Deforestation-Driven Increases in Shallow Clouds are Greatest in Drier, Low-Aerosol Regions of Southeast Asia

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Key Points:

- Deforestation in Southeast Asia drives a robust shift towards more widespread and shallower clouds on an annual timescale.
- This effect has been debated in modeling studies, but we show it for the first time observationally using two decades of satellite data.
- Some regions are especially vulnerable to deforestation-driven changes in clouds, depending on atmospheric moisture and aerosol loading.

Abstract

Anthropogenic activity drives extensive tropical deforestation, particularly in Southeast Asia where 16% of total forest cover was lost between 2000 and 2020. While land surface changes significantly affect the atmosphere, their net impact on convective clouds is not well-constrained. Here, we use satellite data to provide the first observational evidence that long-term deforestation in Southeast Asia robustly alters cloud properties, and that the magnitude of this response depends on the atmospheric environment. Deforestation drives a shift towards more widespread, shallower clouds during the daytime, with amplified effects in dry inland areas compared with moist coastal regions. Aerosols only weakly modulate the cloud fraction response, but offset the cloud top height response to deforestation, suggesting the influence of aerosol indirect effects. We conclude that the local signature of forest loss is not uniform, and regional differences in climatology must be considered when assessing deforestation impacts on clouds and the climate system.

Plain Language Summary

Humans are driving widespread deforestation in the tropics. Changes to the land surface following forest loss are generally known to affect the atmosphere, but it is hard to tell how deforestation will impact clouds in a given area. Here, we focus on Southeast Asia, a region of the world facing dramatic large-scale deforestation. We use two decades of satellite data to estimate how the loss of tropical forests impacts cloud properties. On average, we find that deforestation leads to more widespread and shallower clouds. We then look further into how this cloud response to deforestation depends on other environmental factors like moisture and aerosols. This gives us a better idea of which regions are most sensitive to changes in forest cover. Overall, our results show there is an observable cloud response to deforestation, but this response may be stronger in some regions than in others depending on underlying moisture and aerosol conditions. As forest loss continues in Southeast Asia and across the world, it is important to further study these region-dependent interactions between the atmosphere and the land surface so we can better understand the impacts of human-driven deforestation on weather and climate.

1 Introduction

Tropical forests are a key component of the global ecosystem through their roles in carbon storage, the water cycle, and biodiversity (Gibson et al., 2011). However, these forests are at increasing risk of clearing or fragmentation across the globe due to anthropogenic activity (Kim et al., 2015; Song et al., 2018). Among the frontiers of tropical deforestation, Southeast Asia has had the most spatially pervasive and highest proportional rate of deforestation in recent years (Turubanova et al., 2018). Widespread logging and expanding palm oil plantations in the region drove a 16% loss of forest cover between 2000 and 2020 (calculated as the percent difference in total forest cover fraction between the two years for the region shown in **Figure 1**), despite increased government regulation of forest clearing during that time period (Margono et al., 2014).

