Pathways to Tropical Cyclogenesis in Rotating Radiative-Convective Equilibrium Simulations

Jacob D. Carstens and Allison A. Wing
Department of Earth, Ocean, and Atmospheric Science, Florida State University, Tallahassee, FL, USA

On large scales, the tropical atmosphere can be thought to be in radiative-convective equilibrium (RCE), the balance between radiative cooling and convective heating. Modeling studies of RCE have shown the potential for previously random convection to "self-aggregate", or organize spontaneously, via feedbacks involving clouds, water vapor, radiation, surface fluxes, and mesoscale circulations.[1] In an environment of rotating RCE, self-aggregation may take the form of a tropical cyclone (TC).[2]

MOTIVATION

- Tropical cyclogenesis remains one of the major open questions in our field.
- Idealized modeling studies revealed importance of radiative effects to accelerate TC genesis.[3]
- By initializing randomly from RCE, convection is allowed to behave on its own, providing a more holistic view of the process.
- Study "low-rotation" RCE cases for the first time to simulate near-equatorial TC genesis.

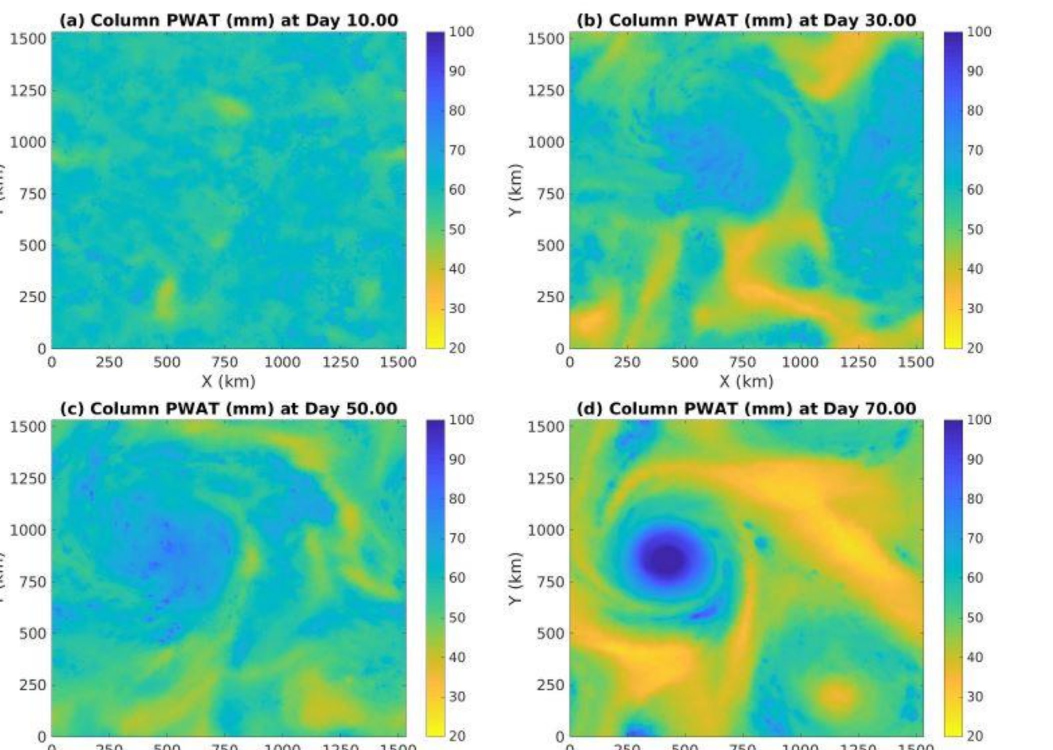


FIG. 1: Evolution of column precipitable water in a 15° f-plane simulation, showing self-aggregated convection in the form of an intense TC.

MODEL DETAILS

- Cloud-resolving model used: System for Atmospheric Modeling (SAM), version 6.8.2.[4]
- 1536 km square, doubly periodic domain; 64 vertical levels; 3 km horizontal grid spacing.
- 100 day simulations with constant solar insolation and 305 K fixed SST.
- 27 total simulations on 10 f-planes, analogous to latitudes from 0.1-20°. 3-5 member ensembles for all f-planes except 0.1°, with different initial random convection distribution.

