Characterizing the Impact of Entrainment Rate in Stratocumulus from ARM Observations and Large-Eddy Simulations

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Findings (read this first!)
- Entrainment velocity estimates from MAGIC are highly variable and exhibit no pronounced diurnal cycle nor dependence on longitude.
- Large-scale vertical motion is highly variable and includes periods of ascent.
- Solar radiation doesn’t shut down entrainment. Even in the presence of substantial afternoon solar heating, entrainment fluxes remain active.
- Thin clouds demonstrate unexpected resiliency. As the short-wave flux decreases later in the afternoon, the relative contribution of long-wave cooling often becomes large enough to offset entrainment warming/drying and result in a reversal of cloud-base (and cloud thickness) tendency.
- Estimates of entrainment rate must be bound with uncertainties and a description of method.

Entrainment rates from MAGIC

Entrainment rates were retrieved as a residual from boundary-layer mass budgets from observations made on board a moving marine platform:

\[
\frac{dh}{dt} + (\bar{u} - \bar{u}_{ship}) \frac{dh}{dx} + (\bar{v} - \bar{v}_{ship}) \frac{dh}{dy} = w_e + w_s
\]

Profiling cloud radar

GOES satellite

ECMWF reanalysis

Sfc. met station on ship

\(h\) = Boundary-layer depth

\(u, v\) = winds in the boundary layer

\(u_{ship}, v_{ship}\) = Ship velocity

\(w_e\) = Entrainment rate

\(w_s\) = Large-scale vertical motion

Factors governing thinning and recovery of thin marine stratocumulus

Use a mixed-layer model (MLM) framework to develop a budget for cloud-base height evolution and apply to LES output (extended from Wood (JAS, 2007), Van der Dussen (JAS, 2014) and Ghonima et al. (2015):

\[
\frac{dz_c}{dt} = \frac{R_h T_c}{\Delta T} \left( \frac{L_v R_d}{\rho_0} \right)^{-1} + \frac{w_c T_c}{\Delta T} \left( \frac{L_v R_d}{\rho_0} \right)^{-1} \left( 1 - \frac{c_p R_h T_c}{R_h L_v} \right) + \frac{1}{g} \left[ \frac{c_p R_h T_c}{R_h L_v} - 1 \right] \frac{w_c \Delta T_c}{\Delta T} + \frac{w_c \Delta T_c}{\Delta T}
\]

\(R_h\) = Cloud radiative forcing

\(T_c\) = Cloud temperature

\(L_v\) = Latent heat of vaporization

\(R_d\) = Radiative heat flux

\(\rho_0\) = Density of air

\(c_p\) = Specific heat at constant pressure

\(w_c\) = Wind velocity

\(\Delta T\) = Temperature change

\(\Delta T_c\) = Cloud temperature change

• Thin (LWP<100 g m⁻²), transient stratocumulus during midday
• SAM LES, setup based on CIRPAS Twin Otter profiles, and large-scale models (ECMWF, NOGAPS)
• 20+ sensitivity simulations to determine what factors most strongly govern entrainment rate
• Analyze LES output in mixed-layer model (MLM) framework to identify governing mechanisms

Budget terms for control simulation over two simulation periods:


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