Remote sensing of droplet number concentration of aerosol-induced clouds during the 2019 fire event in Borneo, Indonesia

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Abstract. The droplet number concentration of liquid water clouds \(N\) is estimated based on the optical thickness \(\tau\) and particle effective radius \(r_{eff}\) retrieved from the measurements of the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard of Terra satellite. Two measurements of MODIS taken from 15 June 2019 (case A) and 15 September 2019 (case B) are analyzed. They represent a condition before and during the 2019 fire event in Borneo, Indonesia. The result shows, that the domains of \(\tau\) and \(r_{eff}\) are comparable for the two cases. While there is no sign of systematic bias in case of \(\tau\), the analysis of \(r_{eff}\) tells differently. Clouds with smaller droplets, less than 12 \(\mu m\), are more prominent in case B, indicating the present of aerosol-induced clouds. In case A, the frequency distributions of clouds with larger droplets, more than 12 \(\mu m\), are systematically higher. The magnitudes of \(N\) in case A are mostly less than 100 \(cm^{-3}\), which exhibit a background condition. Extreme magnitudes of \(N\), from 200 to 800 \(cm^{-3}\), are found in case B. Those excessive numbers are attributed to the region where the aerosol-induced clouds are observed.

1. Introduction

Cloud and aerosol are important components in our atmosphere, which govern the Earth’s energy budget. Therefore, understanding their cycles and interactions are important. At certain sizes and conditions, aerosol particles serve as the cloud condensation nuclei (CCN). Aerosols serving as CCN are important elements for the hydrological cycle and climate. They are capable to change cloud microphysical and radiative properties. The cloud droplet number concentration \(N\) is a major indicator, that is commonly used to study impacts of aerosol particles (hereafter referred to as aerosols) on cloud optical and microphysical properties. Changes in \(N\), driven by changes of the number of aerosols, lead to changes of the cloud albedo. Under increasing aerosol number concentrations, clouds tend to have more, but smaller droplets, and thus reflect more solar radiation. [1] argued, that enhanced CCN concentrations for a fixed liquid water content \(LWC\) enhance \(N\), leading to an increase of cloud albedo. This phenomena is widely known as the first aerosol indirect effect or the Twomey effect [2]. Furthermore, aerosol-cloud interactions directly influence the cloud microphysical process, thus leading to changes of spatio-temporal distribution of precipitation, rather than on the globally-averaged amount of precipitation [3].
Increased $N$ has been argued to suppress precipitation and lead to thicker and more persistent clouds [4]. This phenomena has been known as the aerosol second indirect effect.

Indonesia is one of the countries with largest areas of peatland. According to [5], nearly 40% of world’s tropical peatland is settled in Indonesia. This becomes the largest among countries in the tropics. Most of areas with peatland are located in Borneo (Kalimantan). Undisturbed peatlands typically have high moisture content, making them naturally resilient to fire. It is widely known, that Indonesia’s peatland are experiencing deforestation and conversion to agriculture. During this conversion, drainage canals are installed, lowering the water table and making the peatland more susceptible to burning. However, most of the fires have been deliberately set to clear peatland for commercial palm oil plantations [6]. The fires emit considerable amounts of aerosols and trace gases, contributing to climate change and causing regional air pollution. The trend of forest fires apparently increase or still exist in upcoming years. Not only brings negative impacts on human and economic, the burning has endangered the environment security and animal (e.g., orang utan) in the region. Severe fire events in Indonesia occur during periods of drought, resulting in strong seasonal and inter-annual variability. Droughts lower the water table, exposing more peat and increasing susceptibility to burning. Fires frequently occur during September-October. Within this period, Indonesia is experiencing dry season, which is commonly coupled by El Nino. As the result, large fires across Borneo and Sumatra are likely. It has been recognised as a consistent and severe environmental threat to Indonesia and its neighbours.