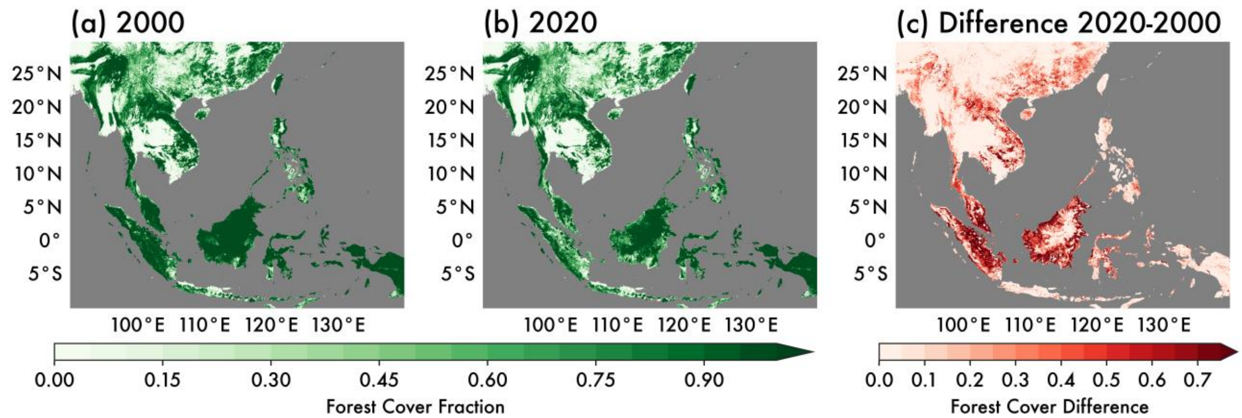

Figure 1. The fraction of forest cover in Southeast Asia in (a) 2000 and (b) 2020. (c) The difference in forest cover fraction (i.e., forest loss) between 2000 and 2020.

Apart from the many damaging ecosystem and societal effects caused by deforestation, loss of forest cover also alters the biogeophysical properties of the land surface (Gentine et al., 2019). These land surface perturbations can propagate via surface fluxes to the atmosphere on local, regional, and even global scales (Gentine et al., 2019; Mahmood et al., 2014). Extensive prior studies show that deforestation leads to increases in near-surface temperatures by reducing evapotranspiration, increasing albedo, and reducing surface roughness (Crompton et al., 2021; Davin & de Noblet-Ducoudré, 2010). The impact of such land surface changes on near-surface temperatures can be of a similar magnitude to that of changes to global CO_2 concentrations in regions where land-atmosphere coupling is particularly strong, such as in the tropics (Avila et al., 2012; Pitman et al., 2012). Land surface changes also impact the hydrological cycle — evaluating the local impacts of forest loss on clouds and precipitation is therefore crucial for managing water availability, especially given that almost half the global population lives in the tropics (Kummu & Varis, 2011). Furthermore, tropical clouds drive large-scale circulations and impact global weather through teleconnections with other regions of the world, which means that changes in local convection due to deforestation in regions such as Southeast Asia can have global consequences for weather and climate (Riehl & Malkus, 1958; Schneck & Mosbrugger, 2011; van der Molen et al., 2006).

Although the impact of deforestation on atmospheric temperature is broadly agreed upon, there is still much uncertainty around the net impact of deforestation on convective clouds and precipitation (F. Chen & Avissar, 1994; Laguë et al., 2021). Many of the fine-scale processes driving land surface-convection feedbacks are not yet sufficiently well-understood nor explicitly represented in climate models (Spracklen et al., 2018). As a result, the magnitude and even the sign of reported deforestation impacts on clouds varies across model types and regions (Lawrence & Vandecar, 2015; Takahashi et al., 2017). In Southeast Asia, contrasting modeling studies have shown that deforestation leads to less clouds due to local drying (Tölle et al., 2017) or that deforestation leads to more clouds due to strengthened moisture transport (C.-C. Chen et al., 2019). Moreover, observational evidence of these land surface-convection feedbacks has been difficult to obtain due to the relative sparsity of data (Lawrence & Vandecar, 2015) and the difficulties in attributing measured impacts to land cover changes specifically. For example, rain gauge networks over parts of Southeast Asia have observed decreases in precipitation since the

1950's (Kanae et al., 2001), but there is debate about whether these changes are driven by deforestation or by other large-scale impacts on the regional climate (Tokinaga et al., 2012).

