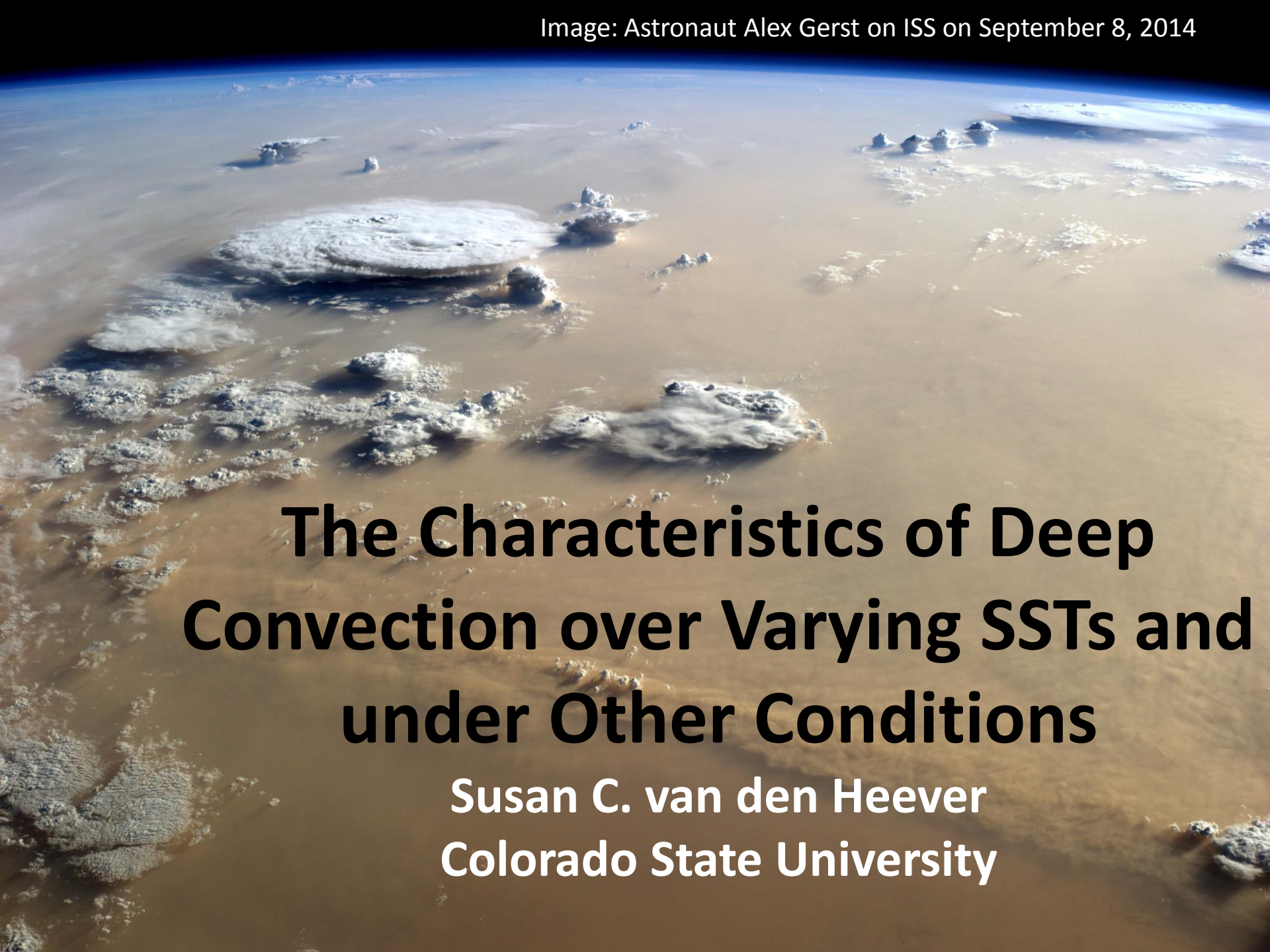


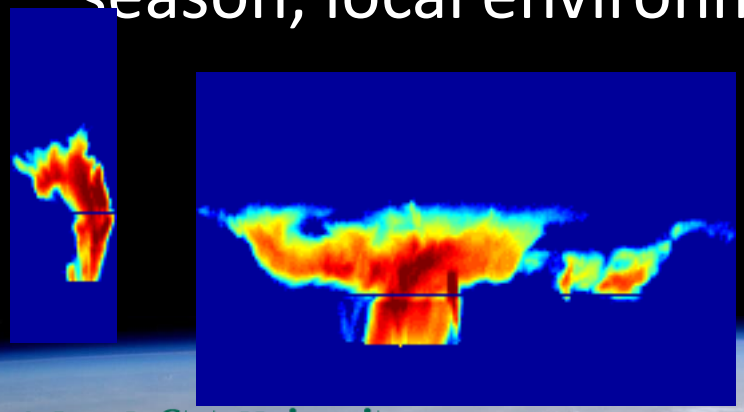
Image: Astronaut Alex Gerst on ISS on September 8, 2014

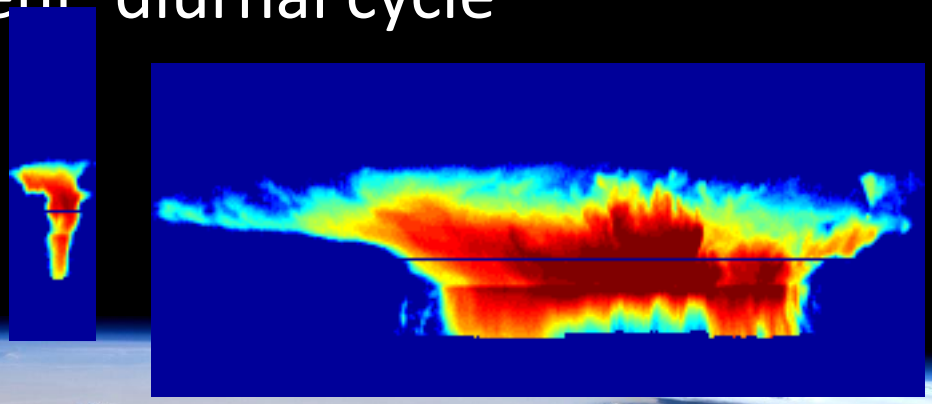
The Characteristics of Deep Convection over Varying SSTs and under Other Conditions

Susan C. van den Heever
Colorado State University

Introduction

- Convective clouds => wide range of length and temporal scales (depth, width, height, lifetime)
- Length scales play fundamental role in the way that clouds interact with LW and SW, as well as in aspects such as their precipitation efficiency, latent heating etc
- Fundamental impacts of clouds on climate cannot be understood without understanding their length scales (Bony 2006) and how they vary as a function of region, season, local environment, diurnal cycle





Goals

- Enhance our understanding of:

1. the impacts of various environmental factors on the horizontal and vertical length scales of deep tropical convection
2. how and why length scales vary regionally
3. convective anvil dynamical-microphysical feedbacks

Today: some results, some ideas and some demonstrations of CRM capabilities with a view to future PROES collaborations

Smorgasbord of Topics

1. Bulk Characteristics of Deep Tropical Convection as Understood using RCE CRM Simulations
2. Bulk Tropical Deep Convection Characteristics from CloudSat
3. Environmental Impacts on Tropical Deep Convection
4. New Cirrus (Anvil or Otherwise) Formation
5. Impacts of Low and Mid Tropospheric Air on Anvil Characteristics

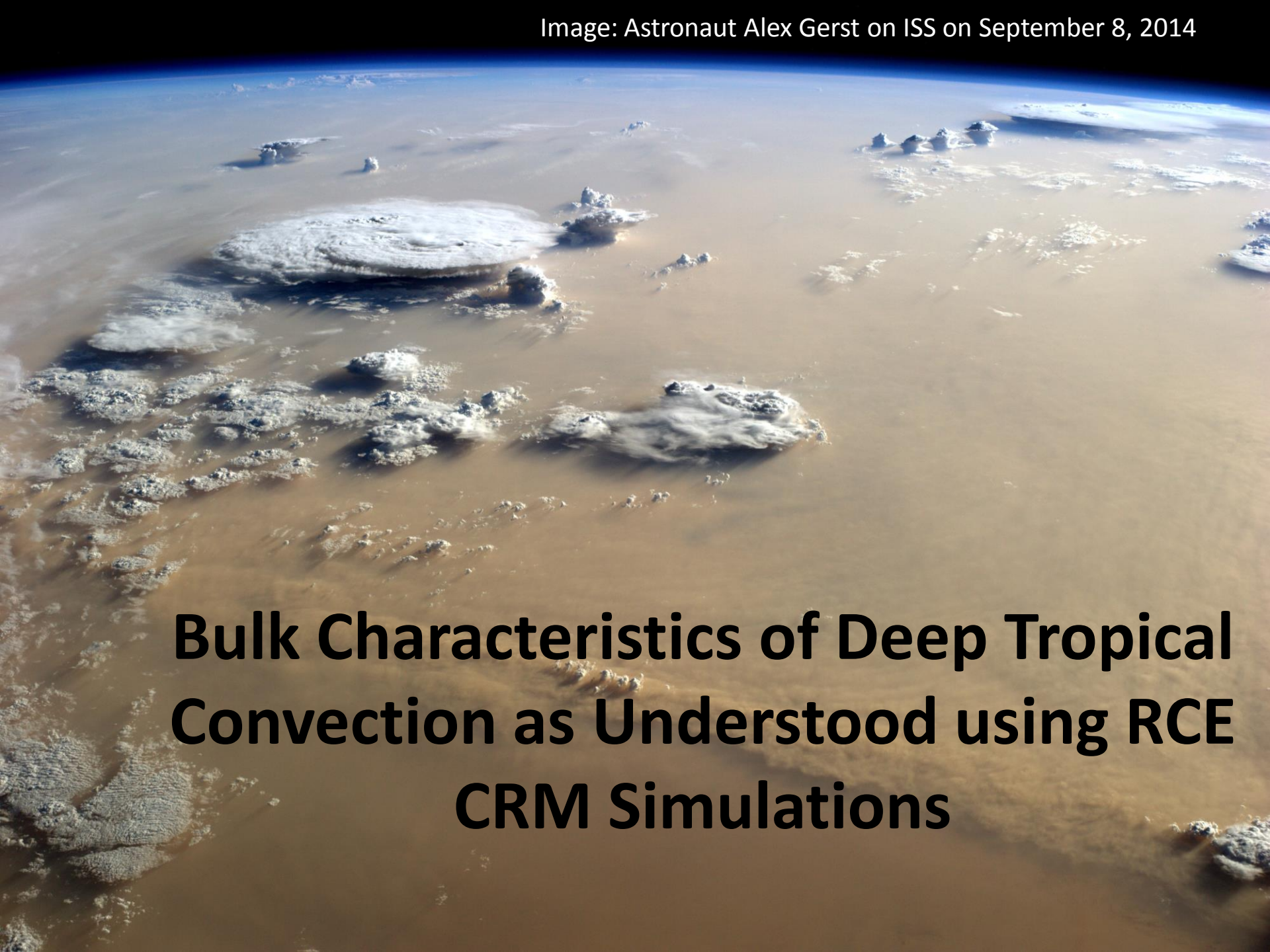


Image: Astronaut Alex Gerst on ISS on September 8, 2014

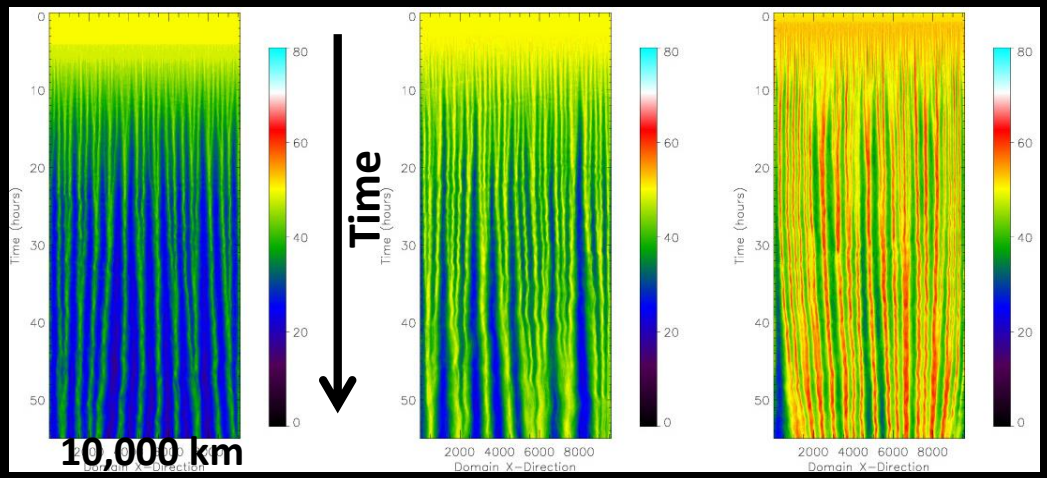
Bulk Characteristics of Deep Tropical Convection as Understood using RCE CRM Simulations

RCE CRM Simulations

- Duration: 50-100 days
- Grid spacing:
  - Δx= Δy=2.4km
  - Δz variable, up to 1km
- Constant (non-interactive) SSTs
- No convective parameterization
- Zero mean wind
- Perturbations to potential temperature
- Fixed solar zenith angle of 50° => daily insolation of 447.2 Wm^{-2} (~mean annual insolation at the equator)
- Self sustained moist and dry bands

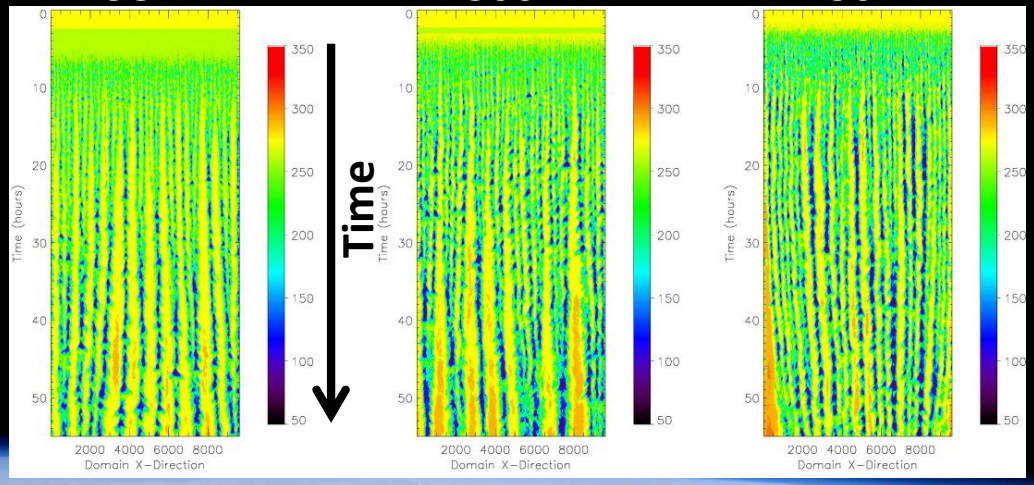
Domain Mean PW

298K 300K 302K



Domain Mean TOA OLR

298K 300K 302K



RCE Simulations

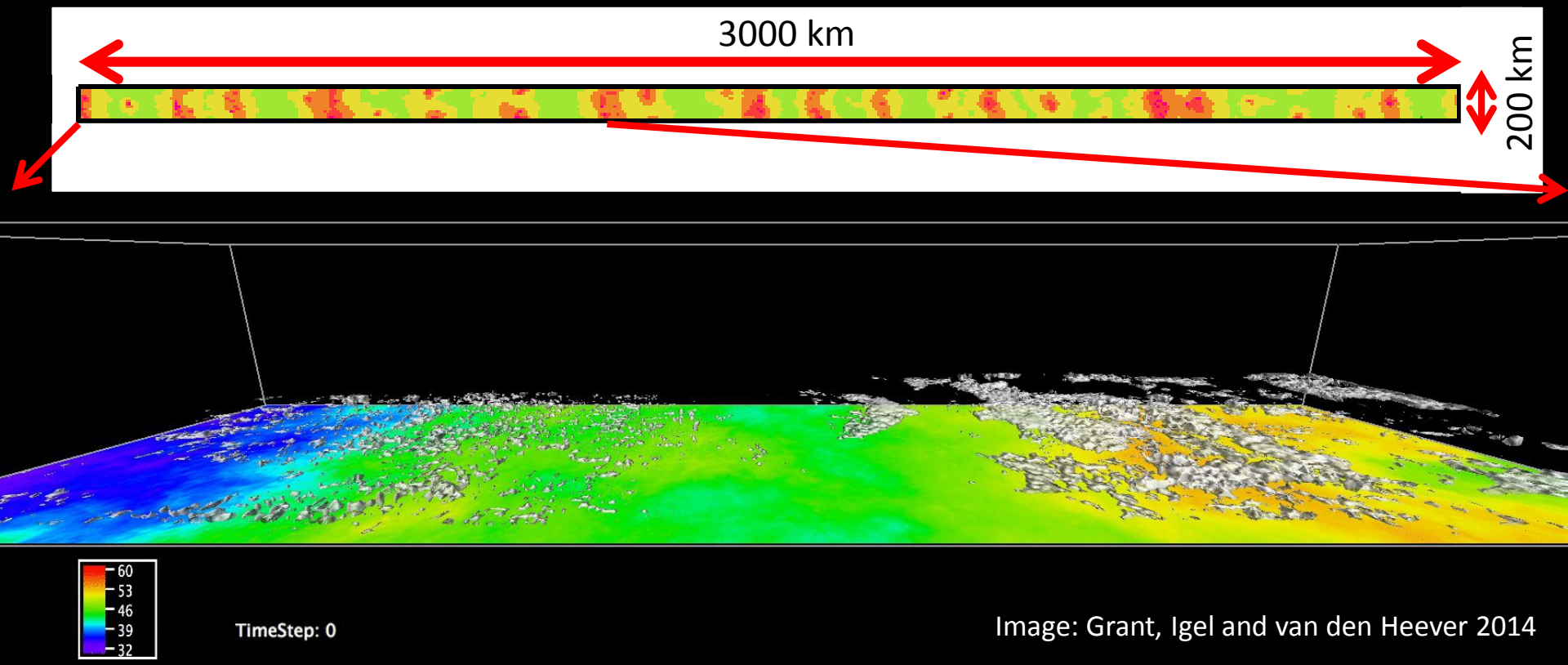


Image: Grant, Igel and van den Heever 2014

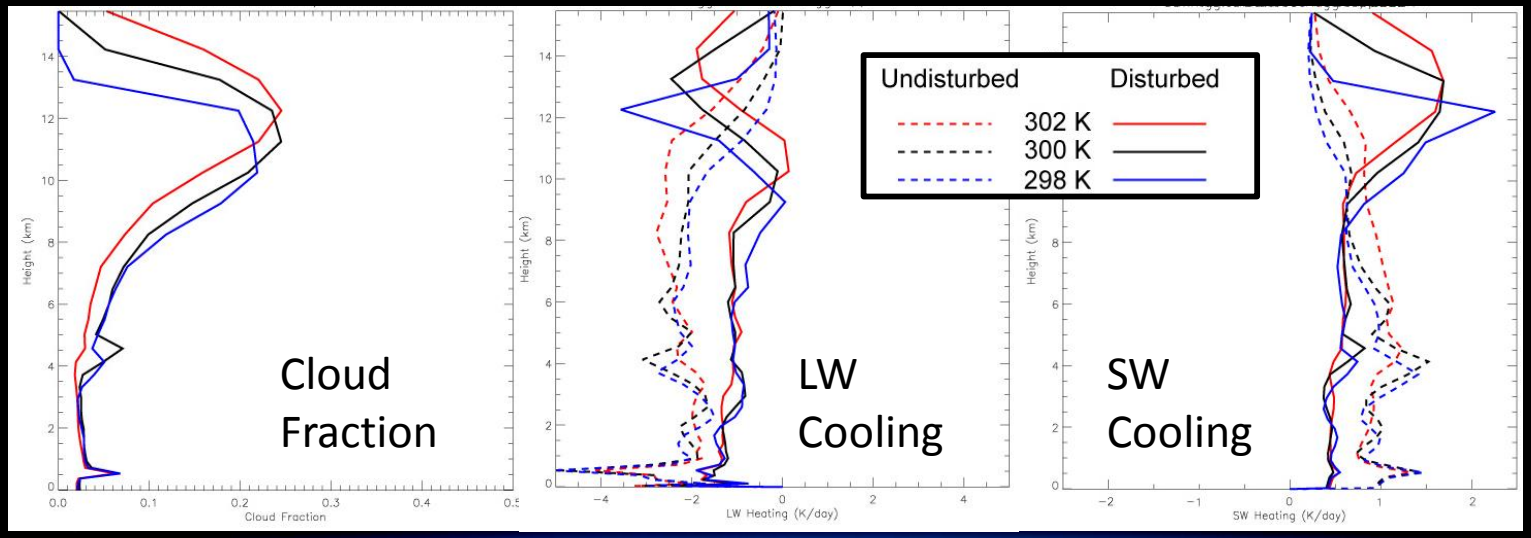
Portion (left 1/3) of an RCE simulation: 1000 by 200 by 25 km for 5 days (66 through 71) at hourly intervals. Shading represents precipitable water (mm); white is a total condensate isosurface of 0.4 g/kg. The animation domain is stretched by a factor of 6 in the vertical and by a factor of 1.5 in the meridional direction.

