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Key Points:

- Radiative impact of cloud overlap in the UTLS is characterized using satellite retrievals
- Its sensitivity to the properties of top and bottom-layer clouds is quantified
- Bottom-layer clouds can fully suppress radiative impact of high clouds

Supporting Information:

- Supporting Information S1

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How Does Cloud Overlap Affect the Radiative Heating in the Tropical Upper Troposphere/Lower Stratosphere?

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Abstract Characterizing two-layer cloud systems has historically been difficult. These systems have a strong radiative impact on the composition of and the processes in the upper troposphere-lower stratosphere (UTLS). Using 4 years of combined spaceborne lidar and radar observations, the radiative impact of two-layer cloud systems in the tropical UTLS is characterized, and its sensitivity to the properties of top- and bottom-layer clouds is further quantified. Under these overlapping cloud conditions, the bottom-layer clouds can fully suppress the radiative heating caused by high clouds in the UTLS, by inducing strong longwave cooling. If the vertical separation between the layers is <4 km, the radiative heating of the high cloud changes sign from positive to negative. Furthermore, the radiative effect at the top of the atmosphere is investigated, and it is found that the characteristic net warming by cirrus with ice water path <50 g/m² is suppressed in the two-layered system.

1. Introduction

On average, clouds cover two thirds of Earth's surface area and play an important role in regulating Earth's water and energy budgets (Stephens, 2005). They form precipitation that returns water to the surface and, when forming, release latent heat into the atmosphere. Moreover, clouds can reflect, transmit, or absorb incoming solar and thermal radiation. In doing so, they either cool or heat the planet and the atmosphere. How a cloud interacts with radiation depends strongly on the clouds optical thickness and cloud top height (CTH; Chen et al., 2000).

Most of the upward mass flux from the troposphere into the stratosphere takes place in the tropics (Holton et al., 1995). Here the transition between the thermally driven troposphere and the wave-driven stratosphere can extend over several kilometers and is usually referred to as the tropical tropopause layer (TTL; Fueglistaler et al., 2009). Sherwood and Dessler (2000) defined this region to extend from the level of zero net radiative heating to the highest level reached by atmospheric convection.

The importance of convection in and around the TTL has been discussed in several studies, such as Gettelman et al. (2004), Fueglistaler and Fu (2006), and Devasthale and Fueglistaler (2010). Air below the level of zero net radiative heating tends to sink, while air above this level often tends to rise. However, the exact mechanisms for the transport from the troposphere to the stratosphere are still unclear. Corti et al. (2006) suggested that cirrus clouds in and around the TTL might play an important role by enhancing the heating rate and by doing so speed up the upwelling. Gouveia et al. (2017) found that 19% (13%) of all cirrus over the Amazon had the cloud top in the TTL during wet (dry) season, while Yang et al. (2010) found profound warming in the TTL caused by cirrus. The same study also found that most cirrus present in the TTL had an underlying cloud layer. The underlying cloud layer could alter the radiative properties of the top cirrus cloud. For example, Hartmann et al. (2001) demonstrated that net radiative cooling results from a cirrus cloud located in the TTL if an optically thick cloud with a sufficiently cold cloud top is present underneath. Cloud types with sufficiently high optical thickness and low cloud top temperature to cause such cooling could be altostratus, nimbostratus, or deep convective clouds. According to Li et al. (2015) 2.5% (2.2%) of all daily observations over land (ocean) contained high clouds above altostratus. The corresponding numbers for nimbostratus and deep convective clouds were 1.0% (1.2%) and 0.4% (0.3%), respectively.

Cloud overlap has historically been difficult to observe since passive satellite sensors cannot capture the vertical structure of cloud systems, while active instruments on the ground and in situ measurements by aircraft have limited spatial coverage. Therefore, we do not have an adequate understanding of the radiative response of cloud overlap in and around the TTL. This changed with the deployment of active sensors in space: the CloudSat and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO). The CloudSat radar provides a detailed vertical structure of cloud systems, while the CALIPSO lidar can detect optically thin cirrus clouds. Using a combined data set that benefits from the strength of both instruments, the present study addresses the following three scientific questions: (1) What is the net cloud radiative heating (CRH) resulting from cirrus clouds in the TTL overlapping with another cloud layer and how does this compare to the CRH from single-layer cirrus clouds in the upper troposphere-lower stratosphere (UTLS) region? (2) How does the optical depth of a cirrus cloud affect its heating capacity under overlap conditions? (3) What role do the physical properties of the underlying clouds play?

2. Data and Method

CloudSat and the CALIPSO were launched in 2006 as part of the A-Train constellation of satellites (L'Ecuyer & Jiang, 2010; Stephens et al., 2002). CloudSat carries a 94-GHz cloud profiling radar (Stephens et al., 2008), while CALIPSO carries the Cloud-Aerosol Lidar with Orthogonal Polarization lidar that measures at wavelengths 532 and 1,064 nm (Winker et al., 2009). Traveling along the same path in the A-Train constellation, the two satellites observe the same footprint within just a few seconds.