Estimating the net impact of deforestation on convection for a specific region is challenging because the exchanges of energy, moisture, and momentum that drive land-atmosphere interactions can also be modulated by environmental properties (Findell & Eltahir, 2003). Global modelling studies show that differences in background meteorology (e.g., moisture availability, wind regimes) across regions drive different emergent responses to surface perturbations (Davin & de Noblet-Ducoudré, 2010; Findell & Eltahir, 2003; Winckler et al., 2017). The presence of aerosol particles absorbing and/or scattering radiation also alters the amount of radiation reaching the surface, and thus the partitioning of the surface energy budget (Jiang & Feingold, 2006; Leung & van den Heever, 2023). This can either dampen or strengthen cloud responses to surface perturbations depending on the aerosol loading (Grant & van den Heever, 2014; Park & van den Heever, 2022). In addition, aerosol particles can also interact with cloud microphysics, leading to either synergistic or competing impacts in cloud properties relative to surface perturbations alone (Tao et al., 2012). The uncertainty surrounding the impact of deforestation on clouds is thus compounded by region-to-region variability in thermodynamic and aerosol environments.

In this paper, we provide the first observational evidence of the impacts of long-term deforestation on cloud properties over Southeast Asia, and the variability of these impacts as a function of environmental factors. This provides insight into which regions are at highest risk of deforestation-induced changes in convective clouds. As forest loss continues to accelerate in Southeast Asia and other tropical forests around the globe, understanding the subsequent changes to clouds is essential to a fuller assessment of how future deforestation may impact humans and the broader earth system.

2 Data and Methods

We take forest cover observations from the Landsat-derived Global Forest Cover (GFC) dataset (Hansen et al., 2013). We take measurements of cloud fraction, cloud top height, precipitable water vapor, and aerosol optical depth from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Platnick et al., 2017).

Changes in the cloud field from one year to another are driven by deforestation or by other sources of interannual variability (e.g., changes in the El Niño Southern Oscillation phase). Our approach leverages the large number of sample points using the "difference-in-differences" method (Crompton et al., 2021) to separate the potential drivers of the observed cloud response. We compare the temporal change in cloud properties over deforested regions to the temporal change over a control intact forest group, which is near enough to experience the same interannual variability but far enough away so as not to experience any direct impacts from the surface deforestation-induced perturbation. The difference between the response in deforested and control regions (represented by ε) can thus be interpreted as the response attributable to the forest loss alone. The same response ε can be calculated for subsamples of the full population, which we group based on quartiles of environmental parameters, namely precipitable water (PWAT) and aerosol optical depth (AOD). Additional details of the method can be found in the **Supporting Information.**

The cloud response metrics are calculated at an annual timescale, given that forest cover metrics are only available annually. Though this does not allow us to detect deforestation impacts on clouds at finer temporal scales, it does capture the integrated annual impact, which is most relevant to the radiative budget and the overall impact of deforestation on the climate system. MODIS cloud observations are available onboard both the Terra and Aqua satellites, which have approximate overpass times of 10:30AM/PM and 1:30AM/PM respectively. We therefore calculate the cloud response separately for each of the four overpass times thereby also providing a picture of the diurnal variability in cloud responses to deforestation.

3 Results

3.1 Estimated cloud response to deforestation

During the daytime (10:30AM and 1:30PM), increasing forest loss leads to an increase in the annual cloud fraction and a decrease in the mean cloud top height (**Figure 2**). In regions facing total forest loss, the annual mean afternoon cloud fraction in the year following the deforestation event increases by up to 5%. At the same time, the annual mean afternoon cloud top height is 200m lower. Taken together, these changes indicate that the removal of forest cover leads to a local increase in coverage of shallow clouds.

