Invigoration of cumulus cloud fields by mesoscale ascent

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Cumulus convection

- Cumuli are highly turbulent, covering a broad spectrum of scales
  - Cloud scale: $O(10^3\text{-}10^4$ m)
  - Sub-cloud drafts: $O(10\text{-}10^3$ m)
  - Inertial subrange: $O(10^{-2}\text{-}10$ m)

- Difficult to represent in regional and global atmospheric models
  - Sensitive to initial conditions
  - Impossible to resolve spectrum of energy-containing scales
- Errors in cloud representation limit the predictive skill of weather/climate models

Cumulus parameterization

- Used when cloud entities are too small to be explicitly represented on a numerical grid
  - Represent collective effects of cloud fields based on parameters of resolved flow
  - Assume clear separation between cloud scale and grid scale

AKIO ARAKAWA AND WAYNE HOWARD SCHUBERT

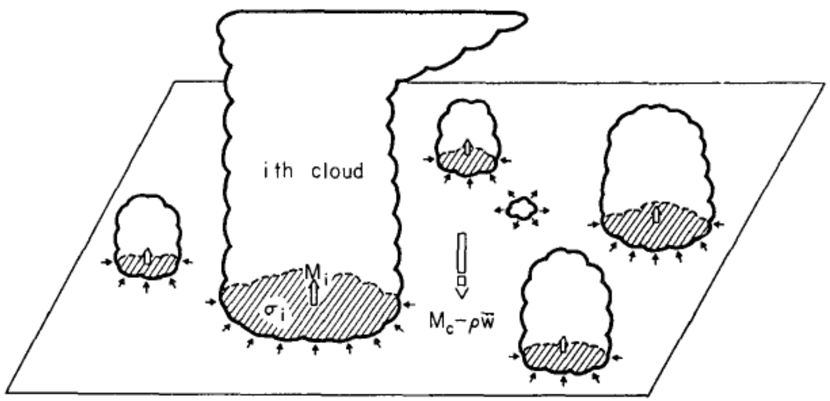


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

Arakawa and Schubert (1973)

Parameterization problems

- Modern weather models moving to “convection-permitting” resolutions to avoid error-prone parameterization schemes
  - Short-range regional forecasts [O(1 km)]
  - Global forecast models [O(10 km)]
  - Problem: grid spacings of 10 km-1 km in the “grey zone”: clouds partially resolved and scale-separation breaks down
- Even outside of grey zone, cumulus parameterization highly problematic
  - Phase error in diurnal convection cycle
  - Clouds fail to organize into realistic larger-scale structures
- How can we overcome these errors?

One source of error

- Modern understanding (and parameterization) of cumuli typically neglects the role of turbulence
  - Treats clouds as adiabatic or entraining/detraining plumes or thermals
  - Interaction with environment and other clouds neglected or externally specified; not informed by theory
  - Fractional entrainment rate critical for climate prediction (e.g., Pascale et al 2011) but poorly constrained

- More logical to treat clouds as buoyancy-containing components of a turbulent field
  - Grant and Lock (2004): scaling/similarity theory based on equilibrium TKE budget

Grant and Lock (2004)

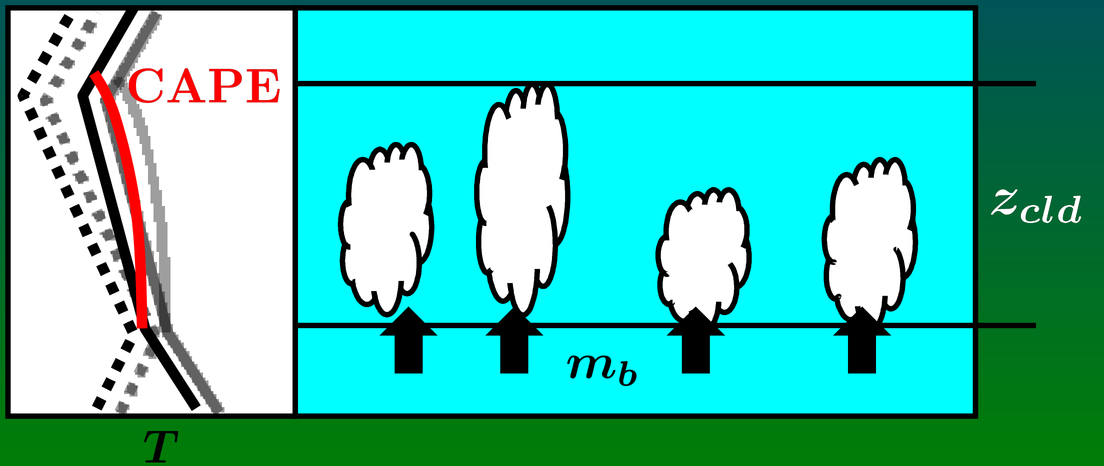
- Consider the equilibrium TKE budget

$$\underbrace{\left(\frac{\partial}{\partial t}\right.}_{\text{TEN}} + \underbrace{\overline{\mathrm{u}} \cdot \nabla}_{\text{ADV}} \left.\right) \overline{e} = \underbrace{\overline{w'b'}}_{\text{B}} - \underbrace{\overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z}}_{\text{S}} - \frac{\partial}{\partial z}\left(\underbrace{\overline{w'e'}}_{\text{T}} + \underbrace{\frac{\overline{w'p'}}{\rho}}_{\text{P}}\right) - \underbrace{E}_{\text{E}}$$

- For equilibrium shallow cumulus convection, B and E roughly balanced (Grant and Lock 2004)

–E~ $\dfrac{(w^*)^3}{z_{cld}}$

–B~ $\dfrac{m_b CAPE}{z_{cld}}$



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–B~ $\dfrac{m_b CAPE}{z_{cld}}$

$$\Longrightarrow \quad \boxed{(\overline{w'b'}, E) \sim \left(\frac{m_b}{w^*}\right)^{1/2} \frac{m_b CAPE}{z_{cld}}}$$

Nondimensional scaling parameter
(fractional cloud “length”)

Does it work?

Grant and Lock (2004)

- Effectively scales B/E for shallow cloud layers in radiative-convective equilibrium
  - Also provides a means to estimate cloud size and entrainment (more later)

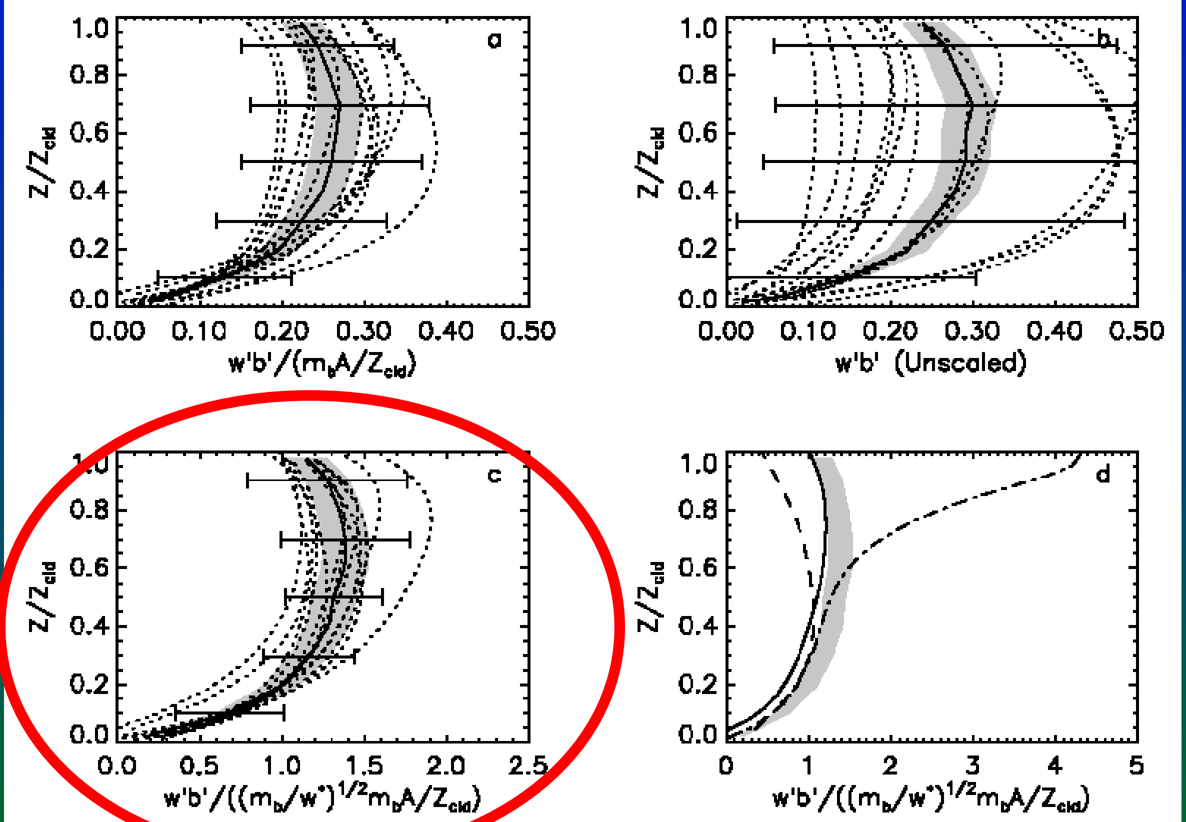
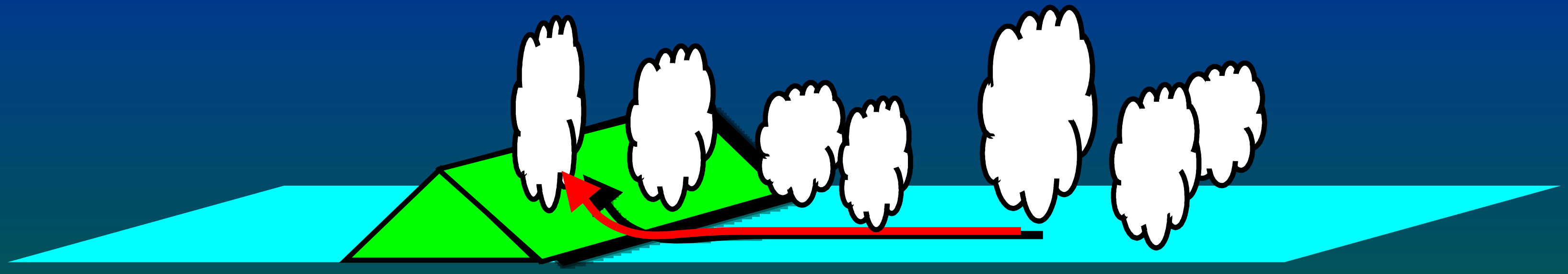


Figure 4. Simulated buoyancy-flux profiles (a) scaled by $m_b A/z_{cld}$, (b) unscaled and (c) scaled by $(m_b/w^*)^{1/2} m_b A/z_{cld}$. (See text for details.) Dotted lines show individual simulations, the full line is the average, full horizontal bars represent $\pm$ two standard deviations and the shaded region shows $\pm$ twice the estimated sampling error. (d) Buoyancy-flux profiles from simulations based on observations from BOMEX (full), North Sea cumulus (dashed) and ATEX (dot-dashed), scaled by $(m_b/w^*)^{1/2} m_b A/z_{cld}$. (See text for acronyms.) The shaded region is the same as in (a)–(c).