Bulk Convective Characteristics

Last 10 days for the RCE simulation

	SST		
	298 K	300 K	302 K
Mean PW, full domain (kg m^{-2})	29.34	38.00	48.20
Mean precipitation rate (mm h^{-1})	2.199	2.384	2.485
Mean OLR, full domain (W m^{-2})	245.04	241.27	240.59
High cloud fraction (%)	33.65	36.31	37.41

Increased T => increasing equilibrium vapor pressure => increased PW
Decreased mean OLR due to increased IR capacity of atmosphere with increased water vapor content and increasing high cloud fraction



Posselt, van den Heever, Stephens and Igel, 2012, J. Clim

Bulk Convective Characteristics

Last 10 days for the RCE simulation	SST		
	298 K	300 K	302 K
Mean w where w > 1	2.665	2.906	3.042
Percent of domain with w > 1 m s^{-1}	1.047%	0.791%	0.783%
Percent of domain with w > 10 m s^{-1}	0.025%	0.032%	0.039%
Percent of domain with precipitation > 250 mm day^{-1}	0.197%	0.212%	0.234%
Percent of domain containing cold pools	2.32	3.38	4.83

- Increase in convective intensity with SST
  - mean W increases with SST while fraction of domain covered by core decreases
  - Number of columns with high precipitation rates and strong W also increases with SST
  - Increased cold pool areal coverage

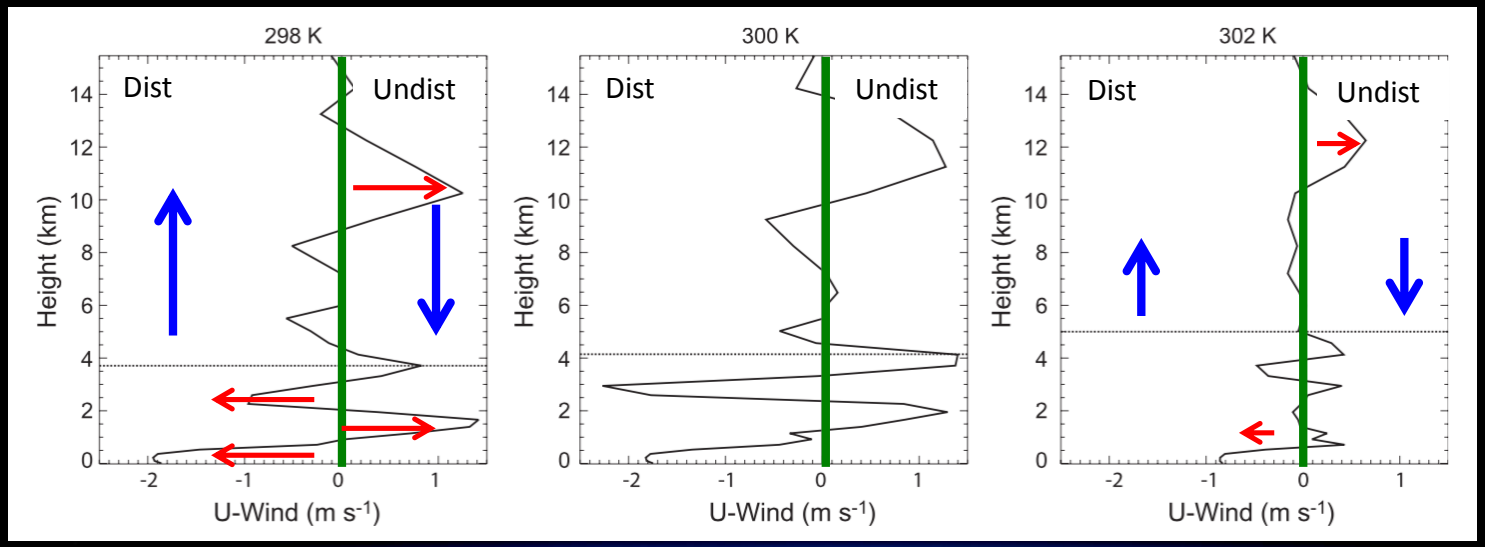
Posselt, van den Heever, Stephens and Igel, 2012, J. Clim

Bulk Convective Characteristics

Last 10 days for the RCE simulation

Consistent with decrease in IR cooling, the radiatively driven circulation slows with SST (see reduced upward and downward mass flux and decrease in mean surface wind speed => move intense convective within slower large-scale circulation)

	SST		
	298 K	300 K	302 K
Mean vertical mass flux: Disturbed regions (kg m^{-2} s^{-1})	0.154	0.125	0.104
Mean vertical mass flux: Undisturbed regions (kg m^{-2} s^{-1})	−0.095	−0.090	−0.076
Mean surface wind speed (m s^{-1})	1.62	1.58	1.33



Disturbed vs undisturbed threshold => 260 Wm^{-2}

Posselt, van den Heever, Stephens and Igel, 2012, J. Clim

Bulk Convective Characteristics

Last 10 days for the RCE simulation	SST		
	298 K	300 K	302 K
Percent deep convective cores	0.732	0.719	0.693
Percent shallow convective	6.113	5.767	5.015
Percent precipitating stratiform	2.987	3.758	2.804
Percent nonprecipitating stratiform	25.645	28.513	29.212
Deep convective precipitation rate	210.848	232.255	269.543
Shallow convective precipitation rate	2.406	3.038	3.707
Precipitating stratiform precipitation rate	18.588	15.965	17.760
Deep convective precipitation fraction	68.025	67.797	72.727
Shallow convective precipitation fraction	6.520	7.127	7.272
Precipitating stratiform precipitation fraction	24.241	24.126	19.426
Deep convective vertical velocity (cloudy, $w > 0$)	0.842	0.821	0.900
Shallow convective vertical velocity (cloudy, $w > 0$)	0.089	0.099	0.105
Precipitating stratiform vertical velocity (cloudy, $w > 0$)	0.132	0.113	0.128
Stratiform vertical velocity (cloudy, $w > 0$)	0.107	0.097	0.098

- Change in the nature of convection around 300K (also noted by others e.g., Masunaga et al 2005; Su et al 2006)
- Deep convective W and precipitation fraction decrease from 298K to 300K and then increase again – WHY?

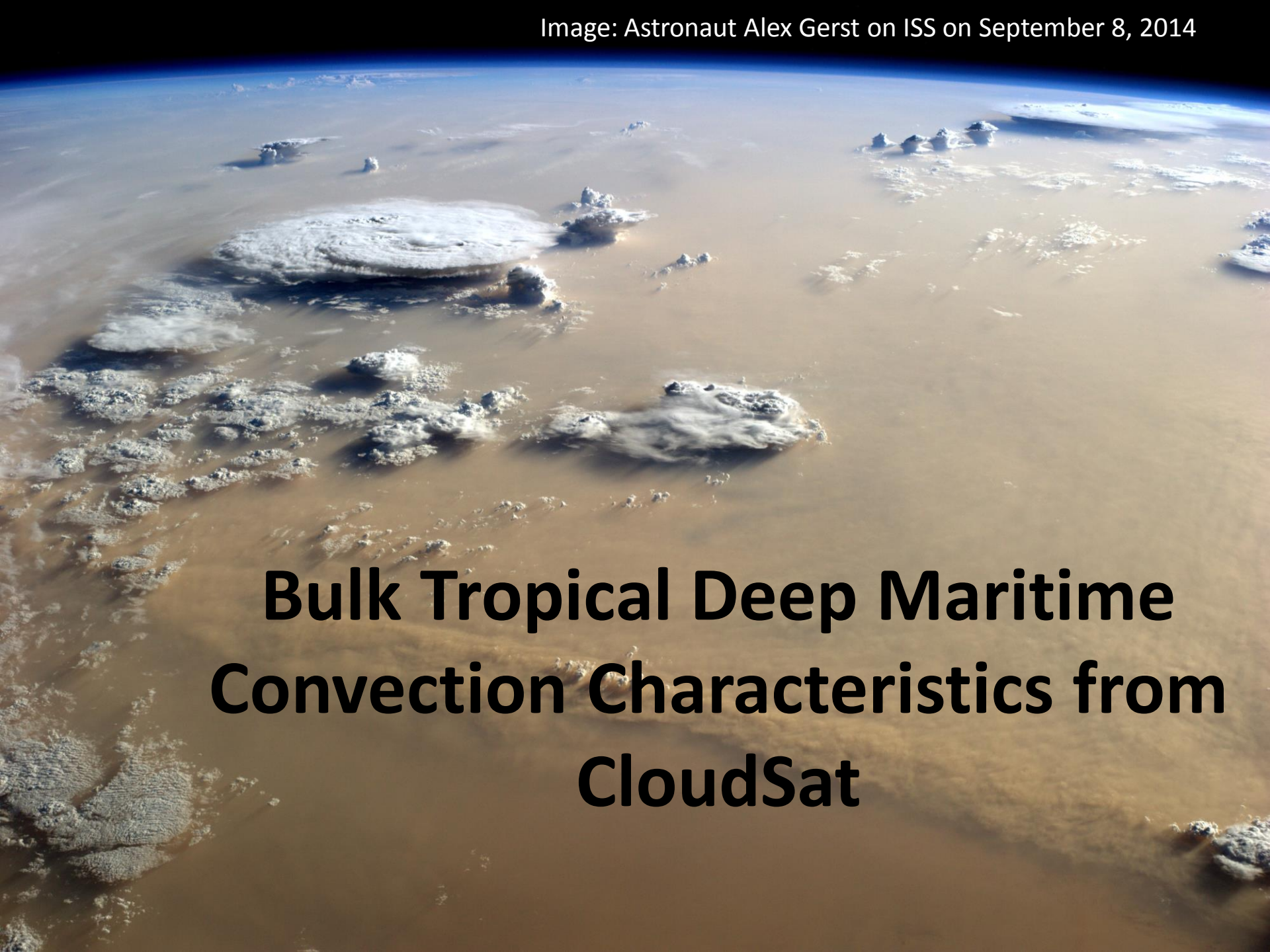
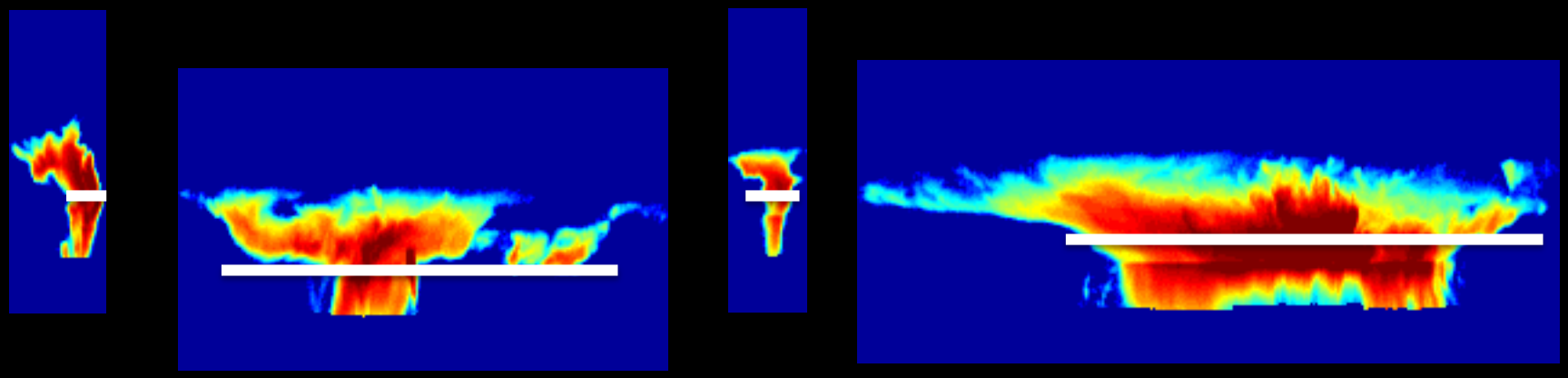


Image: Astronaut Alex Gerst on ISS on September 8, 2014

Bulk Tropical Deep Maritime Convection Characteristics from CloudSat

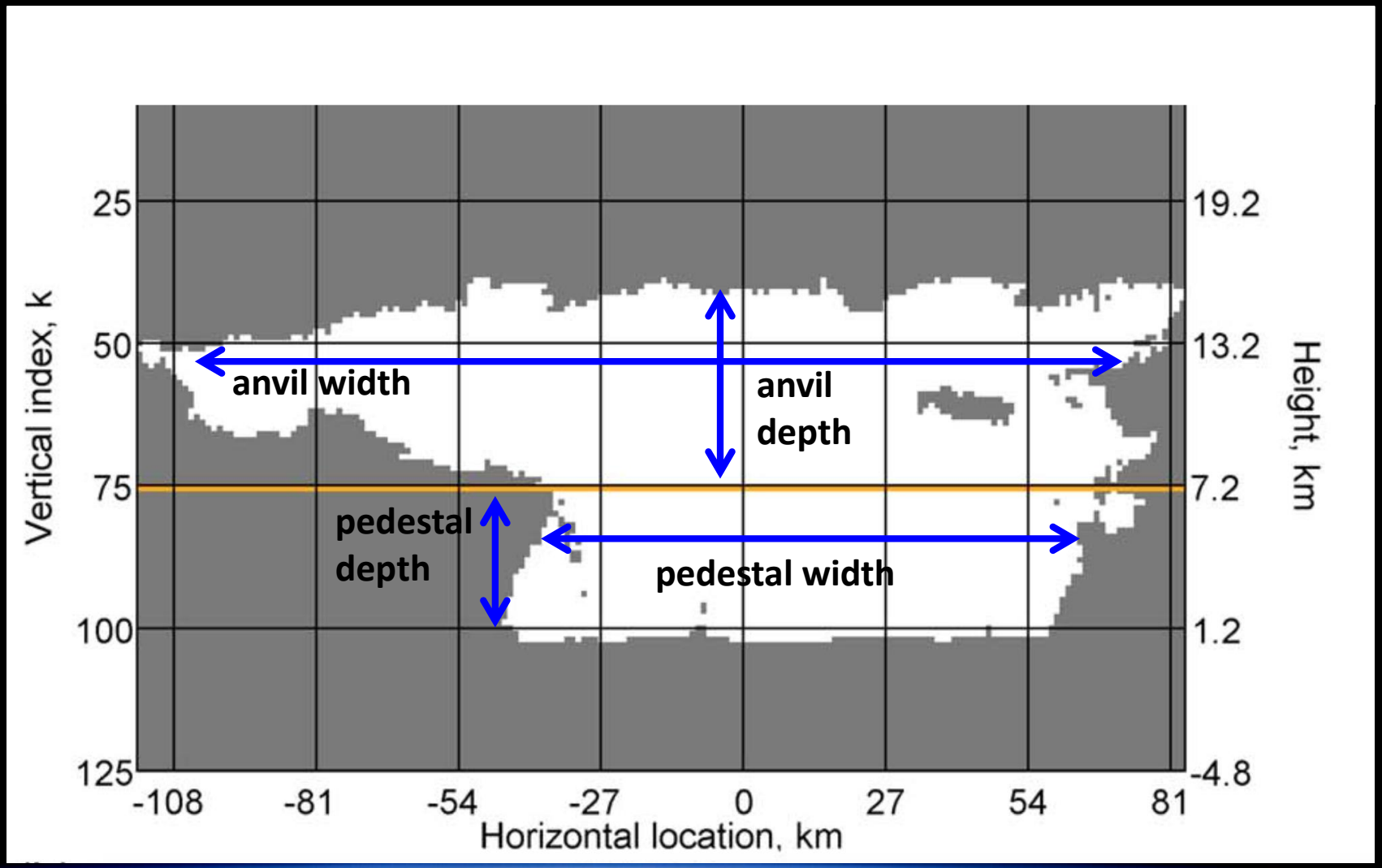
Observed Horizontal and Vertical Length Scales

- We use CloudSat and define deep tropical convective cloud objects using (Igel et al, 2014) (somewhat similar to Bacmeister and Stephens 2011):
  - Provides measures of size/shape of individual deep clouds
  - Temperature and other variables from ECMWF Reanalysis, MODIS etc
- Anvil Cutoff algorithm developed
- HUGE dataset of ~22k independent cloud objects
  - Strong statistical significance
- Highly selective, but inclusive dataset (strictly mature and deep convective storms)

