The influence of aerosol on the sunlight divergence in the atmospheric Indonesia

Rosida
Center for Atmospheric Science and Technology
National Institute of Aeronautics and Space
rosida2009@gmail.com

Abstract. Solar radiation is the source of energy for the earth. The amount of solar radiation that reaching the earth's surface, is strongly influenced by the interaction of solar radiation with the atmospheric that is passed through. This paper analyzes the effect of aerosols on solar radiation balance in the Indonesian atmosphere using radiation data from the Clouds and the Earth's Radiant Energy System (CERES) and aerosol optical depth that is obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) - Terra, from March 2000 to February 2016. Aerosol optical depth data (AOD) and shortwave (SW) radiation that reach the top of atmosphere and the earth's surface were analyzed spatially and temporally with the observation area of the 15°S – 15°N and 90°W – 150°E. Moreover, the sample of several locations was analyzed such as Palangkaraya, Pontianak, Banjarmasin and Samarinda, to look at the cases of forest fires which generate aerosols that quite high. Results of data analysis showed a significant influence of aerosols on the divergence of short-wave solar radiation in the atmosphere of Indonesia. The divergence of short-wave radiation shows how much solar radiation is absorbed in the atmosphere. Some cities such as Palangkaraya and Pontianak showed a strong correlation (0.7 - 0.95) between AOD and the value of shortwave radiation divergence. Temporal pattern from time series analysis showed that the increase in the value of AOD due to the fires incident, give the biggest influence on the decrease in solar radiation that reaches the earth's surface.

Keywords : aerosol, divergence, CERES, MODIS, radiation.

1. Introduction
Radiation is fundamental in climate. Almost all of the energy entering the climate system comes from the sun in the form of electromagnetic waves. Although there are other additional sources such as geothermal heating, but the contribution is very small so that the effect can be neglected [1]. In the IPCC [2] report explained about the solar radiation absorbed, infrared radiation emitted, and the balance that occurs between these things which include the process of absorption, transfer and emission from radiation that occurs throughout the globe for many years. McGuffie and Henderson-Sellers [3] explain that in the process of radiative transfer there is heating on the surface through absorption of short waves, and heating or cooling in the atmosphere that occurs through absorption and emission of infrared radiation. Whereas the controller of the interaction is cloud albedo and absorbtivity to short waves.

Net radiation flux is one of the important parameters that can show energy loss or stored energy in one layer. This concept is important for defining radiative heating or cooling from each element of the atmosphere or surface. Heating or cooling that occurs due to energy stored or lost, which will affect the
energy balance. Therefore this energy balance is important, and the simplest concept of radiation balance has become the basis in climate models by considering how radiation is absorbed, transferred and emitted back by the atmosphere. Sellers [4] explained that in the radiative transfer process, there are several factors that control the interaction, namely albedo and absorptivity to shortwaves, which absorptivity to radiation is strongly influenced by the composition of the atmosphere. Thus, fluctuations in absorption of radiation in the atmosphere can be one of the benchmarks for changes in the components in the atmosphere. Based on the statements of Palmen and Newton [5] and also from the results of Alexander and Schubert’s research [6] elucidate that the storage and transfer of energy in the ocean-atmosphere system has an important role in determining the average climate and evolution of climate anomalies. The energy balance model has proven to be very useful in determining processes that affect climate by providing a balance in storage, flux divergence, energy sources and sinks in the related region.

Divergence of radiation flux is a value that can show how much stored or lost energy is obtained from the difference between net radiation flux in the top of atmosphere (TOA) and on the surface [7][8]. Observation of the divergence of radiation flux was first carried out by Funk [9] and Fuggle and Oke [10]. They observed it on grasslands at altitudes of 0.5 and 1.5 m and recorded the divergence of radiation flux at night which tends to show cooling speeds at -120 K day\(^{-1}\). Lieseke and Stroschein [11] reported the results of their first measurements on snow at two air levels of 1 m and 5 m above Alaska, they found an average radiation heating effect at 120 K day\(^{-1}\). Rascke et al [8] explained that the absorption of sunlight in all conditions is positive, and for the average annual value in the tropics reaches a value of up to 90 watts/m\(^2\). Bohren et al [16] found negative flux divergences related to heating and almost all occur in the atmospheric layers at altitudes below 30 km. Under 15 km, heating occurs by the absorption of solar radiation which rapidly increases like a cooling event that occurs due to emissions of terrestrial radiation. Total flux divergence between 8 km and 14 km is positive, while between 8 km to ground is negative.