More challenging situations

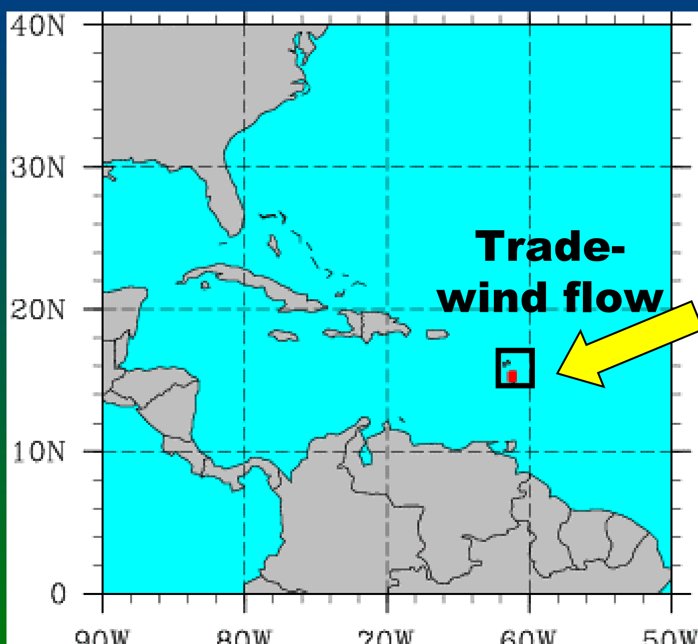
- Most cloud fields are not in equilibrium
  - Cloud fields often controlled by mesoscale features like mountains, fronts, outflow boundaries, etc.



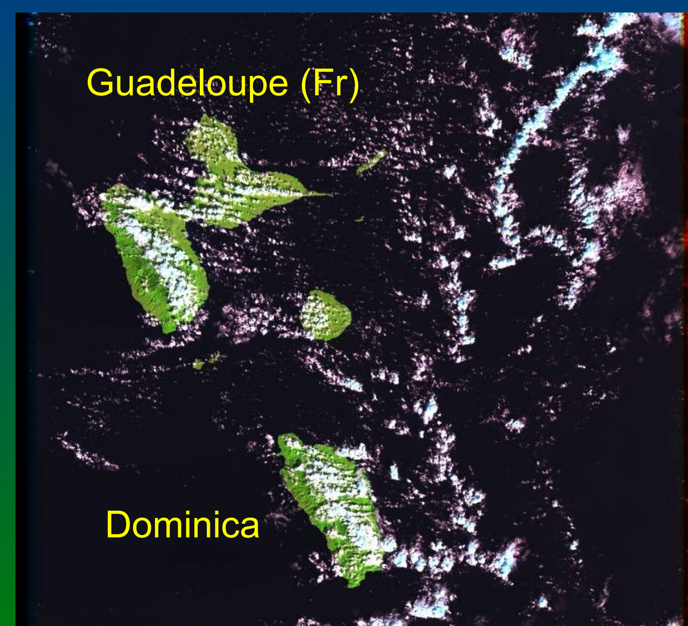
- Does similarity theory hold for evolving cloud fields?
  - Only if B and E remain the dominant terms of TKE budget

The testing ground: Dominica

- Natural laboratory for terrain-forced convection
  - Persistent conditional instability
  - Simple quasi-2d geometry
  - Trade-wind flow ascends island's high (1.5-km) terrain



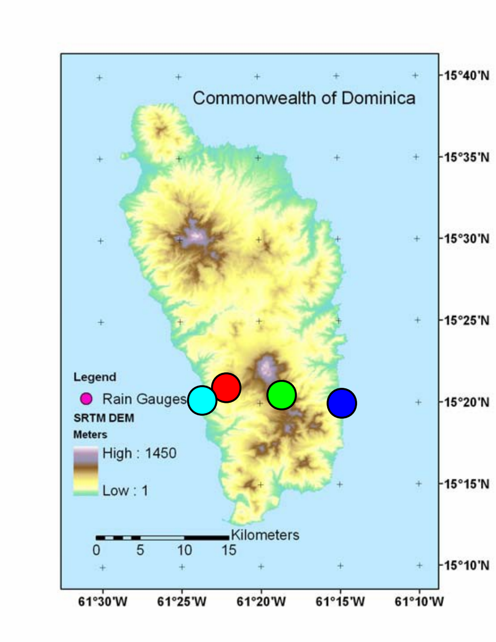
Landsat, JD320, 2002

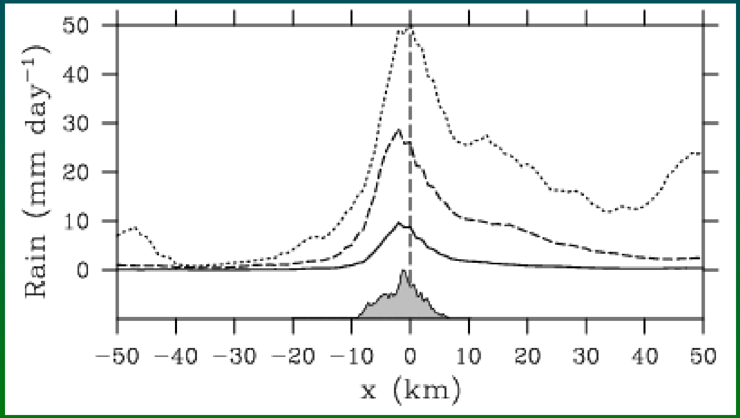


Experiments in Dominica

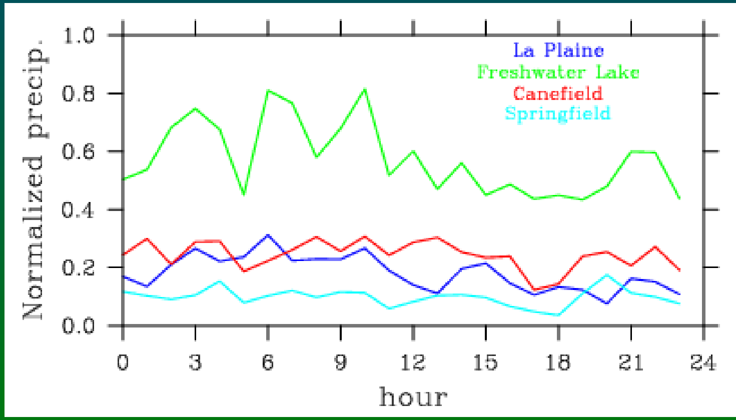
- In 2007 raingauges installed along lower transect
  - Complemented by Météo-France radars on French islands to north and south
  - Intense orographic enhancement
  - Minimal diurnal signature; mechanical forcing dominates over thermal

(Smith et al 2009; Kirshbaum and Smith 2009)





7 months of radar (2008)

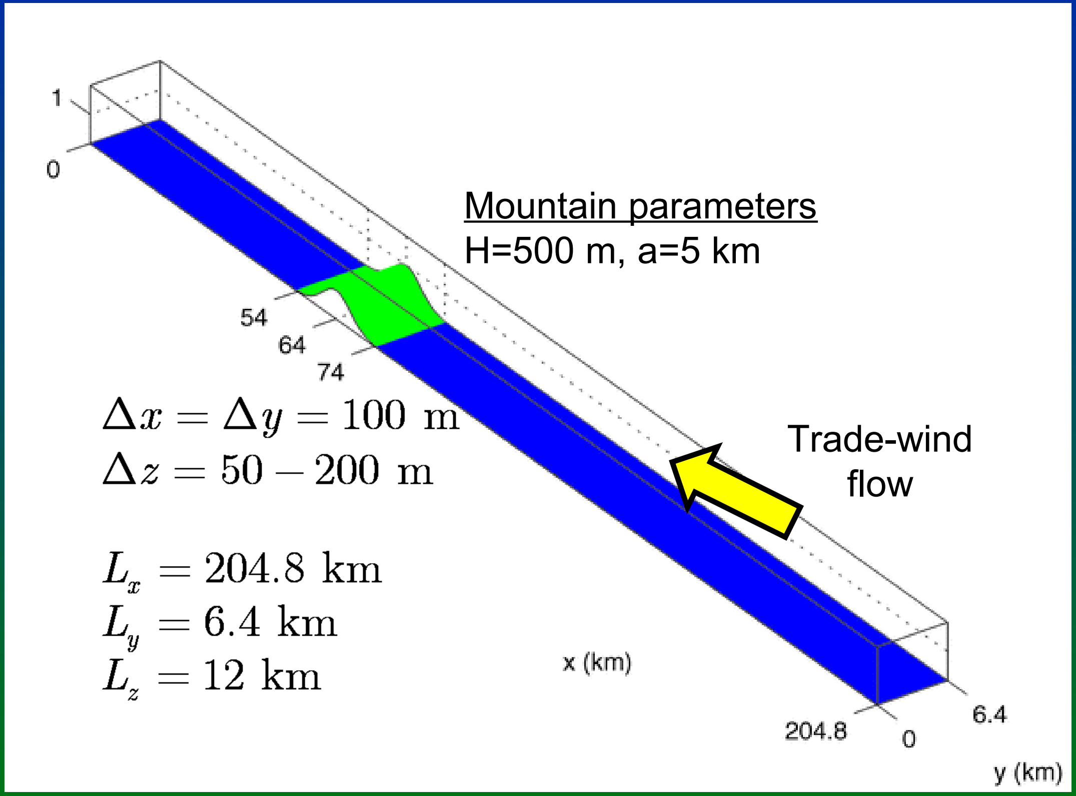


12 months of rain gauges (2007-2008)

Large-eddy simulations

- Bryan cloud model v13 (Bryan and Fritsch 2002)
  - Fully nonlinear, nonhydrostatic, compressible
  - Eulerian with split time step for acoustic modes
  - 6th-order horiz. adv. (explicit diffusion)
  - 5th order vert. adv. (implicit diffusion)

• TKE 1.5-order mixing
• Morrison 2-M warm-rain microphysics (Seifert & Beheng 2001)



