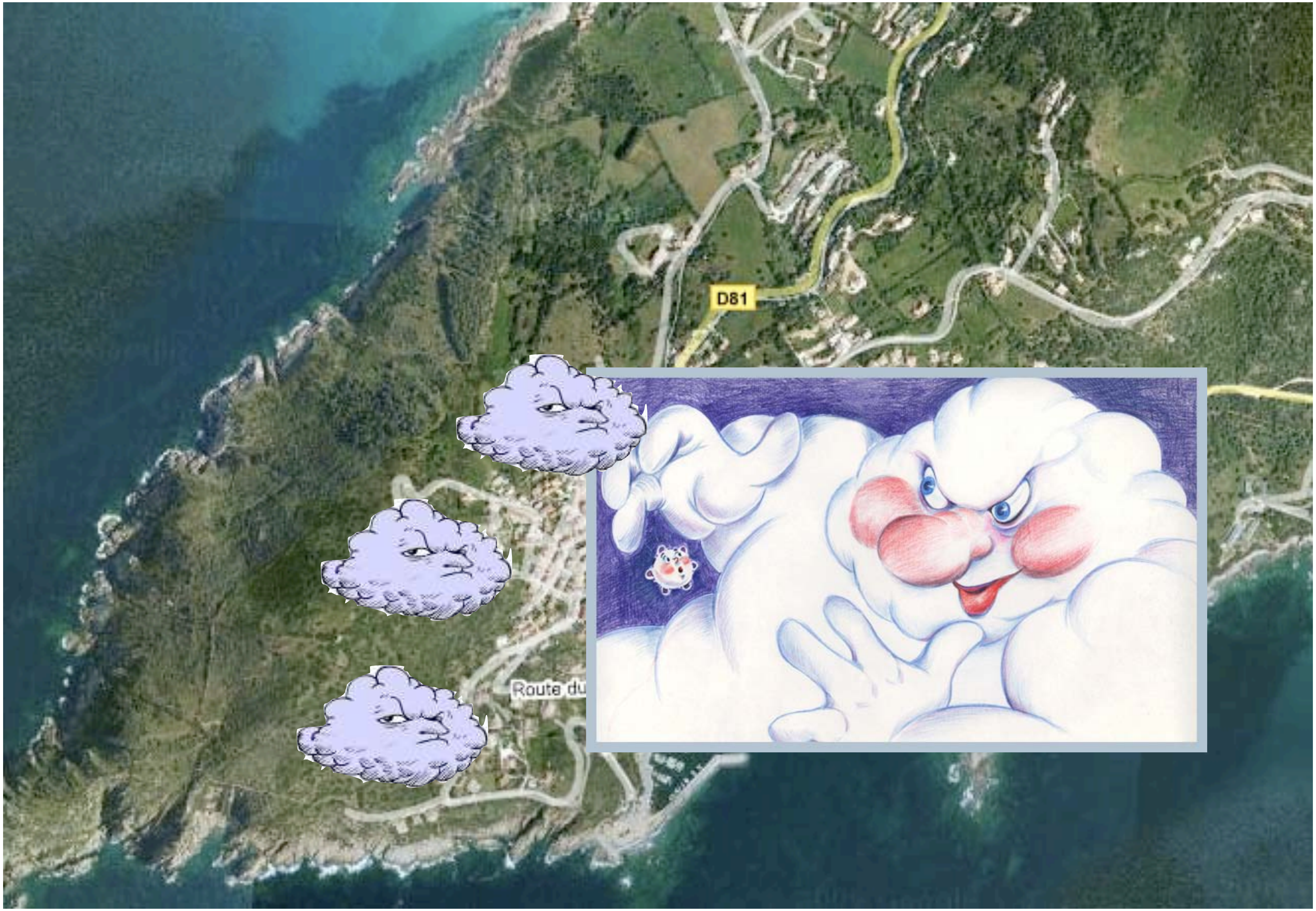
Convection II

Steve Sherwood
Cargese Summer School 2009

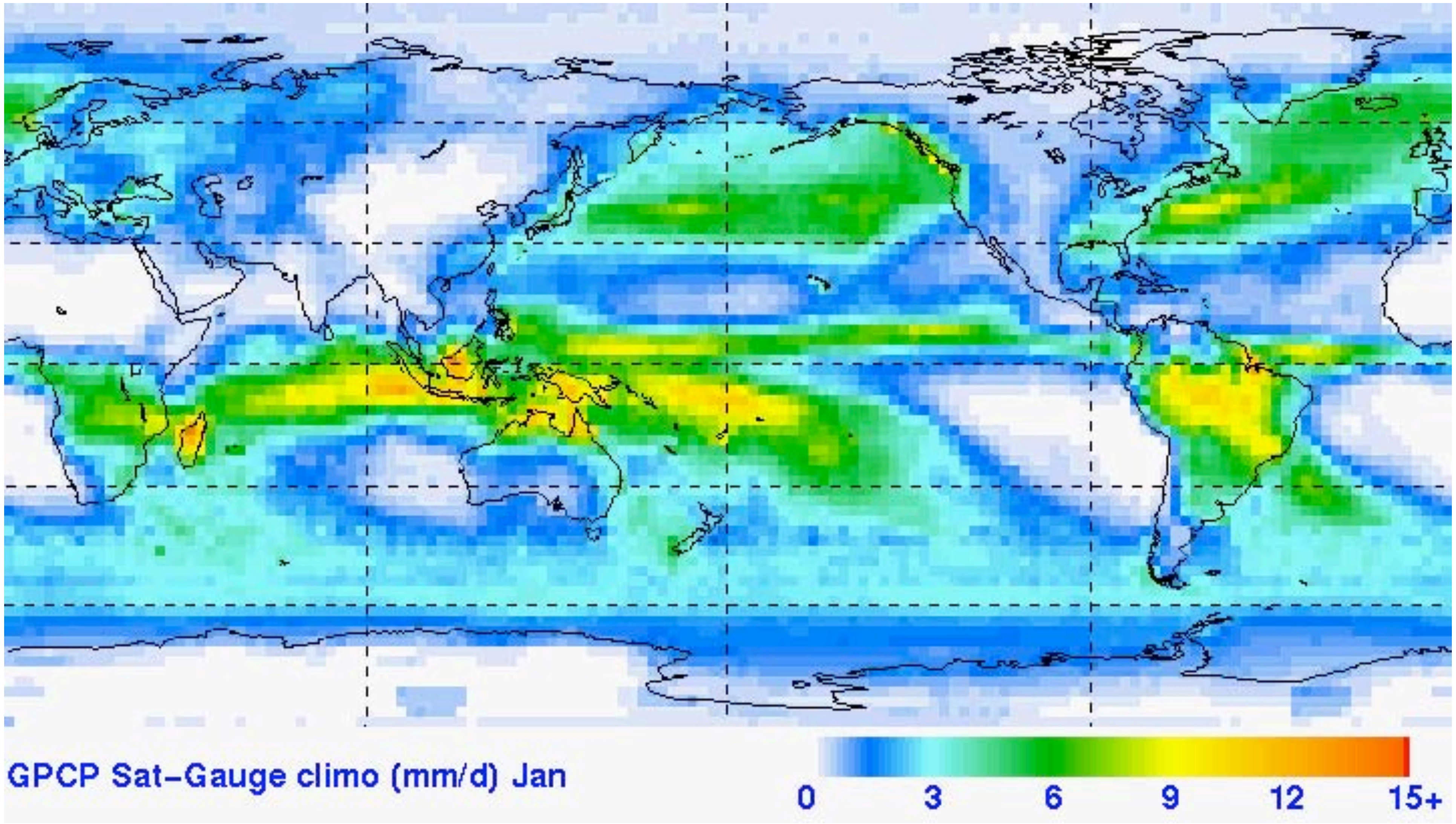
(Deep convection)


D81
Route du

Where does it rain?

Most rain comes from glaciated ("cold") clouds.
Glaciation occurs at T from -10C to -35C.

Where does it rain?



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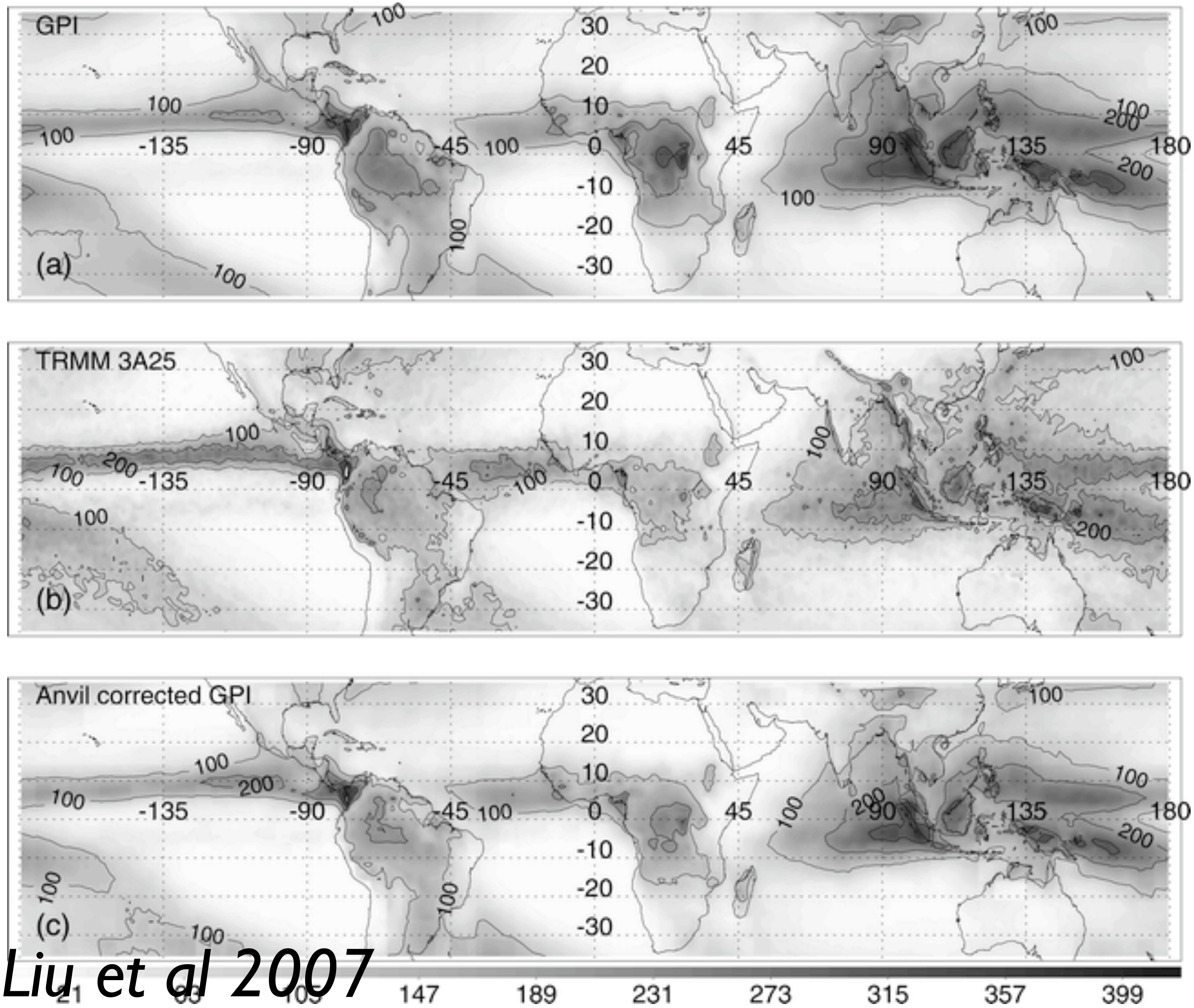
How good are satellite estimates?



Traditional 235K IR threshold method

Tropical Rainfall Measuring Mission Radar

Improved IR

Liu et al 2007

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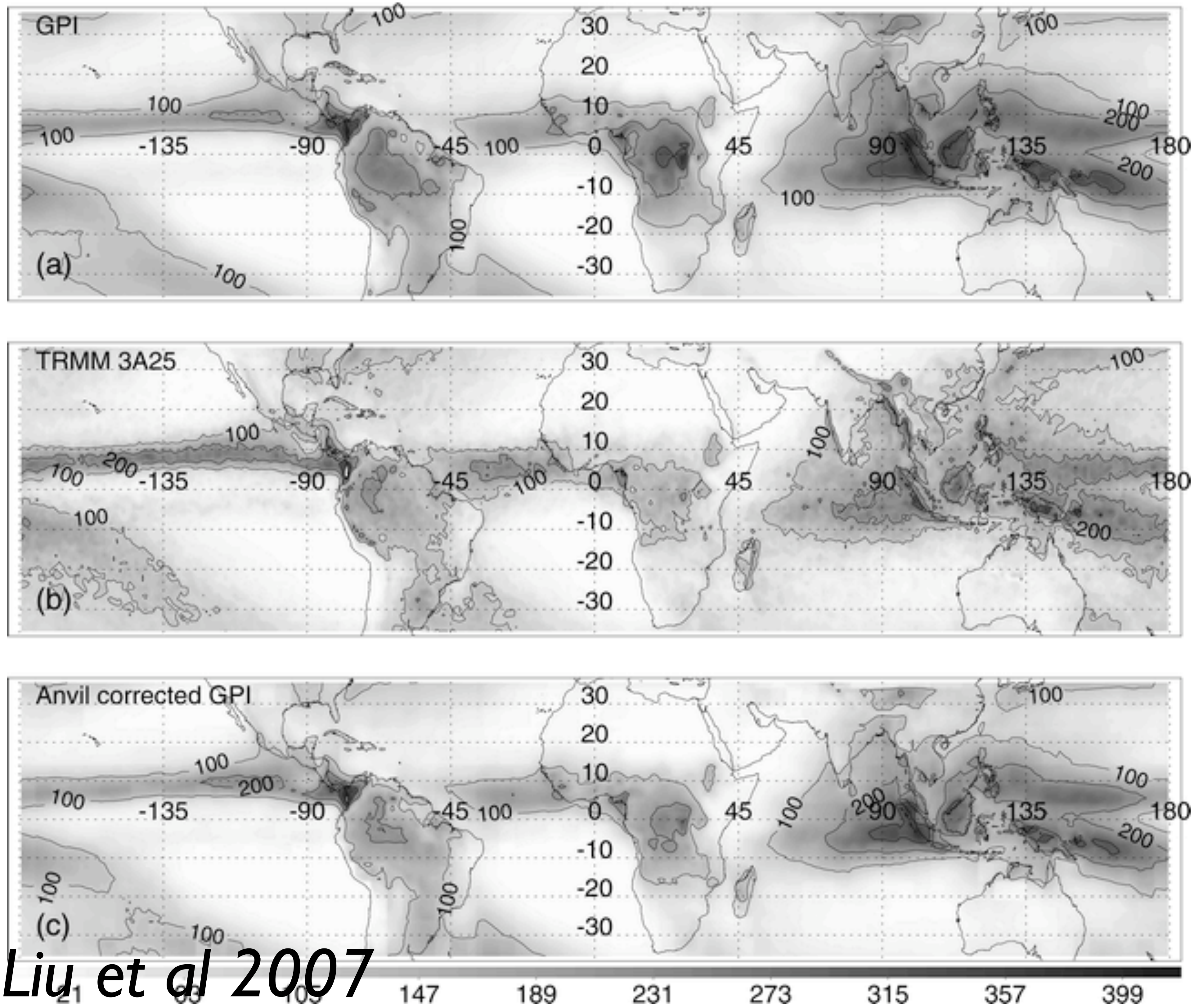


Traditional 235K IR threshold method

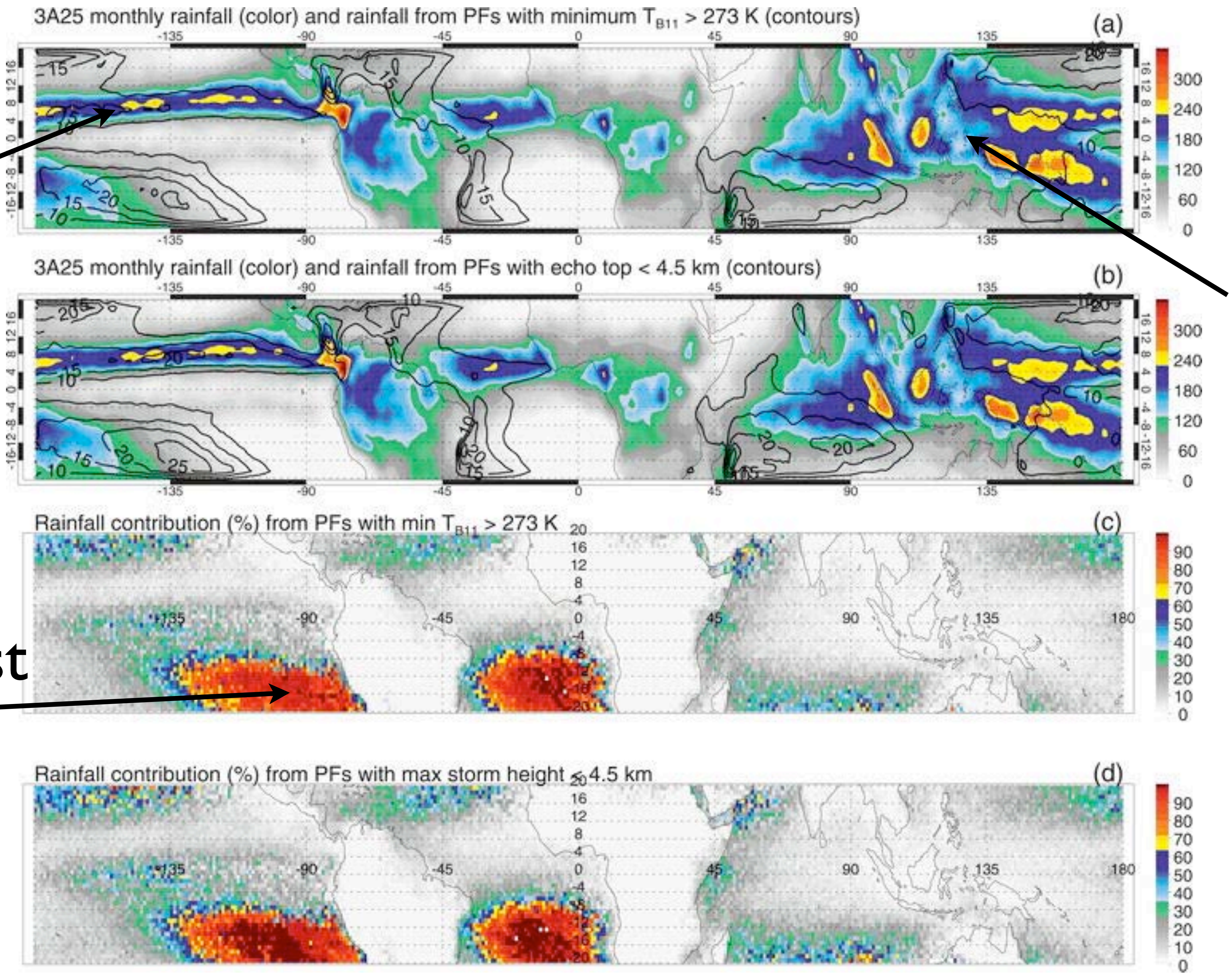
Tropical Rainfall Measuring Mission Radar

Improved IR

Liu et al 2007

...and don’t forget about microwave, rain gauges.

How much rain comes from warm/shallow clouds?



3A25 monthly rainfall (color) and rainfall from PFs with minimum T_{B11} > 273 K (contours) (a)

3A25 monthly rainfall (color) and rainfall from PFs with echo top < 4.5 km (contours) (b)

Rainfall contribution (%) from PFs with min T_{B11} > 273 K (c)

Rainfall contribution (%) from PFs with max storm height ≤ 4.5 km (d)

some

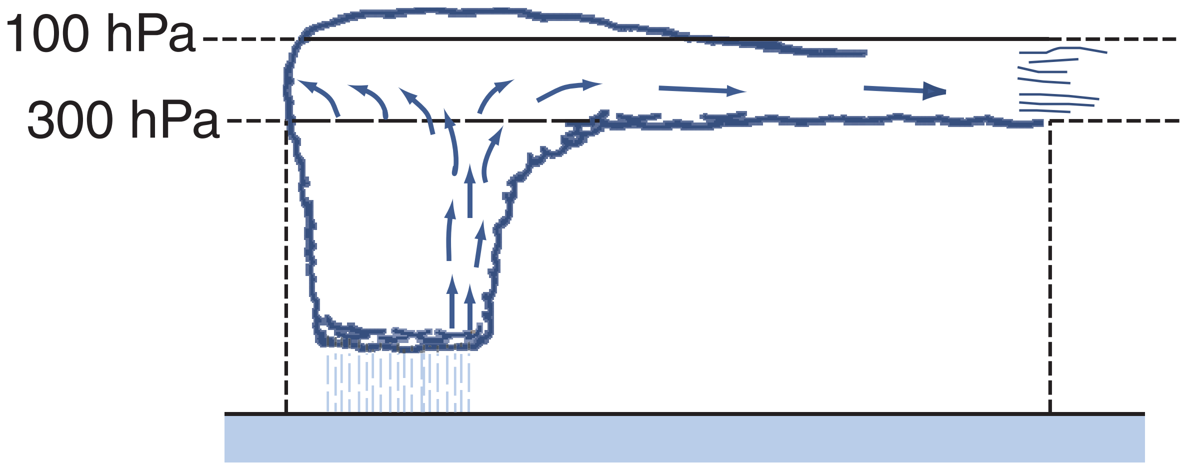
none

almost all

Liu and Zipser 2009

What do deep convective storms look like?

Traditional picture: upward motion, detrainment, uniform environmental subsidence



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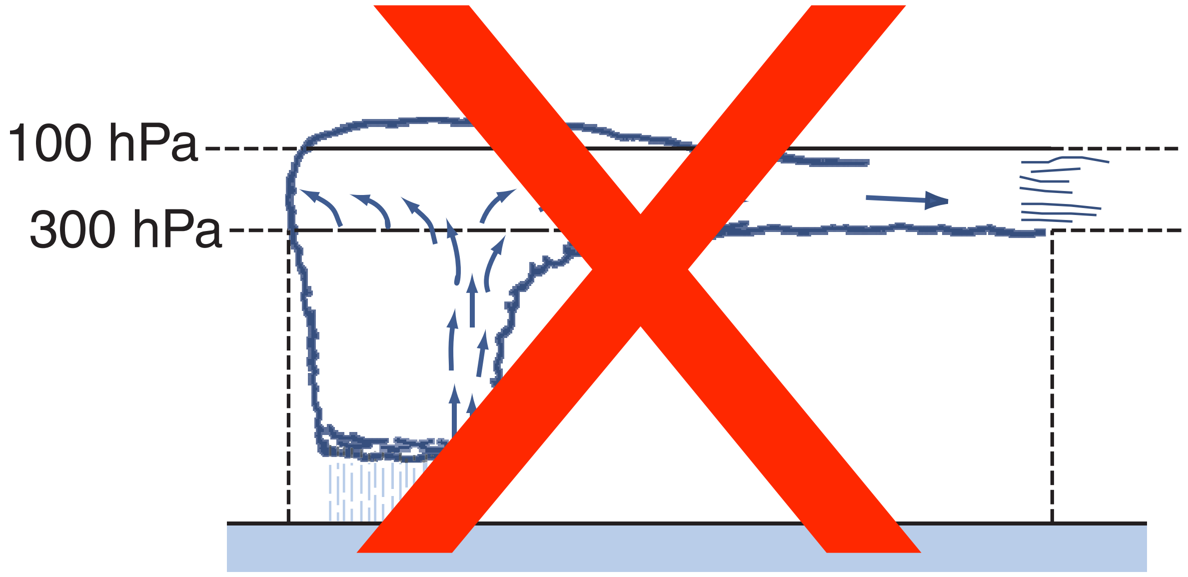

Non!

