A study of macrophysical and microphysical properties of warm clouds over the Northern Hemisphere using CloudSat/CALIPSO data

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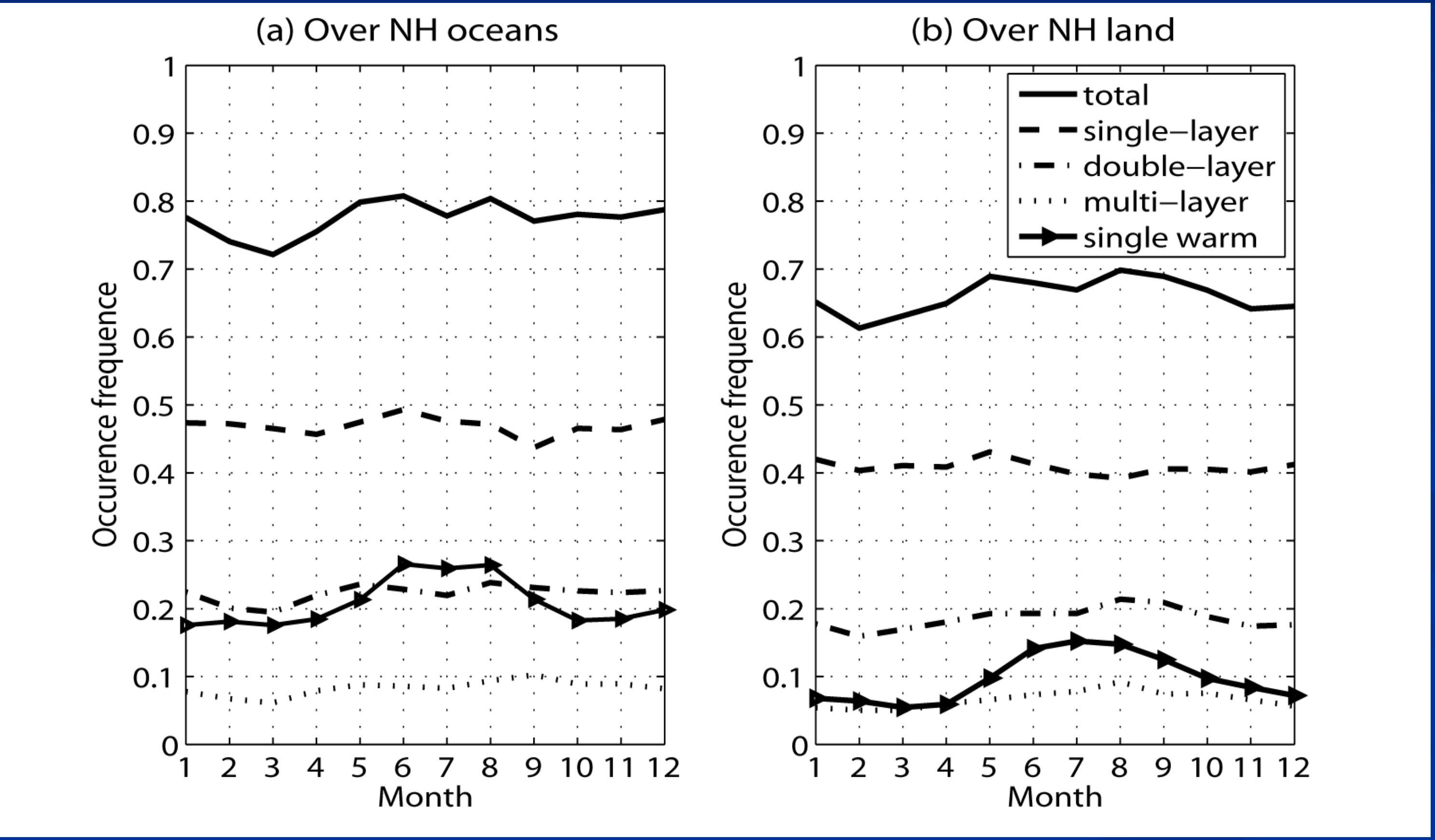
Motivation

- The single-layer warm clouds account for a considerable fraction of the total cloud types, so the warm clouds and associated thermodynamic processes are crucial components of the Earth's climate system.
- This study investigates the general macro- and microphysical properties of single-layer warm clouds over the Northern Hemisphere (NH) ocean and land regions, aimed at increasing the understanding of warm clouds vertical structure, the growth processes of hydrometeors from cloud droplet to drizzle and to rain with increasing liquid water path (LWP). The results can provide a valuable reference for evaluating outputs from cloud-resolving models.

Data and method

- The CloudSat standard data products (R04) , 2B-GEOPROF, 2B-CLDCLASS-LIDAR, 2B-CWC-RVOD, and 2B-TAU for the year of 2008 are utilized. All the statistical analyses except the occurrence frequency of hydrometeor are performed with column optical depth greater than 0.1 and LWP greater than 0.0 kg m^{-2}.
- In an attempt to study the evolution processes of cloud systems, the LWP is employed to serve as an indirect indicator for the life stages of warm clouds. We form the ensemble averages of different variables as a function of LWP values in the five groups of 0.0-0.5, 0.5-1.0, 1.0-1.5, 1.5-2.0, and 2.0-2.5 kg m^{-2}, respectively.

