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Pacific Northwest National Laboratory is seeking an experienced global atmospheric modeler to join our team and help lead our climate science enterprise

For more information contact: Gary.Worrell@pnnl.gov, (509) 372-4721

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When do the details matter?: Being mindful of overlooked or neglected aspects of Earth System Modeling

Phil Rasch and Collaborators

- Computational Issues
- Physical Processes, and Parameterization Complexity

Computational Artifacts in Climate Models

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Hui Wan, Phil Rasch*, Shixuan Zhang, Kai Zhang (PNNL)
Xubin Zeng (U. Arizona)

- Modern parameterizations are getting more and more sophisticated, e.g.
  - Detailed aerosol lifecycle
  - Detailed cloud microphysics
  - High-order closure for turbulence
  - ”Scale-aware” parameterizations
- Wider spectrum of time scales
- Bigger challenge for time integration
- Computational Artifacts are frequently compromising solutions

Quantifying and Reducing Numerical Errors in Global Climate Models

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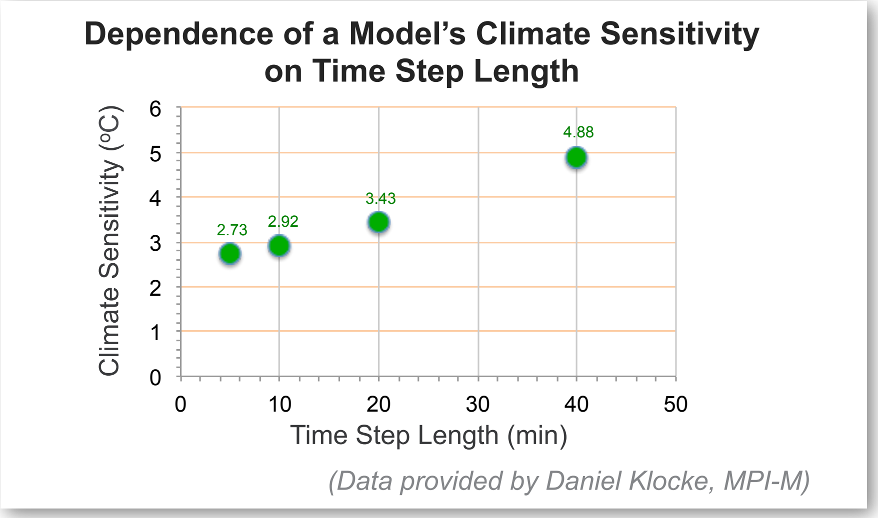
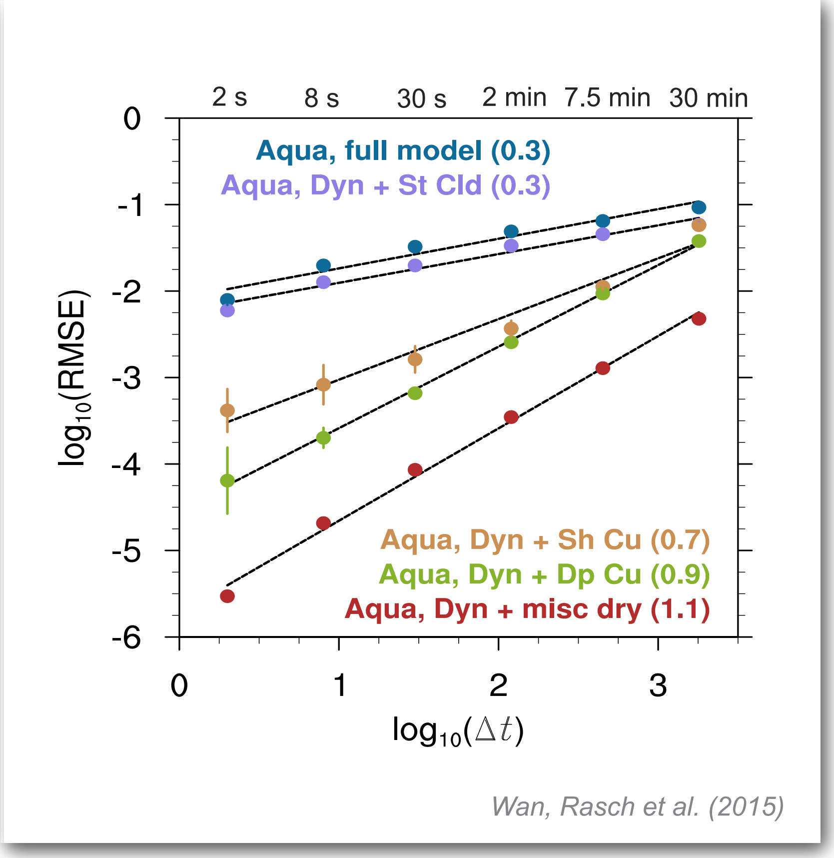
Examples of numerical artifacts

MPI-ECHAM



Our time step convergence test

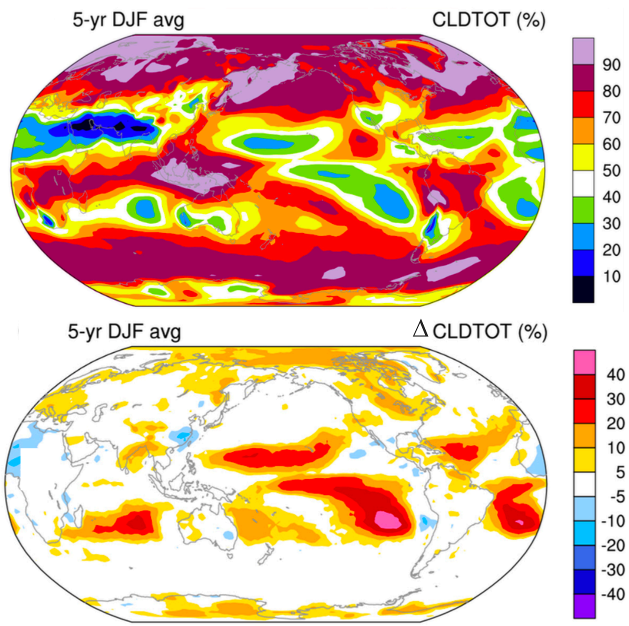
is a simple method to identify some sources of numerical error



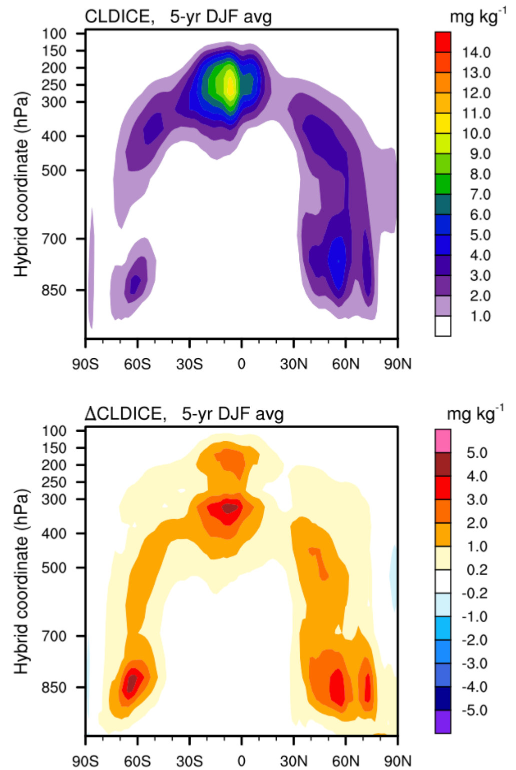
Present-day Climate Simulations

- Time-step sensitivity in CAM5

Total Cloud Cover



Cloud Ice Mass Concentration



Default model (2-degree FV, 30-min step size)

Difference due to reduction of step size to 4 min

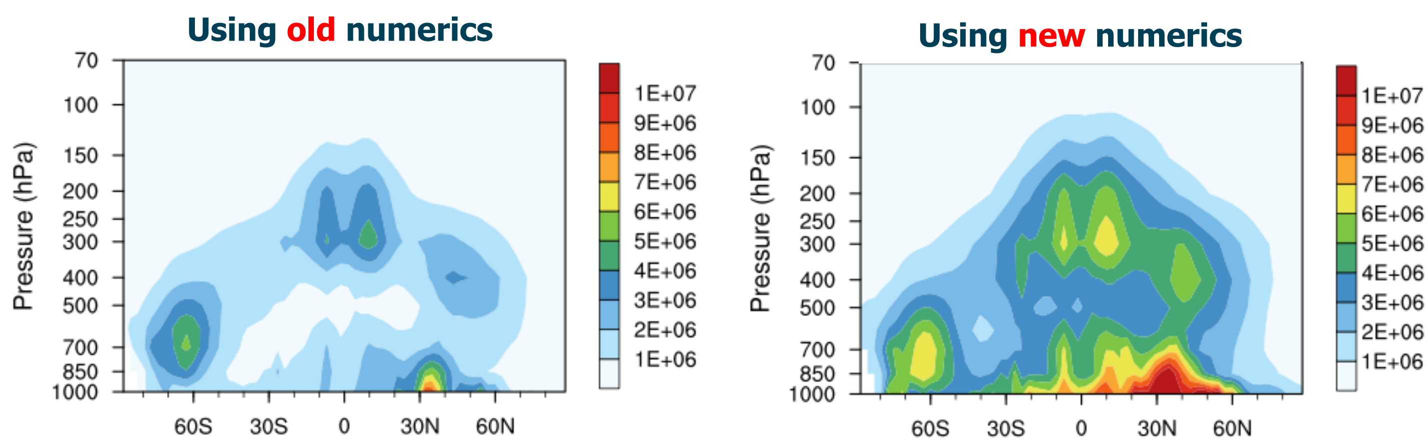
Wan, Rasch et al. (2014, GMD)

- E3SM v0 uses a different dynamical core but shows very similar results, indicating the issues are in the parameterizations

