CLOUD OBJECT MODELING AND OBSERVATIONS FOR CLIMATE STUDIES

Kuan-Man Xu[1], Bruce A. Wielicki[1], Takmeng Wong[1], and Lindsay Parker[2]

[1]NASA Langley Research Center, Hampton, VA, USA
[2]Science and Application International Corporation, Hampton, VA, USA

1. INTRODUCTION

One of the largest uncertainties in the climate system is cloud feedback. Current climate models continue to struggle to accurately model cloud feedbacks. One of the persistent problems is the difficulty of comparing cloud observations with climate models to the accuracy requirement of climate sensitivity studies. Achieving a statistically significant sampling of observing cloud feedbacks without the influence of weather "noises" requires a minimum of a month of data over a region, and often up to a year. This is because significant cloud feedbacks can result from changes in global mean cloud properties as small as 1% per decade, or regional change of 1% per year. Use of classic gridded monthly or annual mean cloud data invariably includes a wide range of atmospheric states and cloud conditions. It then becomes very difficult in this time-averaged Eulerian view to diagnose which type of cloud is being poorly represented in climate models. This diagnosis is crucial to improve these models' representation of cloud processes.

On the other hand, a Langragian approach, called the "cloud object" approach, groups instantaneous cloud objects by cloud-system type, independent of where and when the cloud-system type occurs. Simulation of these cloud objects is also performed, driven by the matched atmospheric state data. This approach offers two advantages: it reduces cloud variability by grouping data from the same cloud-system type and it reduces sampling noises by combining results from a wide range of geographic regions. Because of its large sample size, the combined results can be stratified according to some measures of atmospheric states such as sea surface temperature (SST) so that the partial derivatives between radiative fluxes and atmospheric variables can be obtained to study cloud feedbacks from observations and model simulations. This study presents the basic methodology and some preliminary results of the cloud object approach.

Corresponding author's address: Dr. Kuan-Man Xu, Mail Stop 420, NASA Langley Research Center, Hampton, VA 23681, USA, k.m.xu@larc.nasa.gov

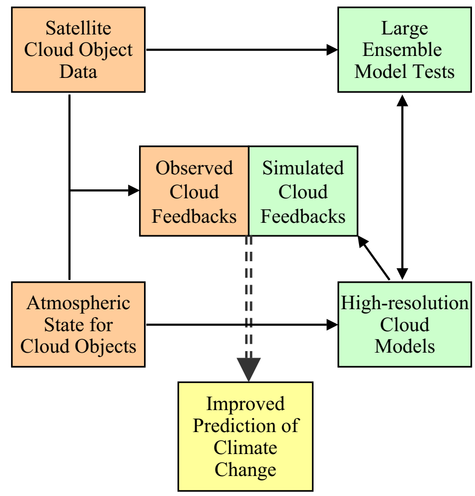

Fig. 1: *A schematic of the approach for cloud object observation and modeling to understand cloud feedbacks.*

2. A NEW METHODOLOGY

Analysis of observational data and high-resolution modeling are integrated in the new cloud object approach to improve the understanding of cloud feedbacks (Fig. 1). In order to reach climate accuracy, satellite data from the Earth Observing System (EOS) are analyzed to generate large ensembles of cloud objects for different cloud-system types. The atmospheric state is matched to each cloud object. The grand mean statistics of observed cloud objects are stratified according to some independent measures of atmospheric states to study cloud feedbacks.

The atmospheric state is also used to drive the simulations of high-resolution cloud models. The statistics of the simulated cloud objects are vigorously compared with those of satellite observations for large ensembles of cloud objects so that systematic errors can be identified and further improvements to the high-resolution cloud models can be made without the need of arbitrary model tuning. The simulated cloud feedbacks can be analyzed and compared with those from satellite cloud object analysis to further improve the high-resolution cloud model. Further testing of the improved cloud models can be performed by embedding them into a global climate model for selected seasonal and interannual simulations. This revolutionary method of climate modeling is called the "Multi-scale Modeling Framework" or "super parameterization" (Khairoutdonov and Randall 2001). Once these tests are passed, decadal climate prediction can be performed to improve the prediction of climate change.

