clustering of CO and CO\textsubscript{2} concentration from Sumatra peat fire haze using HYSPLIT and K-means algorithm

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Abstract. Peat fires in Indonesia could have a negative impact for human life such as the emergence of haze. Therefore, this research aims to analyze concentration of CO and CO\textsubscript{2} due to peat fires in Sumatra in 2015 using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) and K-Means algorithm. The results of this study indicate that HYSPLIT can be used to obtain the concentration of CO and CO\textsubscript{2} from the haze. Clustering using K-Means algorithm produces an average of the highest concentration of CO is 11.1471 μg/m\textsuperscript{3} and CO\textsubscript{2} is 88.5882 μg/m\textsuperscript{3}. Generally, pollutants have an average concentration of 0.0487 μg/m\textsuperscript{3} for CO and 0.3687 μg/m\textsuperscript{3} for CO\textsubscript{2}. The pollutant concentration is contained in 45 525 (95%) positions in haze trajectory and the haze spread starting from Riau to Nanggroe Aceh Darussalam.

1. Introduction

Indonesia has abundant natural resources, one of which is peat that has area more than 10% of Indonesia’s land area. Peatland is one of the natural resources that has an important role in the economy of the country as a provider of various timber and non-timber products. Additionally, peatlands also provide a range of benefits that are important to people’s lives, including water supply, flood control, carbon storage and protection for biodiversity that live in it [1]. Given the importance of the peatlands role, peatlands should be prevented from any destruction including peat fires.

Peat fires are more difficult to handle than the fires in the highlands because the fire spread under the surface [2]. Global Forest Watch analysis shows 75% warning of hotspots occur in peatlands which is mostly composed of decomposed organic material [3]. Meanwhile, in this decade area of peat fires reached an average of 32.1% in Sumatra and 25.1% in Kalimantan [4].

Peat fires can cause a very broad impact for human life, not only nationally but also globally. One of the impacts of peat fires is the emergence of haze. Haze due to forest fires may bother some neighbouring countries. That is because the haze is an object that the direction of movement influenced by other factors such as weather, directions and speed of wind which making it difficult to predict which areas will be affected by the fire. Negative impact of fire smoke can trigger respiratory disease, decline in crop production and fisheries, disruption of transportation services, and tourism industries. The worst impacts experienced in Indonesia is deteriorating levels of health, loss of standing timber, a plane crash, and the possible extinction of some species [5].

The forest and peat fires that were occurred in Indonesia left a devastating trail of destruction, one of which produces harmful haze in large numbers. This resulted in the closure of hundreds of schools and several local airports, as well as respiratory disorders that affect more than 50,000 people [3]. Anticipating the negative impact of peat fires can be done by analyzing the trajectory patterns and the
distribution of pollutant concentrations of haze of fires. By knowing the trajectory and the concentration distribution, information regarding to which areas, how far haze can spread and how much concentrations of pollutants can be obtained.

One indicator of peat fires is a hotspot. Various satellites such as National Oceanic and Atmospheric Administration (NOAA) and MODIS monitor hotspots periodically. The location of hotspots occurred sequentially can be used as the initial location of the movement of haze due to peat fires. Negative impact of haze due to peat fires can be anticipated based on the haze trajectory information, pollutant concentration and location of the hotspots. For example, by knowing the direction of haze movements related parties could inform early warning to the community about the haze and pollutant contained. In addition, this information is also important in evacuation activities.

Research on trajectory pattern has been done before by Anugrah [6] using The Air Pollution Model (TAPM). In addition to TAPM, the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) can be used to identify trajectory patterns. HYSPLIT model has been used to simulate the spread of pollutants NO₂ and SO₂ in the study by Fairuzi [7]. The study by Wang et. al [8] identified the transportation path of PM₁₀ in Beijing. In addition, the work by Luo & Chen [9] studied the potential sources and transportation path of PM₂.₅ in Shanghai using HYSPLIT modelling, K-Means clustering algorithm, and methods of analysis Concentration-Weighted Trajectory (CWT). This study aims to obtain haze distribution due to peat fires in Sumatra in 2015 using HYSPLIT model and to cluster CO and CO₂ concentrations using K-Means clustering algorithm. It is expected that the results can be used in anticipating the negative impact of fires such as health problems by providing the information about CO and CO₂ concentrations of haze from forest and land fires.