Large-eddy simulations

- Narrow, deep y-periodic domain
  - Wide enough in y to fit multiple clouds
  - Waves, clouds can penetrate into free troposphere
  - Quasi-steady cloud field forms upstream of terrain
  - Modified flow exits outflow boundary

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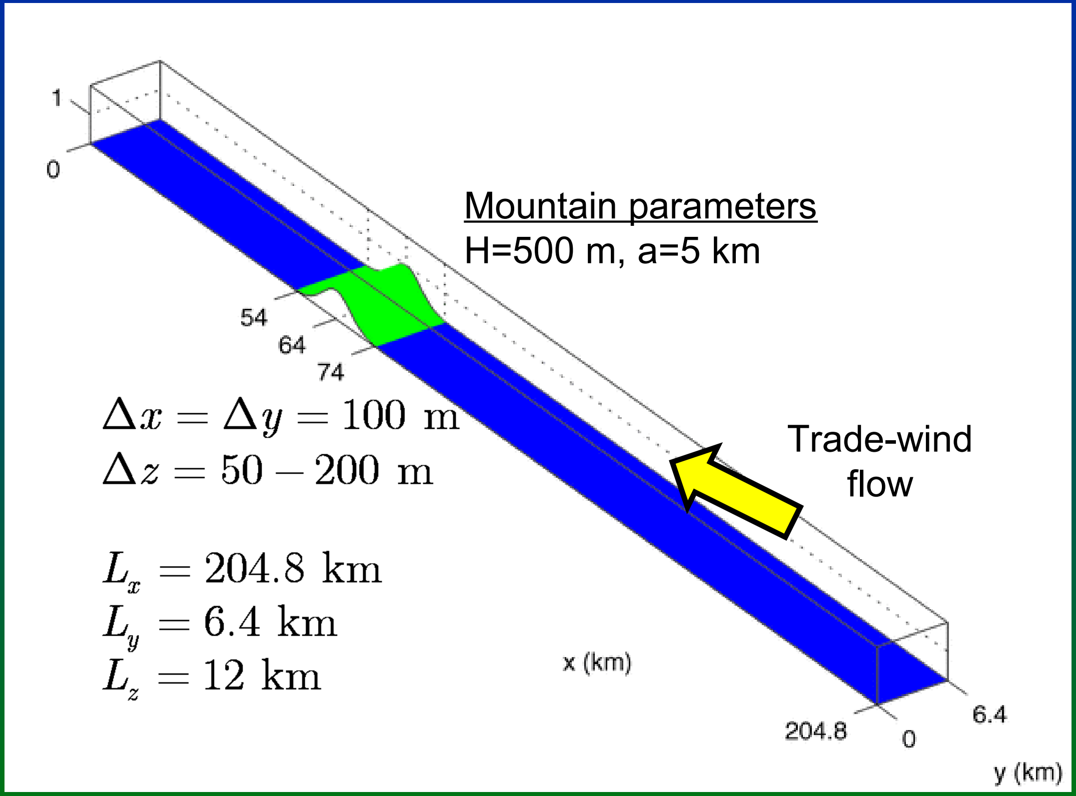
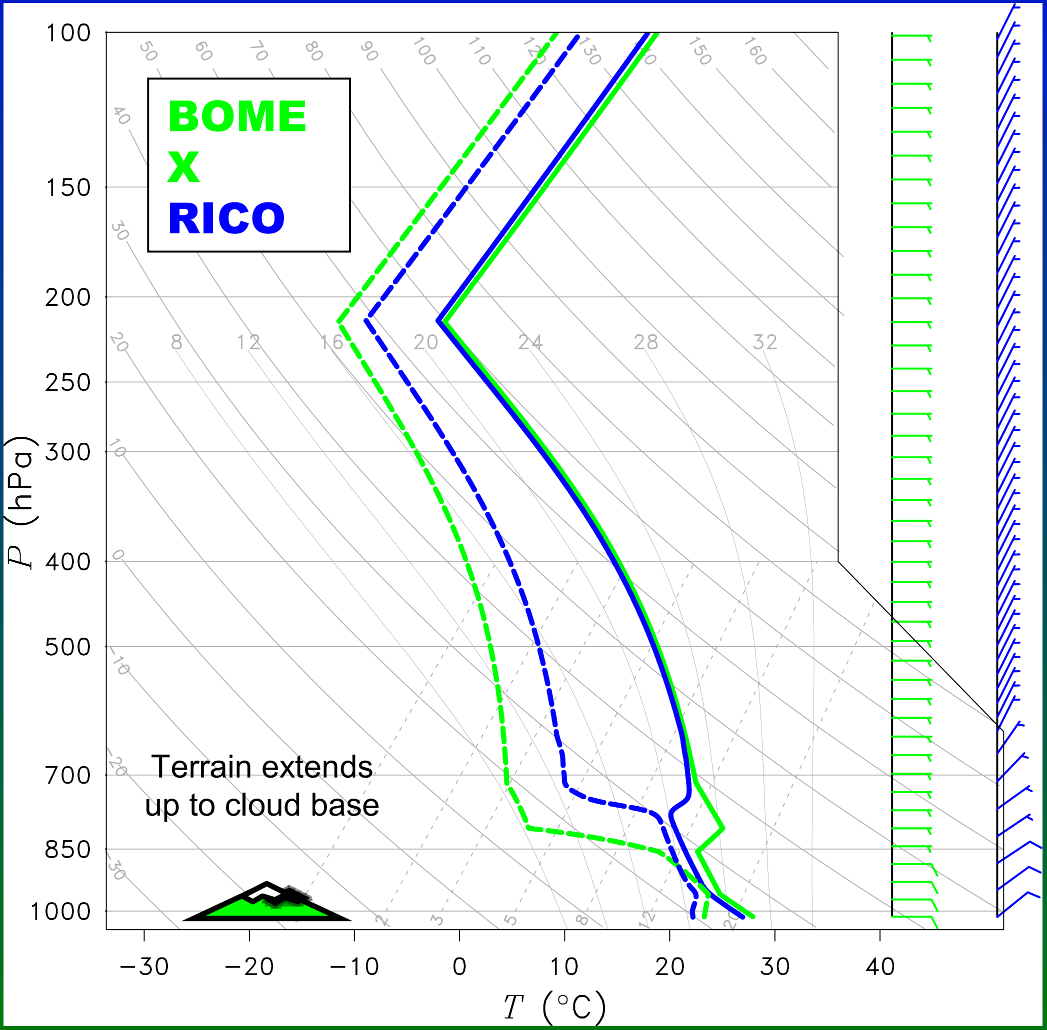


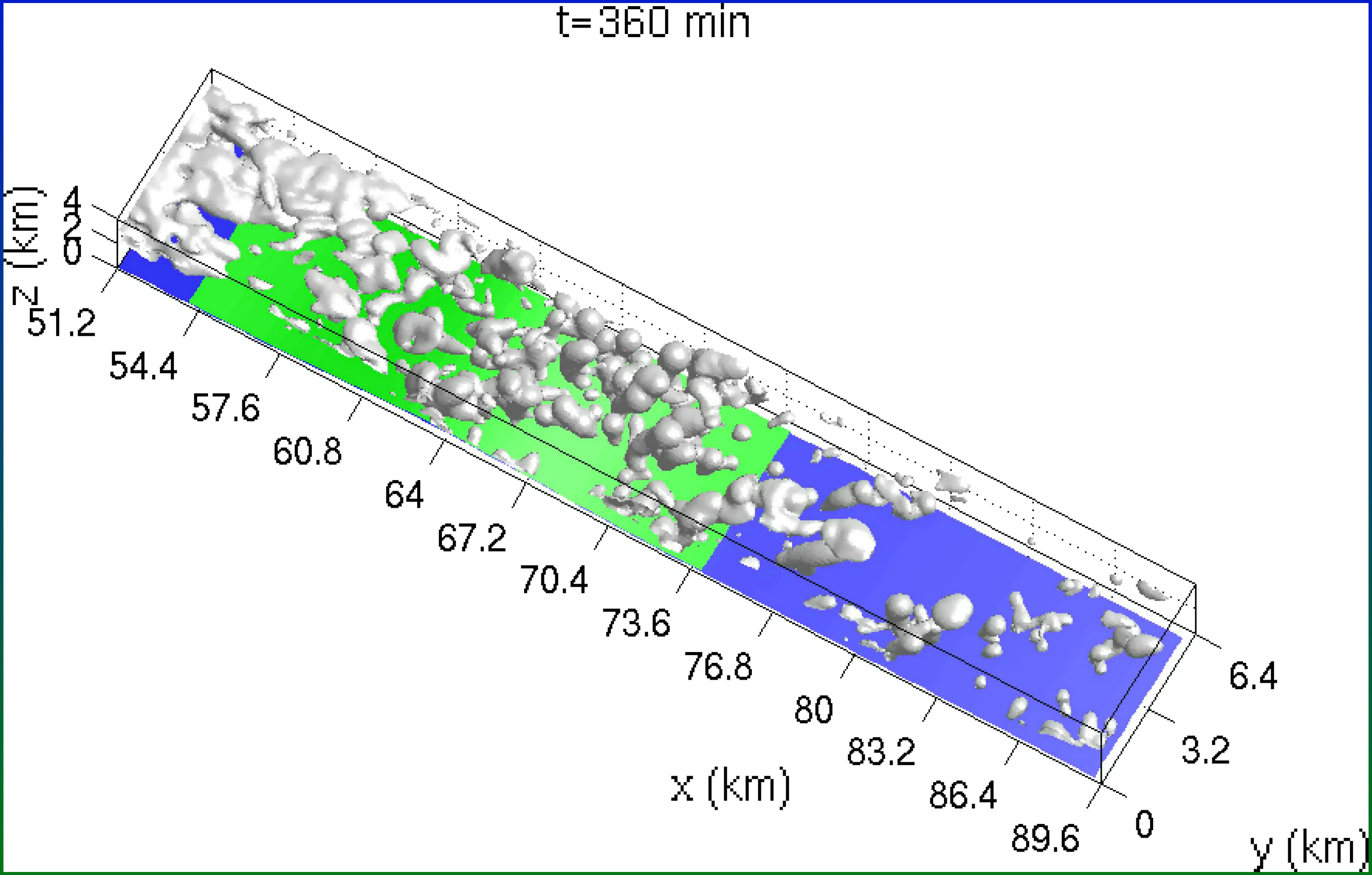
The upstream flow

- Dominica located close to two trade-wind field campaigns
  - BOMEX (1969)
  - RICO (2004)

