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.

Ghate, V. P., D. B. Mechem, M. P. Cadeddu, E. W. Eloranta, M. P. Jensen, M. L. Nordeen, and W. L. Smith, Jr., 2019: Entrainment in closed cellular marine stratocumulus clouds from the MAGIC field campaign. *Quart. J. Roy. Meteor. Soc.*, 1–14, https://doi.org/10.1002qj.3514.

McMichael, L. A., D. B. Mechem, S. Wang, Q. Wang, Y. L. Kogan, and J. Teixeira, 2018: Assessing the mechanisms governing the daytime evolution of marine stratocumulus using large-eddy simulation. *Quart. J. Roy. Meteor. Soc.*, **145**, 845–866.

The importance of entrainment to stratocumulus cloud properties

Rate of change of cloud-base height with time:

$$\frac{dz_{cb}}{dt} = \underbrace{-\frac{R_d T_{cb}}{g\bar{q}_T}\left(\frac{L_v R_d}{C_p R_v T_{cb}} - 1\right)^{-1}\frac{w_e \Delta\bar{q}_T}{z_i}}_{\text{drying term}} + \underbrace{\frac{1}{g}\left(1 - \frac{C_p R_v T_{cb}}{R_d L_v}\right)^{-1}\frac{w_e \Delta\bar{S}_l}{z_i}}_{\text{warming term}}$$

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

$$\begin{aligned}
\bar{q}_T &= 8.0 \text{ g kg}^{-1} \\
\Delta\bar{q}_T &= -7.5 \text{ g kg}^{-1} \\
\Delta\theta &= 10 \text{ K} \\
T_{cb} &= 280 \text{ K} \\
z_i &= 840 \text{ m}
\end{aligned}$$

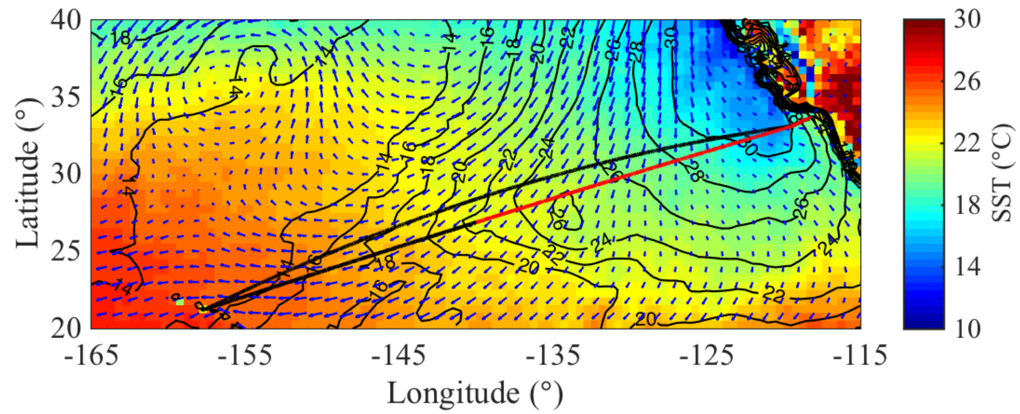
$\longrightarrow$

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!