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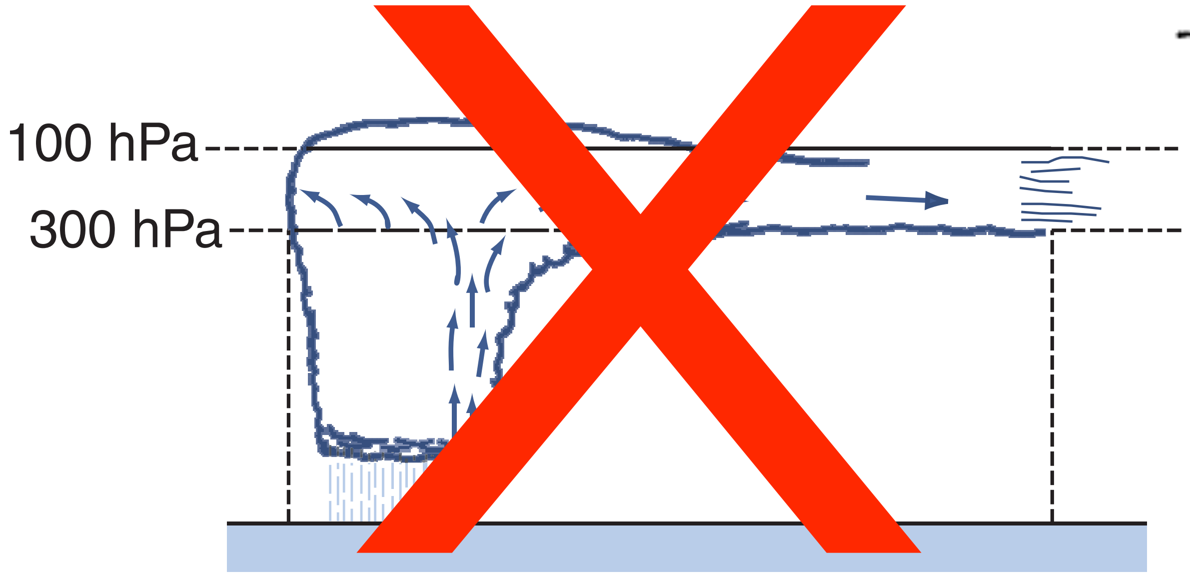
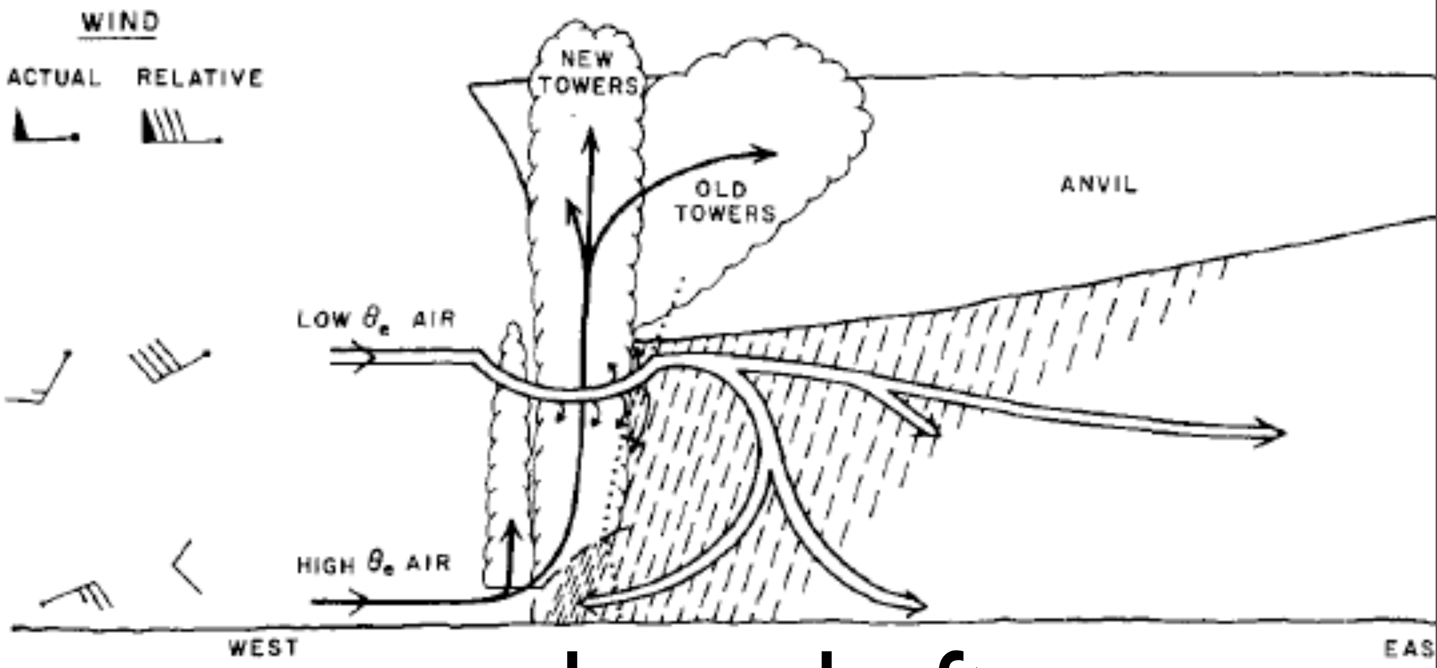
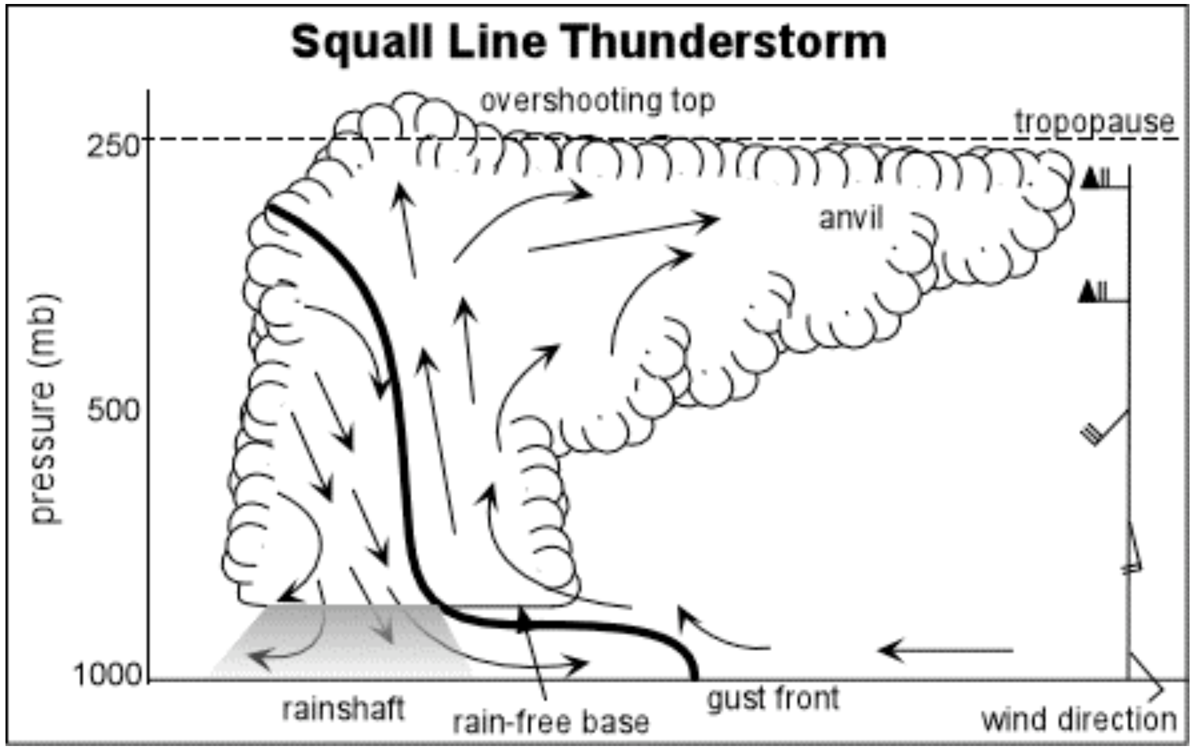


Non!

Zipser, 1969



downdrafts



Unsaturated downdrafts stabilize the environment, create gust fronts

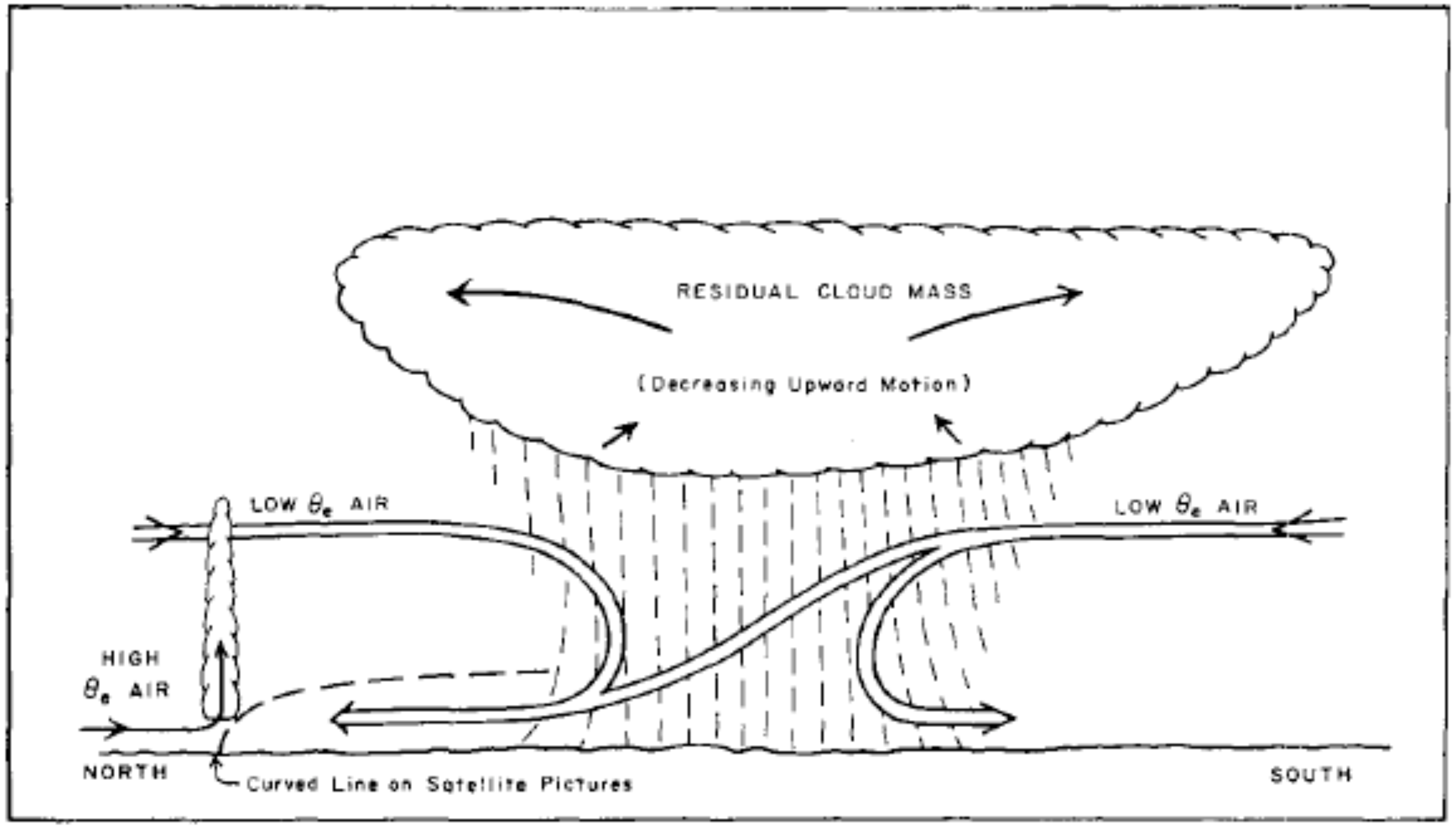
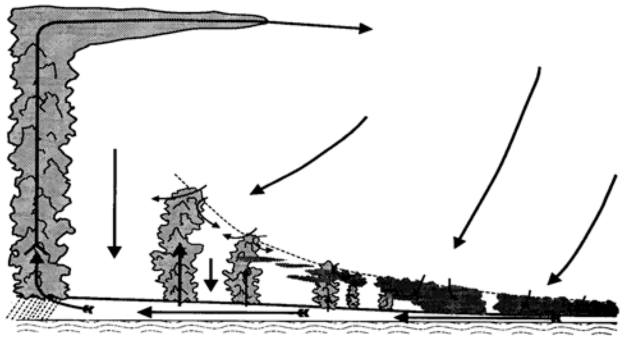


FIG. 15c. A north-south section similar to Fig. 15b, but representing the dissipating phase of the disturbance, when maintenance of the downdraft is primarily by rain falling from the extensive cloud shield, although with considerable mesoscale variations in intensity not depicted in this diagram.

Classic problems in atmospheric precipitating convection

• What controls transition from shallow to deep convection - when will this occur - "triggering" - how high will it go?	weather, climate, stratospheric effects
• How to predict convective heating/drying/rainfall/transport given large-scale conditions	dynamics
• What controls the appearance of severe storm characteristics (hail, lightning, tornadoes) or tropical cyclones?	impacts
• Properties of resulting clouds	climate change

Transition from shallow to deep convection



GigaLES simulation
(M. Khairoutdinov)
2048x2048x256,
100m grid, one day

Cloud

Humidity near surface
(dark = humid)

Rain

GOES Project
NASA-GSFC

GOES-9

Rapid-scan test
8 am - 8 pm EDT
July 2, 1995

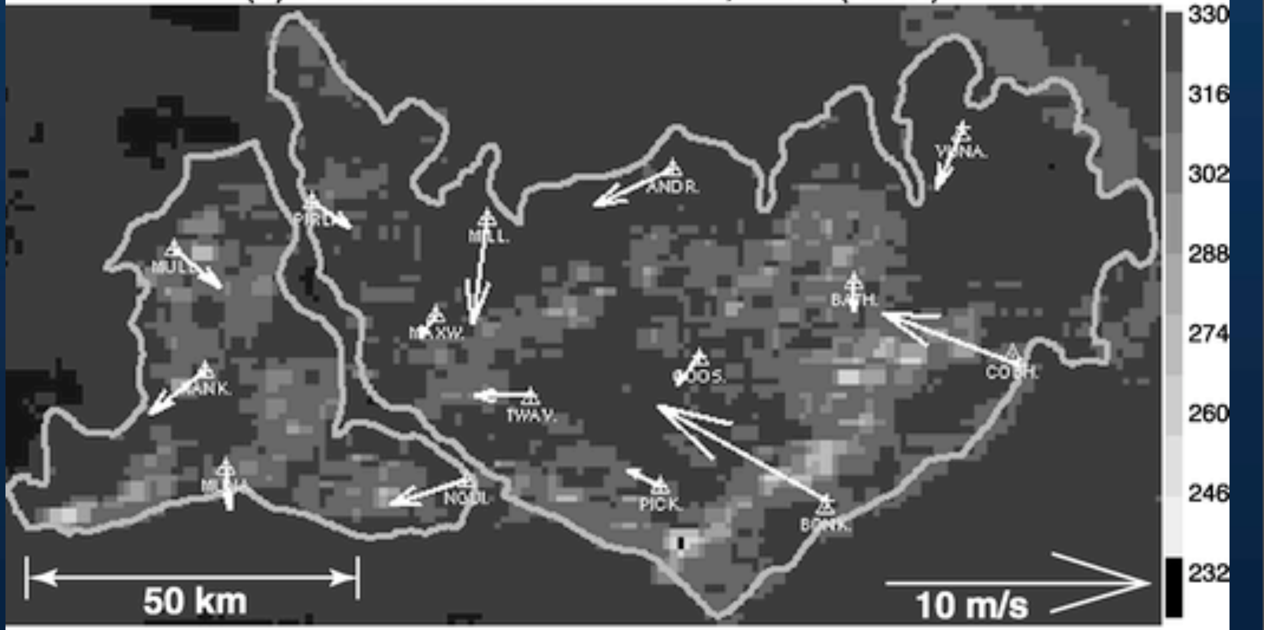
South Florida

July 13th edition

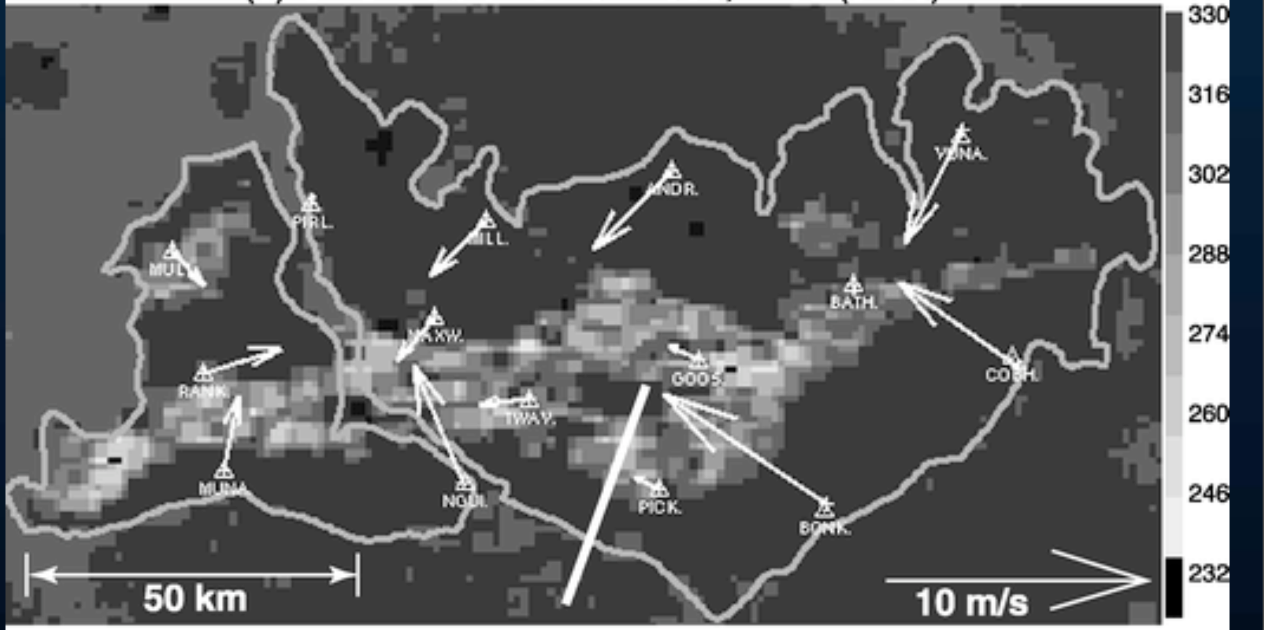
Observations of frontal collisions

- Interaction between sea-breeze fronts and cold-pool outflows on Melville/Bathurst Islands (Carbone et al. 2000). Similar behavior long noted in Florida peninsula.

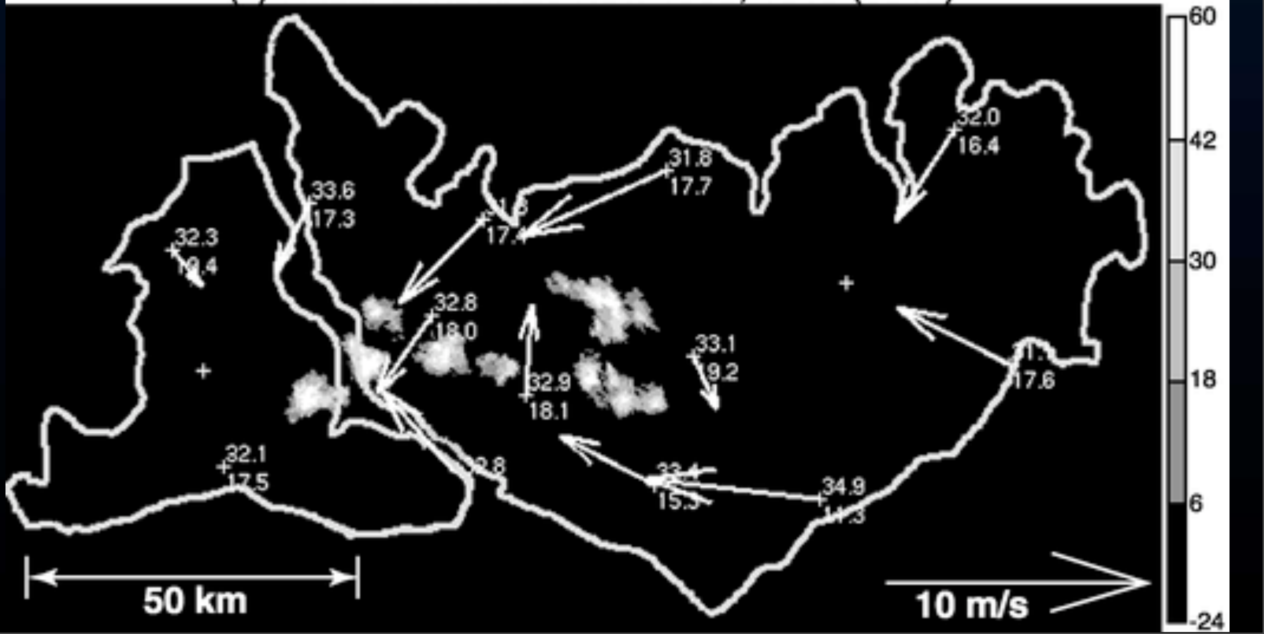
(a) GMS Visible 26 Nov. 1995, 1200 (0230)



(b) GMS Visible 26 Nov. 1995, 1400 (0430)



(c) Radar Echoes 26 Nov. 1995, 1515 (0545)



Observations
frontal collision

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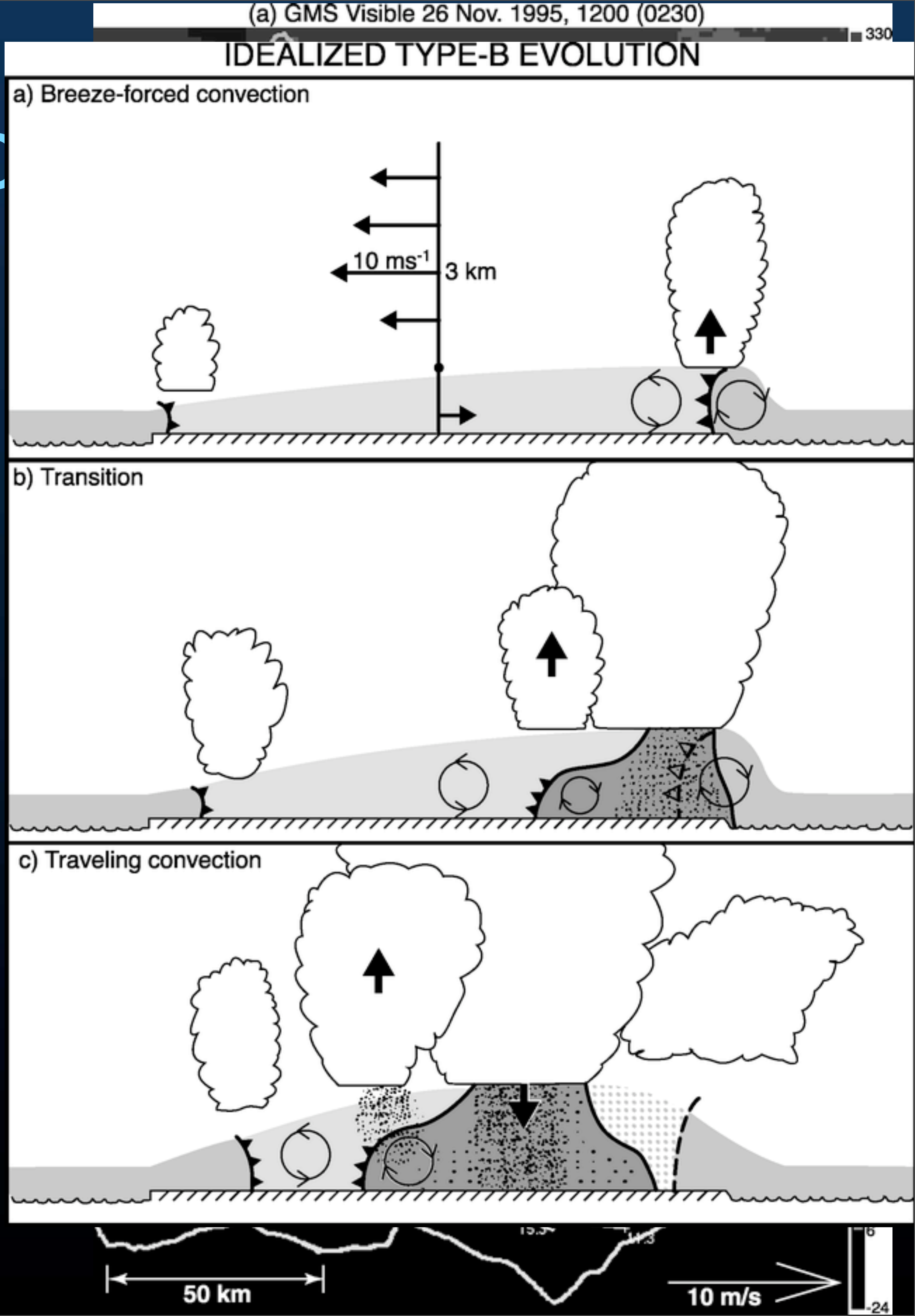


Idealized, no shear

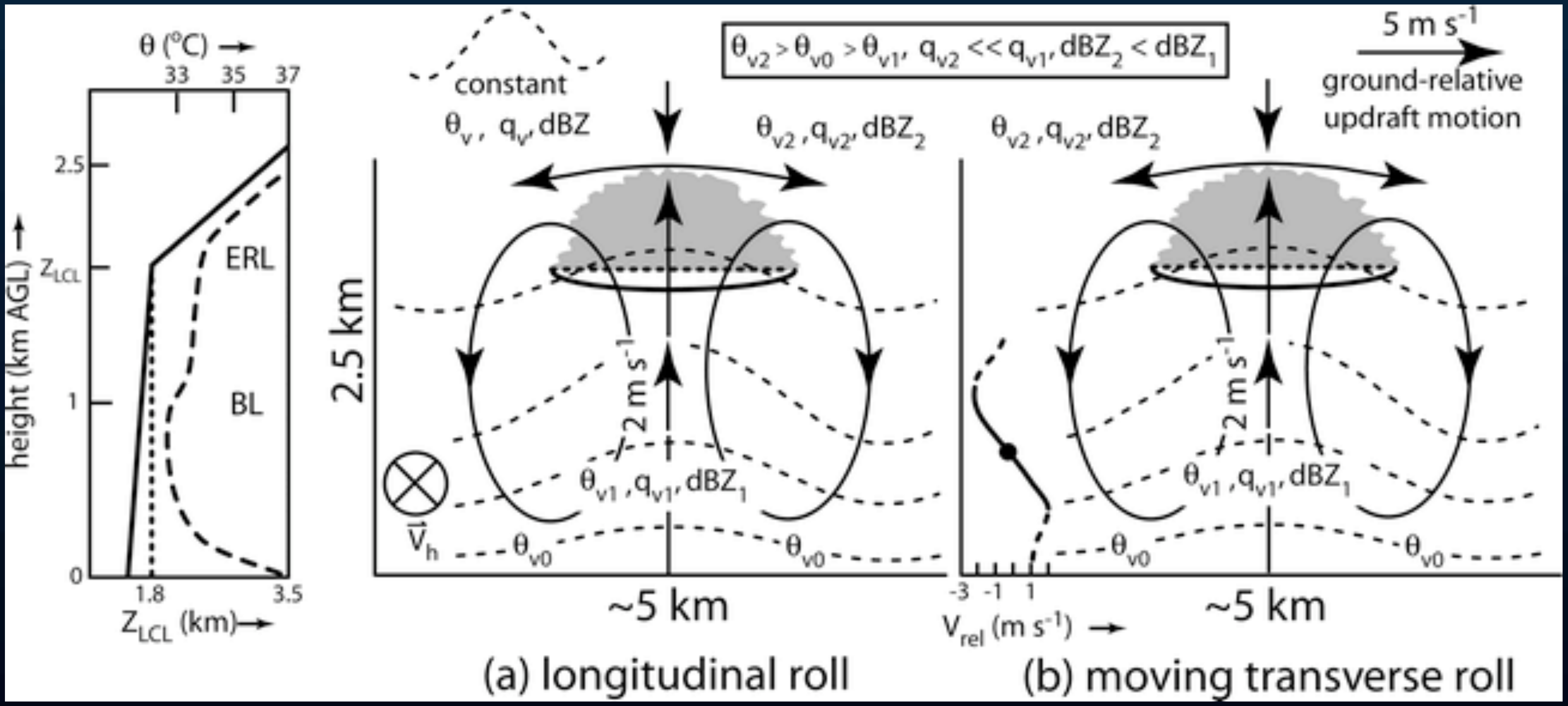
Uniform “top hat” diurnal surface heating of 300 W/m^2 peak

