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

ASR Atmospheric System Research

ARM CLIMATE RESEARCH FACILITY

D. B. Mechem[1], V. P. Ghate[2], L. A. McMichael[1], J. M. Eissner[1], M. P. Jensen[3], and S. E. Giangrande[3]

[1]University of Kansas, Lawrence, KS [2]Argonne National Laboratory, Lemont, IL [3]Brookhaven National Laboratory, Upton, NY

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.* These results suggest that mechanistic evaluation of low-cloud behavior in climate models cannot be obtained from climatological mean estimates alone.
- *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

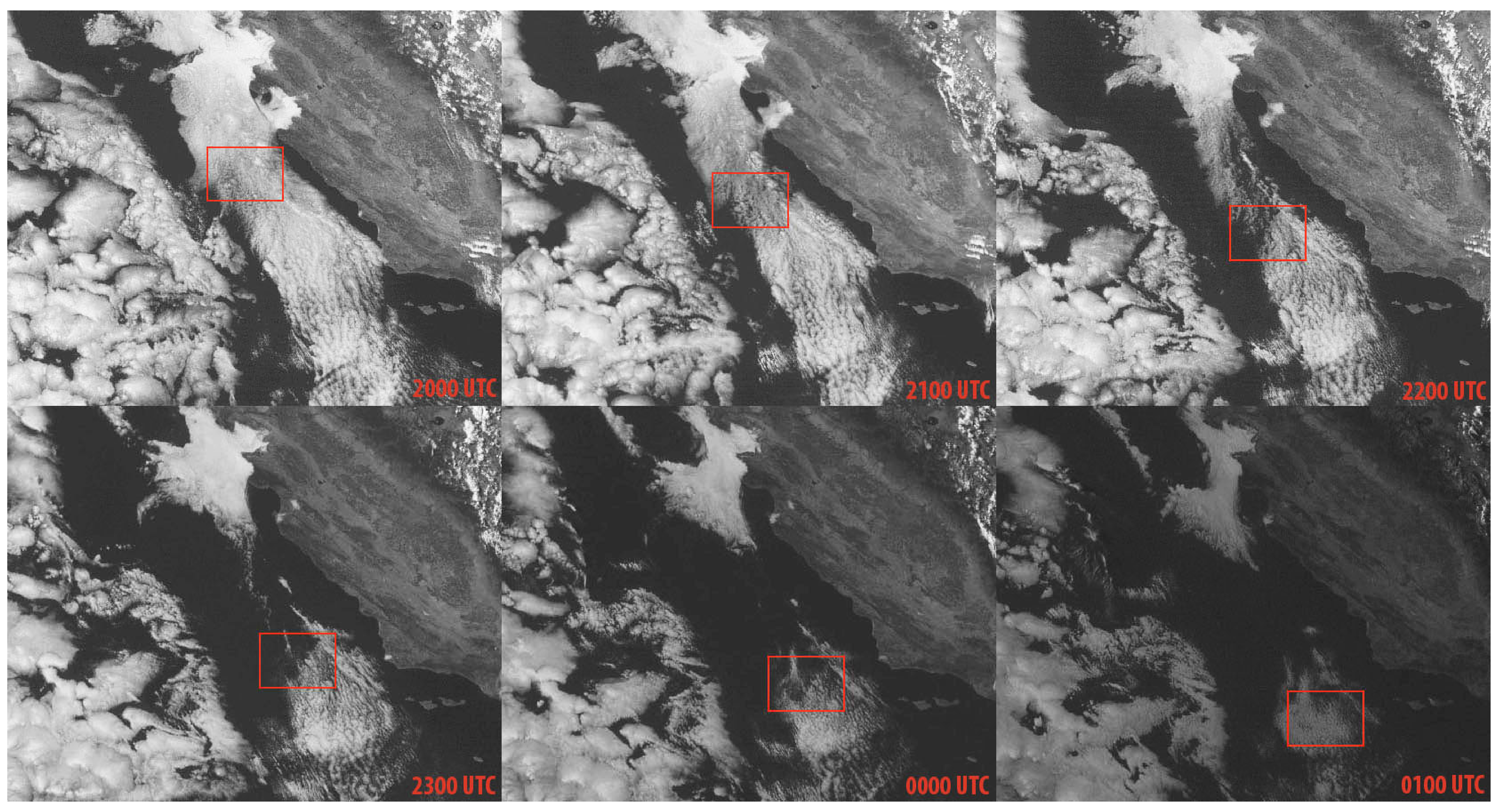
Entrainment rates were retrieved as a residual from boundary-layer mass budgets from observations made on board a moving marine platform:

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

Sfc. met station on ship ($\bar{u}_{\text{ship}}$, $\bar{v}_{\text{ship}}$); Profiling cloud radar ($\partial \bar{h}/\partial t$); GOES satellite ($\partial \bar{h}/\partial x$, $\partial \bar{h}/\partial y$); ECMWF reanalysis ($w_s$)

h = Boundary-layer depth
u, v = winds in the boundary layer
$u_{\text{ship}}, v_{\text{ship}}$ = Ship velocity
w_e = Entrainment rate
w_s = Large-scale vertical motion

Factors governing thinning and recovery of thin marine stratocumulus



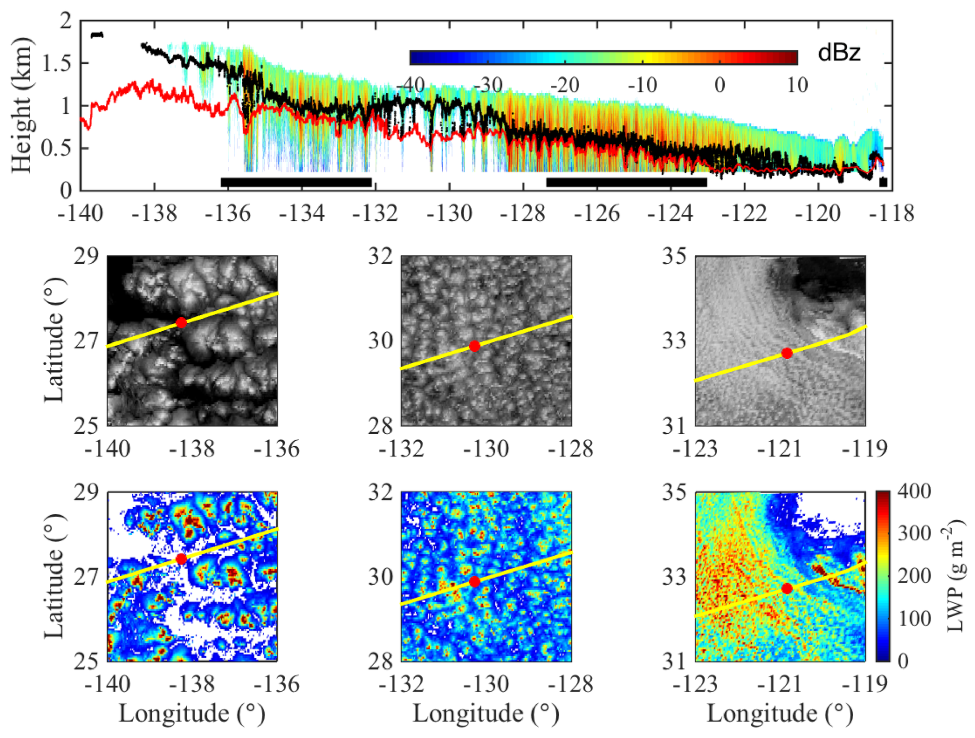
Use a mixed-layer model (MLM) framework to develop a budget for cloud-base height evolution and apply to LES output (extended from Wood (JAS, 2007), Van der Dussen (JAS, 2014) and Ghonima et al. (2015):

$$\frac{dz_{cb}}{dt} = \underbrace{-\frac{R_d T_{cb}}{g q_T}\left(\frac{L_v R_d}{c_p R_v T_{cb}} - 1\right)^{-1}}_{\frac{\partial z_{cb}}{\partial q_T}} \underbrace{\left(\frac{w_e \Delta q_T + \frac{q_{Tsfcflux}}{\rho * L_v} - P_0}{h} - \overline{\boldsymbol{v} \cdot \nabla_h q_T}\right)}_{\frac{\partial q_T}{\partial t}}$$