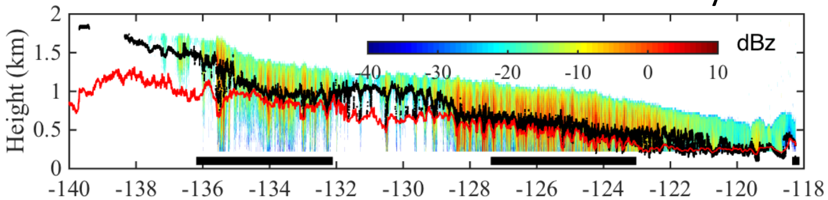
MAGIC field campaign

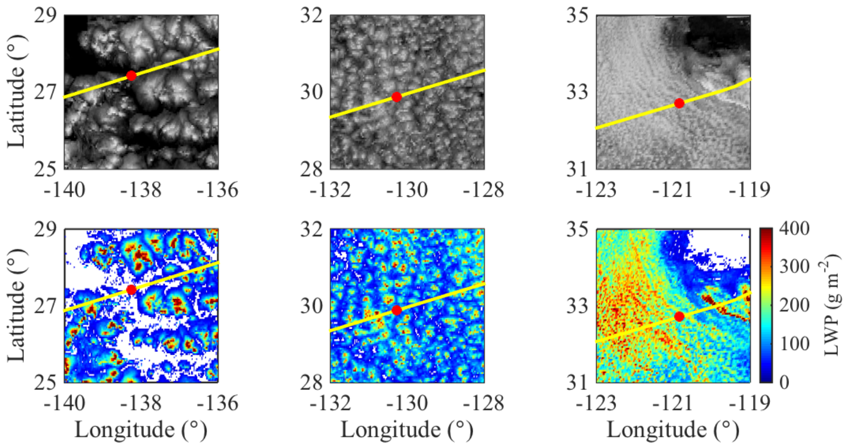
+ AMF2

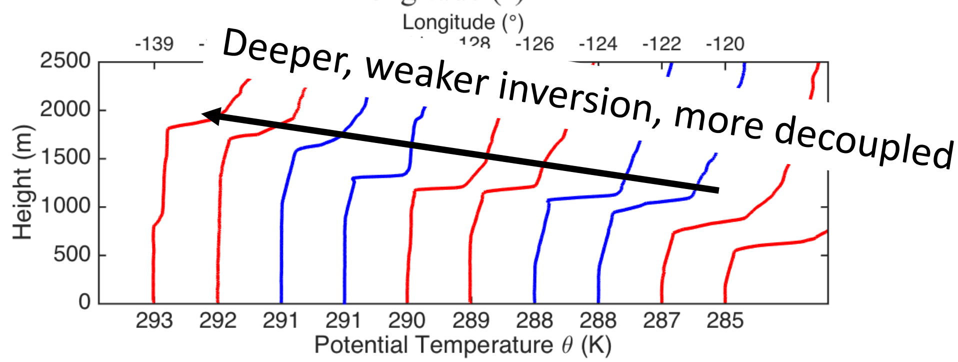
Zhou et al. (J. Climate, 2015)

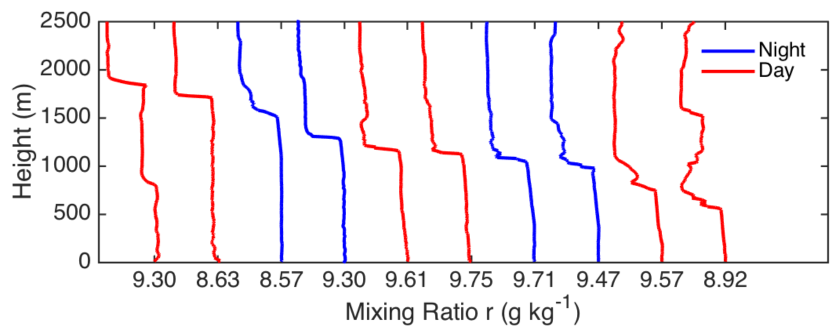


20–25 July 2013









Calculating MAGIC entrainment rates from mass budget

Sfc. met station on ship

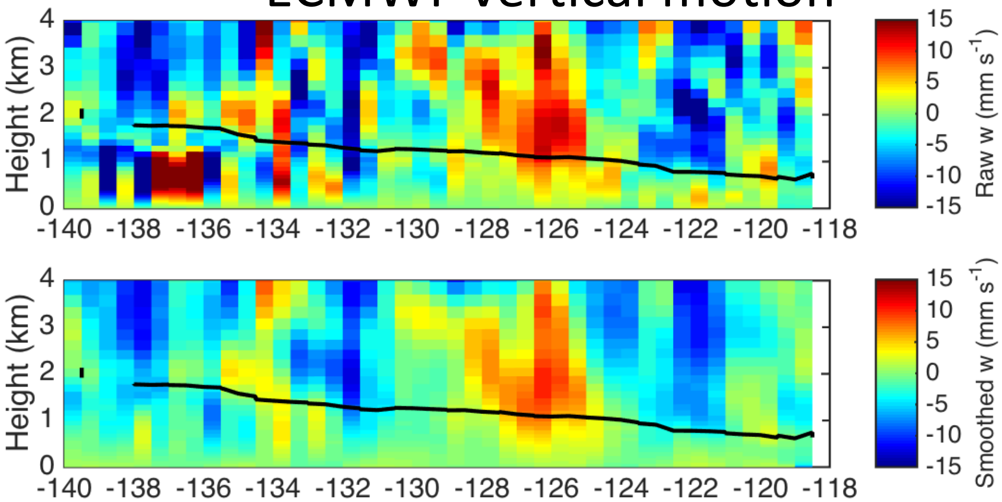
$$\frac{\partial \bar{h}}{\partial t} + (\bar{u} - \bar{u}_{\mathrm{ship}})\frac{\partial \bar{h}}{\partial x} + (\bar{v} - \bar{v}_{\mathrm{ship}})\frac{\partial \bar{h}}{\partial y} = w_{\mathrm{e}} + w_{\mathrm{s}}$$