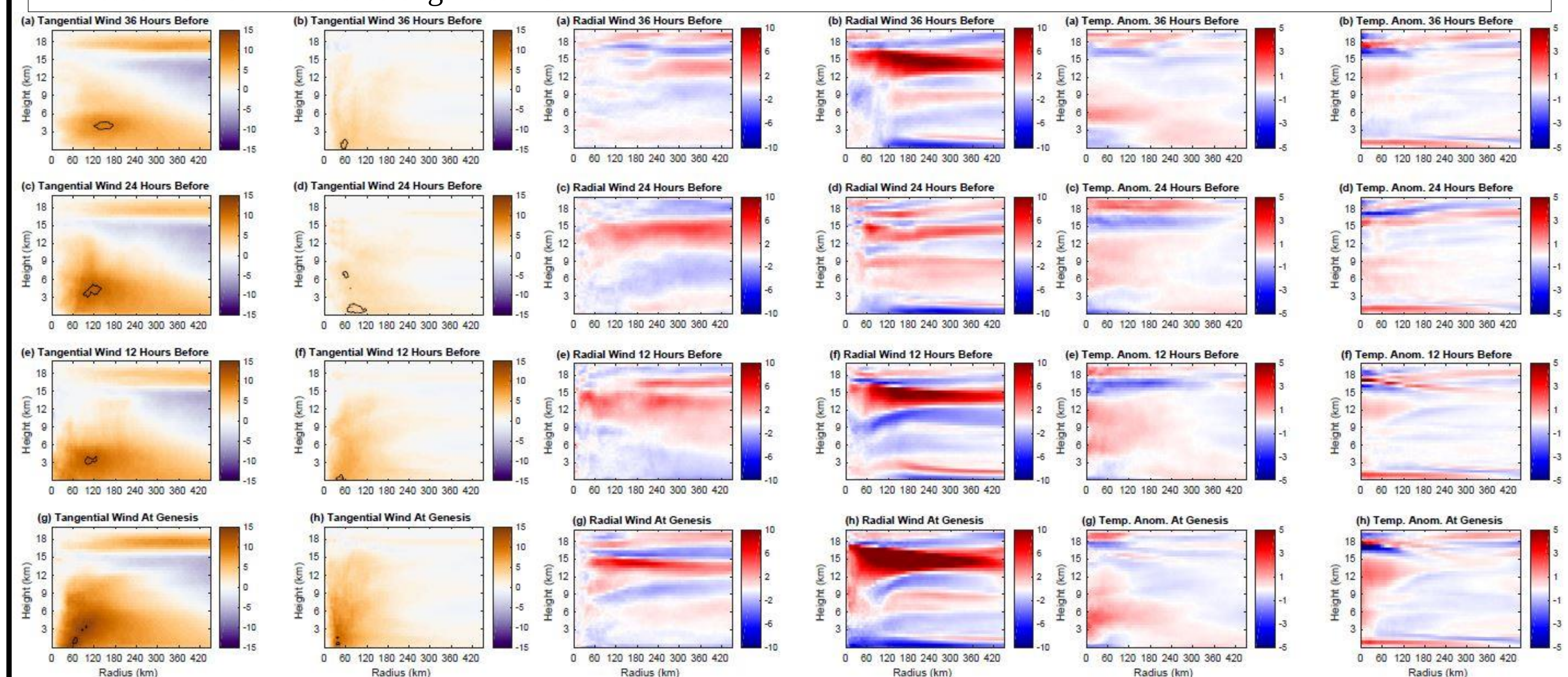
"Low-f": 0.1°, 1°, 2°, 3°, 5°. 13 simulations.

"High-f": 10°, 15°, 20°. 11 simulations.

A 7.5° group will be discussed separately.

"HIGH-F" PROCESSES

- Broad circulation develops while self-aggregation feedbacks operate and convection organizes.
- Vortex generally emerges in middle troposphere; thermodynamic response favors strong vertical mass flux below.
- This leads to increased mass/vorticity convergence near the surface, eventually contributing to TC spinup.
- Some 20° simulations begin development at lower levels, but mid-level vortex emergence still precedes intensification to a TS-strength surface vortex.



15° 2° 15° 2° 15° 2°

FIG. 2-4: Azimuthally averaged tangential wind (left), radial wind (center), and virtual temperature anomaly (right) prior to TC genesis for 15° and 2° cases.