3. ANALYSIS OF CLOUD OBJECTS

A cloud object is defined as a continuous region composed by individual cloud pixels that satisfy a set of physically-based cloud-system selection criteria. Due to the limited width of satellite swath and the selection criteria, a cloud object can just include part of a cloud system. The limited width of satellite swath can truncate a cloud system. The selection criteria can break a large cloud system into several smaller cloud objects. A "region-growing" strategy based on imager-derived cloud properties is used to identify the cloud objects within a single satellite swath (Wielicki and Welch 1986). A key part of this task is to label the boundaries of an individual cloud object along the scan lines of satellite. Two scan lines are examined simultaneously to identify the boundary pixels of a large continuous cloud region. Assuming that pixels are square, a cloud pixel is flagged as a cloud edge pixel if one or more of its sides is adjacent to a clear pixel. A cloud object is uniquely determined if no cloud edge pixels are adjacent to another cloud object.

This study will examine only the cumulonimbus and its associated thick upper tropospheric anvils over the Pacific Ocean using TRMM data. Four criteria are used to define the tropical deep convection type: 1) the pixels must have 100% cloud fraction; 2) a minimum value of 10 for the cloud optical depth is used to eliminate thin anvil clouds; 3) the cloud top height must be greater than 10 km and 4) the cloud pixels must be located within 25° S and 25 $^\circ$N of the Pacific Ocean. After individual cloud objects have been identified, grand mean statistics in terms of probability density functions (PDFs) are produced for a group of cloud objects as a function of SST, geographic location and size. A number of measured and retrieved variables is available from both the EOS-Terra and EOS-Aqua satellites. A few PDFs will be shown below to illustrate the sensitivity of cloud properties in tropical convection to change in SSTs and cloud object size ranges.

4. PRELIMINARY RESULTS

Figure 2 shows the number of tropical deep-convective cloud objects in the Pacific during January-August 1998. The numbers of cloud objects are obtained for five different SST ranges and three cloud-object size classes. The SSTs represent the values with the peak probability densities associated with individual cloud objects. The cloud-object size class is defined in terms of equivalent diameters of cloud objects. It appears that the distribution for the smallest cloud objects with equivalent diameters of 100-150 km is more Gaussian than that of the largest cloud objects. This suggests that higher SSTs are preferred by larger cloud objects during this period, even though the range of the SSTs is only 2 K.

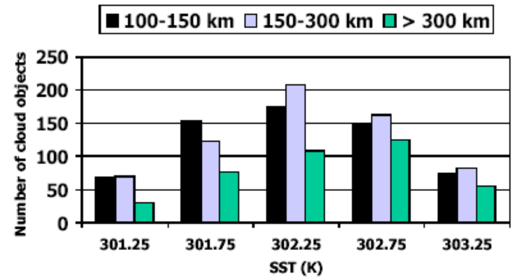

Fig. 2: *Number of cloud objects at different sizes and at different sea surface temperature (SST) ranges.*

