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Mechanisms behind low-cloud optical depth response to temperature in ARM site observations

Christopher Terai, Yunyan Zhang, Stephen Klein, and Mark Zelinka
Lawrence Livermore National Laboratory, United States (terai1@llnl.gov)

Most state-of-the-art climate models predict the cloud optical depth increases with warming in the mid- and high-latitudes. Proposed mechanisms exist in the literature to support this increase in cloud optical depth, and the cloud processes driving the negative cloud feedback have been identified in several climate models. However, recent studies find that this negative cloud feedback in the mid- and high-latitudes is likely overestimated in climate models. For example, an analysis of satellite retrievals suggests that the optical depth of low-level clouds decreases with warming. Less attention has been placed on understanding the cloud processes that drive cloud optical depth changes in observations.

In this study, we use ground-based observations from three mid- and high-latitude sites, managed by the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) Program, to determine the mechanisms that drive cloud changes at those sites. We test whether there is evidence in the observations that support three mechanisms that have been proposed to drive a cloud optical depth response to warming. We test a) whether cloud liquid water content increases with warming following changes in the adiabatic lapse rate of the saturated water vapor, as determined by the Clausius-Clapeyron relationship, b) whether the change in phase-partitioning of clouds due to warming increase the optical depth by changing the cloud optical and microphysical properties and processes, and c) whether warming leads to a thinning of clouds by enhancing the drying efficiency of cloud top mixing.

We find that although increases in cloud liquid content with warming is consistent with the Clausius-Clapeyron relationship at the one oceanic site, they do not hold over the two continental sites. We also find that the liquid-ice partitioning of total cloud water differs between sites and find evidence that increasing ice fraction leads to clouds with lower LWP. We also test whether the transition of cloud properties from ice-dominated to liquid-dominated clouds can be understood as a shift of populations between two sets of different clouds. Finally, because we find that boundary layer heights and stability change substantially with warming and vary between sites, we explore the environmental variables beyond cloud temperatures that control cloud optical depths. The findings of this study provide the basis for diagnostics which can be used to test whether climate models capture the cloud processes necessary to predict future changes in cloud optical depths.

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