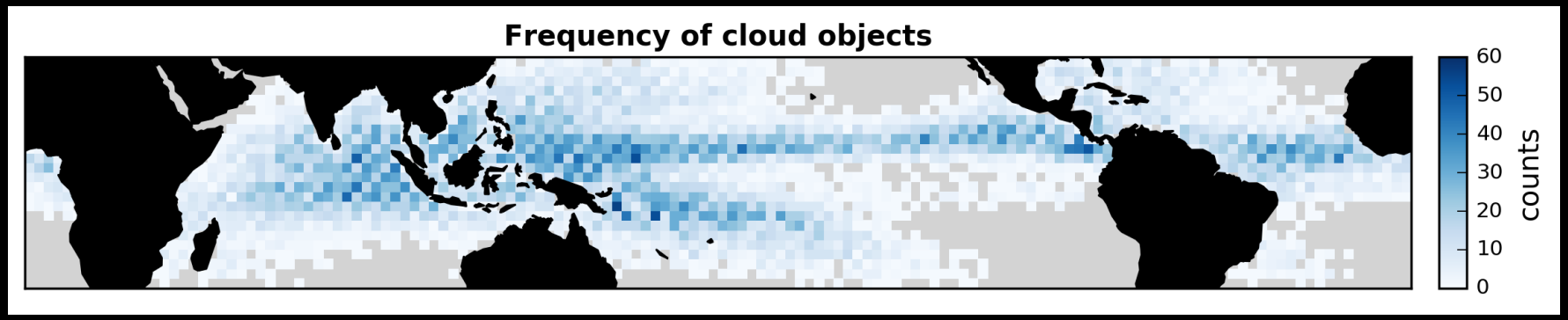


Terminology

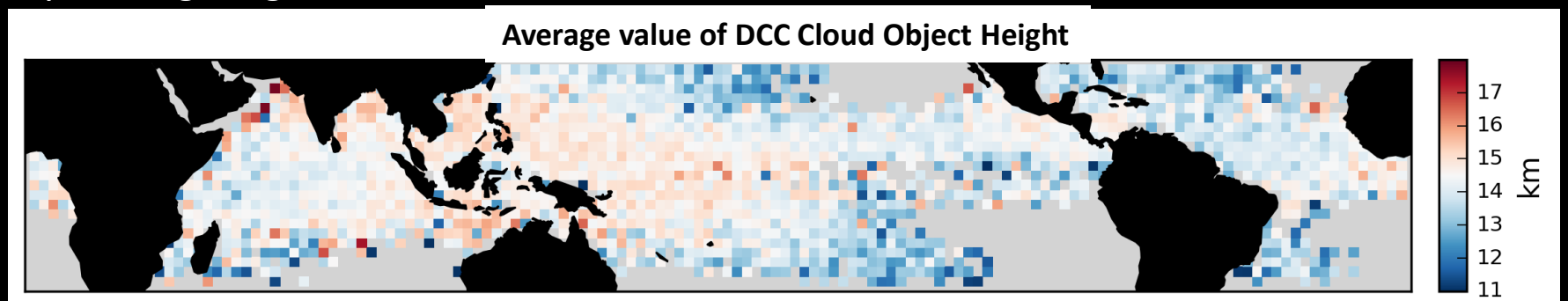
Igel et al 2014

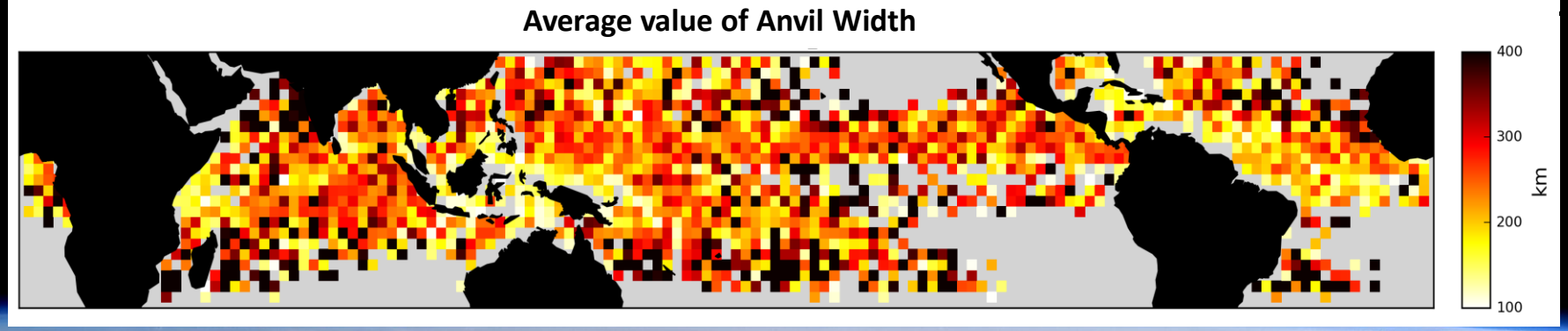


Spatial Distribution of Cloud Objects



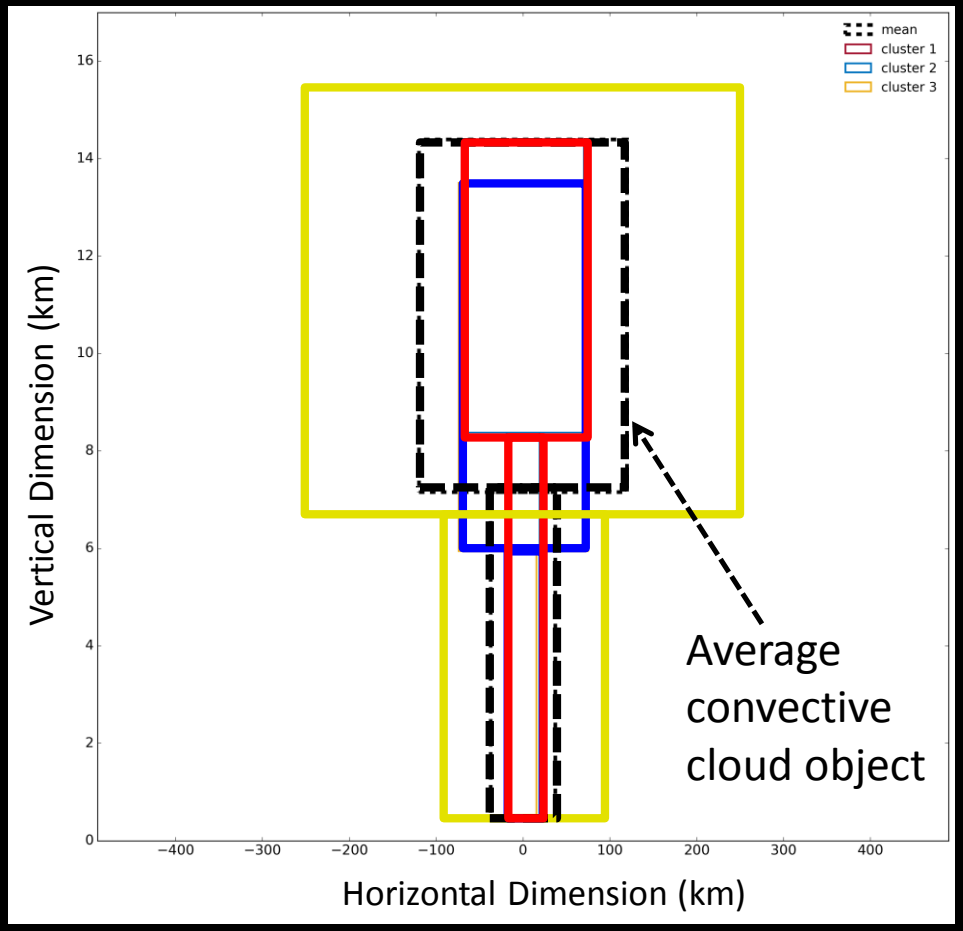
Frequency of cloud objects derived from CloudSat between 2006-2011 binned into 2.5 by 2.5 degree grid cells



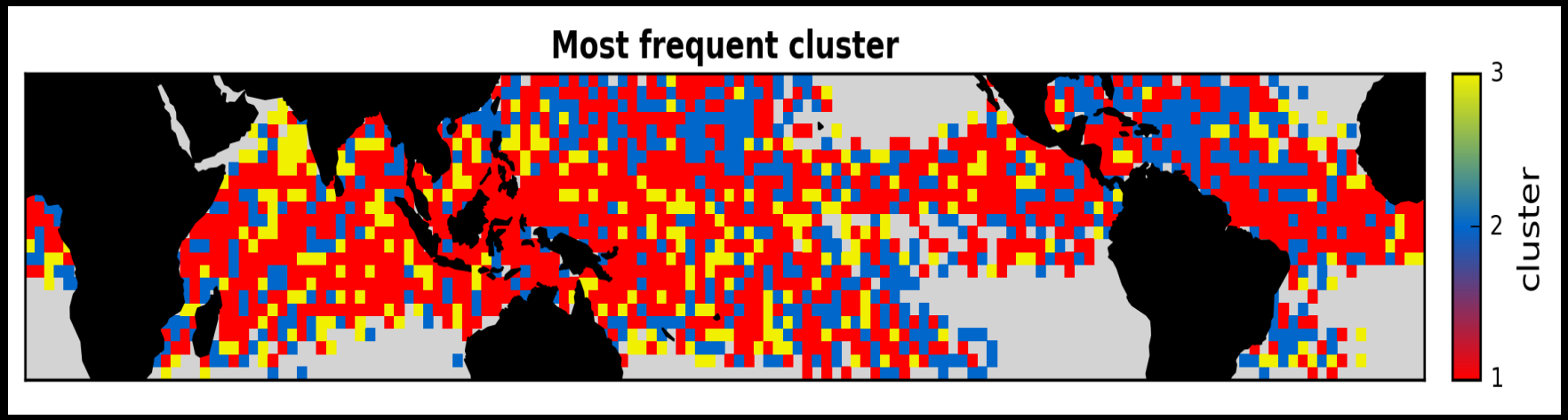


Clustering of Cloud Objects

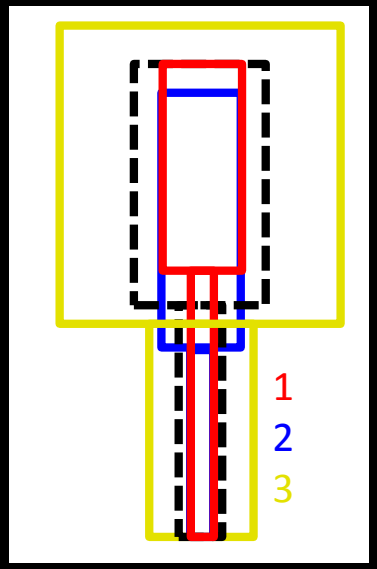
- K-means clustering
- 3 clusters a priori
- Top rectangle => anvil scale; bottom rectangle => pedestal scale
- Cluster 3 (yellow): wide anvils, potentially multi-core systems
- Cluster 1 (red): narrow convective systems with taller than average pedestal heights and shorter than average anvil heights
- Each object is only signed to one cluster group

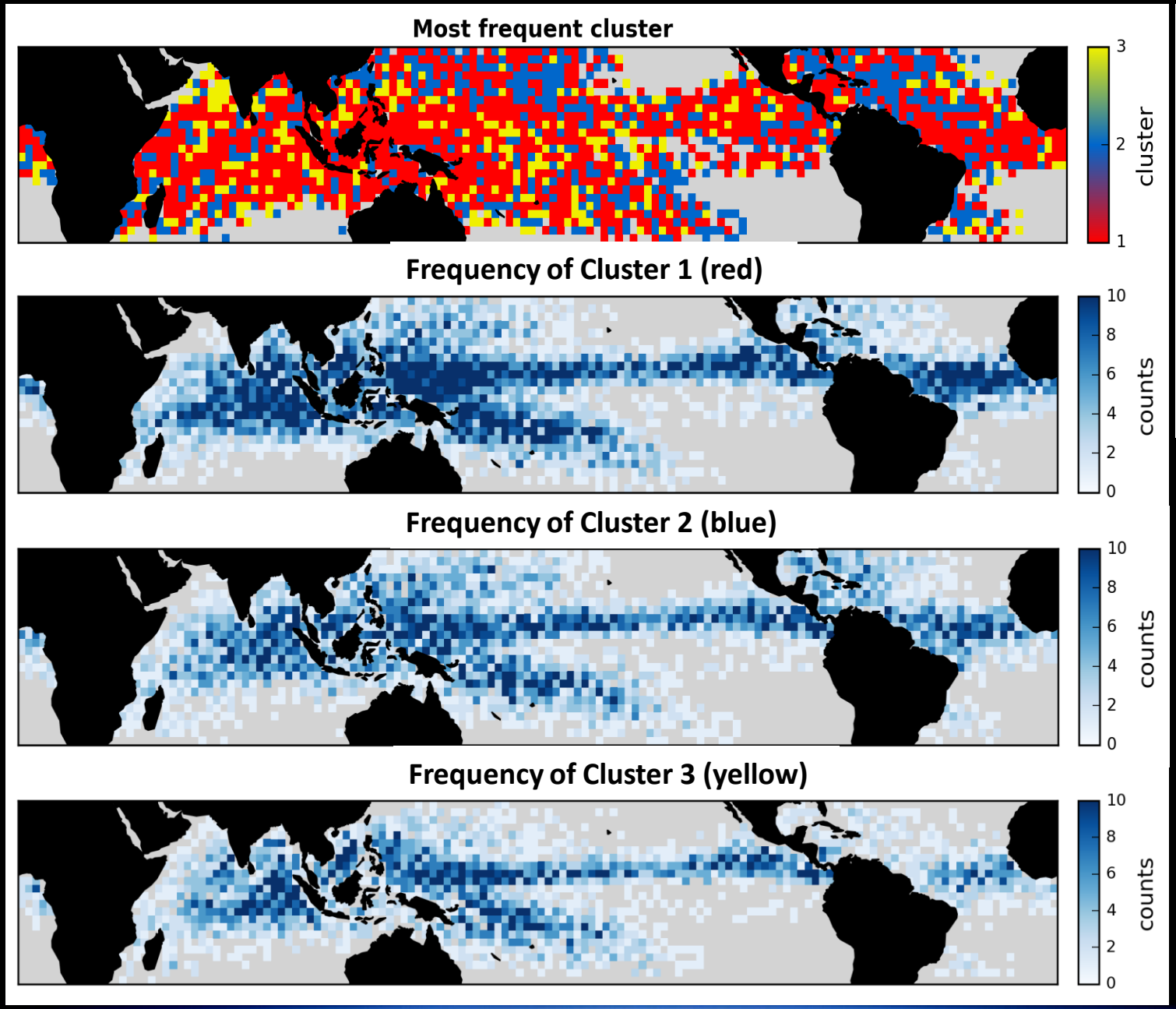


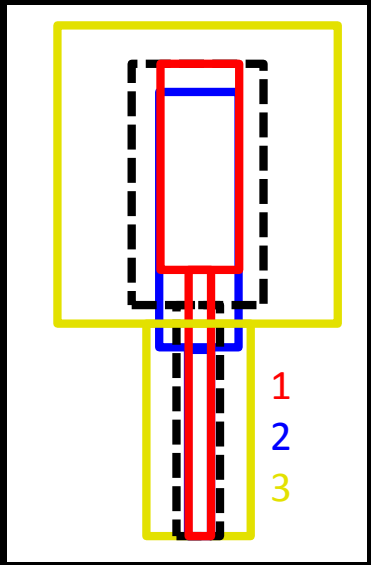
Cluster Frequencies



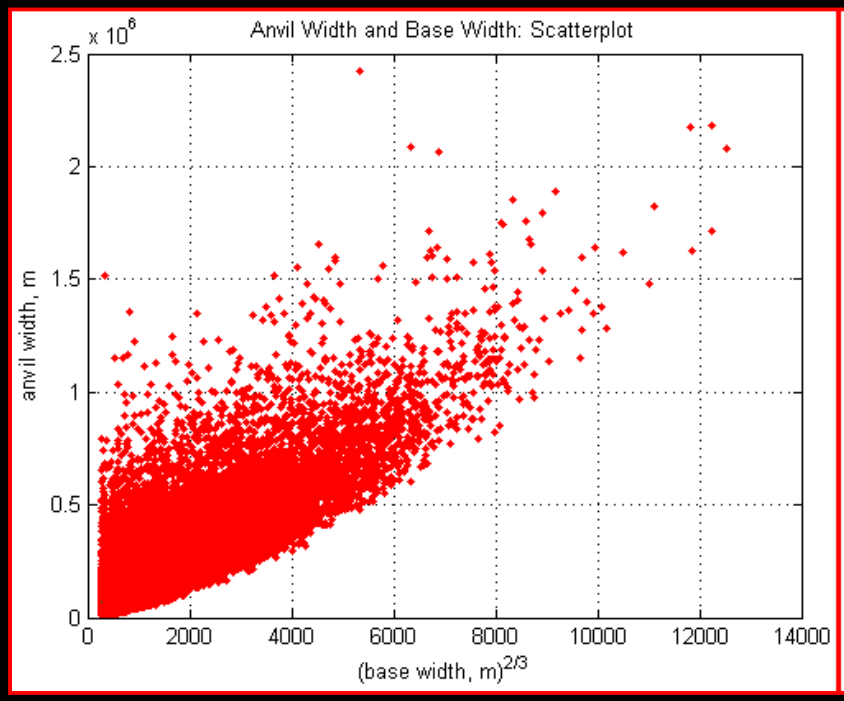
- Narrow deep convective pedestal with shallow anvil heights (cluster 1; red) occur most frequently
- Wide deep convection (cluster 3, yellow) is the least frequent => occurs more frequently at equator, the southern tropics and around Indian when it does occur

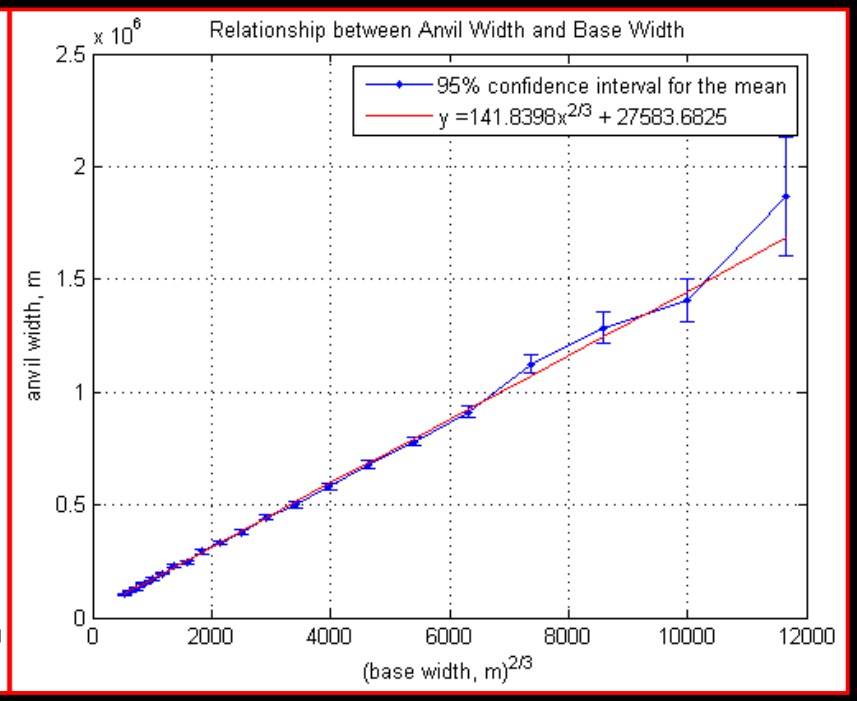



Most frequent cluster
cluster
3
2
1
Frequency of Cluster 1 (red)
counts
10
8
6
4
2
0
Frequency of Cluster 2 (blue)
counts
10
8
6
4
2
0
Frequency of Cluster 3 (yellow)
counts
10
8
6
4
2
0