To evaluate the radiative properties of multilayer clouds, 4 years of CloudSat and CALIPSO data, from January 2007 to December 2010, are used in this study. The vertical radiative heating (RH) and the top of atmosphere (TOA) cloud radiative effect (CRE) were collected from the 2B-FLXHR-LIDAR product (Henderson et al., 2013; L'Ecuyer et al., 2008). This product uses a broadband two-stream plane-parallel doubling-adding radiative transfer model forced by cloud and aerosol properties derived from CloudSat and CALIPSO. Scene-specific temperature and specific humidity profiles corresponding to each CloudSat profile are obtained from European Centre for Medium-Range Weather Forecast (ECMWF) analyses that have been interpolated to each radar bin and are available the ECMWF-AUX data set. The 2B-CLDCLASS-LIDAR product (Sassen et al., 2008) provides the cloud layer structure and cloud type of the top-layer cloud together with the cloud top and cloud base heights of the different layers. The optical thickness comes from the 2B-TAU product, while 2B-CWC-RVOD (Austin et al., 2009) provides the water and ice paths. Cloud microphysical information from the 2B-TAU and the 2B-CWC-RVOD products, if available, are also used for the radiation calculations in the 2B-FLXHR-LIDAR product (Henderson et al., 2013).

The term “cloud overlap” can be interpreted as either separate cloud layers with cloud-free layers in between or as a single cloud with internal layers of different microphysical structure. In this study, cloud overlap is defined as a two-layer cloud system separated by a cloud-free layer. First, all clouds that the 2B-CLDCLASS-LIDAR product defines as a two-layer cloud with a high cloud (i.e., cirrus or cirrostratus) on top are selected. Out of these two-layer cloud systems, cases when the bottom-layer cloud has an optical thickness of at least 3.6 and a CTH of at least 3.5 km are selected. This corresponds to the International Satellite Cloud Climatology Project cloud classifications of altostratus, nimbostratus, and deep convective clouds (Rossow & Schiffer, 1999). These cloud overlap cases are additionally divided into four groups, depending on the optical thickness of the top layer: 0–1.3, 1.3–3.6, 3.6–9.4, and 9.4–23. This separation is also based on International Satellite Cloud Climatology Project cloud-type classification.

The data are analyzed for the entire tropical region (30°S to 30°N). All values indicate annual means. Only daytime conditions are presented, as both longwave and shortwave components are investigated. CloudSat and CALIPSO are flying in a Sun-synchronous orbit with an inclination of 98.14°, passing the equator at 13:30 local time each day leading to a midday sampling bias. Since shortwave radiation changes depend on the solar zenith angle, a normalization of the vertical shortwave RH rates is performed using the process described in Johansson et al. (2015).

3. Results and Discussion

Figure 1 shows the vertical structure of absolute net CRH together with the longwave and shortwave components for three scenarios: SINGLE_HIGH (3.91% of all cloudy pixels, 2,467,766 cases), single-layer cloud classified as high ice cloud by the 2B-CLDCLASS-LIDAR algorithm with an optical thickness <23.

