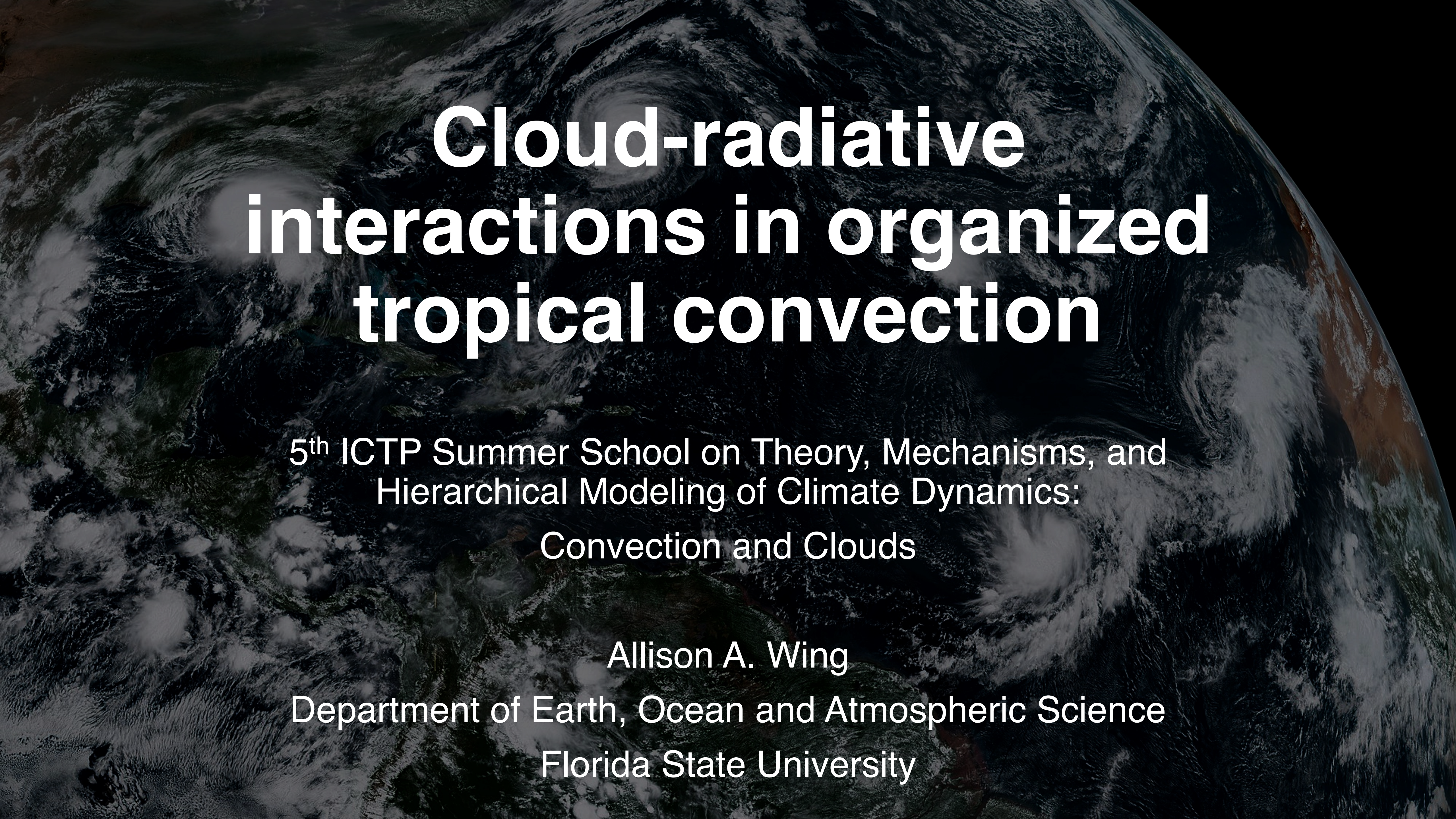


Cloud-radiative interactions in organized tropical convection

5th ICTP Summer School on Theory, Mechanisms, and Hierarchical Modeling of Climate Dynamics:

Convection and Clouds

Allison A. Wing

Department of Earth, Ocean and Atmospheric Science

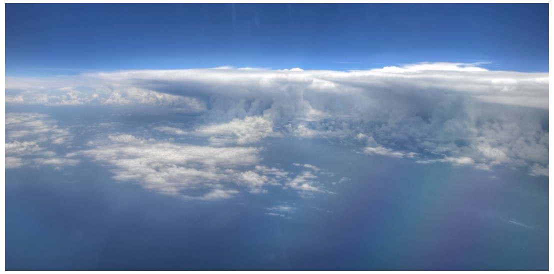
Florida State University

Convection in Earth’s atmosphere organizes on a variety of spatiotemporal scales

O(100 km)

Squall lines

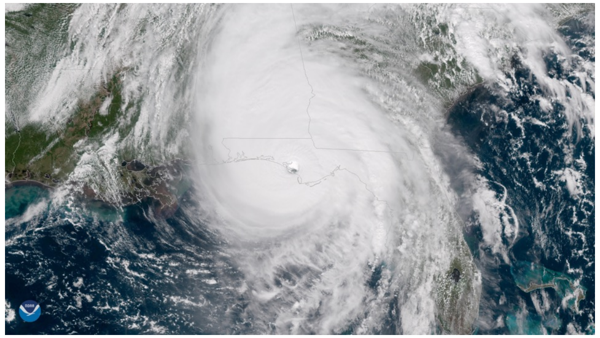
Mesoscale convective systems

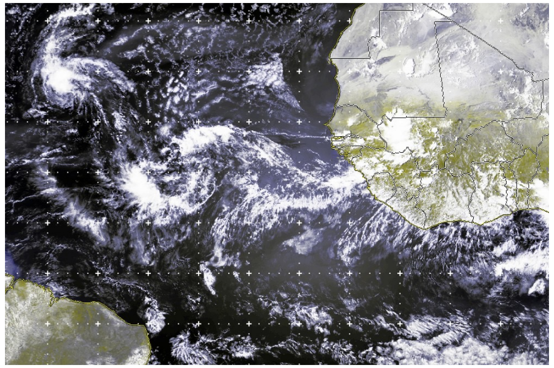


O(1000 km)

Tropical cyclones

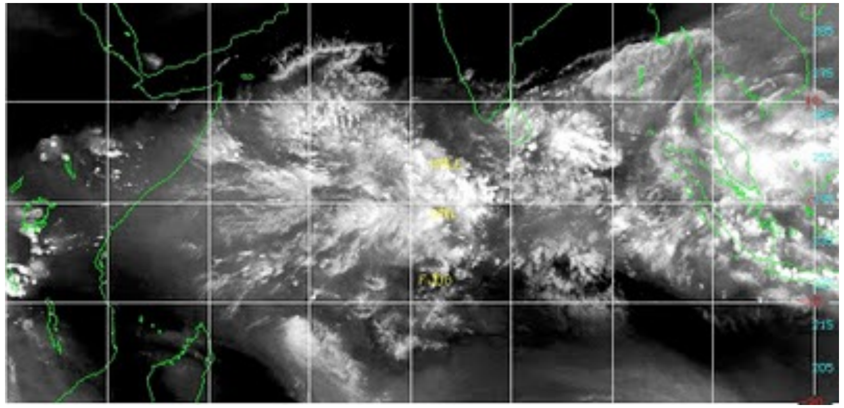
Equatorial waves





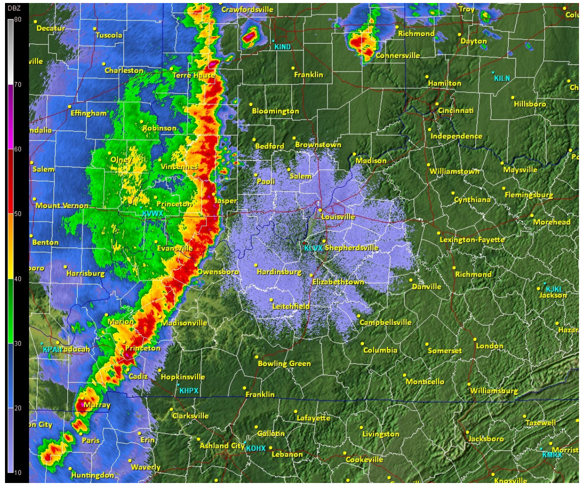
O(10,000 km)

Madden-Julian Oscillation

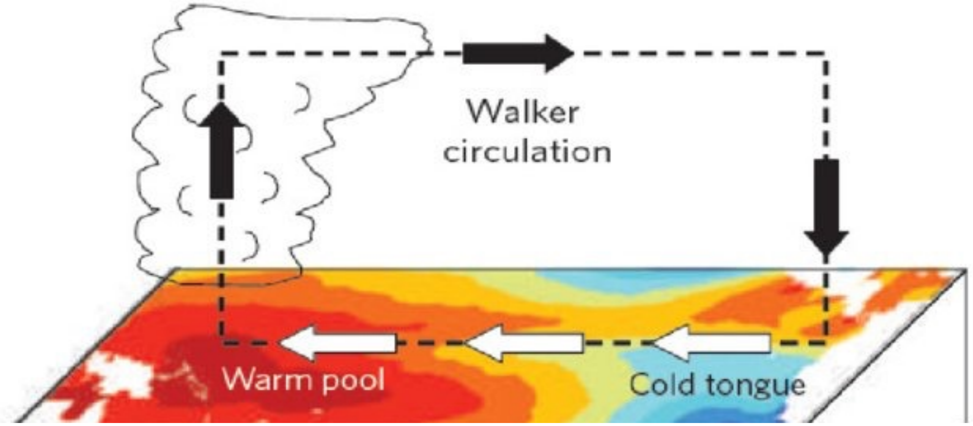


…and is organized by a variety of mechanisms

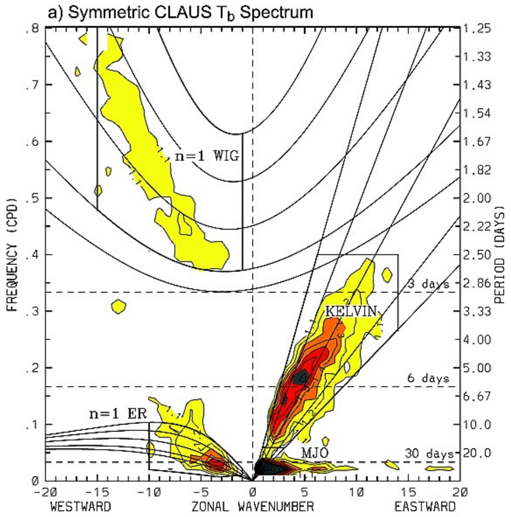
Vertical wind shear



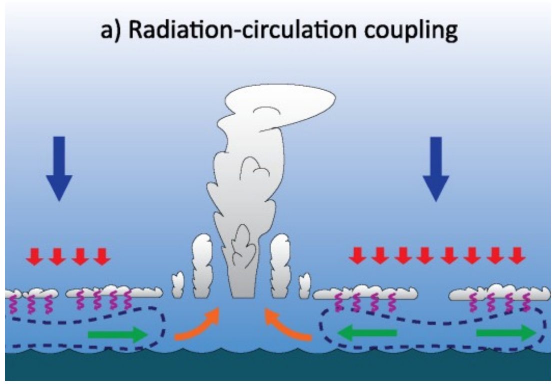
Sea surface temperature gradients



Dynamical disturbances



Radiative-convective feedbacks



Self-aggregation: spontaneous transition from randomly distributed to organized convection despite homogeneous boundary conditions

Moist regions get moister, dry regions get drier

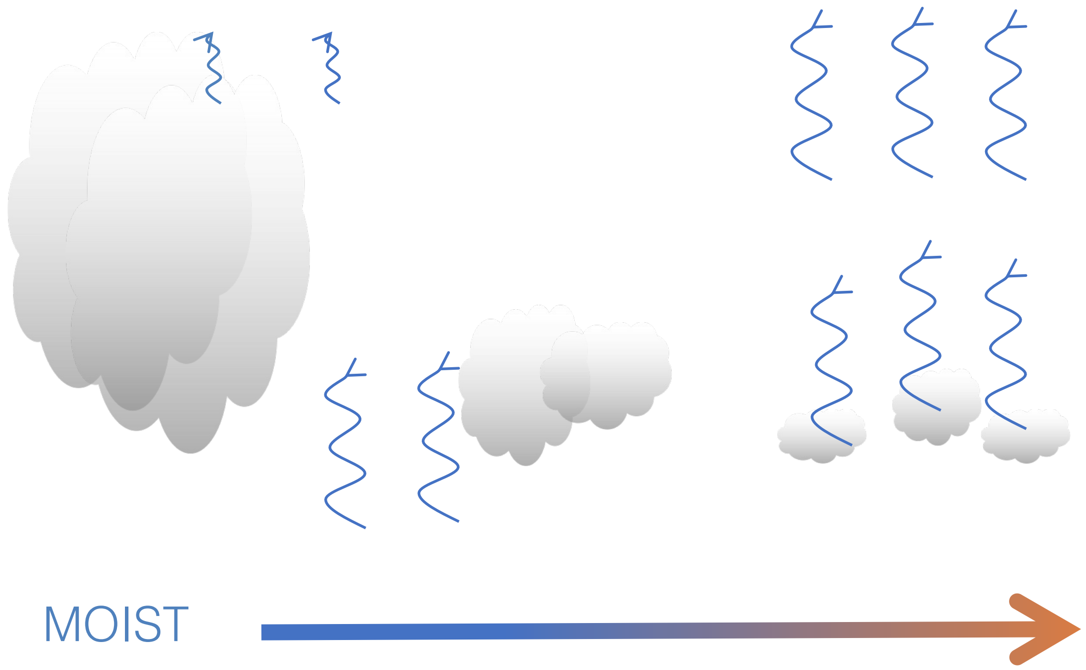
- Self-aggregation begins as a dry patch that expands.
- Convection is suppressed in the dry patch and becomes increasingly localized into a single cluster.

Results from interactions between convection and environment involving clouds, water vapor, radiation, surface fluxes, and circulation

Localization of convection first seen: Held et al 1993

Reviews: Wing et al 2017, Wing 2019

Positive Longwave Radiation Feedback



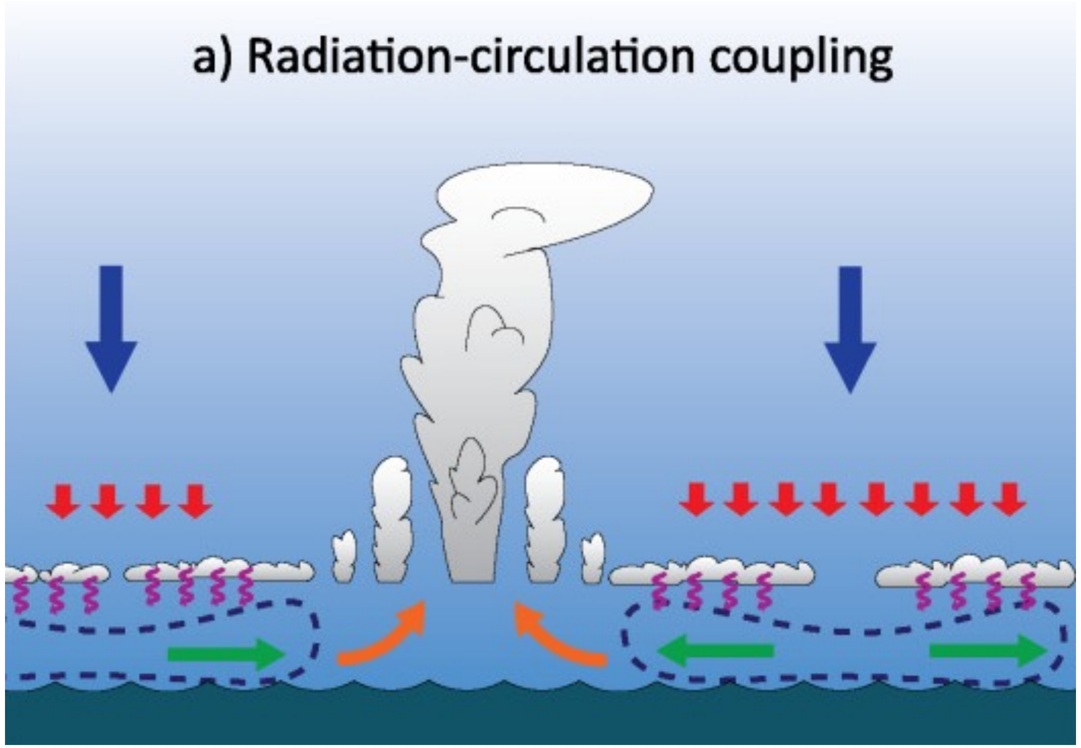
MOIST

DRY

Small atmos. LW cooling

LARGE atmos. LW cooling

Cloud-Circulation Coupling



Subsidence in dry region promotes formation of low-level clouds which radiatively cool the lower troposphere

Low-level cooling drives shallow circulations that increase the subsidence in dry areas and of “radiatively-driven cold pools” that force the convection to aggregate outside of these cold/dry areas

Coppin and Bony (2015)

How is self-aggregation manifest in the real world?