1
2
3

Relationship Between Anvil Width and Cloud Base (Pedestal) Width



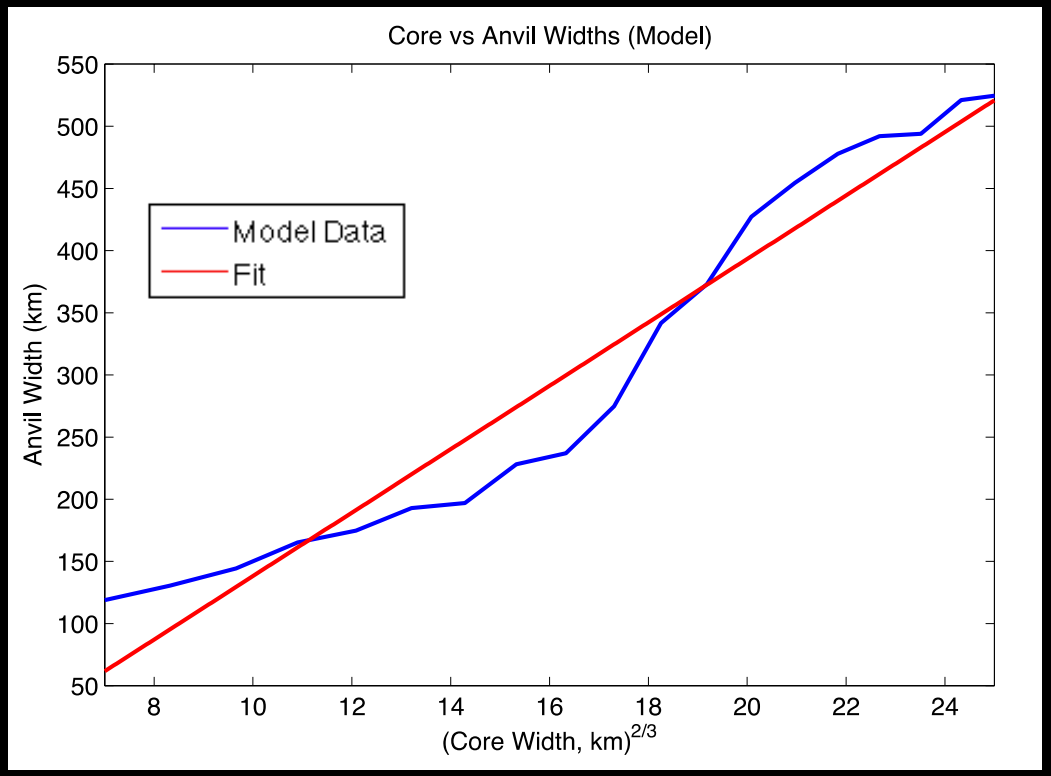


- For clouds with base widths above 10 km, we observe a robust scaling relationship (in the mean):

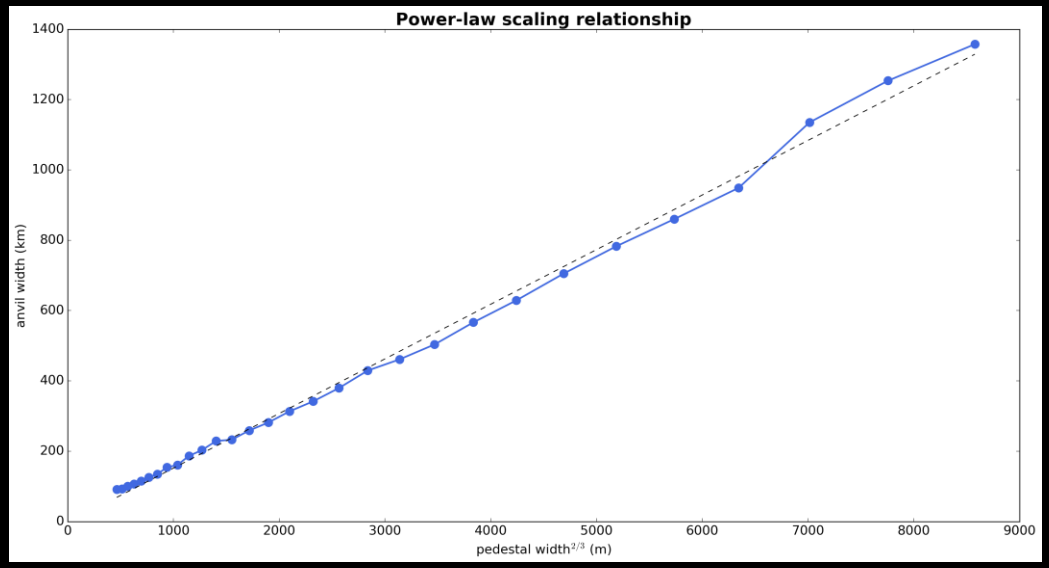
Anvil Width ∝ (Base Width)$^{2/3}$

Relationship in RCE Simulations

- Relationship appears to hold in these simulations

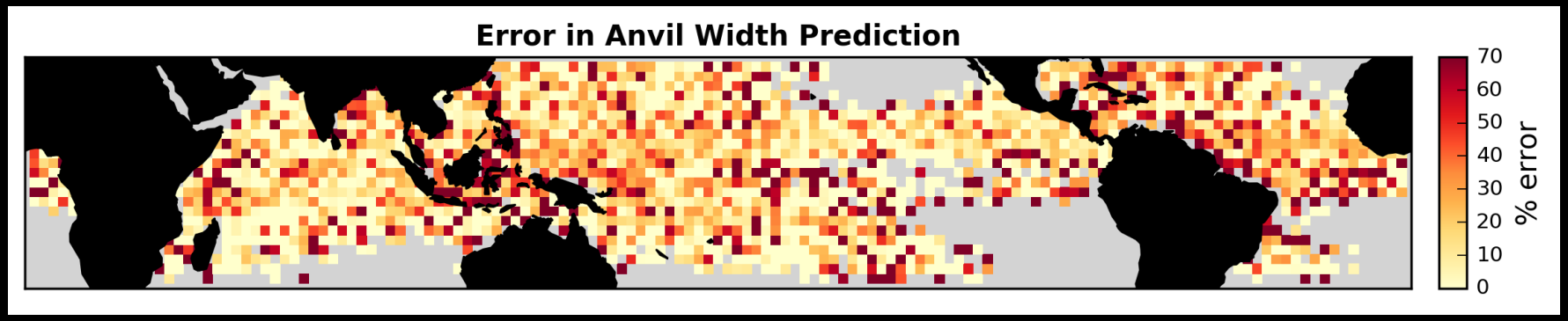


Mean anvil width binned by pedestal width to the 2/3rd. Gray line depicts the linear best fit line (after Igel and van den Heever 2015)



$$\bar{R}_A = m * \left(\bar{R}_p\right)^{2/3} + b$$

Although the scaling appears to perform less well for the largest convective scales the simple power-law relationship performs well across a wide range of pedestal and anvil widths.



75% of grid cells show error less than 37% implying the 2/3rd scaling does a reasonable job predicting anvil width from pedestal width across a significant portion of the tropics. Regional differences do emerge => significantly better over the Indian Ocean and significantly worse over North Atlantic.

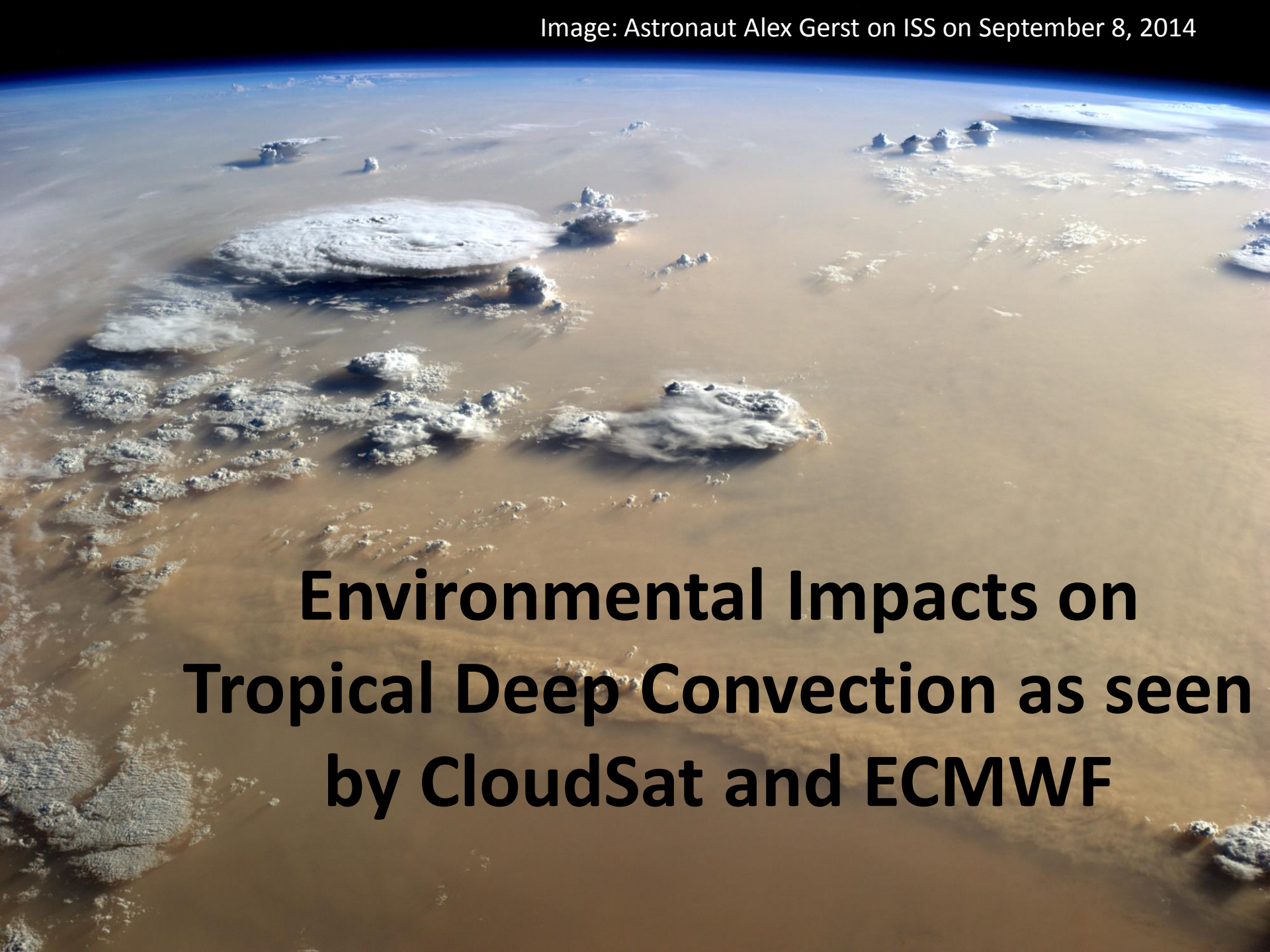


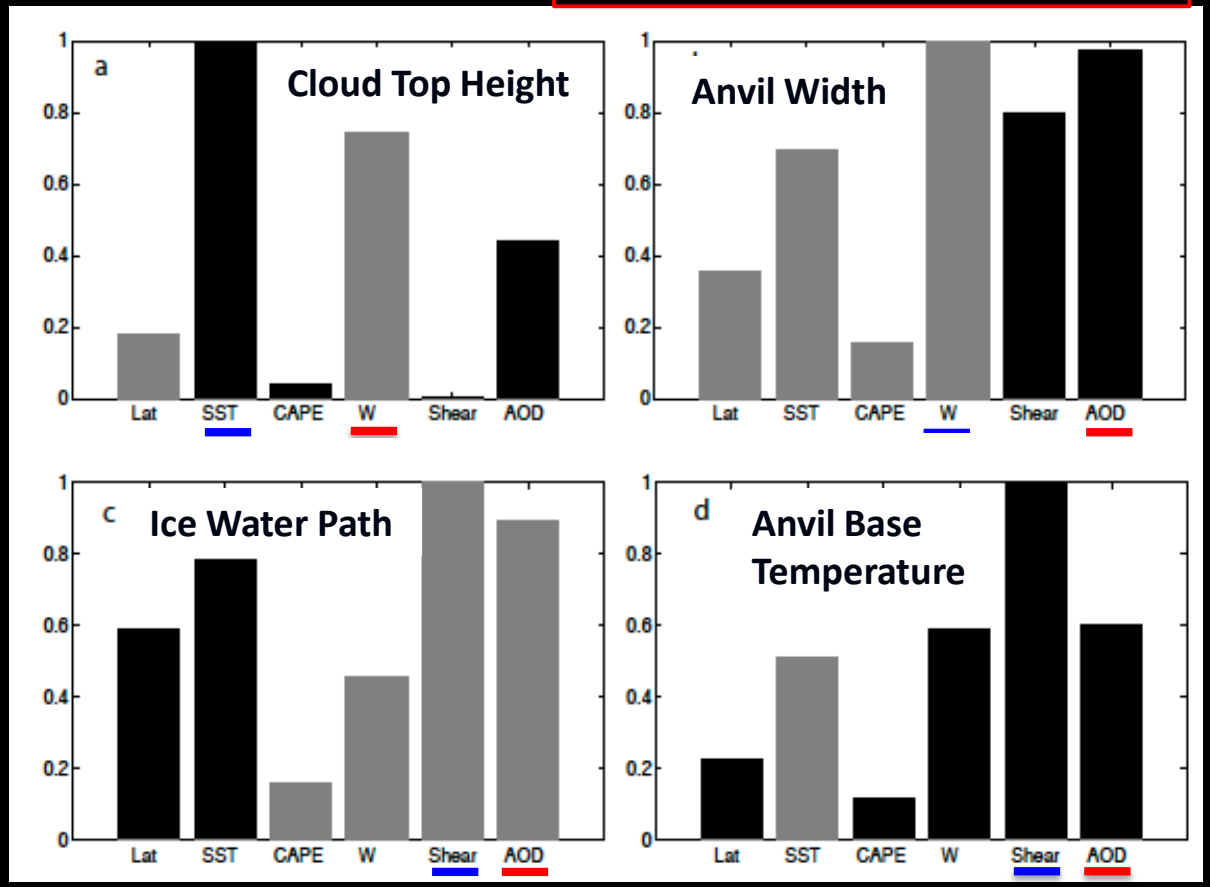
Image: Astronaut Alex Gerst on ISS on September 8, 2014

Environmental Impacts on Tropical Deep Convection as seen by CloudSat and ECMWF

Relative Role of Environmental Factors in Cloud Morphology

Igel and van den Heever, 2014

- Relative and independent influence of environmental factors on various cloud features
- Gray bars indicate negative values
- W is omega at 500mb
- T, P, RH and SST from ECMWF mapped to CloudSat
- Shear and Omega-500mb from ERA-I
- AOD - MODIS



Normalized multiple linear regression coefficients for each predictor (latitude, SST, CAPE, W, shear, AOD - each bar) for various cloud attributes (each panel). Gray bars indicate negative values. Red underline is AOD; blue is leading order