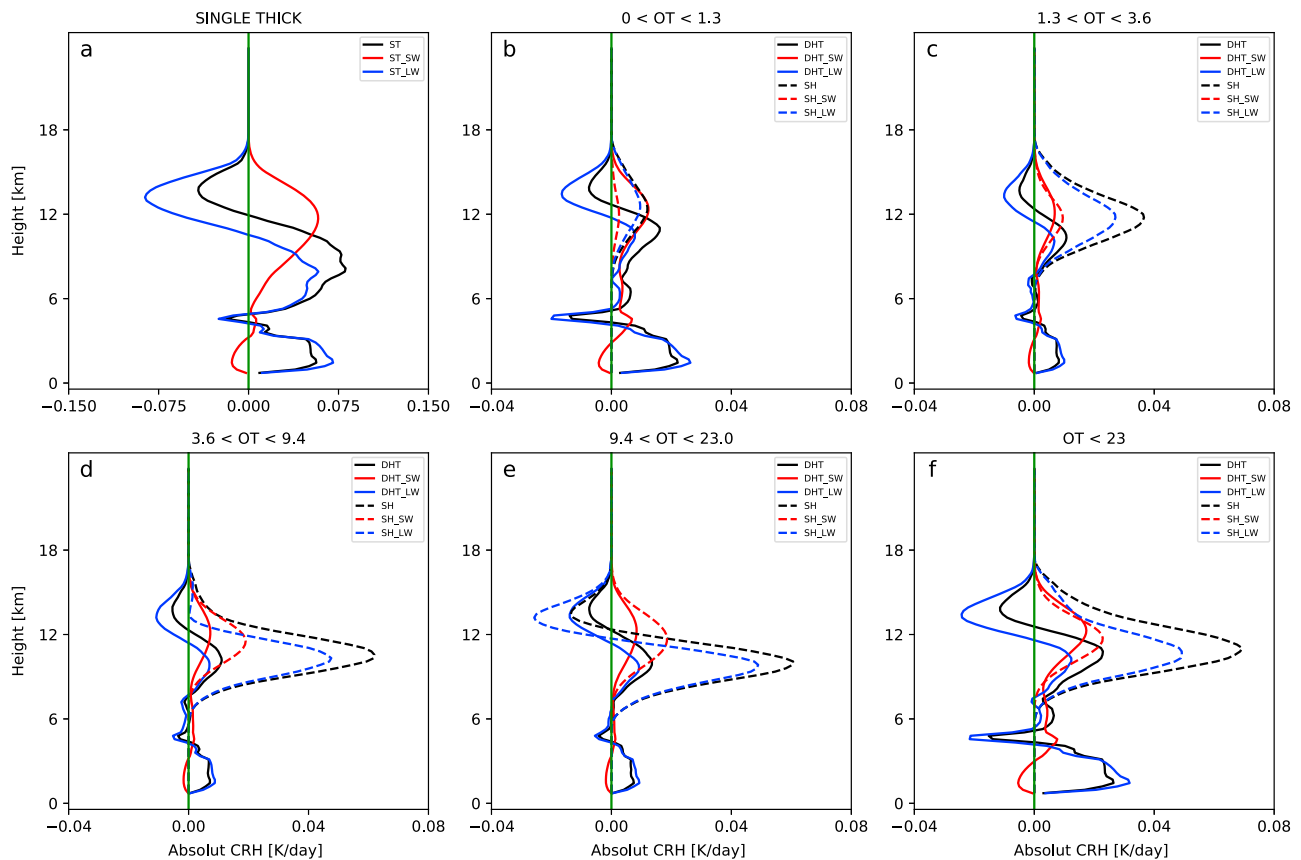


Figure 1. The vertical structure of absolute CRH. Subplot (a) shows the CRH for single-layer clouds (with optical thickness greater than 3.6, that is, scenario SINGLE_THICK discussed in the text, label ST), while the subplots (b) to (e) show CRH under two-layered cloud system (scenario DOUBLE_HIGH_THICK, label DHT) when the top-layer clouds are partitioned into different categories from optically thinnest to thickest and finally (f) that is subplot (b) to (e) combined into one category. The dotted lines show the CRH when the corresponding top-layer cloud in scenario DOUBLE_HIGH_THICK is present as a single layer (scenario SINGLE_HIGH, label SH). The red line represents the shortwave component (label SW), the blue line the longwave (label LW) component, and the black line the net CRH. The green line corresponds to zero CRH. Values below 750 m are masked out since data from the cloud-radar onboard CloudSat might be contaminated with ground clutter below this height. CRH = cloud radiative heating.

This scenario typically contains thin or thick cirrus, anvil clouds, or the remnants of deep convection; SINGLE_THICK (6.91% of all cloudy pixels, 4,356,063 cases), single-layer, optically thick cloud (optical thickness ≥ 3.6) with CTH ≥ 3.5 km and not classified as high ice cloud by the 2B-CLDCLASS-LIDAR algorithm. This scenario typically contains deep convective or altostratus and nimbostratus clouds; DOUBLE_HIGH_THICK (0.61% of all cloudy pixels, 385,250 cases), two-layer cloud system with an upper-layer cloud categorized as in scenario SINGLE_HIGH and a lower-layer cloud categorized as in scenario SINGLE_THICK. It is to be noted that, even though the THICK layer is defined in the same way for the different categories, the physical properties between them might differ (cf. Figures 2a and 2b discussed later). The CRH is calculated by subtracting the RH rates for cloudy-sky conditions with that from clear-sky conditions. This is done for longwave, shortwave, and net CRH (i.e., longwave plus shortwave). The CRH is then multiplied by the cloud fraction for each vertical layer to obtain absolute CRH (see details in Johansson et al., 2015).

Clouds described as in scenario SINGLE_THICK (Figure 1a) induce significant longwave cooling above 9 km, peaking at -0.08 K/day around 13 km. The shortwave heating peaks at 0.05 K/day around 12 km; this is also where the net CRH changes sign from warming to cooling. Below 9 km both components will contribute to a warming, except for the lowest 3 km where the albedo effect will dominate the shortwave radiation, causing it to cool the atmosphere.

The net warming by single-layer cirrus clouds (scenario SINGLE_HIGH, dashed lines in Figures 1b–1f) in the UTLS region increases as their optical depth increases until the optical depth reaches the value of 9.4,