Self-aggregation: Spontaneous clustering of convection in homogeneous environment driven by radiative-convective feedbacks

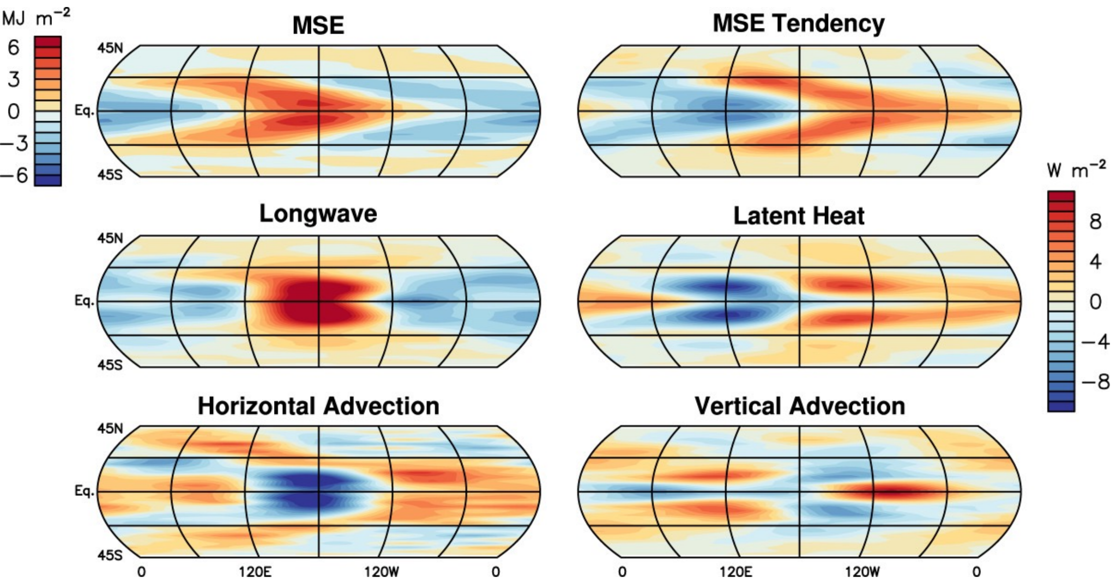
Problem: The real world is not homogeneous!

Possible applications:

- Amplification of convection initially organized by other means by radiative-convective feedbacks
- Madden-Julian Oscillation
- Tropical cyclone formation

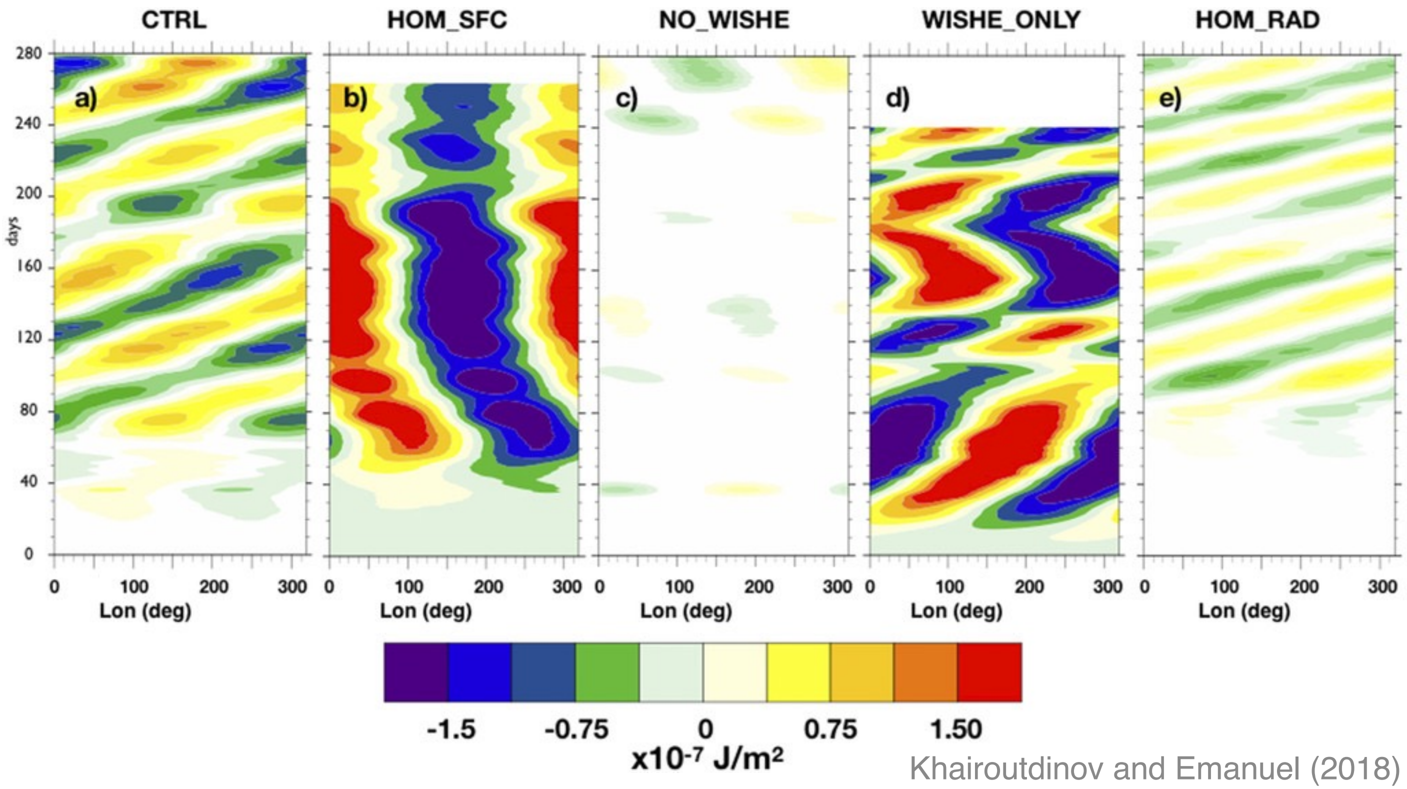
MJO as self-aggregation on an equatorial beta plane

Growing evidence* from observations and simulations that the MJO is in part a “moisture-mode”, amplified by cloud-radiation interactions, with surface flux feedbacks and moisture advection contributing to the Eastward propagation



Arnold and Randall (2015)

Rotating RCE simulations with super-parameterized GCM

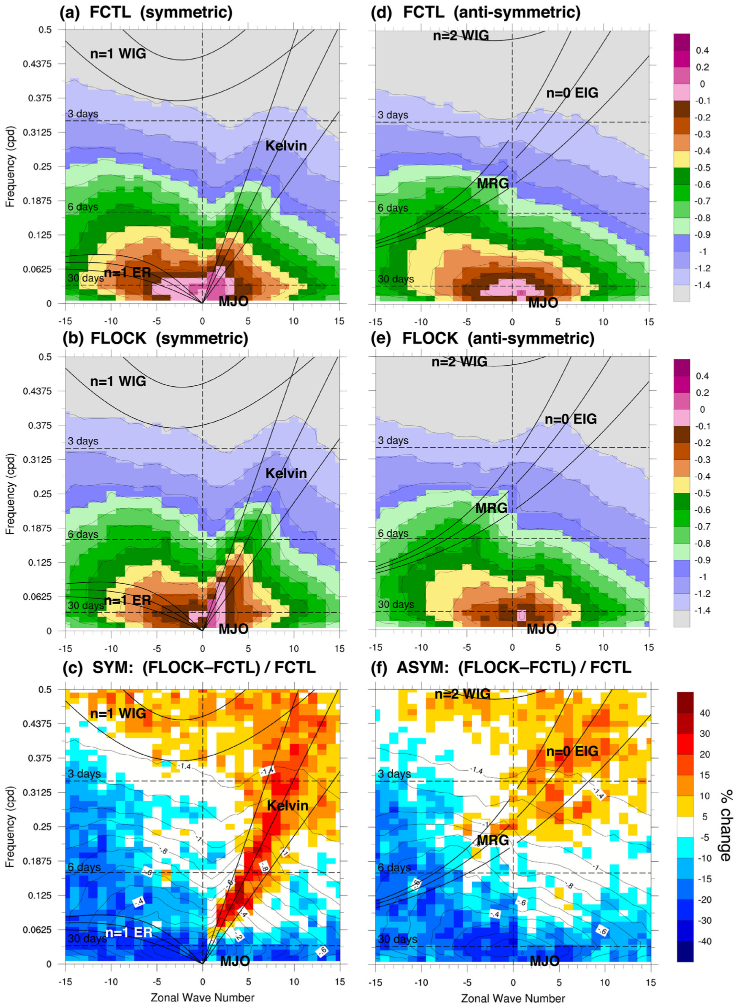


Khairoutdinov and Emanuel (2018)

*Not universal, there are several plausible theories for the MJO

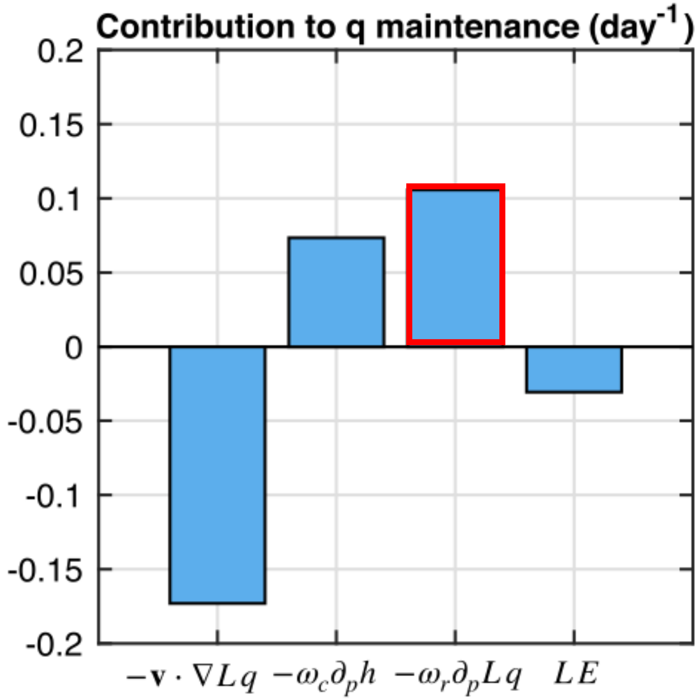
Near-global cloud-permitting rotating RCE simulations

Importance of cloud-radiative heating in the maintenance of MJO



Benedict et al. (2020)

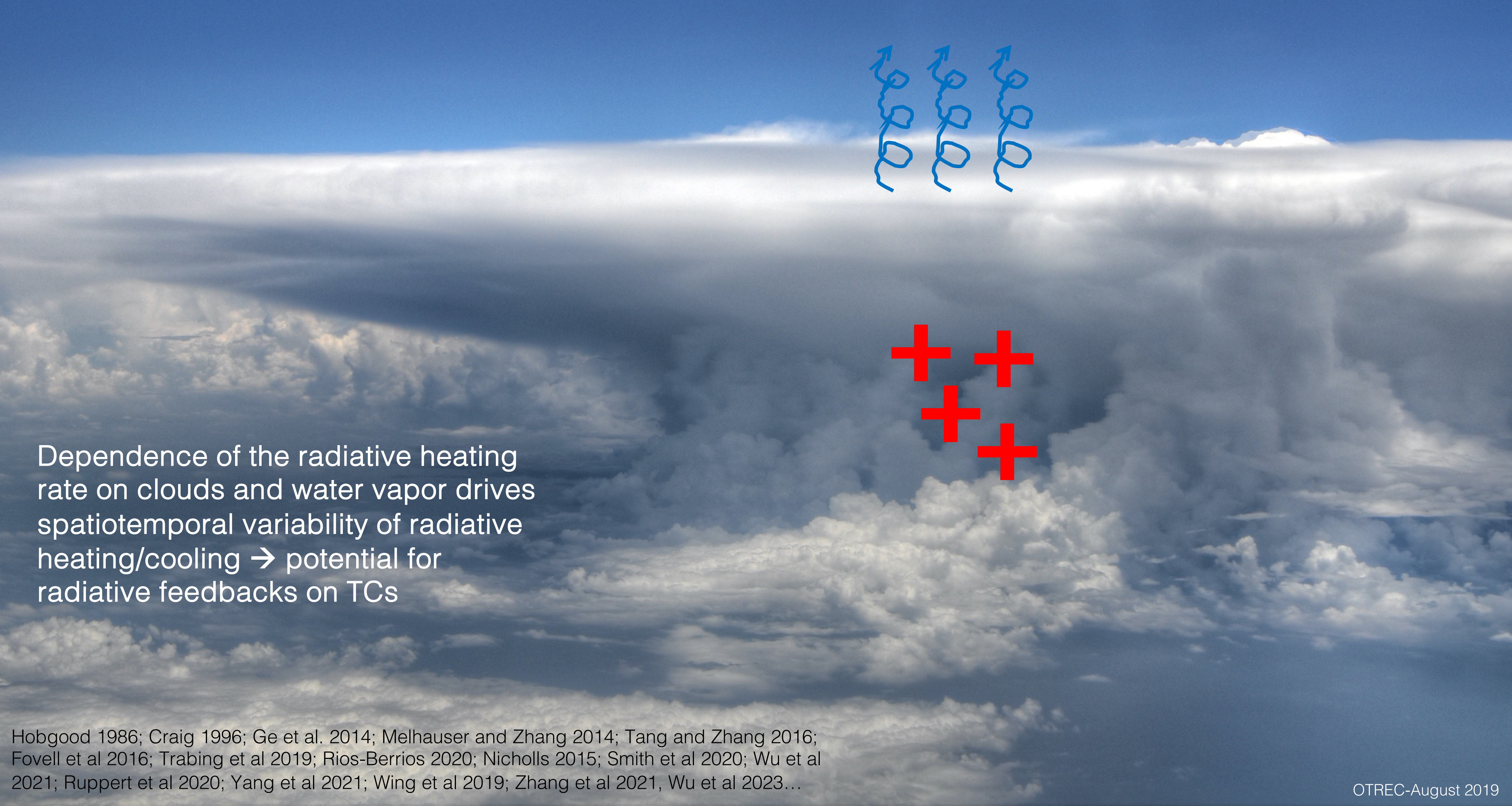
MJO activity is weakened when cloud-radiation interactions are turned off in a GCM



Adames and Maloney (2021)

Vertical moisture advection from anomalous cloud-radiative heating is leading term in maintenance of MJO moisture & precip anomalies

Growing evidence that cloud-radiative interactions are important for tropical cyclone development



Dependence of the radiative heating rate on clouds and water vapor drives spatiotemporal variability of radiative heating/cooling → potential for radiative feedbacks on TCs

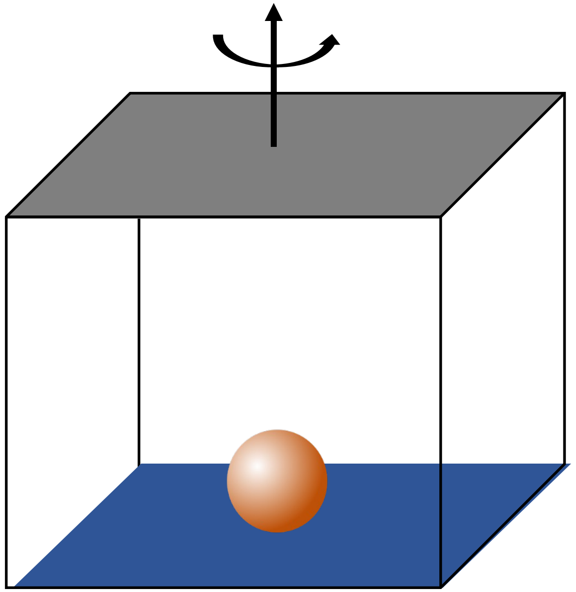
Hobgood 1986; Craig 1996; Ge et al. 2014; Melhauser and Zhang 2014; Tang and Zhang 2016; Fovell et al 2016; Trabing et al 2019; Rios-Berrios 2020; Nicholls 2015; Smith et al 2020; Wu et al 2021; Ruppert et al 2020; Yang et al 2021; Wing et al 2019; Zhang et al 2021, Wu et al 2023…

OTREC-August 2019

Our Approach

1. Idealized cloud-resolving simulations with SAM

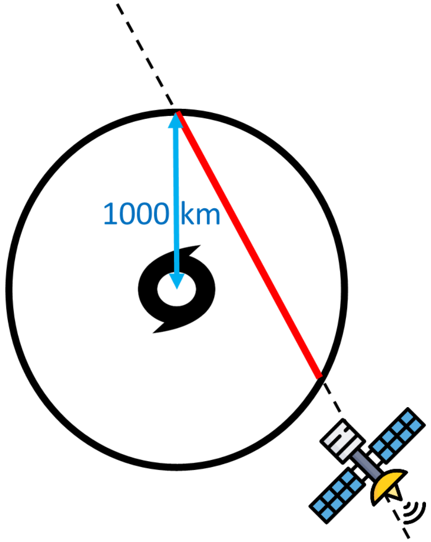
- SAM v6.11.2 (Khairoutdinov and Randall, 2003)
- Initialized from a mesoscale warm, saturated bubble on an f-plane, in an otherwise quiescent and moist neutral environment
- 2048 km x 2048 km domain, 2 km horizontal resolution, 74 vertical levels



Wing (2022)