- Use composite background flow and large-scale forcing for each case

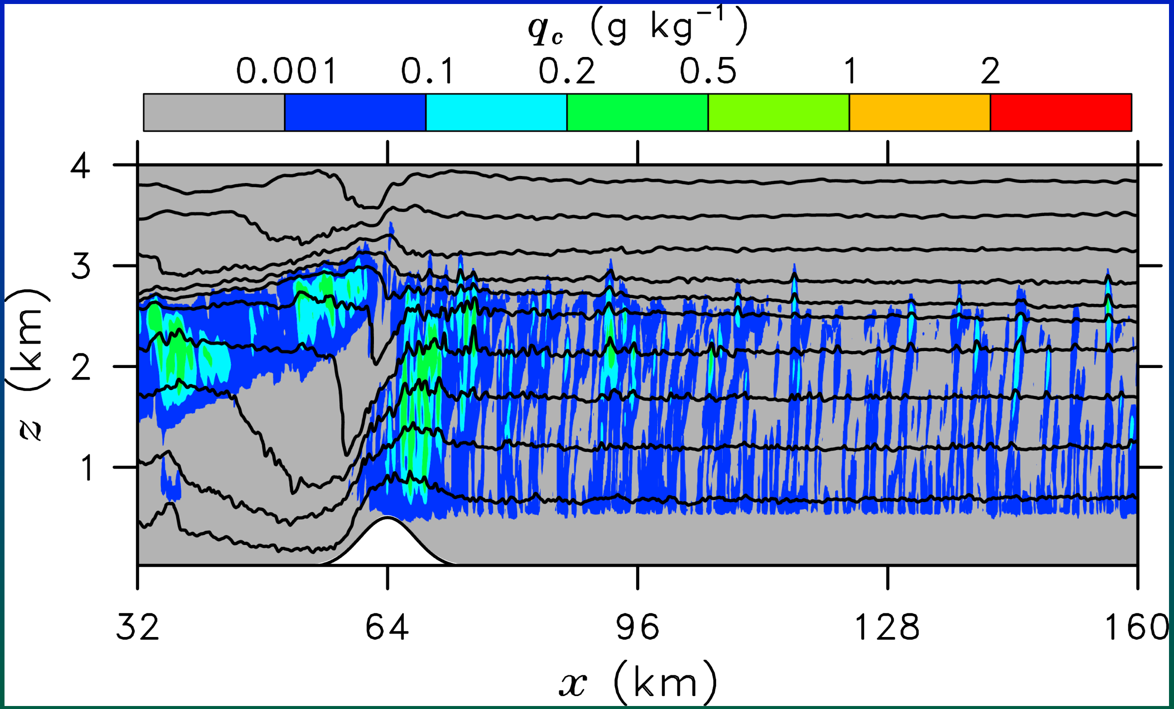


RICO simulation



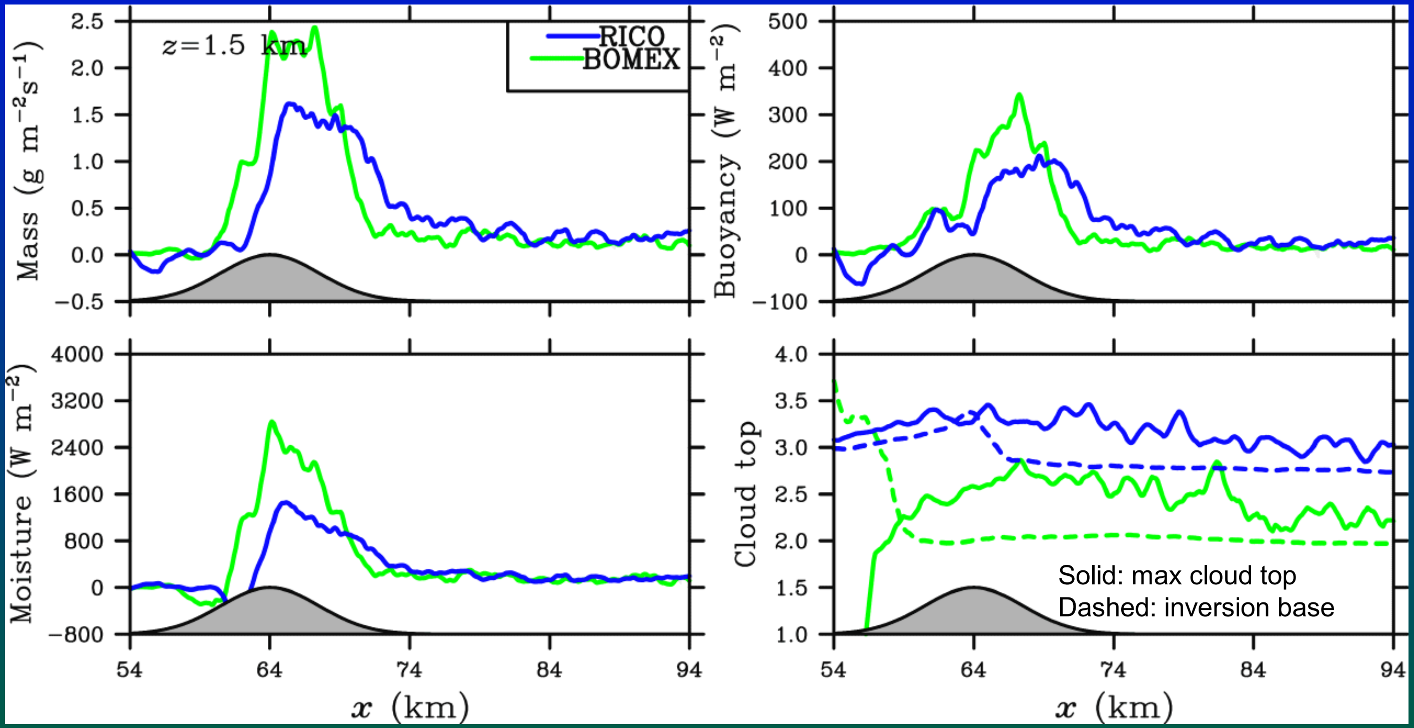
Vertical cross-section

Contours of mean cloud water (filled) and θ_L (K) (lines)



- Quasi-steady upstream trade-wind cloud field
- Inversion slowly rises, then sinks rapidly over mountain
  - Hydraulic, shallow-water-like response to terrain

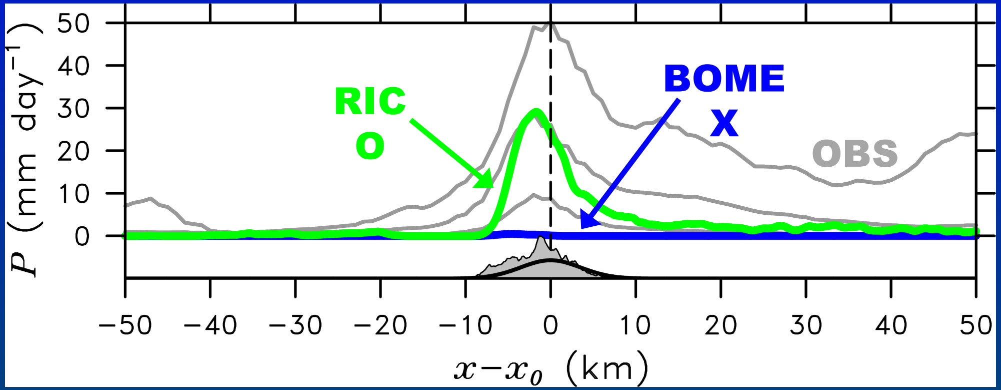
Vertical fluxes (t=3-6 hr)



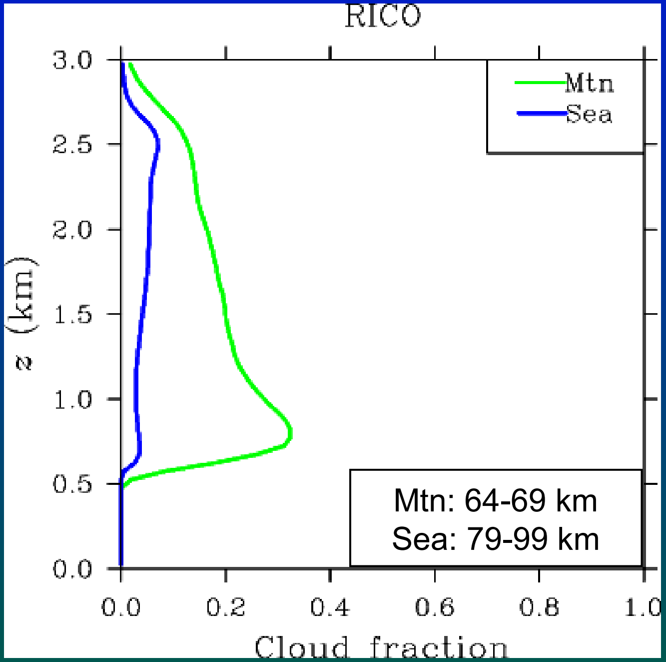
- Clouds deeper in RICO, but more vigorous in BOMEX
  - Owing to stronger potential instability in BOMEX?

Precipitation and cloud fraction

Averaged rain rate over t=3-6 hr



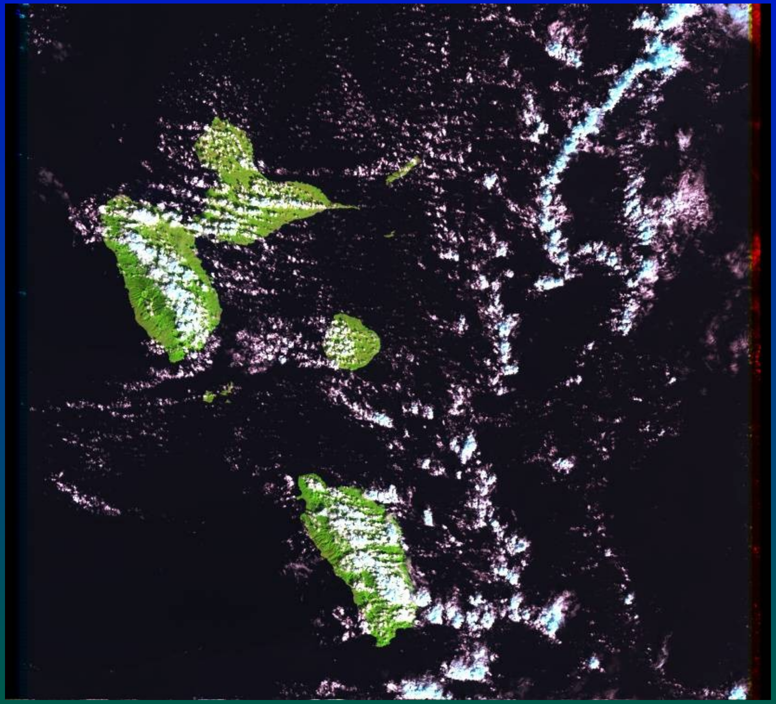
Mean cloud fraction (RICO)