Color = θ’

H_2O-free simulation (no evaporative downdrafts)

Sea breeze interaction with nonuniform stability profile

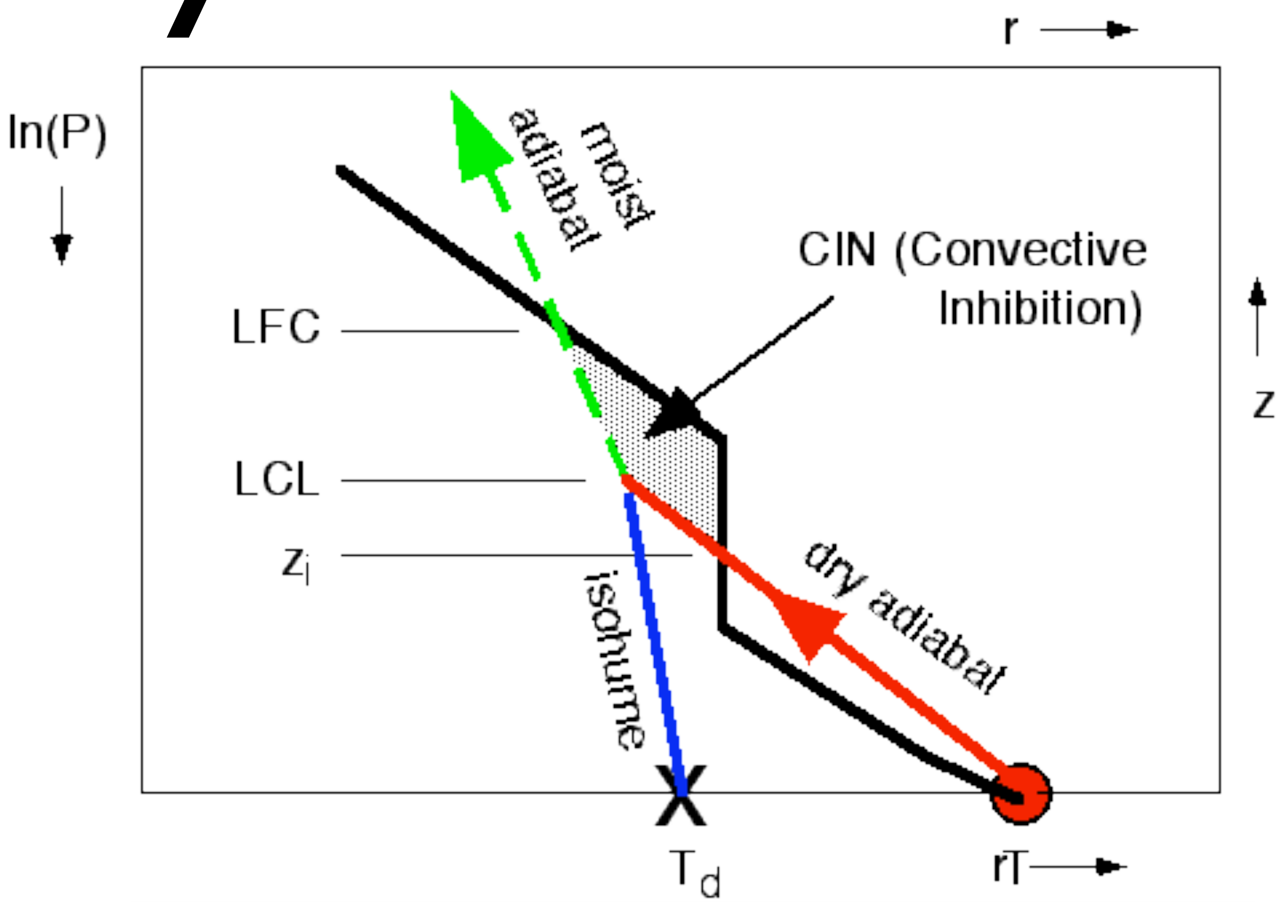
Rolls, organization by the mean flow (common in midlatitudes)

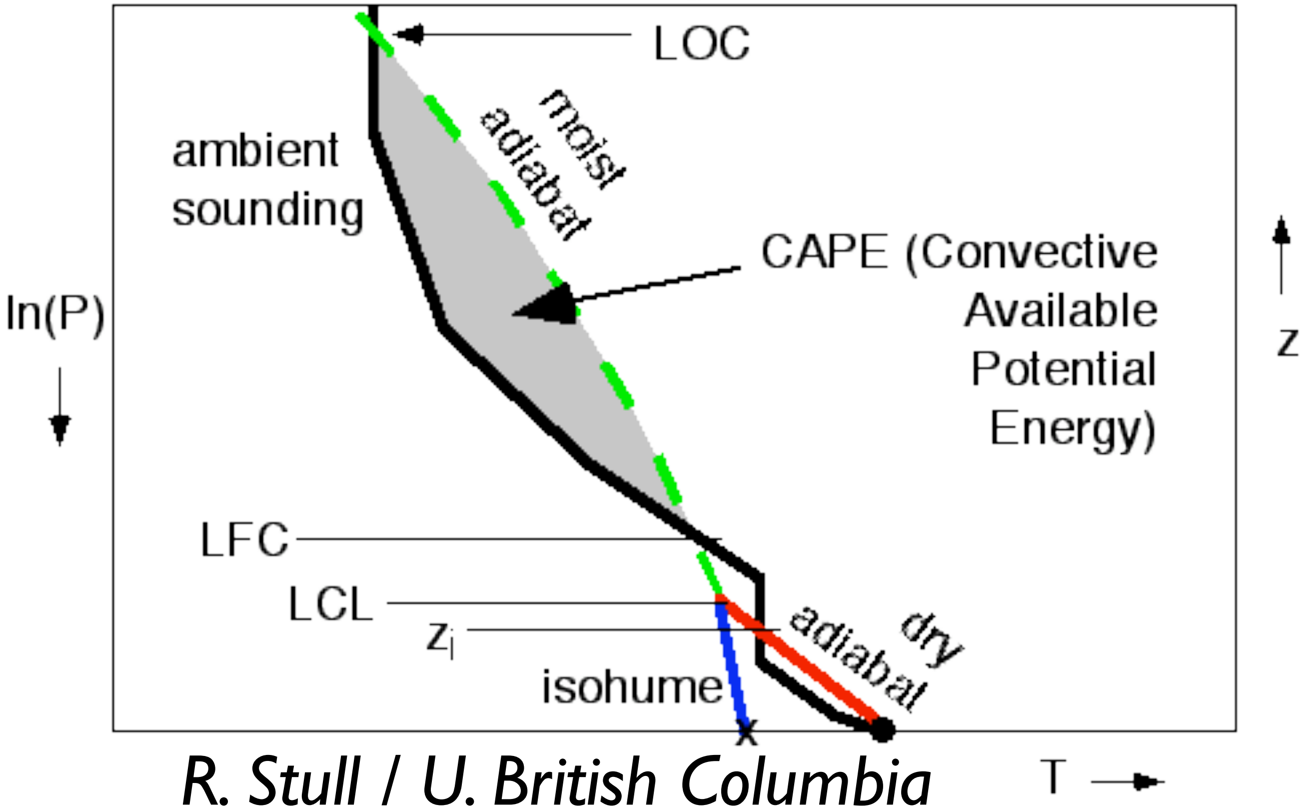


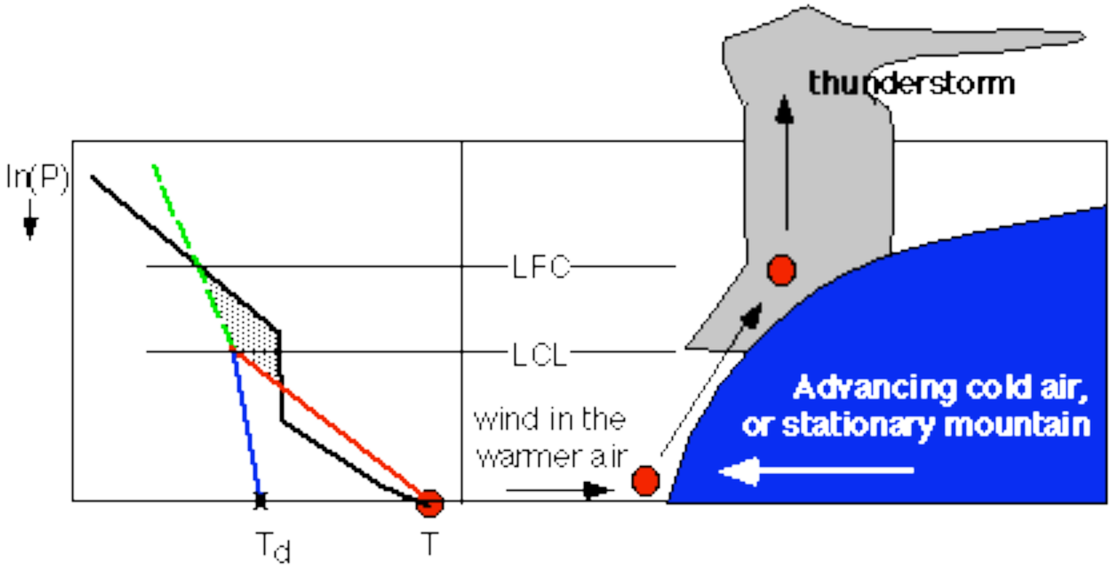
Ziegler et al 2007

Classical theory

- Based on pseudoadiabatic ascent, perhaps including mixing-dilution along the way.
- CIN must be overcome
- CAPE governs severity
- LNB governs depth





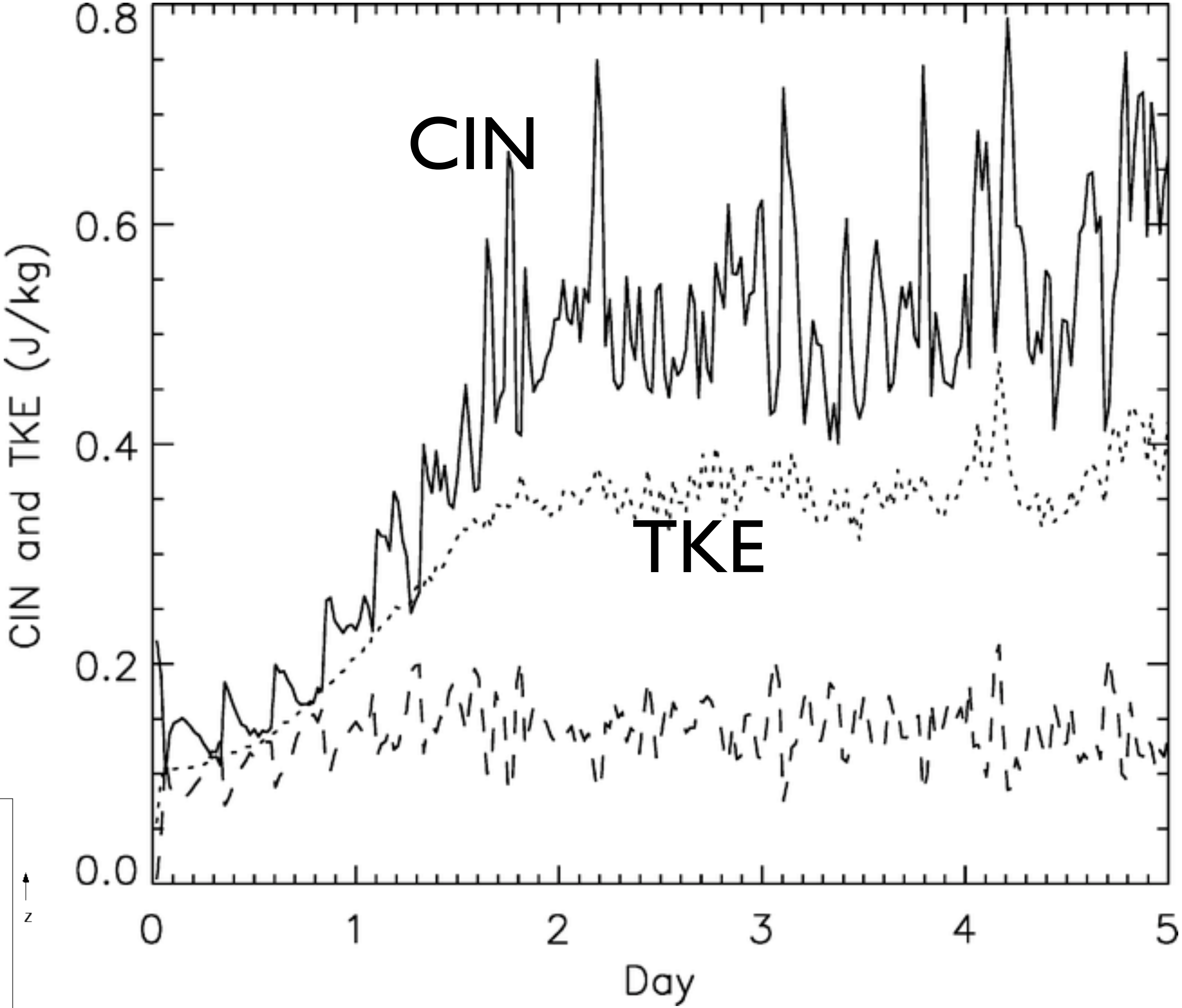


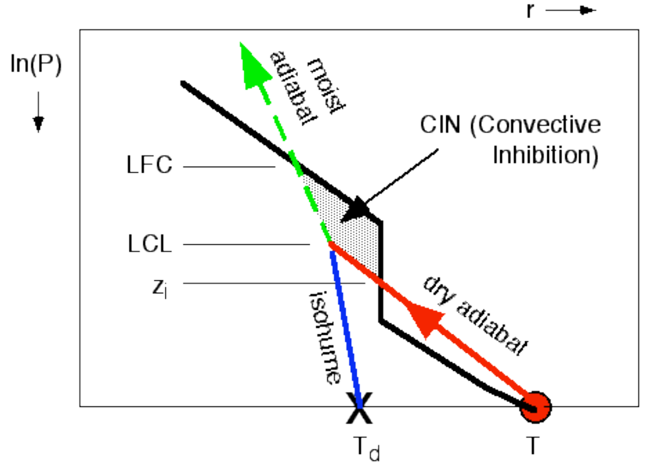
R. Stull / U. British Columbia

Some shortcomings

- Little evidence that CIN inhibits convection even in simulated convection (e.g., Khairoutdinov and Randall 2006)
- Large CAPE necessary but far from sufficient for strong convection (Sherwood 1999, ..., KR06); takes time for convection to deepen.
- Undilute parcels not seen aloft in numerical simulations (Kuang and Bretherton 2005, KR06)
- Does not explain some observed variations in storm intensity

Quasi-equilibrium between CIN and turbulent kinetic energy (TKE) in the mixed layer?





Kuang and Bretherton 2006

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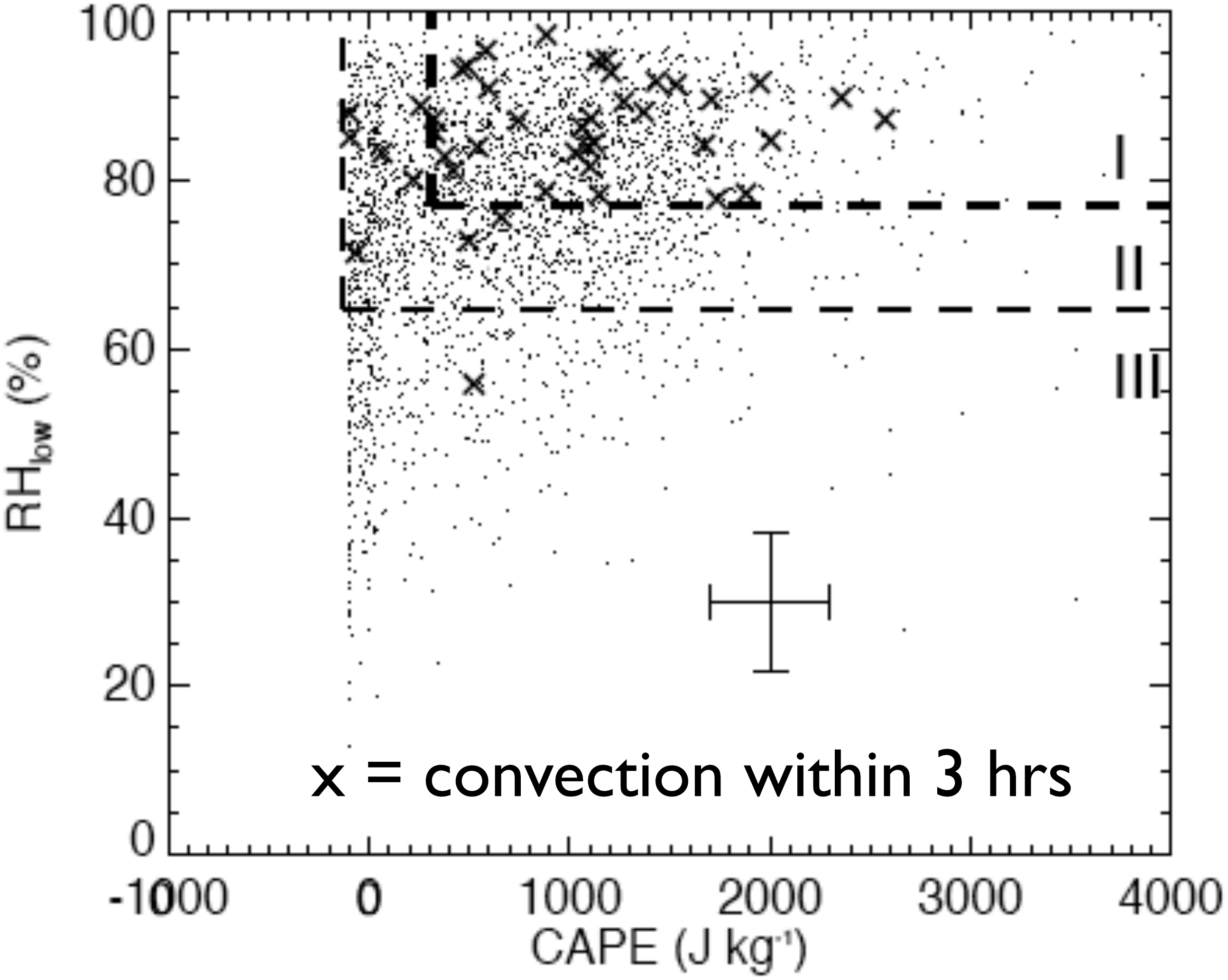
RH must be high throughout low-mid troposphere for deep convection



x = convection within 3 hrs

Sherwood 1999

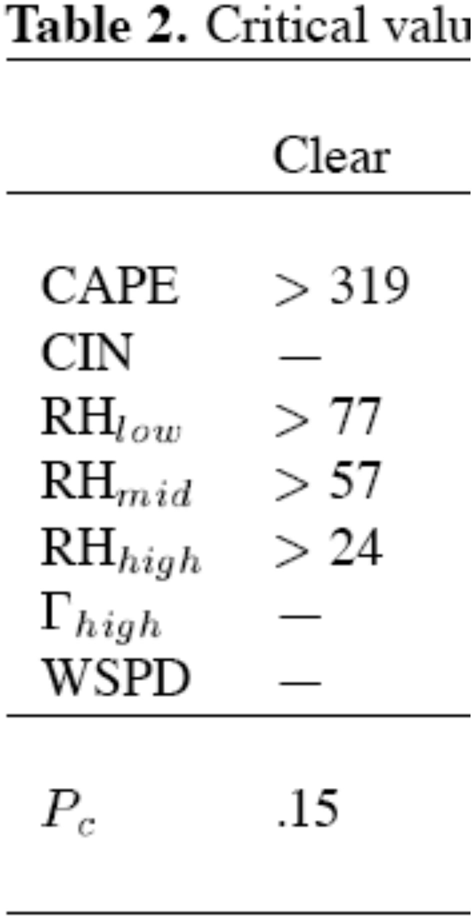


Table 2. Critical valu

	Clear
CAPE	> 319
CIN	—
RH$_{low}$	> 77
RH$_{mid}$	> 57
RH$_{high}$	> 24
Γ_{high}	—
WSPD	—
P_c	.15

Optimal discriminant set

See also many other studies (e.g. Jensen and Del Genio 2006)

“Hector” storm (north of Darwin, Australia)

Courtesy of Roger Smith

“Hector” storm under shear + drier mid-troposphere

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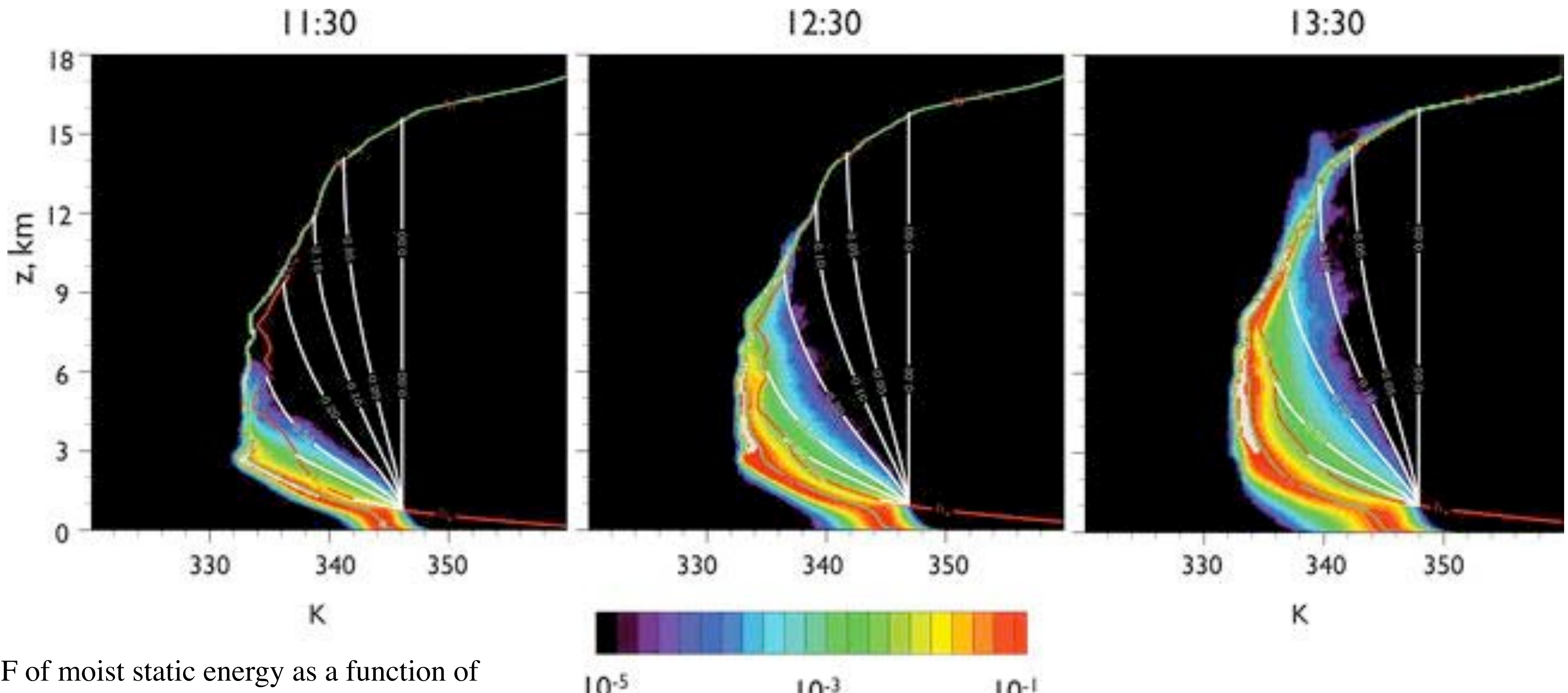
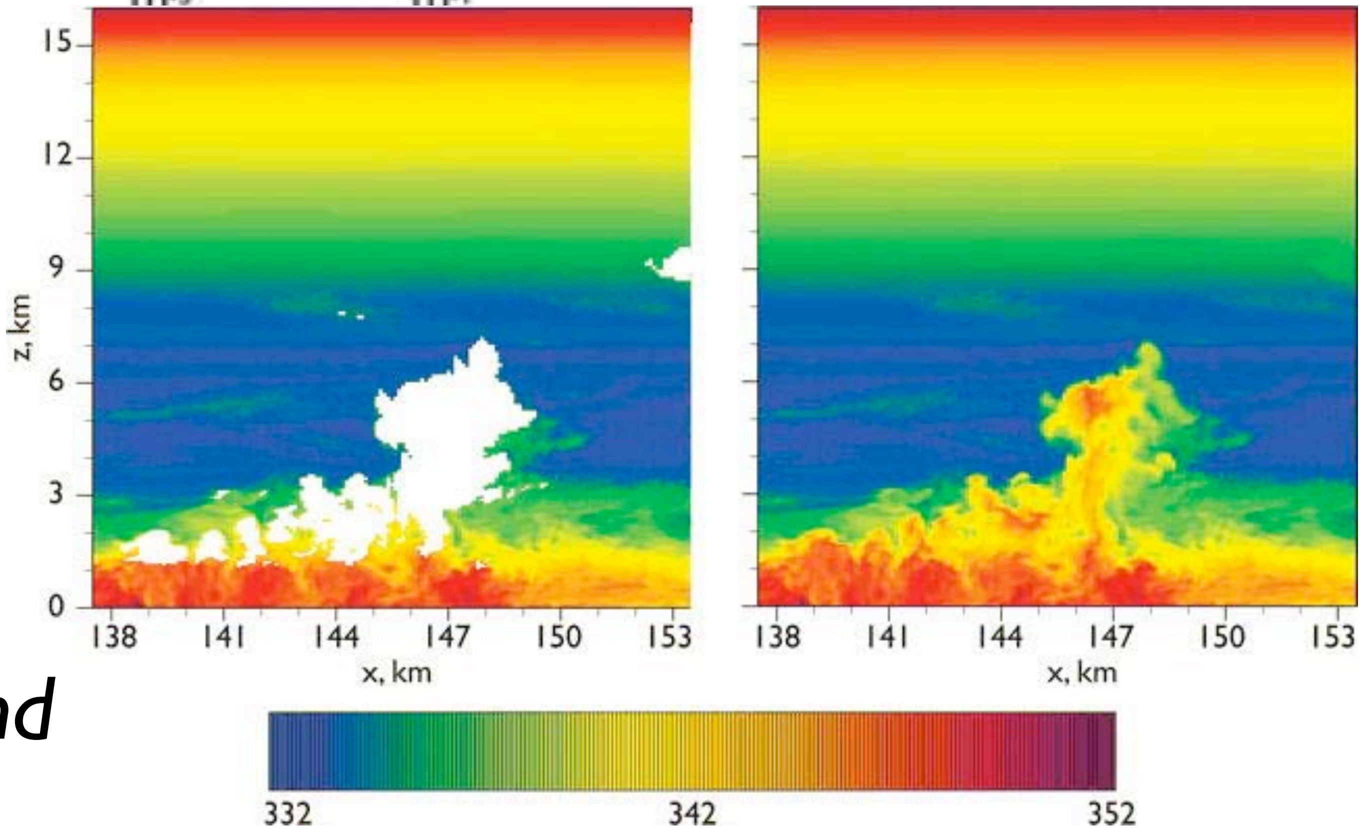
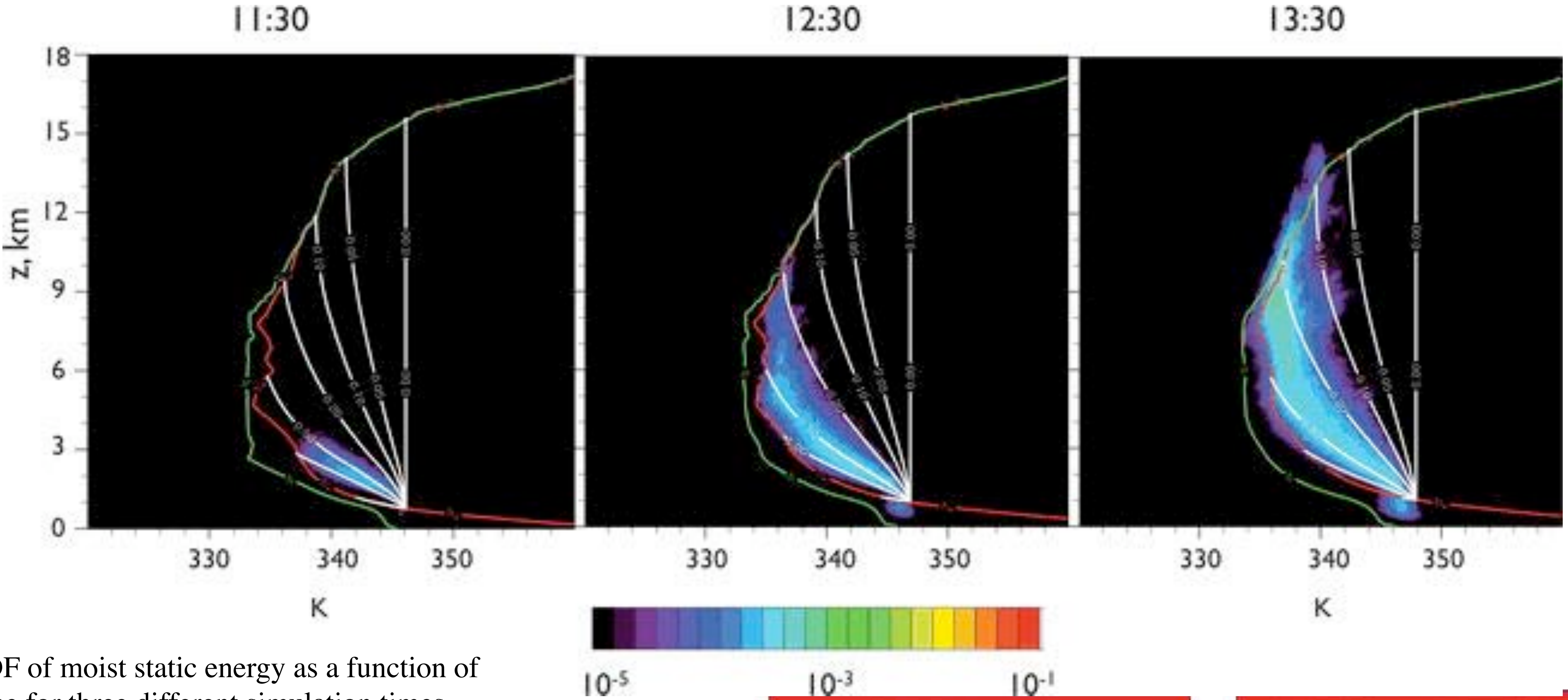