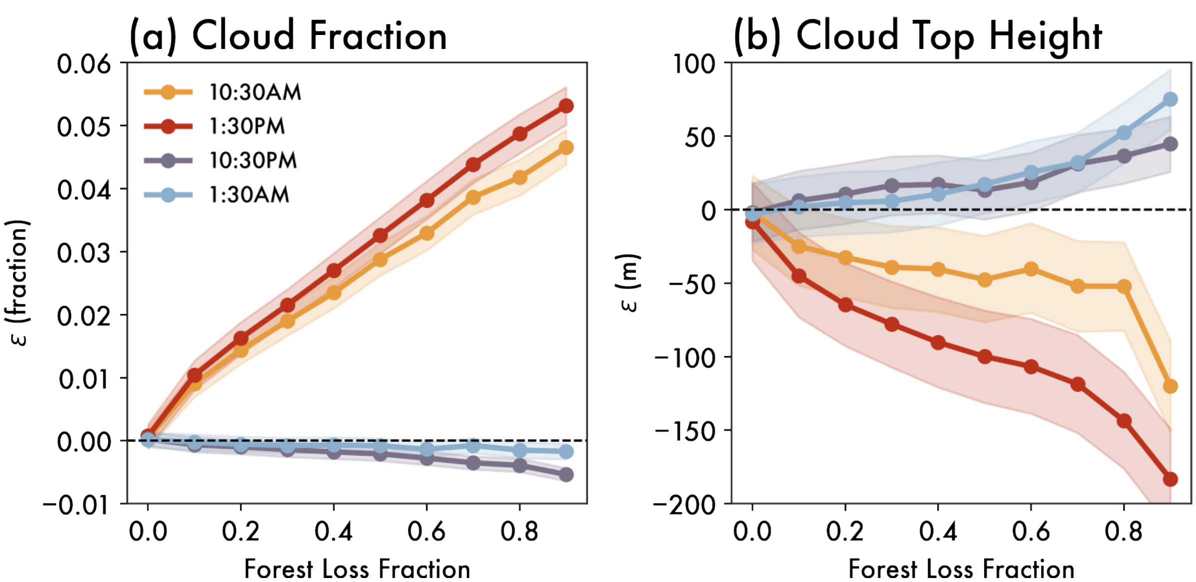

Figure 2. Estimated cloud response (ε) to mean forest loss within a 1km radius for the annual mean (a) cloud fraction and (b) cloud top height (m). Different colored lines indicate swaths from different times of day. Solid lines indicate the bootstrapped estimate of the mean (n=1000), and shaded areas span the 25th to 75th percent confidence interval.

The daytime shift to more widespread shallow clouds following deforestation provides observational evidence for previously hypothesized mechanisms involving differential heating-driven mesoscale circulations and increased moisture transport (C.-C. Chen et al., 2019). Following a conversion from forest to bare soil, the reduction in soil moisture and evapotranspiration drives local drying (Werth & Avissar, 2005), which tends to hamper cloud formation. However, the anomalous local heating due to a combination of albedo, roughness, and moisture effects (Crompton et al., 2021) can also induce mesoscale circulations that provide additional lift and transport moisture into the deforested area (Durieux et al., 2003; Wang et al., 2009). If the additional moisture source is sufficient, the combination of increased sensible heat fluxes due to a warmer surface and the additional moisture source due to mesoscale transport can then support increased cloud formation. This has previously been demonstrated using both models and observations for more well-studied regions like the Amazon (Khanna et al., 2017; Wang et al., 2009). However, the same may not necessarily apply for Southeast Asia, where the land area covers a much smaller fraction of the surface and is more maritime in nature. Though a handful of regional models have proposed the same mechanism may also apply in Southeast Asia (C.-C. Chen et al., 2019; Lee & Lo, 2021), this work provides the first observational evidence that deforestation in Southeast Asia causes more widespread and shallower clouds through these effects on the mesoscale circulation.

The magnitude of the cloud response to deforestation is largest during the afternoon (1:30PM) and close to negligible at nighttime (10:30PM and 1:30AM) (**Figure 2**). This diurnal variation supports the idea that any changes in the cloud field following forest loss are driven by differential solar heating between forested and deforested regions. In the afternoon, the cloud response is largest, since surface heating has had sufficient time to drive strong mesoscale circulations and moisture transport. At night, however, the circulations and associated moisture transport into the deforested region is shut down and the local moisture sources are no longer sufficient to support additional cloud development.