- Precipitation increases faster (15-fold) than cloud fraction (4-fold)
  - Island clouds more numerous *and* efficient (precipitation efficiency increases from 4% to 12%)

Potential mechanisms

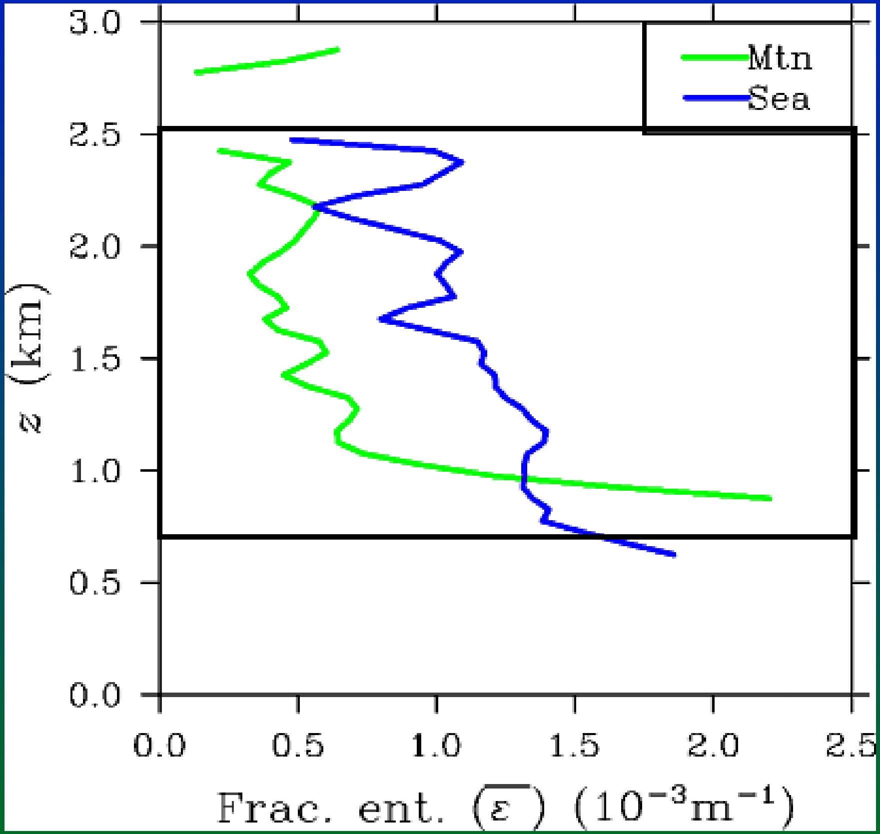
- Why are island clouds more efficient?
  - Stronger instability or deeper cloud layer over island? NO (not shown)…
  - More vigorous and liquid-rich? YES… but why?
- Hypothesis: island clouds are wider and less diluted by entrainment than ocean clouds
  - Enhances cloud vigor and precipitation efficiency
  - Can this be explained using TKE scaling?



Reduced dilution

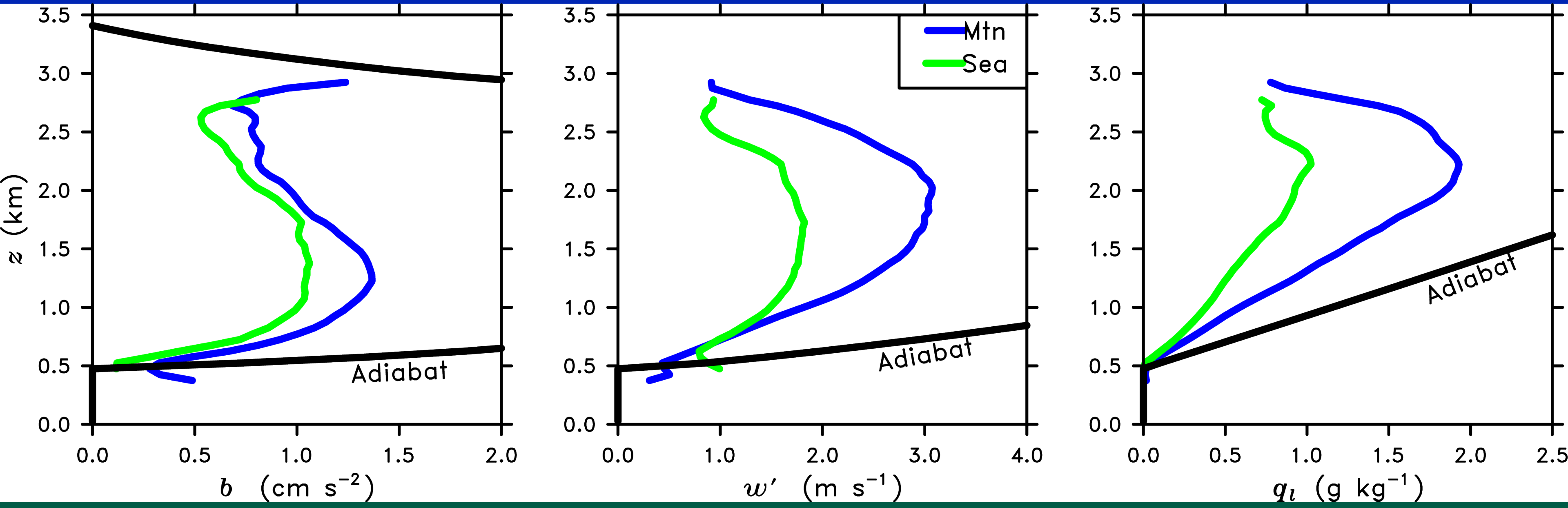
- Island clouds have much lower entrainment rates
  - Can also be seen from mixing ("Paluch") diagrams

Fractional entrainment profiles (computed based on moist static energy)



Conditional core averages (t=3-6 hr)

Perturbations relative to local y-average (RICO simulation)



- Reduced dilution renders island cloud cores more buoyant, vigorous, and liquid-rich

Dilution and cloud size

- Is decreased cloud dilution related to increased cloud size?
  - Fundamental hypothesis of entraining plume models [e.g., Morton (1957)]
  - Khairoutdinov and Randall (2006): reduced dilution in wider clouds facilitates transition to deep convection

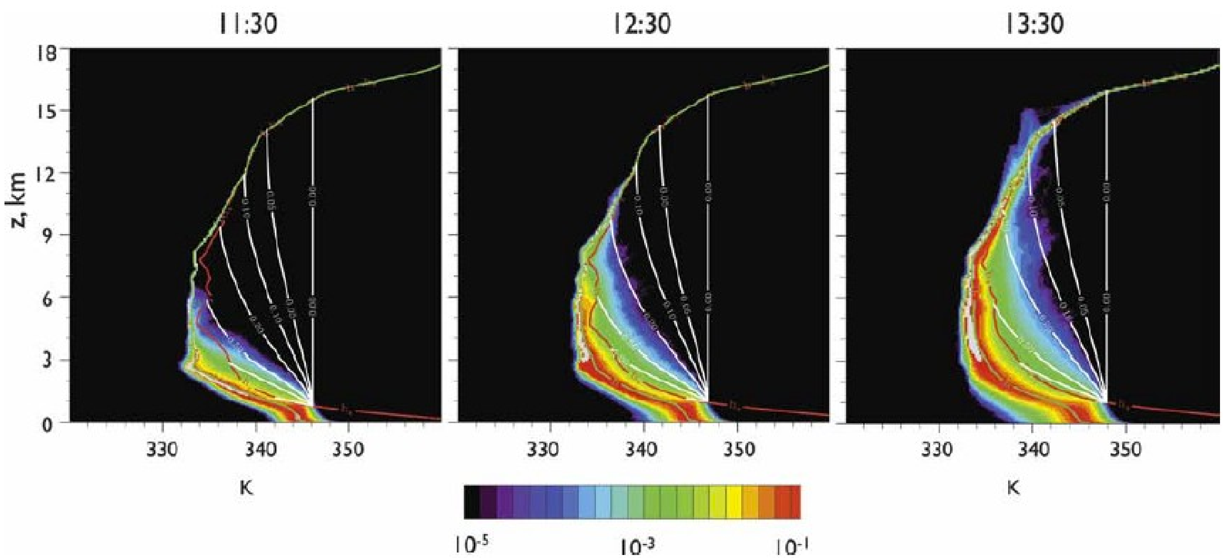


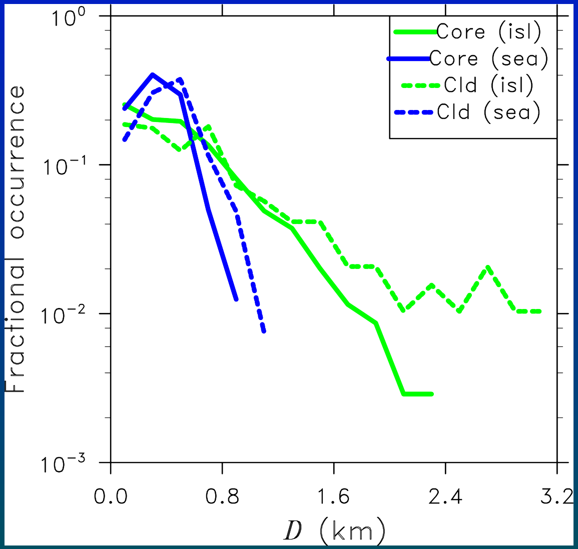
FIG. 11. PDF of moist static energy as a function of time for three different simulation times. White lines show the trajectories that the entraining plumes would follow given different values of entraining parameter, in km^{-1}: 0 (vertical line), 0.05, 0.1, 0.2, 0.5, 1.0. The mean moist static energy is shown by the green line; while saturated moist static energy is shown by the red line.