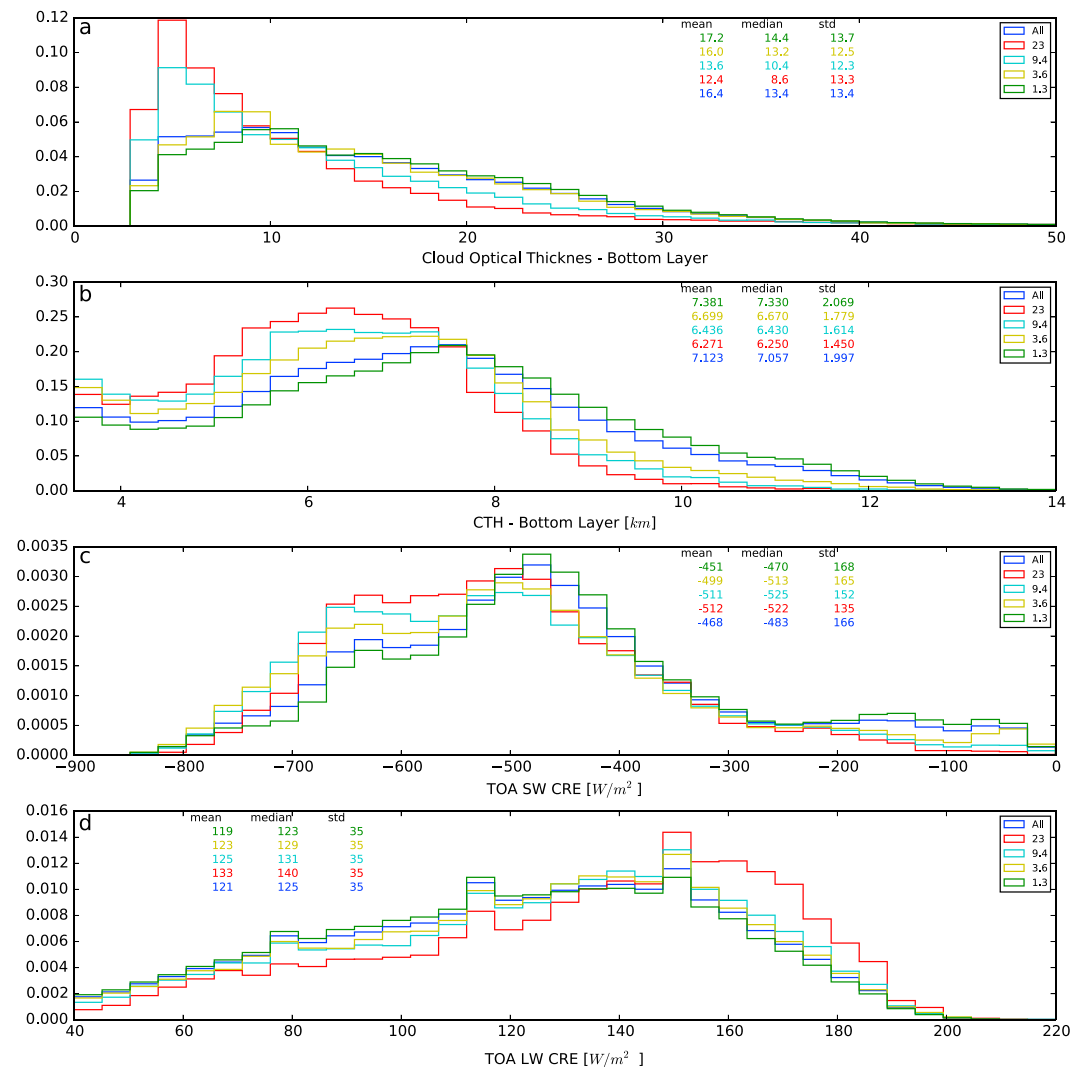


Figure 2. Histograms for clouds described by scenario DOUBLE_HIGH_THICK (cf. Figure 1) as a function of the optical thickness of the top-layer cloud. Histograms of the optical thickness for the bottom-layer cloud (a), CTH of the bottom-layer clouds (b), shortwave CRE at the TOA (c), and longwave CRE at the TOA (d) are shown. The mean, median and standard deviation values for each histogram are also shown in the subplots. CRE = cloud radiative effect; CTH = cloud top height; TOA = top of atmosphere.

peaking at 10–14 km. As these high clouds get optically thicker, strong longwave cooling at the cloud tops (-0.03 K/day) start to dominate in the UTLS region. In-cloud heating occurs at lower altitudes, and it is likely that these clouds mostly represent anvils and remnants of deep convection rather than thin cirrus. When cloud overlap occurs (scenario DOUBLE_HIGH_THICK, full lines in Figures 1b–1f), the heating caused by top-layer clouds is completely suppressed by the bottom-layer clouds to the extent that a net cooling is induced in and around the UTLS. The magnitude of this suppression is sensitive to the optical and physical properties of both layers, as discussed later.

Figures 2a and 2b describe the CTH and the optical thickness of the bottom cloud layer in scenario DOUBLE_HIGH_THICK, as a function of optical thickness of top-layer cloud (cf. categories described in Figure 1). The optical thickness of the bottom-layer cloud is positively skewed for all groups. However, the bottom-layer clouds get optically thinner as the top-layer clouds get optically thicker and vice versa. Consequently, the bottom-layer cloud reaches higher in the atmosphere as the top-layer cloud gets thinner. This result could imply that the thicker top-layer cloud radiatively suppresses the formation of a more vigorous bottom-layer cloud. Luo and Rossow (2004) found that 56% of all cirrus in the tropics were created in situ, while the rest were created by detrainment from deep convective clouds. Cirrus clouds resulting from deep