2. Data and methods

2.1. Dataset

The data used in this research are sequence hotspots in peatland of Riau in Sumatra in 2015 and the meteorological data in 2015. Hotspot sequences were obtained from the previous work by Abriantini [10] in which the duration of occurrence is two days. The meteorological data were collected from the Global Data Assimilation Systems with a resolution of one degree (GDAS1). The data are available on the website of Air Resources Laboratory (ARL) NOAA. Each grid data on the GDAS1 has size of 111.1984 km for every longitude and latitude. Meteorological data GDAS1 have several attributes including complex surface pressure (hPa), speed of vertical pressure (hPa/s), height of geopotential (m), temperature (°C), the components of wind U and V (m/s), relative humidity (%), wind direction (degrees) and wind speed (m/s). Wind direction and wind speed are two attributes that have much influence in haze trajectory pattern of peatland fires.

In addition to hotspot sequence data and meteorological data, this study also used emissions data and characteristics of each pollutant as input parameters for determining the concentration of pollutants. Data of CO and CO₂ emissions were obtained from the Global Fire Emissions Database version 4.1 (GFED4.1s) [11]. Emissions data are available on GFED4.1s which are annual emission data for different types of fires distinguished by each region in the world. The data used in this study are peat fire emissions for the region of Indonesia that has the name of Equatorial Asia (EQAS) on GFED4.1s. Pollutant characteristics required in submenu of pollutants deposition in HYSPLIT include molecular weight (g/mol), velocity (m/s), and Henry’s constant (mol/L.atm). This study uses the following values of pollutant characteristics. The molecular weight of CO is 28.01 g/mol and 44.01 g/mol for CO₂. Average speed for CO and CO₂ are 454 m/s and 362 m/s respectively [12], Henry’s constant is 9.7 × 10⁶ mol/L.atm for CO and 3.3 × 10⁴ mol/L.atm for CO₂ [13].

2.2. Trajectory pattern mining

Trajectory pattern mining is an extension of the paradigm of sequential pattern mining which analyze the trajectory of moving objects. Trajectory pattern is a pair of dimensional space (areas visited during the movement) and time (duration of the movement). Trajectory pattern mining evolves studies of the spatio-temporal sequential pattern and temporally annotates sequences. In trajectory pattern mining,
the Region of Interest (RoI) is associated with the movement area of an object and typical travel time is associated with the movement of an object from one region to another [14].

2.3. Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT)
HYSPLIT is one of the models used to predict the trajectory, dispersion and concentration of pollutants. This model explains the relationship between the dispersion of pollutants with meteorological components in a certain area. In addition, this model can be applied to identify sources and pathways of pollutant transport. HYSPLIT was developed by the National Oceanic and Atmospheric Administration (NOAA). According [15] HYSPLIT applies two approaches that are Eulerian and Lagrangian. Lagrangian approach is based on a parcel of air flowing in the trajectory which is affected by meteorological factors. Change movement of the pollutants from the initial location is included in the Lagrangian approach. Eulerian approach is based on the use of grid in the model. Changes in the concentration of pollutants are involved in this approach. Transport processes and chemical reactions are influenced by meteorological factors occurred in the grid. The process causes change of the pollutant concentration at any time, therefore the concentration of pollutants act as a function of time.

2.4. Clustering
Clustering is a technique to divide objects into groups or clusters so that objects that are in the same cluster have similar characteristics to each other and different from the objects that are in another cluster [16]. The K-Means algorithm is a partitional clustering algorithm which is often used because it is simple and efficient [17]. K-Means algorithm is summarized as follows [16]:
1. Select k initial objects as the centroid of the cluster,
2. Insert the objects into clusters whose object is most similar based on the average value of objects that are in a cluster,
3. Renew the centroid of cluster by calculating the average value of objects for each cluster,
4. Repeat step two and three until the objects in the cluster have not changed.

3. Result and discussion
Stages of this research include pre-processing data, determining the location of the initial movement of haze, determining the concentration of pollutant using HYSPLIT, and clustering of CO and CO\textsubscript{2} concentration using K-Means algorithm.