Khairoutdinov and Randall (2006)

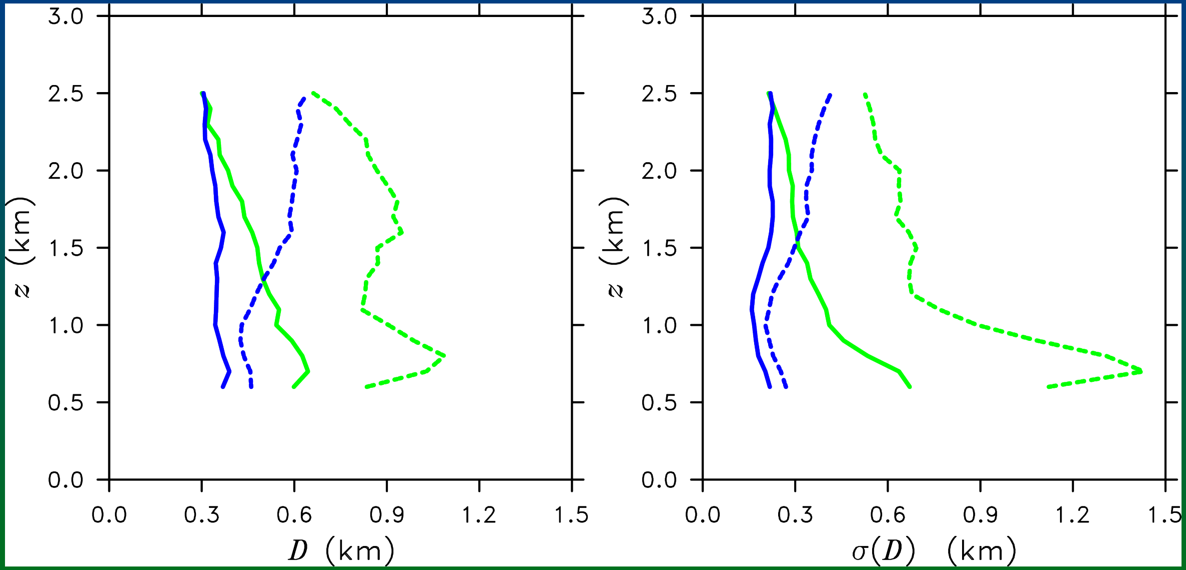
Cloud size (RICO simulation)

- Clouds (and cores) significantly wider over island
  - Most noticeable near cloud base

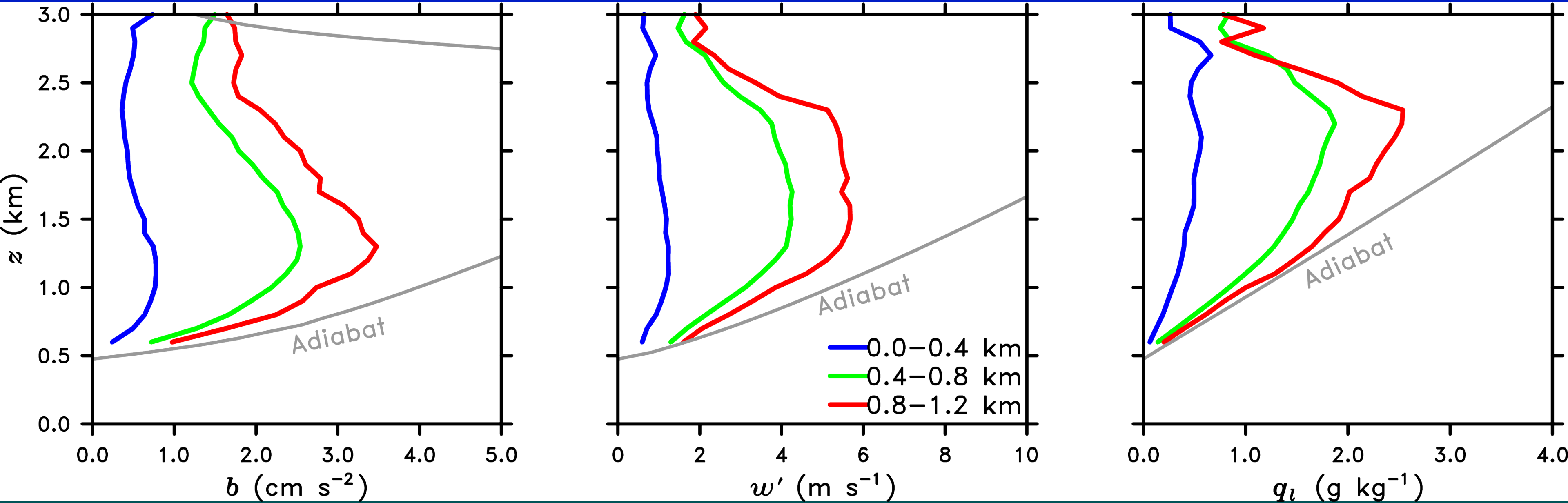
Size spectra at z=1 km



Mean size profiles



Sensitivity of vigor to cloud size



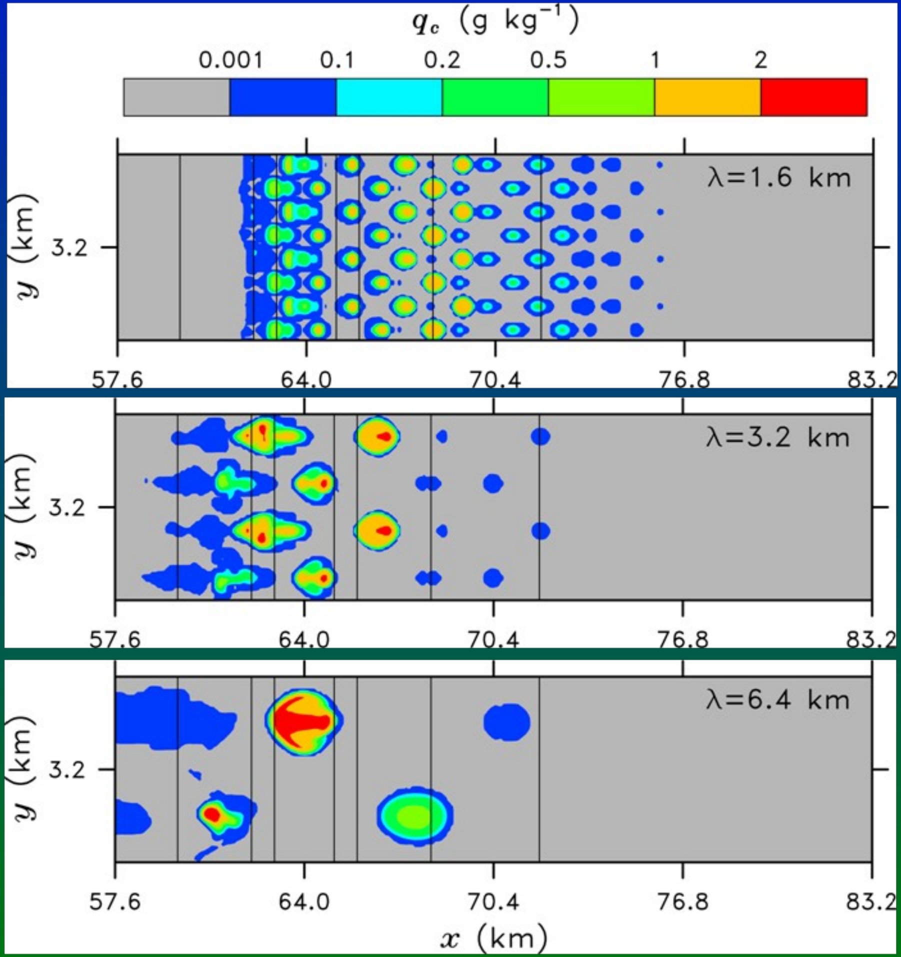
- Wider clouds more vigorous and liquid-rich
- More efficient precipitation production due to
  - Higher accretion rates (Kirshbaum and Smith 2009)
  - Larger in-cloud hydrometeor residence times

Controlling the cloud size

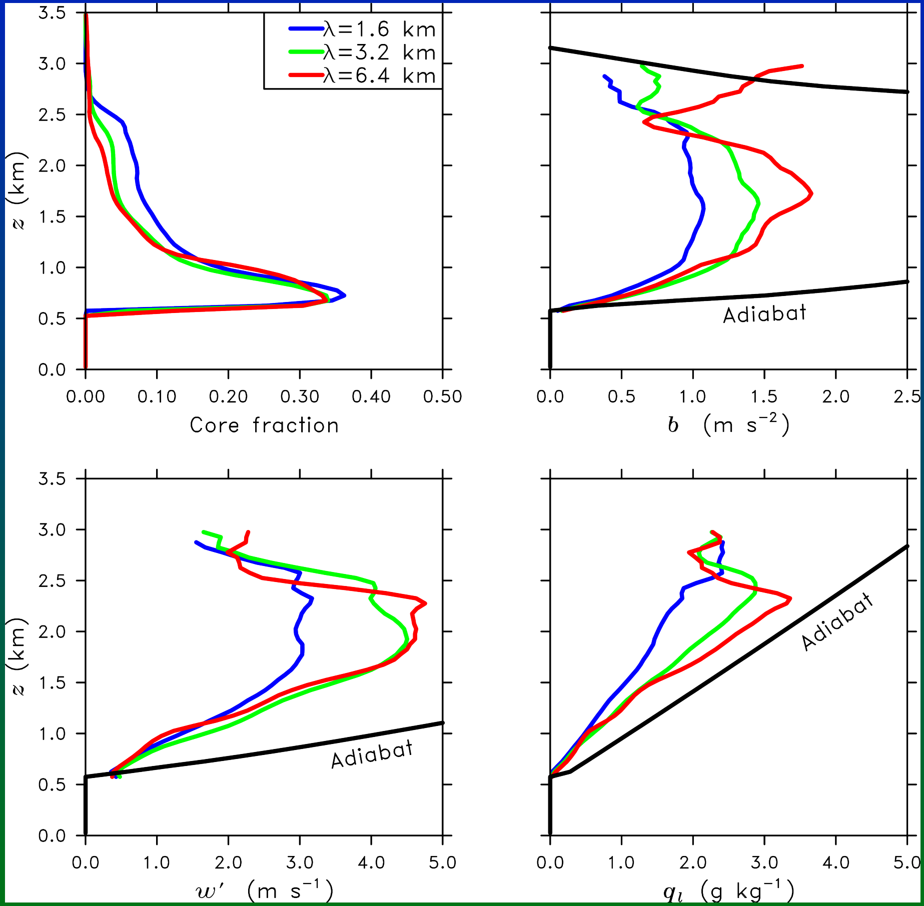
- Can isolate cloud-size mechanism by conducting experiments that control the cloud size, with all else held fixed
- Create neutrally buoyant moisture “patches” in upstream flow with fixed horizontal wavelengths
  - Perturbations columnar in shape
  - Use sounding from RICO, but without surface fluxes or large-scale forcings (suppresses upstream convection)
  - Convection only forms directly over the island

Controlling the cloud size

Clouds at t=3 hr



Core profiles



Intermediate conclusions and outlook

- What we have shown
  - Clouds are wider over the island than over the sea
  - Wider clouds are generally more vigorous and liquid-rich
  - Together with increased cloud number, this explains the increased precipitation observed over the island