PDF of moist static energy as a function of time for three different simulation times. White lines show the trajectories that the entraining plumes would follow given different values of entraining parameter, in km–1: 0 (vertical line), 0.05, 0.1, 0.2, 0.5, 1.0.

No undilute air (in simulations)

Khairoudtinov and Randall 2006





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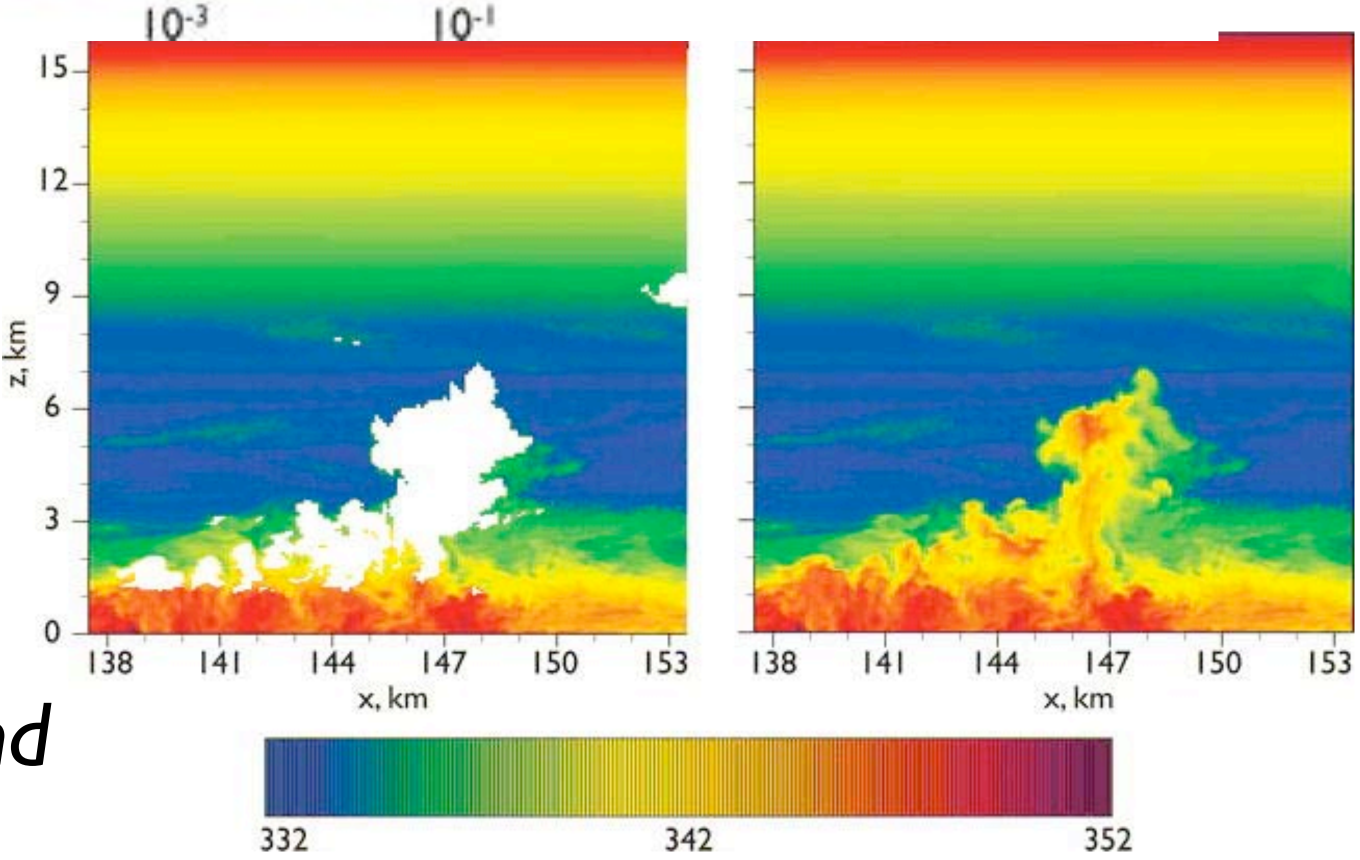

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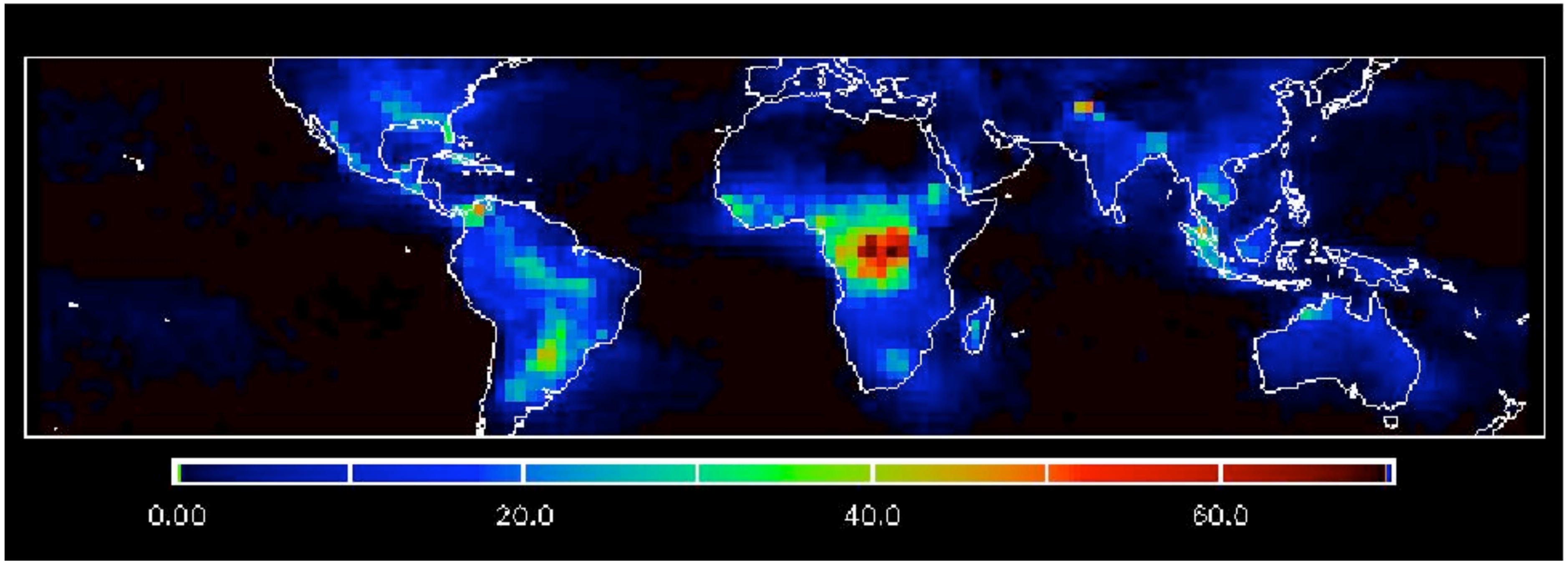
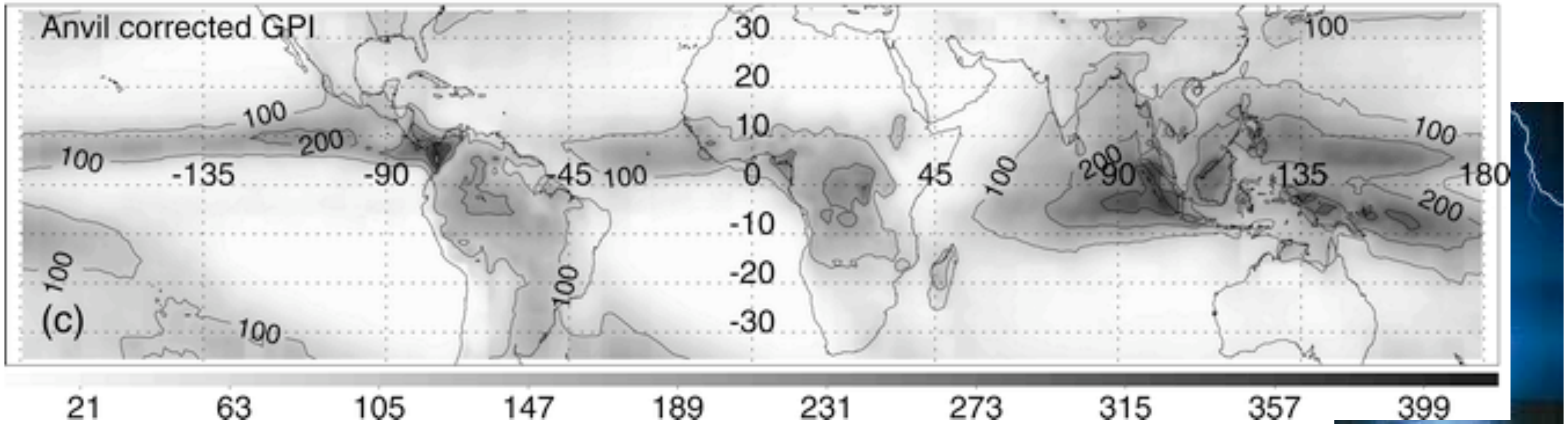
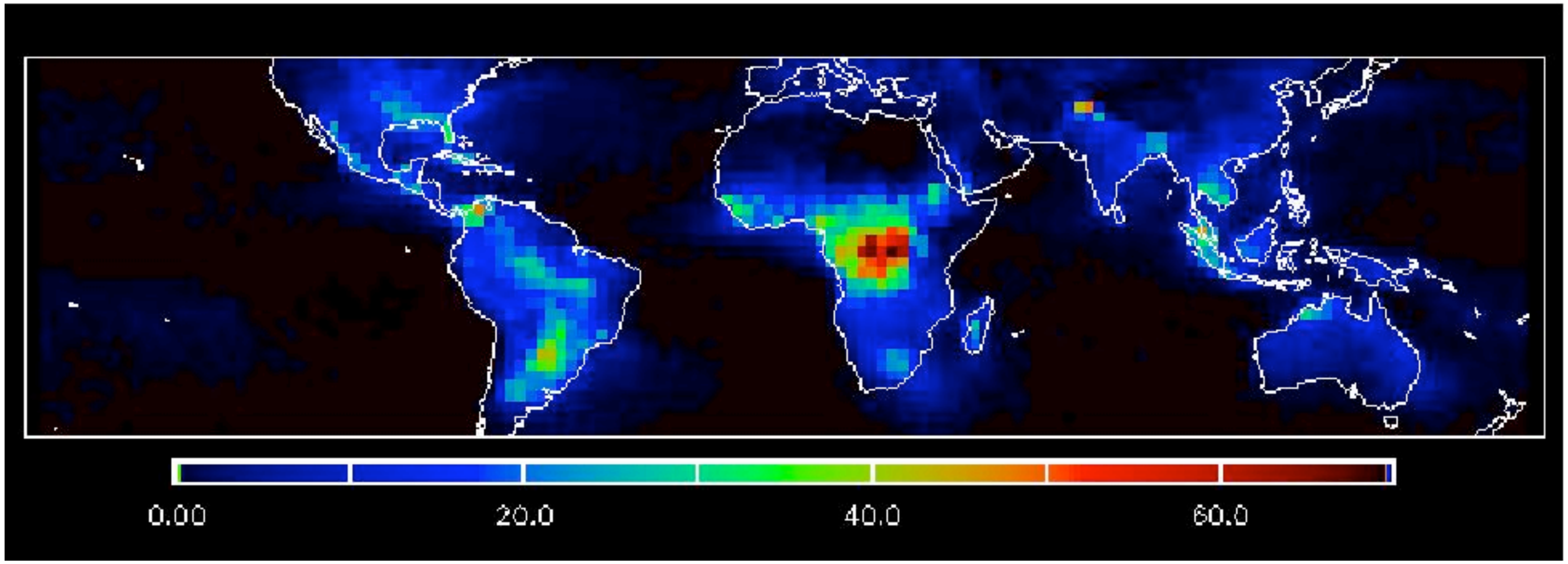
Lightning strike rate (LIS)



Land storms (reaching 14 km) produce similar rainfall but 15x as much lightning as maritime storms..why?

CAPE is not systematically different.





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Liu and Zipser, 2005

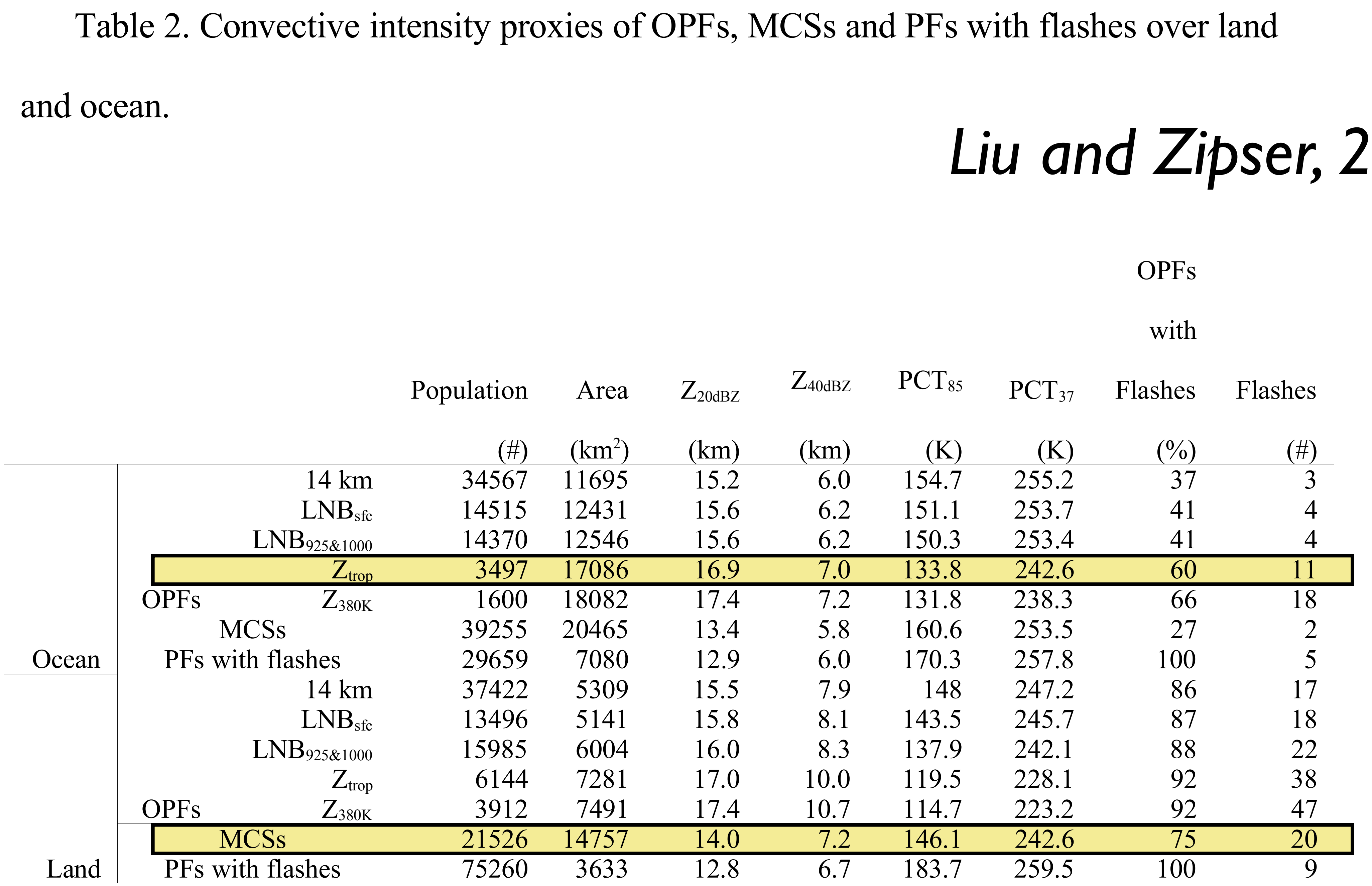


Table 2. Convective intensity proxies of OPFs, MCSs and PFs with flashes over land and ocean.

			Population (#)	Area (km^2)	Z_{20dBZ} (km)	Z_{40dBZ} (km)	PCT_{85} (K)	PCT_{37} (K)	OPFs with Flashes (%)	Flashes (#)
Ocean	OPFs	14 km	34567	11695	15.2	6.0	154.7	255.2	37	3
		LNB_{sfc}	14515	12431	15.6	6.2	151.1	253.7	41	4
		$LNB_{925\&1000}$	14370	12546	15.6	6.2	150.3	253.4	41	4
		Z_{trop}	3497	17086	16.9	7.0	133.8	242.6	60	11
		Z_{380K}	1600	18082	17.4	7.2	131.8	238.3	66	18
	MCSs		39255	20465	13.4	5.8	160.6	253.5	27	2
	PFs with flashes		29659	7080	12.9	6.0	170.3	257.8	100	5
Land	OPFs	14 km	37422	5309	15.5	7.9	148	247.2	86	17
		LNB_{sfc}	13496	5141	15.8	8.1	143.5	245.7	87	18
		$LNB_{925\&1000}$	15985	6004	16.0	8.3	137.9	242.1	88	22
		Z_{trop}	6144	7281	17.0	10.0	119.5	228.1	92	38
		Z_{380K}	3912	7491	17.4	10.7	114.7	223.2	92	47
	MCSs		21526	14757	14.0	7.2	146.1	242.6	75	20
	PFs with flashes		75260	3633	12.8	6.7	183.7	259.5	100	9

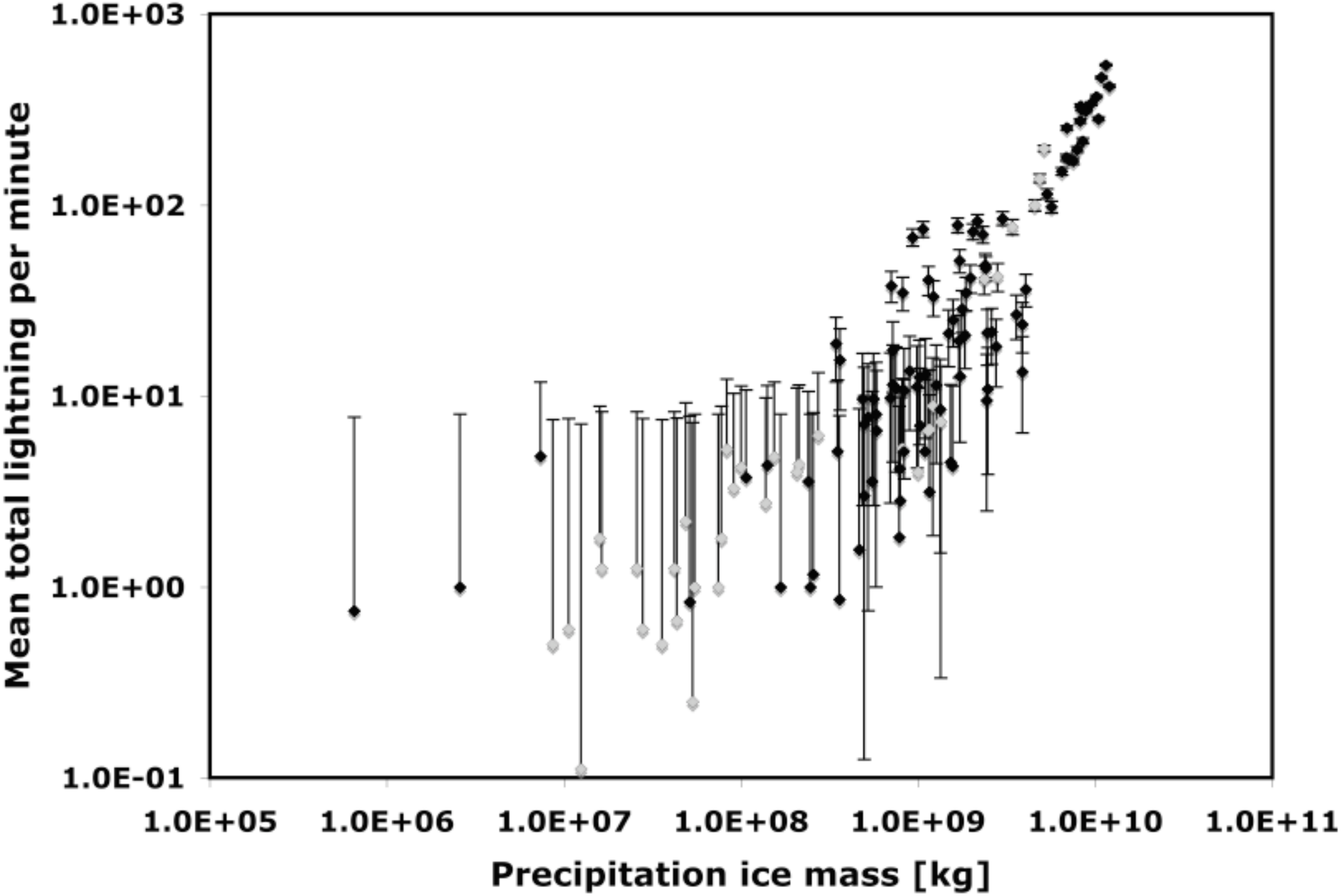
6.6/storm

15/storm

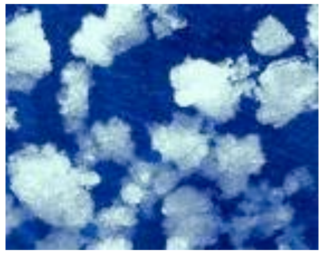
... lightning more prevalent over land, even compared to tropopause-penetrating maritime storms!