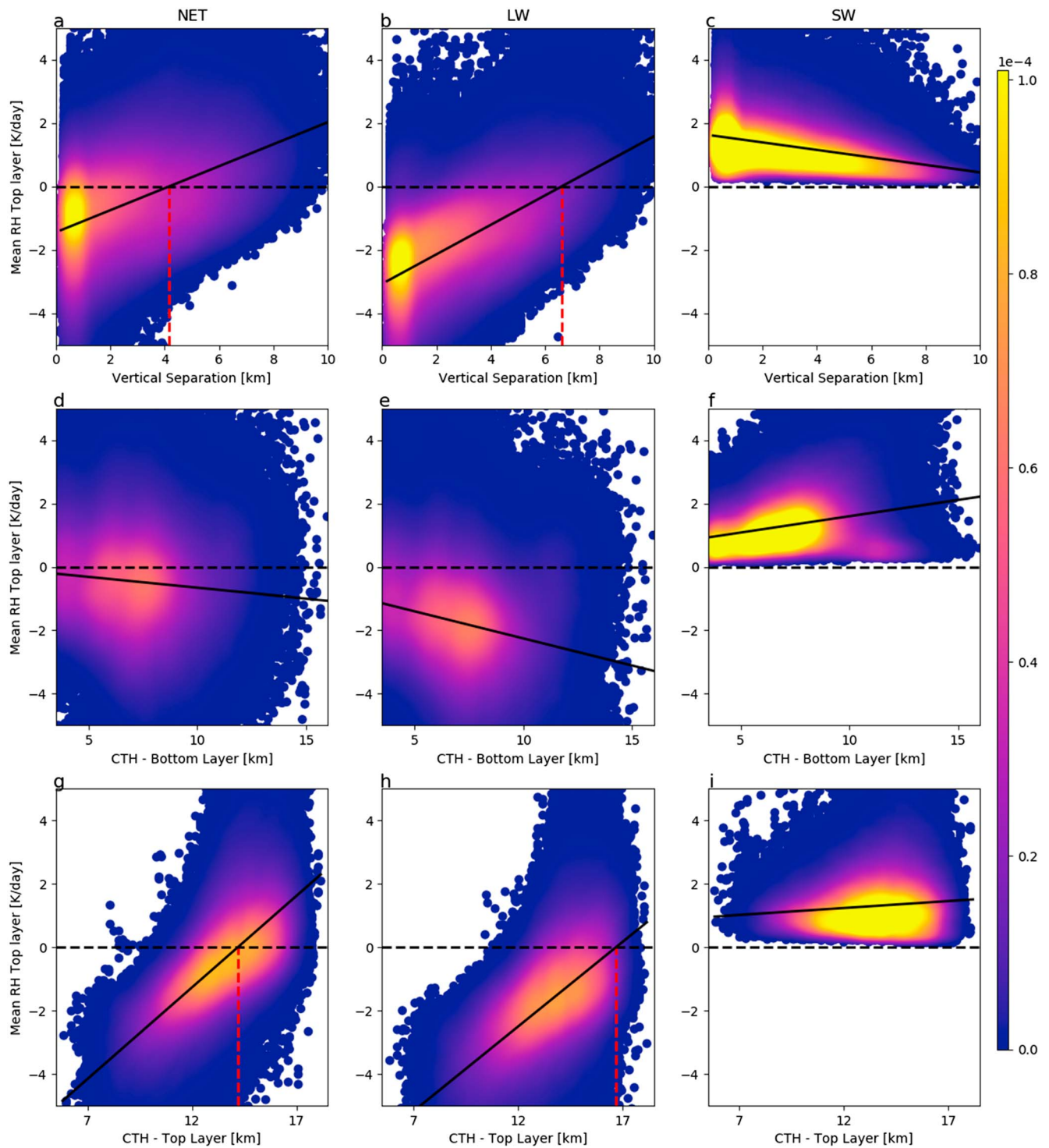


Figure 3. A kernel density estimation: (a–c) sensitivity of RH of the top-layer clouds to the vertical separation, (d–f) sensitivity of RH of the top-layer clouds to the CTH of the bottom-layer clouds, and (g–i) sensitivity of RH of the top-layer clouds to the CTH of the top-layer clouds. The net RH (column 1) as well as longwave (column 2) and shortwave (column 3) components are shown separately. All sensitivity analyses are for scenario DOUBLE_HIGH_THICK. The black line is a least squares polynomial fit to the displayed data. CTH = cloud top height; RH = radiative heating.