- Why, then, do the clouds widen over the island? Two hypotheses:
  1. Turbulent constraints
  2. Sub-cloud moisture anomalies

Recall Grant and Lock (2004)

- Consider the equilibrium TKE budget

$$\underbrace{\left(\frac{\partial}{\partial t}\right.}_{\text{TEN}} + \underbrace{\left.\overline{\mathrm{u}}\cdot\nabla\right)}_{\text{ADV}}\overline{e} = \underbrace{\overline{w'b'}}_{\text{B}} \underbrace{- \overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z}}_{\text{S}} - \frac{\partial}{\partial z}\left(\underbrace{\overline{w'e'}}_{\text{T}} + \underbrace{\frac{\overline{w'p'}}{\rho}}_{\text{P}}\right) - \underbrace{E}_{\text{E}}$$

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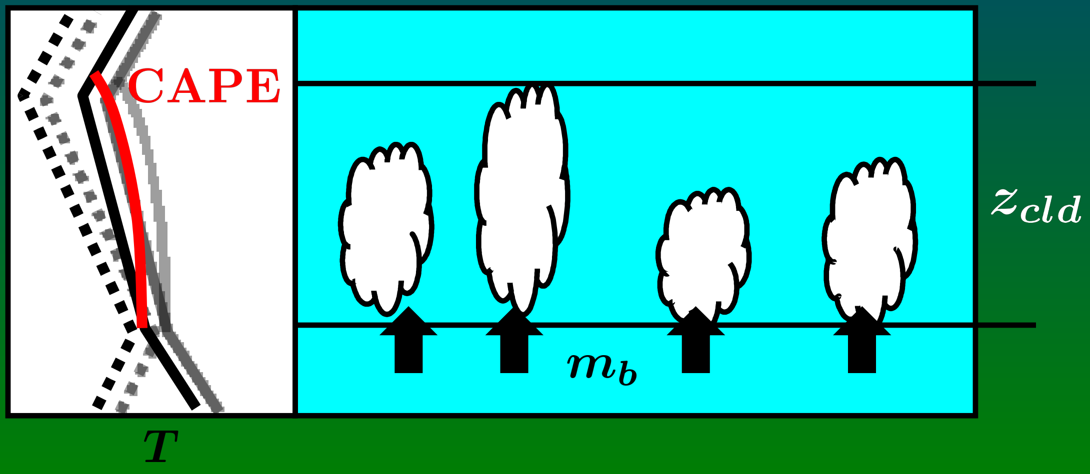


Applying scaling to simulation

- Scaling from Grant and Lock (2004) works well, even for non-equilibrium island flow
- Details of dynamics over windward slope:
  - B, E, and ADV all increase but not simultaneously
  - E lags ADV by eddy-turnover time (z_{cld}/w^*)
  - Equilibrium approximation overestimates dissipation (and hence w*) in this region

TKE-budget terms, integrated over cloud layer

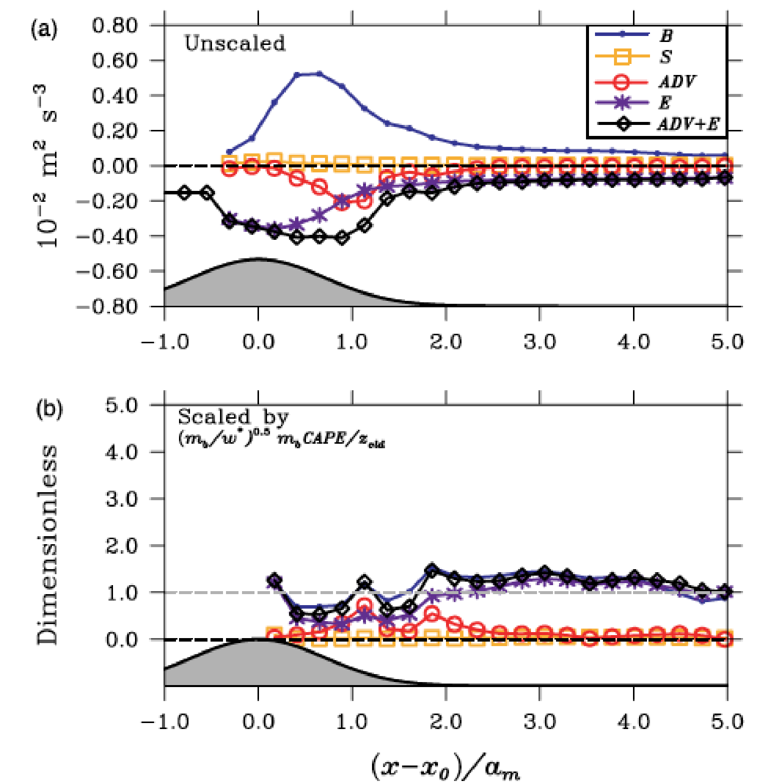


Figure 15. Horizontal profiles of the terms of the cloud-layer TKE budget including buoyancy production (B), shear production (S), advection (ADV), dissipation (E), and advection plus dissipation ($ADV + E$): (a) unscaled and (b) scaled by dividing the absolute values of the terms by $(m_b/w^*)^{1/2}\, m_b CAPE/z_{cld}$. The profiles are averaged in the y-direction, in the z-direction (over the depth of the cloud layer) and in time (over 3 to 6 h). This figure is available in colour online at wileyonlinelibrary.com/journal/qj

From Kirshbaum and Grant (QJ, 2012)

Scaling cloud size and dilution

- Can use TKE scaling to link gross characteristics of cloud layer with internal cloud properties

- Cloud diameter

$$\boxed{D \sim \left(\frac{m_b}{w^*}\right)^{1/2} z_{cld}}$$

Fractional "length" of cloudy updrafts

Depth of cloud layer

- Fractional entrainment rate
  - Balance: kinetic energy supplied to entrained air scales with turbulent dissipation rate

$$\epsilon m_b w^{*2} \sim A_\epsilon \frac{w^{*3}}{z_{cld}}$$

$$\boxed{\epsilon \sim A_\epsilon \frac{z_{cld}}{D^2}}$$

Testing the scaling

- Scaling captures trends of changing cloud field
  - But overestimates D increase due to assumption of constant cloud density

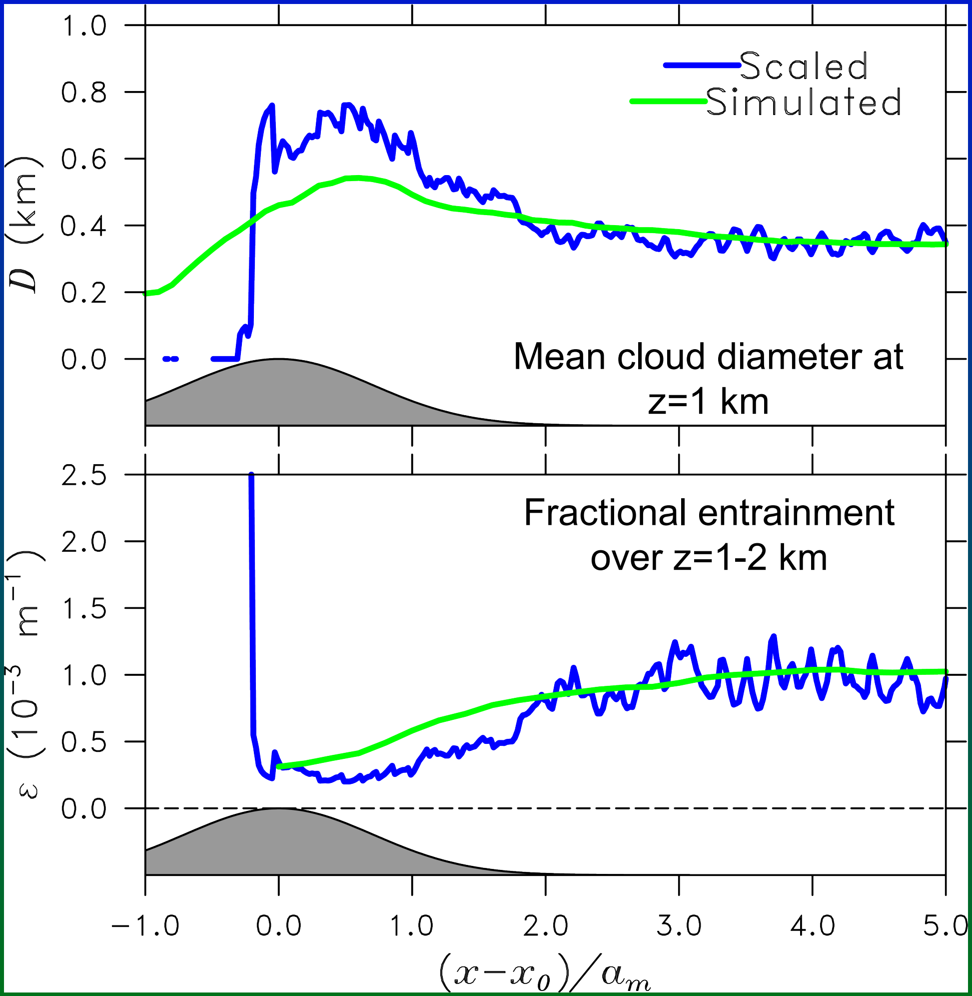


Table 2. Comparison of simulated values and theoretical estimates of the mean core size ($\overline{D}$) and mean fractional entrainment ($\overline{\epsilon}$). The latter is computed over $z = 1$ to 1.5 km in BOMEX and $z = 1$ to 2 km in RICO, in accordance with their different cloud-layer depths.

Case	$\overline{D}_i$	$\overline{D}_o$	$\overline{\epsilon}_i$	$\overline{\epsilon}_o$
	(km)		(10^{-3}m^{-1})	
BOMEX (theory)	0.40	0.19	0.39	1.82
BOMEX (sim)	0.50	0.31	0.58	0.80
RICO (theory)	0.68	0.34	0.26	1.00
RICO (sim)	0.53	0.34	0.42	1.02

'i' and 'o' subscripts denote island and ocean regions; description of these is given in the text.