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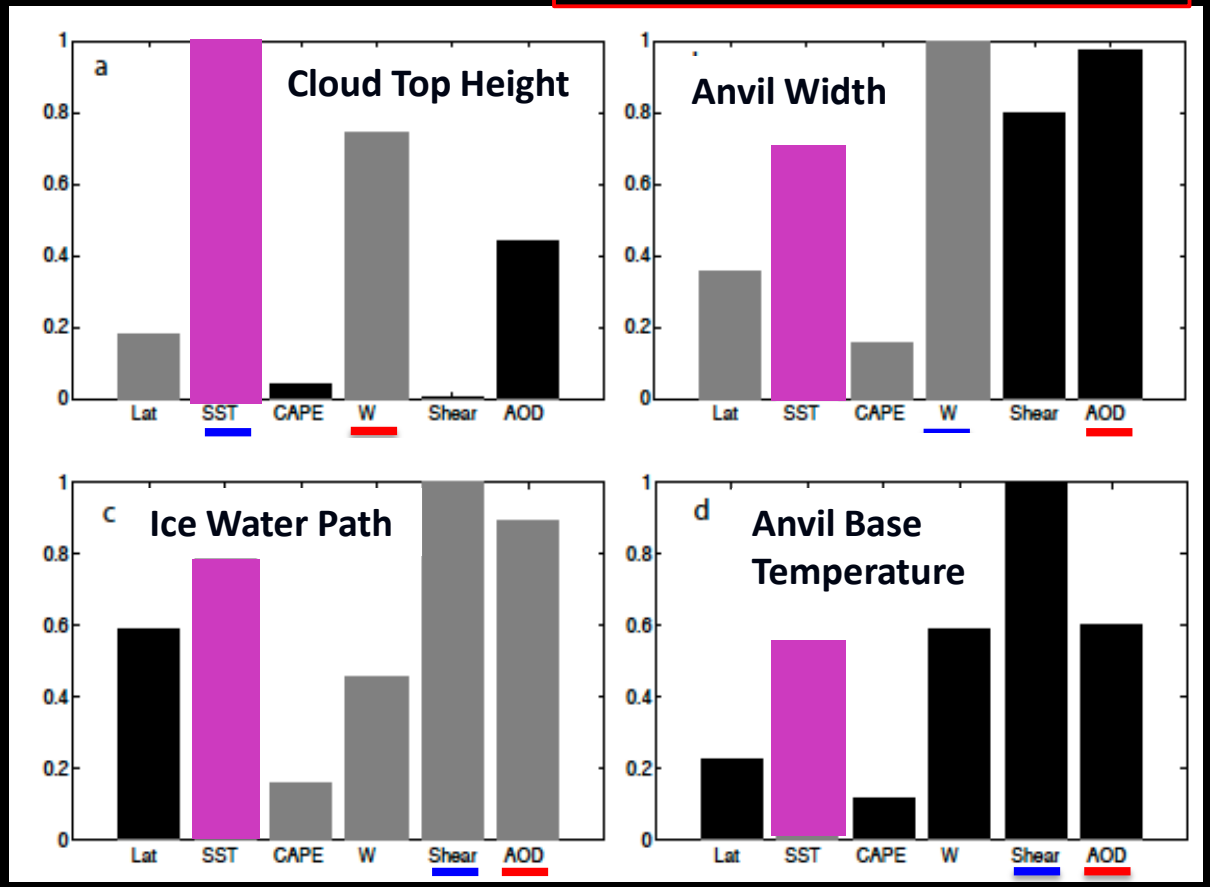
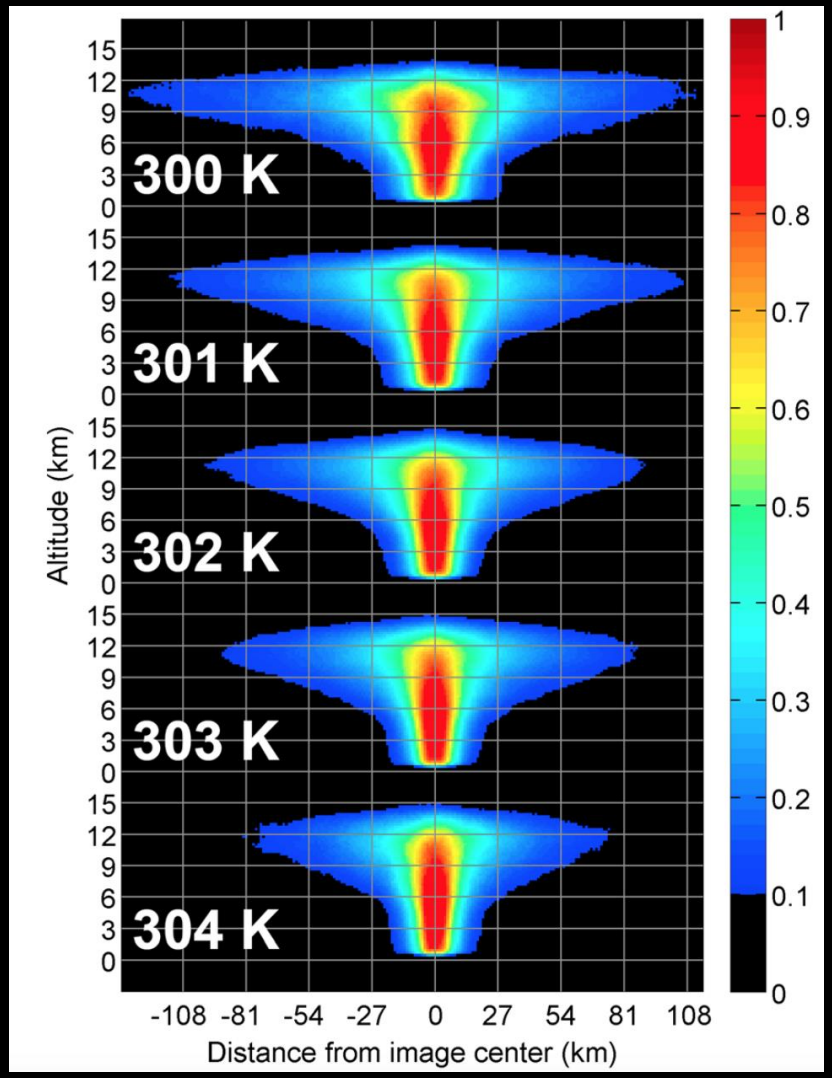


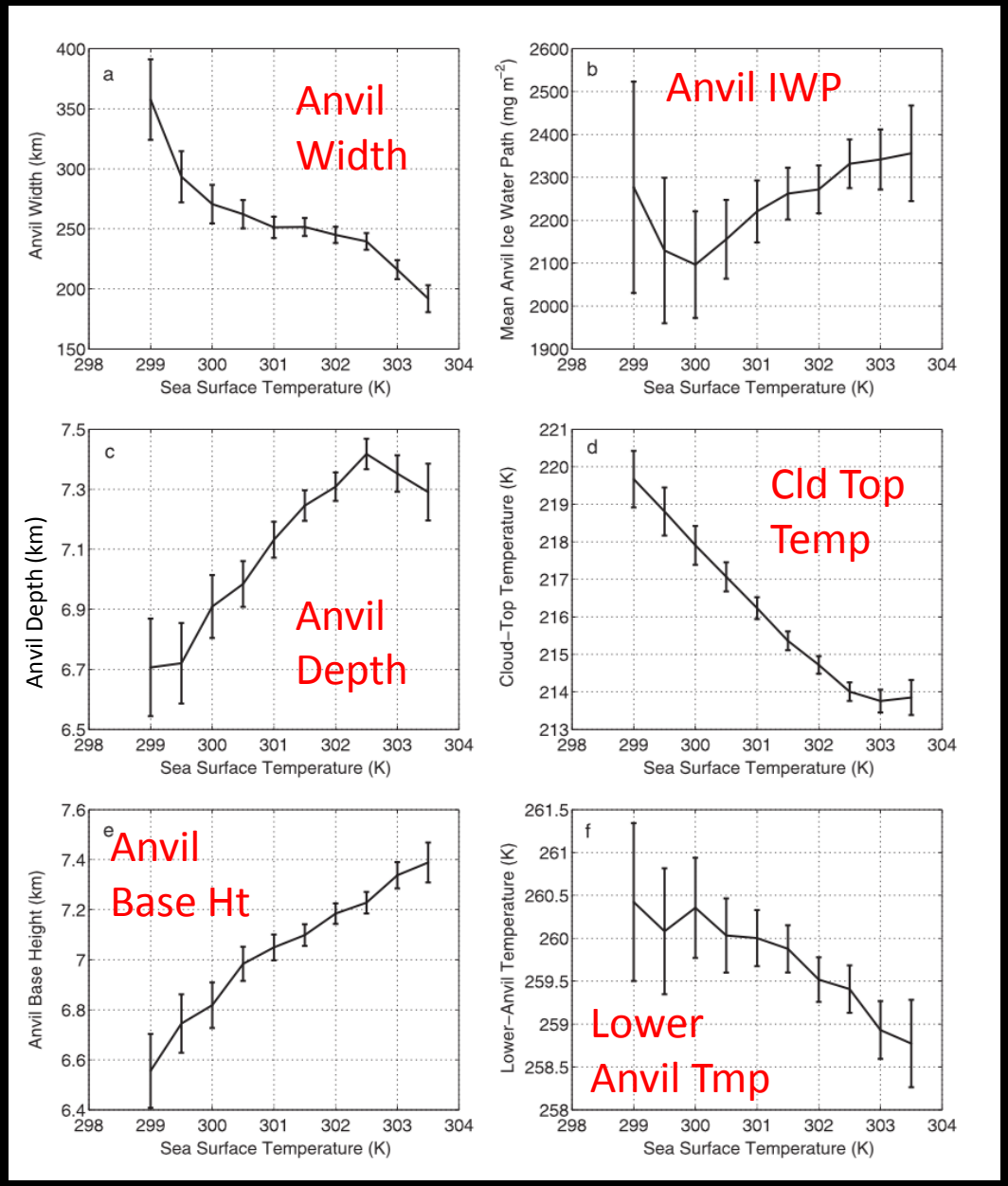
Normalized multiple linear regression coefficients for each predictor (latitude, SST, CAPE, W, shear, AOD - each bar) for various cloud attributes (each panel). Gray bars indicate negative values. Red underline is AOD; blue is leading order

Anvil Variations with SST



- Fraction of cloud objects at each listed SST that would overlap at a certain grid point if all cloud centers were collocated.
- The magnitude indicates the fraction of clouds with cloudiness at each pixel relative to its pedestal base center.
- It shows that anvils narrow and rise with increasing SSTs

Anvil Variations with SST

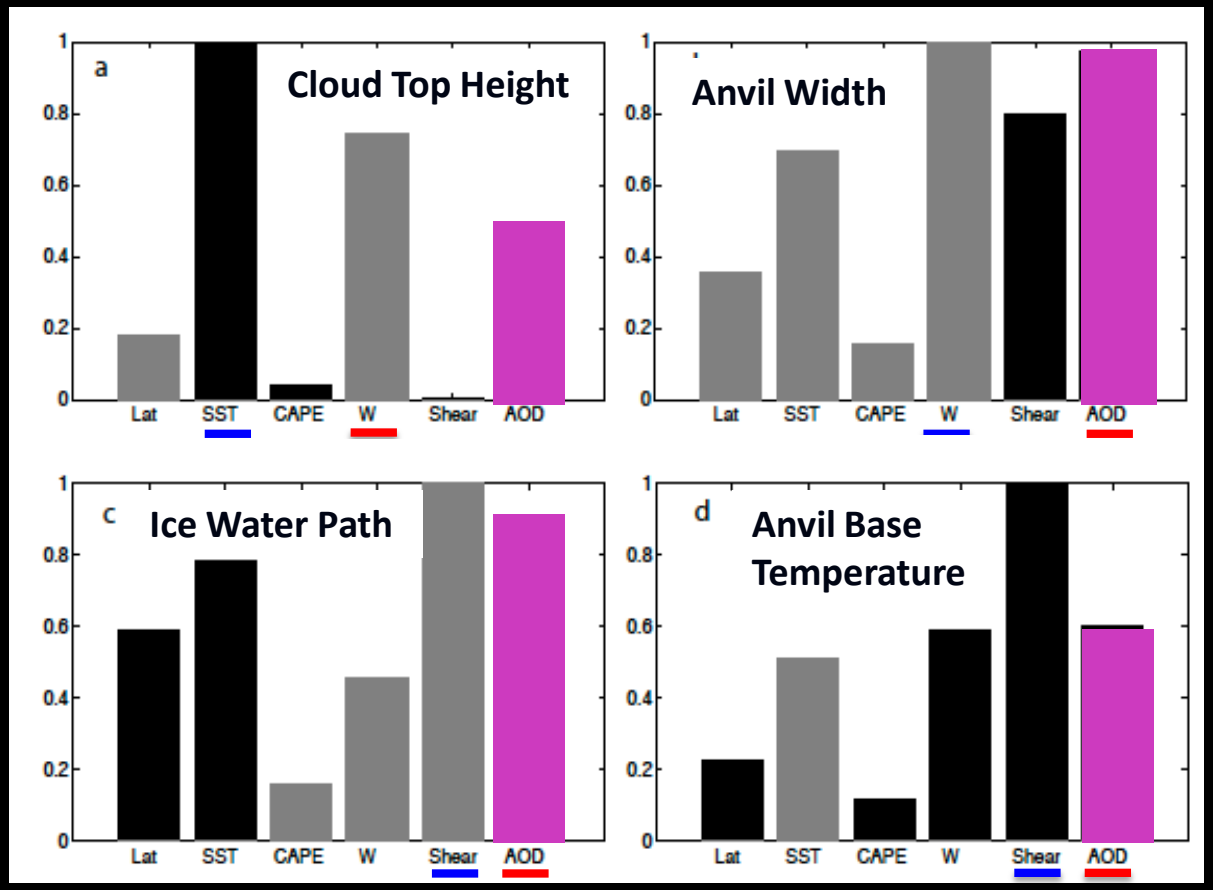


Binned mean anvil widths (as a function of SST with confidence intervals in vertical bars), (b) Anvil ice water path, (c) Physical mean anvil depth, (d) ECMWF analysis temperature at the level of cloud top, (e) Anvil base height, and (f) ECMWF analysis temperature at the level of anvil base. Error bars indicate 95% confidence intervals for the mean in each SST bin.

IWP - 2B-CWC-RVOD product [Austin et al., 2009]

Relative Role of Environmental Factors in Cloud Morphology

- Relative and independent influence of environmental factors on various cloud features
- Blue and red lines indicate the predominant factors impacting cloud characteristics
- Gray bars indicate negative values

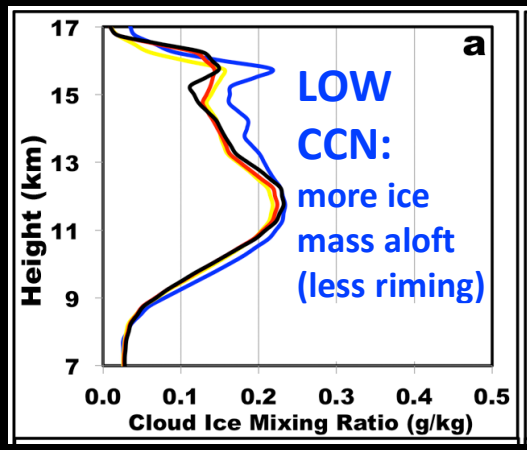


Normalized multiple linear regression coefficients for each predictor (latitude, SST, CAPE, W, shear, AOD - each bar) for various cloud attributes (each panel). Gray bars indicates negative values. Red underline is AOD; blu is leading order (after Igel and van den Heever, 2014)

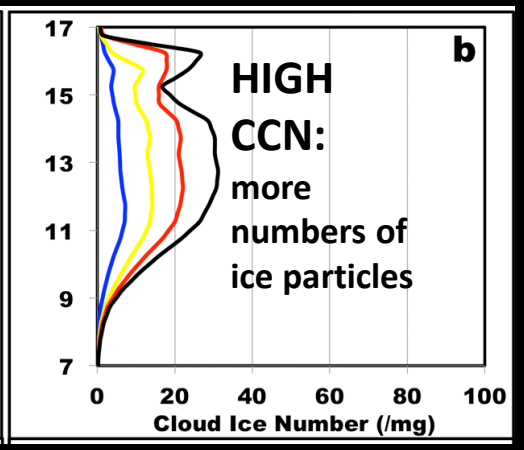
AOD and Anvil Microphysics

- An increase in aerosol concentration led to:
  - Greater number of smaller ice crystals from homogeneous freezing of more numerous, smaller lofted cloud droplets
  - Reduced mixing ratios of cloud ice in the upper levels due to greater rime collection of the largest cloud droplets at lower altitudes
  - Enhanced albedo from more numerous, smaller ice particles
  - Reduced OLR due to less anvil mass and/or emission at higher altitude
  - Broader anvils due to smaller ice crystal fall speeds

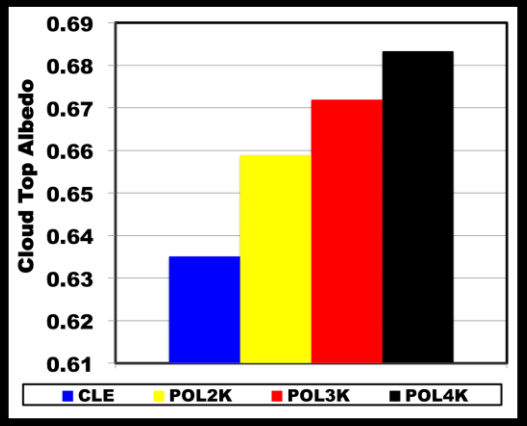
Cloud Ice Mixing Ratio



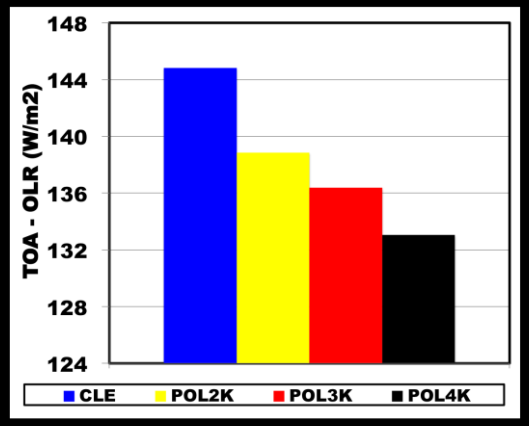
Cloud Ice # Conc.



Cloud Top Albedo



Top-of-Atmosphere OLR (W m^{-2})