2. Satellite observations of clouds and radiative transfer calculations

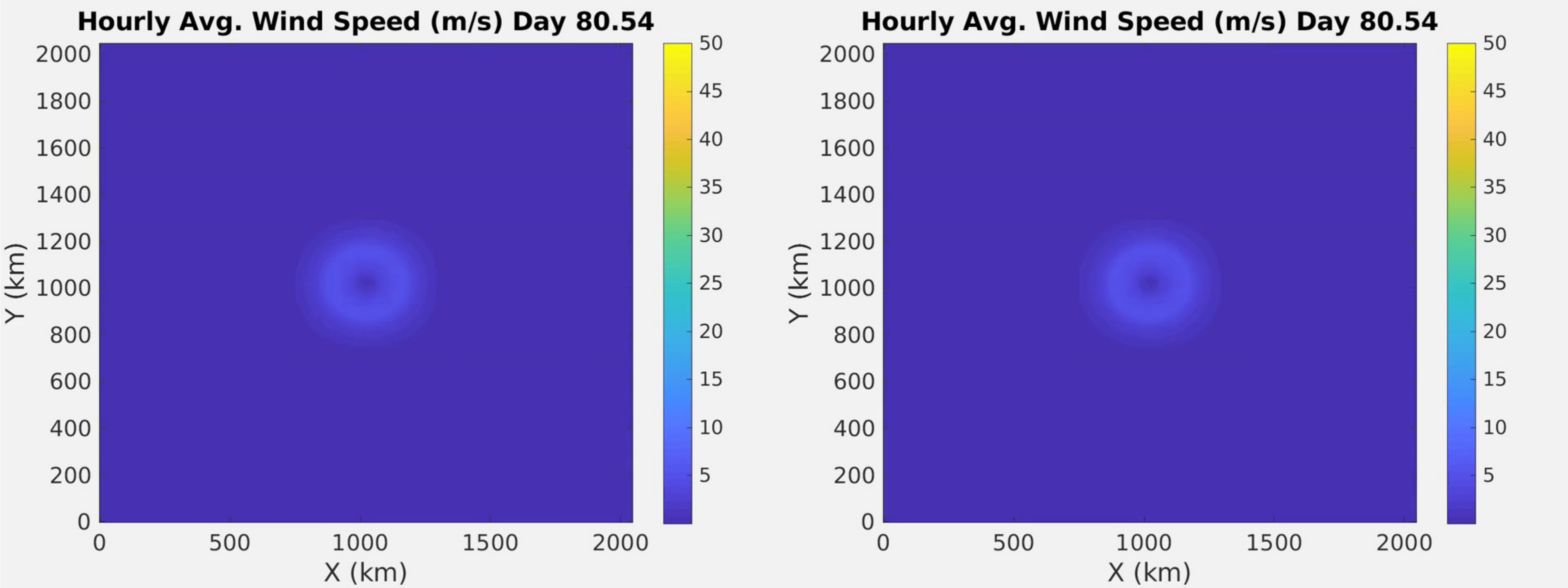
- CloudSat Tropical Cyclone (CSTC) dataset (Tourville et al. 2015)



Lee and Wing (2024)

Idealized Moist Bubble Simulations

Compare control simulation to one with radiative heating rate horizontally homogenized at every level at each time step



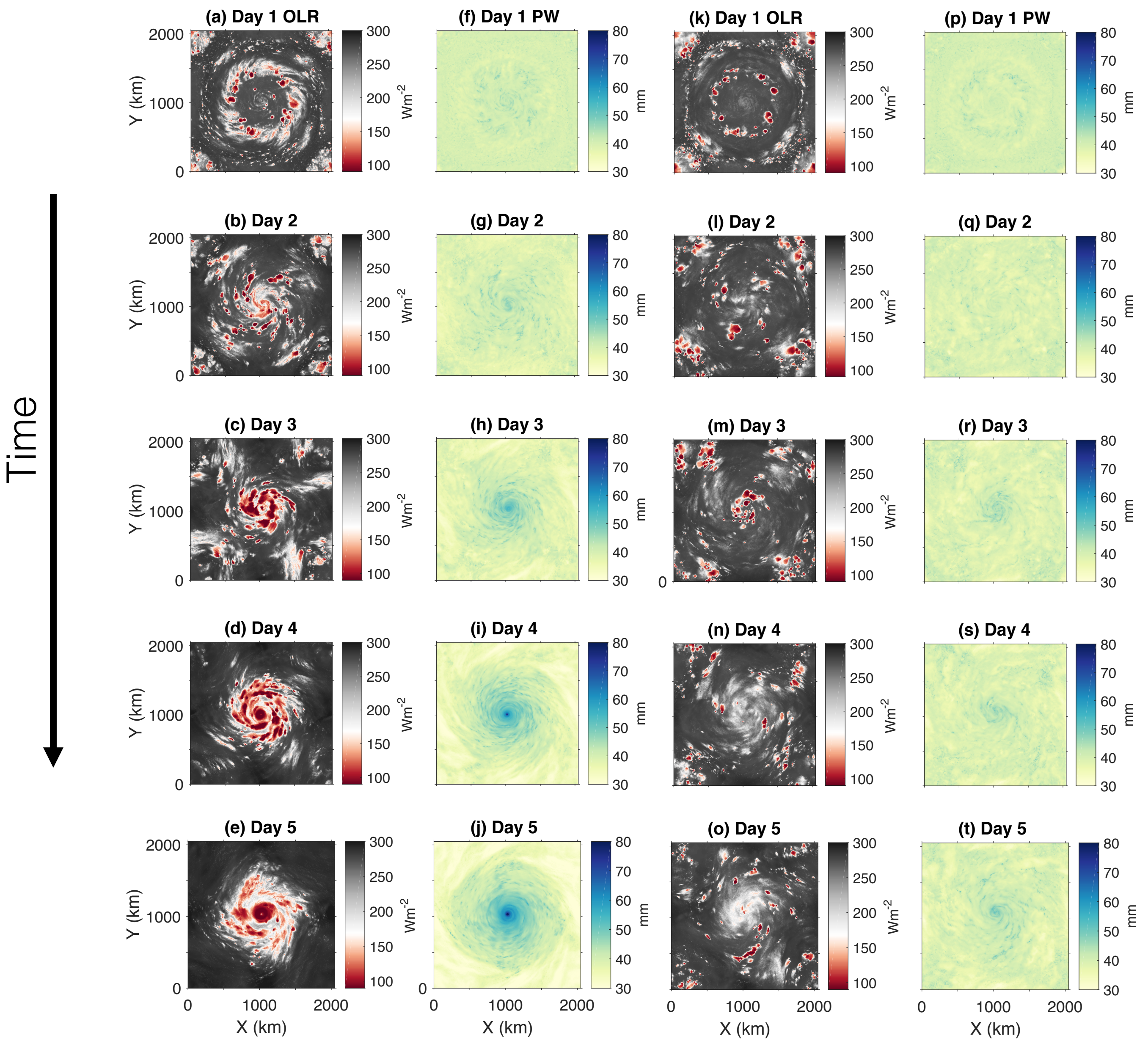
With Radiative Feedbacks

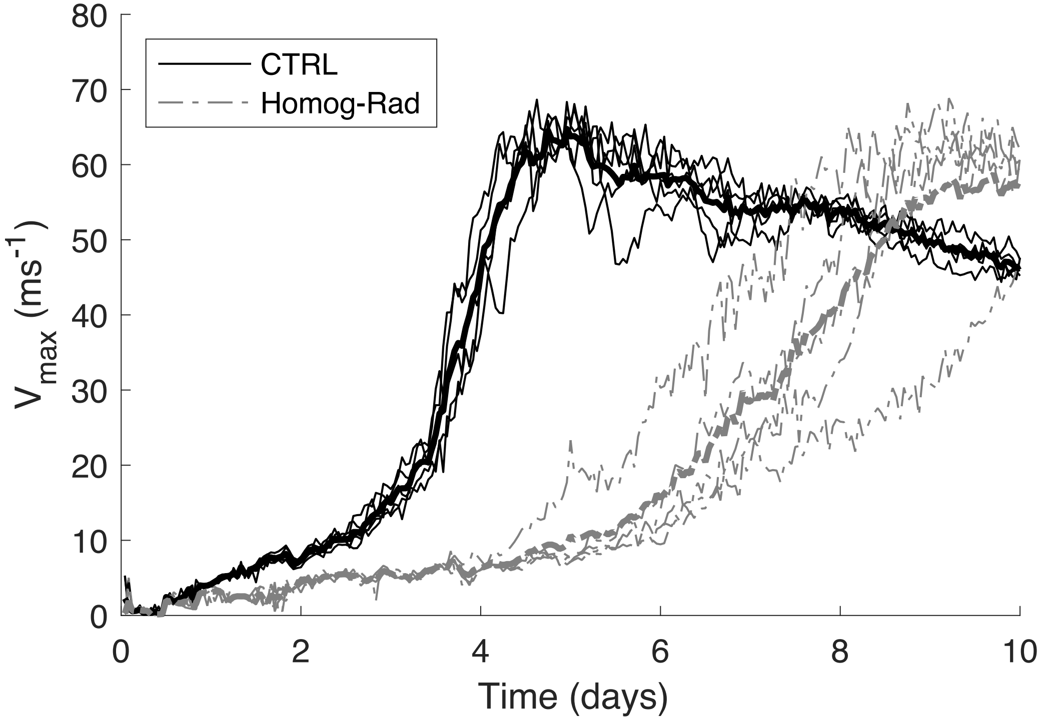
Without Radiative Feedbacks

Wing (2022)

TC formation significantly delayed without radiative feedbacks

With Radiative Feedbacks Without Radiative Feedbacks

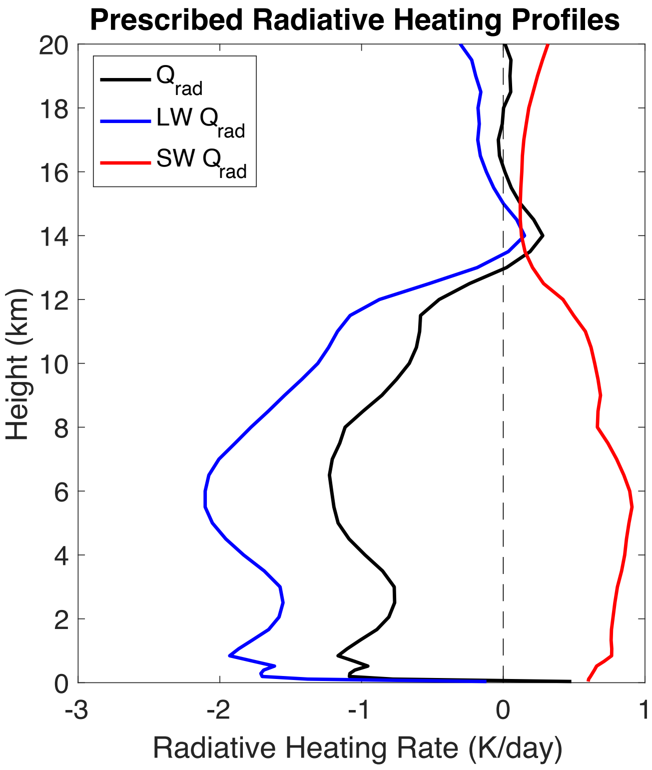


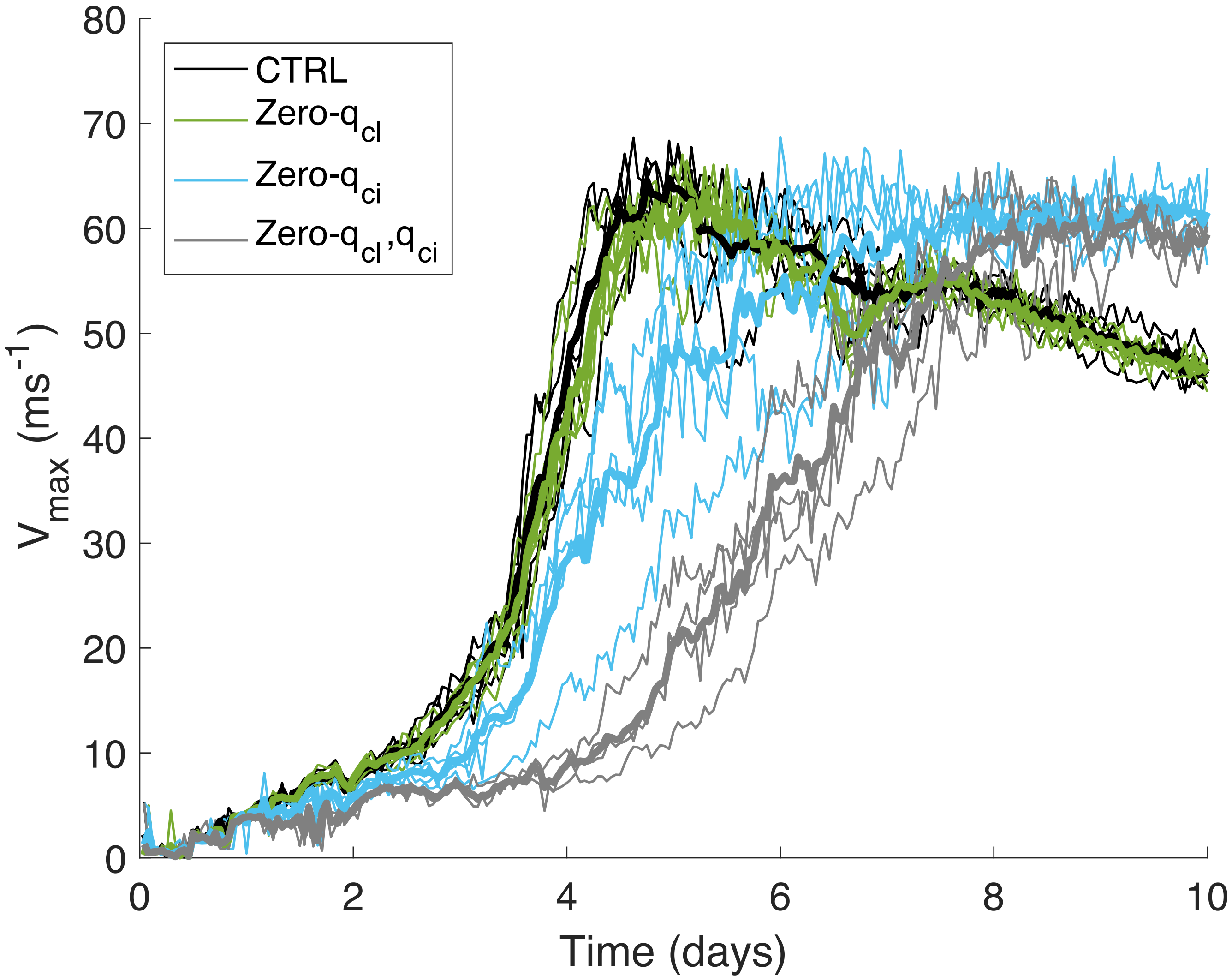


5-member ensemble generated by varying the small amplitude white noise (on top of bubble perturbation)

Wing (2022)

Which part of the radiative feedback is it?





~~Shortwave~~

Longwave

~~Water Vapor~~

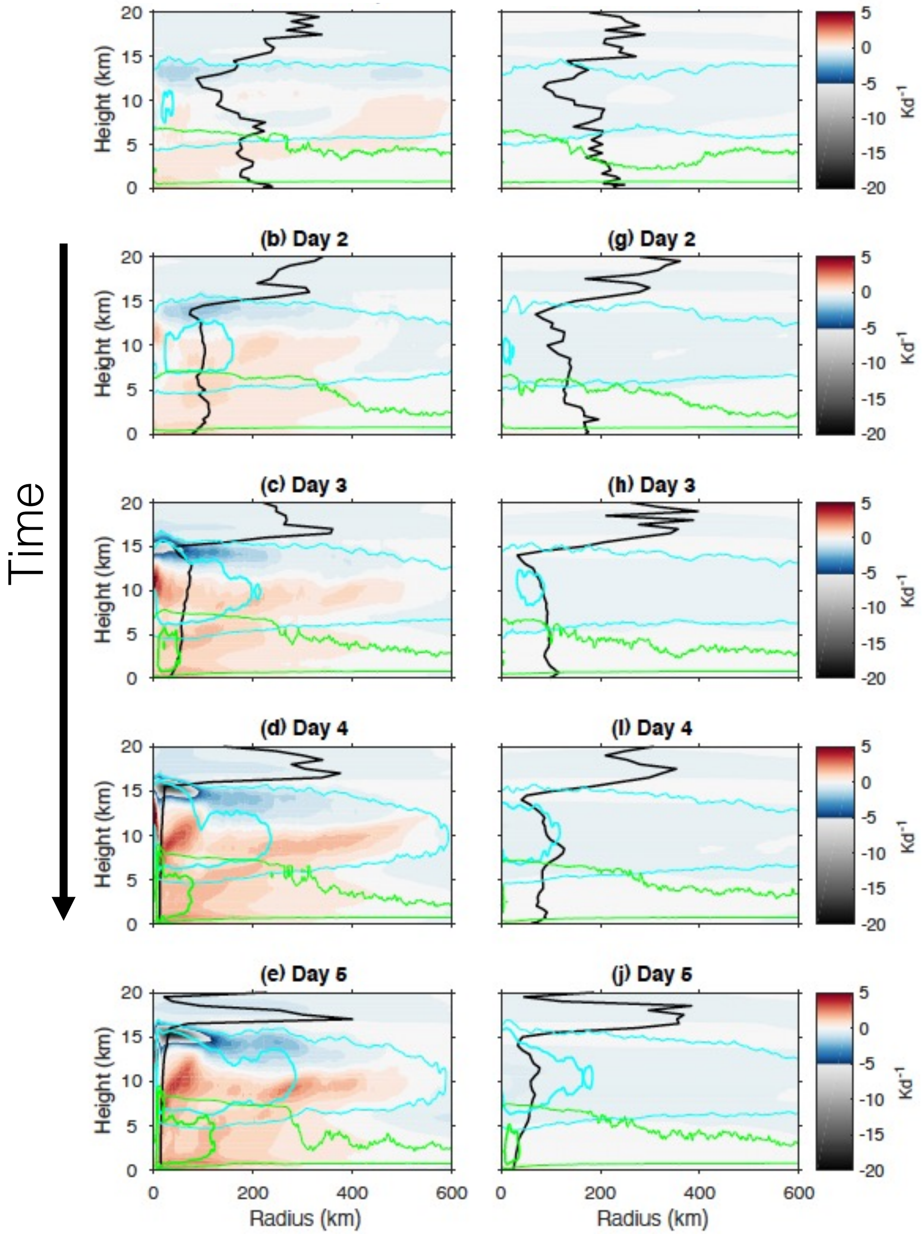
Clouds

Wing (2022)