From Kirshbaum and Grant (QJ, 2012)

Physical interpretation

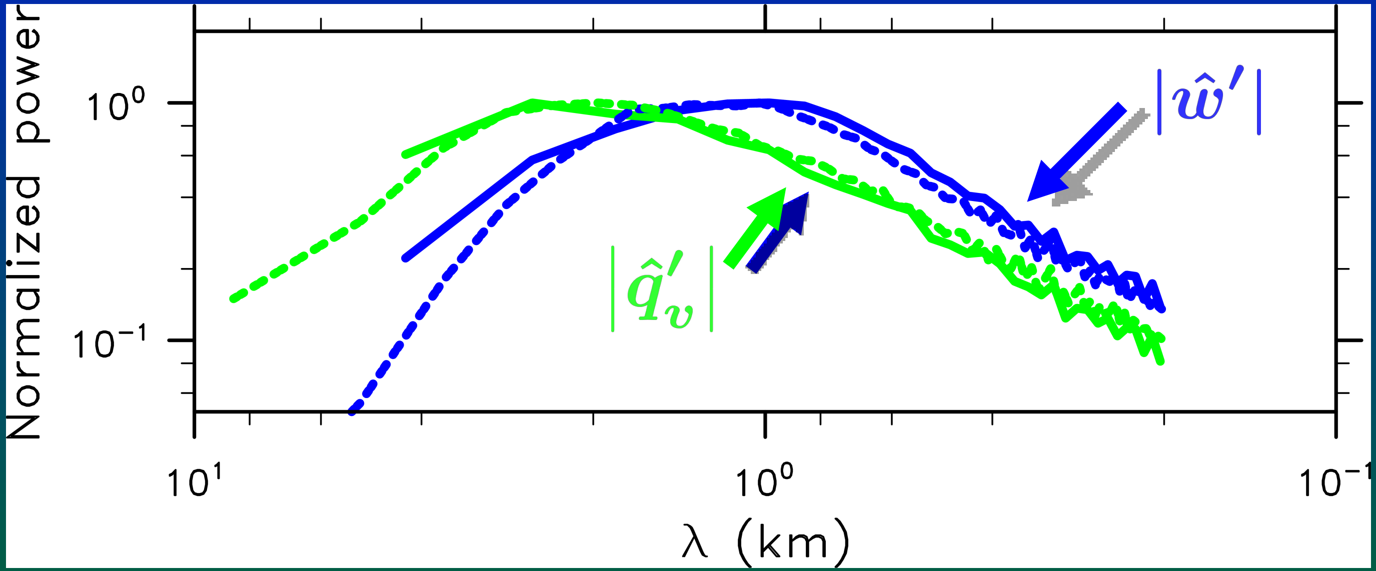
- Turbulent constraints on w^* control cloud response as m_b increases over island
- Increased cloud diameter:
  - w^* constrained by instability (which remains roughly constant), cannot keep pace with increased m_b
  - For a given cloud density, increased m_b requires increased D
- Decreased fractional entrainment:
  - Dissipation, which scales with w^{*3}, also cannot keep pace with increased m_b
  - For balance to be maintained between entrainment and dissipation, ε must *decrease*

A secondary mechanism: sub-cloud moisture anomalies

- Consider basic mechanisms for cloud formation
  - Ocean clouds: sub-cloud eddies ascend through cloud base
  - Island clouds: forced lifting of moist air
- Island clouds linked to moisture anomalies in sub-cloud layer (e.g., Woodcock 1960; Kirshbaum and Smith 2009)
  - Moist patches saturate first when lifted by the island
  - Become buoyant through latent-heat release
- Morphological changes to clouds tied to spectral differences between sub-cloud kinematic and moisture fields

Sub-cloud moisture anomalies

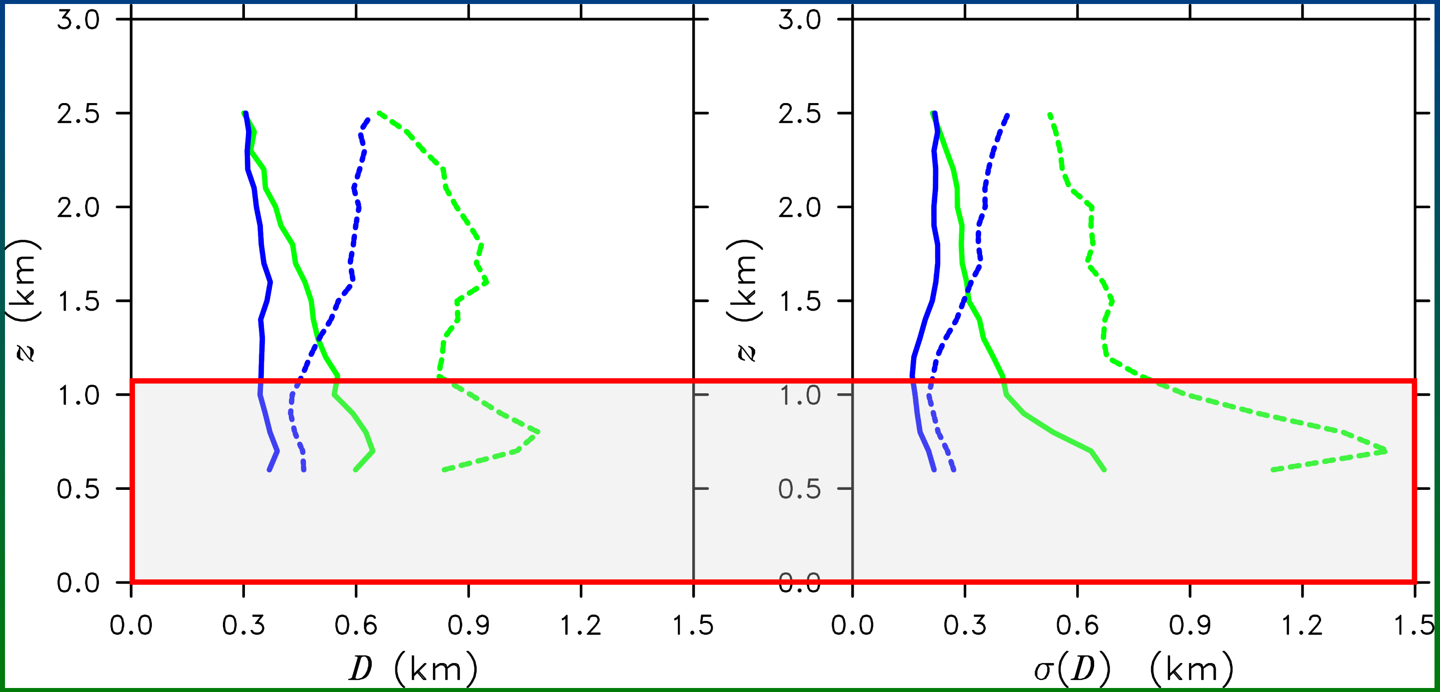
- Power spectra of upstream w' and q_v' fields at z=500 m



  - w perturbations control cloud sizes over ocean
  - q_v perturbations control cloud sizes over island

Which mechanism is it?

- Speculation
  - Below ~1 km: strong lifting, non-equilibrium. Sub-cloud moisture patches determine morphology



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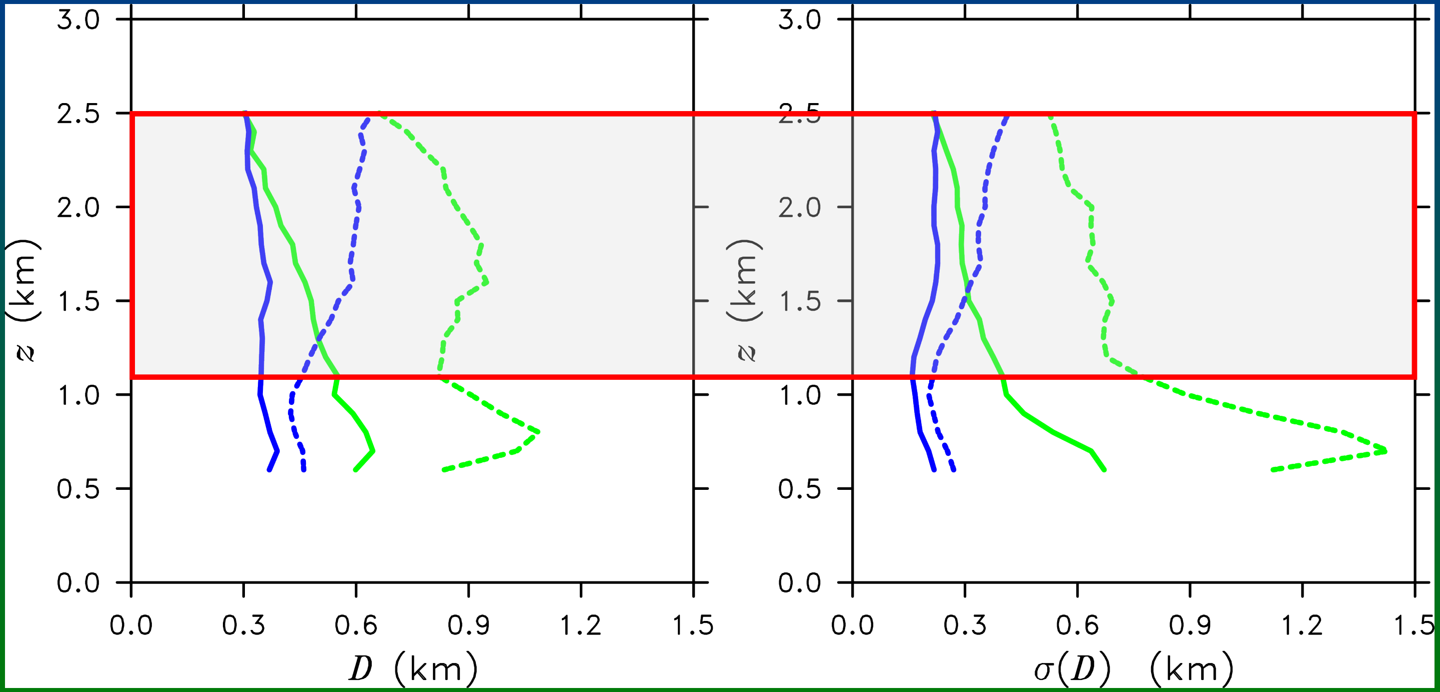
  - Above: clouds evolving toward equilibrium state. TKE scaling increasingly relevant.



Summary

- Sharp uplift over narrow island dramatically increases turbulent fluxes and precipitation
  - Enhancement not just due to increased cloud coverage
  - Clouds themselves are invigorated
- Hypothesis: reduced dilution in wider island clouds creates more intense and liquid-rich updafts
- Clouds widen and purify for two reasons
  - Forced saturation of broad sub-cloud moisture “patches”
  - Turbulent constraints on updraft velocities force clouds to widen and become less diluted

Conclusions and future work

- Findings relevant to basic understanding and parameterization of convection
  - TKE scaling provides a link between grid-scale parameters and internal cloud properties
  - Allows entrainment rate (the great unknown) and cloud size to be inferred from mesoscale environment
- Future work
  - Use turbulence theory for observational entrainment retrievals
  - Incorporate TKE scaling into convection parameterization schemes (may need to design new schemes from the ground up)