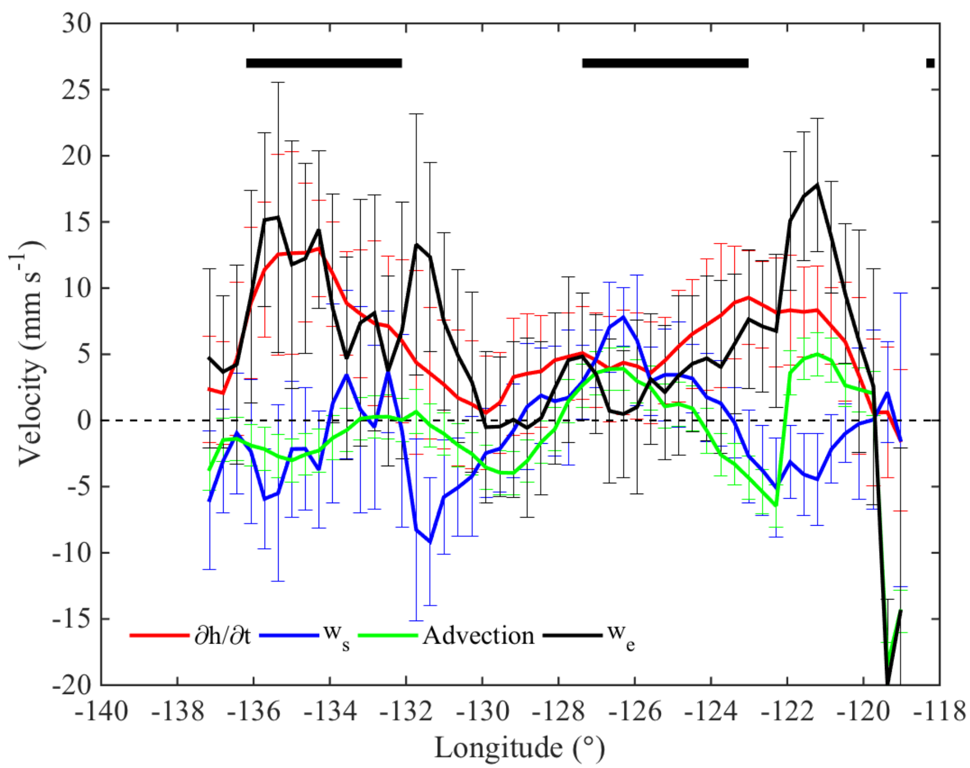
Profiling cloud radar

GOES satellite

ECMWF reanalysis

ECMWF vertical motion



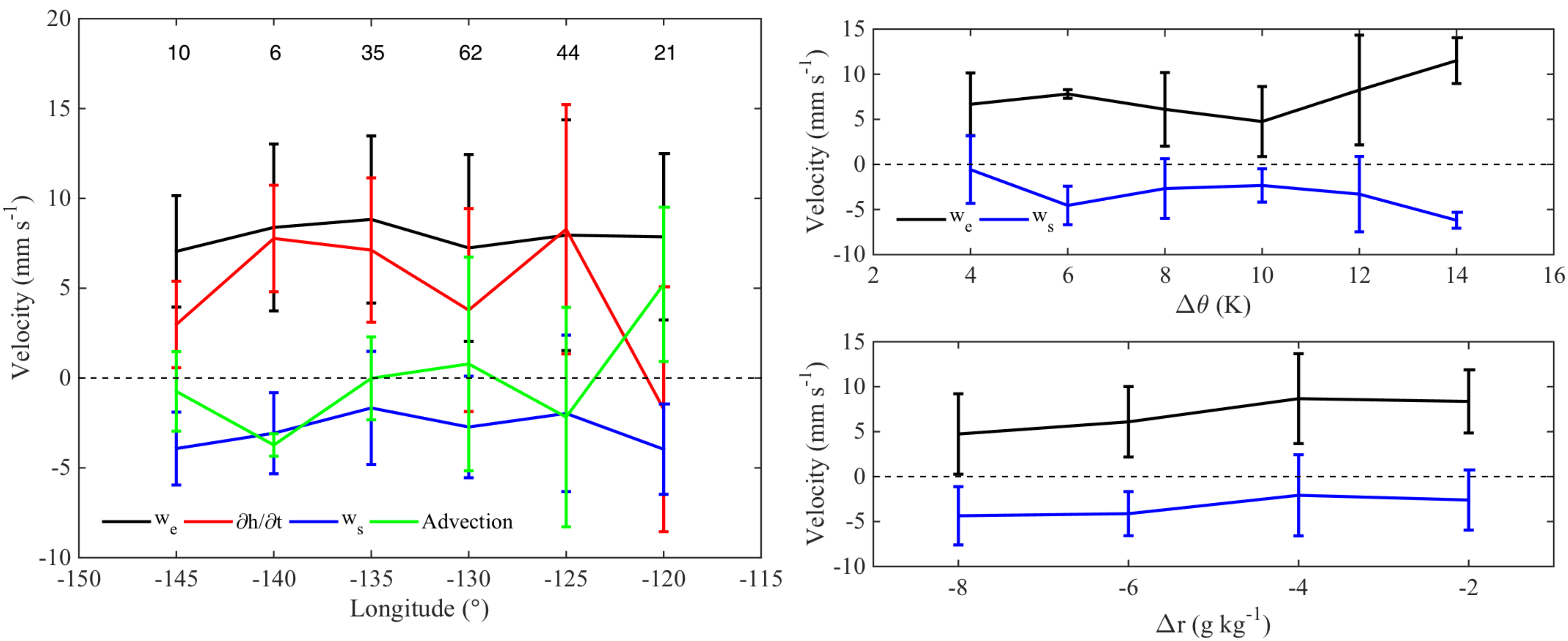


MAGIC entrainment rates

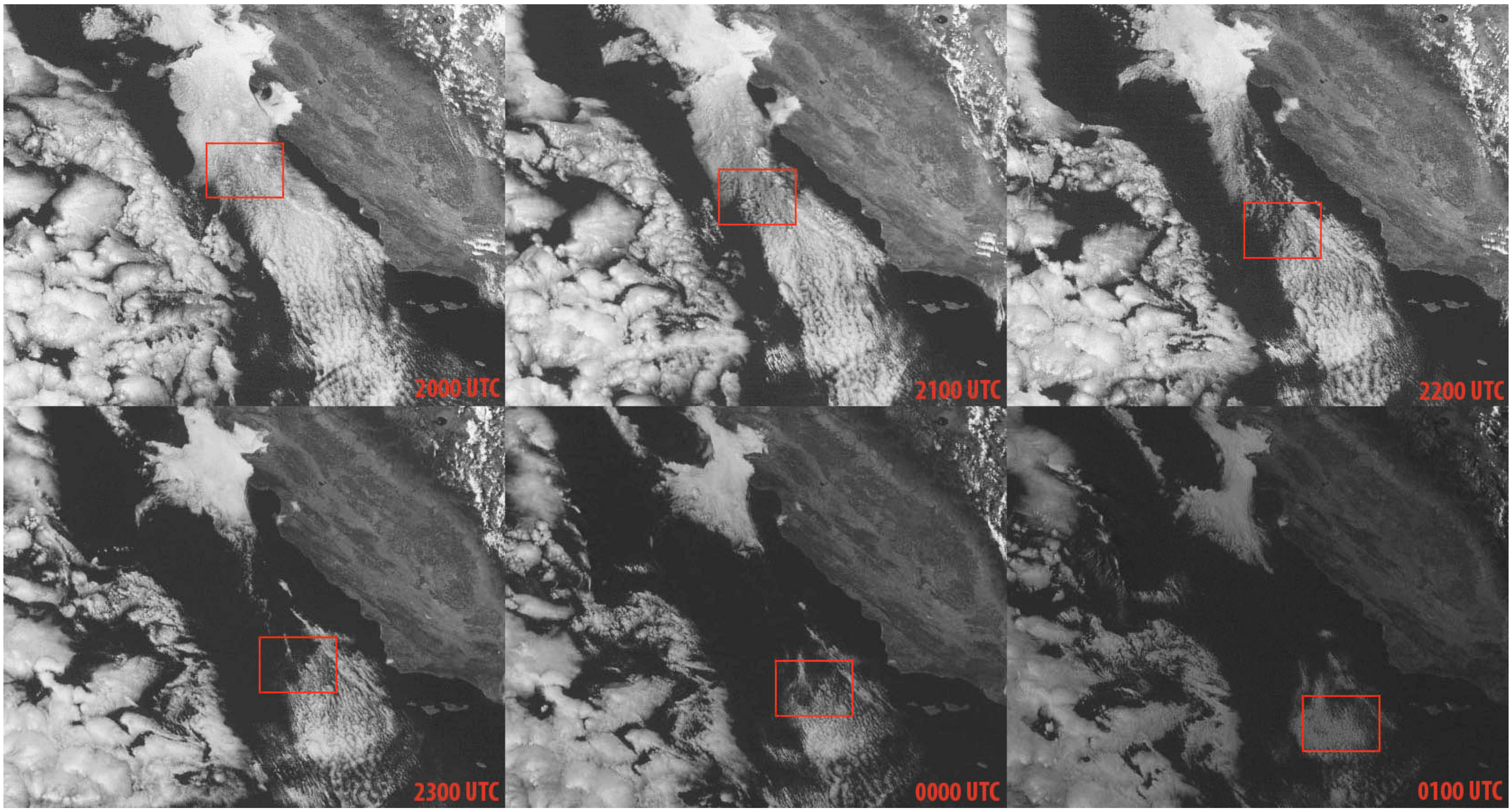
$$\frac{\partial \bar{h}}{\partial t} + (\bar{u} - \bar{u}_{\mathrm{ship}}) \frac{\partial \bar{h}}{\partial x} + (\bar{v} - \bar{v}_{\mathrm{ship}}) \frac{\partial \bar{h}}{\partial y} = w_{\mathrm{e}} + w_{\mathrm{s}}$$