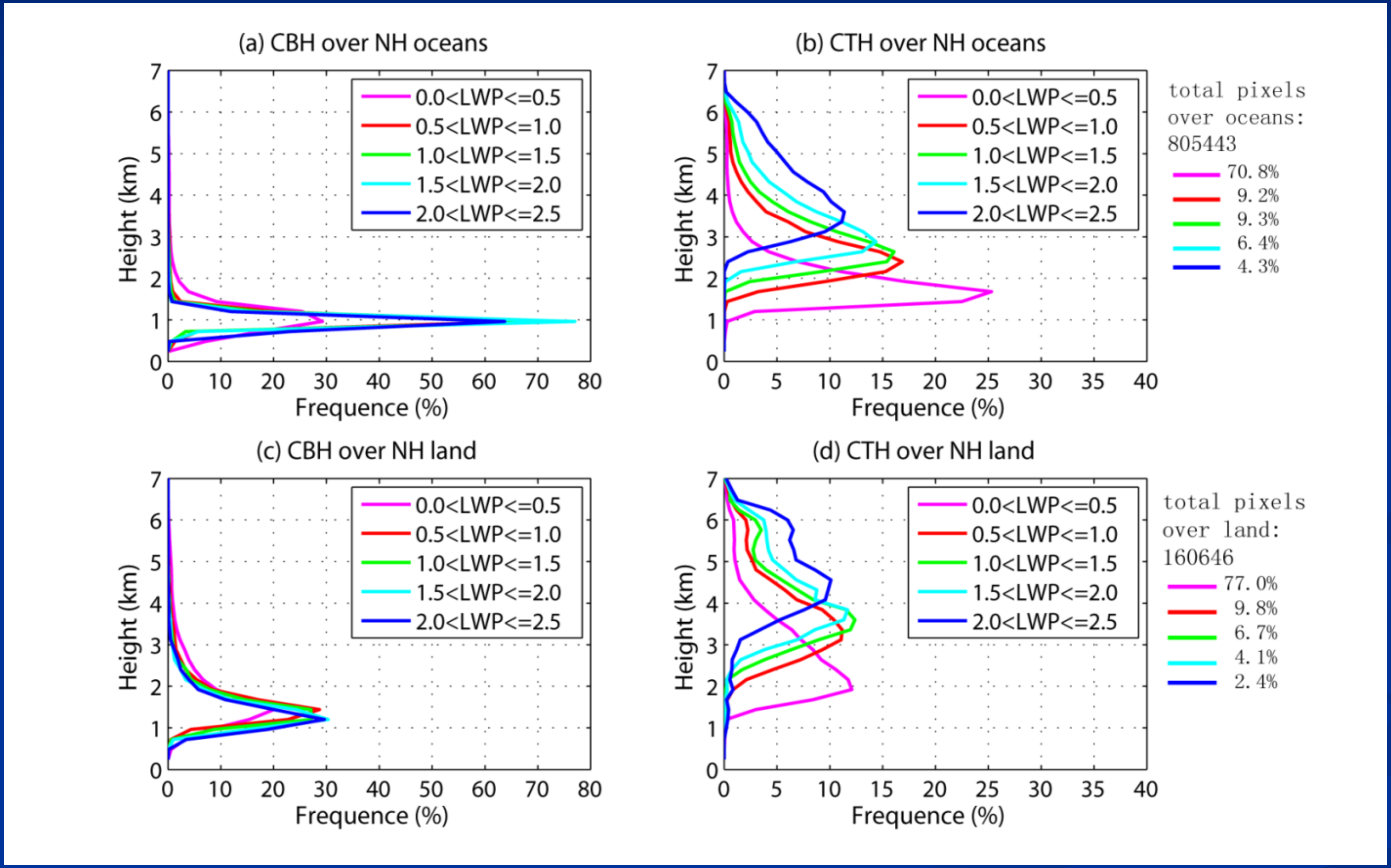
- Occurrence frequencies of single- and multilayer clouds



The total occurrences are 0.7-0.8 over oceans and 0.6-0.7 over land. The occurrences of single-layer clouds are the highest to the total profiles. The single-layer warm clouds also occur relatively frequently, which contribute 20.9% over oceans, 9.5% over land to the total profiles, respectively.

Monthly averaged occurrence frequencies of all cloud layers and single-, double-, and multilayer clouds, respectively, over (a) NH oceans and (b) NH land during 2008.