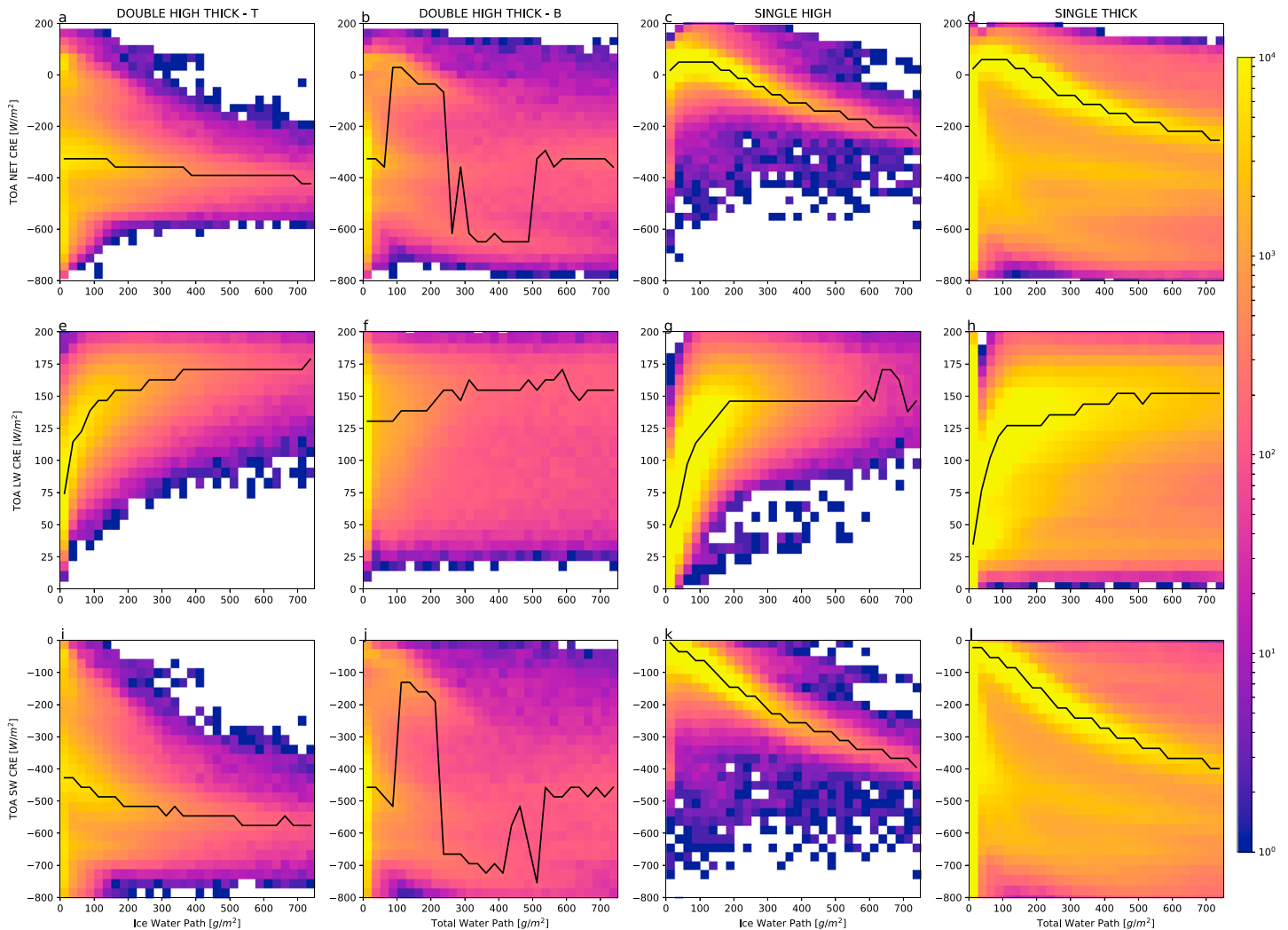


Figure 4. Two-dimensional histograms showing the sensitivity of the net CRE at the TOA in scenario DOUBLE_HIGH_THICK as a function of the ice water path of the top-layer cloud (first column) and the total water path of the bottom-layer cloud (second column). For comparison, similar statistics for single-layer clouds is also shown (third column for clouds from scenario SINGLE_THICK and fourth column for clouds from scenario SINGLE_HIGH). The top row shows the histograms for net CRE, while the middle and bottom rows show results for the longwave and shortwave components, respectively. The black line is a trend line that corresponds to the most common value for each x bin. CRE = cloud radiative effect; TOA = top of atmosphere.

convective clouds can persist 3–4 days after a convective event (Gehlot & Quaas, 2012). The top-layered clouds observed by CloudSat and CALIPSO can, therefore, be from the detrainment of either bottom-layer clouds or cirrus formed in situ. The CTH for the top layer and the distance between the top and bottom layer show no significant difference between the different groups and are therefore not presented in the figure. The mean CTH for the top layer is just below 14 km, but clouds as high as 18 km are observed, while the mean distance between the layers is around 2.8 km calculated from all overlap cases. This means that the mean physical thickness of an optically thin top layer, <1.3 , is around 4 km, while the corresponding value for the optical thickest top-layer cloud is 5 km.