A Story from ECHAM-HAM

- 2008-2011, aerosol module upgrade from version 1 to version 2
- Modified time stepping overwhelmed the impact of new aerosol nucleation scheme

H_2SO_4 gas concentration (unit: cm^{-3}), zonal and annual mean (note the logarithmic color scale)



Wan, Rasch et al. (2013, GMD)

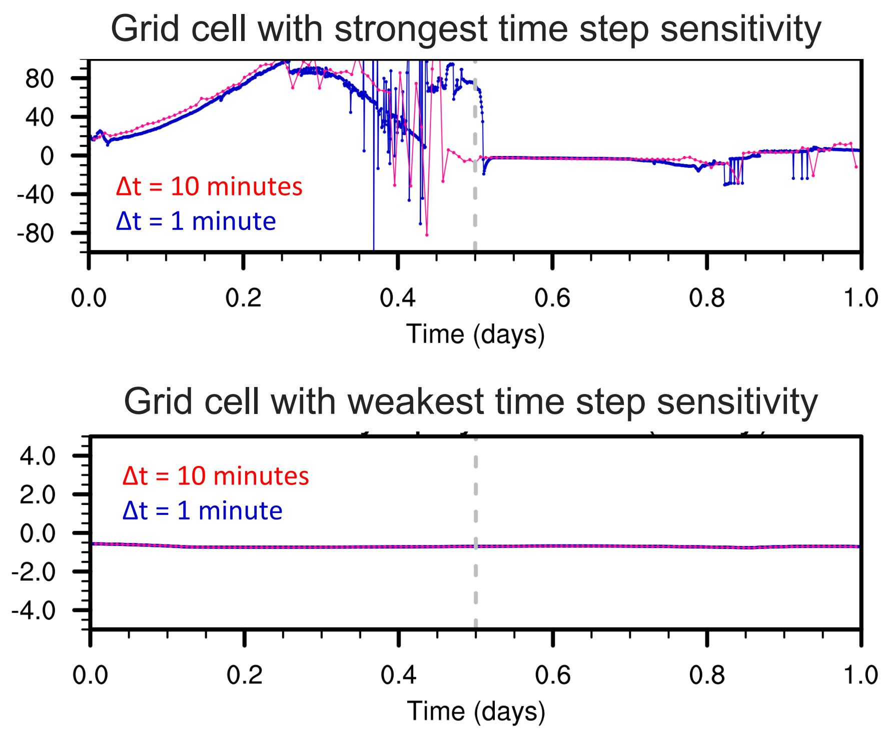
- Time stepping error in old scheme compensated by very strong clipping
- Balance between processes substantially biased
- More accurate solution obtained without significant increase in CPU time
- Same problem has been seen in CAM5-MAM

Connection to Other Properties

In CAM5/E3SM, **poor convergence** of global solution is typically caused by grid cells with clouds that show

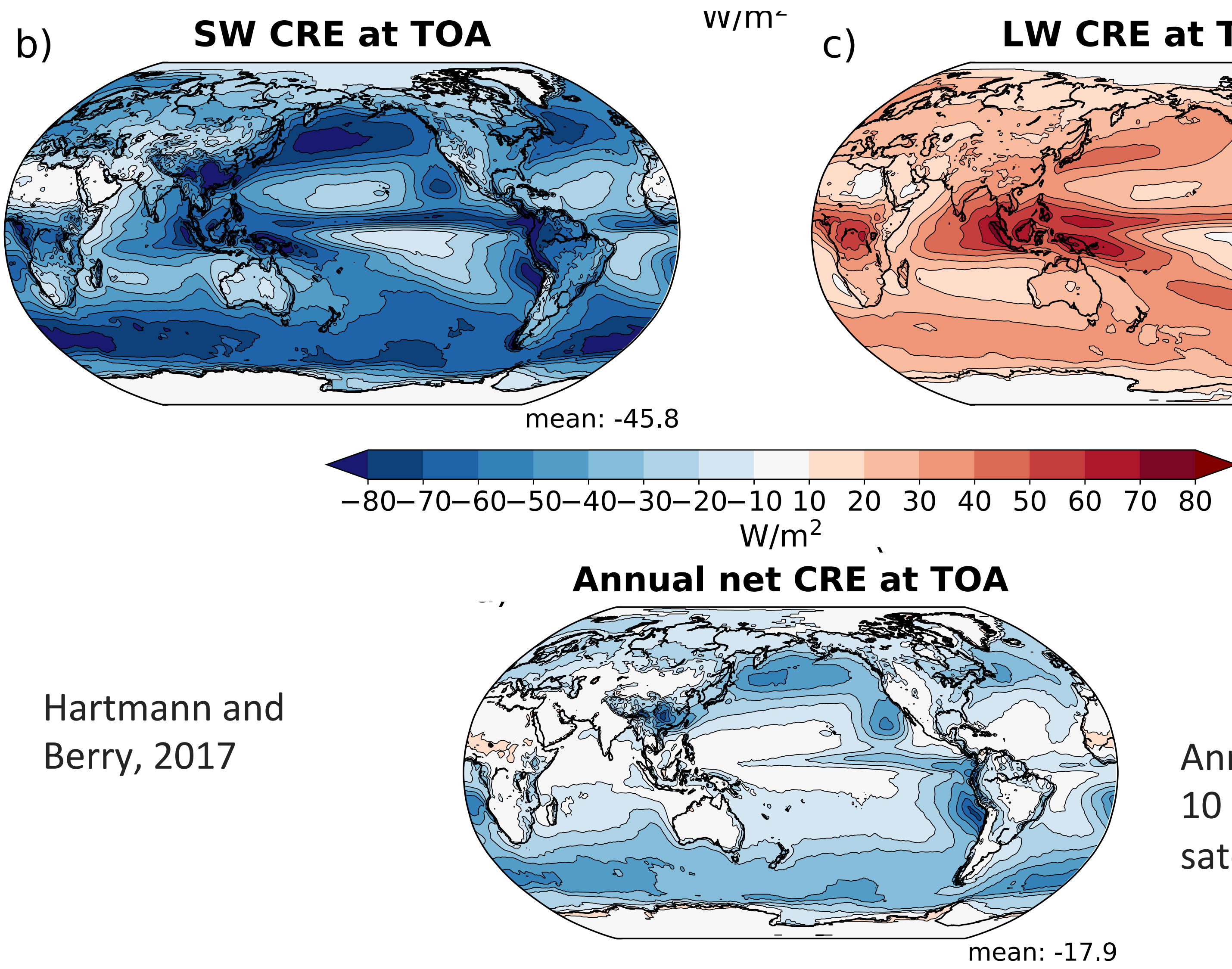
- Strong time step sensitivity
- Very noisy time series
- Very large physics tendencies that are likely unphysical

1-day time series of T tendency (K/day) at 700 hPa from E3SM v0 physics



Challenges in Producing a Consistent Physical Treatment of processes (a progress report)

Blaž Gasparini, Dennis Hartmann, Sara Berry, Peter Blossey (UW)



Hartmann and Berry, 2017

Annual net CRE from 10 years of CERES satellite data

Which cloud types are most common in deep tropics (focus on tropical western Pacific [TWP])?

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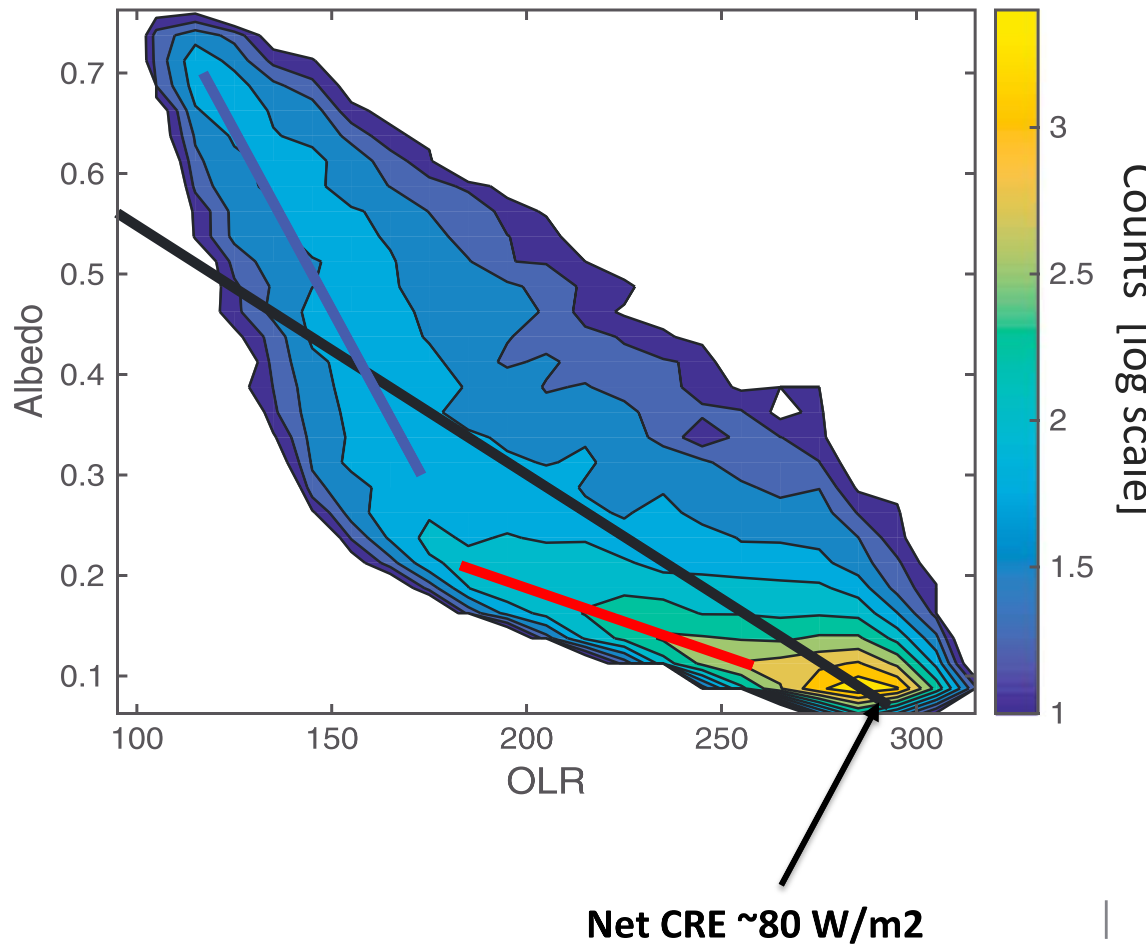
CERES outgoing longwave radiation [OLR] vs. (total) albedo histograms



