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

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Objectives

• Observationally constrain stratocumulus entrainment rates from the DOE MAGIC cruises and explore sensitivity to environmental parameters
• Use LES to investigate the importance of entrainment mechanisms relative to other processes governing cloud properties.


The importance of entrainment to stratocumulus cloud properties

Rate of change of cloud-base height with time:

\[
\frac{dz_{cb}}{dt} = -\frac{R_d T_{cb}}{g \bar{q}_T} \left( \frac{L_v R_d}{C_p R_v T_{cb}} - 1 \right)^{-1} \frac{w_e \Delta \bar{q}_T}{z_i} + \frac{1}{g} \left( 1 - \frac{C_p R_v T_{cb}}{R_d L_v} \right)^{-1} \frac{w_e \Delta S_l}{z_i}
\]

\text{drying term} + \text{warming term}

Assume a typical stratocumulus example (DYCOMS–II RF01):

\[
\bar{q}_T = 8.0 \text{ g kg}^{-1}
\]

\[
\Delta \bar{q}_T = -7.5 \text{ g kg}^{-1}
\]

\[
\Delta \theta = 10 \text{ K}
\]

\[
T_{cb} = 280 \text{ K}
\]

\[
z_i = 840 \text{ m}
\]

An uncertainty/error of 2.0 mm s\(^{-1}\) in entrainment rate leads an uncertainty of 108 m in cloud thinning over a 6-hour period!
MAGIC field campaign

Zhou et al. (J. Climate, 2015)

20–25 July 2013

Deeper, weaker inversion, more decoupled
Calculating MAGIC entrainment rates from mass budget

\[ \frac{\partial \bar{h}}{\partial t} + (\bar{u} - \bar{u}_{\text{ship}}) \frac{\partial \bar{h}}{\partial x} + (\bar{v} - \bar{v}_{\text{ship}}) \frac{\partial \bar{h}}{\partial y} = w_e + w_s. \]

Profiling cloud radar
GOES satellite
Sfc. met station on ship
ECMWF reanalysis

ECMWF vertical motion
### MAGIC entrainment rates

\[
\frac{\partial h}{\partial t} + (\bar{u} - \bar{u}_{\text{ship}}) \frac{\partial h}{\partial x} + (\bar{v} - \bar{v}_{\text{ship}}) \frac{\partial h}{\partial y} = w_e + w_s
\]

<table>
<thead>
<tr>
<th>Start date (YYYYMMDD)</th>
<th>Local change in cloud top height (mm/s)</th>
<th>Horizontal advection (mm/s)</th>
<th>Large-scale vertical air motion at cloud top (mm/s)</th>
<th>Entrainment rate (mm/s)</th>
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MAGIC entrainment rates

Graph showing the variation of velocity with longitude and temperature difference.
Factors governing thinning and recovery of marine stratocumulus
Factors governing thinning and recovery of marine stratocumulus

- Thin, transient stratocumulus (31 Aug 2012) — midday-to-afternoon
- 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 cloud properties
- Analyze LES output in mixed-layer model (MLM) framework
Mixed-layer model analysis of LES output

- Based on Wood (JAS, 2007), Van der Dussen (JAS, 2014); Ghonima et al. (2015)
Factors governing thinning and recovery of coastal stratocumulus

Cloud thinning

Cloud thickening

Discrepancy associated with decoupling during early period
Conclusions

- Entrainment estimates from MAGIC are highly variable and exhibit no obvious diurnal cycle nor dependence on longitude.
- Large-scale vertical motion is highly variable and includes periods of ascent.
- Even in the presence of substantial afternoon solar heating, entrainment fluxes remain active.
- Thin clouds demonstrate unexpected resilience.
- Estimates of entrainment rate must be accompanied by uncertainties and a description of method.