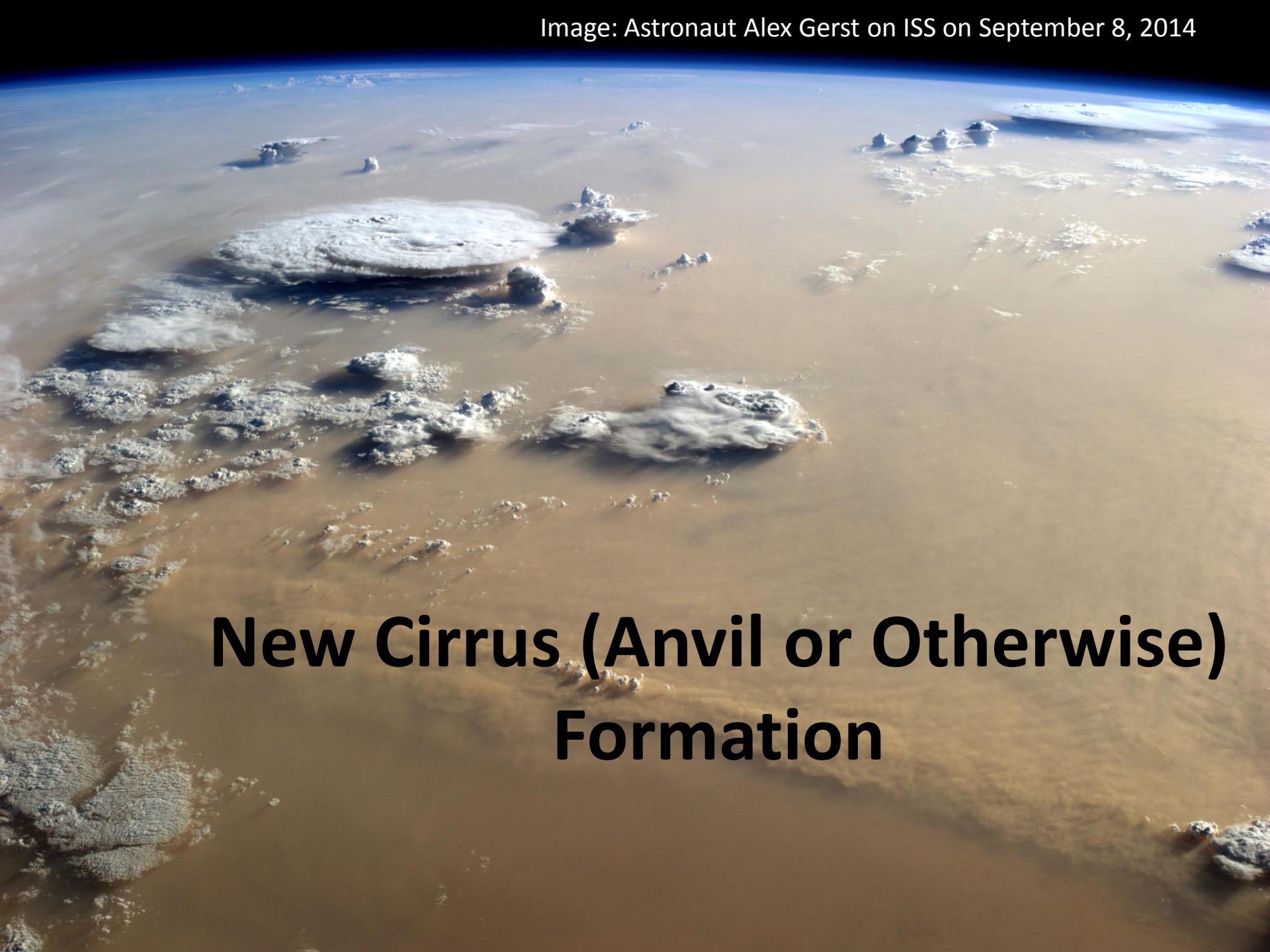
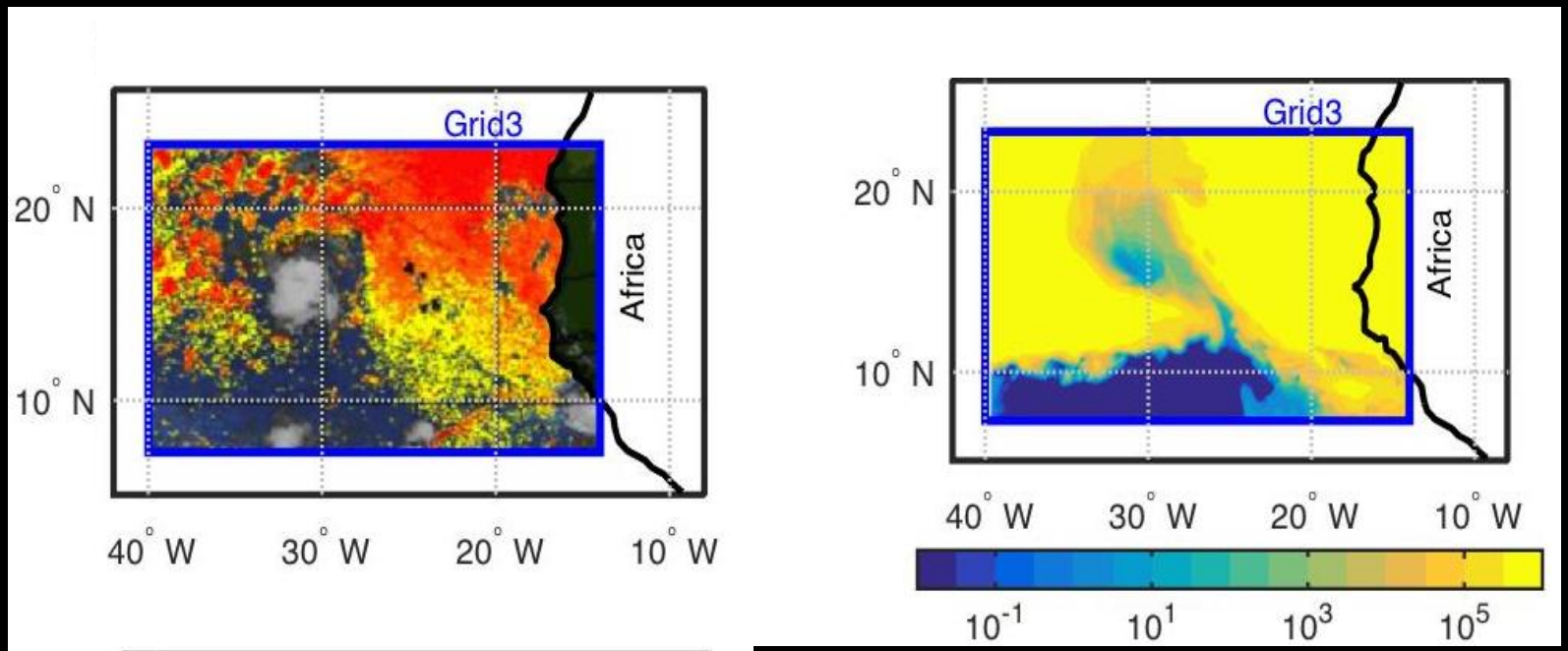
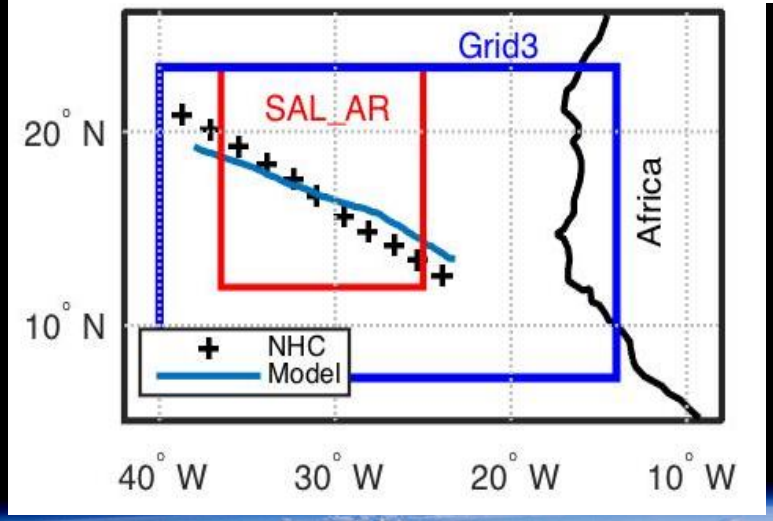


Image: Astronaut Alex Gerst on ISS on September 8, 2014

New Cirrus (Anvil or Otherwise) Formation

Dust Transport by TCs

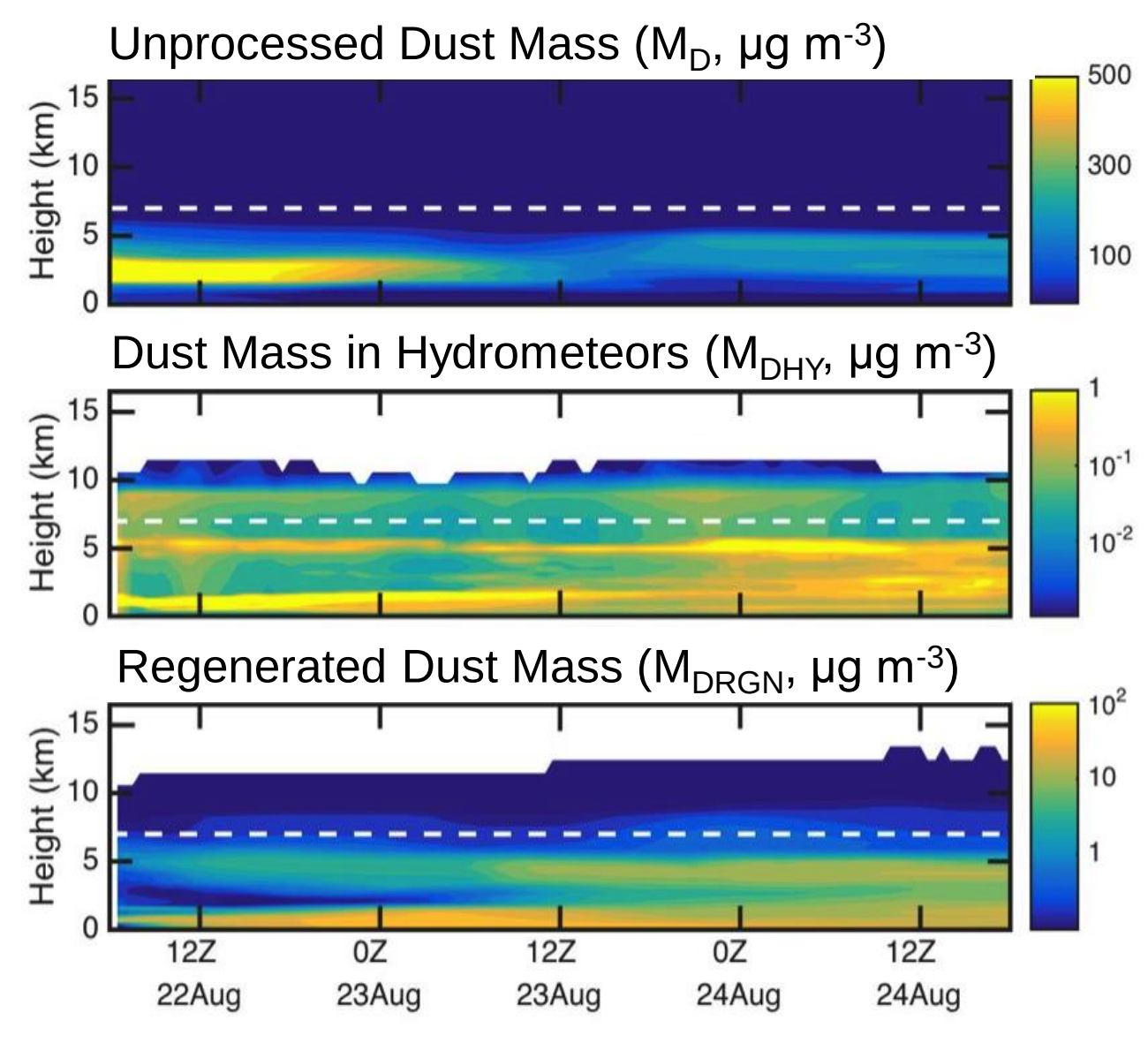




Top: (left) Visible imagery and the SAL product (U. Wisc) and (right) vertically integrated dust mass (M_D, µg m^{-2})
Bottom: NHC best track compared with that of the model. Red box shows where dust budget analysis being conducted.

Herbener, Saleeby, van den Heever and Twohy 2016 GRL

Simulations of Saharan Dust Redistribution



Most unprocessed dust mass between 2 km and 4 km initially – later reduced and better mixed

M_{DHY} increases both below and above FL (~ 5.5 km elevation) – greater amounts below FL due to active warm rain process

M_{DRGN} increase both below and above FL - maxima between 6 and 7km AGL

Herbener et al, 2016, GRL

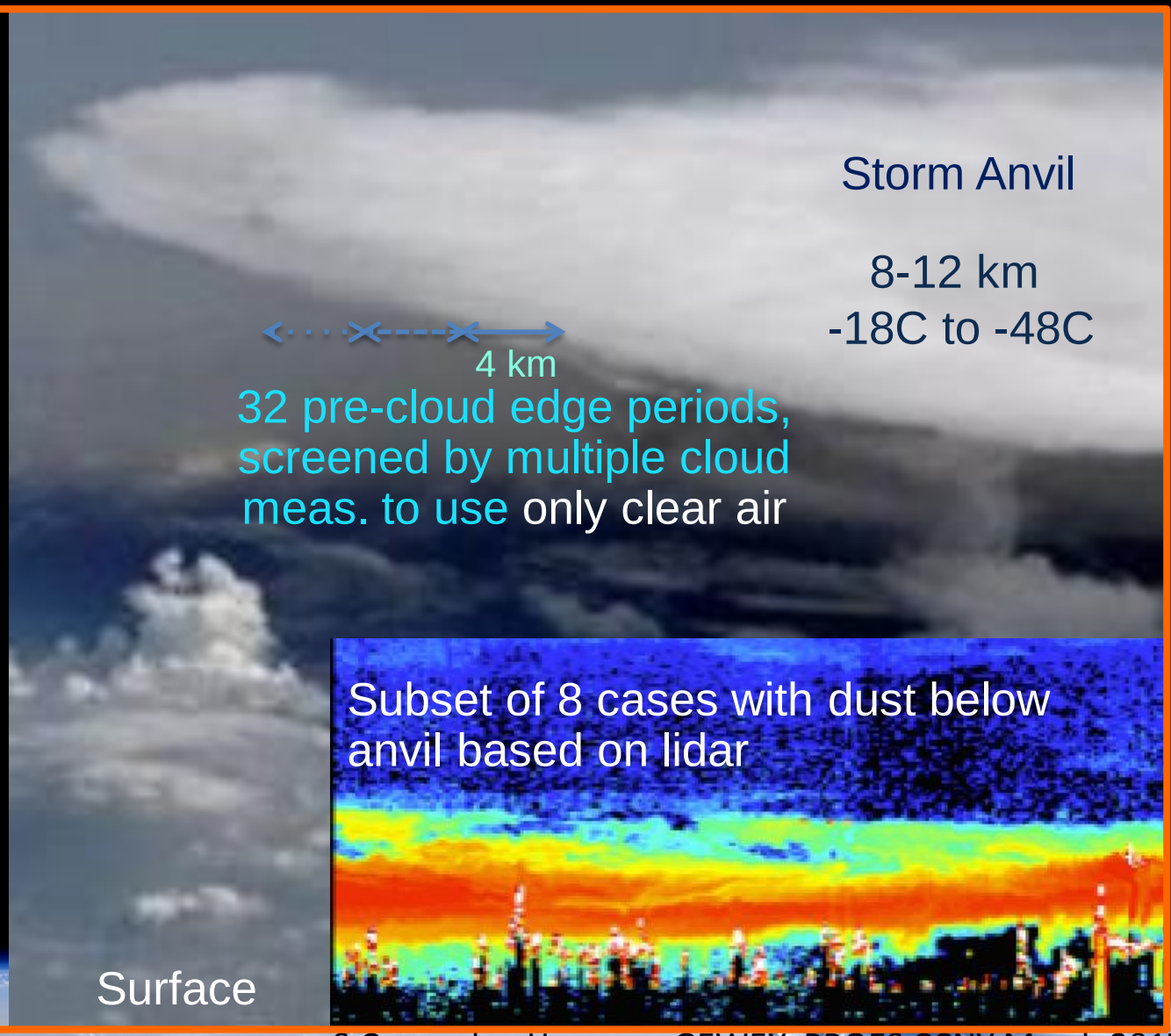
Aerosol Measurements: Background UT versus Anvil Edge

Dry Aerosol Scattering Coeff, Size Distributions (*Anderson Data*)

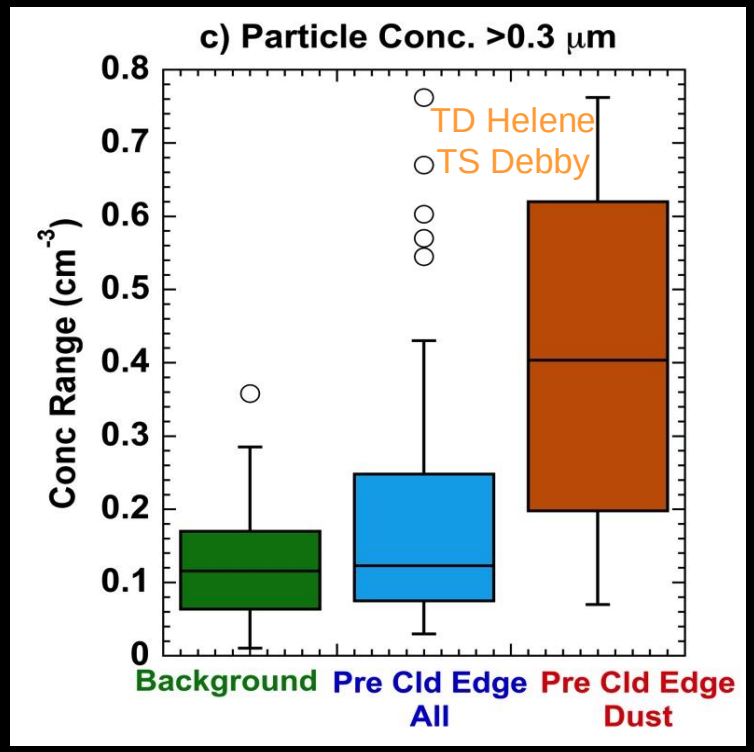
Background air

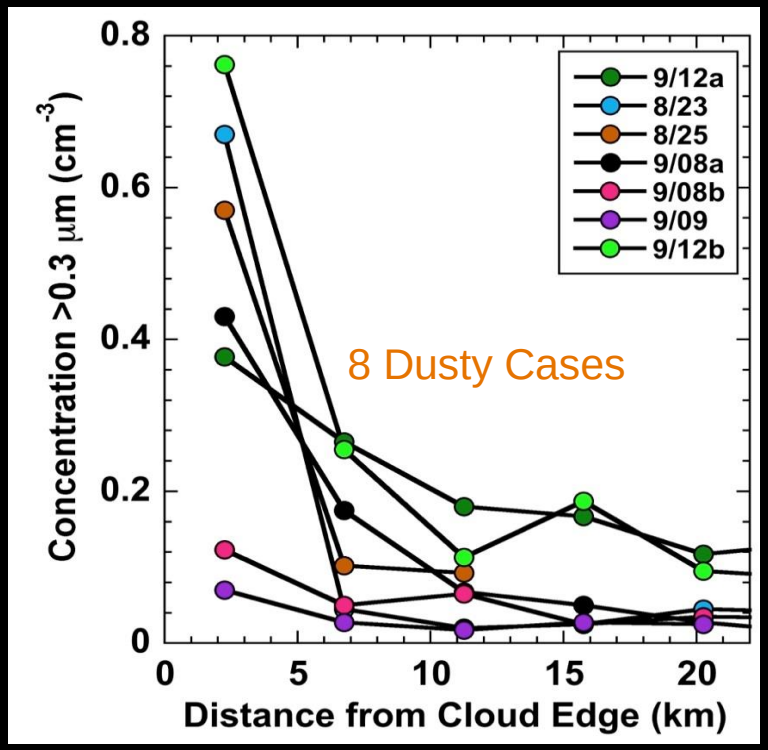
> 40 km from cloud edges (61 cases)