Hartmann and Berry, 2017

Cloud Type from Cloudsat Calipso

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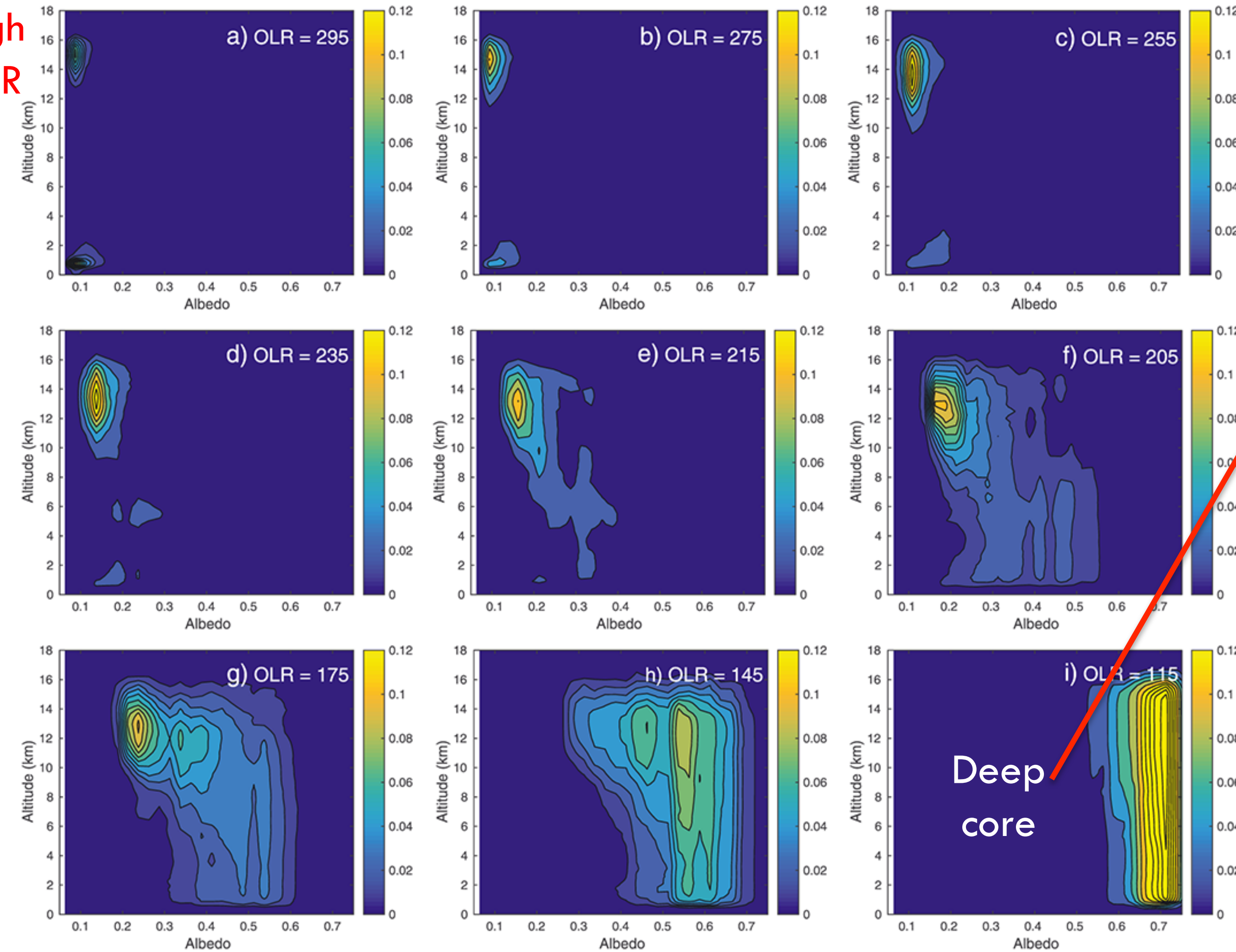
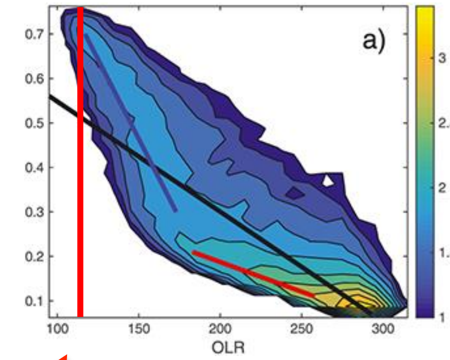
High
OLR





LOW
OLR

Hartmann and
Berry (2017)

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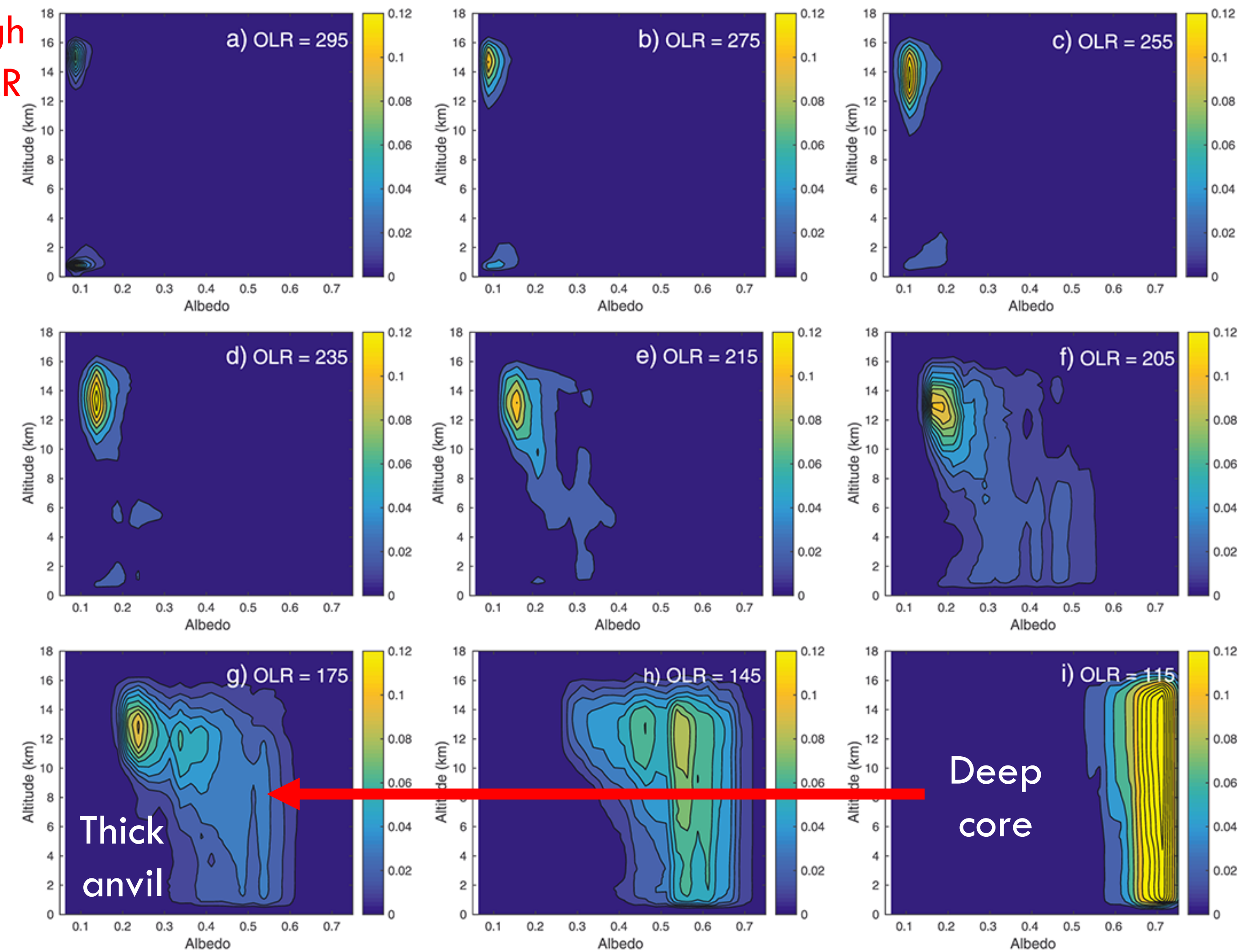

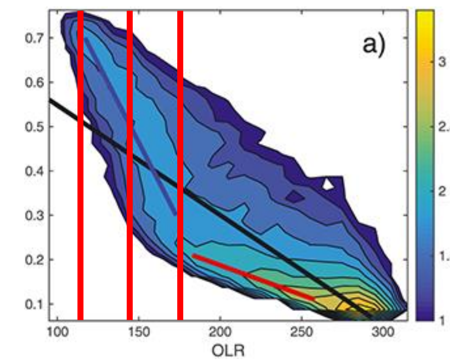

Slide courtesy Sara Berry

Hartmann and Berry (2017)