... the latter are much taller but the former have more large particles at lower levels

Lightning closely correlated with total ice mass in the storm

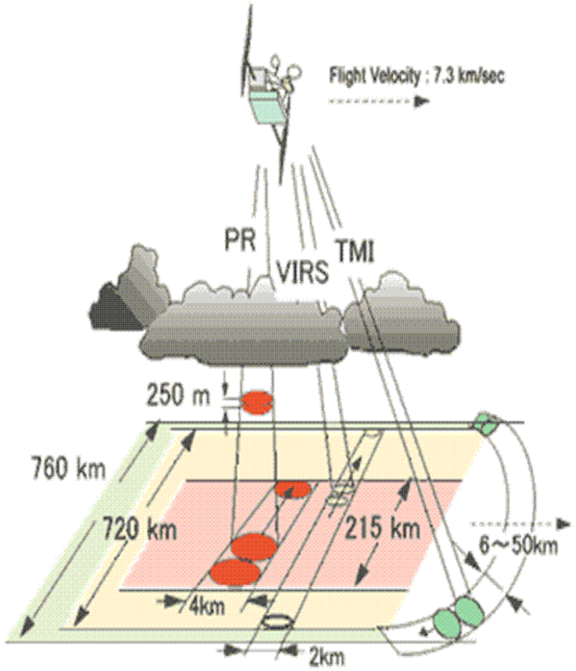


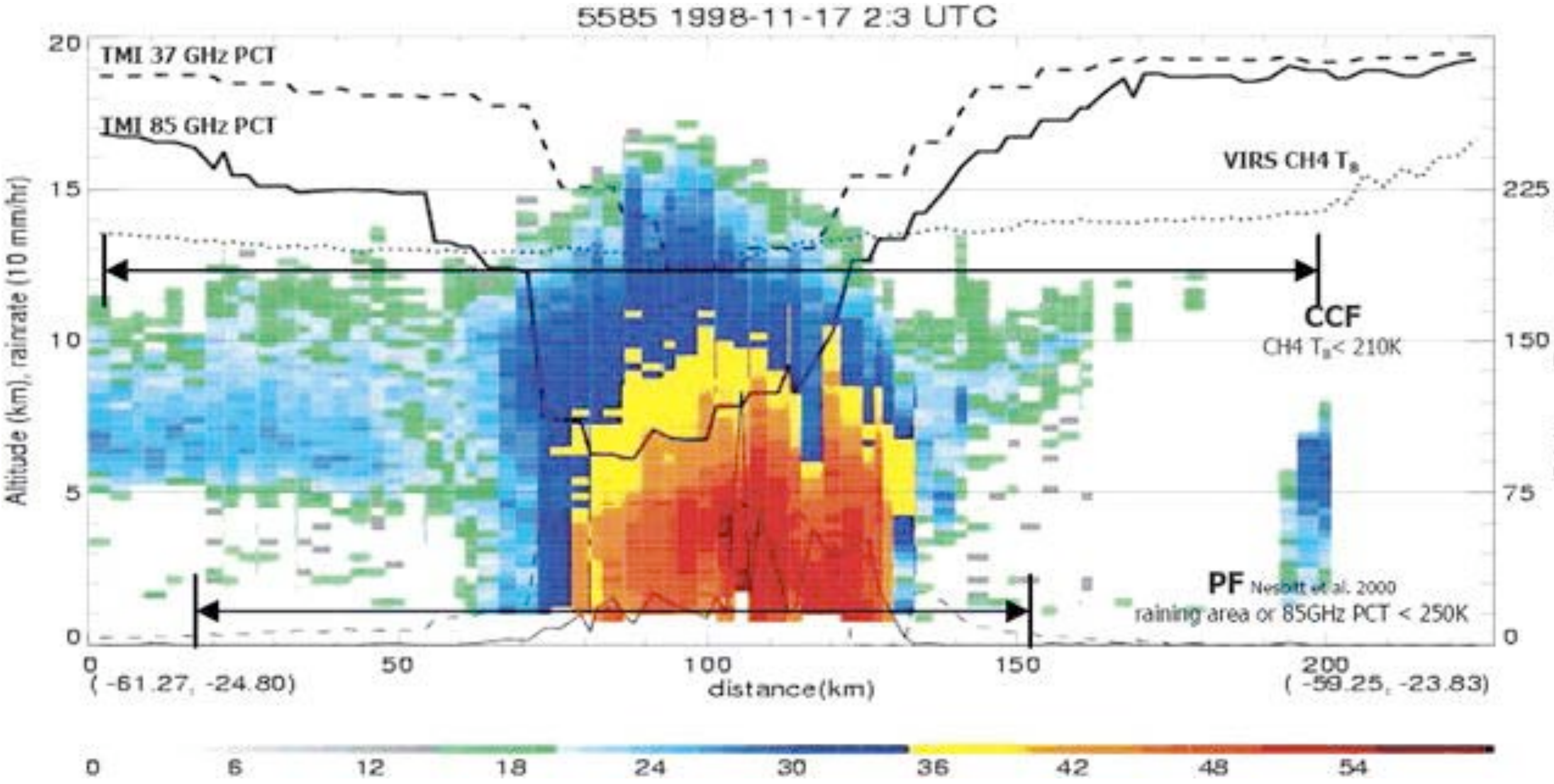
Deierling et al 2008



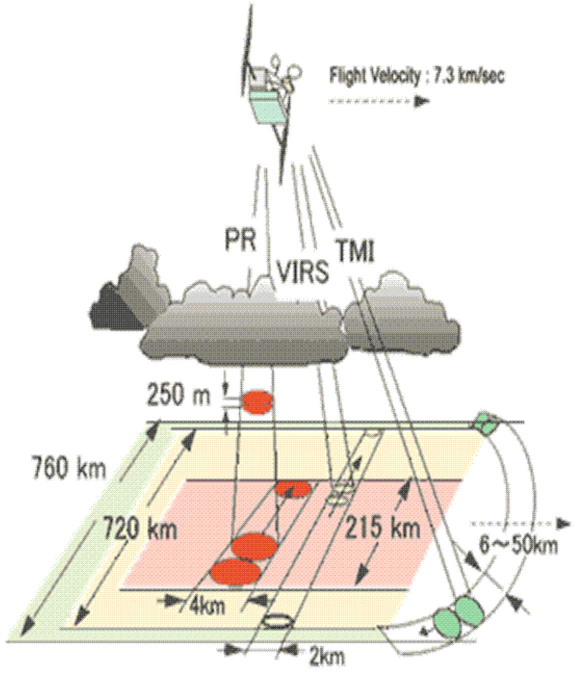
Lofting of large particles
requires strong updrafts.

Multiple obs available from TRMM (Tropical Rainfall Measuring Mission satellite)





Liu et al 2007



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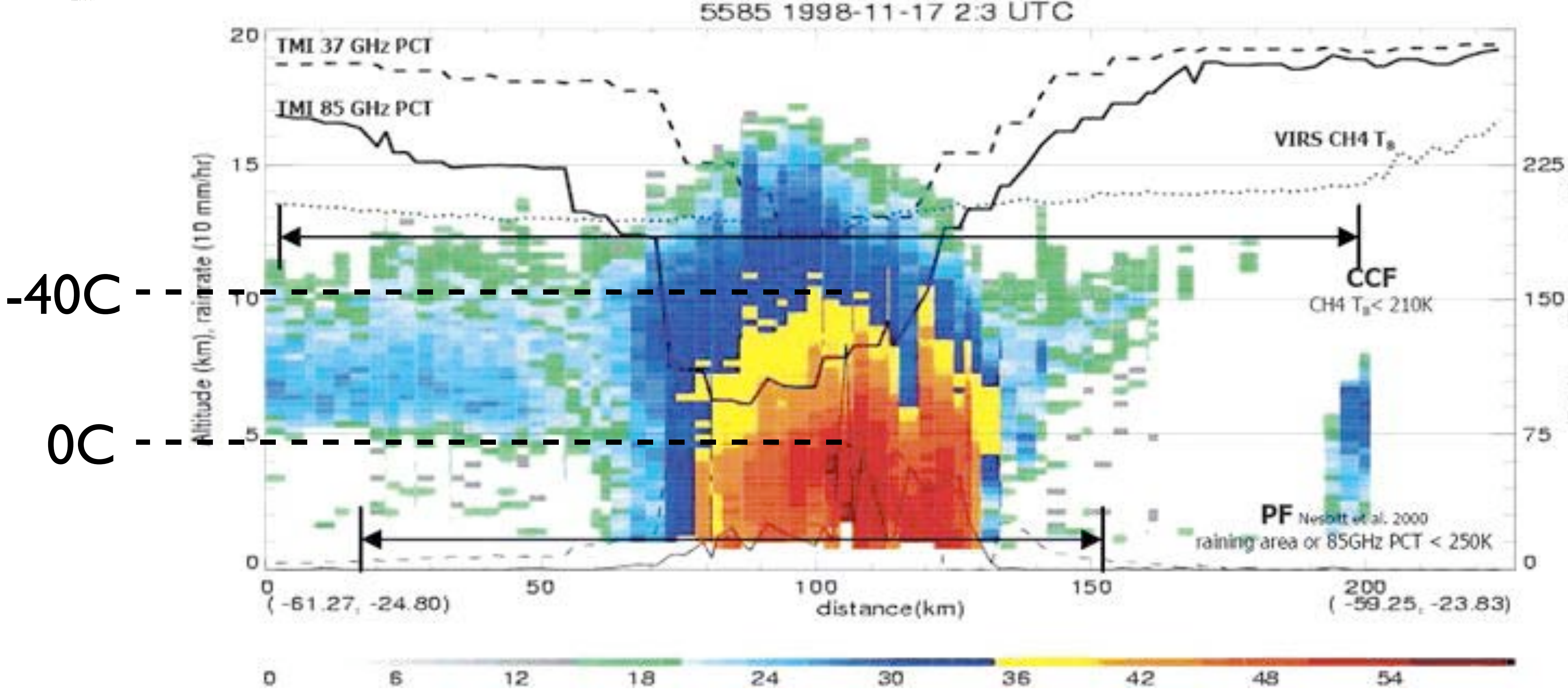

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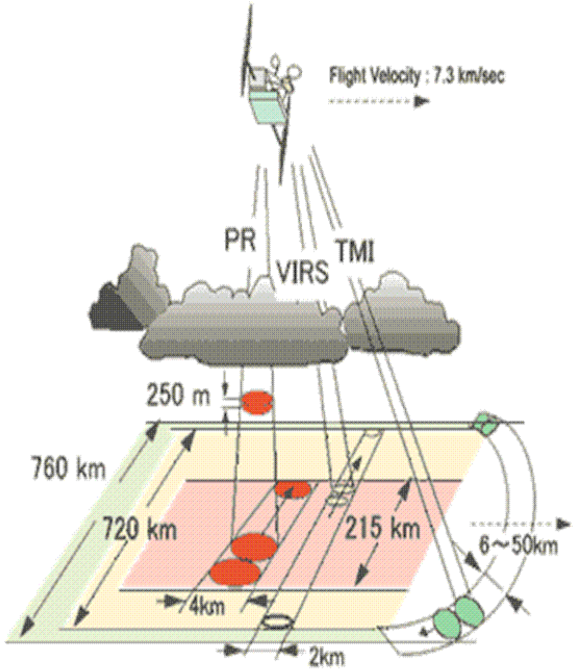
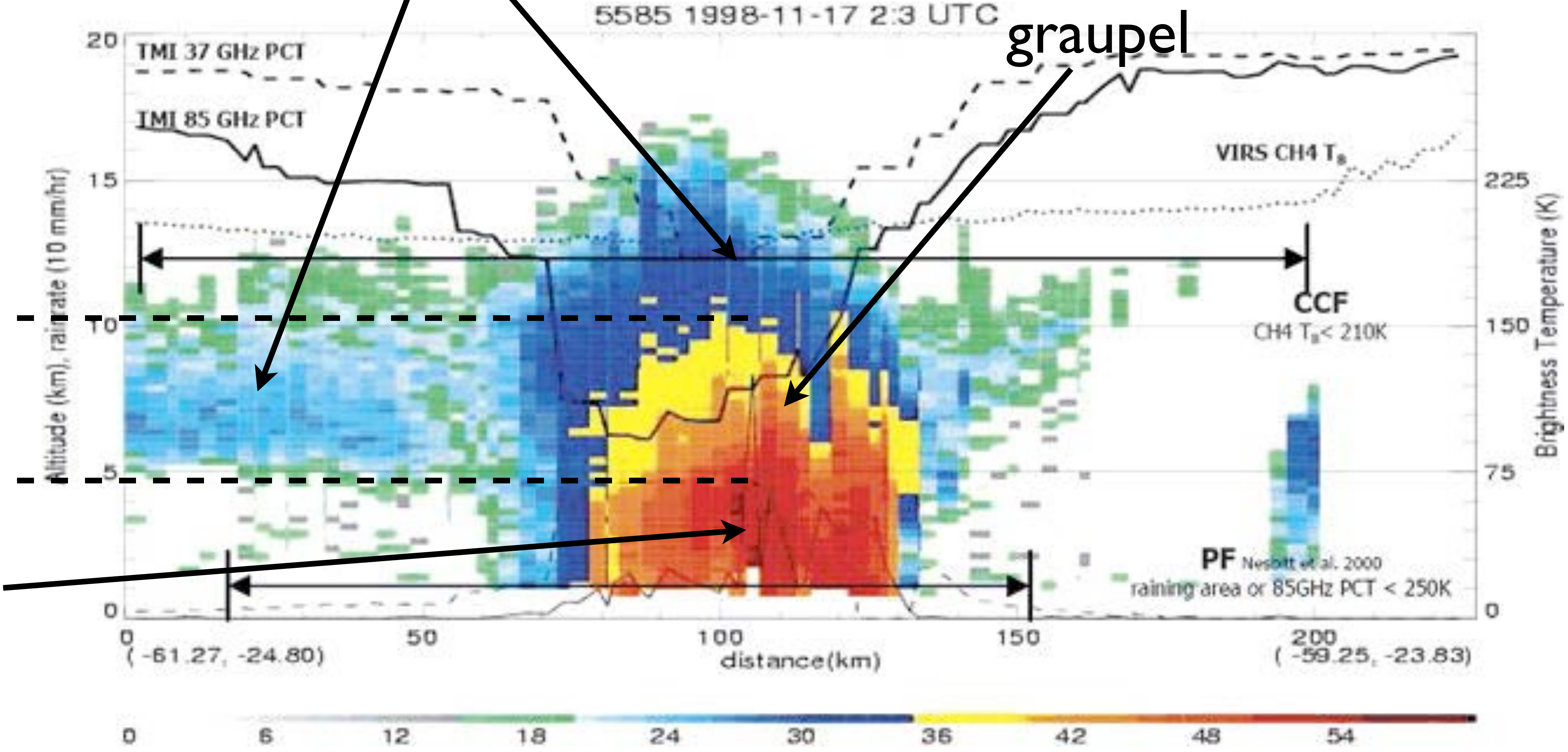




snow, ice

supercooled
water
droplets,
graupel

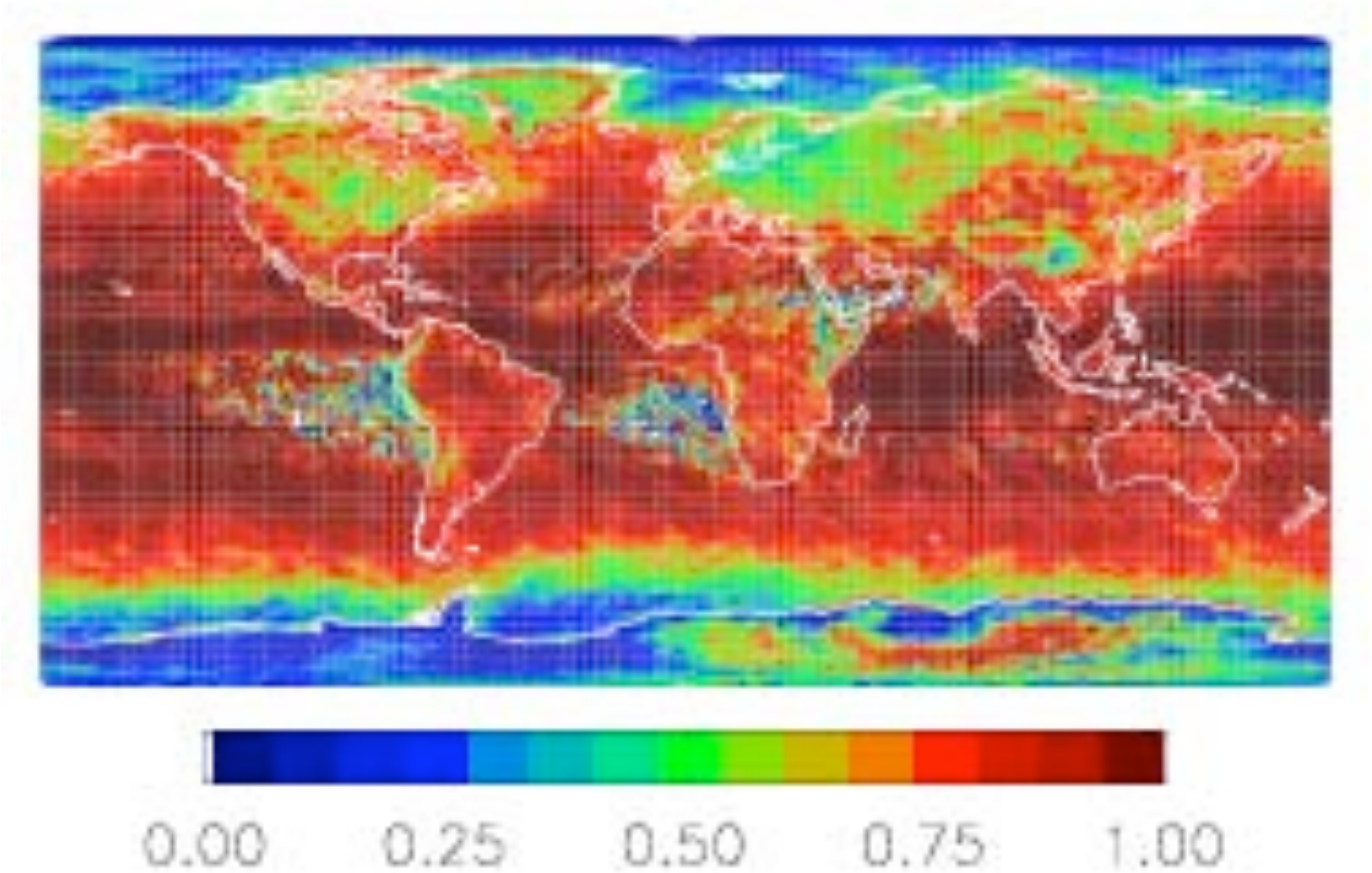
-40C

0C

Raindrops

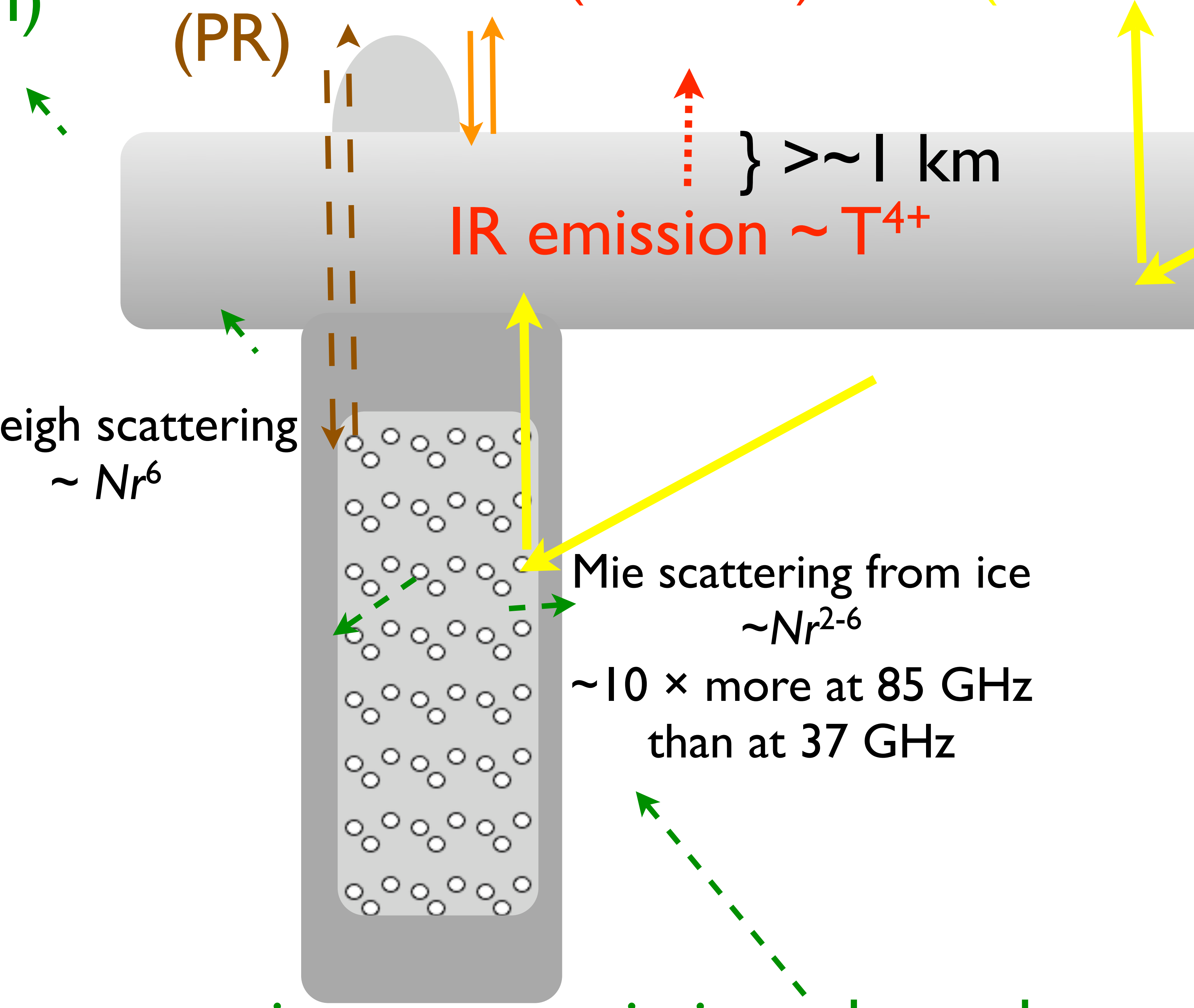
Liu et al 2007

Glaciated fraction of clouds with tops in the mixed-phase temperature range (0 to -40C) from MODIS.



Higher specific humidity, gentler storms --> cloud glaciates while still relatively warm.

Satellite observables (TRMM) -- how do they work?