The extent to which the CRH of cirrus are dampened by the underlying layer depends on the vertical separation between the two layers and the altitude of the bottom layer (Hartmann et al., 2001). Therefore, we investigated the sensitivity of the RH rates of the top-layer clouds described by scenario DOUBLE_HIGH_THICK to the vertical separation (clear-air) and CTH of the bottom layers, as shown in Figures 3a–3c and 3d–3f, respectively. RH is the same as CRH except that the clear-sky heating is not subtracted. The top layer, which typically heats the UTLS, can turn to cool the UTLS with the presence of a cloud layer beneath inducing sufficient longwave cooling from its top. However, if the vertical separation between the two layers is large

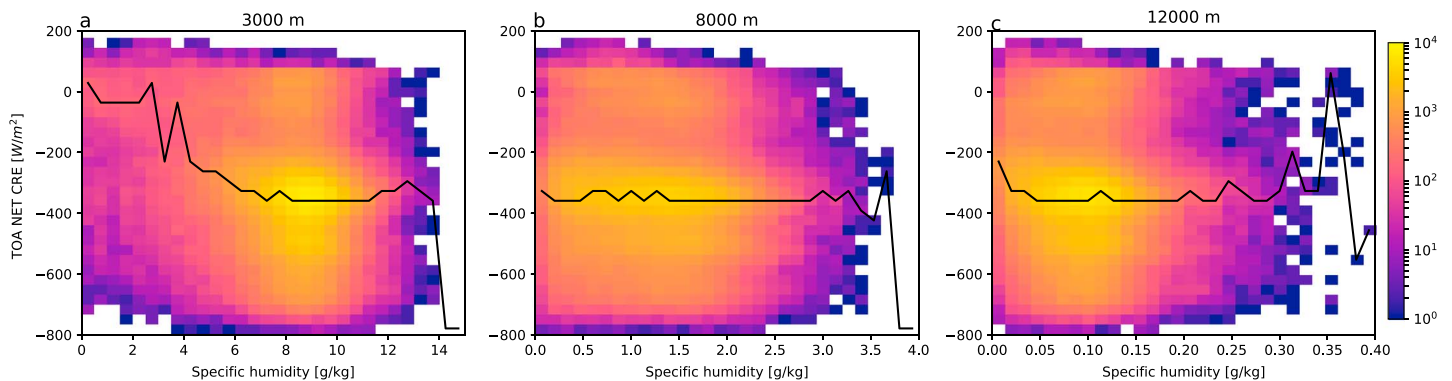


Figure 5. Two-dimensional histograms showing the sensitivity of the net CRE at the TOA in scenario DOUBLE_HIGH_THICK as a function of the net specific humidity at 3,000-, 8,000-, and 12,000-m altitudes. The black line is a trend line that corresponds to the most common value for each net specific humidity bin. CRE = cloud radiative effect; TOA = top of atmosphere.

enough, the atmosphere in between the two layers will interact with the radiation and reduce this effect. If the vertical separation between the two layers is <2 km, the result is mean net cooling rates in the order of -1 K/day (Figure 3a). As the distance increases, the heating also increases and at a separation of about 4 km the heating rates changes sign from net cooling to net heating. Considering the longwave radiation alone (Figure 3b), the change in sign of the heating rates appears at 6.5 km, while the shortwave heating is always positive (Figure 3c). When downwelling shortwave radiation not absorbed by the top layer is reflected upward from the bottom-layer cloud, the top-layer cloud can absorb this reflected, now upwelling, radiation; this increases the total RH of the top layer. Just as for the longwave radiation, this effect decreases as the distance between the cloud layers increases.

Due to the temperature profile of the troposphere, a cloud with a higher CTH will emit longwave radiation at a colder temperature than a cloud with a lower CTH, leading to less longwave radiation reaching the top-layer cloud. When the bottom-layer cloud CTH is at 4 km, the longwave cooling rate in the top layer is -1 K/day (Figure 3e). These cooling rates increase to more than -2 K/day when the CTH reaches 12 km. Because of less absorption by the atmosphere, a bottom-layer cloud with a high CTH will be able to reflect more shortwave radiation, leading to increased warming in the top layer (Figure 3f). The shortwave heating rates of the top layer will, therefore, increase from 0.5 to 2 K/day as the CTH increase from 4 to 12 km. The net RH remains predominantly cooling, ranging from -0.25 K/day at 4 km to -1 K/day at 12 km (Figure 3d). The sensitivity of RH in the top-layer cloud is further investigated as a function of the CTH of the top-layer cloud in Figures 3g–3i. The longwave heating rates increases from -5 K/day at 7 km to 1 K/day at 18 km, while at the same time, the shortwave heating rates remains positive for all heights, ranging from 1 K/day at 7 km to 1.5 K/day at 18 km. The transition from negative to positive heating rates occurs at 17 km for the longwave heating rates and 14.5 km for the net RH.

While understanding the vertical structure of CRH in the UTLS is important to understand processes affecting the composition of, as well as the transport within, the TTL, investigating the CRE at TOA is necessary to fully appreciate the climatic impact of two-layered cloud systems. Here we investigated the sensitivity of the CRE to the water path (WP), that is, ice water path (IWP) of the top-layer and the total water paths (TWP) of the bottom-layer clouds, as well as the optical thickness. The histograms of longwave and shortwave CREs at TOA are presented in Figures 2c and 2d as well as in Figure 4 and Figure S1 in the supporting information. The shortwave TOA CRE in Figure 2c decreases (increasing cooling) as the optical depth of the top-layer cirrus increases, while the longwave TOA CRE in Figure 2d increases. As discussed before, the CTH of the top layer does not change significantly with changing optical thickness. Therefore, the increase in longwave CRE is most likely caused by the increasing optical thickness of the top layer. This dominates the effect of the decrease in CTH and the optical thickness of the bottom-layer cloud displayed in Figures 2a and 2b. For single-layer clouds described by scenarios SINGLE_HIGH and SINGLE_THICK, the shortwave cooling is proportional to WP; compare Figures 4k and 4l. However, Figures 4g and 4h show a steep increase in the longwave warming for WPs up to 200 g/m², especially for clouds in scenario SINGLE_HIGH. Hence, the resulting net CRE increases and remain positive for WPs <50 g/m²; this warming effect diminishes with increasing WP (Figures 4c and 4d). This result corroborates previous studies by, for example, Ackerman et

