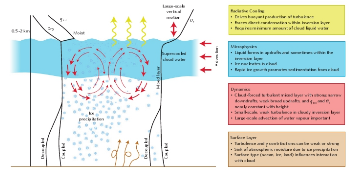
Unraveling the Complexity of Arctic Mixed-Phase Clouds

Research Highlight

The Arctic is particularly sensitive to climate change, with potentially dramatic consequences for the regional ecosystem. Arctic mixed-phase clouds, comprising both ice and supercooled liquid water, have been observed to occur frequently in all seasons and persist for many days at a time. They have a large impact on the shortwave and longwave radiative transfer and consequently play an important role in regulating the flow of energy in the system. Due to the inherent instability of ice-liquid coexistence, the persistence of these clouds is remarkable.

We review the literature on Arctic mixed-phase clouds and develop a conceptual model of their existence and persistence. Complex feedbacks between various local processes related to supercooled liquid water, radiation, turbulence, entrainment, surface heat and moisture fluxes, aerosol, and ice microphysics collude to create a resilient cloud system. Because these interactions are nonlinear and interlinked in numerous ways, poor understanding of any one process or its interactions may have important consequences for understanding the overall system behavior. Thus, it is particularly difficult to predict how the cloud system will behave based upon a strictly reductionist, process-level approach. This complex web of interactions between various physical processes has made it difficult to assemble an overall picture of how Arctic mixed-phase clouds persist. This uncertainty is reflected in the poor simulation of these clouds by numerical models at all scales, which erodes confidence in model estimates of Arctic cloud-climate feedbacks and climate sensitivity. Despite this complexity, the mixed-phase cloud state exhibits distinct emergent properties. This evokes the concept of "self-organization", defined as "internal, local process interactions giving rise to global order". Self-organization prevails in a range of natural and man-made systems. In the central Arctic, observations provide evidence for the existence of two preferred, quasi-steady states corresponding to low-level mixed-phase clouds and radiatively clear conditions. These states exhibit sharp differences in net surface longwave radiation, as well as surface temperature, sensible heat fluxes, and atmospheric humidity and temperature structure. Based on these observations, only a 5% shift in frequency of occurrence from the radiatively-clear state to the mixed-phase state would result in an overall increase in net surface LW of about 1.5-2 W m-2, all else being equal. The key question, then, is what conditions select the occurrence of these states? Phase diagrams indicate that while the mixed-phase cloud state is resilient and often lasts for several days, transitions between it and the radiatively clear state typically occur over timescales of hours or less. Thus, system evolution appears to be influenced by both slow and fast timescale processes. Slow timescale processes are generally associated with the large-scale meteorological environment, with a characteristic timescale on the order of a day or longer. Fast timescale processes are associated with local process interactions between clouds, radiation, aerosol, turbulence, and the surface. The importance of both fast and slow timescale processes may explain why it has been difficult to clearly relate these Arctic states to large-scale environmental conditions. We hypothesize that local process interactions tend to keep trajectories "slaved" to slow manifolds (i.e., slowly evolving surfaces of phase space), leading to resilience and persistence of the states. However, if changes to the large-scale environment are significant enough to disrupt these local process interactions, then rapid transition between the states may occur. Large-eddy simulations of the Arctic mixed-phase cloud boundary layer support this hypothesis.

In spite of the process-level complexity and often limited observational constraints, the persistence of distinct Arctic states indicates that the problem may be more tractable than the process-level complexity suggests. Given the sensitivity of the Arctic system to climate change, it is imperative that we continue to pursue this problem with both existing and new observational strategies, numerical modeling



A conceptual model that illustrates the primary processes and basic physical structure of persistent Arctic mixed-phase clouds. Although this diagram includes many features, it does not fully represent all manifestations of these clouds.

efforts, and conceptual approaches that have proven successful in predicting the characteristics of other complex systems. In particular, a merging of reductionist and systems-based approaches may prove useful.

Reference(s)

Morrison H, G de Boer, G Feingold, J Harrington, M Shupe, and K Sulia. 2011. "Resilience of persistent Arctic mixed-phase clouds." Nature Geoscience, 5, doi:10.1038/ngeo1332.

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Cloud Life Cycle