Biomass burning from open vegetation fires, such as peatland, is one of the largest aerosol sources worldwide. It contributes to a significant fraction of the CCN burden. The burning injects particles into the air and cause CCN concentration outbursts in the respective region [7]. Satellite remote sensing is commonly used to study and observe global $N$ in recent years. This technique brings a major step forward in advancing science questions due to vastly increased spatial and temporal sampling. In this study, we aim to use a satellite passive remote sensing to analyze the impacts of recent fire in Borneo, Indonesia. It is assumed for being related in altering the cloud optical and microphysical properties, and therefore $N$. In this paper, data and satellite measurements are discussed in Sec. 2. Sec. 3 explains the research methodology, including forward simulation and retrieval technique. The estimation of droplet number concentration is given in Sec. 4. Results are discussed in Sec. 5 and ultimately, conclusions are given in Sec. 6.

2. Data and satellite measurements

Primary data are taken from measurements of the Moderate Resolution Imaging Spectroradiometer (MODIS) - Terra version 6.1, namely MOD021KM. The instrument detail has been described in e.g., [8]. Therefore, only essential features are discussed here. The product contains calibrated and geolocated radiances at 36 spectral bands distributed between 0.41 and 14.2 μm. Those bands include 20 reflective solar bands (RSB) and 16 thermal emissive bands (TEBs), that have a nadir horizontal resolution of about 1 km. For further data processing, the geolocation product is needed. The corresponding geolocation product, namely MOD03, provides geodetic coordinates, ground elevation, and measurement geometries.

Figure 1 shows MODIS-Terra images over Borneo, Indonesia, which are analyzed in this study. Two cases have been selected to represent the condition before and during the 2019 fire event in Borneo, Indonesia. Those are represented by measurements on 15 June 2019 and 15 September 2019, respectively. Both measurements are taken at 02:30 UTC. Therefore, both represent a condition during the dry-season in Indonesia. In the first image from 15 June 2019 (hereafter referred to as case A), it can be seen that the atmosphere is covered by natural clouds (cumulus and cirrus) only, which spread all over the island. There are no point sources observed. In contrast, the second image from 15 September 2019 (hereafter referred to as case B) clearly indicates few point sources attributed to the burning forest or peat. The smokes are blown from
Figure 1. MODIS RGB images from 15 June 2019 and 15 September 2019. Both images are taken at 02s:30 UTC. The red box indicates point sources and aerosol-induced clouds.

South-East to North-West direction, following the wind direction. The trails are exposed clearly in Figure 1b, inducing cloud developments in the respective direction (see the red box). Those are identified as the aerosol-induced clouds.

3. Retrieval methodology

3.1. Forward simulation

One-dimensional (1-D) radiative transfer simulation is performed to calculate the spectral upward radiance $I$ (hereafter referred to as the forward model) using the discrete ordinate radiative transfer solver (DISORT) version 2 [9] in the library for radiative transfer libRadtran [10]. The simulation covers wavelengths in the visible to near infrared (VNIR) and the short-wave infrared (SWIR) region. To simplify the model, a standard vertically homogenous cloud is applied. The cloud altitude is fixed between 2 and 3 km, that represents characteristics of liquid water clouds. As the retrieval does not use absorption wavelengths of trace gases, such as water vapor $\text{H}_2\text{O}$ and oxygen $\text{O}_2$, the assumption made for the cloud altitude should not be critical. To account the surface heterogeneity in the model, the spectral surface albedo $\rho$ is taken from the MODIS albedo product [11]. The standard atmospheric profile of tropical summer by [12] and the standard aerosol profile by [13] are implemented. The optical properties of liquid water droplet are derived from [14], whereas the reference spectra of extraterrestrial irradiance is taken from [15]. For the molecular and gas absorption, the parameterization of the low atmospheric transmission (LOWTRAN) by [16] adopted from the Santa Barbara DISORT atmospheric radiative transfer (SBDART) [17] is used. The output altitude is set at the top of atmosphere (TOA) to represent the instrument altitude.