Radial Anomaly of Longwave Radiative Heating Rate

CTRL

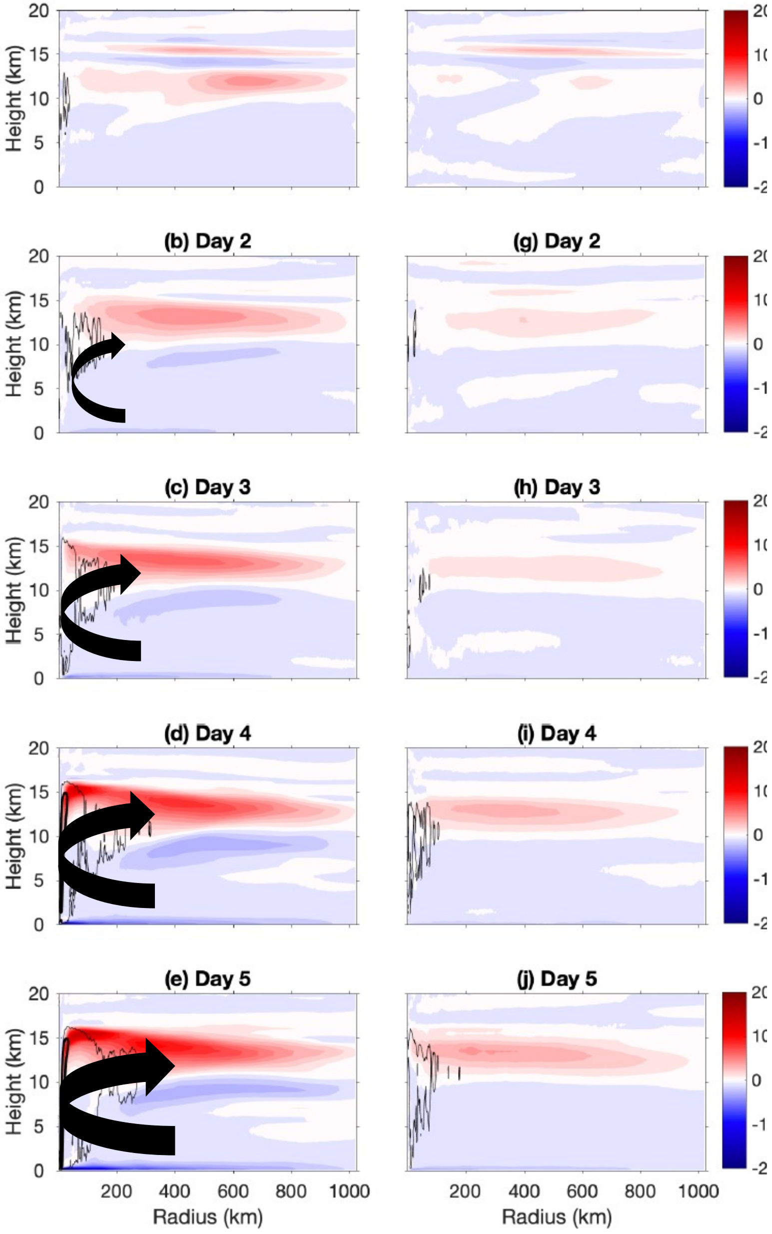
Zero Clouds



Radial and Vertical Wind

CTRL

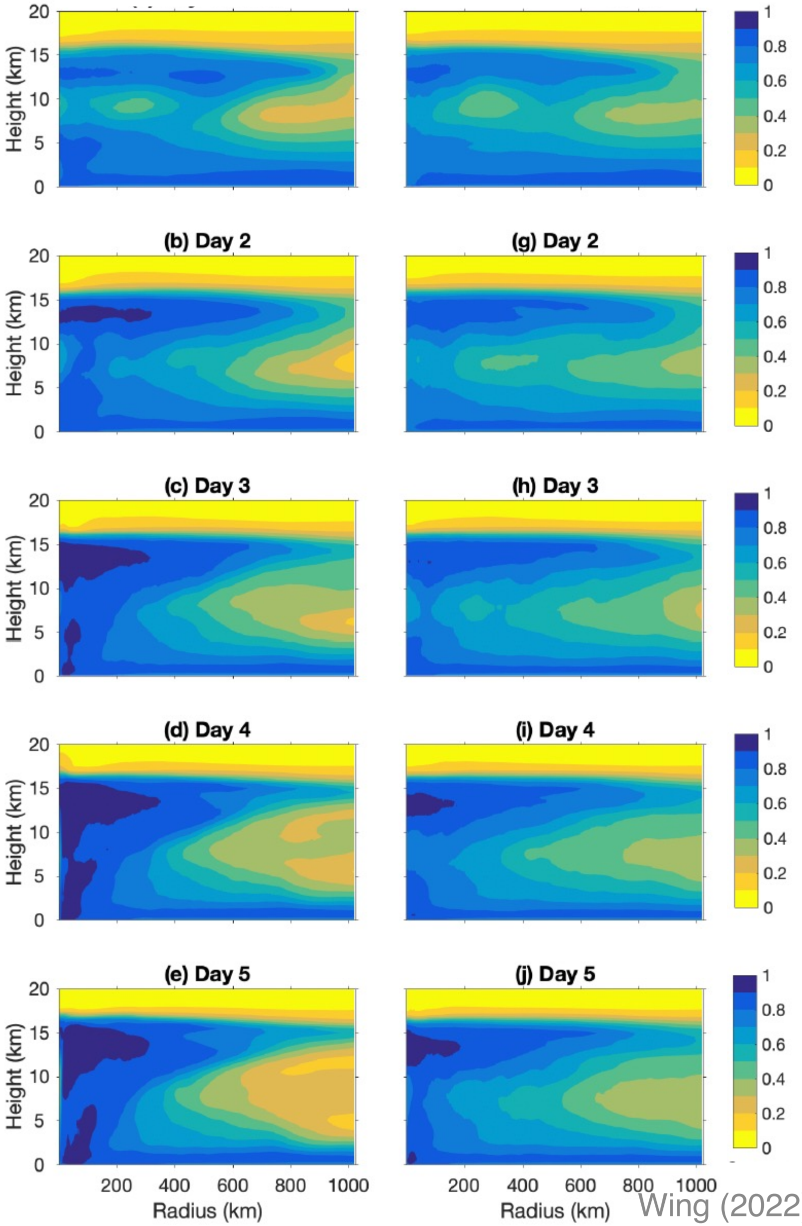
Zero Clouds



Relative Humidity

CTRL

Zero Clouds



Wing (2022)

Feedback Quantification: Budget for Column-Integrated Frozen Moist Static Energy Variance

First developed for convective organization (Wing and Emanuel 2014)

$$\hat{h} = \int_0^{z_{top}} h\,\rho\,dz$$

Applied to TCs in cloud-resolving models (Wing et al 2016)

Adapted for GCMs (Wing et al 2019)

$$h = c_pT + L_vq + gz - L_fq_{ice}$$

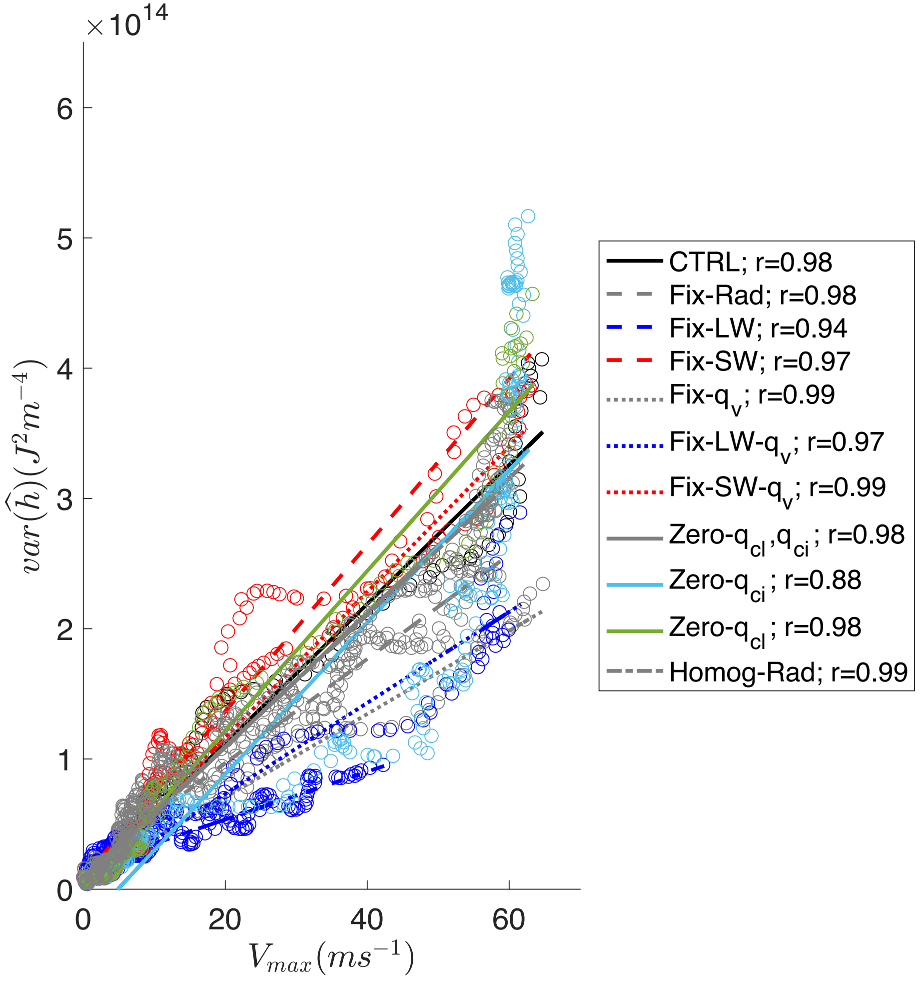
$$\frac{\partial \hat{h}'^2}{\partial t} = \frac{\partial var(\hat{h})}{\partial t} = \boxed{2\langle \hat{h}'F'_K\rangle} + \boxed{2\langle \hat{h}'N'_S\rangle} + \boxed{2\langle \hat{h}'N'_L\rangle} \boxed{-2\langle \hat{h}'\nabla_h\cdot\widehat{\mathbf{u}h}\rangle},$$

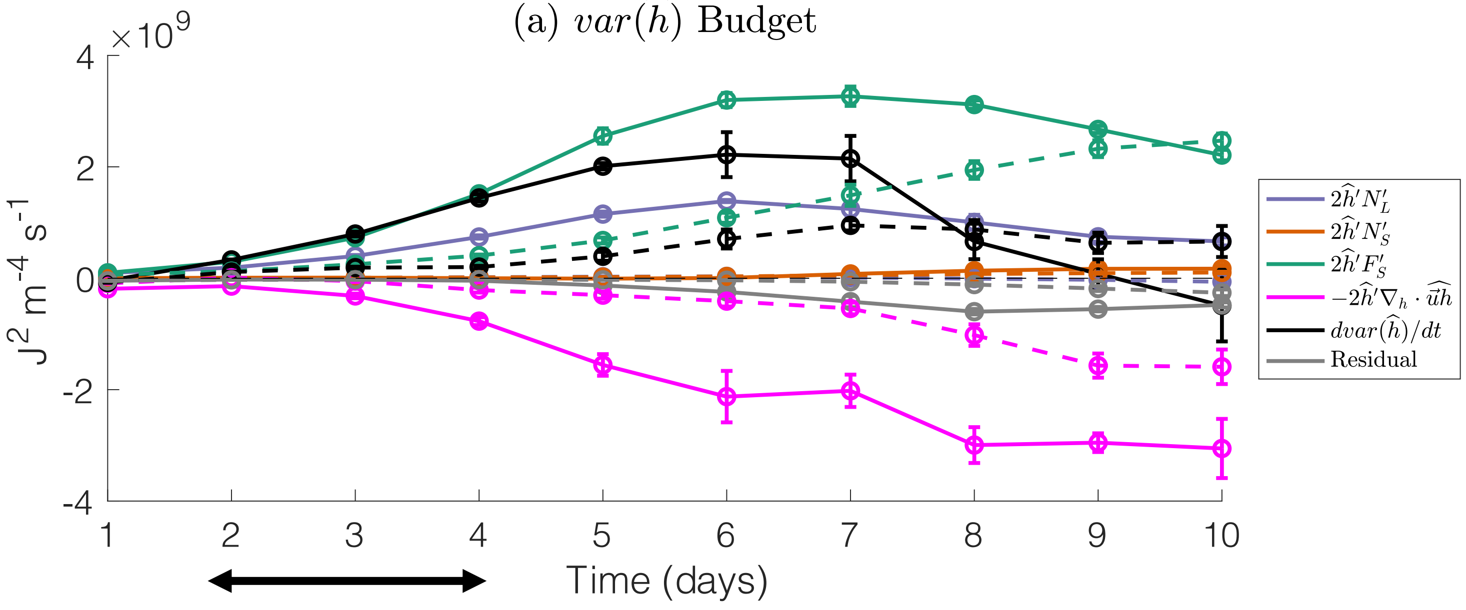
Feedback term: FMSE anom * Source/sink anom

Positive Feedback: Process increases FMSE of already moist region, contributes to moisture aggregation & TC formation

Negative Feedback: Process decreases FMSE of moist region

Spatial variance of column FMSE variance increases with TC intensity



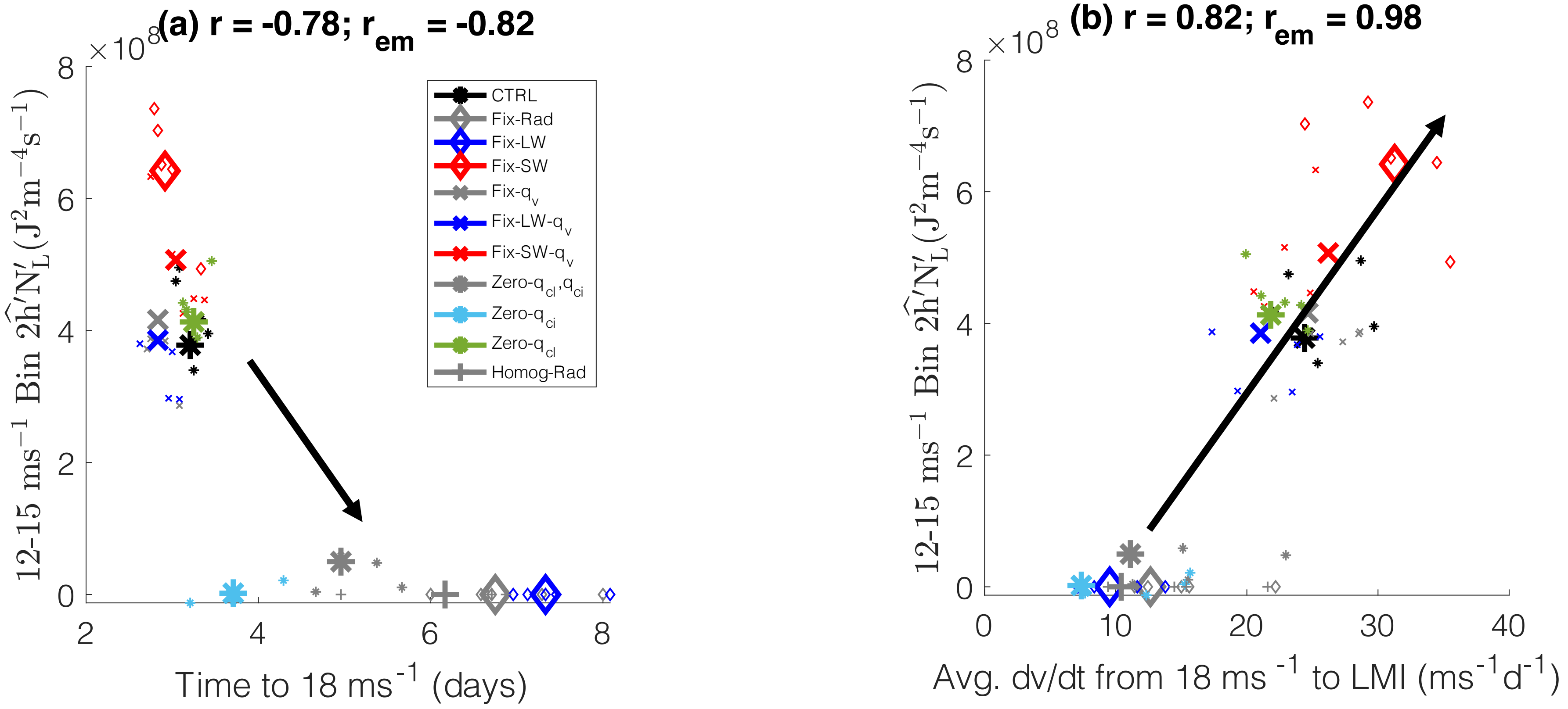


- LW feedback contributes most (relative to surface flux feedback) in early stages
- LW feedback remains ~1/3 of surface flux feedback as approach max intensity

$$\frac{d\mathrm{var}(\widehat{h})}{dt} = 2\langle \widehat{h}' F_K' \rangle + 2\langle \widehat{h}' N_S' \rangle + 2\langle \widehat{h}' N_L' \rangle - 2\langle \widehat{h}' \nabla_h \cdot \widehat{\mathbf{u}h} \rangle,$$

Wing (2022)

Contribution of LW feedback, composited over intensities from 12-15 $\mathrm{ms^{-1}}$



Simulations with no cloud-radiative feedbacks take longer to reach tropical storm strength