The role of aerosols in the climate system and radiation balance has been widely discussed by researchers, including Crutzen and Andreae [17], Ichoku et al [18], Keil and Haywood [19], Kaufman, et al [20] and Breon et al [21]. They explained that during the period when the aerosol load was very high, the balance of the solar radiation budget would be disrupted. Kaufman et al [20] asserted that the accumulation of aerosol particles that occurred in the Indian Ocean in 1998-1999 came from the transportation of particulate pollutants which is emitted from the Indian sub-continent. The accumulation of aerosol particles has caused a reduction in the amount of solar radiation that reaches the surface by 15%.

Fouquart et al [22] observed aerosol potential in influencing global radiation budgets from Earth-atmosphere systems in desert regions, the results showed that aerosols on a small scale were able to have a significant impact on the balance of radiation energy in the atmosphere and on the surface. In the case of aerosol dust, Fouquart et al [22] found a drastic reduction in the budget for short-wave radiation caused by the accumulation of aerosols particle dust originating from the desert. From research of Benas et al [23] in the Mediterranean region where environmental conditions were heavily polluted by dust, showed that the accumulation of aerosol particles covering the Mediterranean region had caused cooling on the surface as a result of reduced radiation reaching 215 watts/m\(^2\), and reduction of radiation at the top of atmosphere reaches 46 watts/m\(^2\).

Rosida and Susanti [24] conducted a spatial analysis of the effects of aerosols on short-wave radiation (SW) which was then linked to forest fires that occurred in Kalimantan and Sumatra. The results of the analysis show that the forest fires that occurred in 2002 and 2006 in Kalimantan and Sumatra, have caused an increase in AOD values that reach more than 300% of the average value, and showed a strong linkage to changes in short-wave radiation fluxes that reached the surface \((r > 0.8)\) [24]. In 2014, Rosida et al [25] also analyzed spatially seasonal influences and the results showed that there was a strong link between net radiation flux, short-wave radiation flux (SW) and long-wave radiation flux (LW) to the
average high of AOD value which is occurred in the transitional season of September-October-November. In that cases anthropogenic factors was estimated to provide a significant role in influencing the balance of radiation budget [26].

The purpose of this study is to determine the magnitude of sunlight divergence in the atmosphere of the Indonesian region at the earth's surface level, namely at the lower troposphere level at an altitude of below 1 km and at the top of atmosphere (TOA) level, which is around 100 km above the surface of the Earth. Data of net radiation flux, short-wave radiation flux, and long-wave radiation flux were used in this study to obtain the magnitude of the radiation flux divergence value. The magnitude of divergence value of the radiation flux which were obtained is then used to gain the amount of radiation energy stored or released. In addition, the aims of this study also to analyze the influence of aerosols on the divergence of sunlight in the Indonesian atmosphere. The importance of the role of aerosols in radiation balance has been widely discussed which generally states that when the aerosol load is very high, the balance of the solar radiation budget will be disrupted. If this is the case, then the amount of aerosol will show a high correlation to the amount of energy stored or released from radiation based on the divergence value of the radiation flux.

2. Research methods
Radiation data used in this study was obtained from the NASA Langley Research Center Atmospheric Science Data Center. The Clouds and the Earth's Radiant Energy System (CERES) experiment is one of the highest priority scientific satellite instruments developed for NASA's Earth Observing System. CERES products include both solar-reflected and Earth-emitted radiation from the top of the atmosphere to the Earth's surface [28]. The radiation data products available on this instrument were short-wave (SW), and long-wave (LW) radiation on the top of atmosphere (TOA), and on the Earth's surface. From one's own the Earth's surface radiation products was consist of components of downward radiation, and upward radiation.

The aerosol data which was used in this study is aerosol optical depth (AOD) that is obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) level 3 (MOD08). This parameter can be downloaded from ftp://ladsftp.nascom.nasa.gov/allData/6/MOD08_M3/. [29] The spatial resolution of aerosol data and radiation data used in this study is 1 degree, and the temporal resolution of the data in the month averages with the data period from March 2000 to June 2017. Study area boundaries are 15°LU - 15°LS and 90°BT - 150°BT and Format data in NetCDF.

Radiation flux divergence is obtained through a series of stages of determining the radiation net SW and LW involving the radiation components downward and upward respectively for the radiation component on the surface and in the TOA [7][8][27]. The value of divergence of the radiation flux which was gaines is used to indicate the magnitude of radiation energy stored or released.

Referring to the explanation of Raschke et al. [8] that the terminology of divergence used here has the opposite meaning to the classical mathematical definition. So if the flux divergence value is positive (+) then it means that there is a release of radiation energy which is usually related to the radiation cooling rate, and vice versa for divergences that are negative (-) then it means that there has been absorption of radiation energy associated with the rate of radiation heating.