3.2 Modulation by precipitable water

To better understand the variability in cloud responses to deforestation, we segment the regional mean response (**Figure 2**) into different environmental regimes (as described in **Supporting Information**). **Figure 3** explores deforestation-induced changes to cloud properties as modulated by precipitable water vapor (PWAT), the integrated amount of water vapor in the atmospheric column. Areas that fall into the lowest quartile of PWAT (~48mm) are generally inland or blocked by terrain, while regions in the highest quartile of PWAT (~57mm) are typically coastal (**Figure S2a**). It should be noted that the low and high PWAT divisions used here are relative terms, since even areas of Southeast Asia with lower values of PWAT are still in the humid tropics and thus have more moisture available than more arid continental areas.

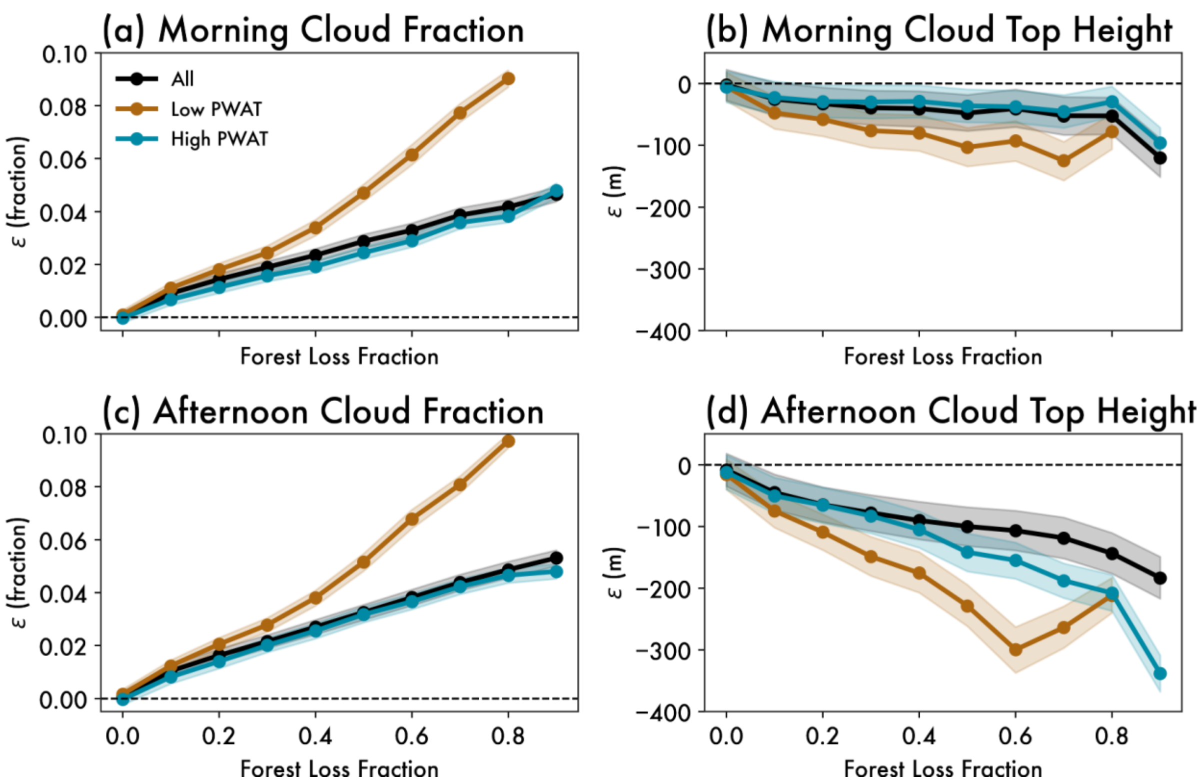

Figure 3. Dry regions experience enhanced deforestation impacts on cloud fraction and cloud top height. As in Figure 2, but data are segmented according to precipitable water (PWAT) quartile as described in the text. (a,b) show the Terra daytime overpasses (10:30AM), and (c,d) show the Aqua daytime overpasses (1:30PM).