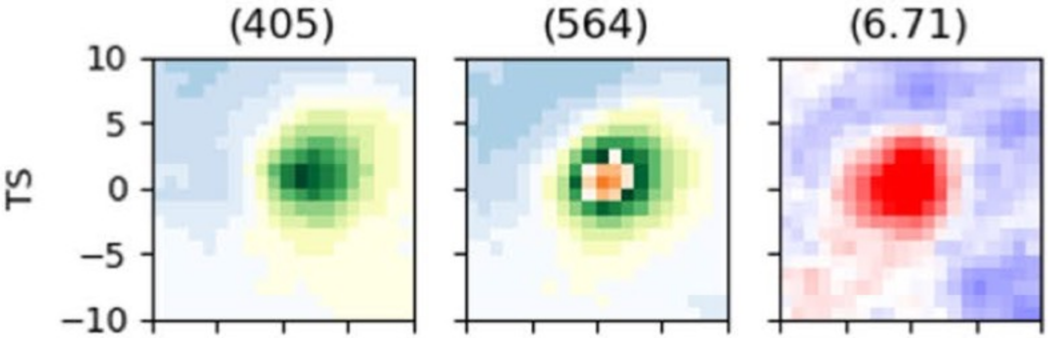
Simulations with stronger LW feedback (at same intensity) have faster intensification rates

$$\frac{d\mathrm{var}(\widehat{h})}{dt} = 2\langle \widehat{h}' F_K' \rangle + 2\langle \widehat{h}' N_S' \rangle + 2\langle \widehat{h}' N_L' \rangle - 2\langle \widehat{h}' \nabla_h \cdot \widehat{\mathbf{u}h} \rangle,$$

Wing (2022)

Estimation of TC cloud-radiative feedbacks from satellite data

Prior work using CERES and CloudSat measurements found that intensifying TCs have greater radiative heating from clouds within the TC area, and thus stronger cloud-radiative feedbacks, than weakening TCs (Wu et al., 2021, 2023)



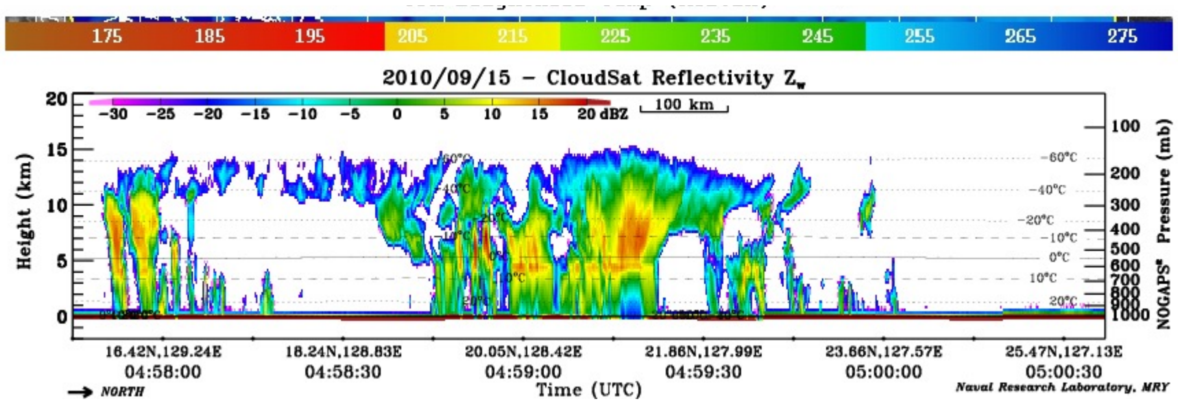
Wu et al. (2021)

Our goals:

- Investigate vertical & radial structure of radiative heating in TCs
- Decompose into contributions from ice clouds, liquid clouds, water vapor
- Diagnose radiatively-driven circulation and role in TC development

Data: CloudSat TC Dataset (Tourville et al., 2015)

- CloudSat overpasses within 1000 km of TC center from 2006-2019



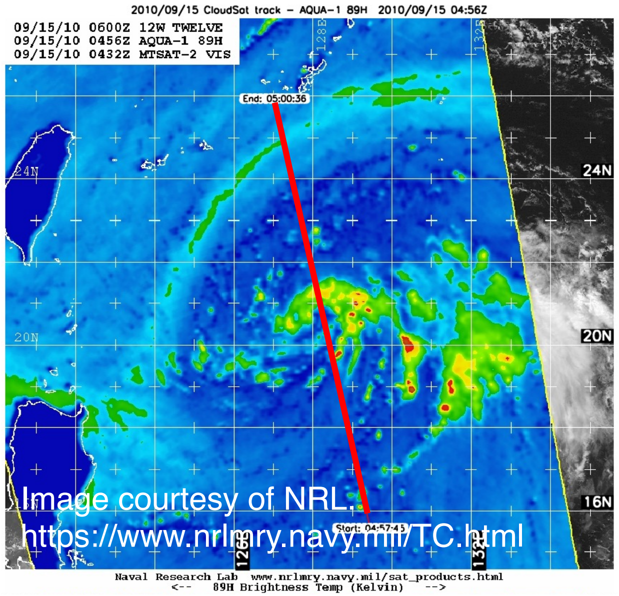


Image courtesy of NRL, https://www.nrlmry.navy.mil/TC.html

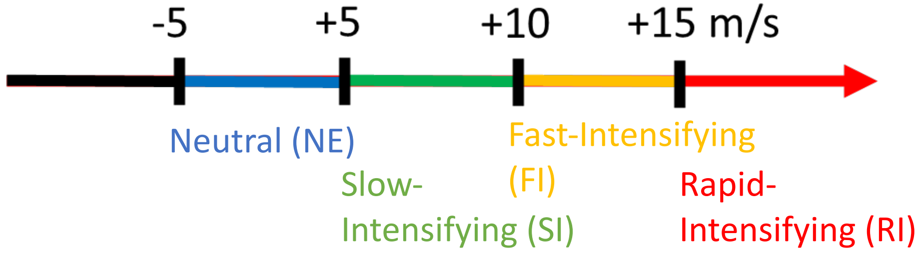
Fanapi (2010): 06Z 09/15/2010, Vmax=30 kts

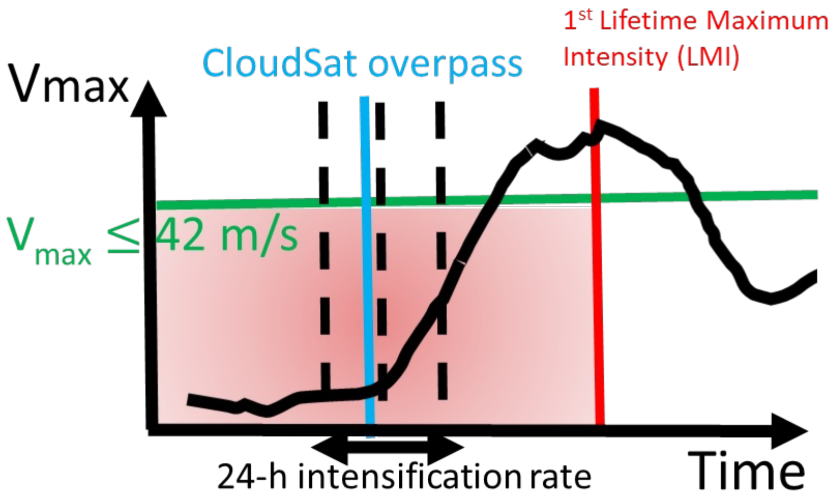
Lee and Wing (2024)

Composite based on intensification rate

24-h intensification rate bins for composite

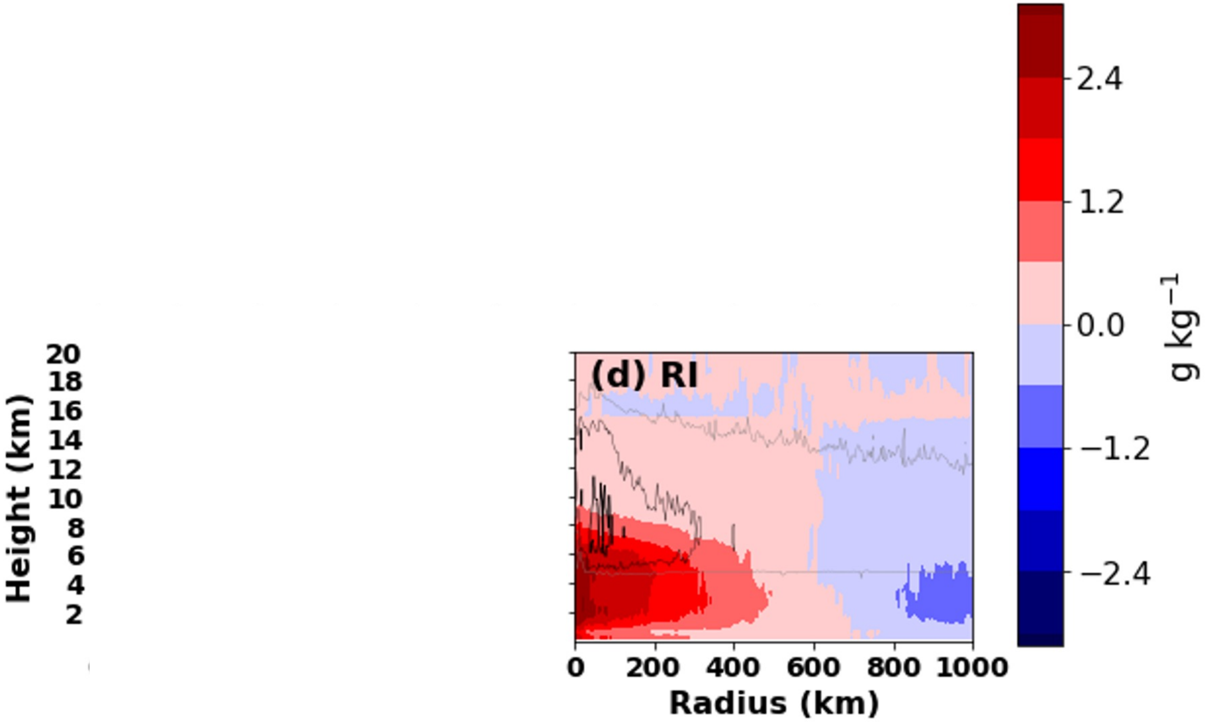
(Kaplan and DeMaria 2003; Rios-Berrios and Torn 2017)





[based on IBTrACS; Knaff et al. (2010)]

Radial anomaly of specific humidity (shading) and ice water content (contours)

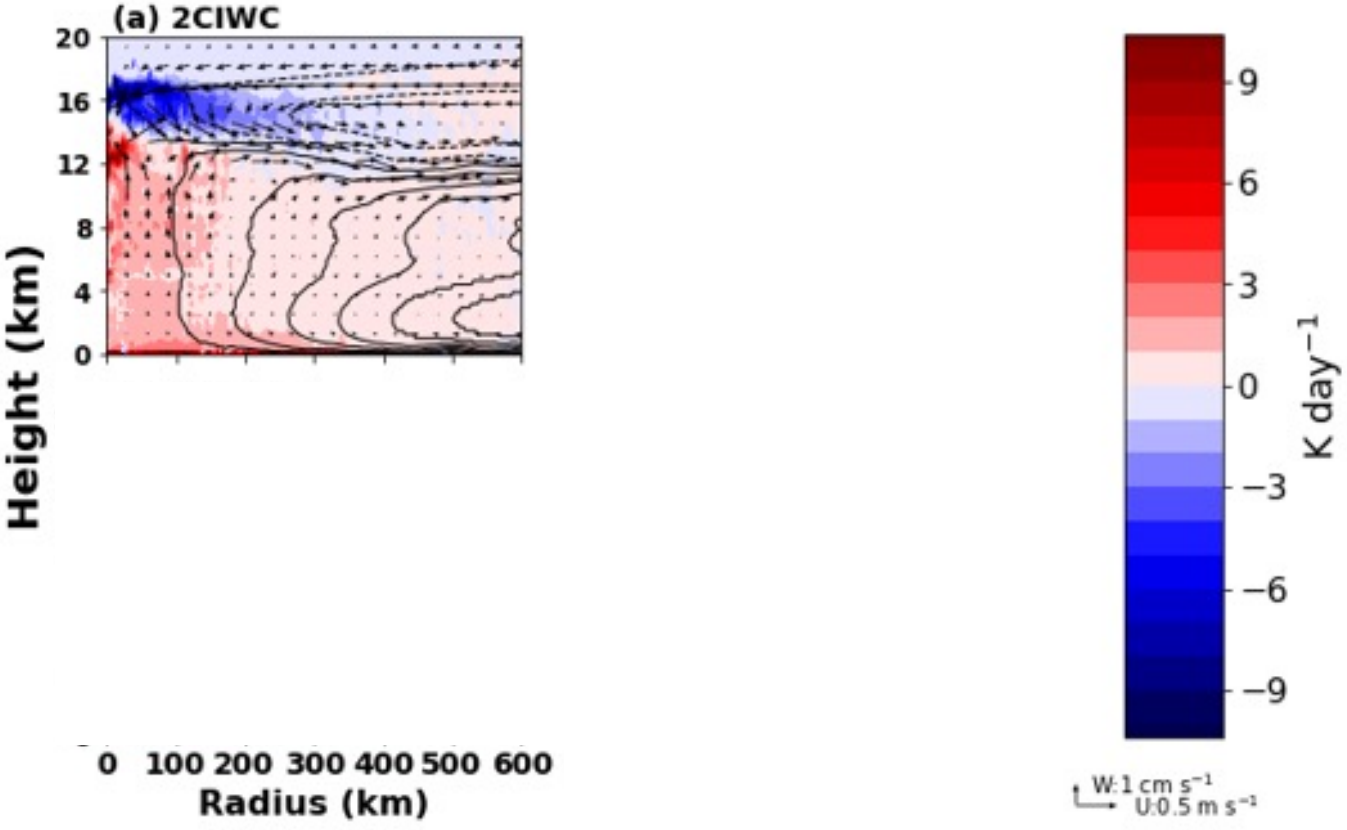


- Greater intensification rate has greater water vapor and greater ice water content within 200 km of the TC center
- Also shown by Wu et al. (2017)

Data source:
q_v : ECMWF product
IWC: CloudSat 2C-ICE product

Lee and Wing (2024)

Decomposition of LW radiative heating rate variability



- LW heating rate anomalies for RI cases + LW radiatively-driven streamfunction + circulation vectors
- Circulation calculated using Sawyer-Eliassen equation, which computes axisymmetric response of the transverse circulation to imposed heating in a balanced initial vortex
  (Shapiro and Willoughby, 1982, Pendergrass and Willoughby, 2009)

- Spatial variability in radiative heating rates and overturning circulation dominated by contribution from **ice clouds**

- **Water vapor** contributes to lower troposphere LW heating variability

Data source:
IWC: CloudSat 2C-ICE product
LWC: CloudSat 2B-CWC-RO product
q_v : ECMWF product

Lee and Wing (2024)

Estimation of radiative feedbacks

$$\frac{d\mathrm{var}(\widehat{h})}{dt} = 2\langle \widehat{h}'F_K'\rangle + \boxed{2\langle\widehat{h}'N_S'\rangle + 2\langle\widehat{h}'N_L'\rangle} - 2\langle\widehat{h}'\nabla_h\cdot\widehat{\mathbf{u}h}\rangle,$$

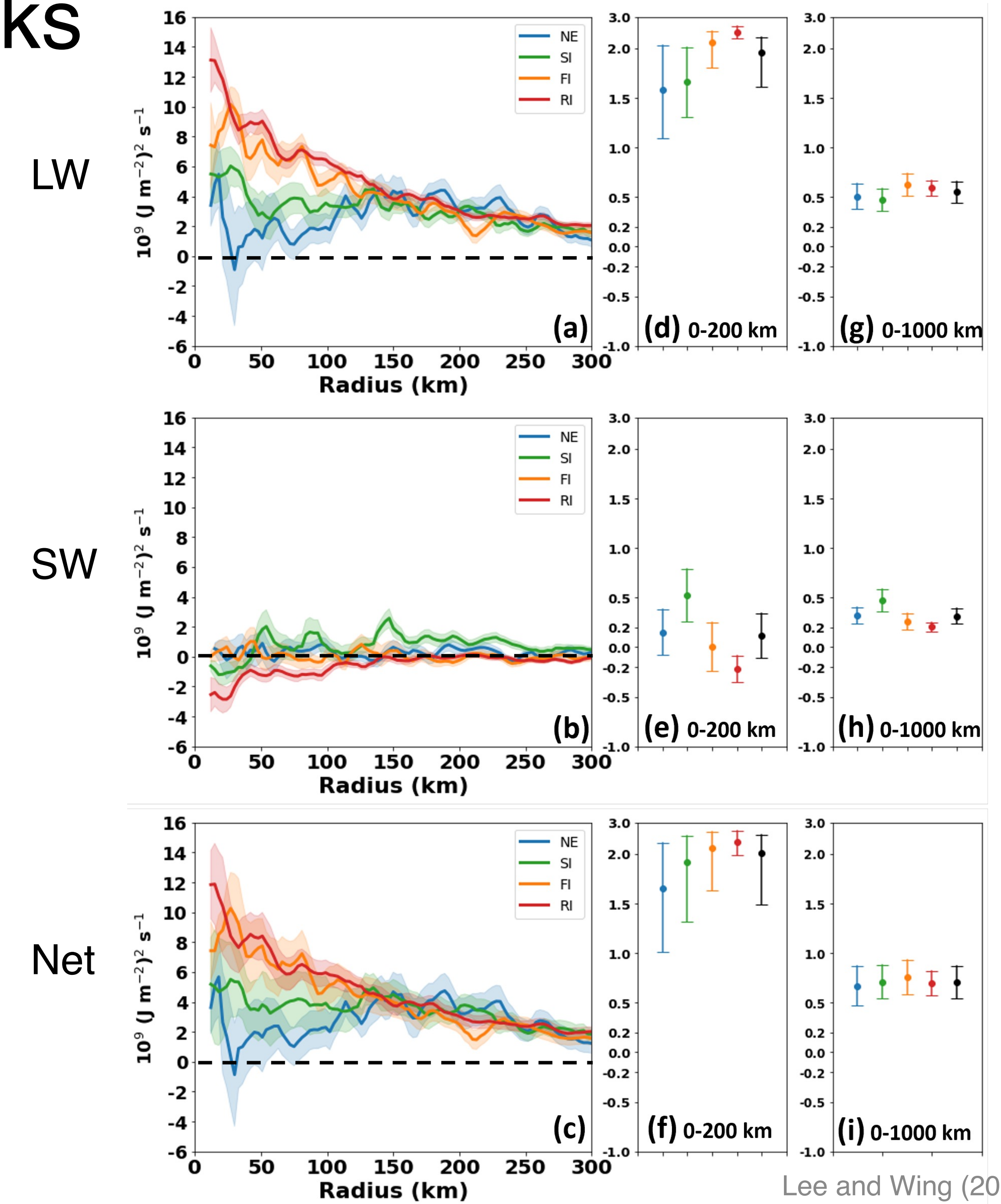
- Positive net radiative feedback → contributes to moistening TC core and TC development.