3. Result and discussion

3.1. Characteristics of Indonesia's regional divergence
From the observation’s results, it can be seen that divergences in the Indonesian region run into fluctuations which were influenced by natural and anthropogenic factors. The results of Rosida's study, et al. [27] related to the radiation divergence of three components of longwave radiation, shortwave radiation and net radiation showed a trend of specific temporal variations and varied fluctuations. The results of data processing for a period of 17 years from March 2000 to June 2017, different characteristics of the climatological patterns of SW divergence and LW divergence were obtained.
Based on the analysis, the average characteristics for the SW divergence and LW divergence patterns present a seasonal cycle that is influenced by the sun's position factor. The minimum value of the average SW divergence is around -238.2 watts/m² which is usually happening in every March. The maximum SW divergence average value occurs in June with a magnitude of approximately -205.2 watts/m². LW divergence indicates a reverse trend of the SW divergence pattern by reaching a minimum in June of 346.8 watts/m² and a maximum of 349.9 watts/m² which is usually occurred in October (Figure 1). Rosida, et al [27] estimated that LW divergence increases by 0.001 watts/m² per month, or 0.012 watts/m² per year.

The spatial distribution of each radiative divergence flux shows very different spatial variations and illustrated the differences in the flux of radiation divergence between land and sea. In this study the divergence flux values calculated are the average land and sea. Hoch [7] and Raschke [8] explain that absorption of solar radiation tends to be largely controlled by the accumulation of material emitted by anthropogenic factors such as aerosol particles, dust, trace gases or other factors such as desert dust, water vapor, clouds and others. Forest fires that often occur in the territory of Indonesia are thought to be the causes that contribute significantly to the fluctuations in radiation divergence in the territory of Indonesia.

Based on the information, forest fires that occurred in 2002, 2006 and 2015 in the western part of Indonesia, exactly in Kalimantan and Sumatera, were events that adversely affected environmental conditions in the region and beyond. The emission of aerosol particles in the form of smoke and dust is very disturbing to public health conditions, especially to respiratory health and interfere with transportation activities both land and air because it affects atmospheric visibility. Several incidents of forest fires, that occurred in 2015 were the largest that had ever occurred in Indonesia.

The trend of SW divergence anomalies during the period January 2001 to June 2017 showed that the fluctuations in the radiation energy absorbed and released were quite low, which the averaged values were no more than -5 watts/m² and 5 watts/m². The data indicated that in October 2006 there was an increase in the radiation energy released by 7.9 watts/m². The highest peak of SW divergence occurred in October 2015, which showed an increase in radiation energy released by 18.1 watts/m² (Figure 2). The trend of net divergence anomalies and LW divergence did not indicate a trend of increasing or decreasing striking or extreme in the magnitude of radiation energy. Fluctuations in radiation energy absorbed and released were in the range of -5 watts/m² to 5 watts/m². Results of the data’s analysis can
be explained that the emission of aerosol particles from forest fires in Kalimantan and Sumatra is more likely to affect SW radiation fluctuations.

Figure 2. Trends in net divergence anomalies, long wave divergences and shortwave divergences for Indonesian regional averages in the period January 2001 to June 2017.

The spatial analysis presented in Figure 3 follows respectively the spatial patterns of the net radiation divergence anomalies, the anomalies of LW radiation divergence and the SW radiation divergence anomalies that occurred in 2015 in the Indonesian region. By using the same period, the anomalous trend of SW divergence and LW divergence was analyzed for its effect on the distribution of aerosol's (AOD) particles spatially. The analysis focused on August, September, October, and November, because of all the observed data, the trend of changes in spatial patterns that indicate a change to increase or decrease is more often found in those periods.

Assumed that the change in SW divergence anomaly that occurred in October 2015 was due to the accumulation of aerosol particles emitted from the forest fire at that time. Changes that occur, are then identified based on changes in the areal extent of the red spatial pattern, both for the spatial pattern of the radiation and the spatial pattern of the aerosols. Results of the data analysis it was concluded that the effect of aerosols on radiation flux would appear to be quite strong in the event of a very large forest fire. For example in the case of forest fires that occurred in 2002, 2006 and 2015, the concentration of aerosols drastically experienced a very sharp increase which was presented by an increase in the AOD value > 2.5. The incidence of increasing the AOD value is very high, generally found almost always occurs in the period September-October-November (SON). The event of forest fires always recurs in almost every year in the same area, namely between Kalimantan and Sumatera with a quantity that is quite varied.