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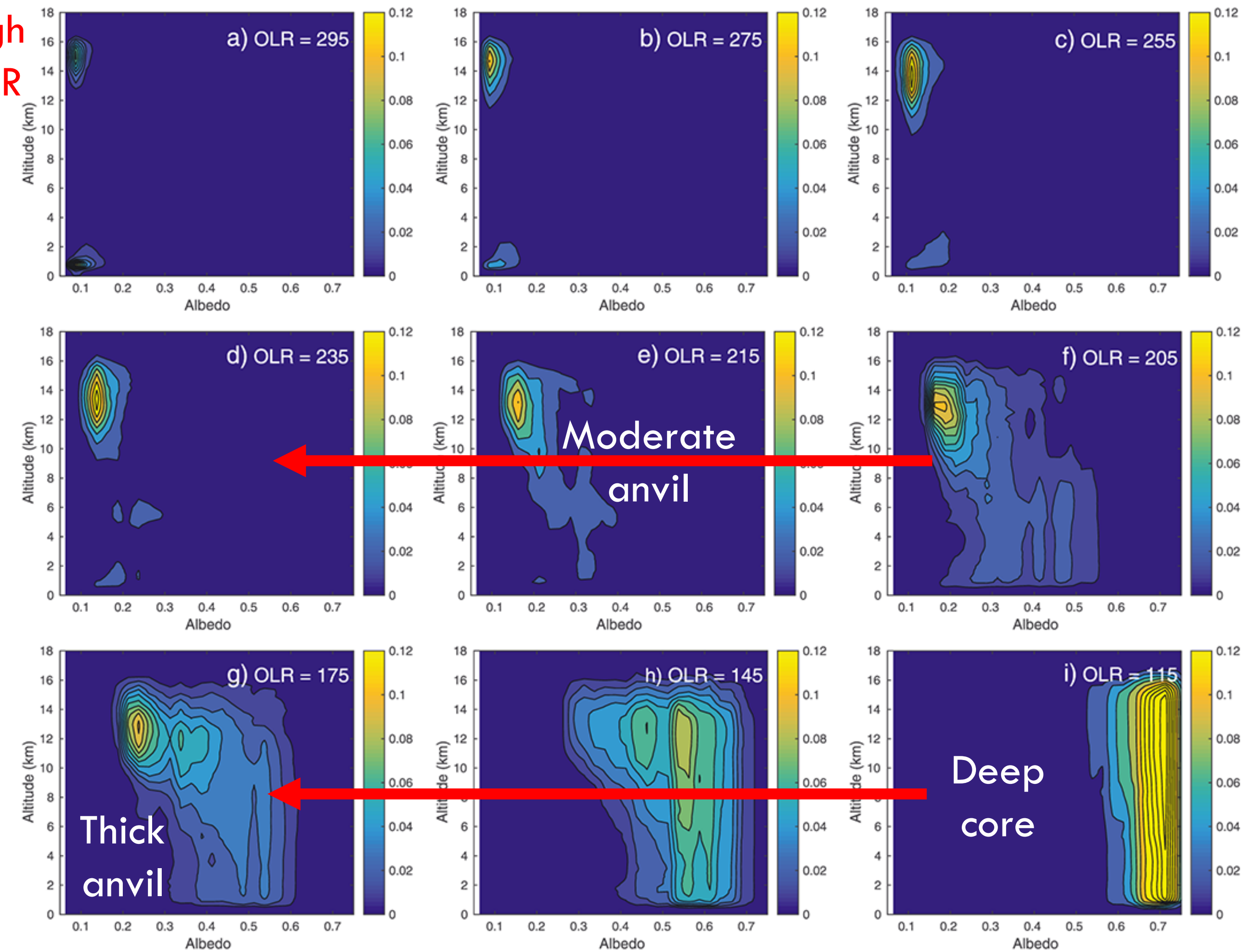
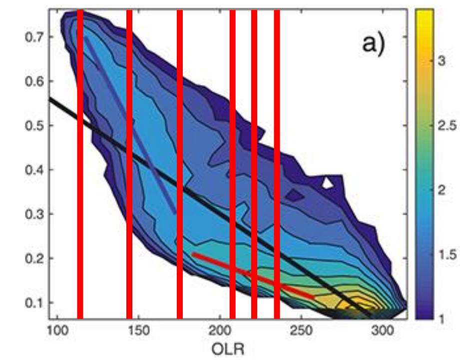
High OLR



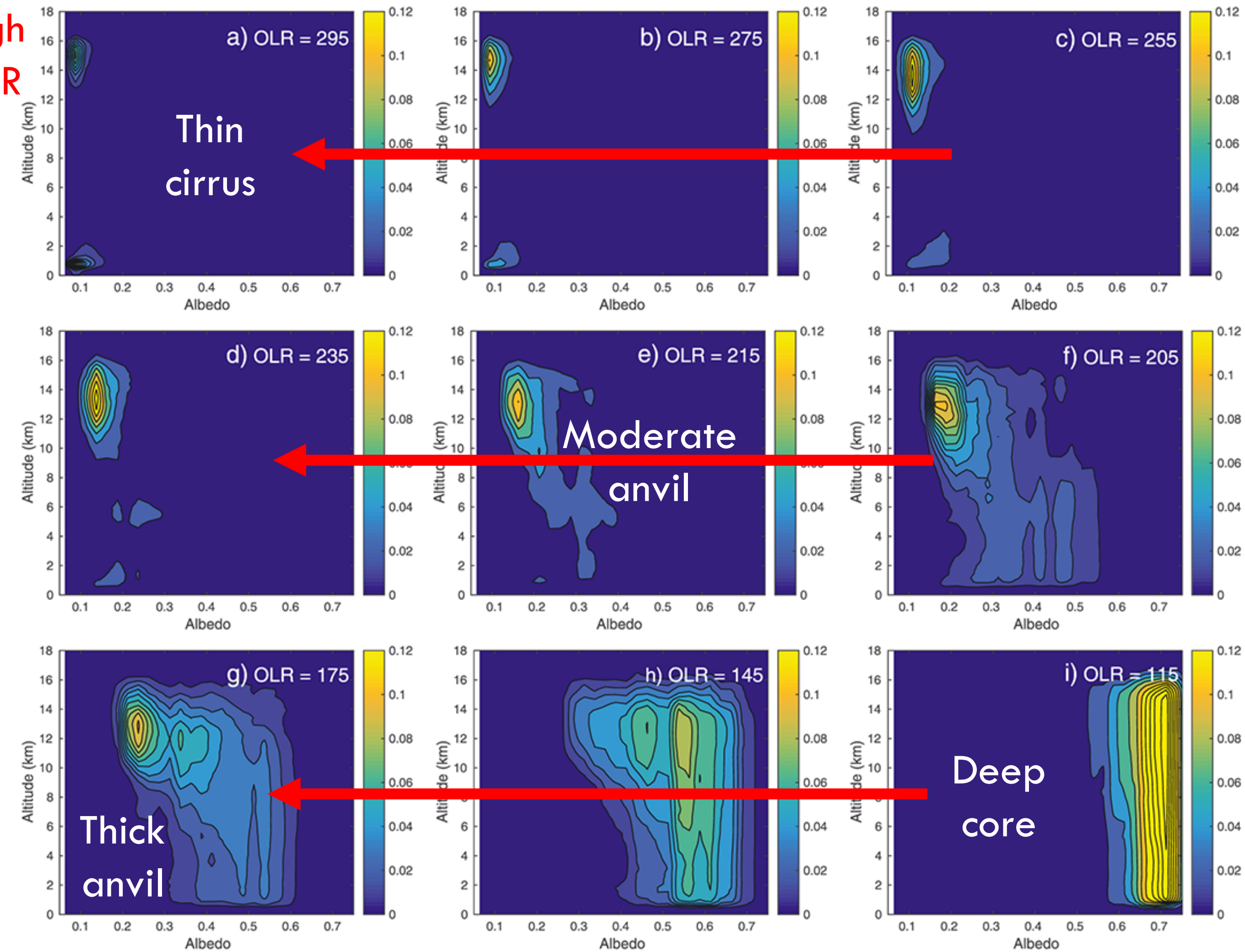


Slide courtesy Sara Berry

LOW OLR

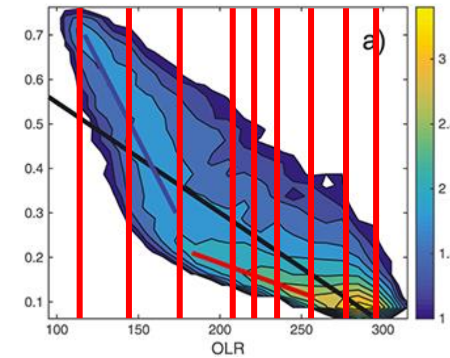
Hartmann and Berry (2017)

High OLR



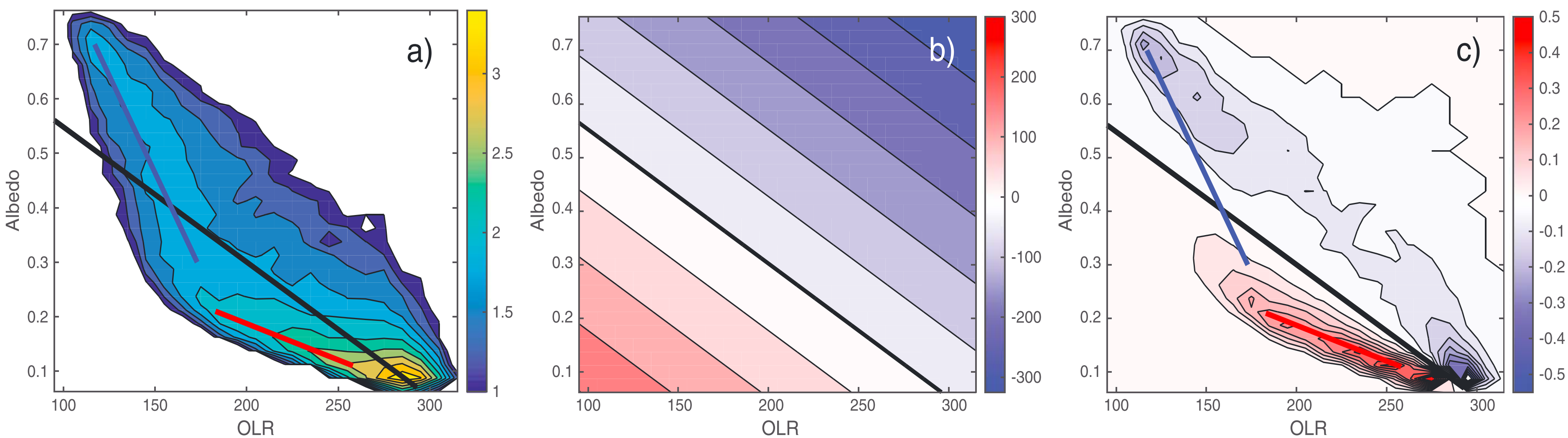
LOW OLR

Hartmann and Berry (2017)



Slide courtesy Sara Berry

How do these clouds impact the net CRE in TWP?