- RI cases have greatest LW feedback in inner core (mostly from ice clouds)

- RI cases have negative SW feedback
  - Clear-sky SW feedback is positive for RI and FI cases, but is greatest for FI cases.

- Results consistent with model simulations and prior observational work.

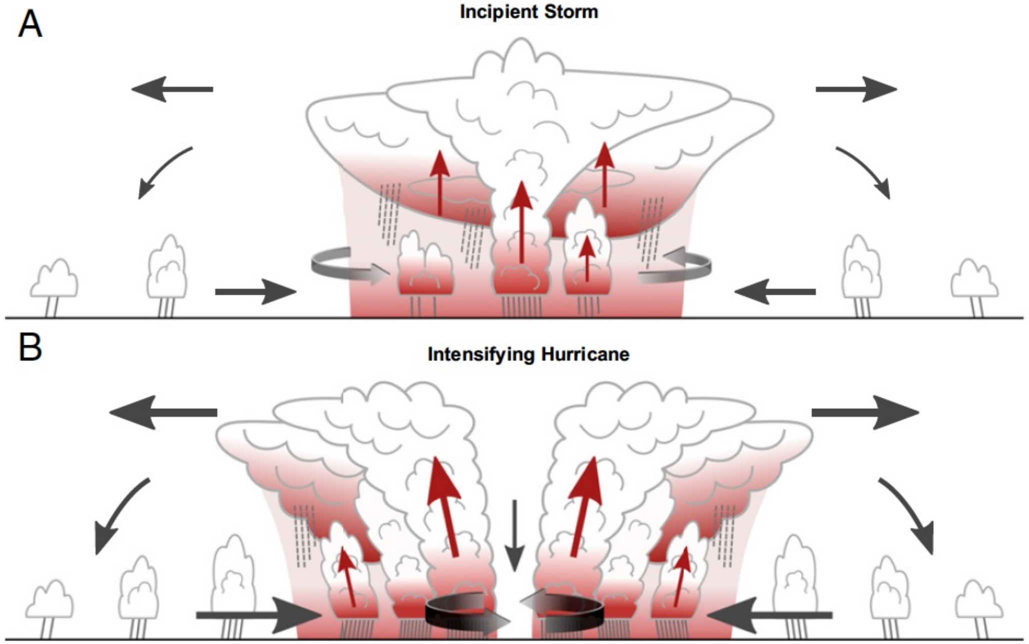
Data source:
IWC: CloudSat 2C-ICE product
LWC: CloudSat 2B-CWC-RO product
T, q_v : ECMWF product



Lee and Wing (2024)

Summary

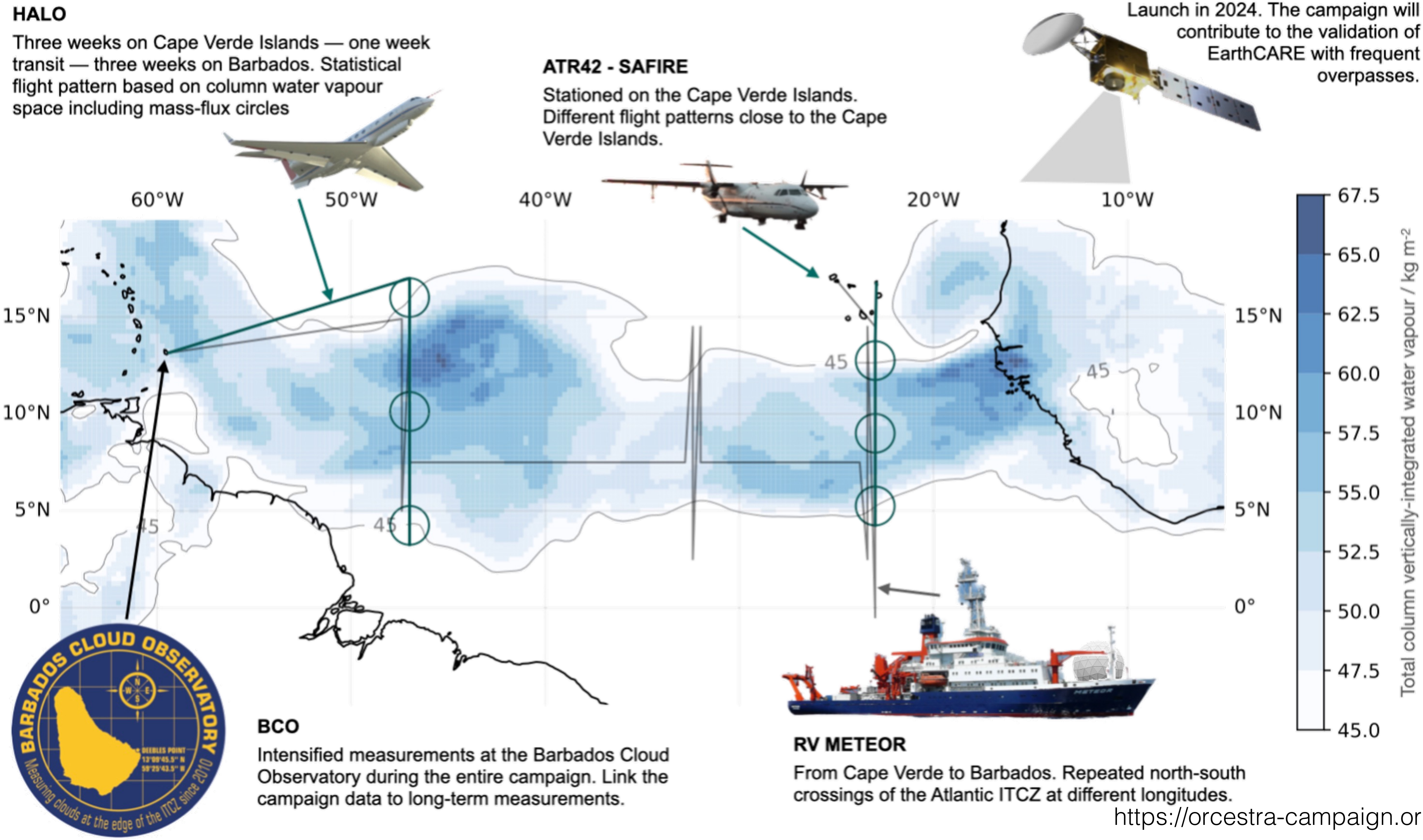
- Cloud-radiative interactions contribute to tropical convective organization
- MJO is amplified by cloud-radiative feedbacks
- Idealized CRM simulations and satellite data agree that radiative feedbacks contribute to TC development
- Effect of ice clouds on longwave radiation is the most important: anomalous warming of lower-mid troposphere enhances the TC overturning circulation and moistens troposphere
- What is the role of cloud-radiative feedbacks in observed mesoscale organization of convection?



Ruppert et al. (2020)

Tsung-Yung Lee

ORCESTRA: ORganized Convection and EarthCare Studies over the TRopical Atlantic



HALO

Three weeks on Cape Verde Islands — one week transit — three weeks on Barbados. Statistical flight pattern based on column water vapour space including mass-flux circles

ATR42 - SAFIRE

Stationed on the Cape Verde Islands. Different flight patterns close to the Cape Verde Islands.

EarthCARE

Launch in 2024. The campaign will contribute to the validation of EarthCARE with frequent overpasses.

BCO

Intensified measurements at the Barbados Cloud Observatory during the entire campaign. Link the campaign data to long-term measurements.

RV METEOR

From Cape Verde to Barbados. Repeated north-south crossings of the Atlantic ITCZ at different longitudes.

https://orcestra-campaign.org

Members of ORCESTRA

- MAESTRO
- PERCUSION
- BOW-TIE
- PICCOLO
- SCORE
- STRINQS
- CELLO
- CLARINET

Overarching objective:

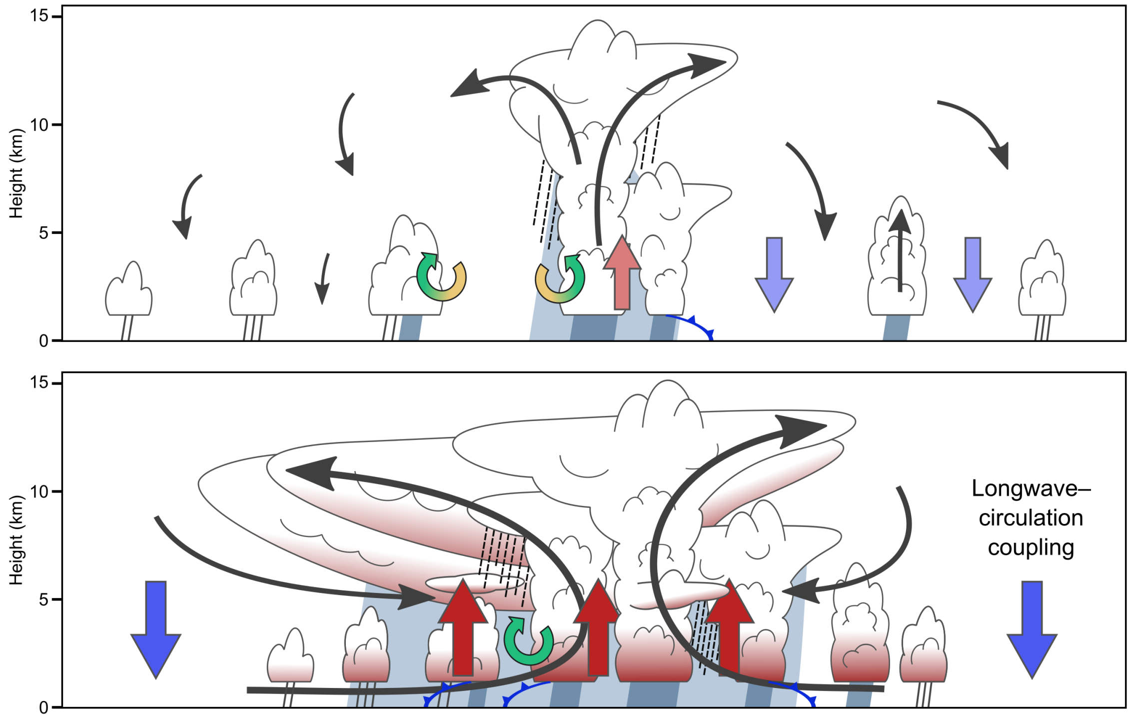
Better understand physical mechanisms that organize tropical convection at the mesoscale, and the impact of convective organization on climate and Earth's radiation budget

MAESTRO is funded by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (ERC Advanced Grant agreement No 101098063). PICCOLO is funded by the US National Science Foundation (NSF). PERCUSION and BOW-TIE are supported by a combination of funding from the Max Planck Society, the German Research Foundation (DFG), German Aerospace Center (DLR) internal funding (Helmholtz), the European Space Agency (ESA), and the European Union through its Horizon 2020 programme. SCORE is funded by the CLICCS excellence cluster (UHH), MPI and ERC.

ORCESTRA/PICCOLO

- Deploy the CSU SEA-POL radar on the R/V Meteor, to characterize the properties of precipitation and its mesoscale organization

- Goals:
    - Investigate the nature, governing mechanisms, and impact of mesoscale organization of precipitating deep convection in the context of the Atlantic ITCZ
    - Characterize the importance of localized *internal* feedbacks in relation to large-scale *external* forcing in the control of convective upscale growth and mesoscale organization.



Allison Wing (FSU), James Ruppert (OU), Michael Bell (CSU), Morgan O'Neill (U. Toronto), v. Chandrasekar (CSU), Chelsea Nam (FSU)

PICCOLO is funded by the National Science Foundation

PERCUSION MAESTRO CELLO SCORE STRINOS PICCOLO BOWTIE CLARINET

ORCESTRA

ORganized **C**onvection and **E**arthCare **S**tudies over the **TR**opical **A**tlantic

August-September 2024

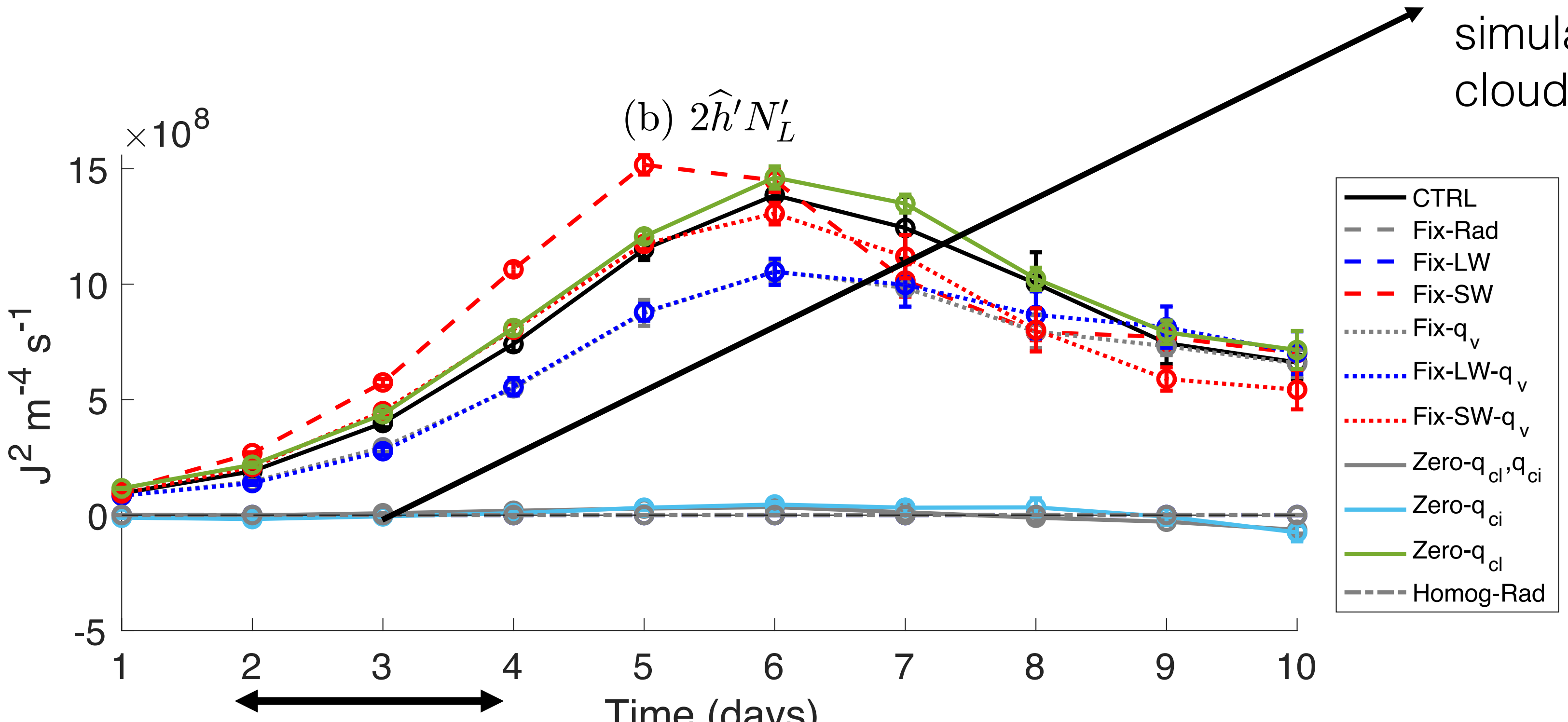
http://orchestra-campaign.org

Cloud-radiative feedbacks in TC development:

Lee, T.-Y. and A.A. Wing (2024): Satellite-Based Estimation of the Role of Cloud-Radiative Interaction in Accelerating Tropical Cyclone Development, J. Atmos. Sci., 81, 959-982, doi:10.1175/JAS-D-23-0142.1.

Wing, A.A. (2022): Acceleration of tropical cyclone development by cloud-radiative feedbacks, J. Atmos. Sci., 79, 2285–2305, doi:10.1175/JAS-D-21-0227.1.