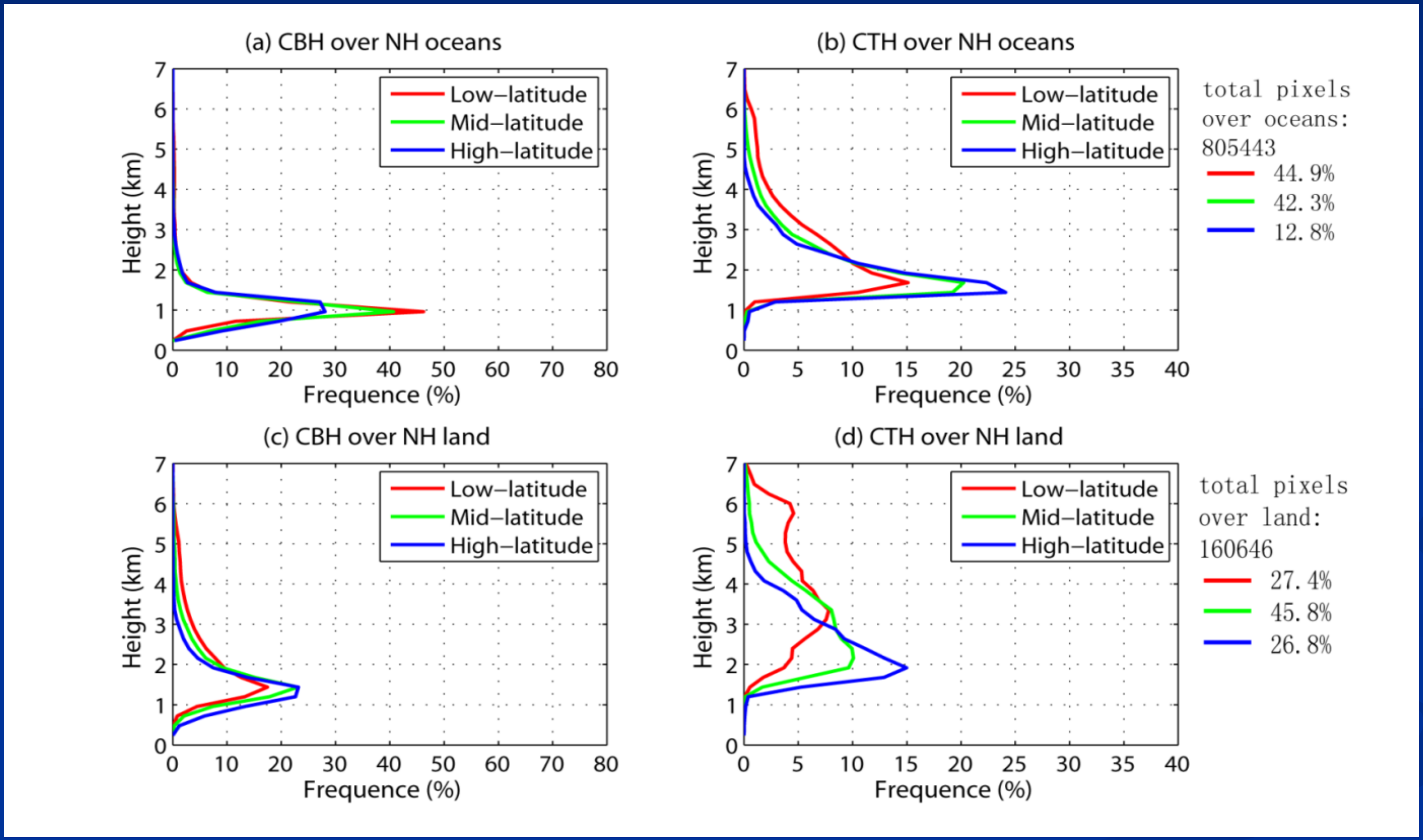
- PDFs of cloud base height (CBH) and cloud top height (CTH)



The CBHs have a dominant mode of near 1 km, may be the limitation of CloudSat. The CTHs of maximum occurrence shift toward higher values as LWP increases. The CTHs over land tend to be less centralized and geometrical thicker than those over oceans. It should be associated with relatively deeper systems such as the shallow warm cumulus clouds over land.

CBHs and CTHs over (top) oceans and (bottom) land. Color solid lines denote the various LWP. Percentages represent the occurrence frequency for each LWP group.