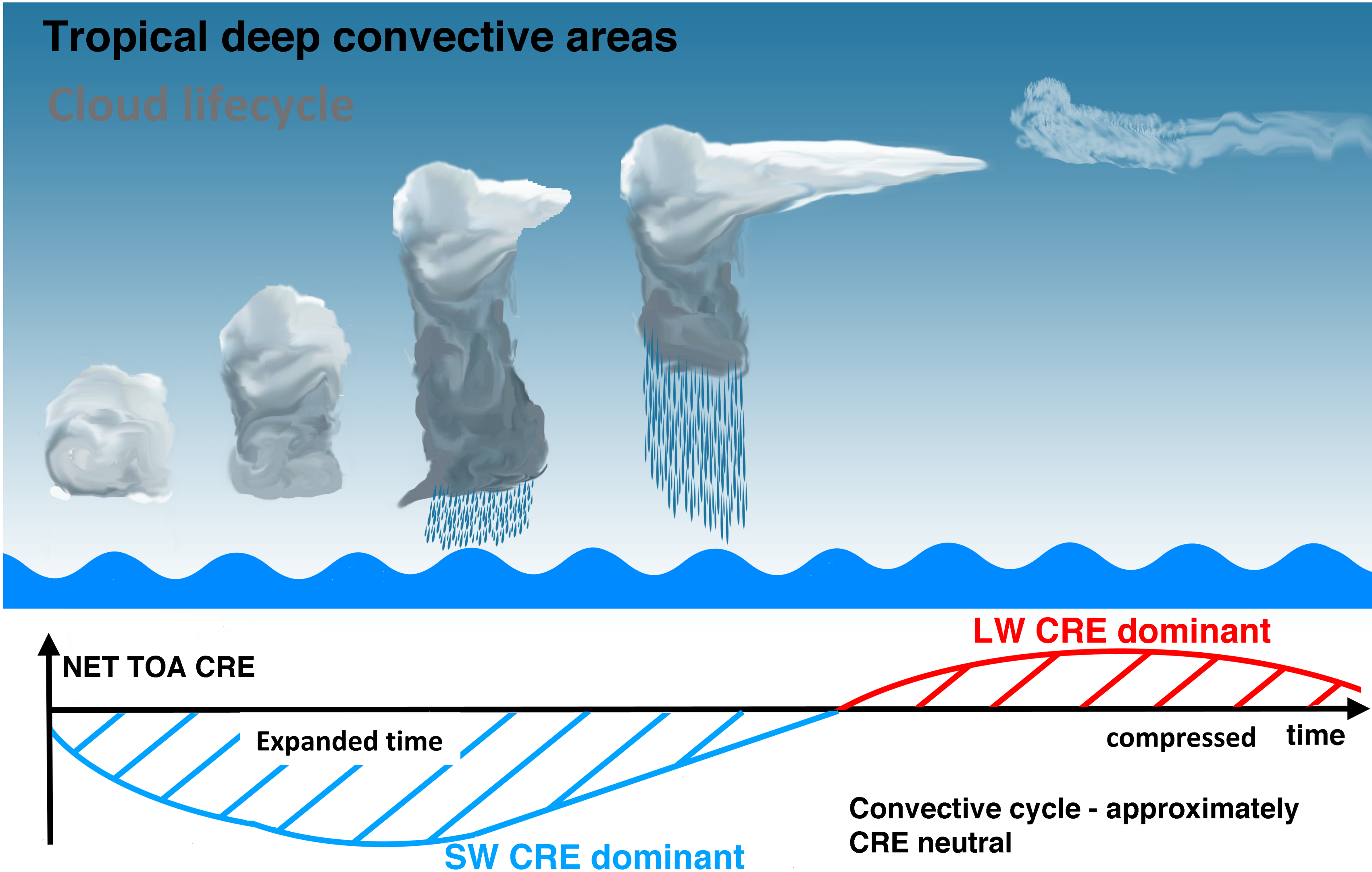


Occurrence
Histogram
log scale

Net CRE
Black line is 80W/m2
contour interval is 50Wm^{-2}

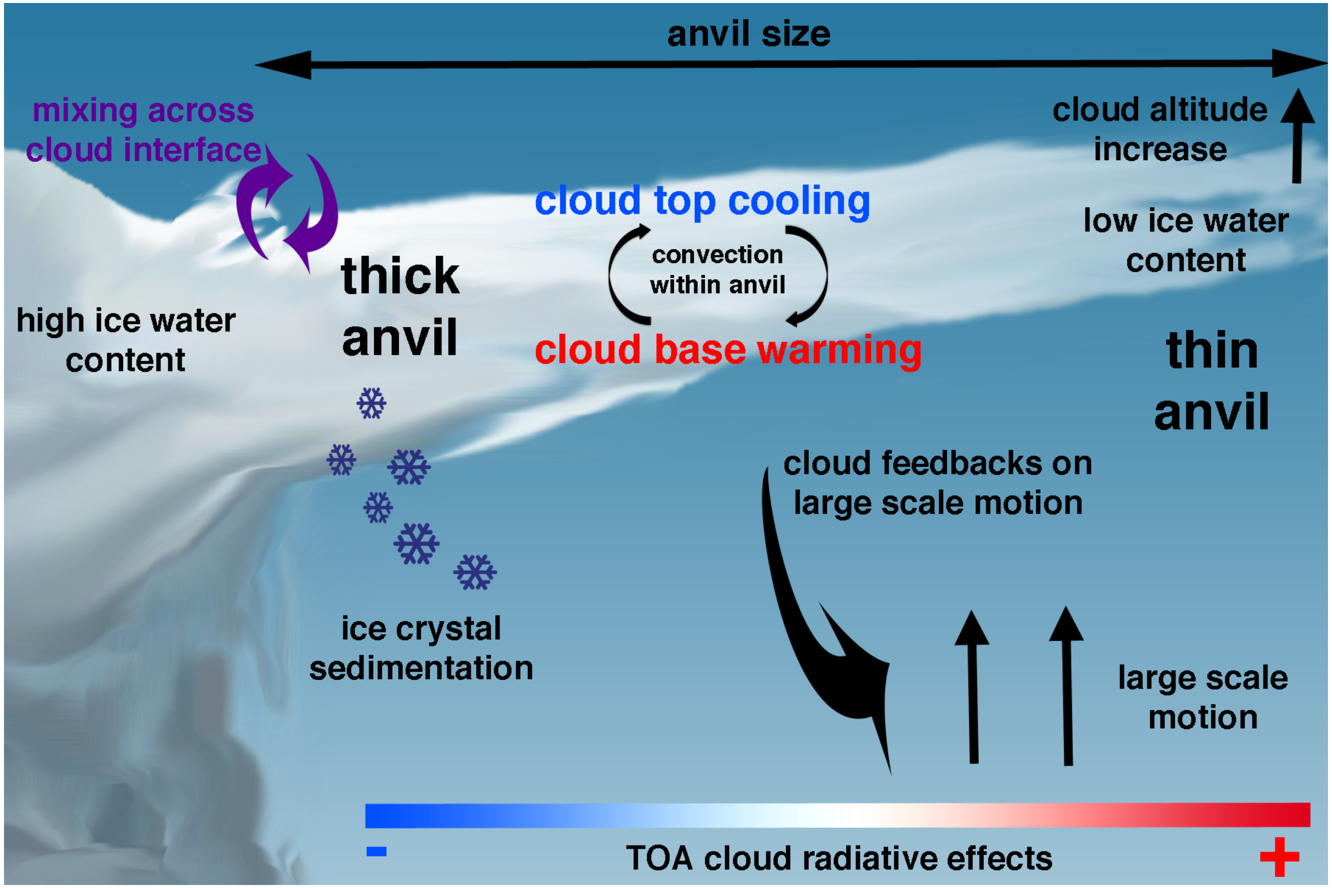
Relative contribution of
Cloud type to CRE Anomaly

Lifecycle of clouds



“radiative heating drives tropical anvil clouds toward a particular distribution of anvil cloud optical thickness that favors a near neutral radiation balance “

Cirrus anvil – a complex interaction of several processes



Processes controlling anvil properties:

- Microphysics and associated diabatic heating
- Sedimentation
- Radiative cloud effect
- Entrainment/ turbulence
- Large scale motion

