The Impact of a Humidity Inversion on the Persistence of a Decoupled Arctic Mixed-Phase Stratocumulus

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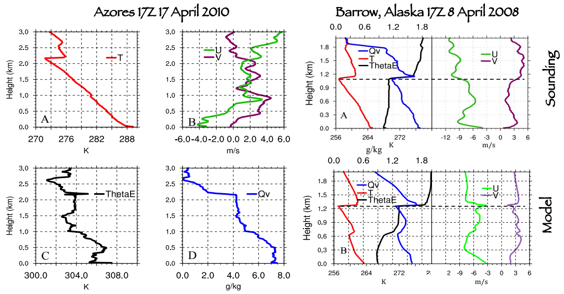
Motivation

Observations indicate that the processes that maintain subtropical and Arctic stratocumulus (Sc) differ, due to the different environments in which they occur. For example, specific humidity inversions (specific humidity increasing with height) are frequently observed to occur coincident with temperature inversions in the Arctic (e.g., Curry et al. 1996, Tjernström et al. 2004, Sedlar and Tjernström 2009). In a recent study, Sedlar et al. (2011) surveyed data from SHEBA, ASCOS and at Barrow, Alaska, to find that specific humidity inversions occurred 75-80% of the time when low-level clouds were present. In addition, this study found a significant relationship between the existence of specific humidity inversions and Arctic Mixed-Phase Stratocumulus (AMPS) that extended into the temperature inversion, highlighting the difference between AMPS and subtropical stratocumulus where the entrainment of dry air aloft prevents cloud liquid water from forming in the temperature inversion. Other important differences between warm Sc and AMPS are more effective cloud top radiative cooling because of the cold, dry overlying Arctic free troposphere, and the vapor diffusion onto ice (Bergeron process) which acts as a potentially large sink of water vapor for AMPS even when there is limited liquid water. In warm Sc drizzle grows by collision-coalescence of droplets, so as liquid water in warm Sc decreases, drizzle will shut off.

In this study we focus on a decoupled AMPS in order to focus on the conditions that make AMPS distinct from subtropical Sc. Specifically, we use nested LES simulations to quantify the role of humidity inversions at cloud top in the persistence of AMPS.

Structure of Stratocumulus Topped Boundary Layers

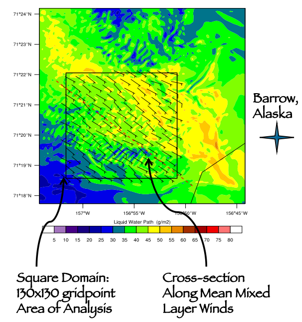


A) Temperature, in units of K. B) Horizontal winds, in units of m s⁻¹. C) Equivalent potential temperature, in units of K. D) Specific humidity, in units of g kg⁻¹.

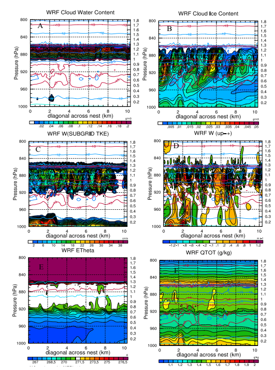
A) Measured 17.6Z April 8 2008 at (71.33N,156.61W). B) 50 m LES simulation 20Z April 8 2008 at (71.33N, 156.91W). The dashed lines mark the height of the cloud liquid water maximum.

Experiment Design

- WRF Version 3.1
- Two-way nesting using 25km, 5km, 1km, 200m, 50m nests
- 16m vertical resolution in mixed layer, 8m resolution in entrainment zone
- Morrison 2-moment liquid and ice microphysics
- Uniform sea-ice surface
- ECMWF 6 hourly forcing at the 25km lateral boundaries
- Aerosols fit to ISDAC measurements



Boundary Layer Structure Along Mean Mixed Layer Winds

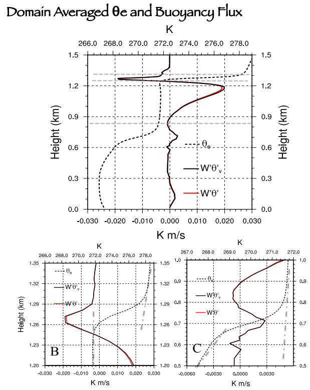


Vertical structure at 20Z along mean cloud layer wind from 50 m nest.