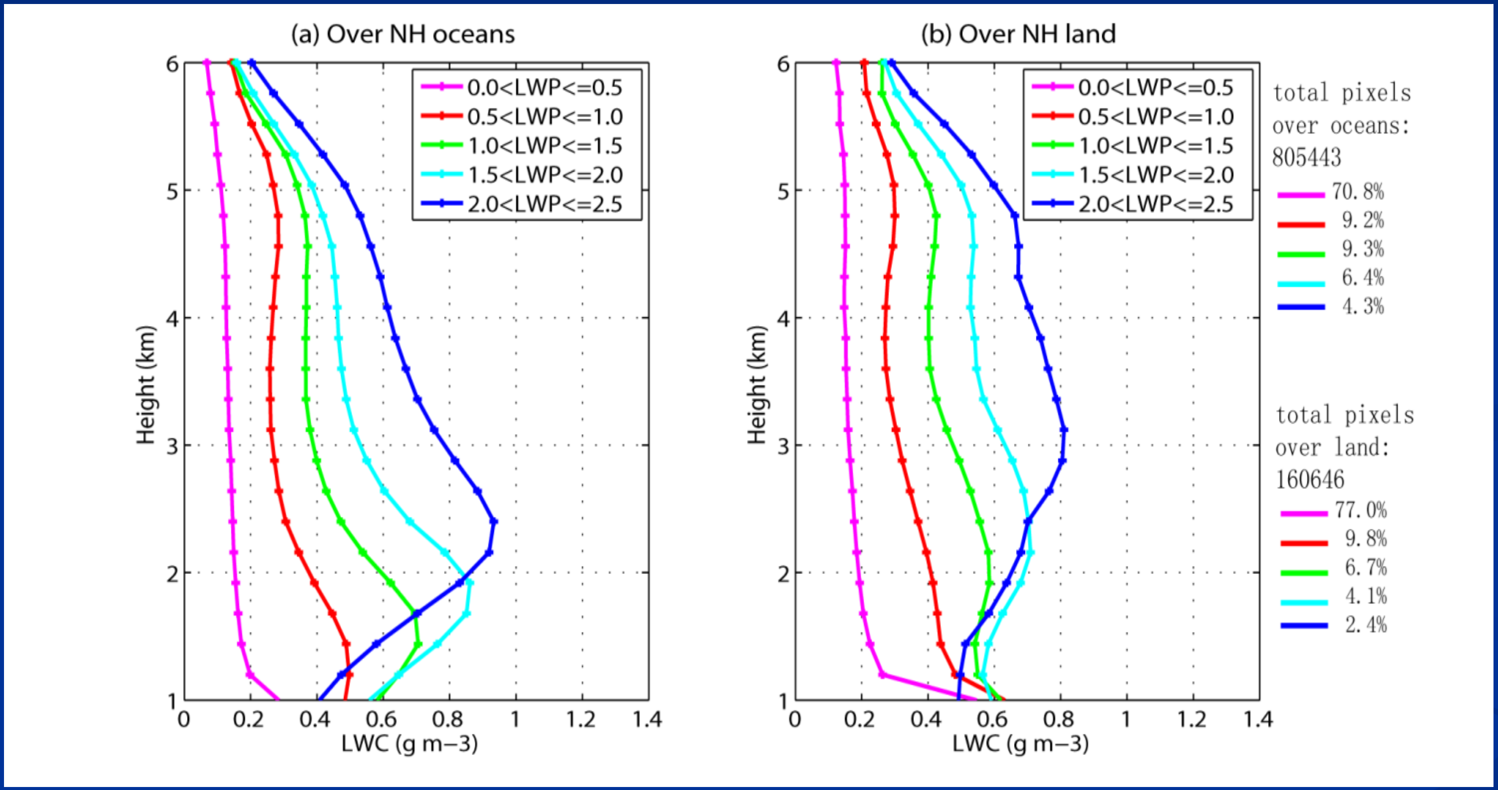
PDFs of CBH and CTH



A considerable portion of warm clouds occur in high-latitude. The CTHs over oceans are highly skewed with a mode 1.5-2 km, implying the existence of prevalent low-level warm clouds. However, the CTHs over land vary significantly with latitude bands. The spectral width over tropical land is obviously broader likely be with more frequent occurrence of stronger cloud systems than that over higher latitudes.

CBHs and CTHs over zonal bands of (top) oceans and (bottom) land. Color solid lines denote the low-, mid-, and high-latitude zones, respectively. Percentages represent the occurrence frequency for each latitude zones.

■ Profiles of liquid water content (LWC)