Twohy et al 2017 in review at JGR – slides from Cindy



Dry Aerosol Properties: Background vs Pre-Cloud Edge





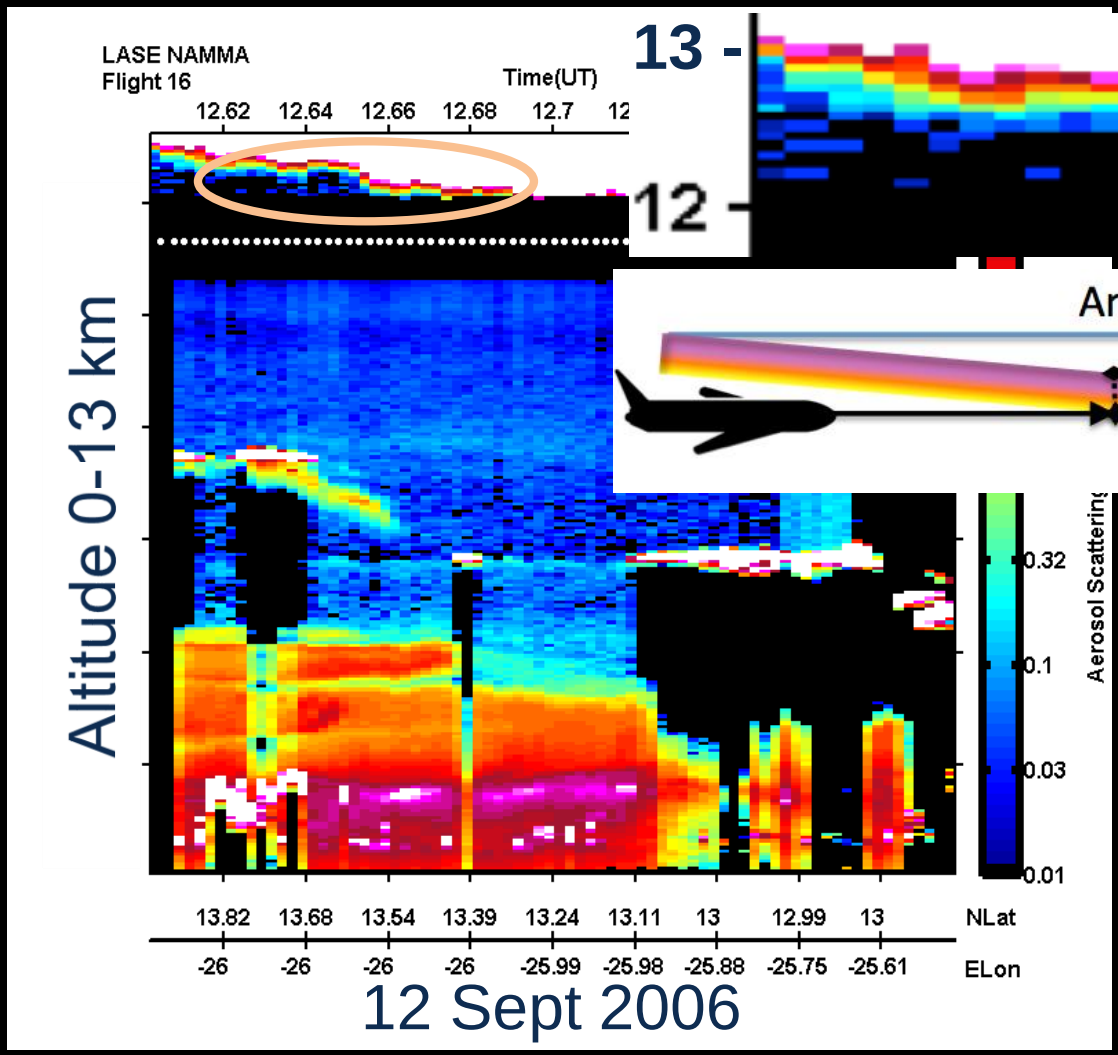
Statistically significant enhancement from background to pre-cloud edges: N_p> 0.3 μm (shown), N_p>0.7 μm, aerosol scattering coeff

Aerosol Enhancement Zone (AEZ) for this study

Enhancement extends ~10-15 km from cloud, similar to satellite "transition zone" or "halo"

but not due to hygroscopic growth (measured dry), cloud contamination or new particle production

Aerosol Enhancement Zone evident from Onboard Lidar



- ~13 km horizontally along aircraft track
- Relative humidity of AEZ is ~60-70% with respect to ice

➔ AEZ is likely residual dust aerosol from sublimated ice crystals at anvil base =>

➔ Source of future upper level clouds

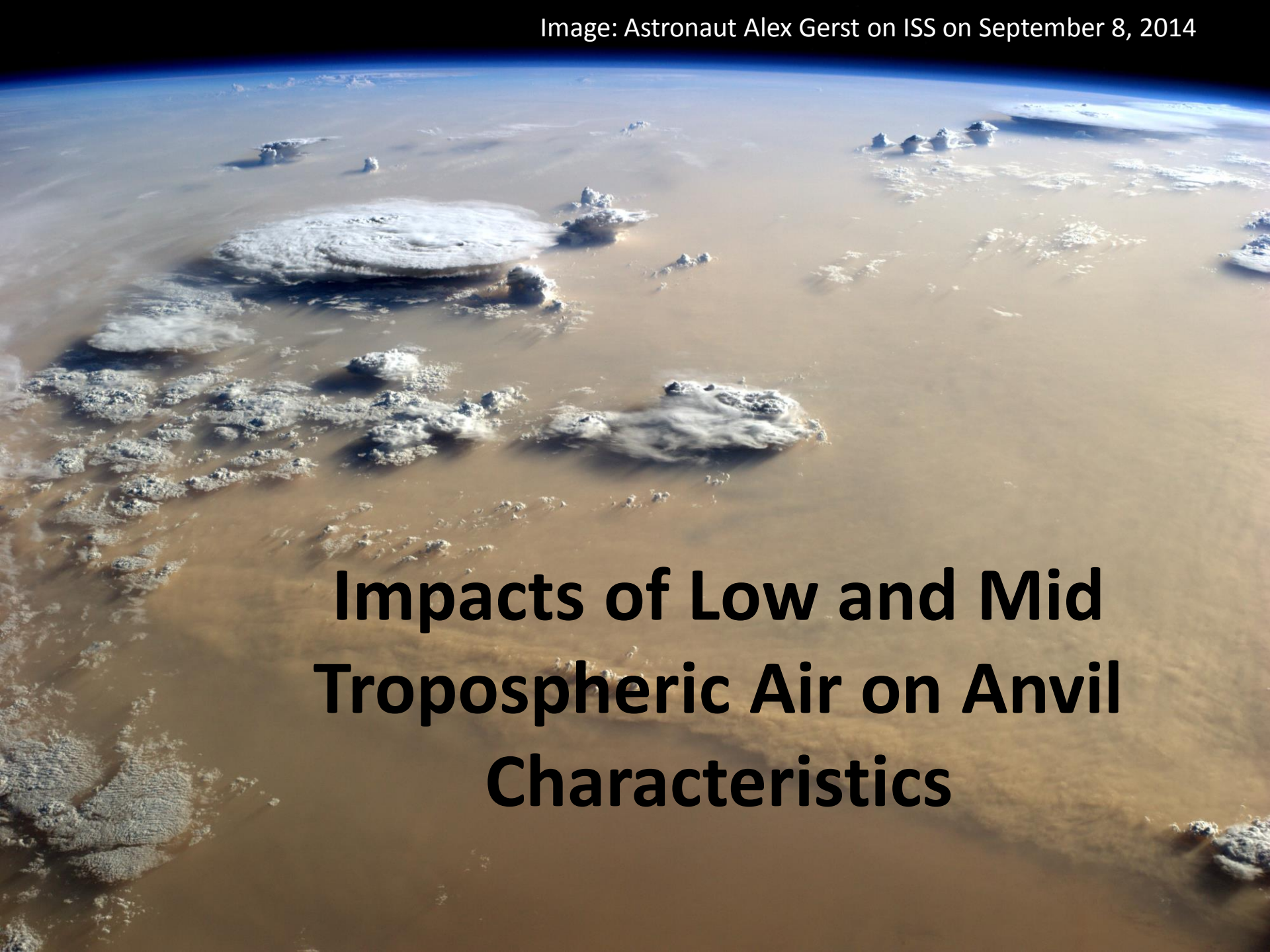
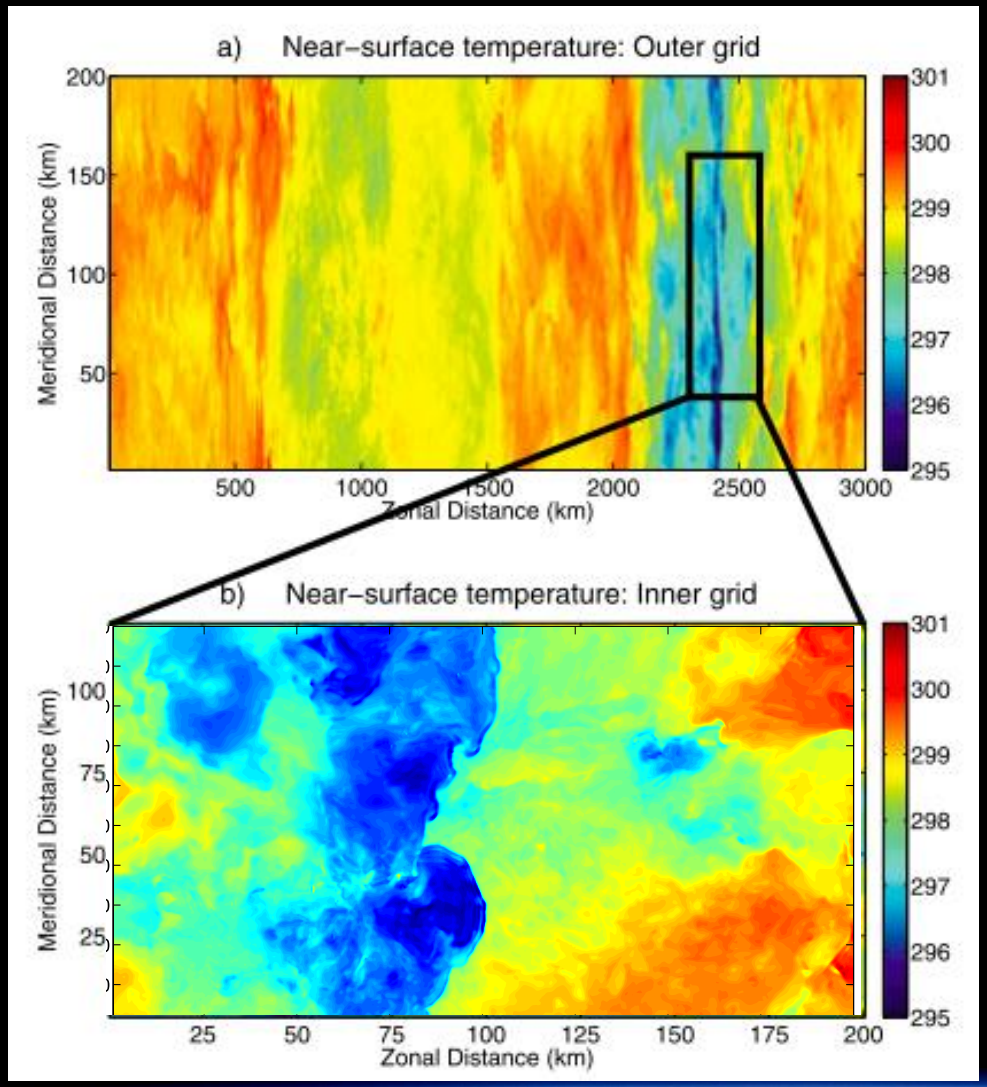


Image: Astronaut Alex Gerst on ISS on September 8, 2014

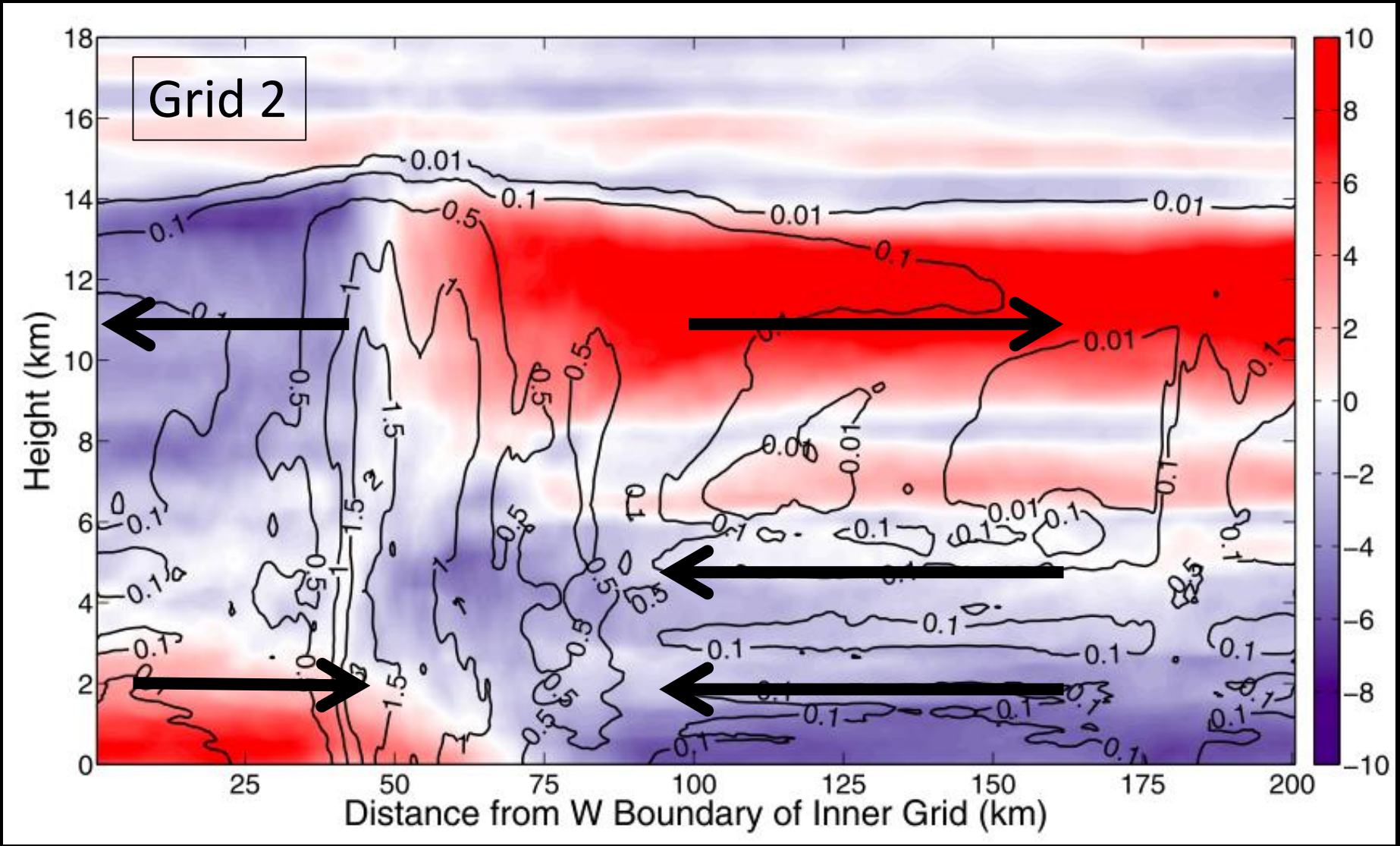
Impacts of Low and Mid Tropospheric Air on Anvil Characteristics

Nested Grid Setup



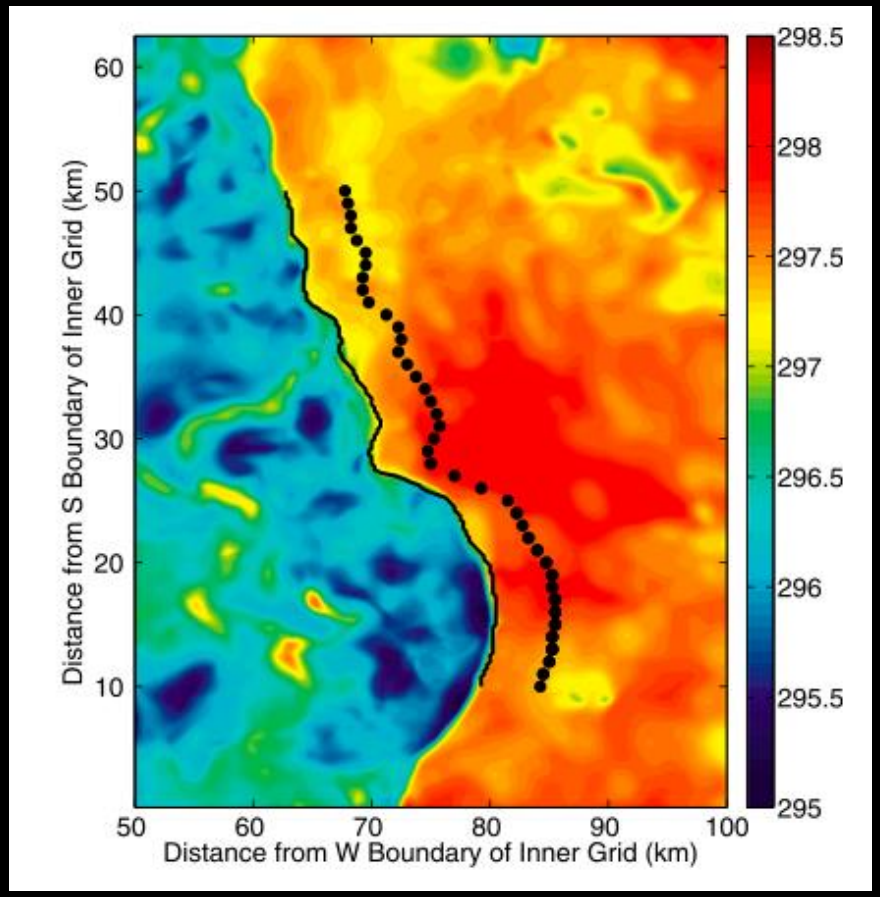
- Grid 1 – environment approaching RCE
- Grid 2 - 250m horizontal grid spacing and 65 vertical levels
- Line of convective cells develops and propagates toward the east along a convergence

McGee and van den Heever 2014



Profile of meridionally averaged zonal wind (shading; m/s) and total condensate mixing ratio (black contours; g/kg)