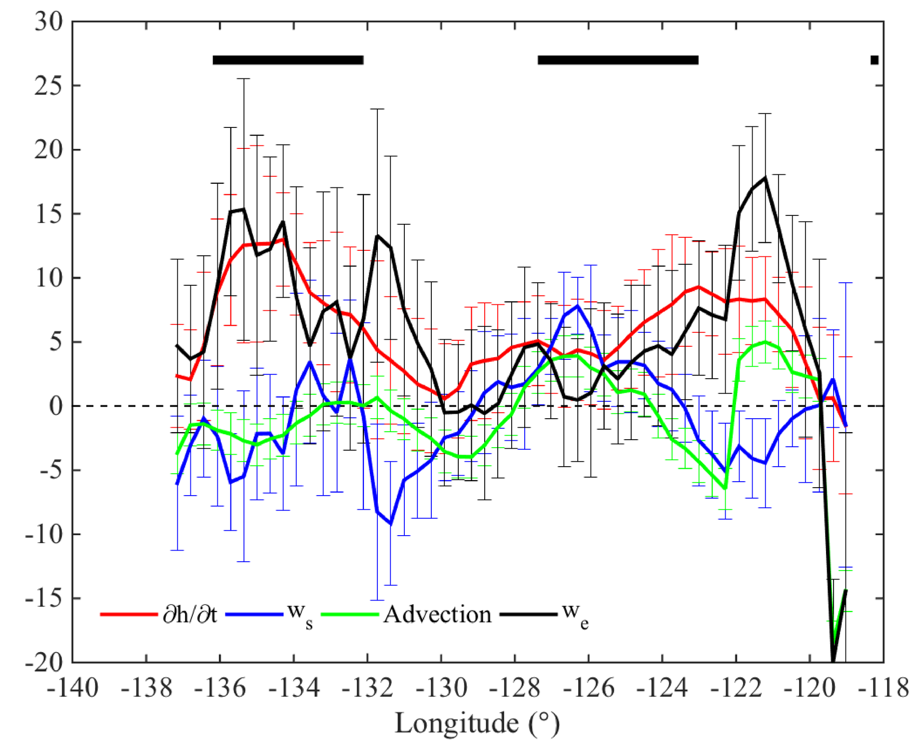
$$+ \underbrace{\frac{1}{g}\left(1 - \frac{c_p R_v T_{cb}}{R_d L_v}\right)^{-1}}_{\frac{\partial z_{cb}}{\partial S_l}} \underbrace{\left(\frac{w_e \Delta S_l + \frac{S_{lsfcflux}}{\rho} - \frac{R_h}{\rho} + \frac{R_0}{\rho} + L_v P_0}{h} - \overline{\boldsymbol{v} \cdot \nabla_h S_l}\right)}_{\frac{\partial S_l}{\partial t}}$$

Terms: EntrainQT ($w_e \Delta q_T$), LHF ($\frac{q_{Tsfcflux}}{\rho * L_v}$), MoistureLoss ($P_0$), MoistAdv ($\overline{\boldsymbol{v} \cdot \nabla_h q_T}$); EntrainSL ($w_e \Delta S_l$), SHF ($\frac{S_{lsfcflux}}{\rho}$), RadFluxDiv ($\frac{R_h}{\rho} + \frac{R_0}{\rho}$), DiabHeat ($L_v P_0$), TempAdv ($\overline{\boldsymbol{v} \cdot \nabla_h S_l}$)

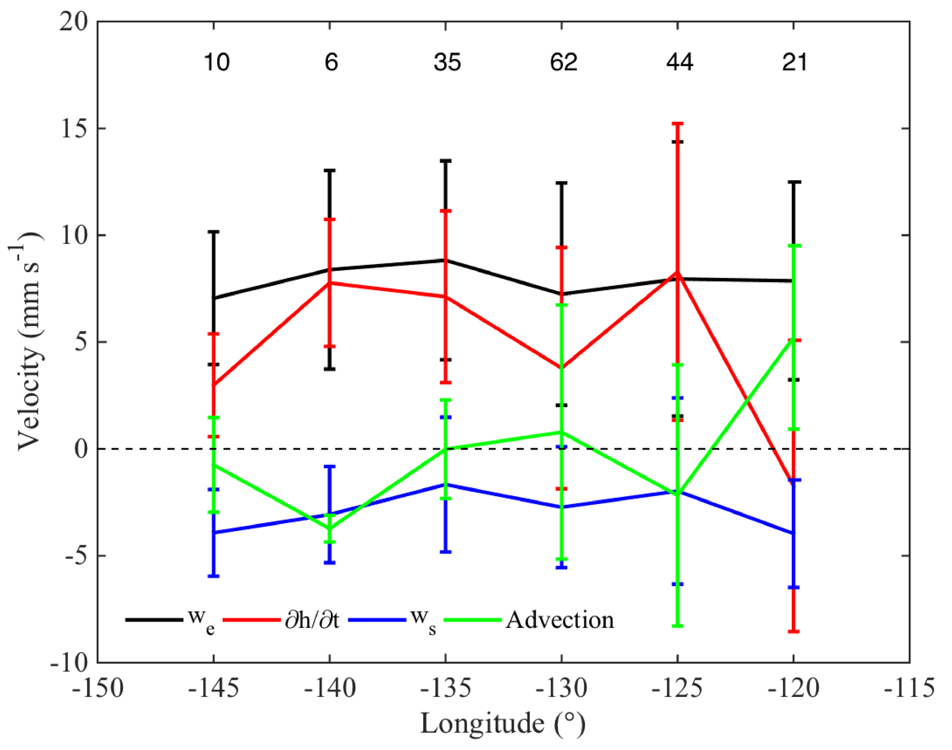
MAGIC 20–25 June 2013 LA-to-HI transect (Leg 15A)