3.1. Pre-processing data
In the pre-processing step, we selected hotspot sequences in the range of July until October 2015 as shown in table 1. Meteorological data were selected based on the hotspots sequence. Meteorological data for each month are divided into five sections namely w1 containing data on 1\textsuperscript{st} to 7\textsuperscript{th} day, w2 containing data on 8\textsuperscript{th} to the 14\textsuperscript{th} day, w3 containing data on the 15\textsuperscript{th} to 21\textsuperscript{st} day, w4 containing data on the 22\textsuperscript{nd} to 28\textsuperscript{th} day, and w5 containing data on 29\textsuperscript{th} to 31\textsuperscript{st} day. Table 2 provides the periods of meteorological data that were determined based on hotspot sequences.

| Period of sequence (2015) | First location \((longitude, latitude)\) | Last location \((longitude, latitude)\) |
|--------------------------|-----------------------------------------|--------------------------------------|
| July 09 – July 11        | 100.457, 2.083 ; 100.455, 2.082         | 100.460, 2.077 ; 100.463, 2.078       |
|                          | 100.459, 2.082                            | 100.456, 2.079 ; 100.459, 2.082       |
| July 22 – July 23        | 101.610, 1.727 ; 101.613, 1.733          | 101.608, 1.728 ; 101.605, 1.726       |
| July 26 – July 29        | 102.707, -0.407                           | 102.712, -0.413                      |
| August 30 – September 01 | 102.272, 0.262 ; 102.269, 0.262           | 102.268, 0.257                       |
| September 01 – September 02 | 101.354, 0.449                         | 101.348, 0.448                       |
|                          | 101.347, 0.447 ; 101.348, 0.452          | -                                    |
| October 21 – October 22  | 102.501, -0.297 ; 102.496, -0.302         | 102.497, -0.298 ; 102.495, -0.295     |
Table 2. Meteorological data selection based on hotspots sequence

| Date of the first hotspot occurrence | Date of the last hotspot occurrence | Meteorological data |
|-------------------------------------|-------------------------------------|---------------------|
| July 09, 2015                       | July 11, 2015                       | gdas1.jul15.w2      |
| July 22, 2015                       | July 23, 2015                       | gdas1.jul15.w4      |
| July 26, 2015                       | July 29, 2015                       | gdas1.jul15.w4 and gdas1.jul15.w5 |
| August 30, 2015                     | September 01, 2015                  | gdas1.aug15.w5 and gdas1.sep15.w1 |
| September 01, 2015                  | September 02, 2015                  | gdas1.sep15.w1      |
| October 21, 2015                    | October 22, 2015                    | gdas1.oct15.w3 and gdas1.oct15.w4 |

3.2. Determining initial point of trajectory

According to table 1, there are several locations for each period of hotspot sequence. By applying spatial operation, a representative point among the hotspot locations is selected for each period of hotspot sequence. The representative point located in the centre of all hotspots is used as an initial point for haze trajectory. Table 3 presents the selected initial point of haze trajectory.

Table 3. Selected initial point of trajectory for each sequence

| Period of sequence (2015) | Longitude | Latitude |
|---------------------------|-----------|----------|
| July 09 – July 11         | 100.445   | 2.080    |
| July 22 – July 23         | 100.550   | 1.845    |
| July 26 – July 29         | 102.662   | -0.583   |
| August 30 – September 01  | 102.103   | 0.660    |
| September 01 – September 02 | 101.281   | 0.432    |
| October 21 – October 22   | 102.493   | -0.279   |

3.3. Determining concentration of pollutant using HYSPLIT

HYSPLIT results CO and CO\textsubscript{2} concentrations based on the characteristics of the pollutant emissions. Parameters required in determining concentration are emissions (per hour), the duration of emission (h), date and time of starting and ending the simulation, and chemical characteristics of each pollutant, such as molecular weight (g/mol), density (kg/m\textsuperscript{3}), velocity (m/s) and Henry's constant (mol/L.atm).

CO and CO\textsubscript{2} emissions data until 2014 are available in GFED4.1s. This study approximate emissions in Sumatra in 2015 based on the emissions in 2014 and area of forest fires in Indonesia in 2014 and 2015 that are obtained from the Sipongi application developed by Ministry of Environment and Forestry of the Republic [18]. The estimation values of emissions are 778 423.973 kg/h of CO and 6 260 780.82 kg/h of CO\textsubscript{2}. The duration of pollutants emission is per three hours.