Cloud resolving model simulations

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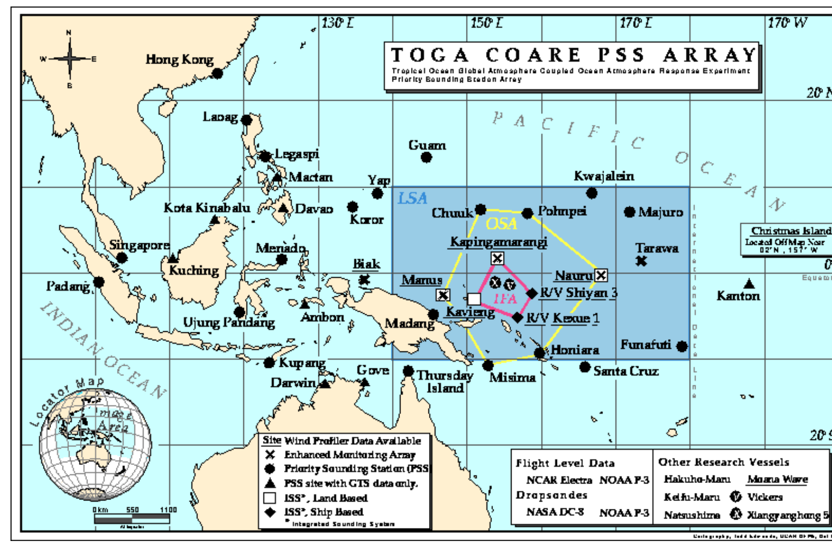
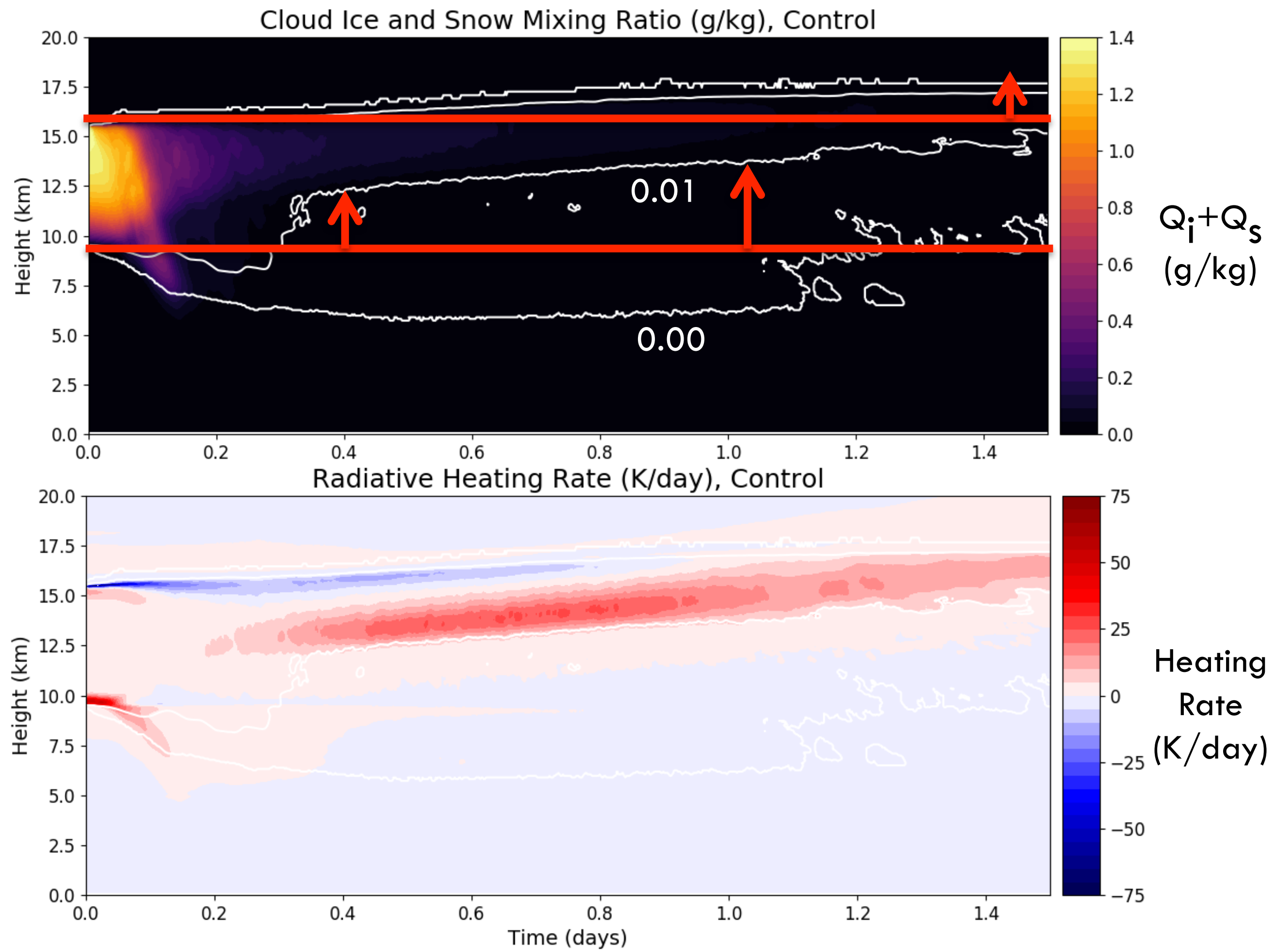
- SAM cloud resolving model [Khairoutdinov and Randall (2003)]
- Periodic boundary conditions
- Either 2D or 3D domain
- Horizontal and vertical resolution:
  - 250 x 25 m in 2D (Sara Berry's MSc Thesis)
  - 250 x 100 m in 2D
  - 250 x 100 m in 3D
  - 250 x 600 m in 3D
  - 2 km x 600 m in 3D
- Morrison 2005 (**M2005**) or Thompson 2008 (**MWRF**) microphysics



6 KM CLOUD

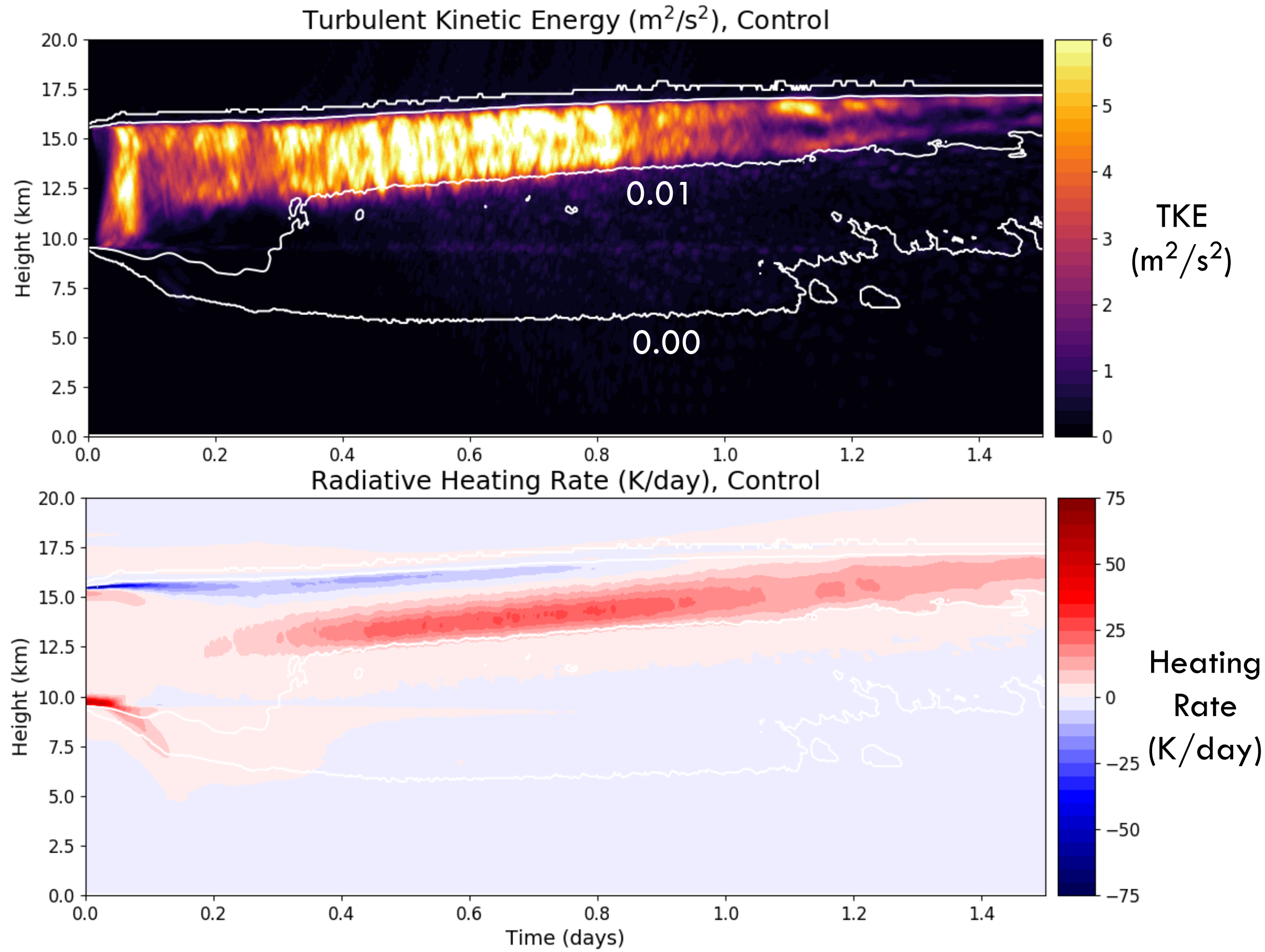
- Cloud rising and thinning
- Radiative dipole develops



Slide courtesy Sara Berry

6 KM CLOUD

- Cloud rising and thinning
- Radiative dipole develops
- Strongest turbulence at intermediate optical depth of cloud