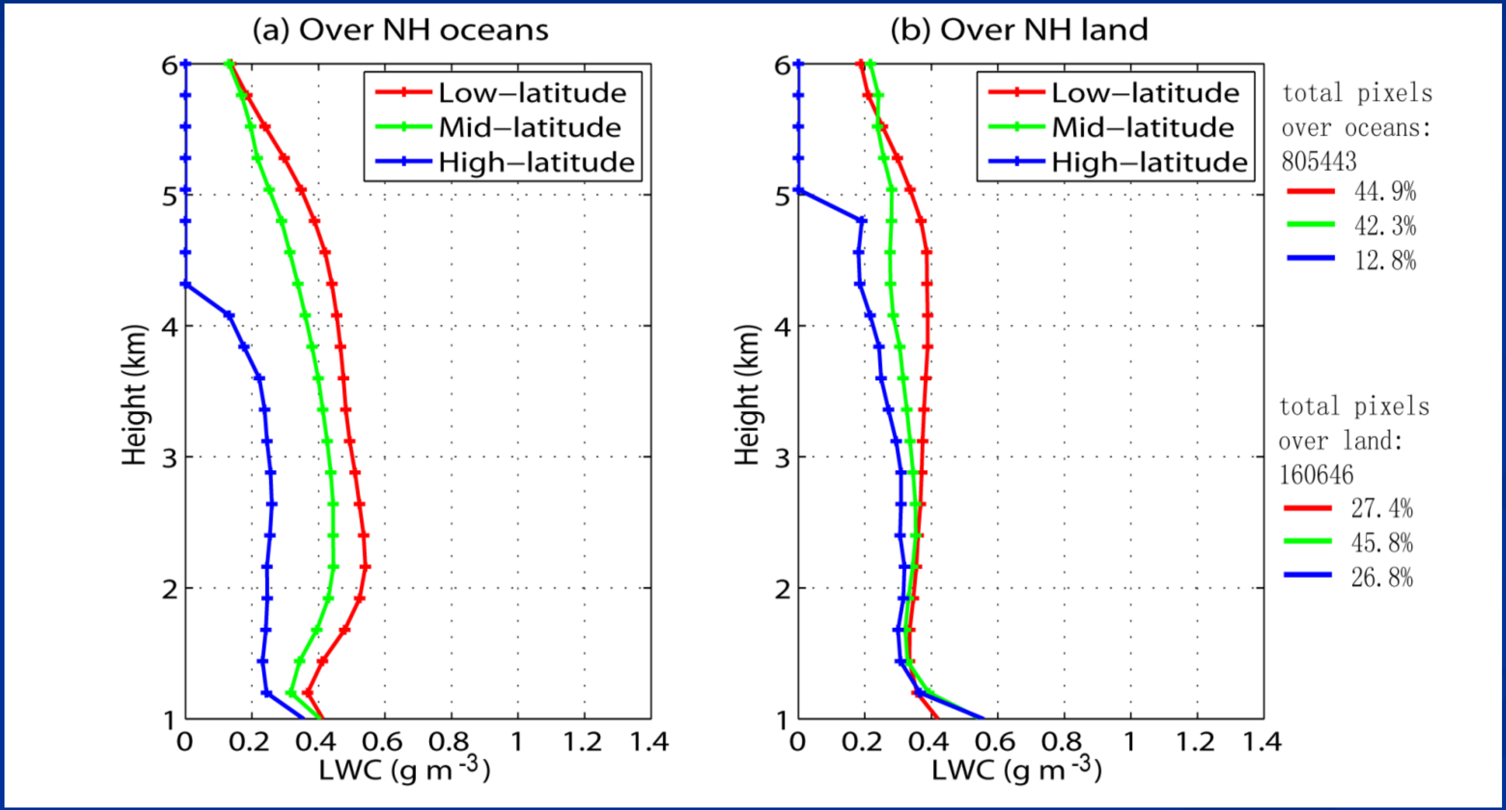


The LWCs shift toward higher values as LWP increases, and the height of maximum LWC also steadily increases. The maximum values of LWC over land are about 10-30% smaller than that over oceans with the same LWP, but the occurring heights are about 0.5 km higher over land, due to the weaker upward motions and larger surface evaporation over oceans.

The mean LWC is calculated by dividing the total number of cloudy pixels at each height level. So it represents the average LWC for the in-cloud portion of the layer.

Vertical profiles of LWC over (a) oceans and (b) land.

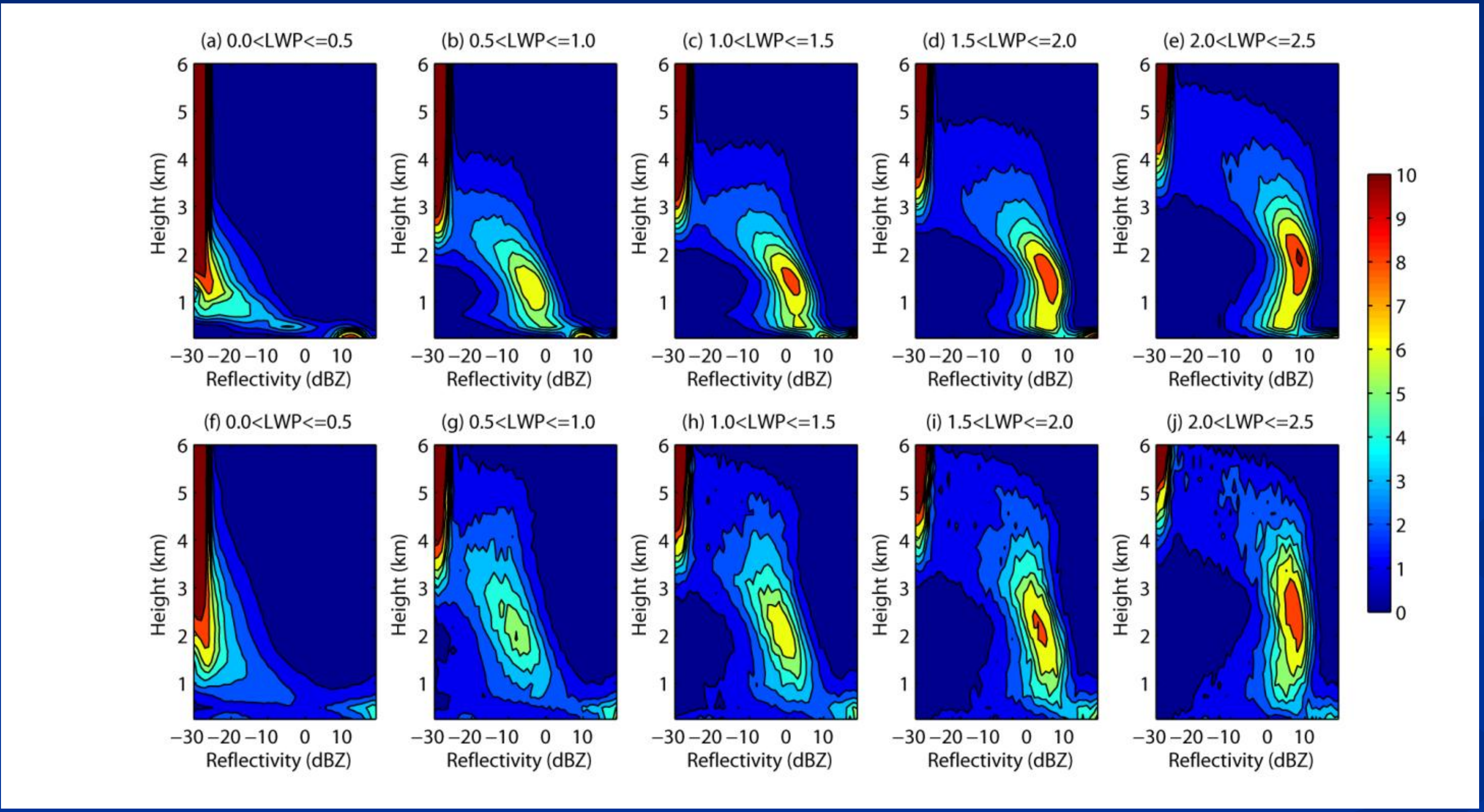
Profiles of LWC



The LWCs over oceans vary significantly with latitude bands. However, they are similar below 3 km over land. A likely reason is that warm single clouds over land are phased locked to warm season that have similar boundary condition in different latitude. The liquid water above 5 km come mainly from the tropics and mid-latitude regions.