Several parameters are assigned to obtain a concentration using HYSPLIT. The parameters include initial location of trajectory, pollutant source height, date, duration and simulation maximum height, as well as the trajectory approach used. The initial location, date and duration are determined based on hotspots sequence. Pollutant source height used is 10 m with maximum height of 10 km. Both values of the parameter are used based on the assumption that all vegetation burned is trees and the maximum of source height is the limit of earth's troposphere. Trajectory approach applied is the Forward Trajectory because the objective of this study is to explore the direction of the haze from the source. HYSPLIT model results as many 47 718 data of pollutant concentration. Figure 1 shows a plot of the concentration of CO and CO\textsubscript{2} which occurred on September 1 at 00:00 until 03:00 UTC or at 07.00 until 10.00 WIB. The concentration plot shows a difference between the CO and CO\textsubscript{2}. The concentration of CO at that time have a maximum value of 7.7 µg/m\textsuperscript{3} and a minimum value of 6.5 × 10\textsuperscript{-6} µg/m\textsuperscript{3}. Meanwhile, at the same time and the same location, CO\textsubscript{2} have a maximum value of 60.0 µg/m\textsuperscript{3} and a minimum value of 9.4 × 10\textsuperscript{-5} µg/m\textsuperscript{3}. In the first 3 hours on September 1, 2015, the result shows that CO\textsubscript{2} concentration is higher than those of CO.
3.4. Clustering of CO and CO\textsubscript{2} concentration

Pollutant concentration data as output of HYSPLIT were converted from kg/m\textsuperscript{3} to a common unit, namely µg/m\textsuperscript{3} before clustering. Clustering was performed using the K-Means module on Flexible Procedures for Clustering (FPC) package that is available in R. Variables included in clustering are concentrations of CO and CO\textsubscript{2}, whereas time (date of occurrence) and the location (longitude and latitude) are used as identifier of pollutant concentration data. Sum Square Error (SSE) of K-means clustering on the concentration of CO and CO\textsubscript{2} on July 9, 2015 until October 22, 2015 showed that the best clustering was obtained at number of cluster (k) of 5. The results of clustering using the K-Means algorithm are given in table 4.

| Cluster | Haze locations | Average concentration of pollutants (µg/m\textsuperscript{3}) | Percentage of cluster members |
|---------|----------------|-------------------------------------------------------------|------------------------------|
|         |                | CO | CO\textsubscript{2}                                      |                              |
| 1       | 369            | 1.7245799 | 14.5298103 | 0.773                        |
| 2       | 17             | 11.1470588 | 88.5882353 | 0.036                        |
| 3       | 1,714          | 0.4561499 | 4.1485998  | 3.592                        |
| 4       | 93             | 4.3258645 | 35.1397849 | 0.195                        |
| 5       | 45,525         | 0.0487478 | 0.3687339  | 95.404                       |

According to table 4, high concentrations of CO and CO\textsubscript{2} on July 9, 2015 until October 22, 2015 are found in cluster 2 whereas low concentrations are found in the cluster 5. As many 17 haze locations are members of cluster 2. Most of haze locations, which are 45,525 data, are members of cluster 5. Figure 2 shows haze locations in cluster 2 in which the average concentration of pollutants in these locations is 11.1471 µg/m\textsuperscript{3} for CO and 88.5882 µg/m\textsuperscript{3} for CO\textsubscript{2}. Pollutants concentrations in cluster 2 spread in several sub districts in Riau province which are Kubu, Tanah Putih, Bangko Pusako, Rimba Melintang, Tanah Putih Tanjung Melawan, Rupat, Bukit Batu, Putri Puyu, Kuala Cenaku, Bagan Sinembah, Siak, Rengat, Batang Gansal, Kempas, Dayun, Bandar Petalangan, Gaung, Rengat Barat, Gaung Anak Serka, and Teluk Meranti, converging toward the northwest to the District of Siak, Rupat, Kuala Cenaku, Rengat, Rengat Barat, and Teluk Meranti. These sub districts are located in Rokan Hilir, Bengkalis, Meranti island, Indragiri Hulu, and Siak district. Time periods of the initial movement of haze are July 9, July 22, July 26, August 30 and October 21, 2015 in the first 3 hours. Table 5 provides concentration value at each period.
Table 5. Maximum pollutant concentrations for each period of haze movement in cluster 2