3.2. Retrieval algorithm

A classical lookup table approach is applied too obtain $\tau$ and $r_{\text{eff}}$ [18, 19]. The lookup table consists of a pair of radiance measurements, one in the visible to near infrared (VNIR) and one in the short-wave infrared (SWIR) region. The selected wavelengths must provide high sensitivity to the retrieved parameters in order to minimize the retrieval uncertainty. It is known that $N$ is very sensitive to $r_{\text{eff}}$. Therefore, well retrieved $r_{\text{eff}}$ should be assured. In this study, a set of measurements at $\lambda = 645$ nm and 2100 nm are utilized. They correspond to MODIS bands.
Radiance at 2100 nm (W m\(^{-2}\) nm\(^{-1}\) sr\(^{-1}\)) and 7, respectively. While \(\lambda = 645\) nm is profoundly sensitive to \(\tau\), \(\lambda = 2100\) nm provides enough information on \(r_{eff}\), particularly that represents particle sizes at the cloud top. It is needed to satisfy the problem of \(N\).

\[
\begin{align*}
\text{Figure 2.} \quad & \text{Lookup tables of spectral upward radiance for various } \tau \\
& \text{and } r_{eff}. \text{ The simulations are made for a solar zenith angle of 30° (grey) and 45° (red).}
\end{align*}
\]

Figure 2 shows an example of the lookup table of \(I\) with various combinations of \(\tau\) and \(r_{eff}\). The radiances are simulated for two solar zenith angles \(\theta_0\), 30° (grey) and 45° (red). For \(\tau\), the lookup table covers values from 2 to 40. Meanwhile for \(r_{eff}\), the simulations cover values from 4 to 24 \(\mu m\). Both are calculated with a relative fine step, 1 for \(\tau\) and 1 \(\mu m\) for \(r_{eff}\). For retrieving all pixels in the MODIS image, such pre-calculated tables need to be made. Not only \(\tau\), \(r_{eff}\), and \(\theta\), other related parameters such as the instrument zenith angle \(\theta\) and the relative azimuth angle \(\phi\) should be varied. The retrieval is performed by interpolating measurements at \(\lambda = 645\) and 2100 nm within the solution space in the lookup table until the optimal solution is found. The lookup tables show that the sensitivity decreases with increasing \(\tau\) and \(r_{eff}\), indicated by the denser grids. In general, this represents higher retrieval uncertainties for larger domains. The uncertainty is further enhanced for larger \(\theta\) as the number of photons is reduced with increasing radiation path length.

4. Estimation of cloud droplet number concentration

In this study, \(N\) is estimated mainly based on \(\tau\) and \(r_{eff}\) with some constraints, as described in [20, 21, 22]. The bulk cloud property of \(\tau\) is defined as,

\[
\tau = \int_{z_{\text{base}}}^{z_{\text{top}}} b_{\text{ext}}(\lambda, z)dz
\]

where \(b_{\text{ext}}\) is the spectral volumetric extinction coefficient in the unit of m\(^{-1}\) and \(z\) is the geometrical altitude above sea. \(\tau\) represents a bulk value due to the integral of \(b_{\text{ext}}\) from the cloud base \(z_{\text{base}}\) to the cloud top \(z_{\text{top}}\). [23] defines \(r_{eff}\) as the ratio of the third (volume) to the second (area) moment of a droplet size distribution to aid the inversion of remotely sensed data.

\[
\begin{align*}
\text{(2)} \quad & r_{eff} = \frac{\int_{0}^{\infty} \pi r^3 n(r)dr}{\int_{0}^{\infty} \pi r^2 n(r)dr}
\end{align*}
\]

where \(n(r)\) is the number concentration of droplets of radius \(r\). Assumptions are commonly used to estimate \(N\). The liquid water content \(LWC\) is assumed to increase linearly with altitude.
The cubic ratio between the volume mean radius $r_{\text{mean}}$ and $r_{\text{eff}}$, namely $k$, is presumed to be constant. In this study, $k$ is set to 0.8, which applies for most liquid water clouds. If it is constant with altitude, $N$ can be formulated as follows,

$$N = \frac{10^{1/2}}{4\pi \rho w^{1/2}} \Gamma_{\text{app}}^{1/2} \frac{r_{\text{eff}}^{1/2}}{r_{\text{eff}}}$$  \hspace{1cm} (3)$$