Vertical profiles of LWC over zonal bands of (a) oceans and (b) land.

- CFADs of radar reflectivity

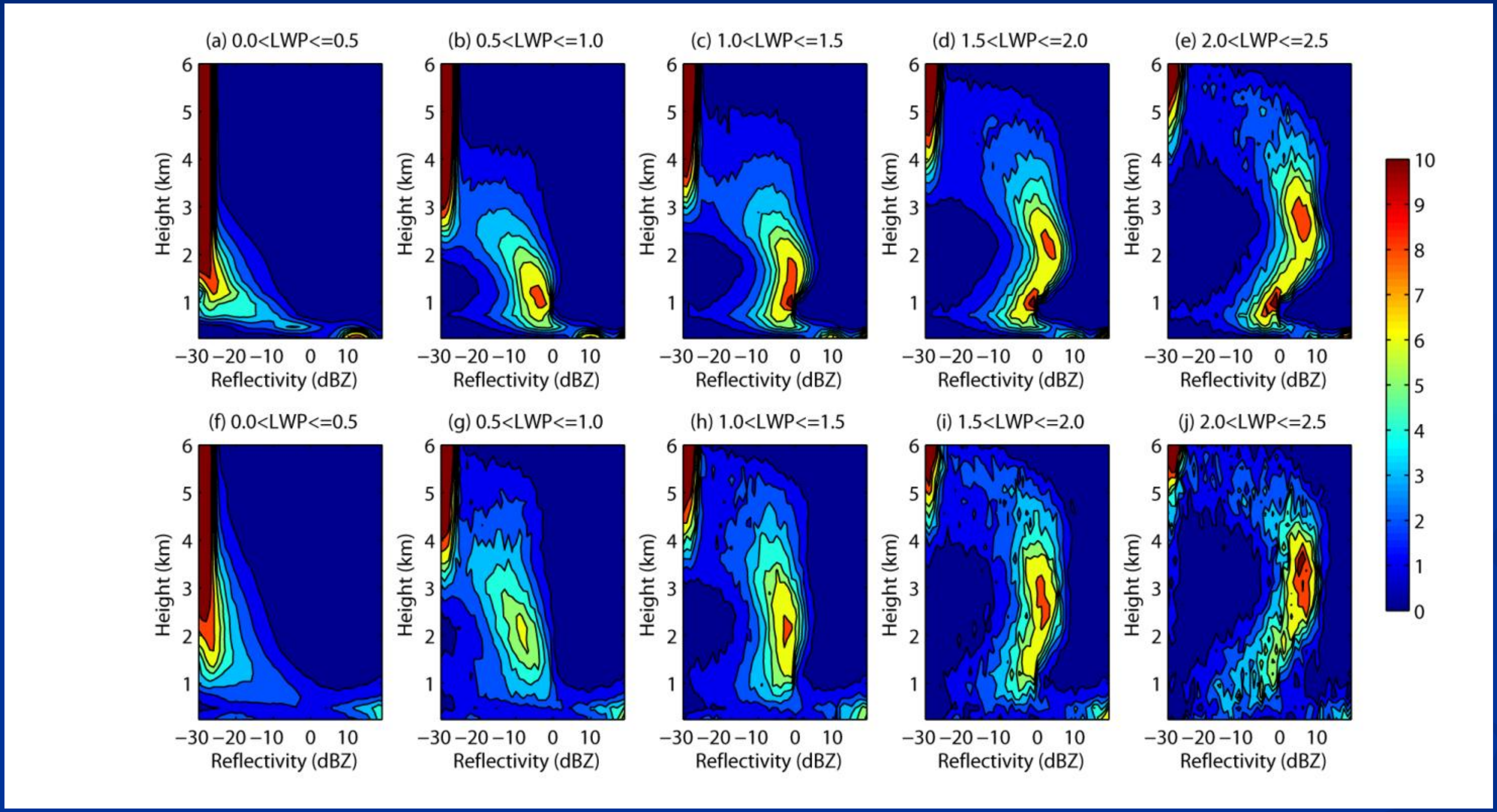


When LWP<0.5 kg m^{-2}, the clouds are mainly consisted of small droplets. The upward particle growth below 1.5 km is the result of condensation process. With increasing LWP to 1.0, -15 to 0 dBZ becomes pronounced. The reflectivity increases with decreasing height, reflecting downward growth by accretion of droplets. When LWP is up to 1.5, the reflectivity continues to grow downward and reaches 5 dBZ, indicating the raindrops begin to form. On the other hand, the dBZ values of maximum occurrence over land are always smaller than those over oceans and the evolution processes seem later with the same LWP, which should be the influence of continental aerosols.

The reflectivity of less than -20, -15 to 0, and 0 to 10 dBZ, are respectively interpreted as to cloud, drizzle, and rain.

CFADs of reflectivity for all cloudy profiles over (top) oceans and (bottom) land.