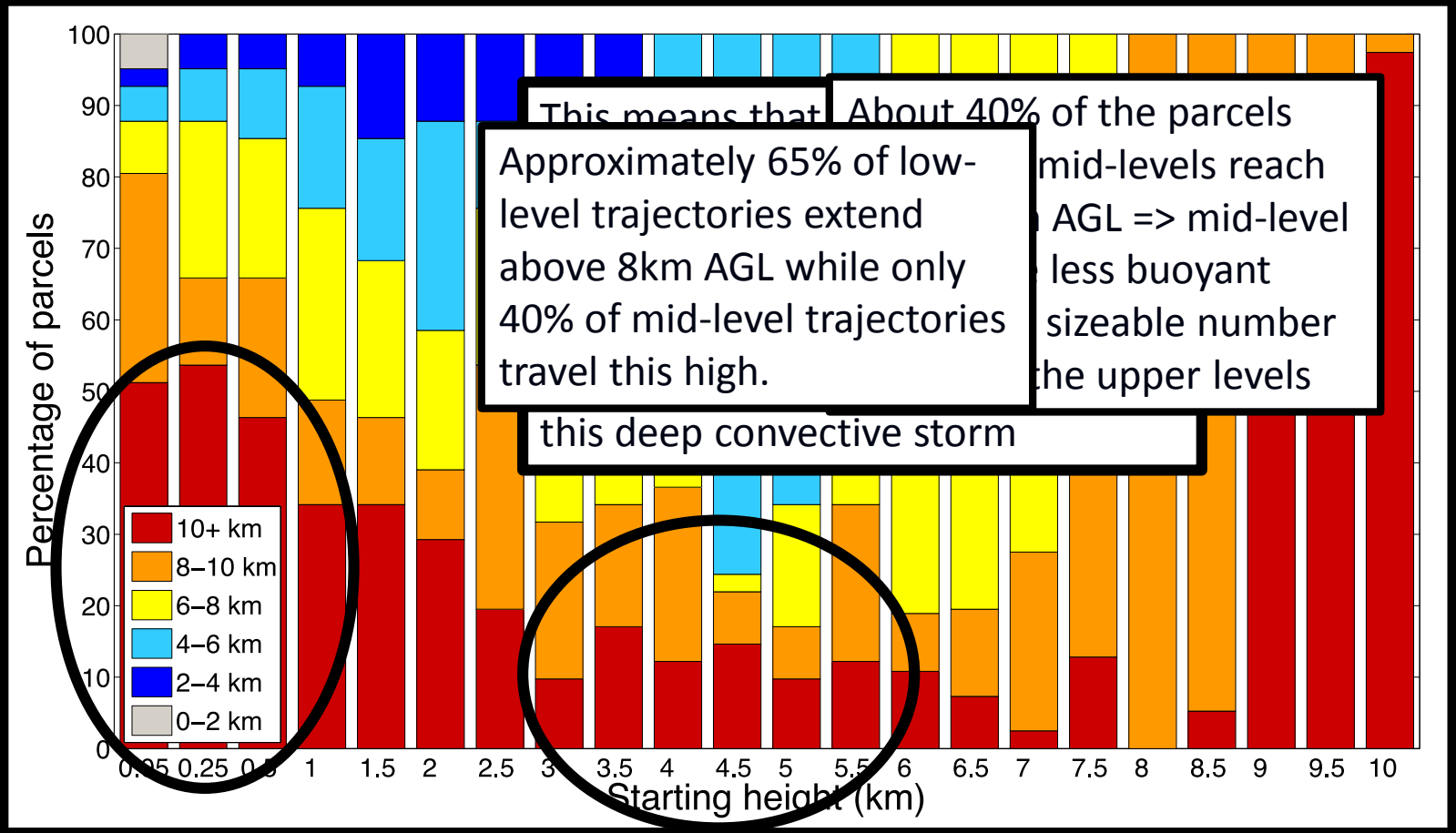
Forward Trajectories



- 873 forward trajectories initiated in a "curtain" 5km east of surface cold pool
- Placed 1km apart in meridional direction and at heights of 50m, 250m, 500m and every 500m after that up to 10km AGL
- Inflow environment is very moist and nearly saturated up to 600 hPa Environmental lapse rate closely follows moist adiabat

(solid black line)

Results: Deep Convective Inflow



Results: Factors Impacting θ_e Profiles

$$\Delta\theta_e \approx \frac{L_v}{c_p}\frac{\theta_e^t}{T^t}(\mathrm{ICE}^t) + \mathrm{mixing}^t + \mathrm{radiation}^t$$

$$\Delta\theta_e \approx \frac{L_v}{c_p}\frac{\theta_e^t}{T^t}(\mathrm{ICE}^t) + \mathrm{mixing}^t$$

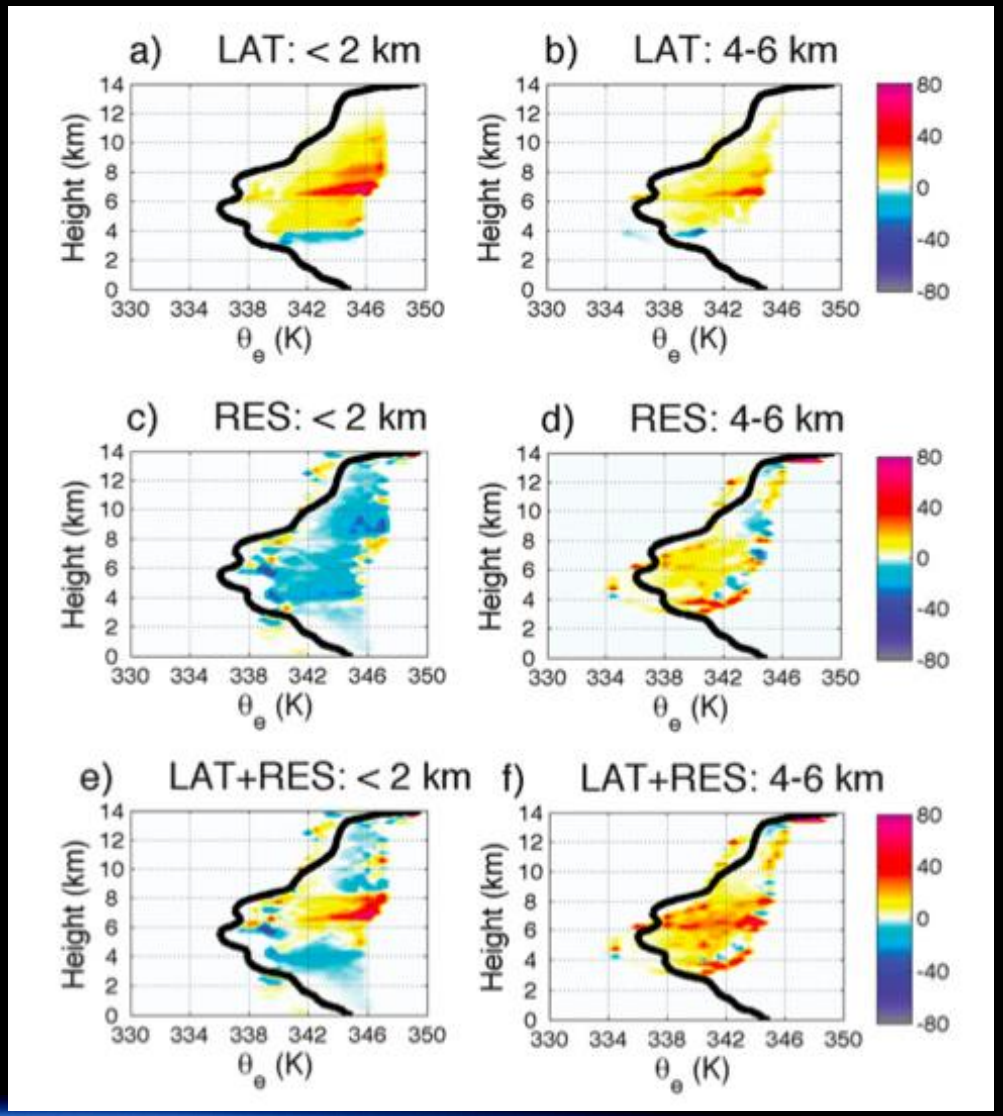
Contributions from radiation determined to be very small => changes due only to ice processes and mixing

We can calculate ice processes and the change in θ_e directly from the model output => mixing calculated as a residual

Results: Factors Impacting θ_e Profiles

(a,b) Average latent heating due to ice processes (LAT);
(c,d) average heating rate due to mixing (RES);
(e,f) LAT + RES.

Left (right) column is for trajectories that begin between 0-2km AGL (4-6 km AGL). The black curve is representative of the near-storm environment.

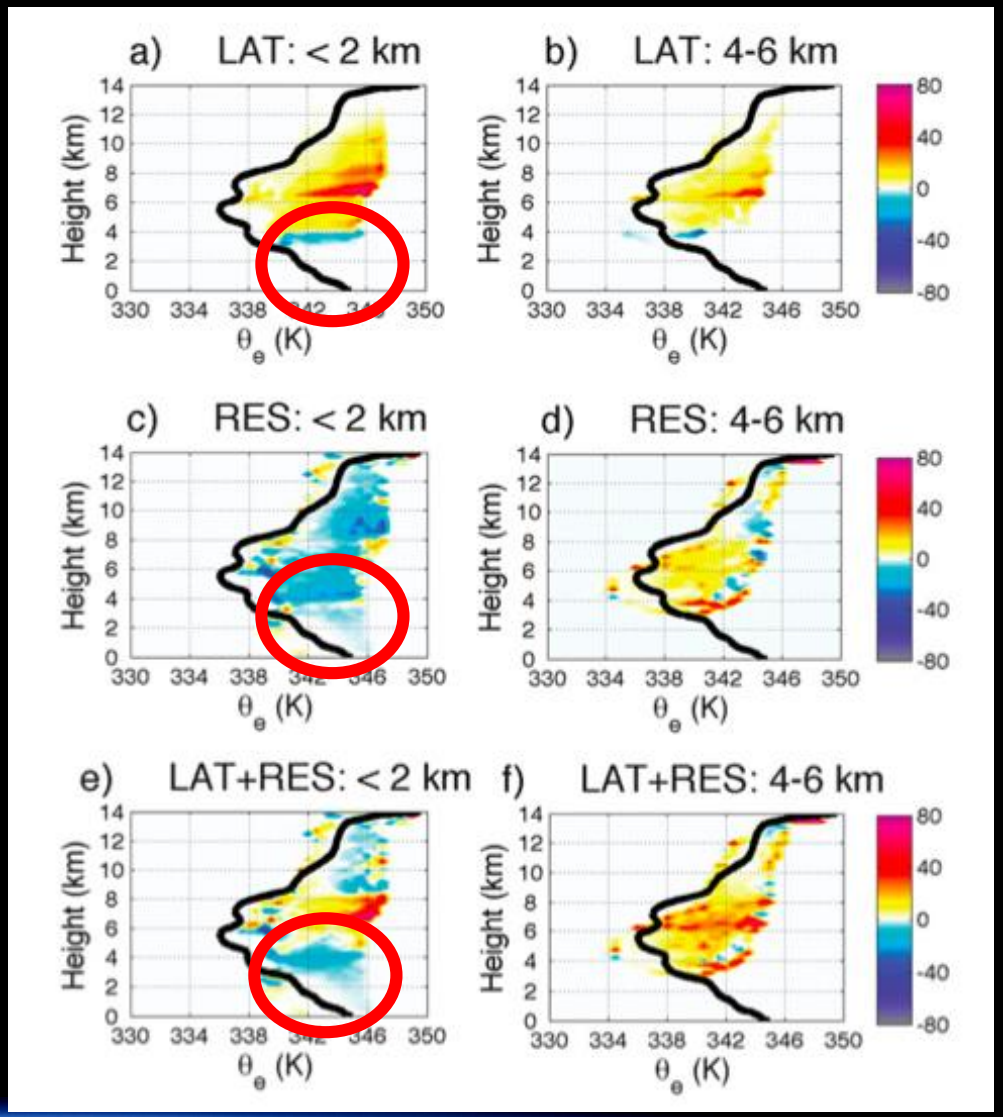


Results: Factors Impacting θ_e Profiles

RES implies that trajectory air is mixing with higher (lower) θ_e air.

RES and LAT are negative from the surface to ~4km AGL for 0-2km trajectories.

As the environmental profile of θ_e decreases with height and LAT is zero in the lower troposphere, negative RES => entrainment of drier / cooler air.

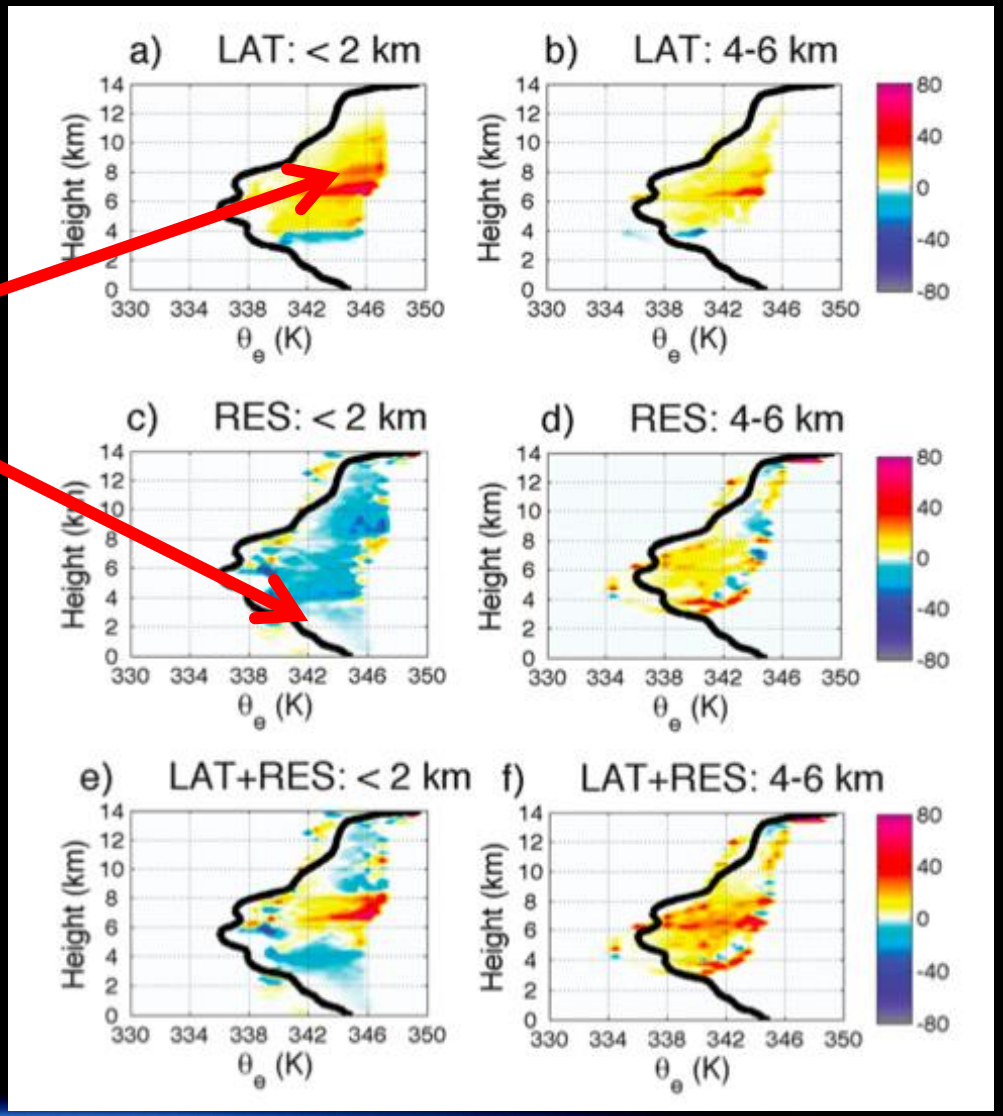


Results: Factors Impacting θ_e Profiles

For those parcels starting near the surface, θ_e:

1. decreases in the lower levels due to entrainment
2. increases in the mid- to upper-levels due to ice processes

Entrainment between 4 and 6km AGL offsets the latent heating due to condensation.

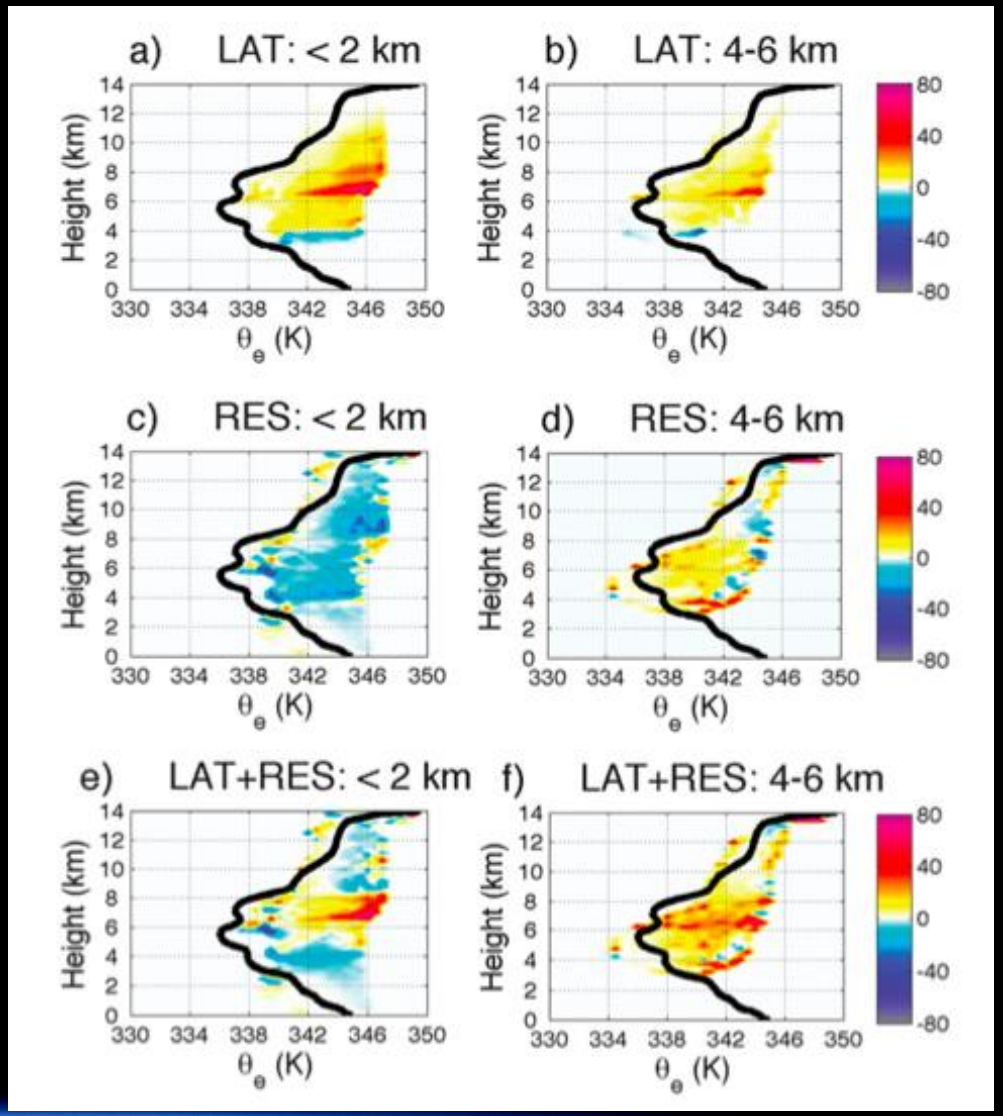


Results: Factors Impacting θ_e Profiles

For trajectories starting between 4 and 6km AGL (right column):

1. LAT is similar to those starting between 0 and 2km AGL, although smaller in magnitude.
2. RES is positive through most of the troposphere due to mixing with the higher θ_e air of the convective cores.

The updrafts become diluted and weaker as a result.



Summary

1. Bulk Characteristics of Deep Tropical Convection as Understood using RCE CRM Simulations
2. Bulk Tropical Deep Convection Characteristics from CloudSat
3. Environmental Impacts on Tropical Deep Convection
4. New Cirrus (Anvil or Otherwise) Formation
5. Impacts of Low and Mid Tropospheric Air on Anvil Characteristics