(TMI)

radar (PR)

lidar

(VIRS IR)

(VIRS vis)

SUN

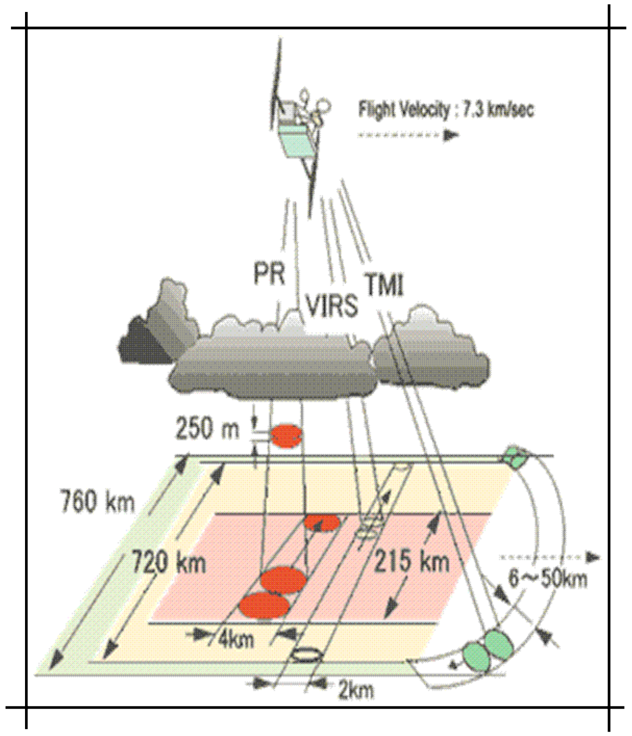
} >~1 km

IR emission ~ T^{4+}

Optical scattering ~ Nr^2

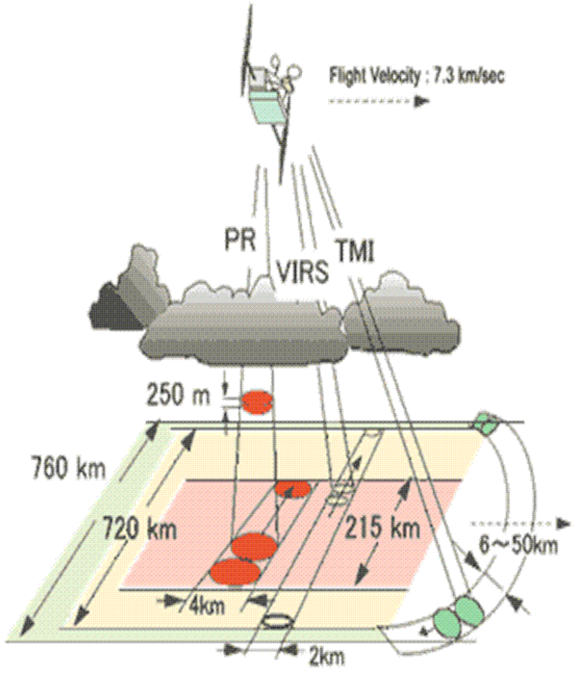
Rayleigh scattering ~ Nr^6

Mie scattering from ice ~Nr^{2-6}
~10 × more at 85 GHz than at 37 GHz

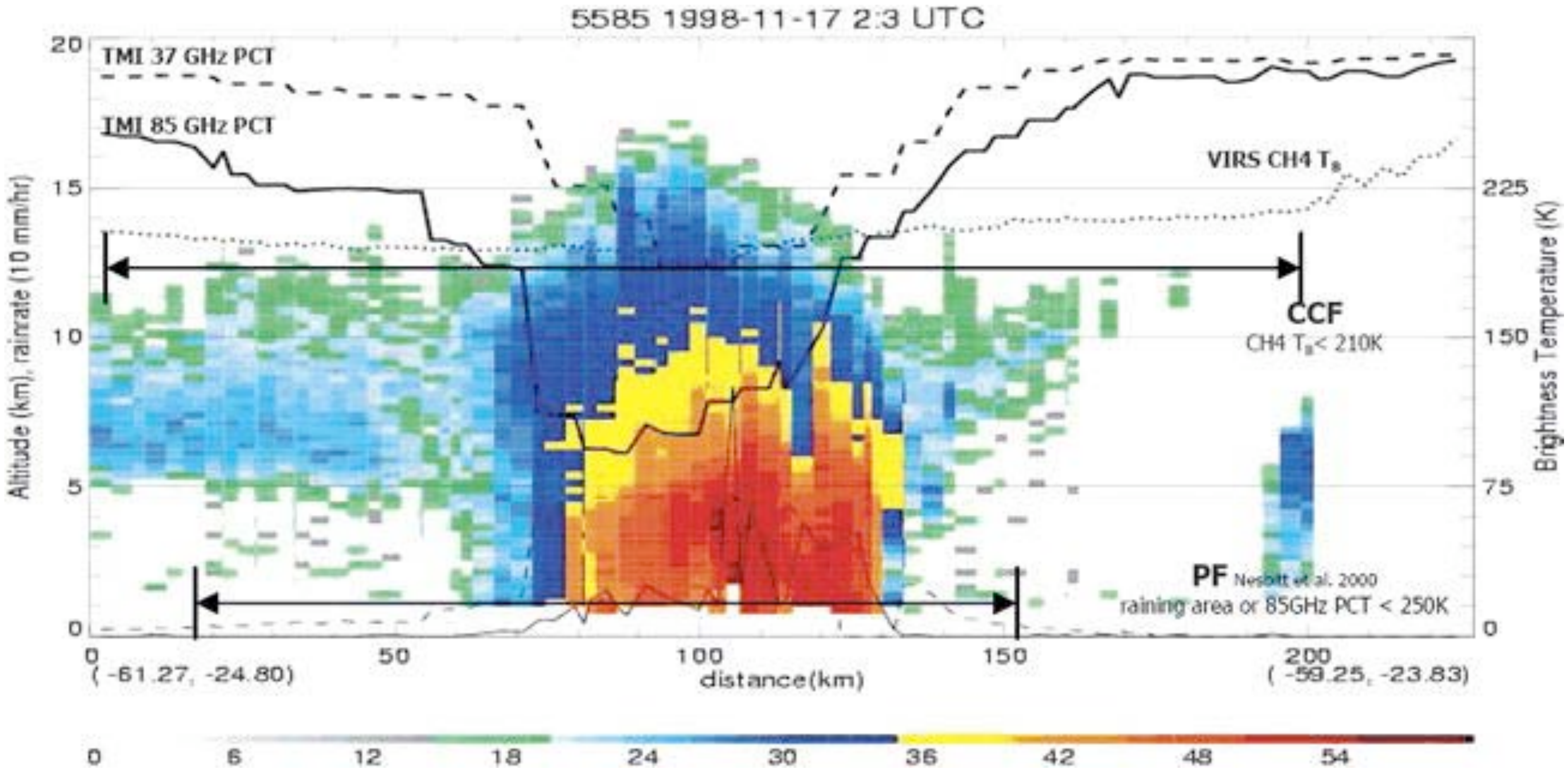


microwave emission--depends on surface, low-level cloud water

Multiple obs available from TRMM (Tropical Rainfall Measuring Mission satellite)

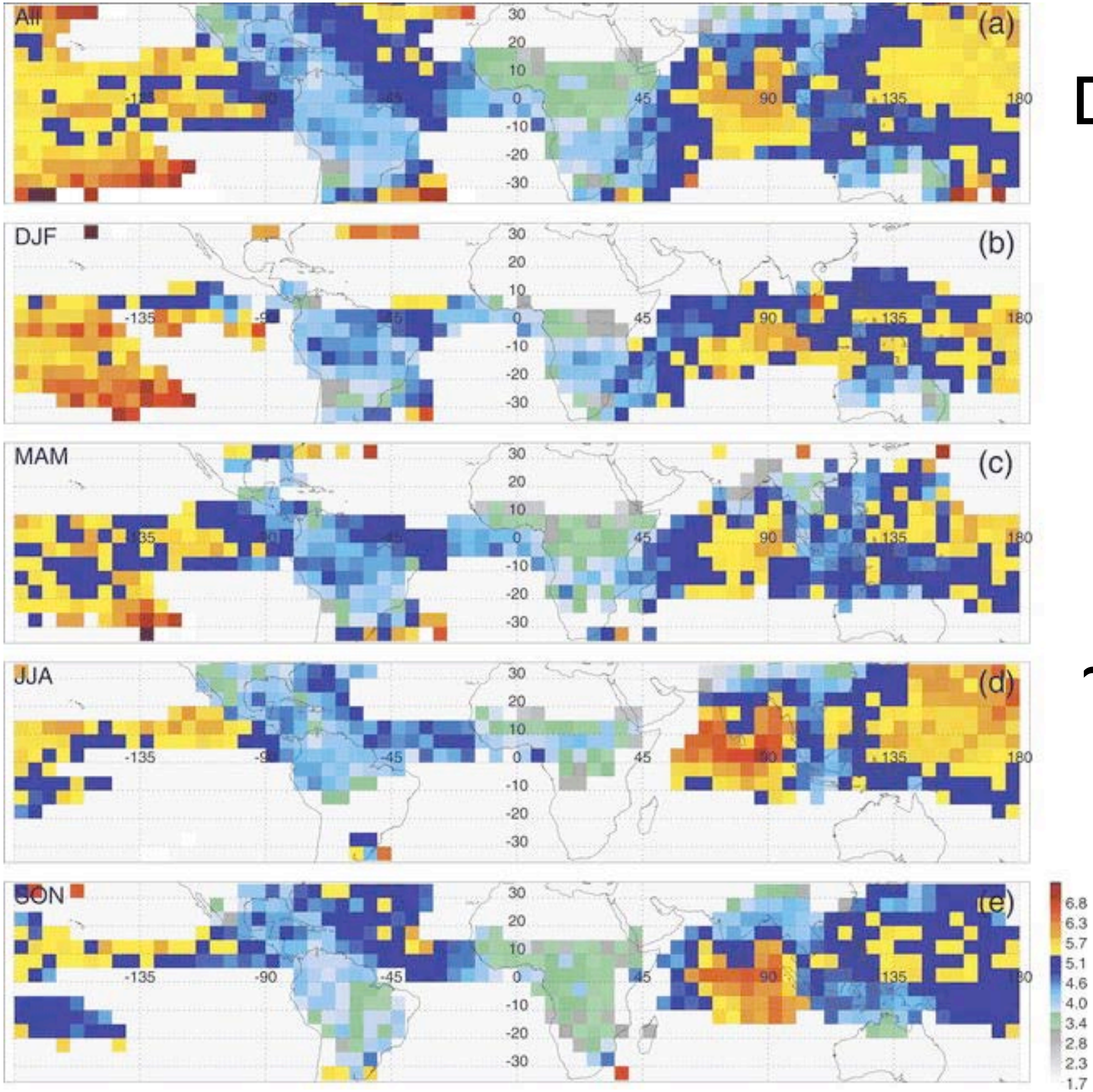


Also has lightning sensor (LIS)



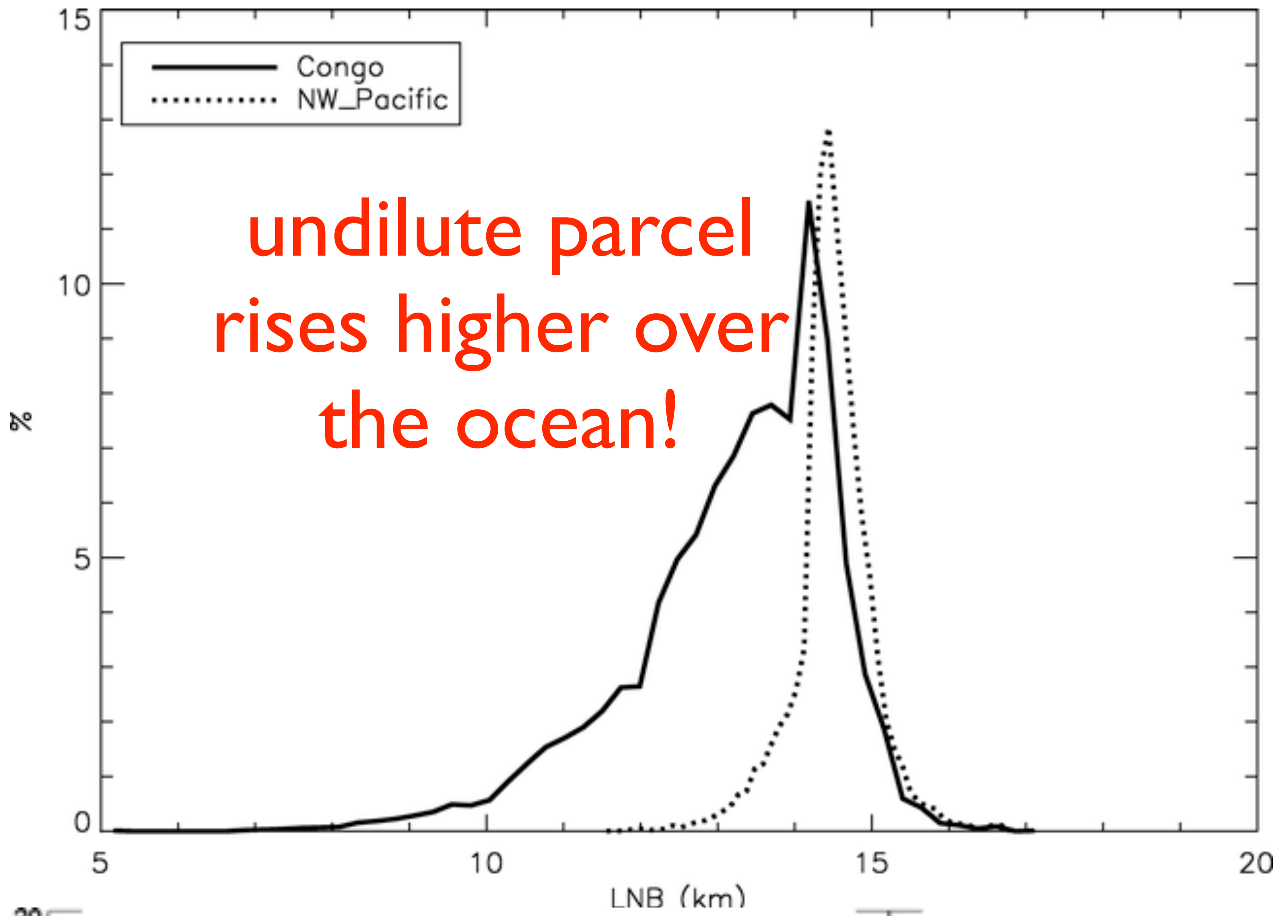
Difference between cloud-top and 20 dBZ radar echo heights in Cbs varies:

~2 km (Africa)
~4 km (S. America)
~6 km (oceans)



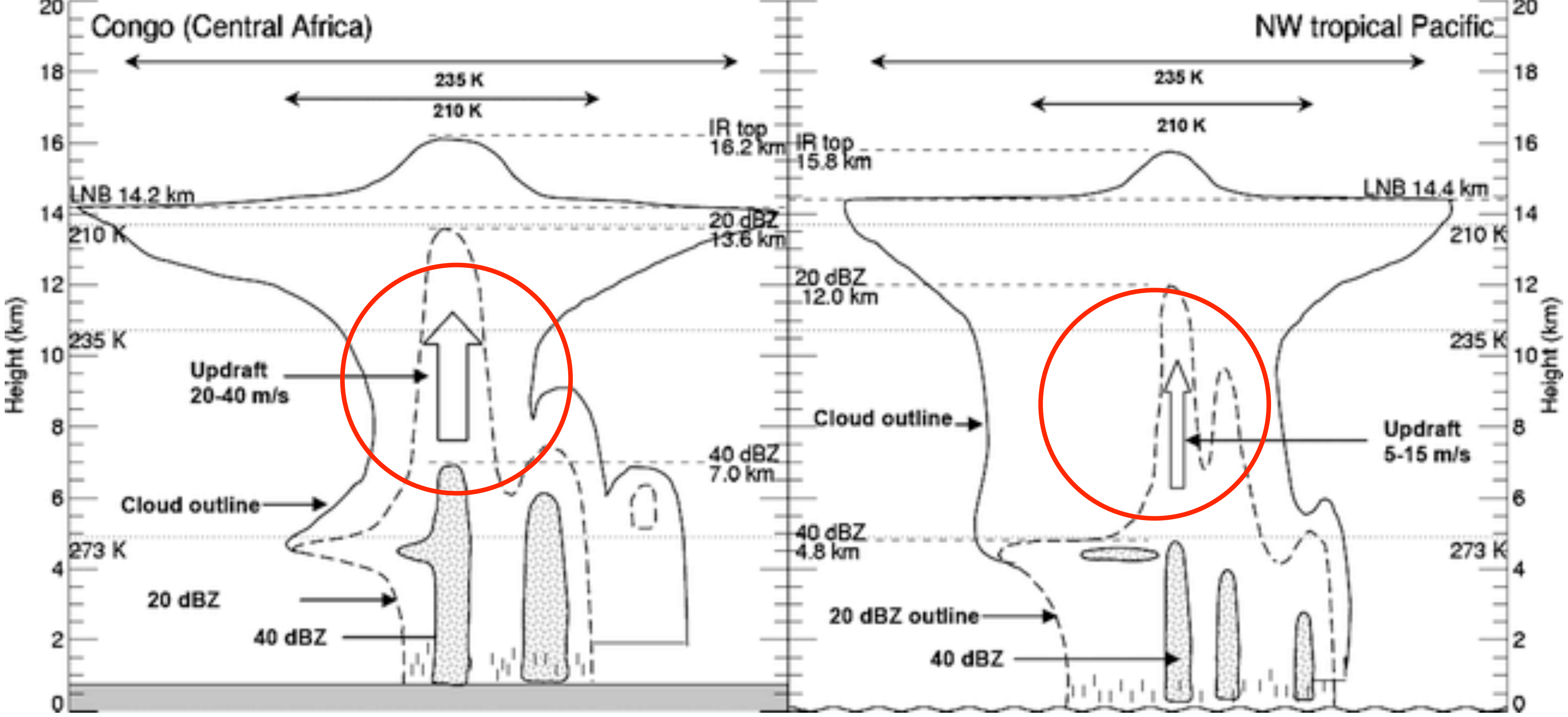
Liu et al 2007

African vs. maritime storms



undilute parcel rises higher over the ocean!

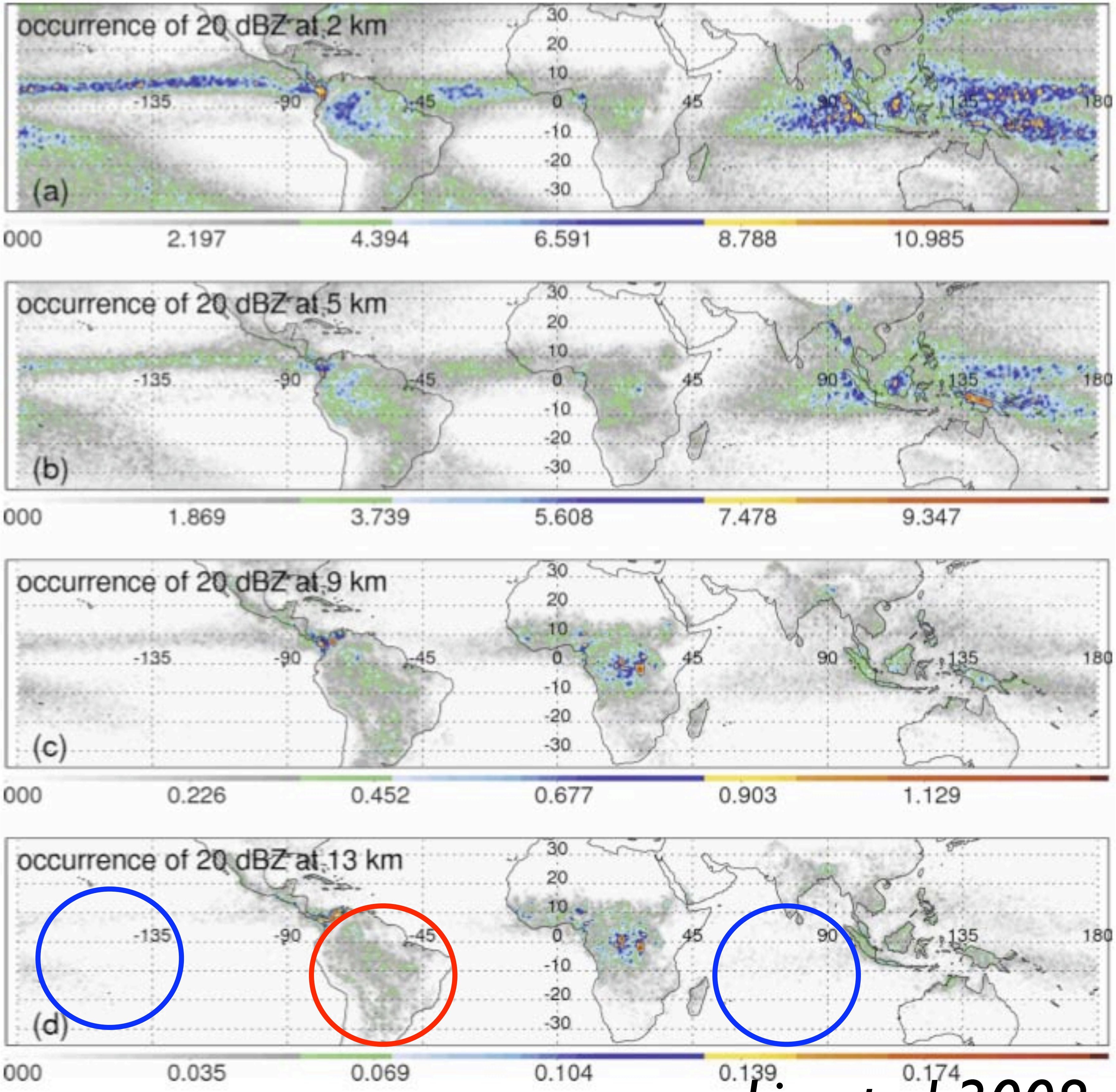
Liu et al. 2007



Schematic of the structure of deep convection (CCF with $T_{B11} \leq 210$ K) over Central Africa and the northwestern tropical Pacific, demonstrating differences between typical strong systems in the two regions.

Futyan and Del Genio 2009 added in METEOSAT data: Continental storms peak early and die more quickly.

TRMM radar echo (rain, graupel) at different heights



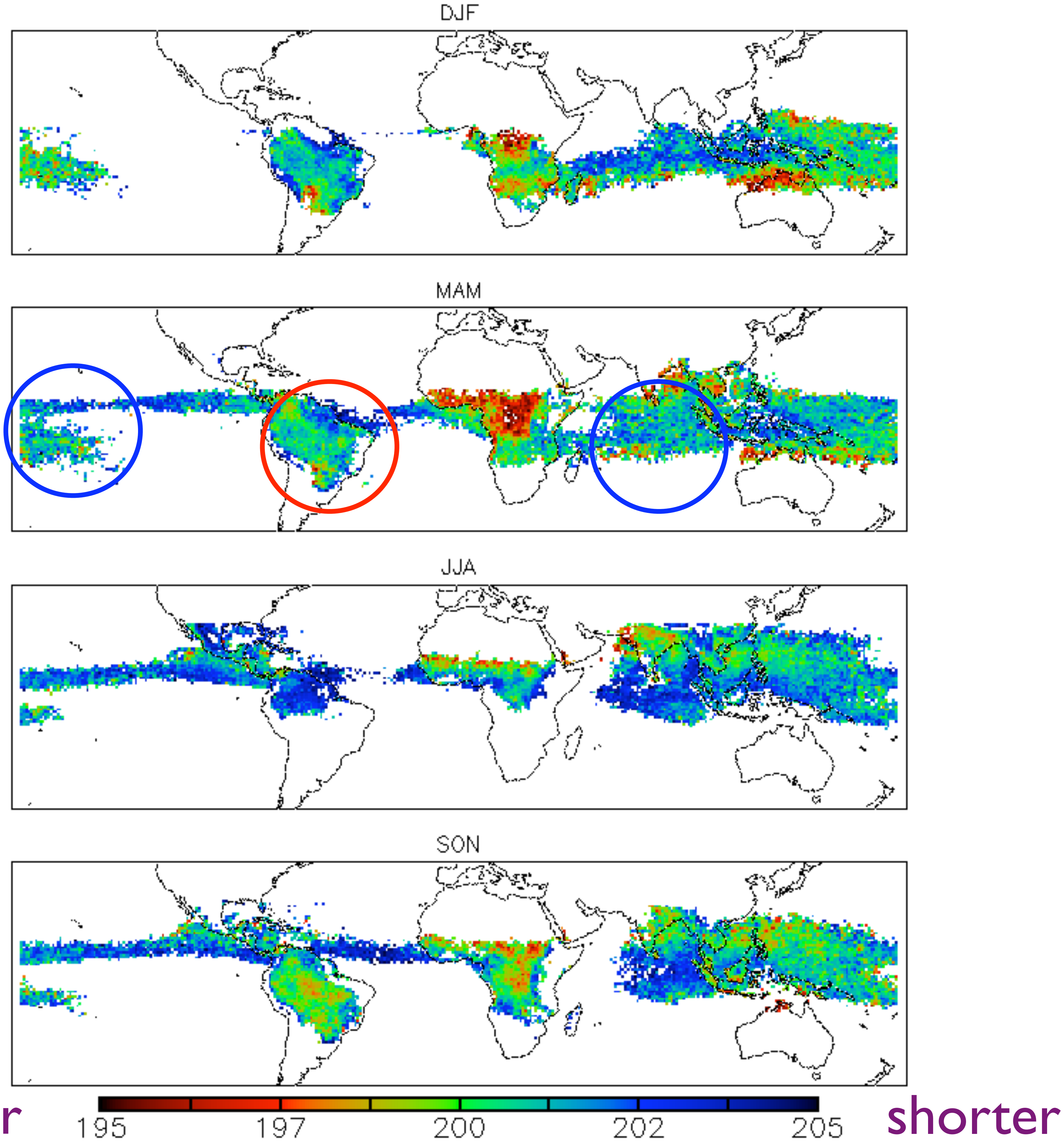
Low

High

Liu et al 2008

Cb height ($<T_{11}>$ when < 210 K)

from AVHRR climatology

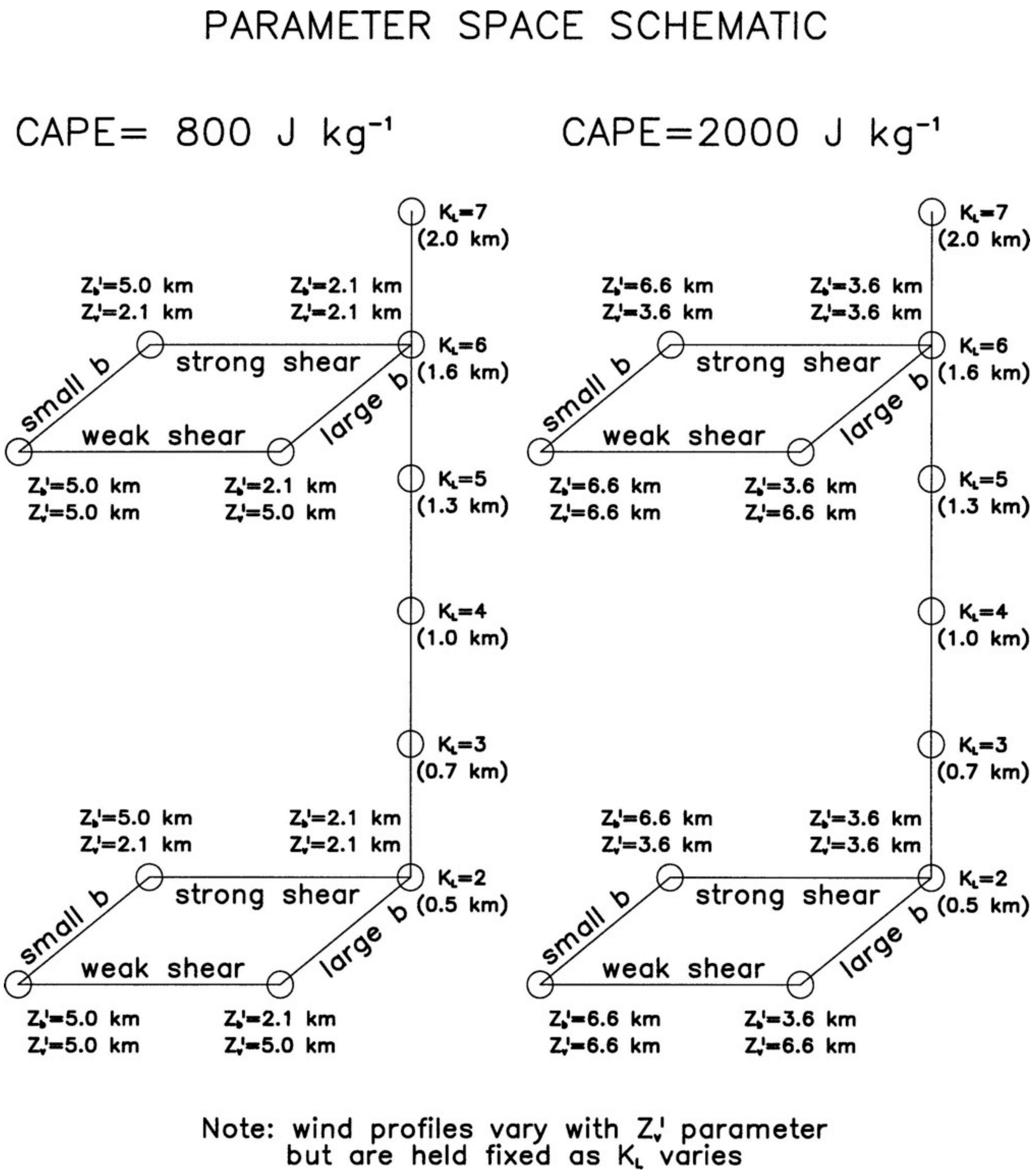


Factors overlooked in traditional parcel model

- Too little mixing/entrainment? Affected by width of cells or other factors?
- Microphysics/entrainment especially affected by buoyancy at low levels ("shape of the CAPE")?
- Heterogeneous forcing at surface?
- Aerosol influences on precipitation onset / freezing / unloading of condensed water?
- Dynamics of compensating subsidence?