CFADs of radar reflectivity

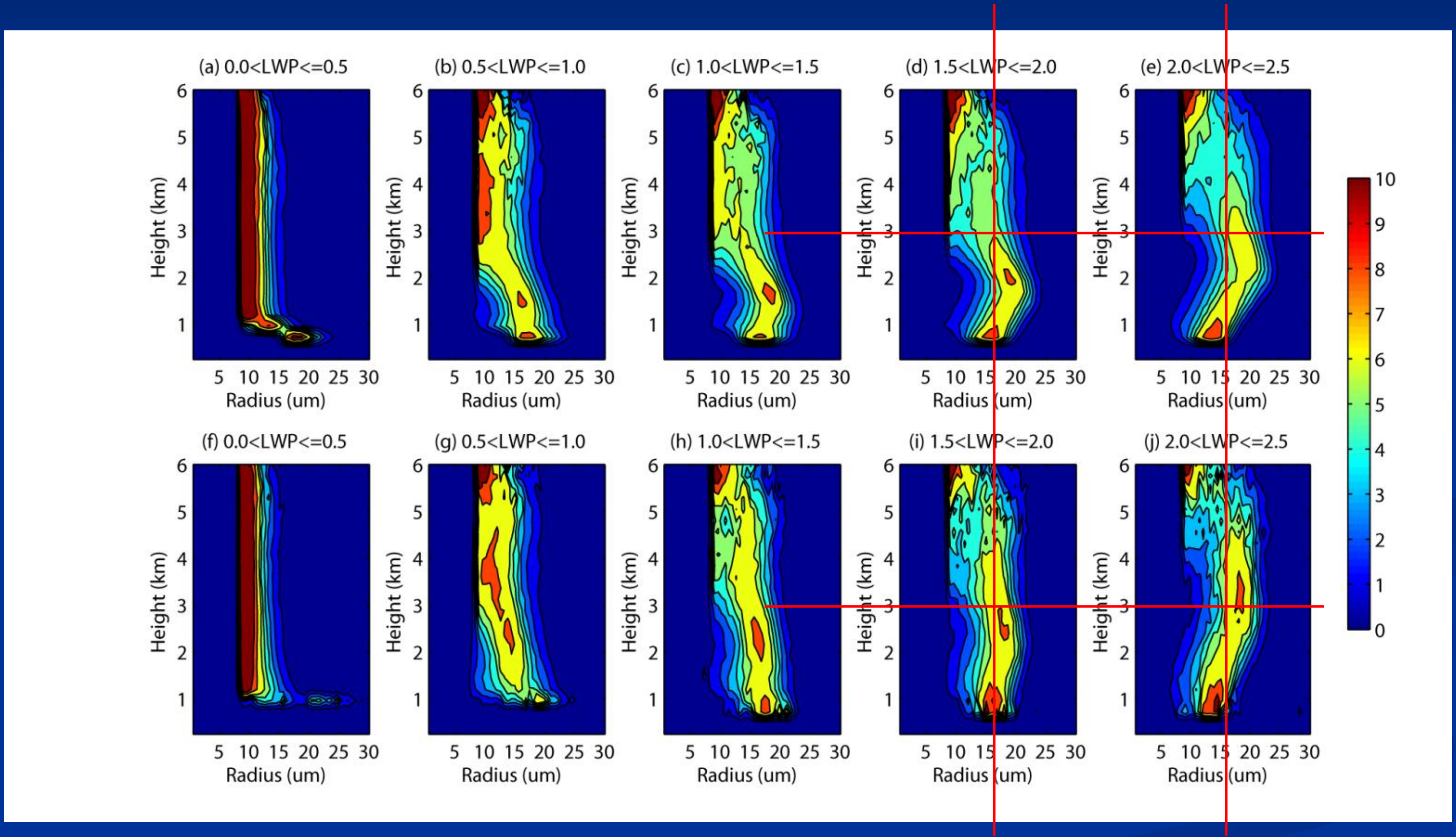


The reflectivities in nonraining clouds decrease rapidly to less than 0 dBZ near surface when LWP>1.0, which related to the rapid evaporation of raindrops. The large reflectivities between 2 and 4 km indicate remaining hydrometeors suspended in clouds. The reflectivities near surface over land show a greater dispersion than that over oceans. The reason is the interactions between downdrafts and updrafts over land, which lead to the formation of mixed regions with wide or irregularly shaped droplet spectra.

Nonraining clouds are screened according to the flag in 2B-CLDCLASS-LIDAR product.

CFADs of reflectivity for the nonraining clouds over (top) oceans and (bottom) land.