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

MAGIC entrainment rates

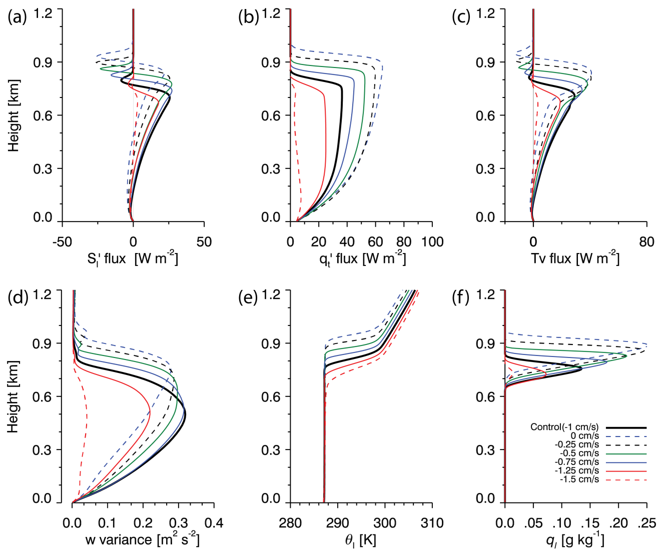


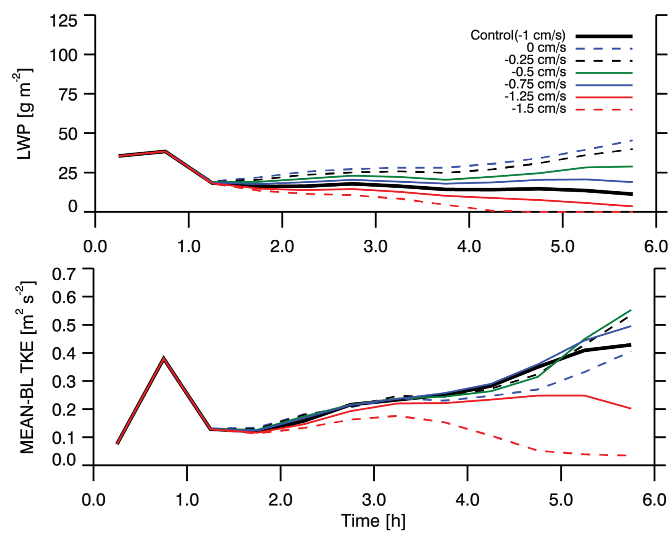
Factors governing thinning and recovery of marine stratocumulus