Parameter space is daunting

- McCaul and Cohen (2002) consider variations in LFC, LCL, CAPE, wind hodograph, buoyancy shape.
- 3-D simulations
- All effect strength of storms (ideal: high CAPE, healthy shear, thick moist layer)



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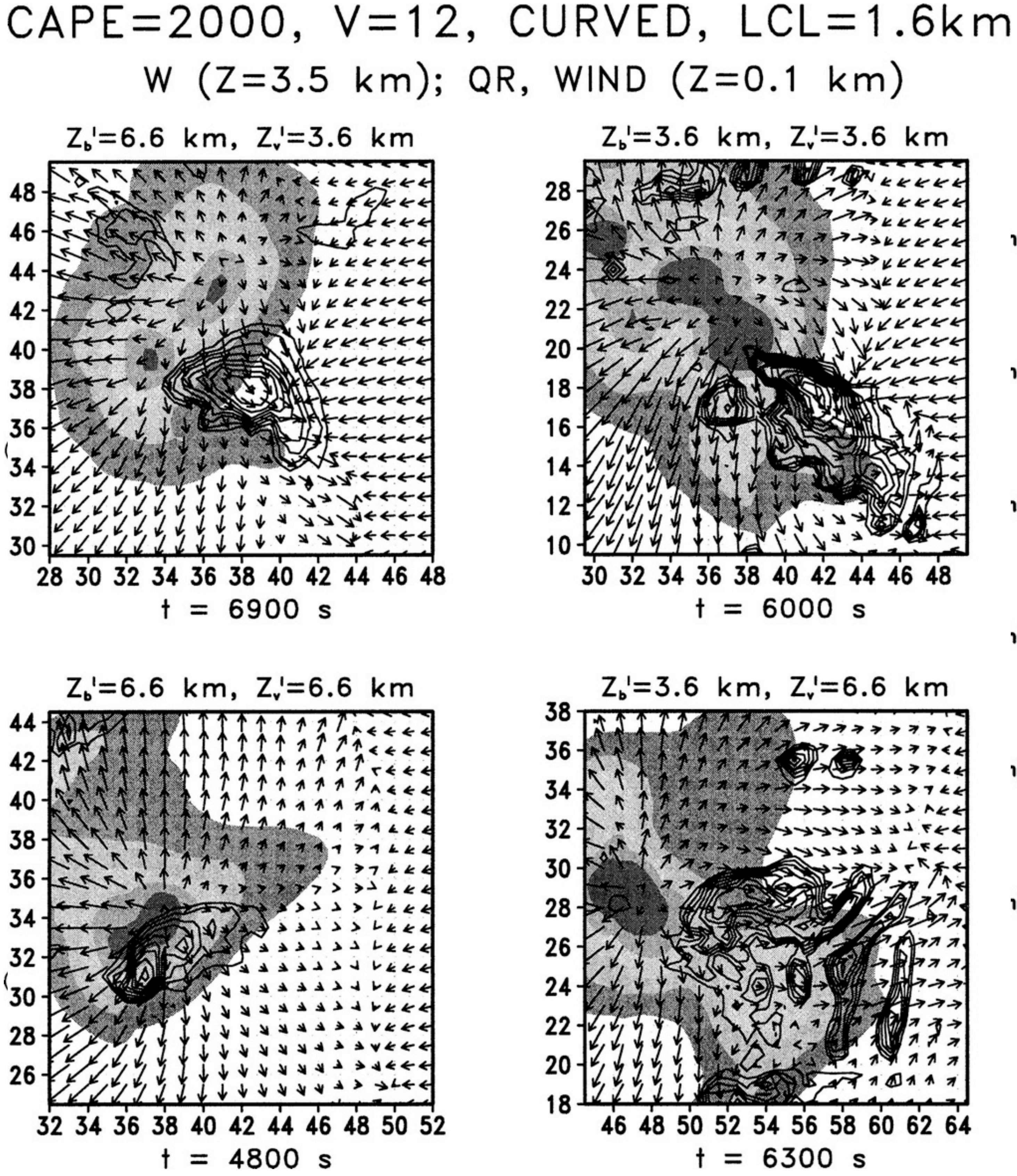

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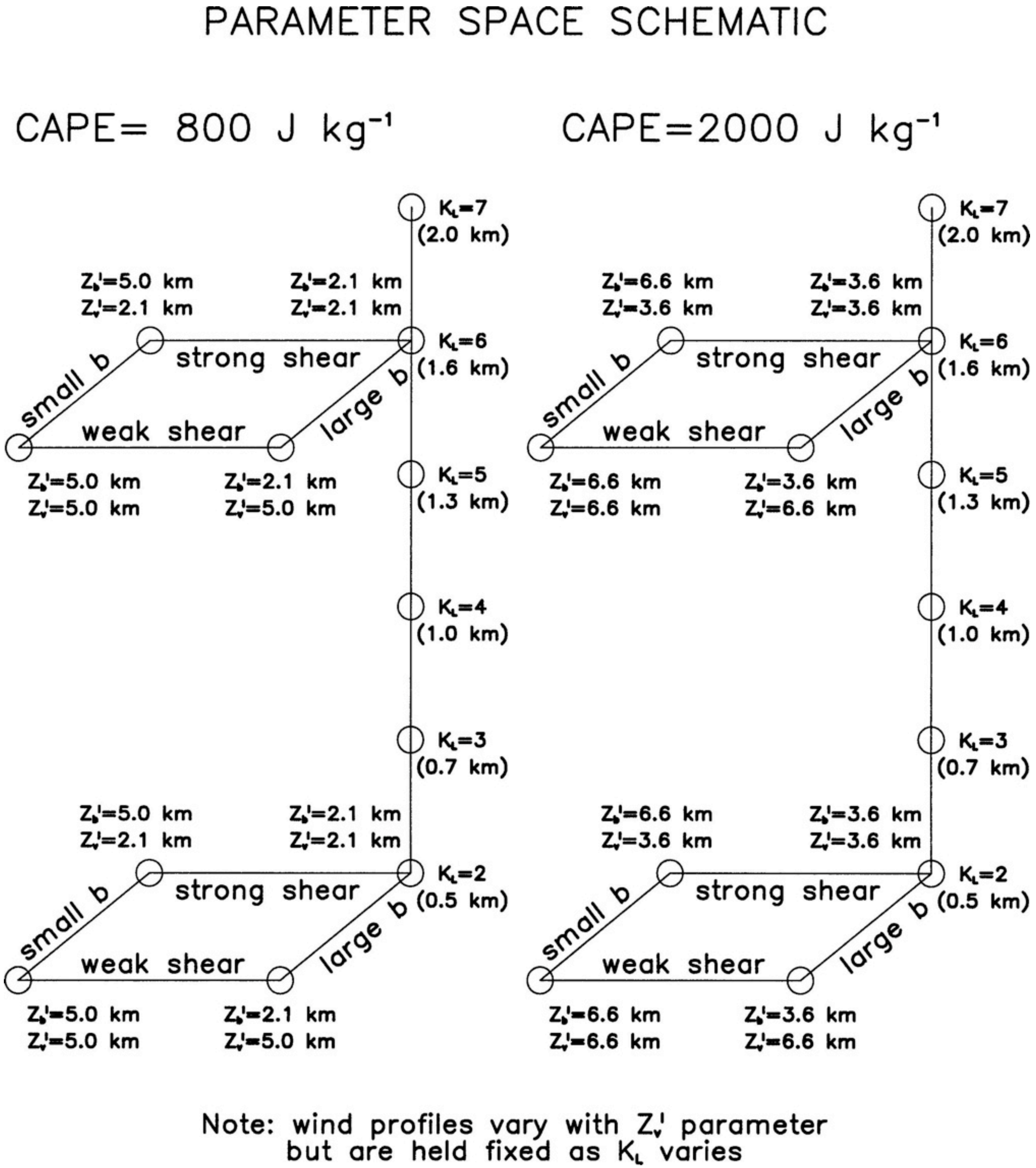
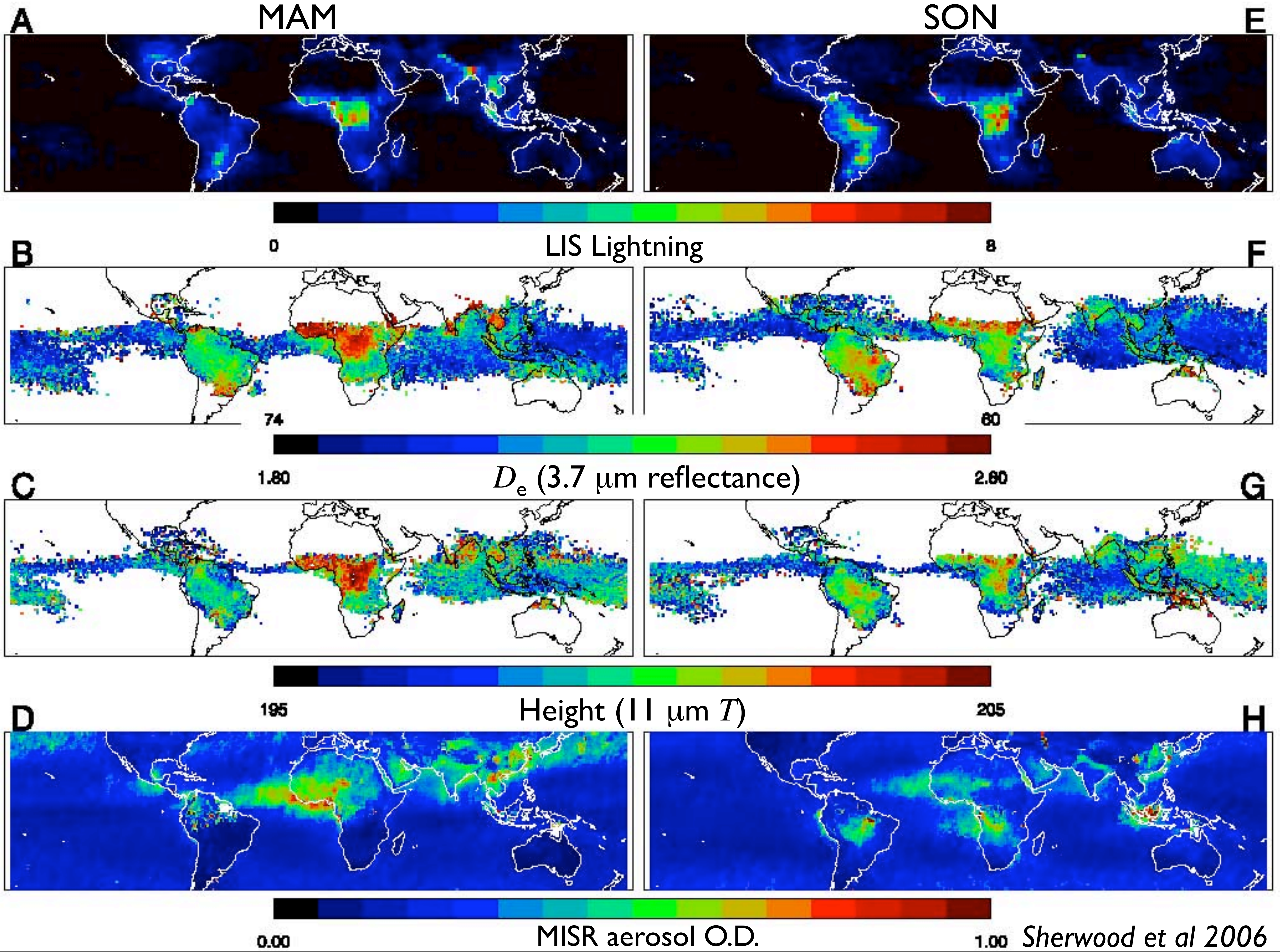




Sherwood et al 2006

Observational Evidence from electrification over islands

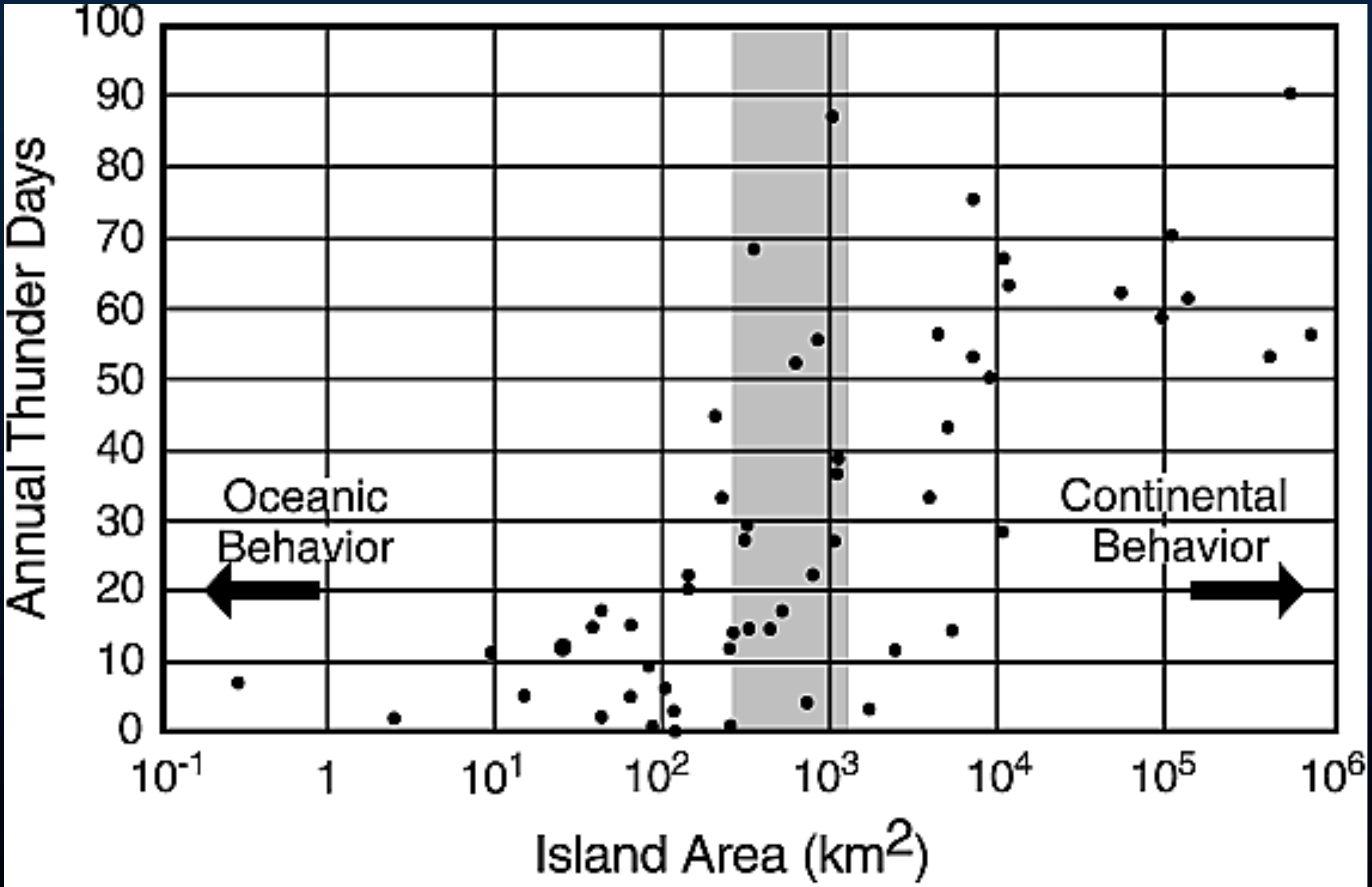


Figure taken from Williams et al., JGR, 2004

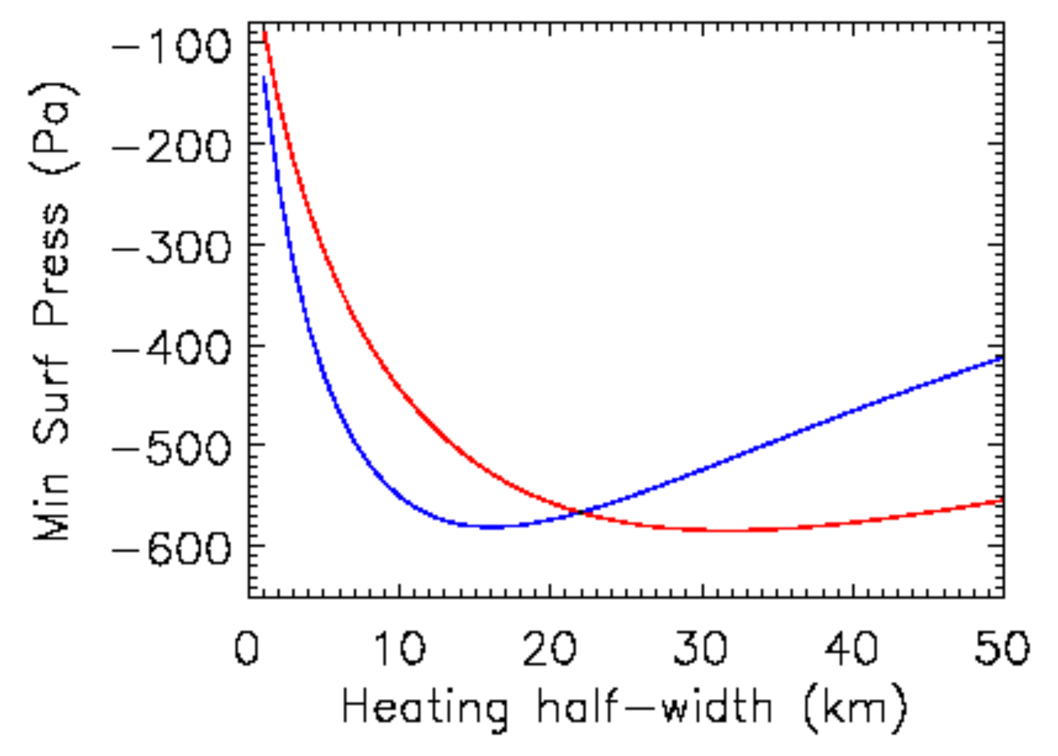
Heat low vs. forcing width: comparison of linear Boussinesq model and WRF 2-D CRM

$$\begin{aligned} u_t &= -p'_x - \alpha u \\ w_t &= -p'_z + b - \alpha w \\ b_t + N^2 w &= B - \alpha b \\ u_x + w_z &= 0 \end{aligned}$$

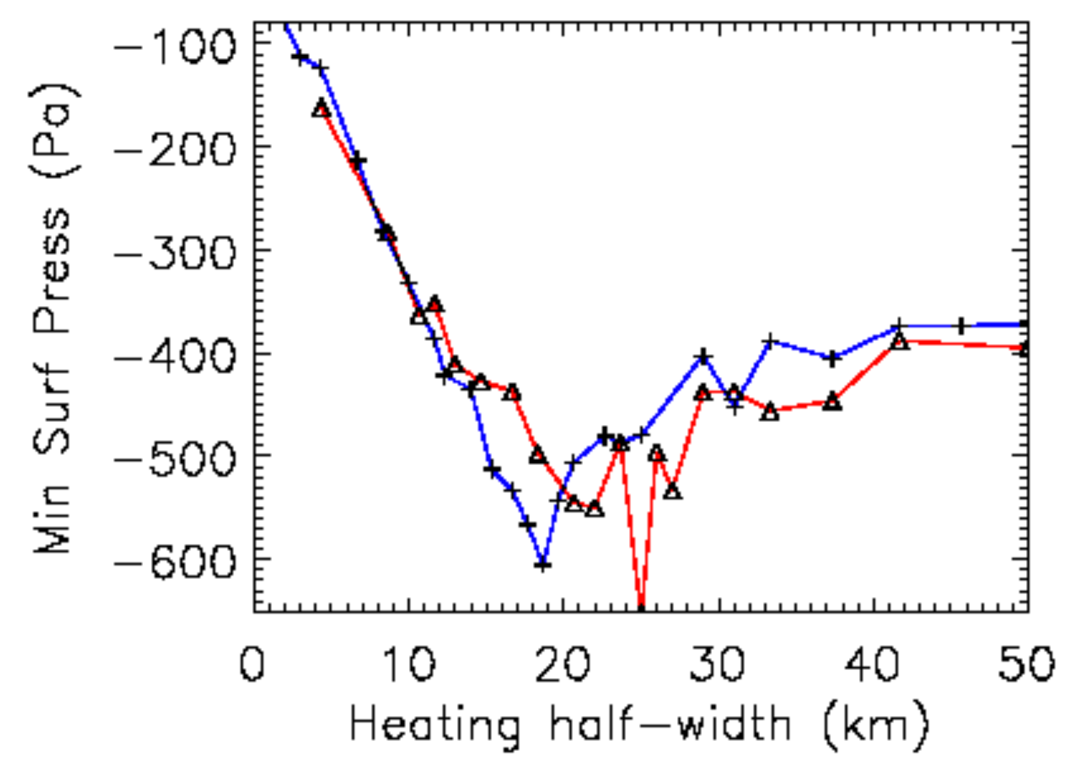
$$B = B_0 e^{-\frac{x^2}{a_0^2}} e^{-\frac{z}{H}} e^{i\left(\frac{t}{\tau}-\frac{\pi}{2}\right)}$$

Robinson, Sherwood and Li 2008

Linear model (dry)

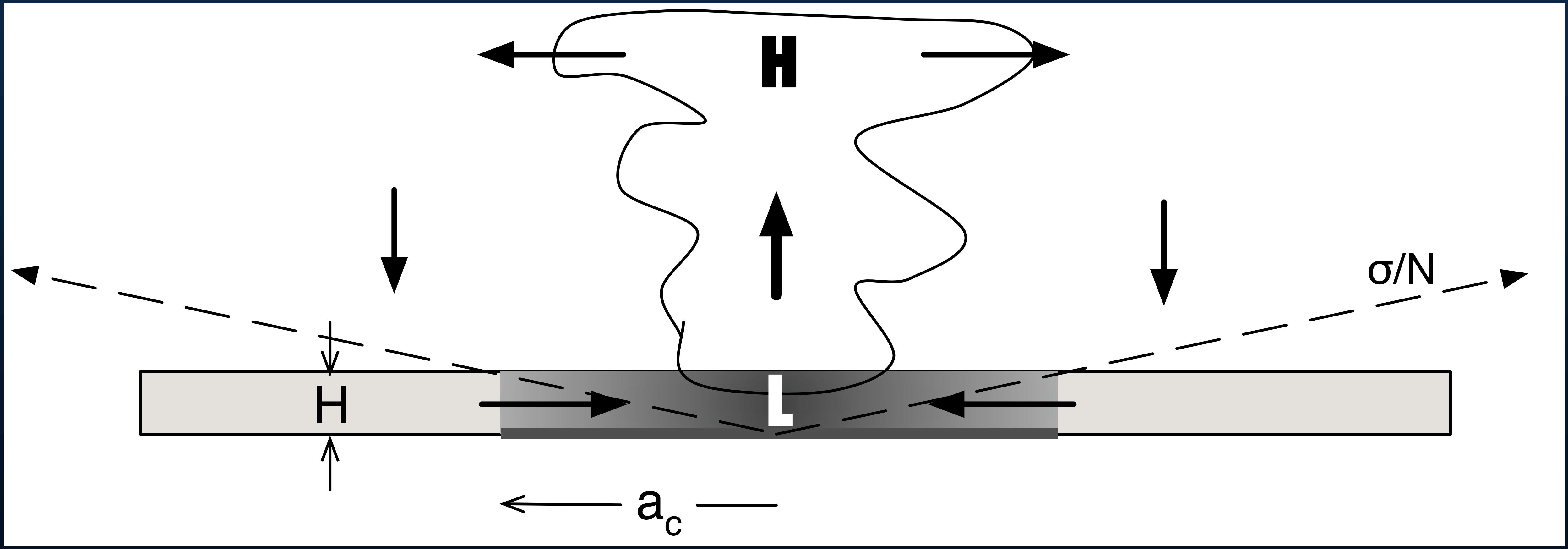


WRF (moist)



(+ similar behavior for w, cloud top height, etc.)

The mechanism



- Resonant response occurs when
  - $\sigma/N = H/L$ ($= k/m$)
  - horizontal dry phase speed × period = L
- Importance of waves not a new idea; see talk #3.