Figure 4 presents the relationship between the increase in the concentration of aerosols emitted from forest fires and the fluctuations in the radiation energy absorbed and lost/released based on the divergence flux value is presented. The accumulation of aerosol particles in the form of smoke and dust emitted from average forest fires almost always occurs in the SON season in the western part of Indonesia. The indication of the extent of burning land, in Figure 4, is estimated from the spatial red changes that indicate the level of aerosol concentration. The accumulation of aerosol particles emitted during the event of forest fires, has enough to have an impact on changes in radiation energy.
In this study, an increase in aerosol concentrations from extreme forest fires that occurred in Kalimantan in the 2015 SON season showed an AOD value of > 1.5. The increase in aerosol accumulation at that time has resulted in a decrease in net radiation with the magnitude of the flux of the divergence of the net radiation released is > -80 watts/m². Slightly different from the results of
research by Rascke et al [8], the accumulation of aerosol dust particles observed by Rascke et al [8] came from highly polluted environmental areas. In extreme conditions, Rascke et al [8] found an increase in the accumulation of aerosol dust particles that showed an AOD value of ~ 2 and resulted in a decrease in radiation flux with a divergence flux value of solar radiation released was > 190 watts/m². At the same time, namely, in the event of very extreme forest fires in Kalimantan in 2015 above, there was also a decrease in SW radiation energy with a large flux of lost SW radiation divergence of > -130 watts/m². In addition, the accumulation of aerosol particles also results in absorption of LW radiation energy with a flux amount of LW radiation divergence of approximately > 370 watts/m².

3.2. Urban divergence
To find out the characteristics within the local scale which showing a high concentration of aerosol’s particles, in this study was carried out cropping data area that is analyzed. In this study the area in Kalimantan was determined within the area boundary of (108,290W -119.60E; -4.60S - 7.070N) that is considered to meet the expected criteria. Figure 5 shows the differences in the spatial pattern of the SW radiation divergence, the divergence of net radiation and the divergence of LW radiation which were analyzed with the accumulation of aerosol particles in the period September-October-November 2015.

The result explains that the accumulation of aerosol particles in Kalimantan tends to have more influence on the pattern of SW radiation compared to LW radiation or net radiation. The concentration of aerosol particles with an average value of AOD = 1.4 is found in this region which is estimated to have caused the absorption of radiation energy of approximately -180 watts/m². Spatially, changes in the area of red spatial patterns also show a stronger influence on SW radiation.

Furthermore, as a comparison, the author analyzes the smaller scope of the urban sphere. Four major cities in Kalimantan are Pontianak in the boundary (109.170W-109.230E; -0.0450S - -0.0160N), Palangkaraya with a limit (113,500W - 113,590E; -2.160S -2.0930N), Banjarmasin in the limit (114,300W- 114,400E; -3.2210S - -3.1540N) and Samarinda with limits (117,010W-117.200E; -0.440S--
0.17°N). For these cities, the divergence of the radiation is determined, then it is analyzed the possibility of its correlation to the accumulation of aerosol loads that occur at the same time.

The results of section 3.1 analysis, it can be concluded that the effect of the accumulation of aerosol particles is more dominant on the flux of the SW radiation divergence compared to the effect on long-wave radiation flux or on net radiation flux. Based on these results, the urban analysis will only examine the flux of the SW radiation divergence. The results of radiation data analysis during the period of January 2001 to June 2017, for each of the urban boundaries mentioned above, the magnitude of the radiation divergence of SW is highly variable. The average amount of radiation energy absorbed is -204.4 watts/m² for Pontianak city, -167.8 watts/m² for Palangkaraya city, -186.1 watts/m² for Banjarmasin city and -181.8 watts/m² for the city of Samarinda.

From divergence analysis in the urban area, the accumulation of aerosol particles that affect the divergence flux of radiation varies with the AOD value of 1.5 < AOD < 3. Figure 6 shows how the increase in aerosol concentration affects the short-wave radiation changes in these cities. From the events of forest fires in the Kalimantan region, extreme conditions were found in 2002, 2006 and 2015. The fires that occurred in those years were indicated by a reduction in the amount of shortwave radiation (SW) above these cities caused by the accumulation of aerosol particles.