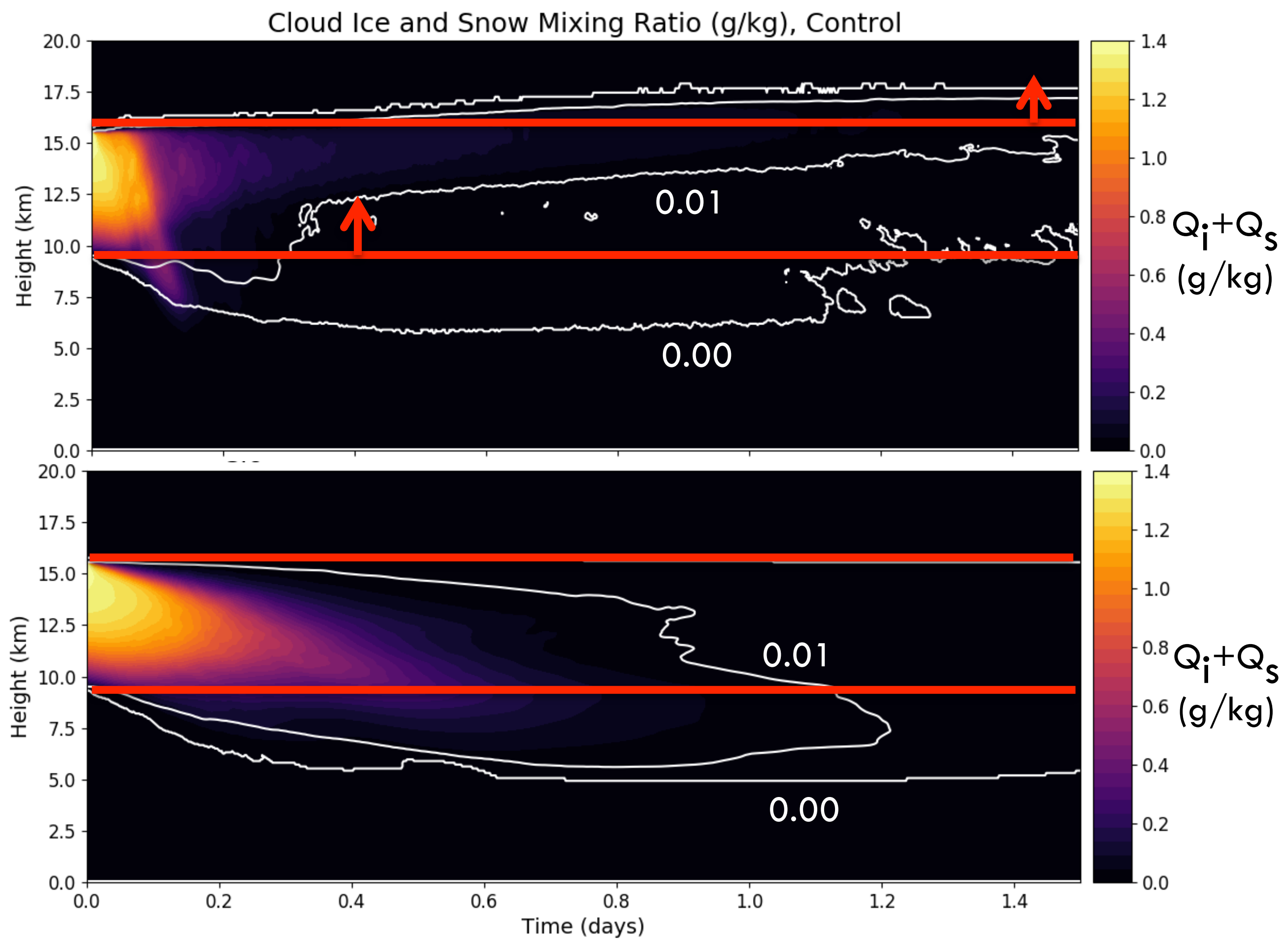
NO INTERACTIVE RADIATION

Slide courtesy Sara Berry

Control

Cloud just sediments out of the atmosphere

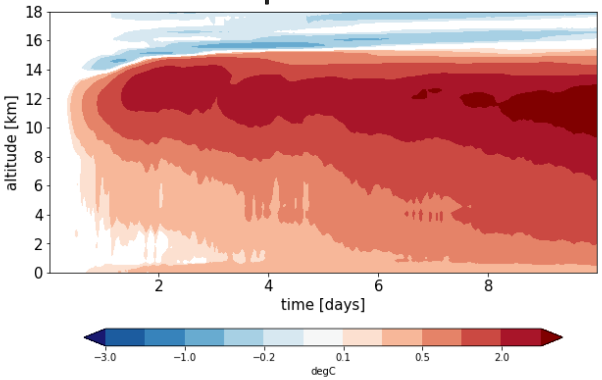
No Radiation



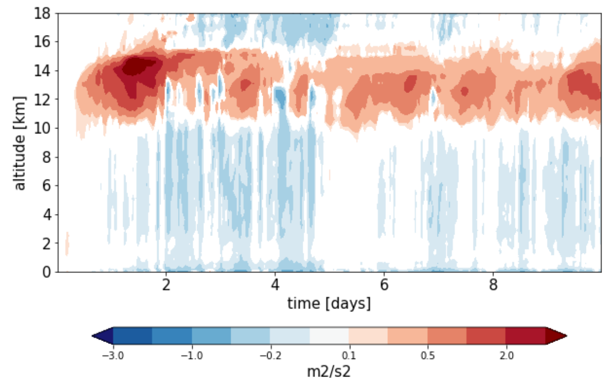
RCE Simulations

Morrison microphysics: RAD - NORAD

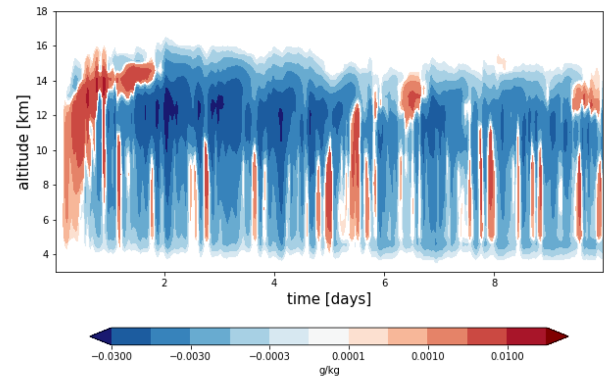
Temperature



TKE



Cloud ice+snow



In-cloud radiative heating results in:

- Lower IWP
- Lower optical depth
- Smaller SW CRE
- LW CRE stays roughly the same
- NET CRE more positive

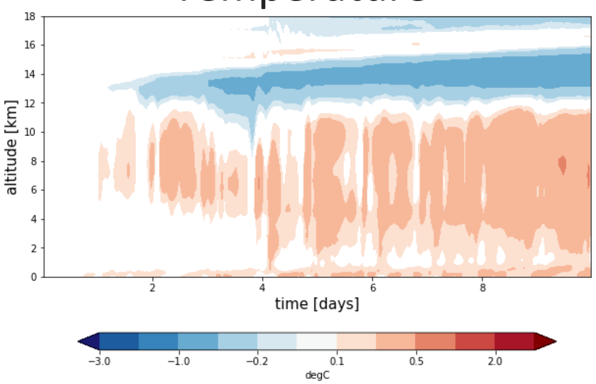
Day 6-10	IWP [g/m2]	COD	LW CRE	SW CRE	NET CRE
M2005	**9.7**	**2.4**	34.1	-35.0	**-0.8**
M2005 norad	**14.9**	**3.4**	35.3	-41.7	**-6.4**

Consistent with Harrop 2016

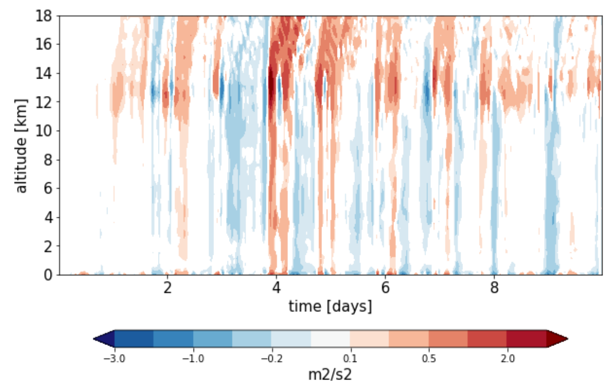
RCE Simulations

Thompson microphysics: RAD - NORAD

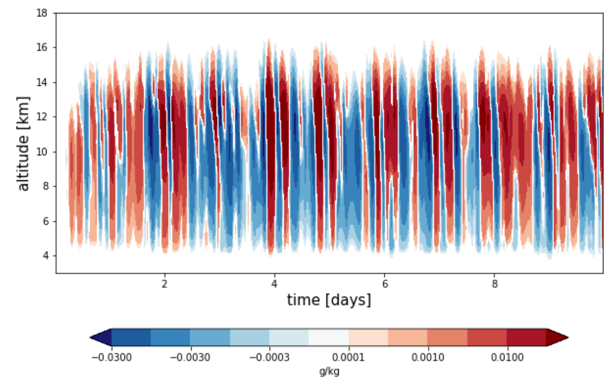
Temperature



TKE



Cloud ice+snow



In-cloud radiative heating results in:

- No large changes, except in temperature
- Without a daily cycle similar changes but much smaller magnitude compared to Morrison

Day 6-10	IWP [g/ m2]	COD	LW CRE	SW CRE	NET CRE
Thomp	4.0	**6.4**	16.5	-32.2	-15.7
Thomp norad	3.5	**7.1**	13.6	-29.0	-15.4

Challenges:

- What are the basic physical processes needed to represent the lifecycle of these clouds?
- How accurate must each component be?
- Can one represent the simultaneous existence of all phases of these clouds if they are treated with sub-grid scale parameterizations?
- How bad are the current formulations at mimicking obs?
  - Do some parameterizations have more potential than others? (ensemble - but not bulk plume- treatments, super-parameterizations?)
  - Are there missing links?
  - What can be done to improve current treatments?

Next Steps:

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1. E3SM evaluation with satellite data, comparison to SAM CRM
   - Radiation, do we get net CRE neutrality
   - Anvil cloud properties
2. Identify the minimum complexity that we need to parameterize the PDF
   - What controls the tropical cloud distributions?
   - What controls the anvil properties?