$\rho_w$ is the water density, that is equal to 1 gm$^{-3}$. Parameter $\Gamma_{\text{app}} = f_{\text{ad}} \Gamma_{\text{ad}}$ defines the estimated water content lapse rate, where $f_{\text{ad}}$ is the adiabatic degree. For non-precipitating clouds, $f_{\text{ad}}$ yields a high proximity to unity, so-called adiabatic clouds. For simplifications, $f_{\text{ad}} = 1$ is assumed, that leads to $\Gamma_{\text{app}} = \Gamma_{\text{ad}}$. Clouds analysed in this study are restricted to those located between 2 and 3 km (800 hPa). This corresponds to the temperature $T \approx 10^5$. In this case, $\Gamma_{\text{ad}}$ yields a value of 2 gm$^{-1}$km$^{-1}$. Substituting all those values to Eq. 3, the final form of $N$ can be written as,

$$N = 1.4067 \times 10^{-6} \left[ \frac{r_{\text{eff}}^{1/2}}{r_{\text{eff}}} \right]$$  \hspace{1cm} (4)$$

It should be kept in mind, that $r_{\text{eff}}$ in Eq. 3 and 4 should represent a condition at the cloud top. Using measurements of satellite passive remote sensing, such as MODIS, $r_{\text{eff}}$ at the cloud top can be inferred using wavelengths with high absorption of cloud particles, such as $\lambda = 2100$ nm. $N$ is commonly expressed in unit of cm$^{-3}$. Hence, the unit of $r_{\text{eff}}$, which is commonly in $\mu$m, needs to be adjusted accordingly.

5. Result and discussion

In order to quantify $N$, conditions described in Sec. 4 must be fulfilled. Ice (cirrus and contrail) and mixed-phase clouds must be filtered. The cloud filtering algorithm by [24] is applied for this purpose. Thus, it should be noted, that only liquid water clouds are analyzed in this study. Additionally, only clouds with $r_{\text{eff}}$ between 4 and 24 $\mu$m are taken into the analysis. While smaller $r_{\text{eff}} (< 24 \mu$m) are often linked to aerosols, larger $r_{\text{eff}} (> 24 \mu$m) are considered to be precipitation droplets. Those can lead to biases in the analysis. Figure 3 depicts the maps of $\tau$ (left), $r_{\text{eff}}$ (middle), and $N$ (right) for cases A (top) and B (bottom). For case A, the clouds are more distributed all over the area. They are not only located over the island, but also over the Java sea (Southern part). Whereas for case B, the clouds are more concentrated over the island. The distribution patterns are attributed to the atmospheric dynamic condition during the measurements. In general, the clouds shown in Figure 3 represent cumulus and convective clouds, indicated by medium-high $\tau$ and $r_{\text{eff}}$. These clouds are typically found near equator, which are characterized by high temperature and relative humidity.

The values of $\tau$ for both cases are located in same domain. It can be judged by the small significant gradation of the color. The same condition applies for $r_{\text{eff}}$. The values of $\tau$ are varied between 2 and 60. Due to the filtering, the values of $r_{\text{eff}}$ are in the range of 4 to 24 $\mu$m. Overall, it can be seen that $\tau$ and $r_{\text{eff}}$ are positively related. Increasing $r_{\text{eff}}$ should be in general followed by $\tau$ as the extinction cross section increases with size. However in the particular area, where the aerosol-induced aerosols are detected (see the red box), the clouds have relatively large $\tau$ (20) but with small $r_{\text{eff}}$ (< 10 $\mu$m). During the fire, a large amount of aerosols, such as smoke and black carbon, are released into the atmosphere. It is known that aerosol serves as the cloud seed, namely the cloud condensation nuclei (CCN). Assuming the similar amount of water vapour in both cases, but more aerosol CCN in case B, this will generate clouds with smaller $r_{\text{eff}}$ in case B, and therefore, higher $N$. Contrarily, due to less aerosol CCN, clouds in case A have larger $r_{\text{eff}}$, and therefore, less $N$. 

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Figure 3. Cloud optical thickness (left), particle effective radius (middle), and droplet number concentration (right) from the cases of 15 June 2019 (top) and 15 September 2019 (bottom). Data only represent liquid water clouds.