As happened in 2002, the accumulation of aerosol particles emitted from forest fires at that time, caused the absorption of SW radiation to only reach -95.6 watts/m² in Palangkaraya, where the AOD value reached 3.15. The relationship between the accumulation of aerosol particles and the amount of radiation absorption that occurs is quite high (R² = 0.70). While the smaller AOD value of 2.99 was found in Pontianak and showed the effect of radiation absorption of SW of -125.5 watts/m², a greater value compared to what happened in Palangkaraya. Statistically, the correlation of relation shows a very high correlation with R² = 0.91. In Banjarmasin and Samarinda, the events of the 2002 forest fire also showed an increase in the AOD value, only the accumulation of aerosol particles that occurred at that time, did not have a significant effect on the flux of the radiation divergence.

Similar to what happened in 2002, in the event of a forest fire in 2006, an increase in aerosol concentrations occurred in Palangkaraya and Pontianak, each of which was indicated by an increase in AOD values of 2.53 and 3.15, respectively. But the response to the increase in AOD values in the two cities was quite different from what happened in 2002. Compared to the increase in aerosol concentrations in Palangkaraya (AOD = 2.53), the concentration of aerosols in Pontianak experienced a higher increase (AOD = 3.15). But in influencing radiation, the accumulation of aerosol particles covering the city of Palangkaraya shows a stronger influence (shortwave divergence values in Palangkaraya -48.1 watts/m²), compared to Pontianak which shows the amount of radiation energy absorption reaches -128.3 watts/m².

The extreme conditions in the event of forest fires in Kalimantan were discovered in 2015. The accumulation of aerosol particles that occurred in 2015 has also led to increased concentrations of aerosol particles in Palangkaraya, Pontianak, Banjarmasin, and Samarinda. However, as happened in 2002 and 2006, a significant increase in the concentration of aerosol particles occurred only in Palangkaraya (AOD = 3.32; R² = 0.95) and Pontianak (AOD = 2.65; R² = 87). While the other two cities, that is Banjarmasin and Samarinda, only showed an increase in AOD value <1.5, and the effect on radiation flux was not significant. Based on the explanation of Rascke et al [8] that the different radiation responses to the AOD magnitude are very dependent on the chemical composition, the diameter size distribution and the type of aerosol particles that greatly affect the reflection power and absorption power.

Kalimantan is known as an area that has peatland content. According to Stockwell et al [30] that the chemical content of peatlands consists of the same chemical composition as carbon, CO, CO₂, CH₄, SO₂, and some heavy metals. The difference that occurs between Palangkaraya and Pontianak both from its AOD value and from the amount of absorption of short-wave radiation that occurs above the two cities, the authors suspect that it is influenced by many factors. Referring to Stockwell et al's explanation [30]...
the differences that occur in Palangkaraya and Pontianak are probably caused by differences in the concentration of each chemical element contained in peat, the type of peat burning itself, or possibly other factors. This is very interesting and needs to be studied more deeply to be able to prove it.

Figure 6. (above) Trends in short-wave radiation divergence in the cities of Pontianak, Palangkaraya, Banjarmasin and Pekanbaru, and (below) trends in the size of aerosol particle emissions (in AOD quantities) for Pontianak, Palangkaraya, Banjarmasin and Pekanbaru in the same time period.

4. Conclusion
The characteristics of short-wave divergence (SW) and long-wave divergence (LW) for the average Indonesian region show seasonal cycles that depend on the position factor for the sun. The minimum SW divergence on average occurs in March, which is around the value of -238.2 watts/m² and the maximum SW divergence on average occurs in June, which amounts to approximately -205.2 watts/m². LW divergence shows a reverse trend of the SW divergence pattern by reaching a minimum in June of 346.8 watts/m² and a maximum of 349.9 watts/m² in October. Anomalous trends for the three components of SW divergence flux, LW divergence flux and net radiation divergence flux during the
period January 2001 to June 2017 showed that the energy fluctuations absorbed and released were quite low, which averaged no more than -5 watts/m² and 5 watts/m².

The emission of aerosol particles originating from very large / extreme forest fires will increase the attenuation value of aerosols (AOD) which will affect the radiation flux of the energy. The accumulation of high concentration aerosol particles (AOD > 2.5) will have a significant effect especially on SW radiation energy flux. As an example of extreme forest fires that occurred in the period September-October-November 2015 in Palangkaraya. In this period the high concentration of aerosol particles shown by the value of AOD = 3.32 has affected the absorption of radiation energy that reaches the surface of the earth.

From the analysis of temporal variations on a smaller scale (urban area) the effect of aerosols on SW radiation flux can be very clearly seen in the case of very large/extreme forest fires. In the urban area, the accumulation of very high concentration of aerosol particles (presented with AOD values > 2.5), shows a very high correlation with changes in the flux of the SW radiation divergence (R² 0.70 - 0.95).

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