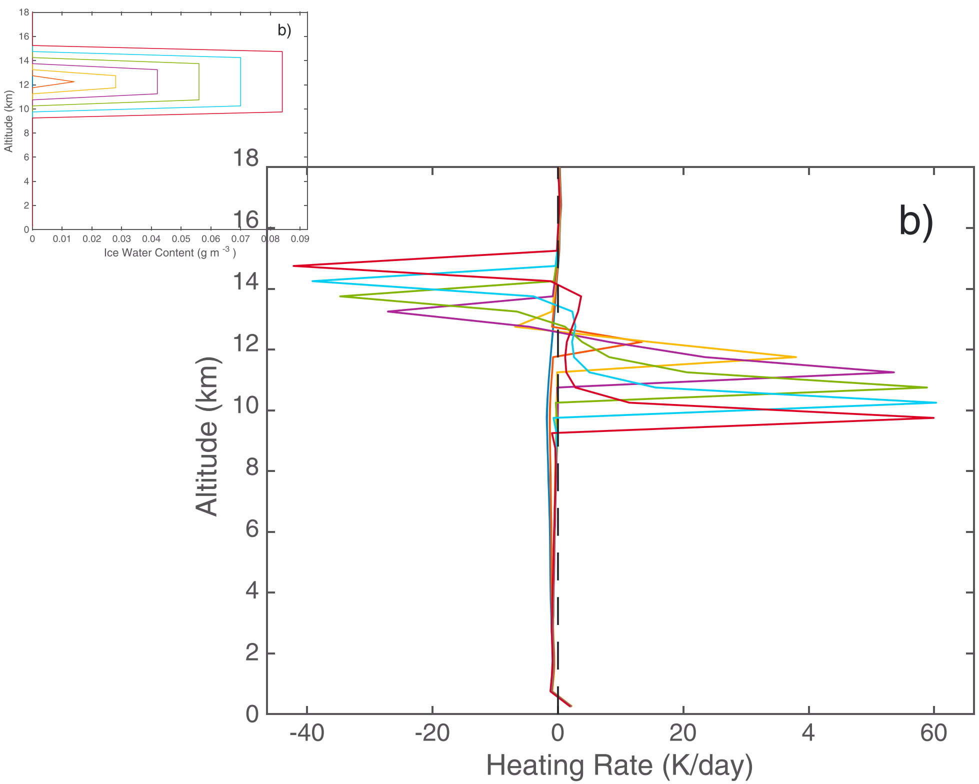
Possible improvements:

- Multiple Cloud Types provided to radiation (per column)?
- Separate Parameterization of core, anvil, and “other” clouds?
- TKE dependent on (cloud top) radiative cooling rates for ice clouds (like Bretherton and Park 2009 for boundary layer clouds)?
- Transport of subgrid cloud fields?

Extra Slides

HYPOTHESIS:

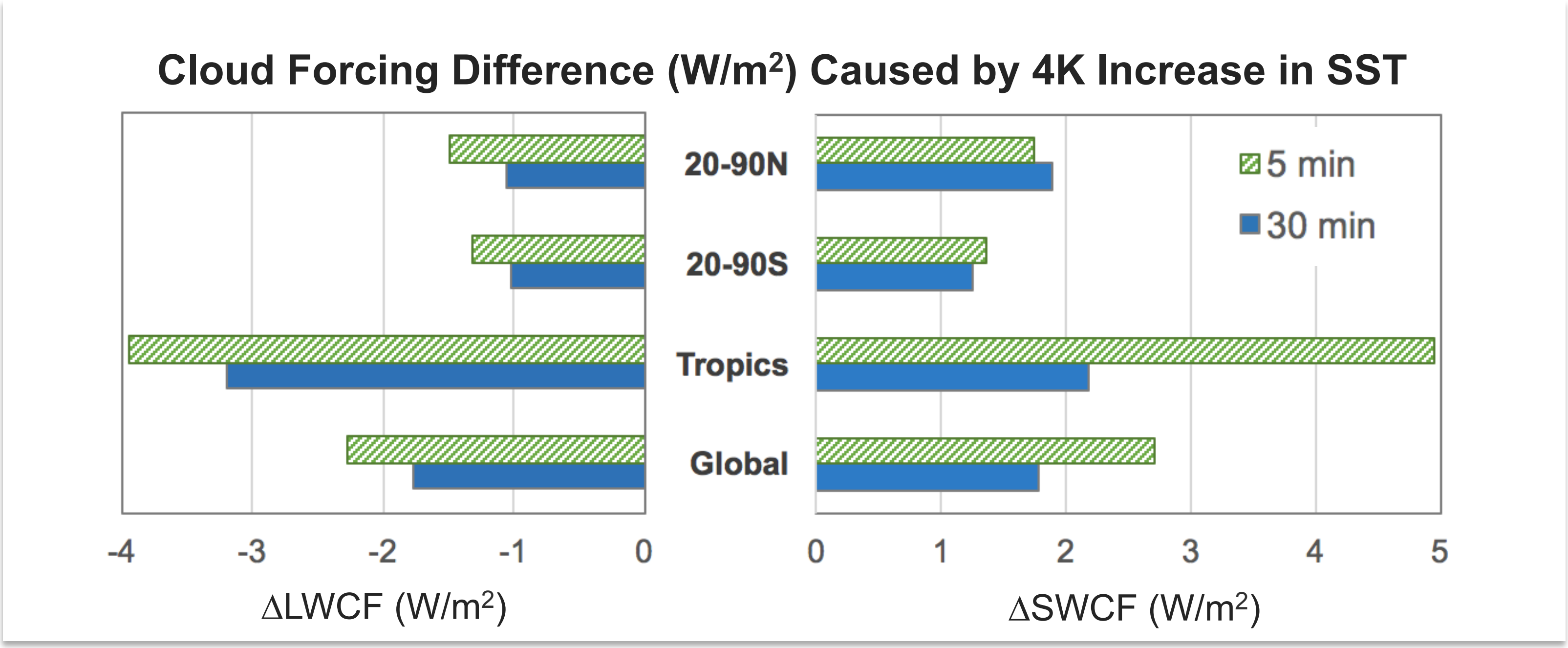
“radiative heating drives tropical anvil clouds toward a particular distribution of anvil cloud optical thickness that favors a near neutral radiation balance “



- Very thick clouds (surface-tropopause): net radiative heating small
- Optically thick cloud with high base: must evaporate or rise rapidly
- Intermediate optical depths: modest (positive) heating rates, strong dipole sustained by radiative heating => highly turbulent!

SST+4K Experiments with E3SM v0

- Model response to SST increase is sensitivity to time step
- Numerical error contributes to uncertainties in future climate projections.



- How to detangle complex interactions and identify culprits?

Cloud resolving model simulations

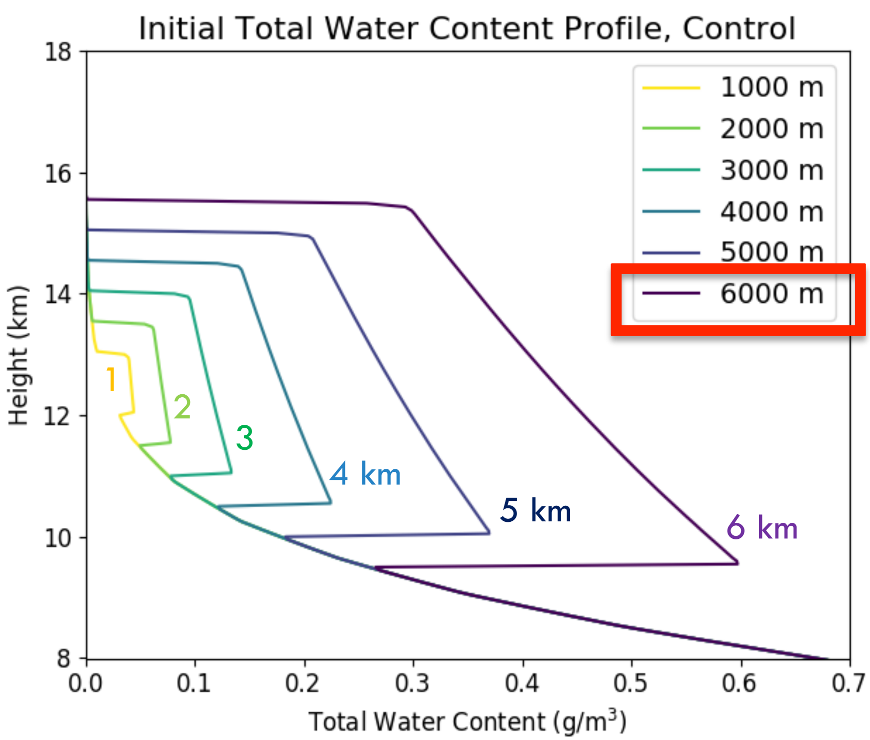


Figure courtesy Sara Berry

+Radiative convective equilibrium

+DYNAMO-forced case

- Horizontally homogeneous cloud
- Vertically uniform total water mixing ratio and
- Liquid-ice static energy
- Cloud midpoint at 12.5 km (so extending from 9.5 to 15.5 km)
- Cloud initialized based on observations from Feofilov et al., 2015
- Mean forcing from TOGA CORE

Hartmann and Berry Quotes

- Tropical convective clouds in climate models are highly parameterized, and global models cannot resolve the small-scale circulations in convective cloud systems that are likely important in determining their optical properties and area coverage.
- The hypothesis that radiative heating drives tropical anvil clouds toward a particular distribution … might be advanced with a set of experiments with a cloud-resolving model that has very realistic microphysics and radiative transfer, and also sufficient spatial resolution to resolve the convective structures within anvil clouds ...
- … realistic simulation of the observed histogram of albedo and OLR pairings in Figure 2a has probably yet to be accomplished.