Contribution of LW feedback to enhancing FMSE (~moisture) anomalies & aiding TC formation and intensification



Near zero LW feedback in simulations with transparent ice clouds

*LW feedback zero in Homog-Rad, Fix-Rad & Fix-LW

$$\frac{d\mathrm{var}(\widehat{h})}{dt} = 2\langle \widehat{h}' F_K' \rangle + 2\langle \widehat{h}' N_S' \rangle + 2\langle \widehat{h}' N_L' \rangle - 2\langle \widehat{h}' \nabla_h \cdot \widehat{\mathbf{u}h} \rangle,$$

Wing (2022)

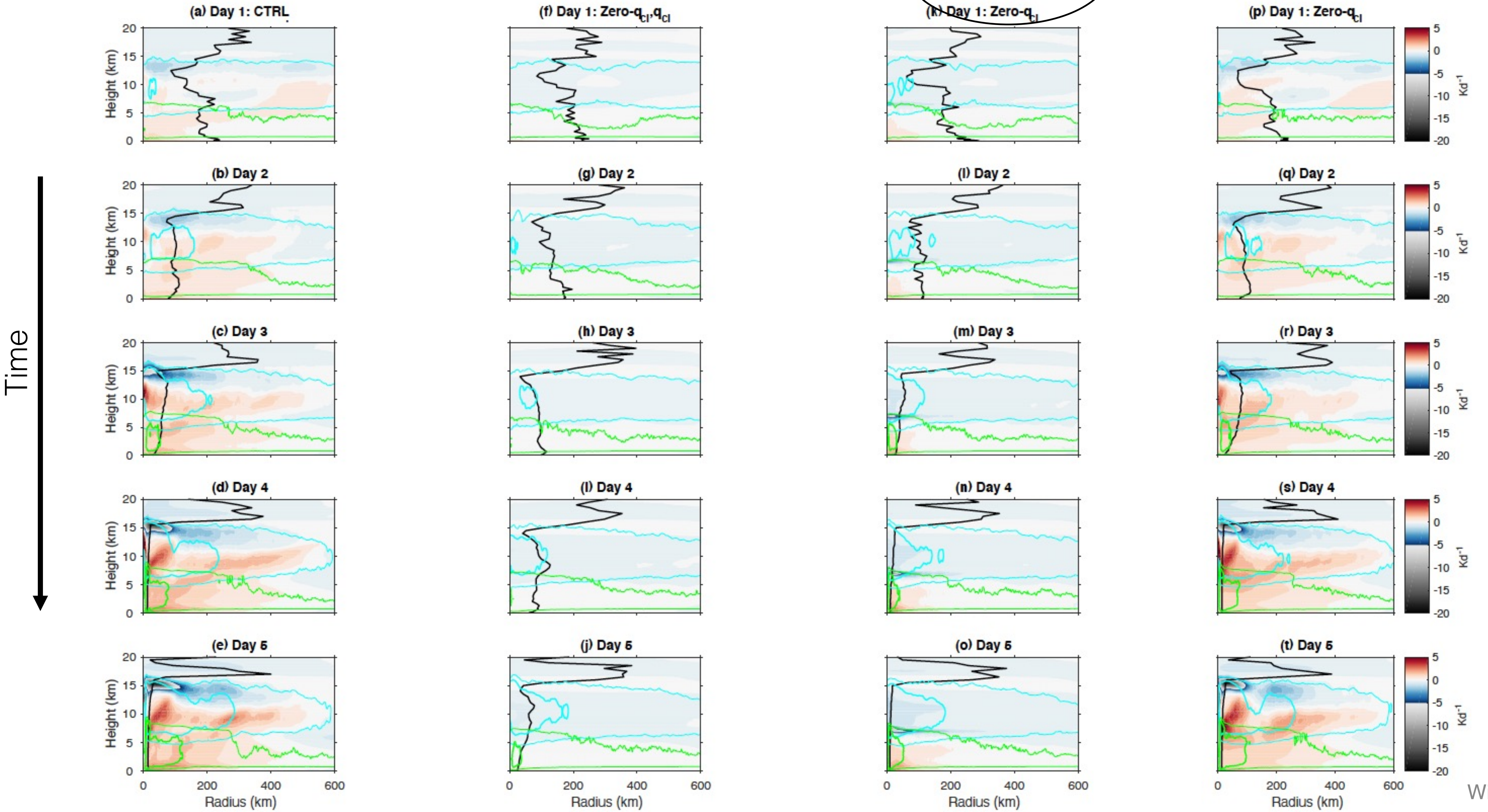
Radial Anomaly of Longwave Radiative Heating Rate

CTRL

Zero Clouds

Zero Ice Clouds

Zero Liquid Clouds



Wing (2022)

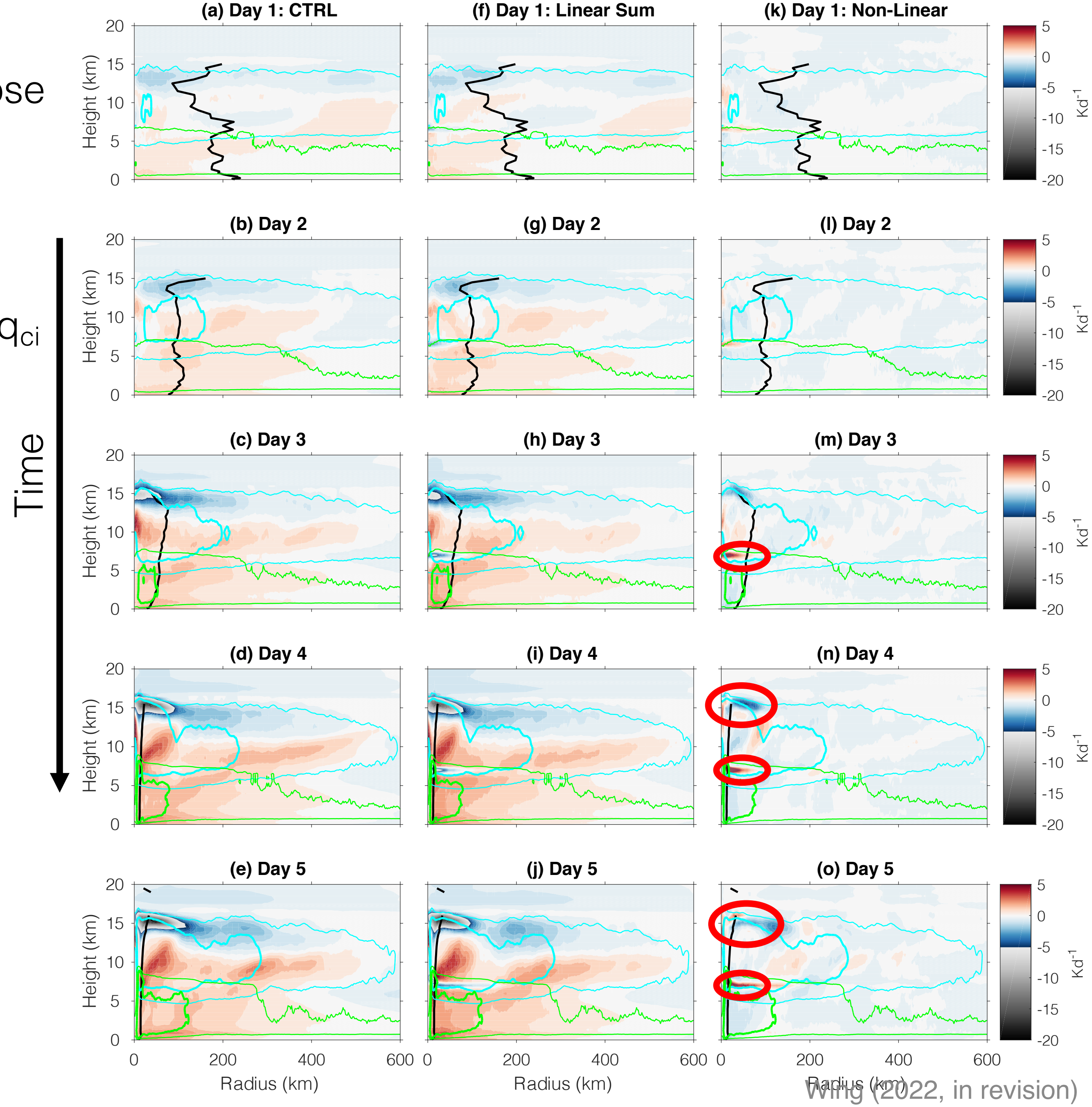
Radial Anomaly of Longwave Radiative Heating Rate

Use factor separation (Stein & Alpert 1993) to diagnose non-linear interaction between ice and liquid clouds:

Linear Sum = Zero-q_{cl} + Zero-q_{ci} – Zero-q_{ci},q_{cl}

Non-Linear = CTRL - (Zero-q_{cl} + Zero-q_{ci}) + Zero-q_{cl},q_{ci}

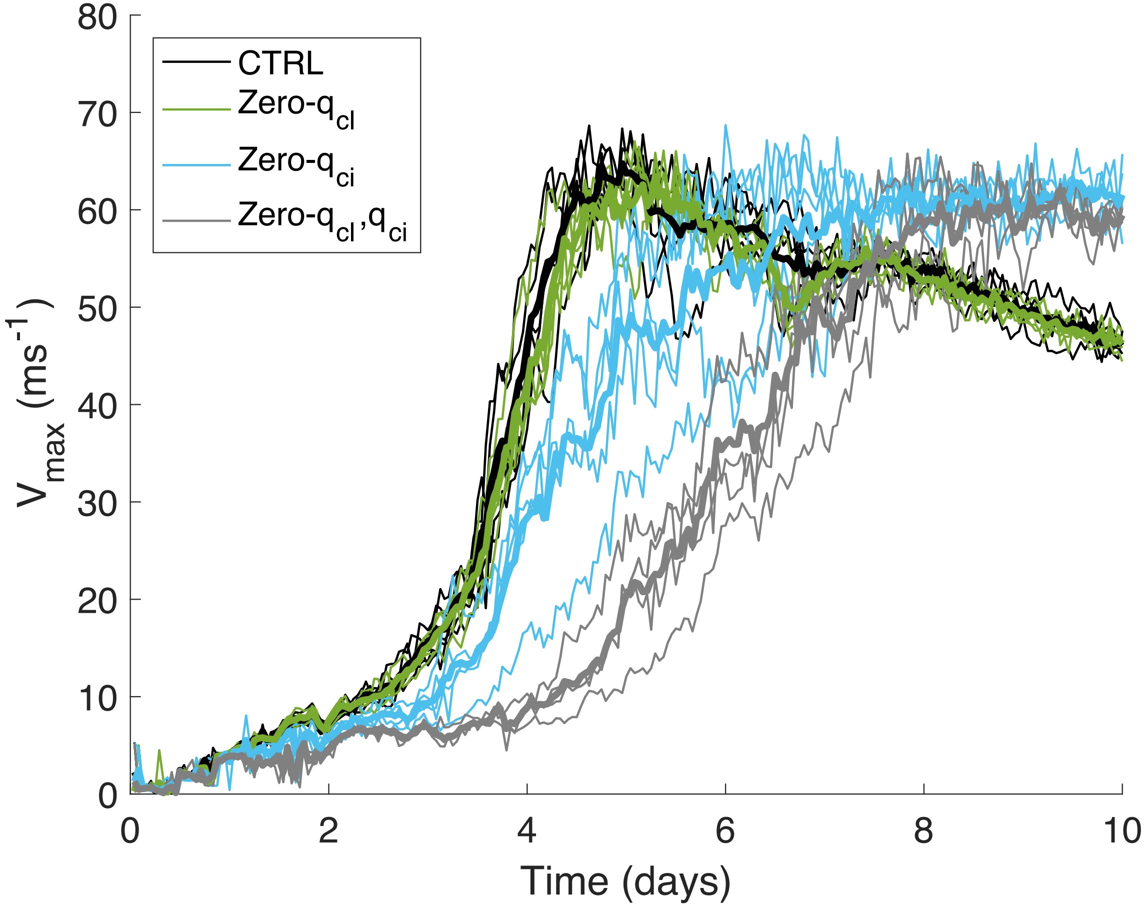
- Overall, LW heating anomalies are well captured by the linear sum (especially lower-mid tropospheric warming)
- Non-linear interaction term doesn't have as clear a structure, but magnitudes are large in some places
    - Above freezing level where there are mixed-phase clouds
    - Deep convective cloud tops



Wing (2022, in revision)

What is going on in the simulation with transparent ice clouds (Zero-qci)?

- Variability in LW heating rates is effectively removed
- LW feedback is near zero
- Yet, there is only a slight delay in TC formation compared to CTRL
- And the TC forms much more quickly than when both ice & liquid clouds are zeroed

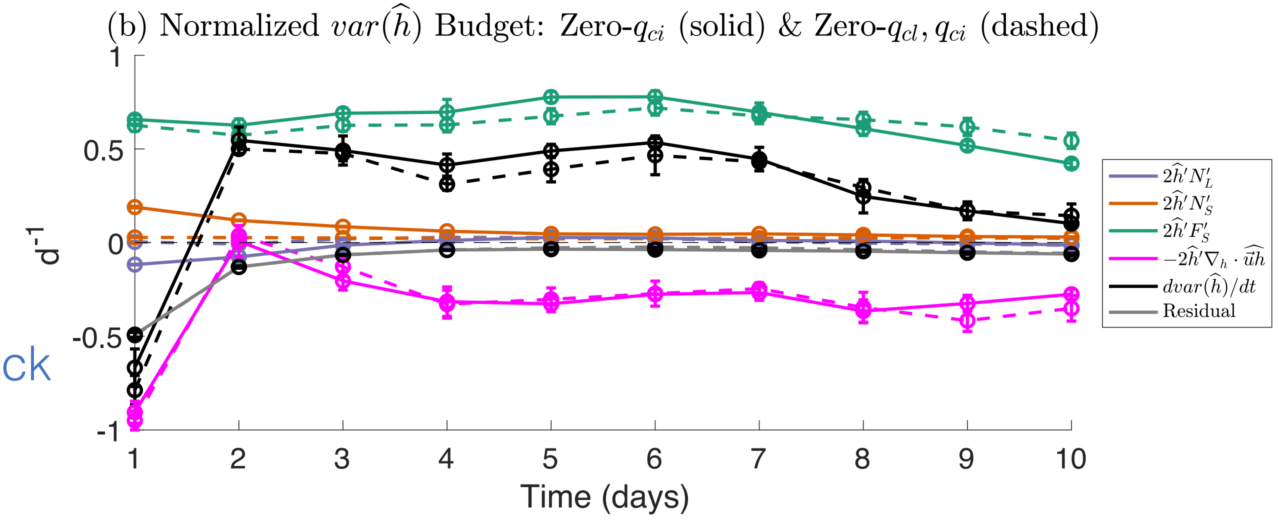


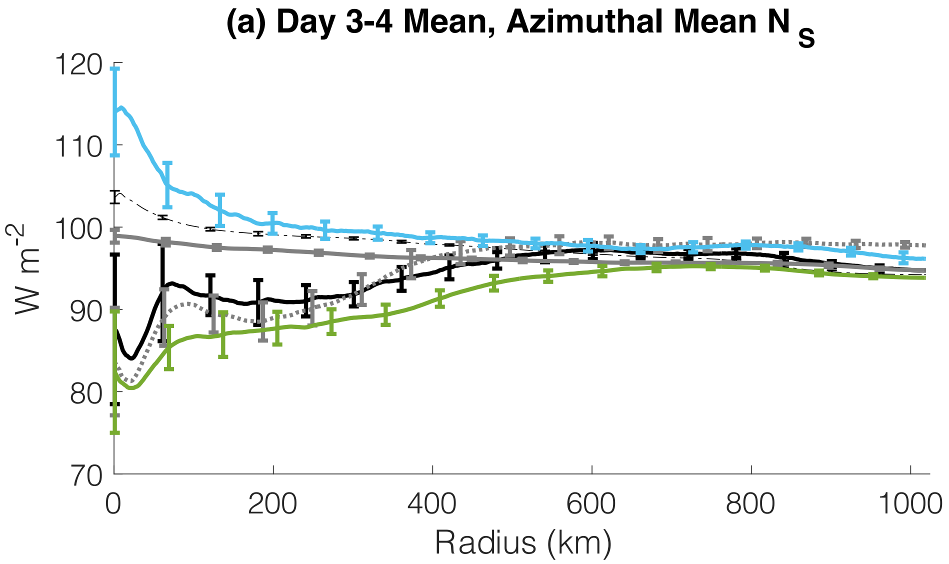
Wing (2022)

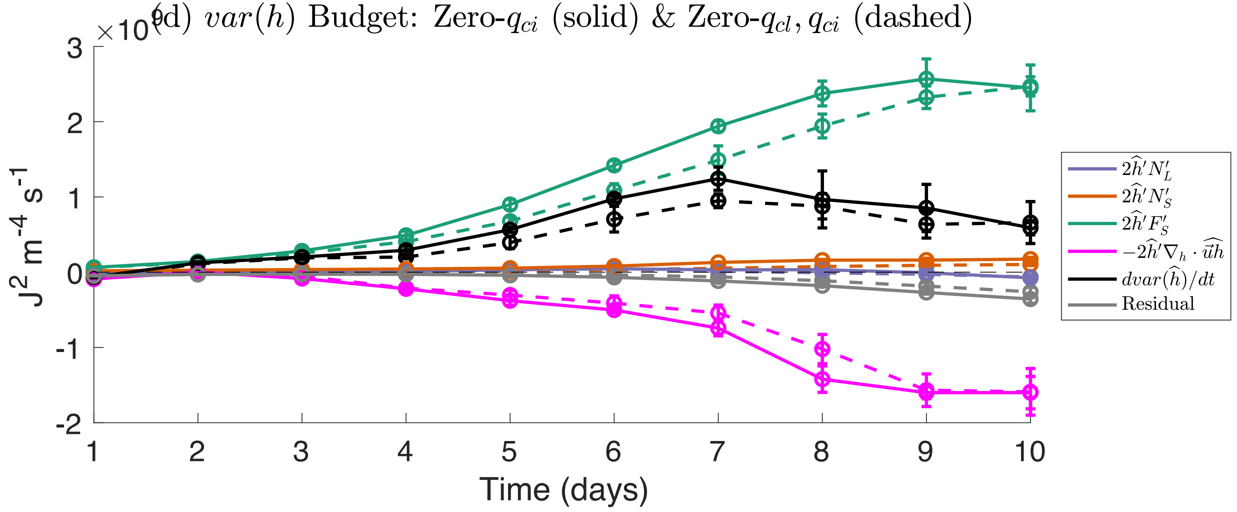
What is going on in the simulation with transparent ice clouds (Zero-qci)?