| Date              | Maximum CO concentration (µg/m³) | Maximum CO₂ concentration (µg/m³) |
|-------------------|-----------------------------------|-----------------------------------|
| July 09, 2015     | 18.0                              | 130.0                             |
| July 22, 2015     | 11.0                              | 96.0                              |
| July 26, 2015     | 20.0                              | 160.0                             |
| August 30, 2015   | 10.0                              | 77.0                              |
| September 01, 2015| 7.7                               | 60.0                              |
| October 21, 2015  | 17.0                              | 140.0                             |

Pollutants concentration in cluster 5 has an average value of 0.0487 µg/m³ for CO and 0.3687 µg/m³ for CO₂. Plot of pollutants concentration in cluster 5 is given in figure 3. Number of haze movement locations in cluster 5 are 45,525 locations in which only 22,363 locations are found in Sumatra island. As many 23,162 movement are located outside Sumatra island. In general haze movements in cluster 5 occurred on all dates of hotspot sequences namely July 9 until October 22, 2015. Pollutants concentration in cluster 5 spread from Riau Province to the west, northwest, east, northeast, north and to Nanggroe Aceh Darussalam.
Figure 4 shows plot of haze movement locations in cluster 1, cluster 3, and cluster 4. Summary of pollutants distribution in each cluster is stated in table 6.

**Table 6. Summary of pollutants distribution in cluster 1, cluster 3, and cluster 4**

| Cluster | Average concentration (µg/m³) | Number of haze movement | Location of movement | Period of movement (in 2015) |
|---------|-------------------------------|--------------------------|----------------------|-----------------------------|
|         | CO  | CO₂ |                          |                      |                             |
| Cluster 1 | 1.7246 | 14.5298 | 369                       | Outside Sumatra island as many as 17 1566 locations in Sumatra island, 148 locations outside Sumatra island, spread toward Riau, Nanggroe Aceh Darussalam and North Sumatra | July 9, July 22, July 26, August 30, September 1 and October 21 |
| Cluster 3 | 0.4561 | 4.1486 | 1,714                     | Riau guild, 714 locations in Sumatra island, 148 locations outside Sumatra island, spread toward Riau, Nanggroe Aceh Darussalam and North Sumatra | July 9, July 22, July 23, July 26, July 27, August 30, September 1, October 21, October 22 |
| Cluster 4 | 4.3259 | 35.1398 | 93                        | Riau | July 9, July 22, July 26, August 30, September 1 and October 21 |

Distribution of concentration of pollutants in all clusters is shown in figure 7. According to figure 7 and table 6, our study conclude that high pollutants concentration is found in small clusters, cluster 2 and cluster 4, with few number of haze movement locations. These locations are found around the initial points of trajectory that were identified based on hotspot sequences. However, low pollutant concentrations are found in large clusters such as cluster 5 and cluster 3. Haze movement locations in these clusters spread away from the initial location of trajectory. Distribution of concentration of pollutants in each cluster can be seen in figure 7.

![Figure 7. Distribution of the pollutants concentration in all clusters](image)

**4. Conclusion**

This study found that CO and CO₂ pollutants from peat fires in Riau Province in 2015 spread to the west, northwest, east, northeast, and north of the Riau Province to the province of West Sumatra, North Sumatra, Aceh and Riau Islands. On July 9, July 22, July 26, August 30 and October 21, 2015, high pollutants concentration spread in some districts in Riau province including Rokan Hilir, Bengkalis, Meranti island, Indragiri Hulu, and Siak. The average concentration of pollutants in these locations is 11.1471 µg/m³ for CO and 88.5882 µg/m³ for CO₂.

Distribution pattern of haze and CO and CO₂ concentration from forest and land fires are important information to anticipate negative impacts of forest and land fires especially in health problems of community and global warming. Based on the information of haze trajectory and pollutant
concentration, authorized parties can perform warning and early evacuation for people who live around the area affected by haze with high pollutant concentration.

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