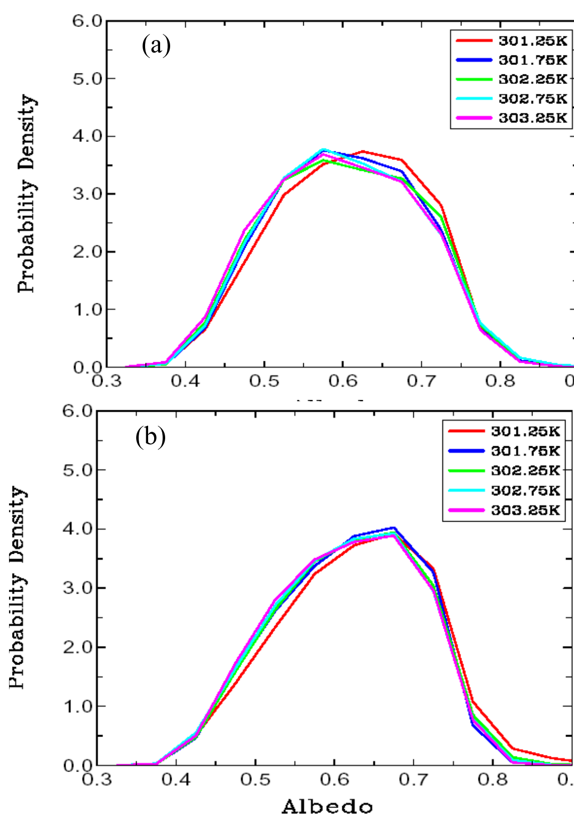

Fig. 3: *Probability density functions of the TOA albedo for (a) 100-300 km and (b) greater than 300 km size classes at five different SST ranges.*

Figures 3 to 7 show comparisons of grand mean PDFs for two size classes (100-300 km; and > 300 km) for TOA albedo, cloud optical depth, ice water path (IWP), outgoing longwave radiation (OLR) flux, and cloud top height. The two smallest size classes shown in Fig. 1 are combined into one (100-300 km). Many of these variables appear to have much greater differences between the size classes than between the SST ranges. The PDFs of OLR fluxes and cloud top heights (Figs. 6 and 7) show slightly greater differences among the SSTs than the rest of the variables. The PDFs of TOA albedos (hereafter, albedo) for both size classes are rather similar among the SSTs except for the lowest SST, in which the clouds are slightly more reflective (Fig. 3). For a given SST, the cloud objects with equivalent diameters greater than 300 km have much higher albedos than those with equivalent diameters between 100 and 300 km. In the small size class, the PDFs are more quasi-normal for all SSTs, while they are slightly skewed to higher albedos in the large size class. This feature is consistent with results of cloud optical depth (Fig. 4) and ice water path (Fig. 5). The cloud optical depths are distributed exponentially while the ice water paths are distributed lognormally for both size classes. The large size class, however, shows higher densities for large values of both variables. This can be more easily seen by comparing the peak densities for low values of both variables in Figs. 4 and 5. The peak densities are much lower for the large size class for all SSTs. An explanation for the differences between the two size classes is that more cumulonimbus cores with slightly thicker anvil clouds are present in the large cloud objects. The small cloud objects are more likely associated with slightly weaker cloud systems which have weaker cumulonimbus cores so that fewer pixels satisfy the selection criteria: cloud top heights greater than 10 km and cloud optical depths greater than 10.

Another interesting result appearing in Figs. 3-5 is that the cloud objects that occur over higher SSTs are slightly less reflective than those that occur over lower SSTs. The PDFs of cloud optical depth and ice water path are also respectively skewed towards lower values of cloud optical depth and ice water path for cloud objects that occur over higher SSTs, although the differences between SSTs are small compared to those between the size classes. This result may be related to the higher cloud tops of the cloud objects that occur over higher SSTs (Fig. 7). Relatively thin anvils are somewhat more abundant when cloud tops are higher. Cloud ice contents of anvil clouds peak well below 10 km. As their heights increase, cloud ice contents decrease and thus more pixels exist with small IWPs.