We find that the overall sign of the cloud responses to increasing forest loss do not depend on PWAT. That is, across all PWAT quartiles, regions with more forest loss tend to have higher cloud fractions and lower cloud top heights, and this effect is strongest in the afternoon. However, we do find that PWAT modulates the magnitude of the cloud response, such that dry regions have a stronger response to deforestation than moist regions do. Deforestation in drier inland Southeast Asia is thus expected to perturb the cloudiness more than it would in the moist coastal areas of the region.

The net impact of forest loss on convection depends on a combination of local changes to moisture availability and mesoscale changes in lifting and moisture transport (Mahmood et al., 2014). We can assess the relative importance of these two processes based on the modulation of deforestation impacts by PWAT. The land surface in dry regions heats up faster than in moist regions, since less energy is needed to evaporate liquid water and drive latent heat fluxes. This leads to stronger thermal contrasts between forested and deforested regions, and thus stronger mesoscale circulations and increased mesoscale moisture transport. Although the deforested area sees a decrease in moisture available from local evapotranspiration, this is apparently outweighed by the increase in moisture available from mesoscale transport. Because we see that the cloud response to forest loss is strongest in low PWAT areas, our findings thus support the notion that mesoscale transport is the dominant process by which deforestation impacts convection in Southeast Asia.

3.1 Modulation by aerosol optical depth

In addition to the role of moisture in deforestation-cloud impacts, we also examine the role of aerosol loading in modulating cloud responses to deforestation. **Figure 4** shows the cloud response to forest loss according to aerosol optical depth (AOD), the integrated amount of light extinction by aerosol particles in the atmospheric column, and which here serves as a satellite-observable proxy for aerosol loading. Areas in the low aerosol category have AODs below ~0.2, while those in the high aerosol category have AODs above ~0.4 (**Figure S2b**). A higher concentration of aerosol particles (higher AOD) would tend to result in less solar radiation reaching the surface, thus reducing the importance of surface perturbations on the overall circulation (Park & van den Heever, 2022).