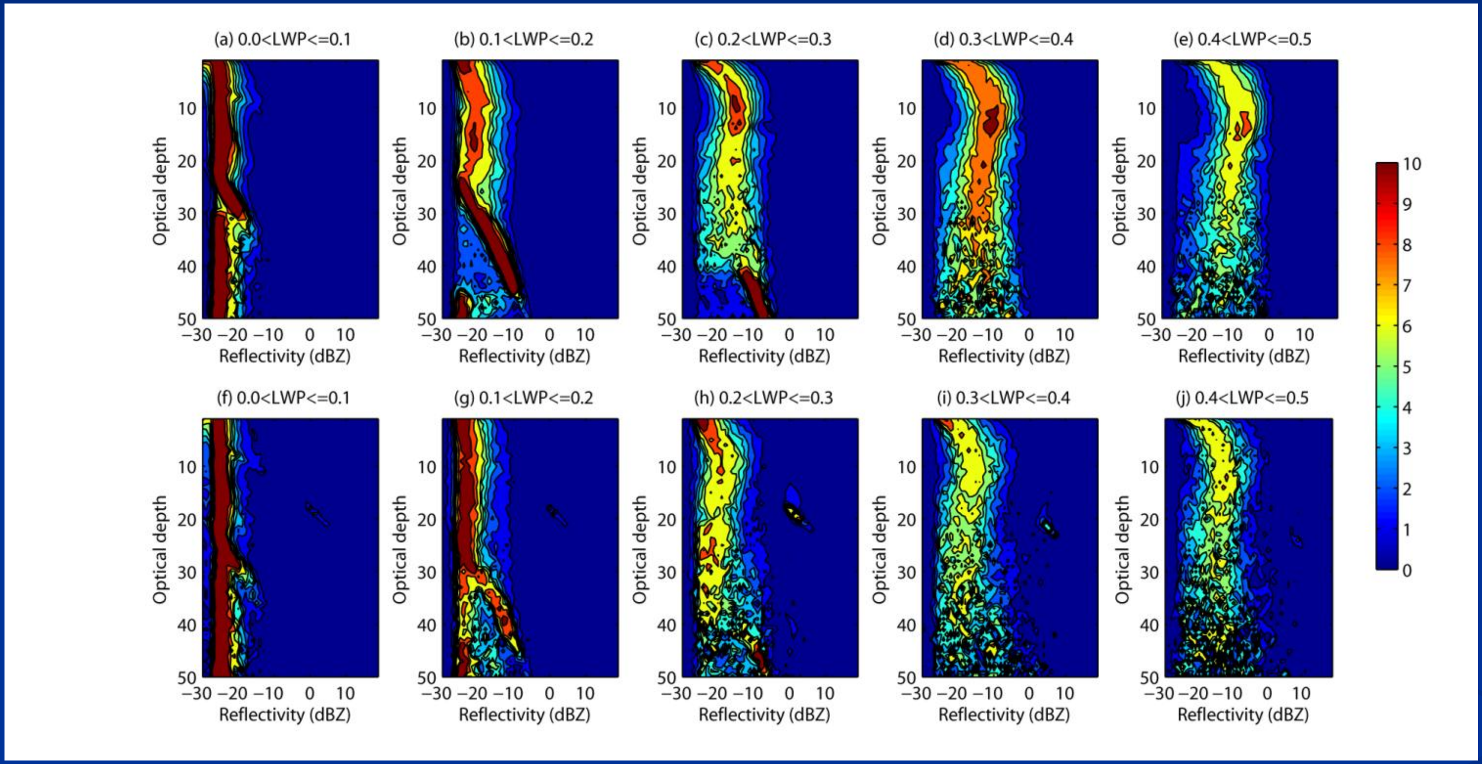
- CFADs of effective radius



The radii increase gradually from nondrizzling cloud to drizzle and rain in the lower part of clouds. The radius over land tends to be somewhat smaller below 3 km that that over oceans due to the influence of continental aerosols. However, the particle size above 3 km over land is obviously larger than that over oceans when LWP is greater than 1.0, which is attributed to the stronger vertical motions that transport large particles to the upper part of clouds.

CFADs of effective radius for all cloudy profiles over (top) oceans and (bottom) land.

CFODDs of radar reflectivity



Contoured Frequency by Optical Depth Diagrams (CFODDs), in which the reflectivity profiles are rescaled as a function of the in-cloud optical depth. Here the LWP is grouped with an interval of 0.1 kg m^{-2}.

There is a significant difference when LWP 0.1-0.2 and optical depth >25. The reflectivities over oceans increase rapidly downward with increasing optical depth and reach -10 dBZ, indicating the drizzle drops begin to form. On the contrary, many reflectivities over land are still smaller than -20 dBZ. This is possibly due to the evaporation-condensation mechanism. The large drops can grow through condensation at the expense of small droplets under a certain water vapor condition. Because few large drops exist over land in the early stage of warm clouds formation as the presence of continental aerosols, the evaporation-condensation mechanism then hardly occurs.

CFODDs of reflectivity for all cloudy profiles over (top) oceans and (bottom) land.

Conclusions

- The yearly averaged occurrence frequency of single-layer warm clouds is 20.9% over ocean and 9.5% over land, respectively. The CTHs over land vary significantly in different latitude bands with a broader spectral width in tropics than that over higher latitudes. The maximum values of LWC over land are approximately 10-30% smaller but the occurring altitudes are 0.5 km higher than those over oceans with the same LWP.
- The reflectivity profiles clearly demonstrate the growth processes of cloud particles and how these processes vary with increasing LWP. The evolutions of reflectivity over land show a frequency shift toward weaker dBZ values relative to that over oceans with the same LWP, suggesting high aerosol

Conclusions

- concentrations may induce suppressed drizzle and delayed precipitation in warm clouds.
- The key finding is that there exists a significant difference in the CFODDs of radar reflectivity between ocean and land areas in the initial period of warm clouds formation. The faster growth of particles over ocean in that period is possible due to the evaporation-condensation mechanism. However, over land, large droplets are unlikely to appear in the early stage because continental aerosols prevent the evaporation-condensation mechanism to occur.

Thanks !