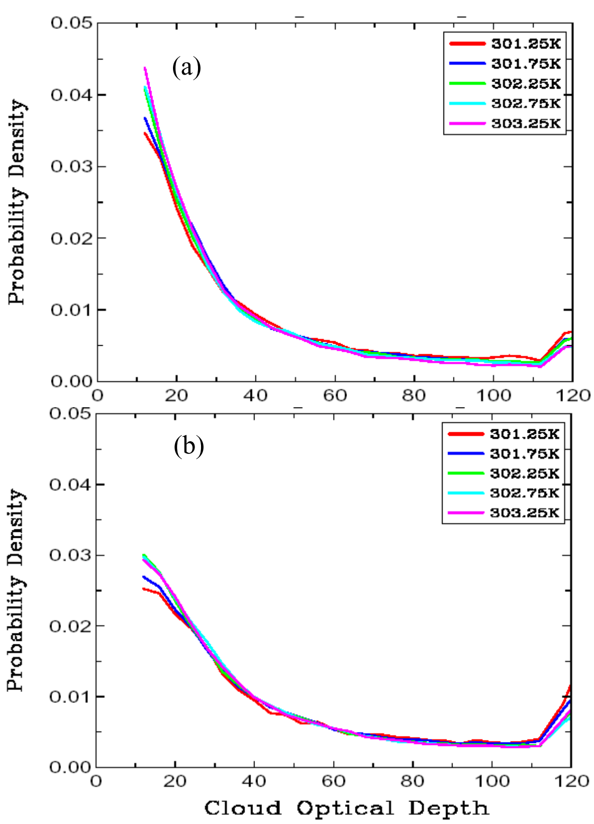

Fig. 4: *Same as Fig. 3 except for cloud optical depth.*

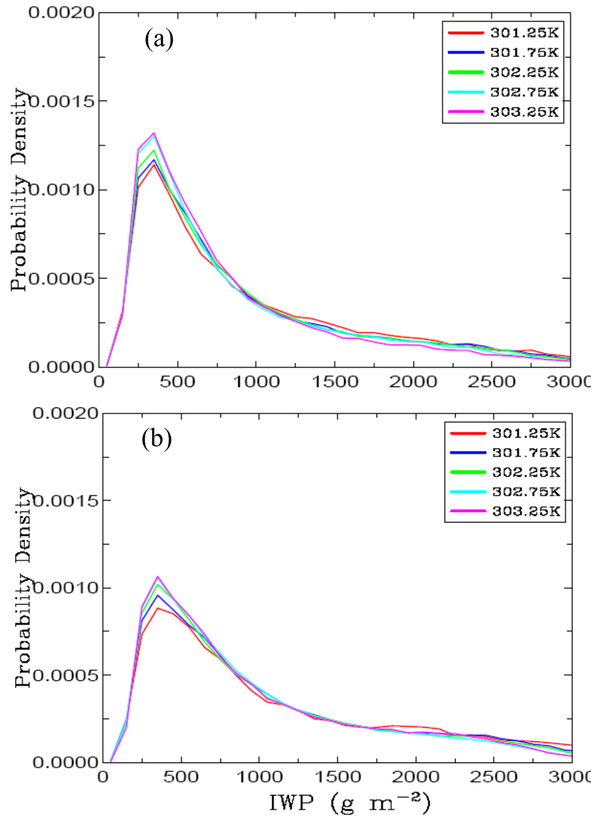

Fig. 5: *Same as Fig. 3 except for ice water path.*

The OLR fluxes also show large differences between the two size classes (Fig. 6). The PDFs are skewed to the right of the peak PDF value (124 W m^{-2}) for the small size class, but less so for the large size class. This result is expected, based upon the differences in cloud optical and microphysical properties between the two size classes shown in Figs. 4 and 5. This is also related to the lower cloud tops for the small size class for a given SST (Fig. 7). The OLR PDFs are separated into two groups with two or three members each in both size classes. The OLR fluxes are lowers for higher SSTs. This result is not consistent with the fixed anvil temperature (FAT) hypothesis of Hartmann and Larson (2002). They hypothesized that the emission temperature of tropical anvil clouds will remain constant during climate change. It should be noted, however, that not all anvils are included in the PDFs shown in Fig. 6 because we restricted our examination to the thick anvil clouds. The dependence of the cloud top heights on the SST is much stronger (Fig. 7). The cloud tops are much higher for higher SSTs in both size classes, especially so in the small size class. These suggest that macrophysical properties of cloud objects are more sensible to change in SSTs.