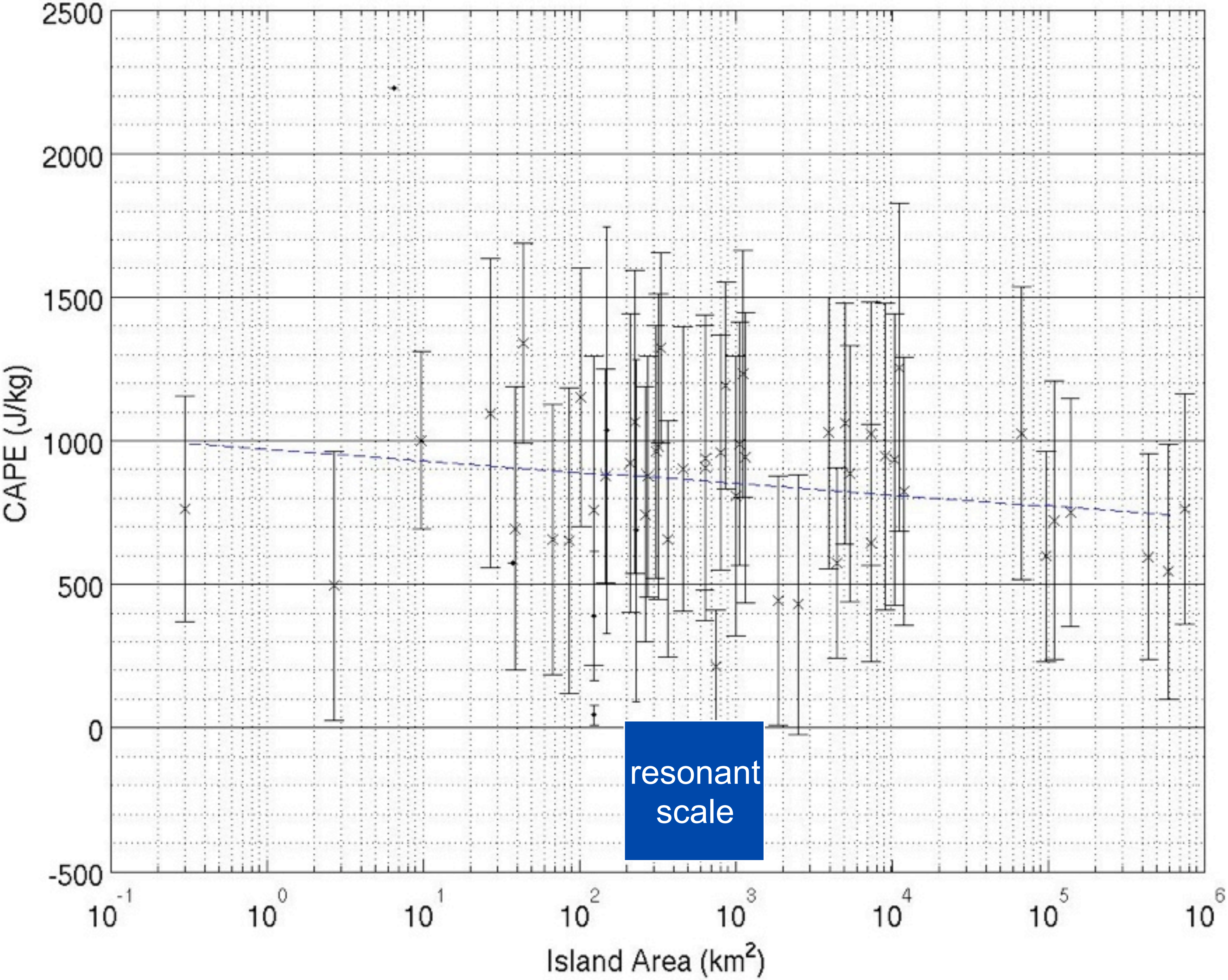
$$m^2 = \frac{k^2(N^2 - \sigma^2)}{\sigma^2} \approx (\frac{Nk}{\sigma})^2$$

Robinson, Sherwood and Li 2008

Comparing WRF and TRMM

- WRF simulations made more realistic:
  - Ice physics (tests --> use Morrison et al. scheme)
  - Uniform heating profile instead of Gaussian
  - Heating by Q-flux (peak of 300 W/m^2) instead of dT
  - New version of WRF model 3.0.1.1
- SDSU TRMM simulator
  - simulates TRMM obs (except LIS) based on model water/ice content (microwave from Kummerow 1993; radar from Masunaga and Kummerow 2005)
  - http://precip.hyarc.nagoya-u.ac.jp/sdsu/sdsu-main.html

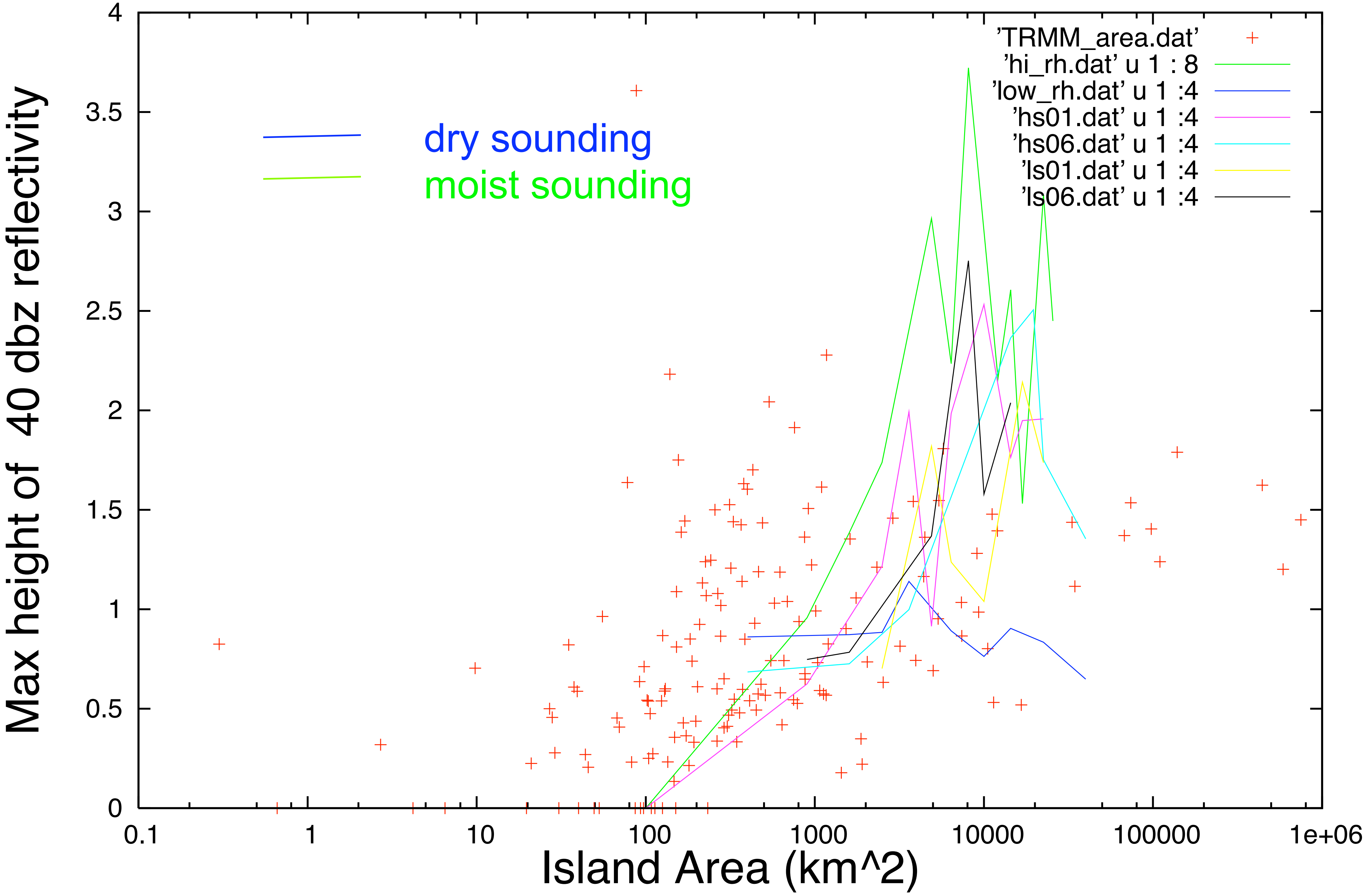
CAPE vs. island size



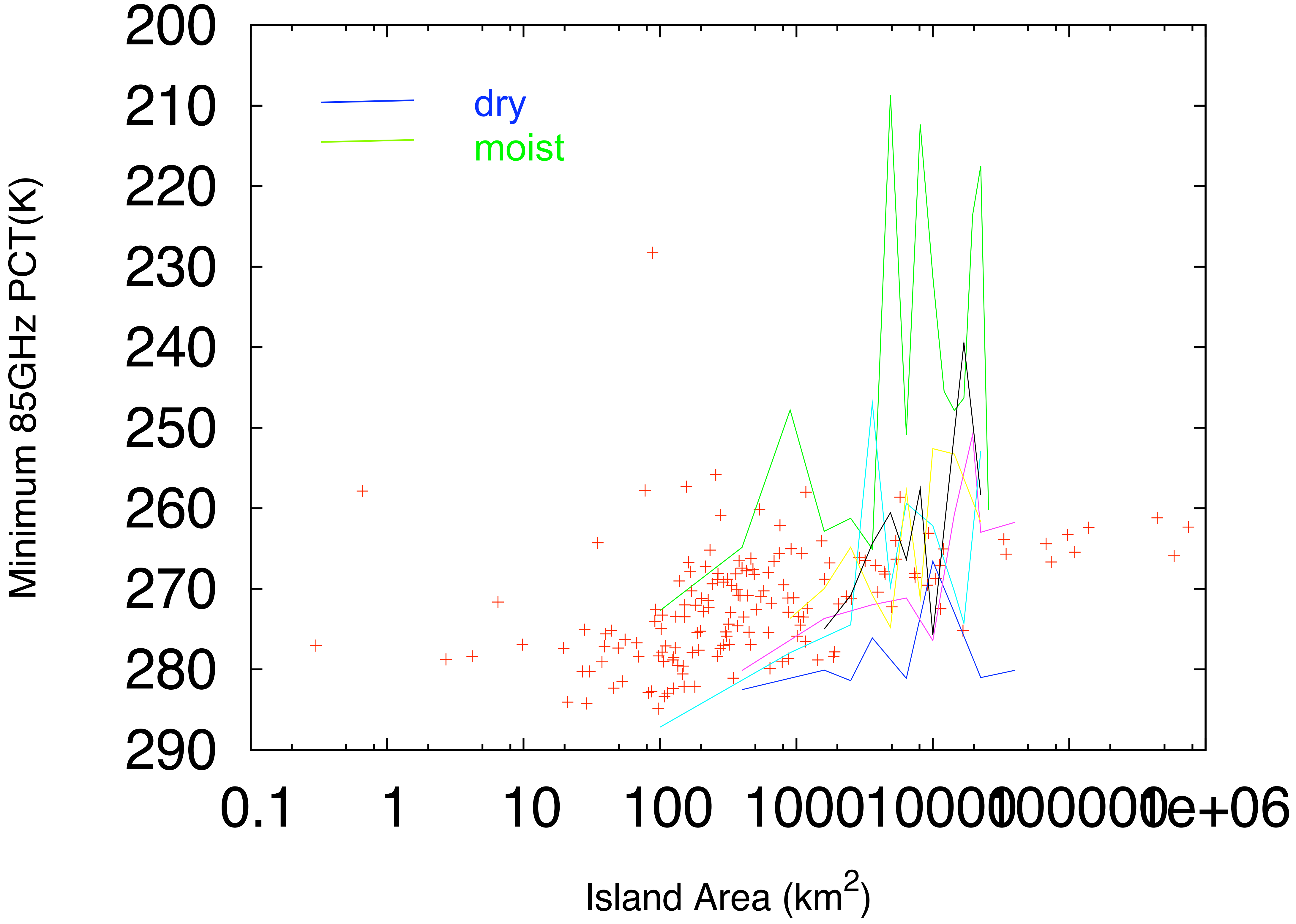
resonant
scale

Radar vs. island size (TRMM vs. WRF)

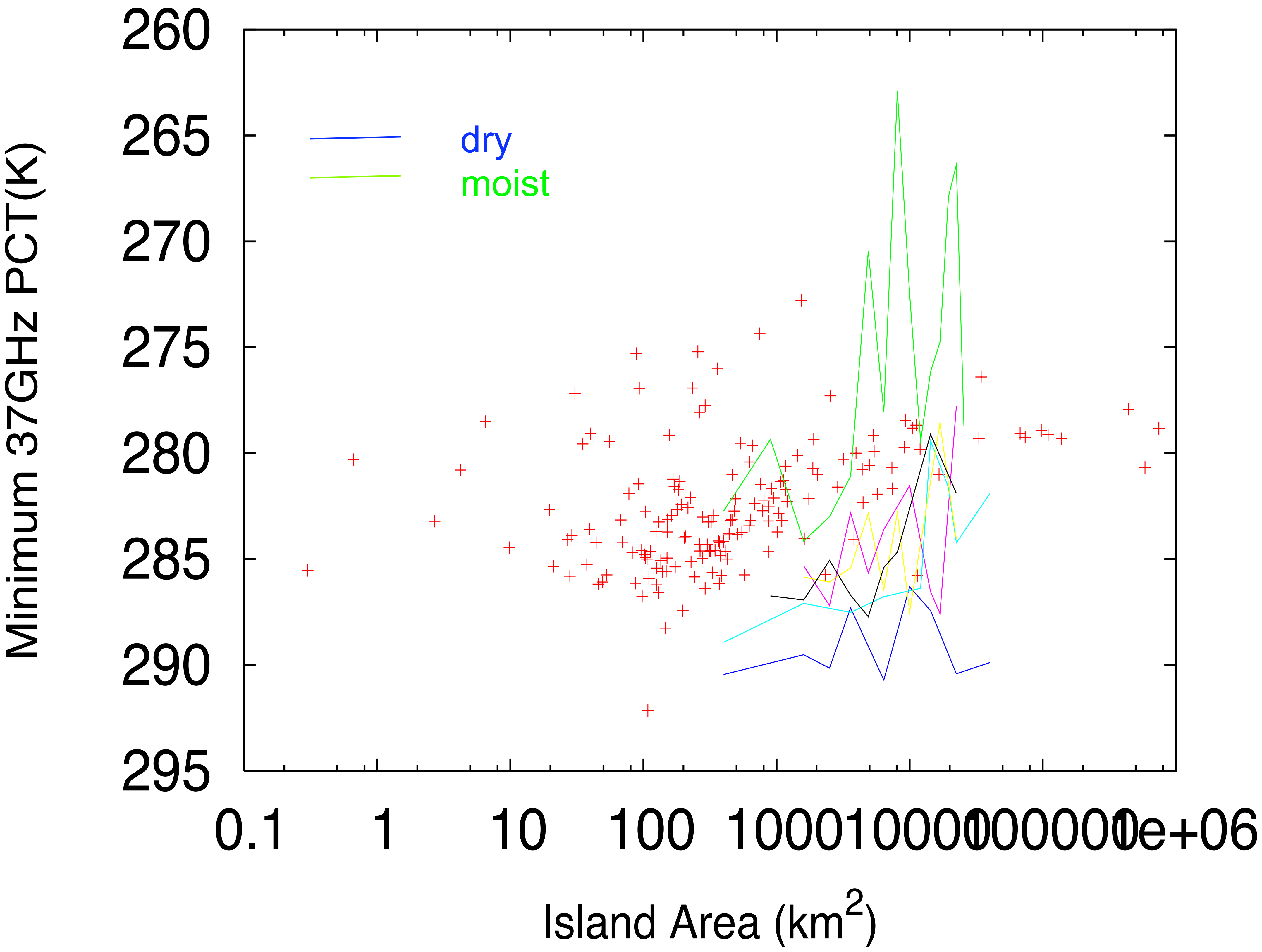
Convective Intensity



TMI 85 GHz vs. island size
(TRMM vs. WRF)



TMI 37 GHz vs. island size
(TRMM vs. WRF)



Other studies examining systematic changes in convection with environment

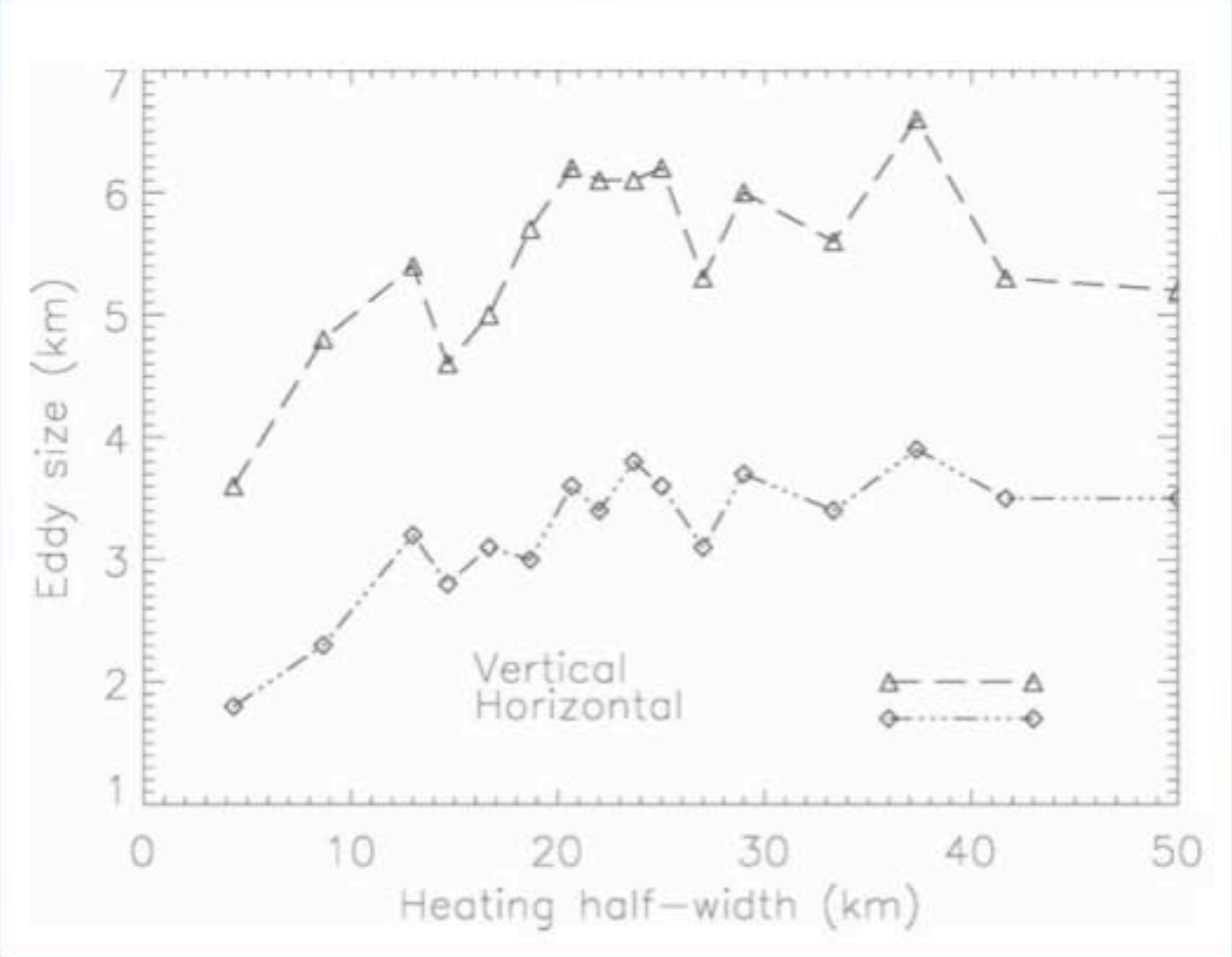
- Wu et al. (2009) find that WRF reproduces active vs. break-monsoon period differences in convection in Darwin region. SCM (parameterization) does not.
- Jensen and Del Genio (2006): entrainment rate determined by CAPE
- Indirectly, wave-mean flow interaction studies (discussed in lecture III)

Some conclusions

- Continental storms much more intense but end quickly.
- Parcel theory a great start, but fails to explain interesting and potentially important trends in storm characteristics.
- Relative humidity must be high through a thick layer (well above mixed layer) for storms to deepen in low-shear environments. Helps intensity too, though role in high shear more complicated.
- Mesoscale gravity-wave and cold-pool/breeze front dynamics are crucial to triggering/location, and possibly even intensity of storms. Land heterogeneity interacts with these to produce stronger storms.
- Powerful new simulation and observational techniques are now available and should (will) be better exploited.

- Draft review paper on tropospheric water vapour and convection is available on my web site. Topics:
    - Review of instrumentation
    - Influence of water vapour on convection
    - Theory of relative humidity regulation
    - Observations of recent trends
    - Some impacts of humidity

3. Updraft *widths*

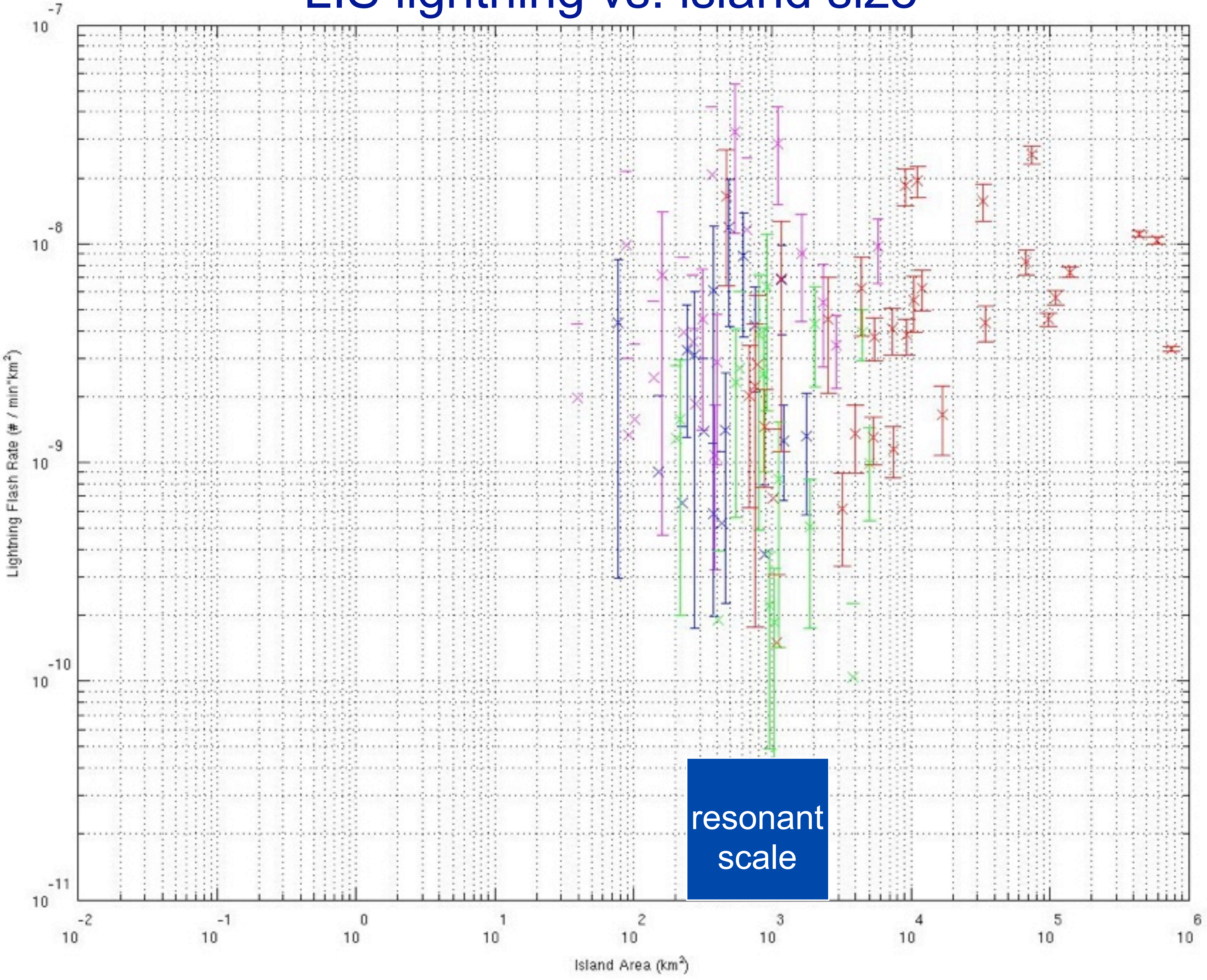


Updrafts are fatter for broader heating despite NO DIFFERENCE in boundary-layer thickness....so width not controlled purely by vertical scale!

Robinson, Sherwood and Li 2008

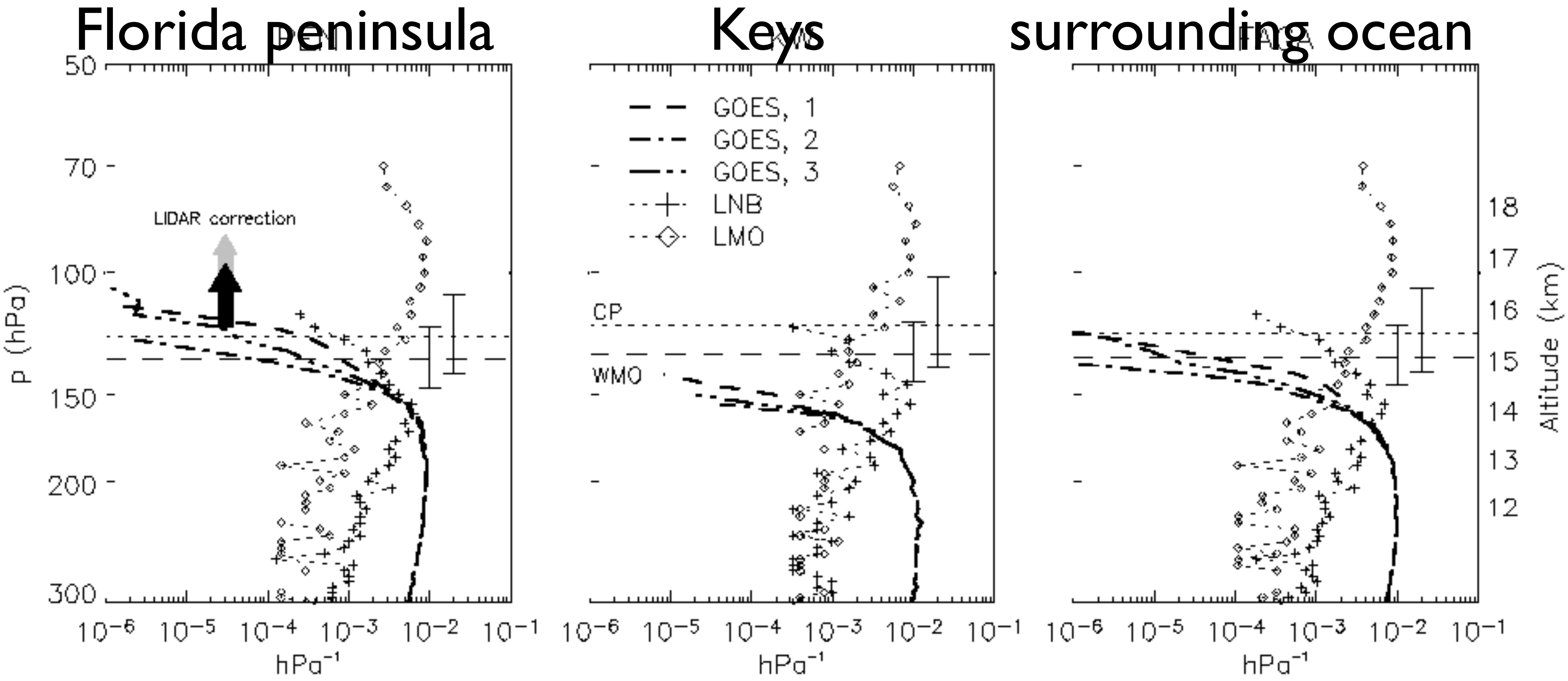
LIS lightning vs. island size

lightning flash rate



resonant scale

LNB, CAPE, humidity, tropopause all useless in explaining regional differences in Florida region mean cloud-top heights☹



Florida peninsula Keys surrounding ocean

Sherwood et al. 2004