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





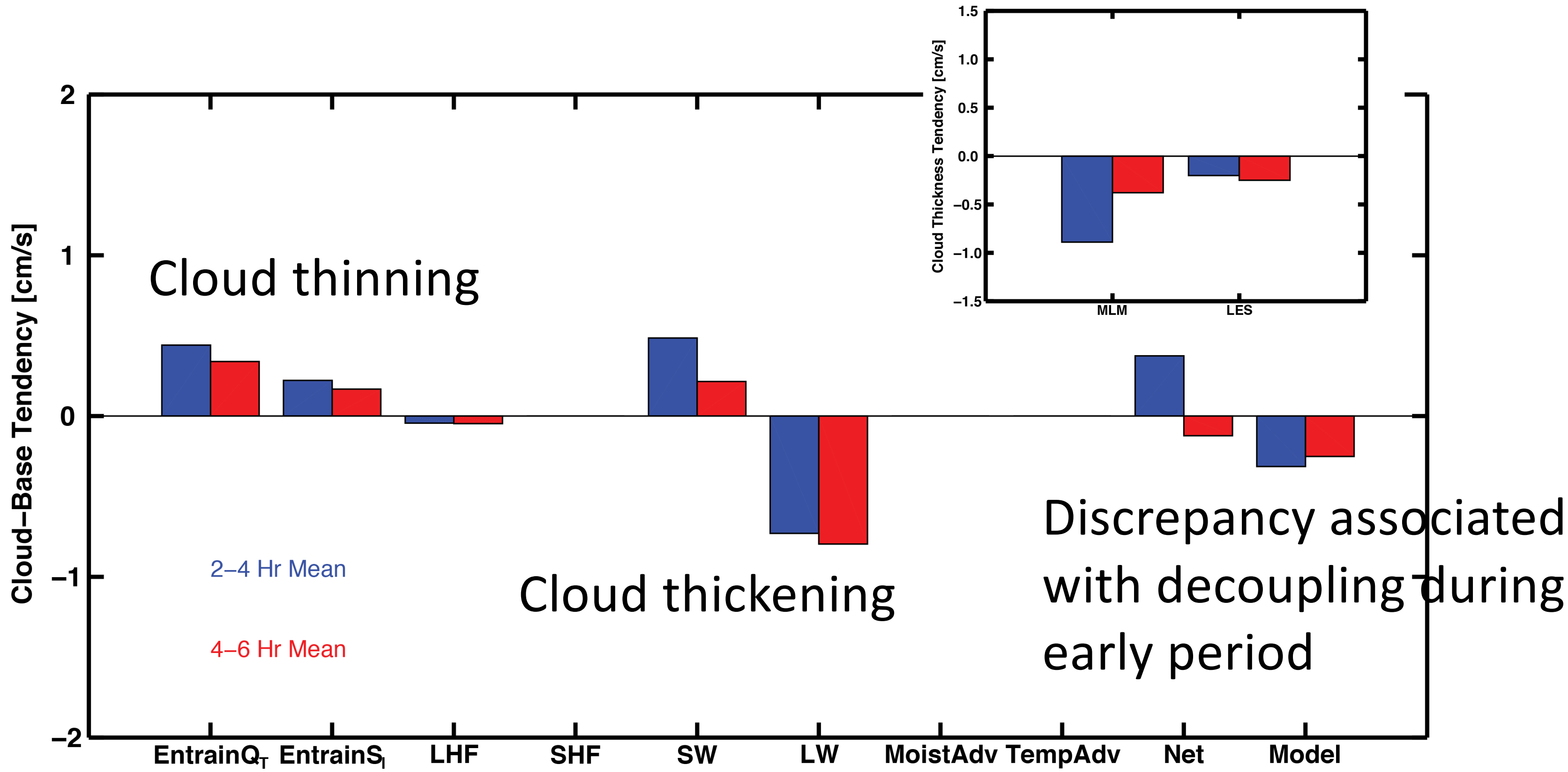
Mixed-layer model analysis of LES output

- Based on Wood (JAS, 2007), Van der Dussen (JAS, 2014); Ghonima et al. (2015)

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

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

Factors governing thinning and recovery of coastal stratocumulus



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.