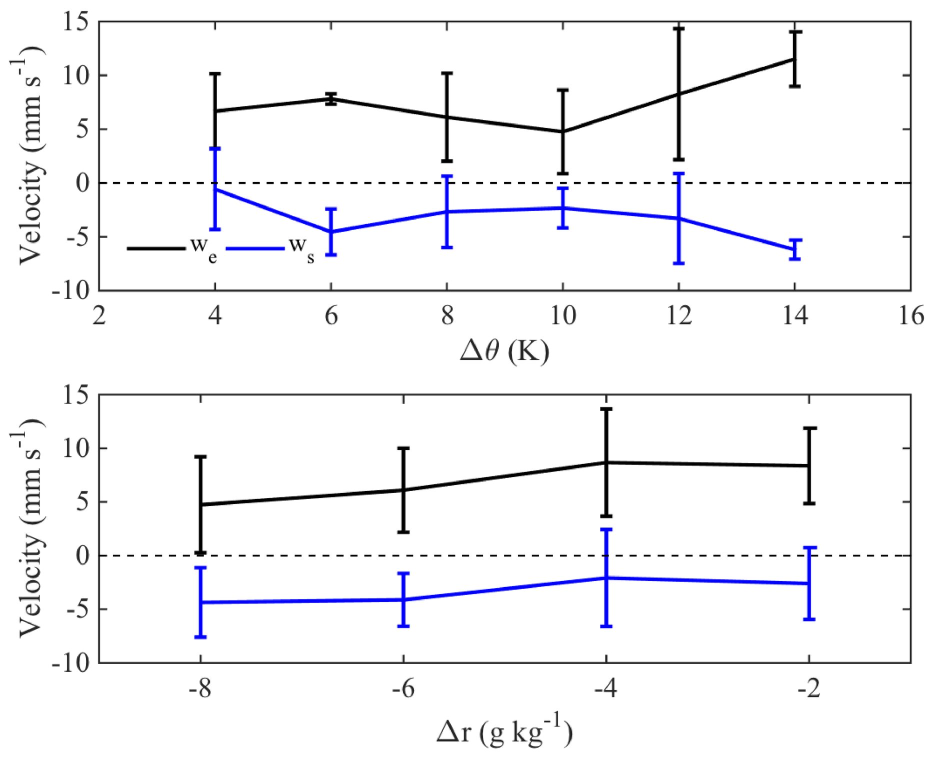
(top) Longitude–height profiles of the KAZR-reported radar reflectivity, ceilometer-reported first cloud base height (black), and LCL. (middle) GOES–15 visible reflectance. (bottom) GOES–15 LWP retrievals.



Terms of the mass budget equation and uncertainty estimates for Leg 15A. Black bars at top of plot indicate nighttime conditions.



Longitude plot of terms in the mass budget equation calculated over 7 ship legs.