Figure 4. Histogram plot of cloud optical thickness (a), particle effective radius (b), and droplet number concentration (c).

Figure. 4 shows the frequency distribution (histogram) of $\tau$ (a), $r_{\text{eff}}$ (b), and $N$ (c) for cases A (grey) and B (black). In this analysis, data are binned in five different domains with bin edges of 0, 6, 15, 30, 60 for $\tau$, 0, 6, 12, 18, and 24 for $r_{\text{eff}}$, and 0, 100, 200, 400, 800 for $N$. Furthermore, data in each bin are normalized to the number of pixels, which are 48,157 for case A and 44,207 for case B. Thus, here the histogram is defined as the normalized value. Please also note, that the labels in Figure 4 represent the mid-value per bin. The histogram of $\tau$ are comparable between both cases with no sign of systematic deviation. In average, both cases are similar. For $r_{\text{eff}}$, the occurrence of smaller particles ($< 12 \mu m$) are higher in case B. This is a clear evidence pointing to the causalities with the fire event, that produces a high amount of aerosol CCN released into the atmosphere. Larger cloud particles with $r_{\text{eff}} > 12 \mu m$ are systematically dominant in case A. It is clear, that for $N$, the histogram of the smallest domain ($< 100 \text{ cm}^{-3}$) is higher for case A This is attributed to the less amount of aerosol CCN (background condition). While for larger domains ($> 100 \text{ cm}^{-3}$), case B strongly outstrips case A. Extreme magnitudes of $N$ in case B (200-800 cm$^{-3}$) indicate, that the clouds in case B are heavily polluted due to the aerosols released by the sources.
6. Conclusion

The quantification of cloud droplet number concentration is important for a better understanding of the cloud-aerosol interactions. For liquid water clouds, the droplet number concentration can be estimated from the cloud optical thickness and the particle effective radius retrieved from the measurements of passive remote sensing. A pair of radiance measurements at 645 and 2100 nm are occupied to retrieve the cloud optical thickness and the particle effective radius simultaneously using the classical lookup table method. Data from the measurements of MODIS-Terra satellite are used to characterize the impacts of the 2019 fire event in Borneo, Indonesia, on the resulting droplet number concentration. Two images from 15 June 2019 and 15 September 2019 are analyzed in study. They represent the condition before (case A) and during the fire event (case B). A cloud filtering algorithm is implemented to discard cirrus and mixed-phase clouds. Subsequently, only cloud properties located in the valid domain are taken into the analysis.

The analysis shows, that there is no systematic deviations found in the optical thickness of the two cases. The frequency distribution of case A surpasses case B for the smallest and the largest domain. In the middle domains, case B introduces a higher number. However, in average, they are comparable. The analysis of particle effective radius shows, that clouds with smaller effective radius (< 12 $\mu$m) are more prominent in case B. Contrarily for larger effective radius (> 12 $\mu$m), the histogram of case A is systematically higher. Due to those conditions, the droplet number concentration becomes higher for case B in general. For case A, the magnitudes of droplet number concentration indicate the background condition (< 100 cm$^{-3}$). Higher concentrations (> 100 cm$^{-3}$) are more prominent in case B. The extreme magnitudes in case B (200-800 cm$^{-3}$) suggest the present of heavily polluted clouds, which are attributed to the location where the aerosol-induced clouds are observed. Based on the analyses in this study, it can be concluded, that the fire event produces an excessive amount of aerosols released into the atmosphere, which subsequently generate clouds with extremely high droplet number concentrations.

Acknowledgments

Trismono C. Krisna acknowledges SRON Netherlands Institute for Space Research for the permission in conducting the research and completing the manuscript. The authors thank the anonymous referees, who are helping to review, and therefore, to improve the manuscript.

Code and data availability

Basic codes for retrievals of cloud optical and microphysical properties are available on the version control on https://bit.ly/3h059op. Data of MODIS-Terra satellite can be downloaded on https://ladsweb.modaps.eosdis.nasa.gov/. Auxiliary data used in this study can be made available by the author upon a reasonable request.
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