Two Main Factors:

1. Zero-qci has slightly larger FMSE variance tendency than Zero-qci,qcl because
   1. Larger surface flux feedback in Zero-qci
   2. Positive SW feedback in Zero-qci compensates for small, negative LW feedback


(b) Normalized $var(\widehat{h})$ Budget: Zero-q_{ci} (solid) & Zero-q_{cl}, q_{ci} (dashed)


(a) Day 3-4 Mean, Azimuthal Mean N_S


(d) $var(\widehat{h})$ Budget: Zero-q_{ci} (solid) & Zero-q_{cl}, q_{ci} (dashed)

$$\frac{d\mathrm{var}(\widehat{h})}{dt} = 2\langle \widehat{h}' F_K' \rangle + 2\langle \widehat{h}' N_S' \rangle + 2\langle \widehat{h}' N_L' \rangle - 2\langle \widehat{h}' \nabla_h \cdot \widehat{\mathbf{u}h} \rangle,$$

Wing (2022)

What is going on in the simulation with transparent ice clouds (Zero-qci)?

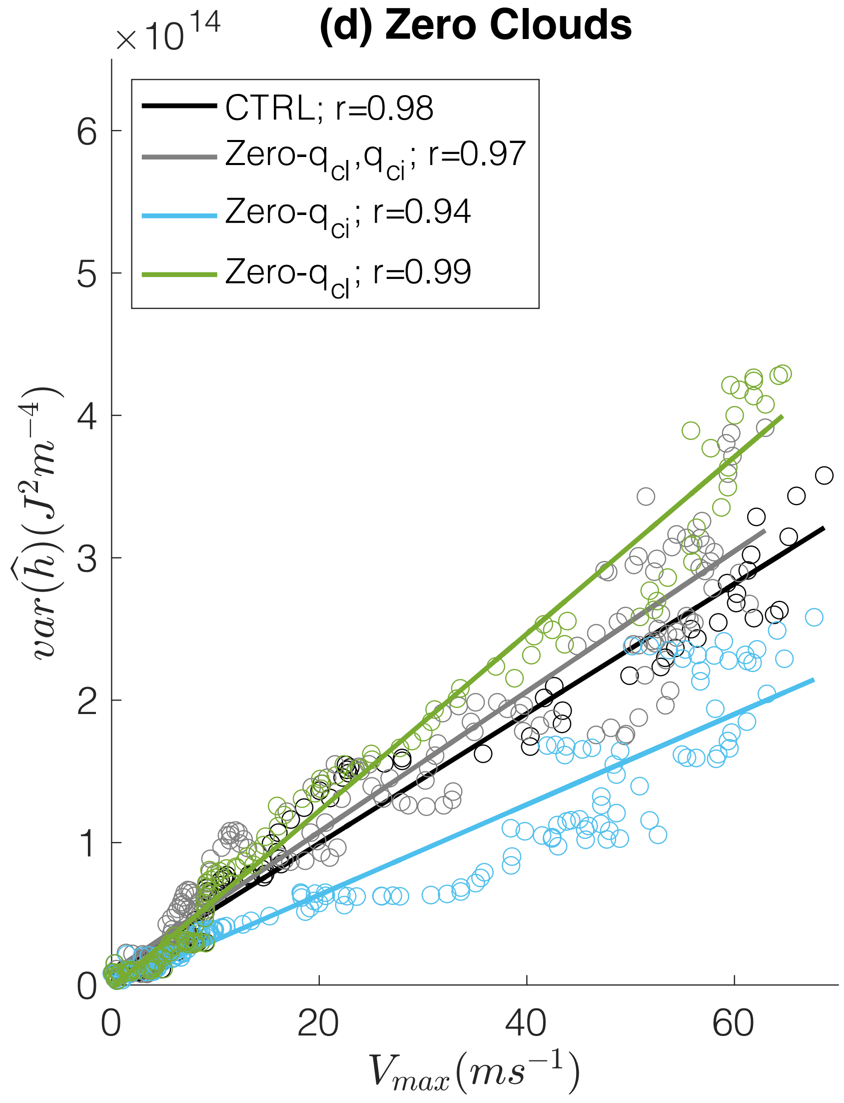
Two Main Factors:

1. Zero-qci has slightly larger FMSE variance tendency than Zero-qci,qcl because
   1. Larger surface flux feedback in Zero-qci
   2. Positive SW feedback in Zero-qci compensates for small, negative LW feedback
2. Zero-qci has a faster increase in Vmax per unit increase in FMSE variance

LW feedback is NOT the only factor contributing to TC development

Limitations of FMSE variance budget

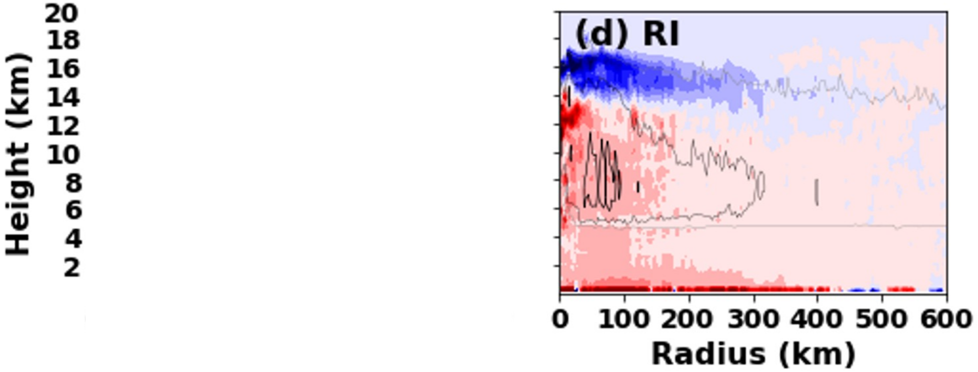
$$\frac{d\mathrm{var}(\widehat{h})}{dt} = 2\langle \widehat{h}' F_K' \rangle + 2\langle \widehat{h}' N_S' \rangle + 2\langle \widehat{h}' N_L' \rangle - 2\langle \widehat{h}' \nabla_h \cdot \widehat{\mathbf{u}h} \rangle,$$



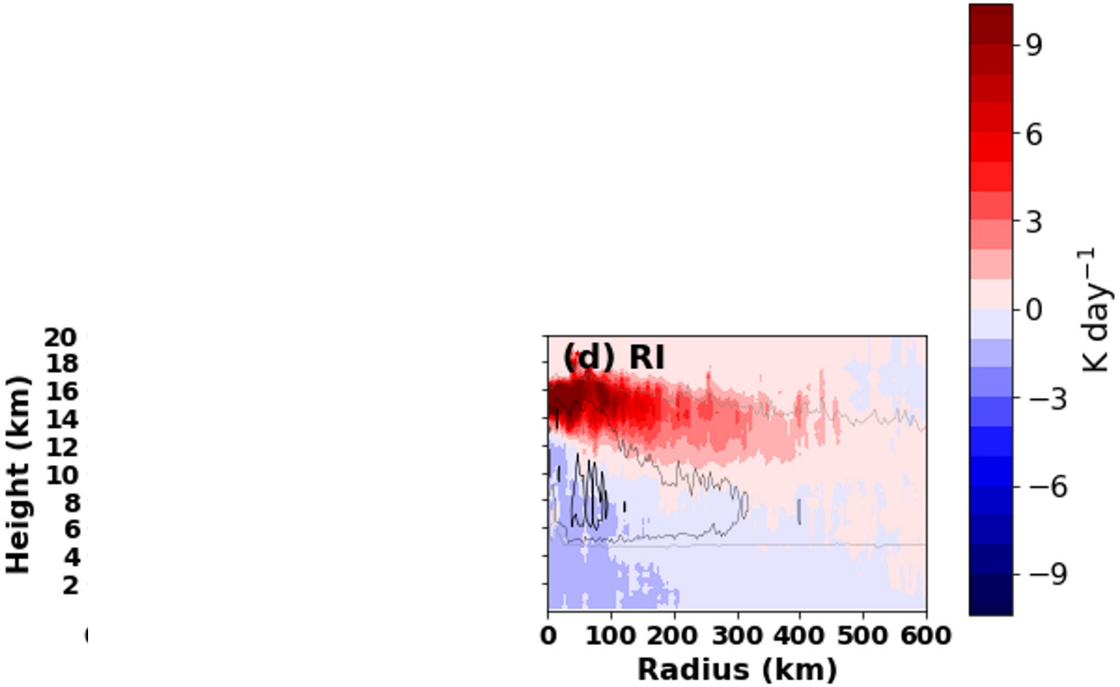
Wing (2022)

Intensification rate composites

LW Radiative Heating Rate Radial Anomaly



SW Radiative Heating Rate Radial Anomaly

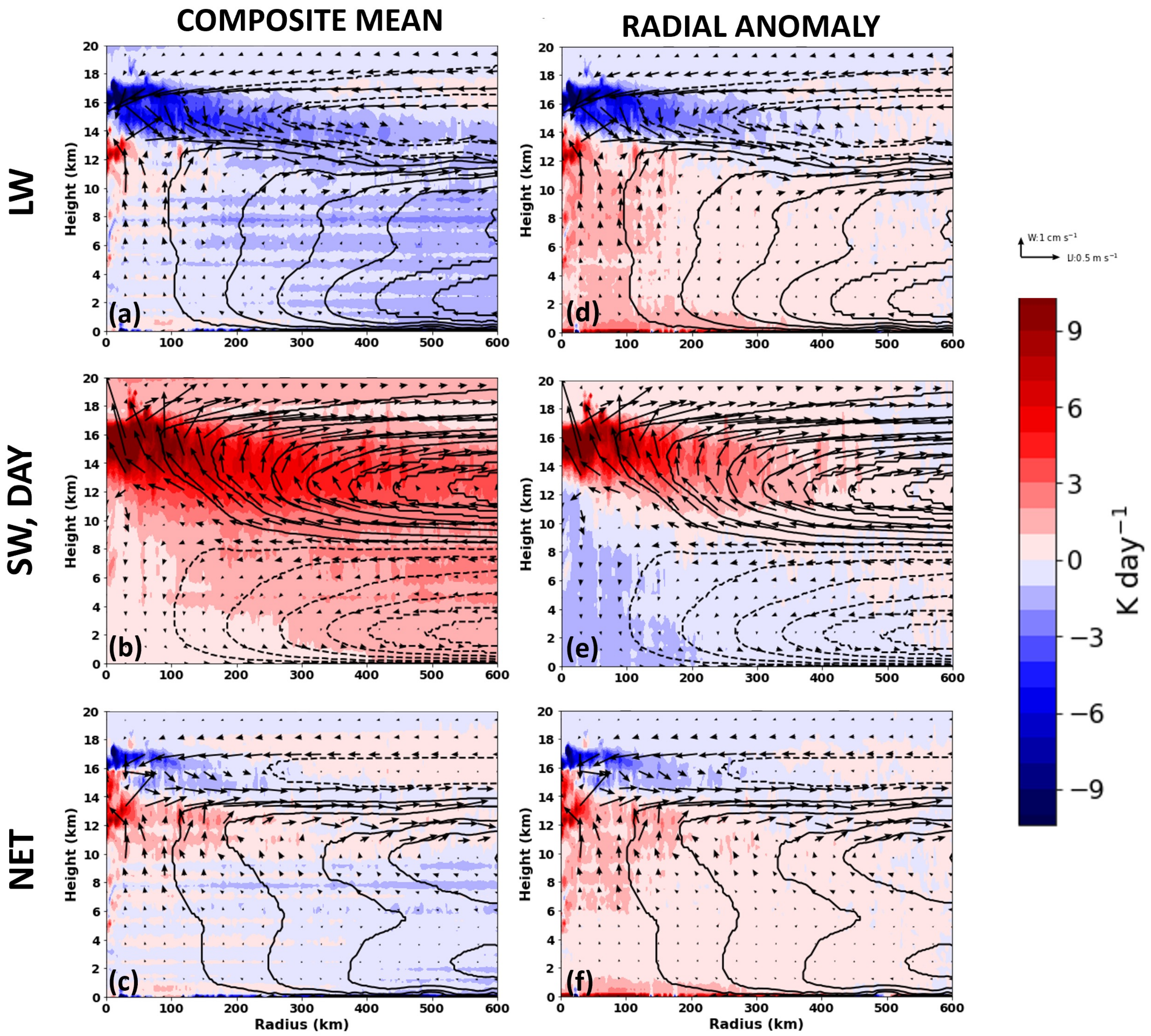


- LW heating in lower troposphere, mid-upper troposphere close to TC center, LW cooling at convective cloud tops
- SW heating at cloud tops, cooling below
- RI cases have greater LW warming in the inner core
- RI cases have greater SW cooling in the inner core, greater SW heating at cloud top

Data source:
IWC: CloudSat 2C-ICE product
LWC: CloudSat 2B-CWC-RO product
q_v : ECMWF product

Lee and Wing (2024)

RI TCs



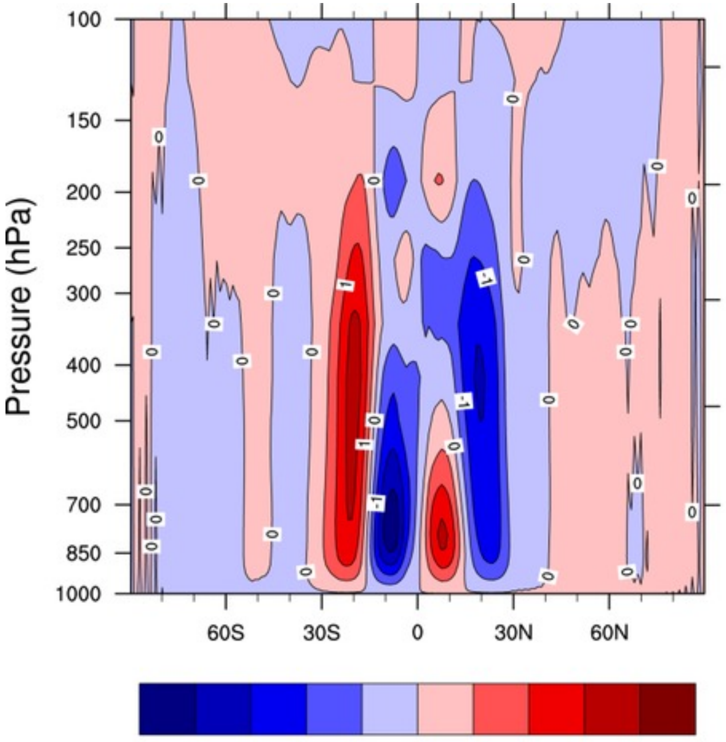
Sawyer-Eliassen Model

- Diagnostic model using the axially symmetric tangential momentum, buoyancy, gradient wind balance, hydrostatic, and mass continuity equations (Shapiro and Willoughby, 1982)
- Computes axisymmetric response of the transverse circulation to imposed heating or momentum forcings in a balanced initial vortex
- Height coordinates with lower boundary assumed to be ocean surface (Pendergrass and Willoughby 2009)
- Initial idealized vortex based on composite mean: Vmax = 20 m/s, RMW = 40 km, vortex height = 16 km, eyewall transition width of 20 km, latitude of 15N

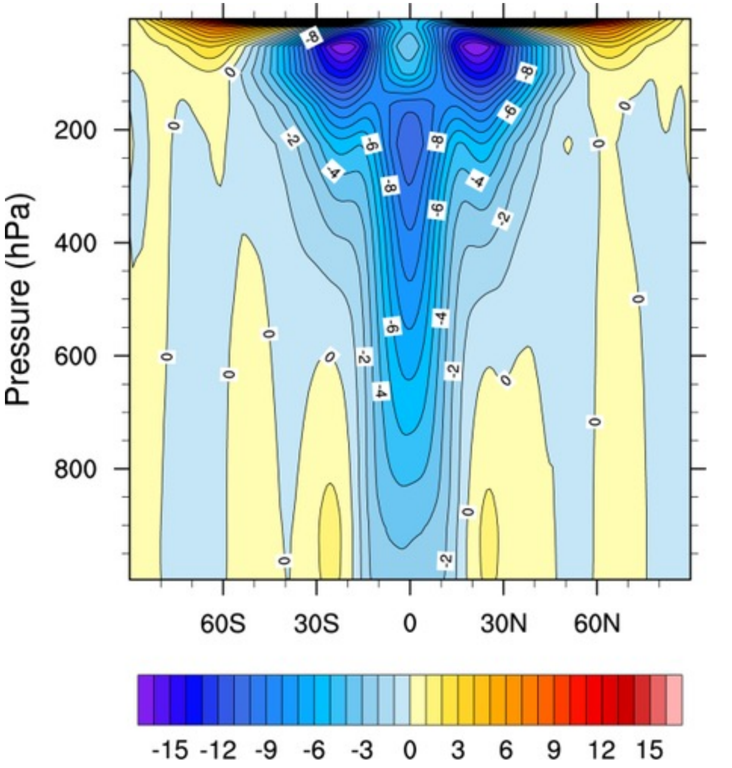
$$
\begin{aligned}
& N^2 \frac{\partial^2 \psi}{\partial r^2} - 2B \frac{\partial^2 \psi}{\partial z \partial r} + I'^2 \frac{\partial^2 \psi}{\partial z^2} \\
& - \left(\frac{N^2}{R_\rho} - \frac{B}{H_\rho} + N^2 \frac{\partial \gamma}{\partial z} \right) \frac{\partial \psi}{\partial r} \\
& - \left(\frac{I'^2}{H_\rho} - \frac{B}{R_\rho} - \frac{3\xi S}{r} - N^2 \frac{\partial \gamma}{\partial r} \right) \frac{\partial \psi}{\partial z} \\
& = r\rho \left[\frac{\partial Q}{\partial r} - \frac{\partial}{\partial z}(\xi M) + \gamma \frac{\partial Q}{\partial z} \right]
\end{aligned}
$$

Is the Hadley Cell a manifestation of self-aggregation?!?

Probably not (existence predicted by dry axisymmetric dynamics), but it can be interpreted an instability of the radiative-convective equilibrium state



Mass streamfunction of zonal mean circulation



Shi and Bretherton (2014)

Zonal mean zonal wind

Cloud-radiation interactions can drive a Hadley Circulation even in the absence of any latitudinal SST or solar heating gradients
(Raymond, 2000)