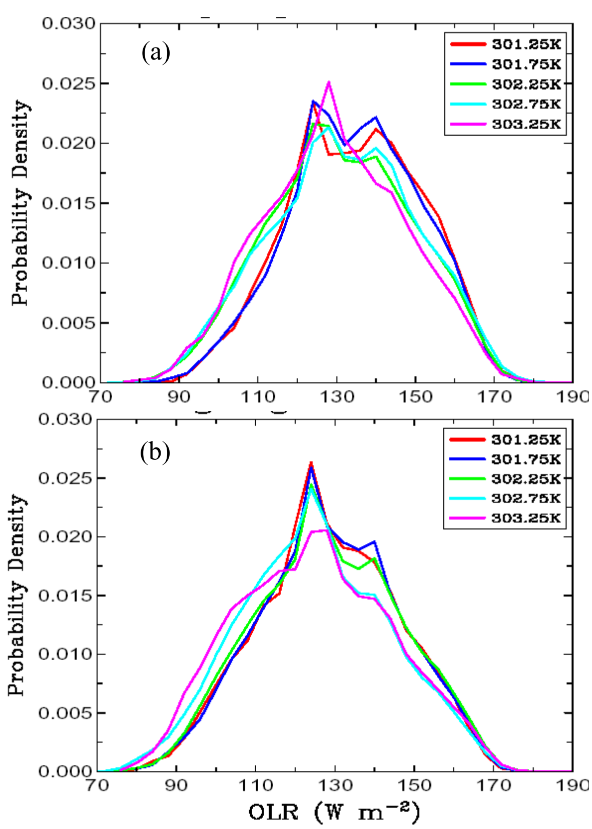

Fig. 6: *Same as Fig. 3 except for outgoing longwave radiative fluxes.*

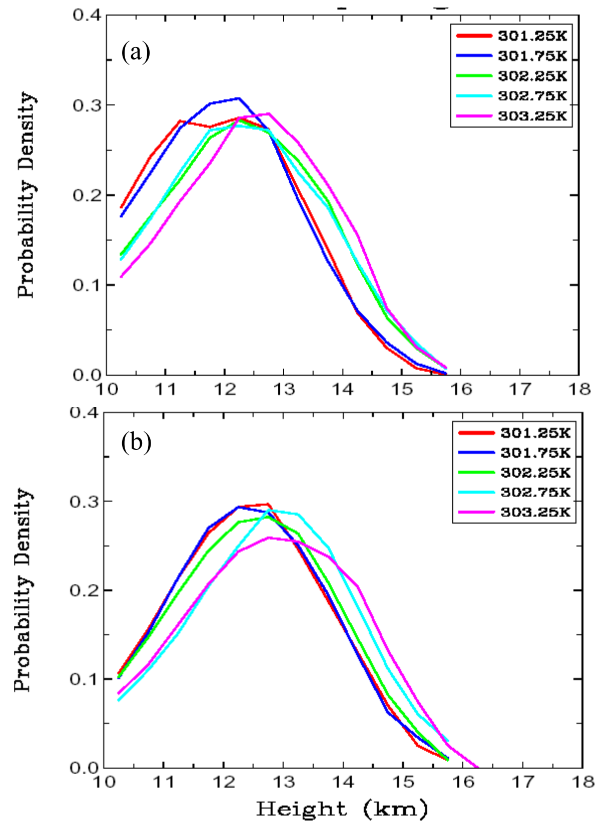

Fig. 7: *Same as Fig. 3 except for cloud top heights.*

5. CONCLUSIONS

This study has presented a new method for studying cloud feedbacks in the climate system through an integrated observational and modeling approach. Satellite data have been analyzed to produce large ensembles of cloud objects for different size classes and SSTs. The statistics of the observed cloud objects are analyzed to understand the sensitivity of cloud feedbacks. It has been found that the differences in the statistics are much greater between the small and large size classes of cloud objects than between different SSTs, especially in cloud microphysical and optical properties. Macrophysical properties show slightly stronger dependency on the SST. Further studies will be performed to compare statistics between observations and high-resolution cloud model simulations.

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