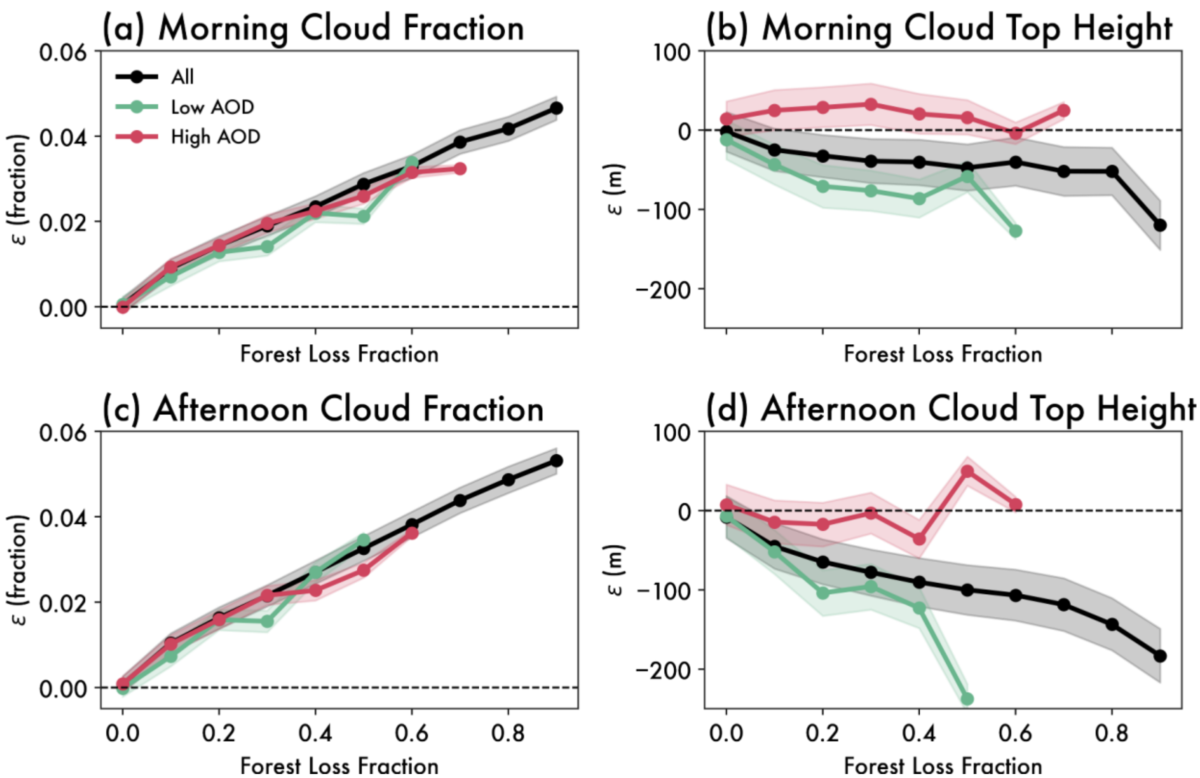

Figure 4. High aerosol loadings dampen deforestation impacts on cloud top height, but do not modulate deforestation-induced changes in cloud fraction. As in Figure 3, but data are segmented according to aerosol optical depth (AOD) quartile as described in text.

Unlike with PWAT, we find that the response of cloud *fraction* to deforestation is not strongly modulated by AOD. In both the morning and afternoon, the low and high AOD categories are not statistically distinguishable from each other or the mean trend. This suggests that—at least for the range of AODs observed here—we do not expect a significant difference in deforestation impacts on cloud fraction between pristine and polluted environments.

On the other hand, AOD strongly modulates both the sign and magnitude of the cloud top *height* response to forest loss. In the regional mean, annual cloud top height tends to decrease with increasing forest loss, indicating a shift to shallower clouds. We find that this is still true for the low AOD category. However, negligible or even positive increases in cloud top height are evident when AOD is high. Aerosol loading could therefore offset or mask the impacts of deforestation on cloud top heights. This modulation is consistent with past work showing that the presence of more numerous aerosol particles shifts the shallow cloud distribution towards higher cloud top heights (Leung et al., 2023; Spill et al., 2019; van den Heever et al., 2011). Though the actual changes to cloud microphysics are difficult to ascertain from satellite data, particularly on annual timescales, these trends do suggest that aerosol loading is an important modulator for deforestation-convection interactions.

