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Boundary-layer processes cause GCM biases in Arctic winter

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Temperature inversions are a common feature of the Arctic wintertime boundary layer. They have important impacts on both radiative and turbulent heat fluxes and partly determine local climate change feedbacks. Inversions and the associated surface fluxes are poorly represented in current climate models, with many models overestimating the typical strength of temperature inversions. Understanding the spread and biases in inversion strength modelled by global climate models is therefore an important step in better understanding Arctic climate and its present and future changes.

Here, we show how the cooling of relatively warm and moist are masses advected from lower latitudes leads to the emergence of a clear and a cloudy state of the Arctic winter boundary layer. During this process of formation of Arctic air, radiative cooling leads to saturation and thus triggers the formation of a high-emissivity liquid-containing cloud which limits surface radiative cooling in the cloudy state. Further radiative cooling drives the transition to a low-emissivity ice cloud which allows the surface to cool radiatively and is therefore associated with the clear state of the boundary layer. Temperature inversions are initially created by warm air advection, then eroded by radiative cooling aloft in the cloudy state and created again by surface cooling in the clear state. This results in stronger typical inversions in the clear than in the cloudy state.

Comparing model output to observations, we find that many CMIP5 models do not realistically represent the cloudy state. This results in excessive surface radiative cooling, which leads to an overestimation of inversion strength in one group of models, whereas other models produce weak inversions despite strong surface cooling.

An idealised single-column model experiment of the formation of Arctic air reveals that the lack of a cloudy state is linked to inadequate mixed-phase cloud microphysics. In models lacking a cloudy state, freezing of cloud liquid water occurs at too warm temperatures. Excessive turbulent and conductive heat fluxes can weaken temperature inversions despite surface radiative cooling, which can explain why some models produce weak inversions despite lacking a cloudy state.

A redistribution from the clear to the cloudy state in a warming climate would act to amplify Arctic surface warming. Results from the MPI-ESM-LR suggest that such a feedback does indeed exist. A better understanding and model representation of Arctic mixed-phase clouds is required to verify and quantify the effect of this mechanism on Arctic climate change.