A) Cloud water, in units of g kg⁻¹.
B) Cloud ice, in units of g kg⁻¹.
C) Subgrid W, in units of cm s⁻¹.
D) Vertical velocity, in units of m s⁻¹.
E) Equivalent potential temperature, in units of K. Red(blue) lines are contours of q_l = 0.12(0.01) g m⁻³ to identify the max(min) of the cloud layer.
F) Total water, in units of g kg⁻¹.

Isotherms are shown with colored contour lines in all figures except (E).

Domain Averaged θe and Buoyancy Flux



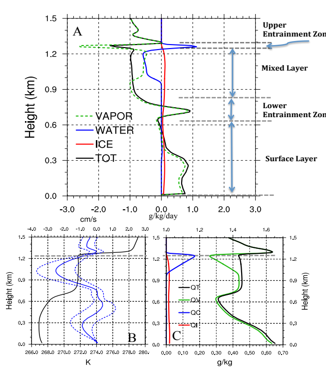
Buoyancy fluxes averaged over total cloud domain, where black (red) lines show $\overline{w'\theta'_v}$ ($\overline{w'\theta'}$) and equivalent potential temperature (<θ_e>) is shown with a dashed line, in units of K m s⁻¹ and K, respectively.

A) Surface to 1.5 km. Gray dashed lines indicate upper entrainment zone and mixed layer heights.

B) Cloud top entrainment zone.
C) Below mixed layer entrainment zone.

Dash-dot gray lines show constant θ_e slopes used to estimate the depth of the entrainment zones: 1.24-1.3 km = 60 m at cloud top and 0.62-0.82 km = 200 m below mixed layer.

Domain Averaged Water Tendencies and Mean Fields



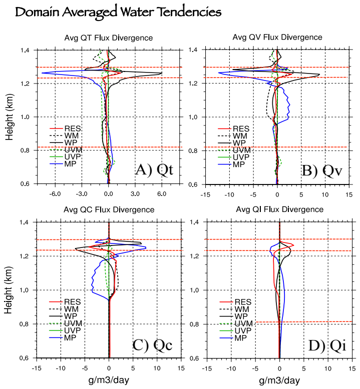
Tendencies averaged over total cloud domain calculated from 15 minutes averages.

A) Cloud water, vapor, ice, and total water tendencies, in units of g kg⁻¹ day⁻¹. Gray dash lines denote boundaries of cloud top entrainment zone, mixed layer, lower entrainment zone, and surface layer. Positive (negative) indicates water gained (lost) by the layer.

B) Mean resolved vertical velocity (blue, dash lines are +/- one standard deviation) and equivalent potential temperature in black, in units of cm s⁻¹ and K, respectively.

C) Mean total water, cloud liquid water, cloud ice water, and water vapor, in units of g kg⁻¹. Gray dashed line indicates height of maximum liquid water.

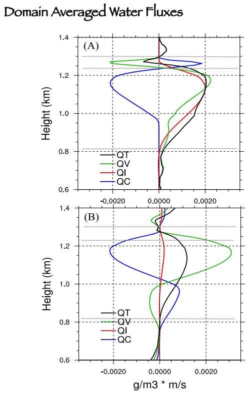
Domain Averaged Water Tendencies



Processes that contribute to 15-minute averaged water content tendencies above the surface layer for the total cloud domain, in units of g m⁻³ day⁻¹. The residual is equal to subgrid scale mixing plus diffusion. Mean advection terms (denoted with WM, UVM) are calculated by horizontally averaging tendencies. Horizontal eddy advection (UVP) is calculated as the divergence of fluxes across the domain. Vertical eddy advection (WP) is the divergence of the vertical eddy flux.

A) Total water
B) Water vapor
C) Cloud liquid water
D) Cloud ice water

Domain Averaged Water Fluxes



Horizontally and temporally averaged vertical water content fluxes, in units of g m⁻³ m s⁻¹. Water components horizontally averaged across the square domain and vertically averaged to 1.5 km are removed before calculating the mean fluxes.

(A) Eddy fluxes
(B) Mean fluxes.

AMPS Conceptual Model

Schematic of AMPS from model results.

A) Evolution from initial cloud-free environment (gray profile) to a decoupled AMPS topped boundary layer (black profile). Red arrows indicate net effect of dynamical mixing and sedimentation.

B) Evolution of decoupled AMPS topped boundary layer over one hour.