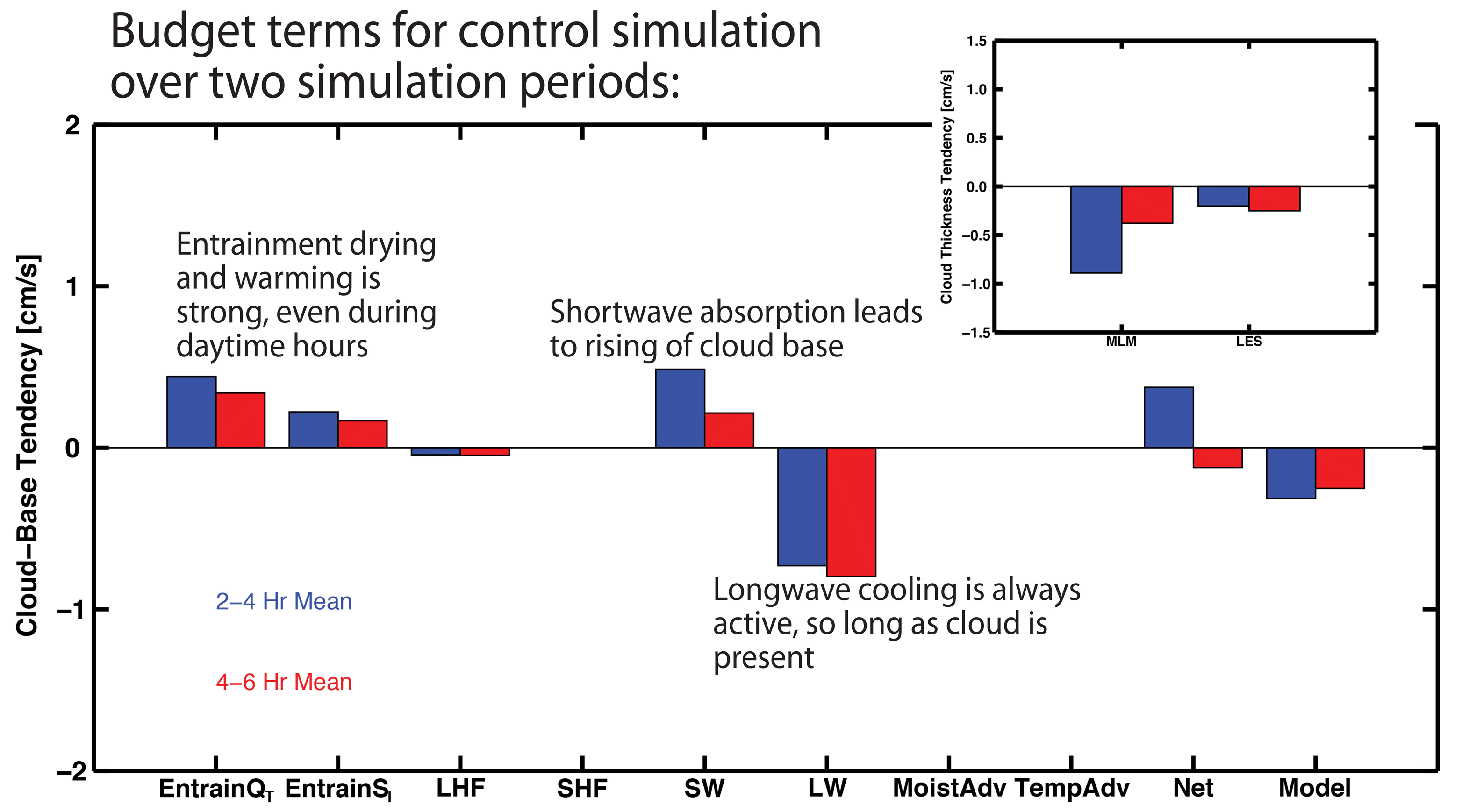


Entrainment (w_e) and large-scale vertical air motion (w_s) binned by strength of boundary-layer inversion in terms of jump in (a) potential temperature and (b) mixing ratio across the inversion.

Start date (YYYYMMDD)	Local change in cloud top height (mm/s)		Horizontal advection (mm/s)		Large-scale vertical air motion at cloud top (mm/s)		Entrainment rate (mm/s)	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
20121104	9.74	2.14	−1.07	1.97	−1.21	3.35	10.24	4.04
20130609	2.81	4.79	4.01	9.05	−1.98	2.23	9.60	5.24
20130708	8.44	4.65	−5.13	5.83	−4.38	2.60	7.64	4.49
20130717	−2.69	6.50	2.52	5.20	−5.69	1.77	5.25	3.55
20130720	6.37	3.24	−0.17	2.83	−0.45	3.81	6.94	4.87
20130730	−3.80	3.57	2.78	3.81	−4.14	2.13	2.58	1.84
20130804	9.62	4.97	0.66	2.21	−2.17	1.74	12.41	5.39
All	4.99	6.44	0.18	5.44	−2.56	3.31	7.83	5.23

- 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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