al. (1988) and Berry and Mace (2014). In Figure S1 the mean values of TOA CRE for each WP bin are plotted together with $\pm 1\sigma$ spread. This figure shows the same tendency as Figure 4, where there is first an increase in SW warming for WPs $< 50 \text{ g/m}^2$. However, for all clouds except single top layer, the mean net CRE is negative for all WPs.

For scenario DOUBLE_HIGH_THICK in Figures 4 and 5, the scene becomes more complex than for the SINGLE_HIGH and SINGLE_THICK scenarios. It is clear that for TOA LW CRE, the trend with increasing WP is similar for scenario DOUBLE_HIGH_THICK (in Figures 4e and 4f) as for scenario SINGLE_HIGH and SINGLE_THICK (Figures 4g and 4h). This is also clear in Figure S1b even though the spread is large. The reflectance from a two-layer system will increase the shortwave radiation reflected back to space compared to a single layer. This effect can be seen both in Figures 4i and 4j when compared to Figures 4k and 4l, respectively, and in Figure S1c, where the TOA SW CRE induce more cooling for a two-layer cloud system compared to a single-layer cloud. When TOA SW CRE is expressed as a function of IWP of the top layer, the spread in CRE is extensive for the lowest IWP values (Figure 4i). This is due to the fact that when the top layers are thin, the bottom layers are most likely to be optically thick clouds (see Figure 2) with considerable variability in their TWP. The net cooling effect imposed by these bottom-layer clouds will drive the observed spread in TOA SW CRE for clouds with a lower IWP. However, as the top layer becomes optically thicker, the contribution from these top layers starts to dominate the SW CRE and the spread is reduced. When TOA SW CRE is expressed as a function of TWP of the bottom-layer clouds (Figure 4j), the spread in SW CRE is also very high at lower TWP values. However, in contrast to Figure 4i, the varying IWP of the top layers initially contributes to most of the observed spread. Thus, this spread in SW CRE causes the large spread in the net CRE (Figures 4a and 4b).

In addition to clouds, water vapor variability also influences the radiative properties of the UTLS and can have an impact on the CRE statistics presented here. Therefore, we first investigated if the net specific humidity, that is, cloudy-sky minus clear-sky, changes significantly under the different scenarios discussed in Figure 1 (cf. Figure S2). It is evident that although the net specific humidity vary considerably below the freezing level, the variability in the UTLS region is negligible. Furthermore, we investigated the sensitivity of the net TOA CREs in the case of double-layered cloud systems to the net specific humidity at the altitudes of 3,000, 8,000, and 12,000 m (Figure 5). The specific humidity at these altitudes is chosen because it corresponds to the mean altitudes where the peak in cloud fraction for the bottom-layer cloud, the minimum cloud fraction between the two layers, and the peak in cloud fraction for the top-layer cloud are observed. At the altitudes of 8,000 and 12,000 m, the peak net TOA CRE remains stable at -350 W/m^2 indicating insensitivity to the net specific humidity variability in the UTLS region, while in the lower troposphere at 3,000 m it changes from near 0 W/m^2 at $0\text{--}1 \text{ g/kg}$ to -350 W/m^2 at $>6 \text{ g/kg}$.

4. Conclusions

Improved understanding of the vertical structure of CRH in the tropical UTLS is essential to understand processes affecting the composition and transport in and around the TTL. Cloud overlap, defined here as a two-layer system, is frequently observed in the tropical regions and can substantially influence the local radiative balance in the UTLS. For the first time, the relation between CRH, cloud overlap, and different cloud properties in the tropics was studied using data from active sensors onboard CloudSat and CALIPSO. We show that during cloud overlap conditions, the bottom-layer clouds can fully suppress the CRH typically caused by high clouds in and around the TTL by inducing strong longwave cooling. If the vertical separation between the layers is $< 4 \text{ km}$, the RH of the high cloud changes sign from positive to negative, and the characteristic net TOA CRE by cirrus with IWP $< 50 \text{ g/m}^2$ is suppressed in the two-layered system. We further quantified the sensitivity of CRH profiles and TOA CREs to the physical properties of the top- and bottom-layer clouds, in double-layered systems as well as to the water vapor variability. It was found that the net CRE of the double-layered cloud systems is insensitive to the water vapor variability in the UTLS region, although the water vapor variability could play an important role in the lower troposphere. The results provide useful statistics to evaluate global climate models, wherein the treatment of cloud overlap remains highly parameterized.

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