4 Conclusions

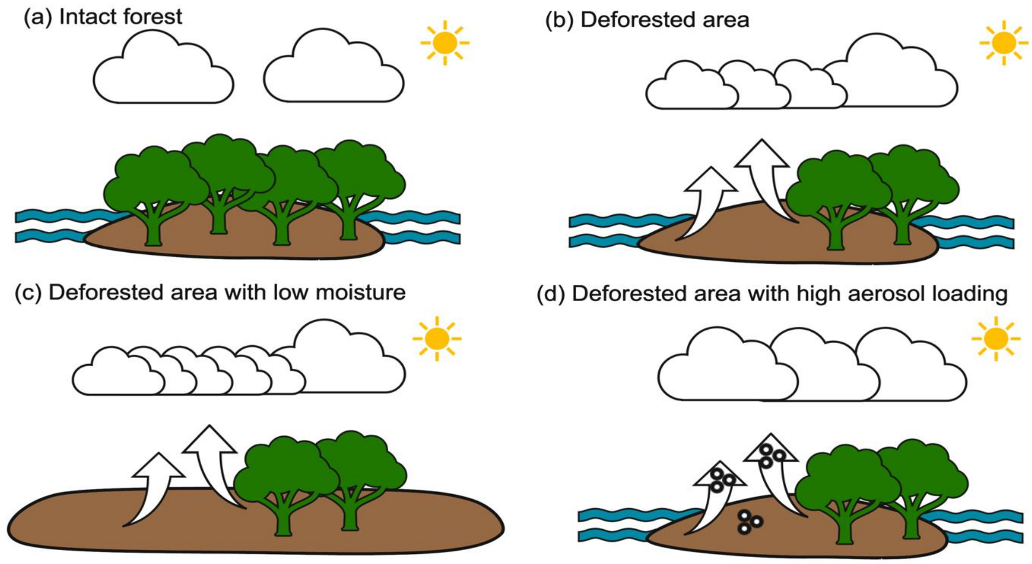

Figure 5. Schematic summarizing the impacts of deforestation on cloud properties in Southeast Asia, as well as how these impacts are modulated by moisture and aerosols. (a) Clouds forming over intact forest during daytime. (b) When area is deforested, mesoscale circulations form (white arrows) that support increased development of shallow clouds (leading to more widespread coverage, but shallower clouds on average in deforested areas compared to forested ones) by transporting moisture from nearby sources, such as oceans. (c) In an inland region that has relatively low moisture available in the atmosphere, the impact of deforestation on clouds is magnified (even more widespread coverage and shallower clouds on average compared to b). (d) In a region with high aerosol loadings (black circles), the impact of deforestation on average cloud fraction is the same (same coverage of clouds as in (b)), but the impacts on cloud top height are dampened (cloud top heights are similar between forested and deforested areas).

In conclusion, these results represent the first observational evidence that there is a robust and detectable cloud response to deforestation in Southeast Asia, and that these cloud responses are dependent on other environmental parameters. Mesoscale circulations between forested and deforested areas are likely the dominant mechanism for providing lift and transporting moisture, particularly in Southeast Asia where much of the deforested land is impacted by maritime airmasses due to proximity with the ocean (**Figure 5a,b**). This study therefore also resolves past debates arising from regional modeling studies regarding whether cloudiness increases or decreases following deforestation. Such perturbations to tropical clouds can have notable consequences through their influence on the radiative budget and the water cycle, resulting in downstream climatic and societal impacts.

Moreover, we also find that the magnitude of the observed cloud response to deforestation is strongly modulated by environmental factors such as moisture and aerosol loading. Dry regions experience a stronger cloud response than moist regions do (**Figure 5c**). Meanwhile, high aerosol loadings may mask the impact of forest loss on cloud top heights due to aerosol-induced surface cooling impacts and aerosol indirect effects offsetting one another (**Figure 5d**). These results emphasize that the local signature of forest loss is not uniform, and that some areas are particularly susceptible to deforestation-driven changes in clouds due to climatological factors. Though often overlooked, taking this variability into account is essential for accurately assessing the impacts of deforestation on weather, hydrology, and future climates, especially as the rate of forest loss continues to accelerate in Southeast Asia and in other tropical forest regions around the world.

Acknowledgments

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Open Research

The UMD Global Forest Cover data are available at https://storage.googleapis.com/earthenginepartners-hansen/GFC-2022-v1.10/download.html. The MODIS cloud property data are available at http://dx.doi.org/10.5067/MODIS/MOD06_L2.006 (Terra) and http:// dx.doi.org/10.5067/MODIS/MYD06_L2.006 (Aqua). The MODIS PWAT data are available at http://dx.doi.org/10.5067/MODIS/MOD05_L2.061 (Terra) and http:// http://dx.doi.org/10.5067/MODIS/MYD05_L2.061 (Aqua). The MODIS AOD data are available at http://dx.doi.org/10.5067/MODIS/MOD04_3K.006 (Terra) and http://dx.doi.org/10.5067/MODIS/MYD04_3K.006 (Aqua). Analysis and plotting code are available on GitHub at: https://github.com/grleung/satlcc.

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