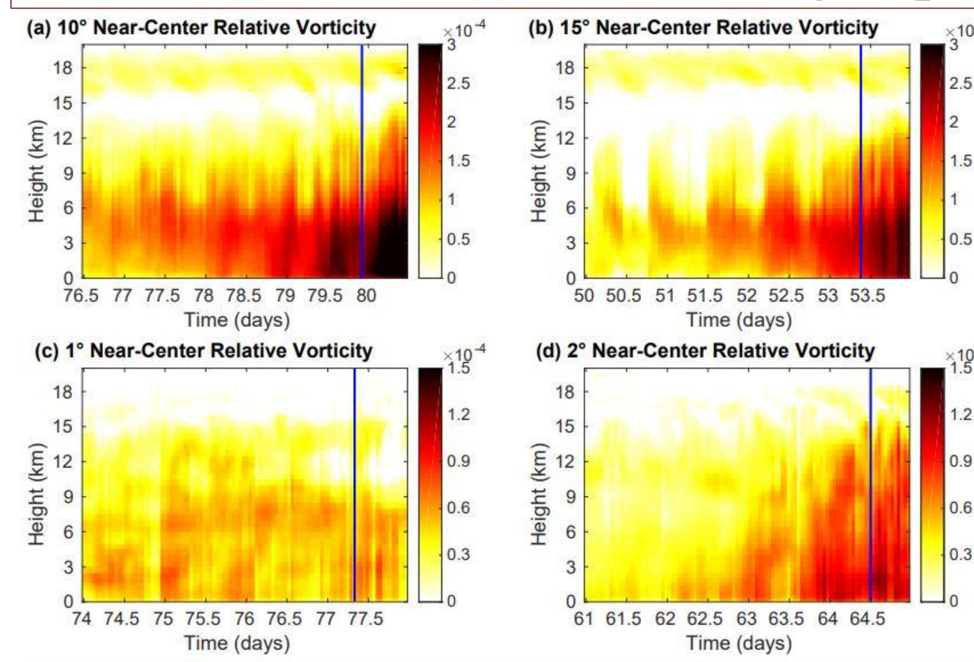
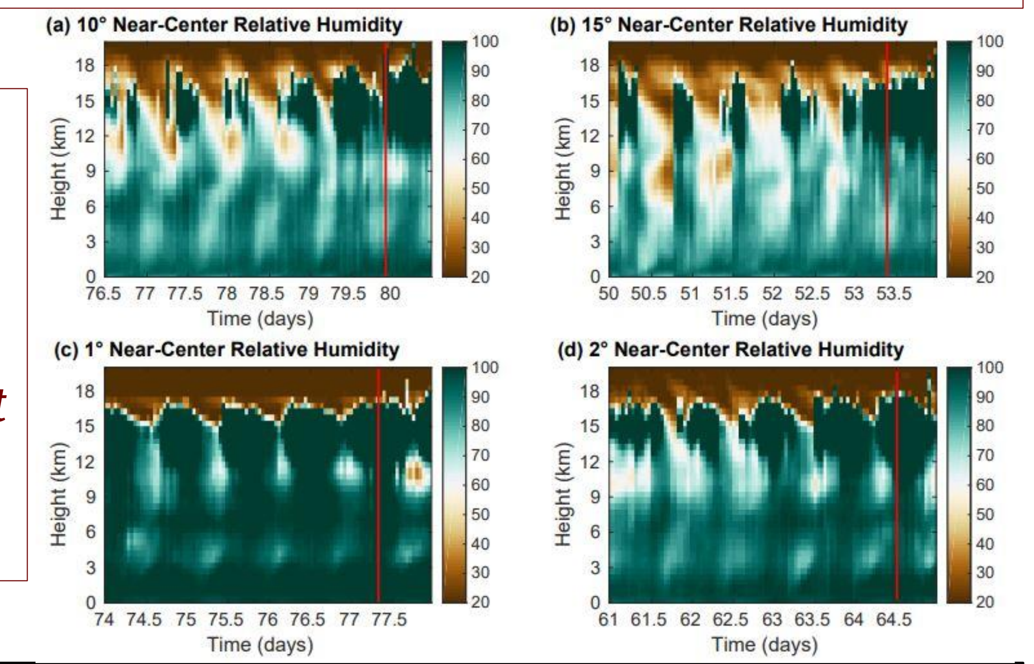


FIG. 5-6: Relative vorticity (left) and humidity (right) averaged in a 150 km box around the incipient TC center prior to genesis.



"LOW-F" PROCESSES

- Vortex spinup does not occur until after self-aggregation into a circular cluster has completed.
- As such, strong low-level convergence, high column relative humidity, and low-level buoyancy/vertical mass flux are already well-established.
- No preceding mid-level vortex is required, and TC development begins at low levels, in agreement with recent reanalyses of real-world near-equatorial TCs.[5]
- Only 3/13 simulations in this group produce a TC. All others self-aggregate as a long band.

CONCLUSIONS

- Key conditions that precede TC genesis in this model: Saturation and low-level inflow.
- Pathways to achieve this differ between the two groups of TC-producing simulations.
  - High-f: Mid-level vortex emergence.
  - Low-f: Complete self-aggregation into a non-rotating, circular cluster.
- Dynamical evolution of low-f TC genesis resembles reanalyses of near-equatorial TCs.
  - Can self-aggregation play a role in these cases?

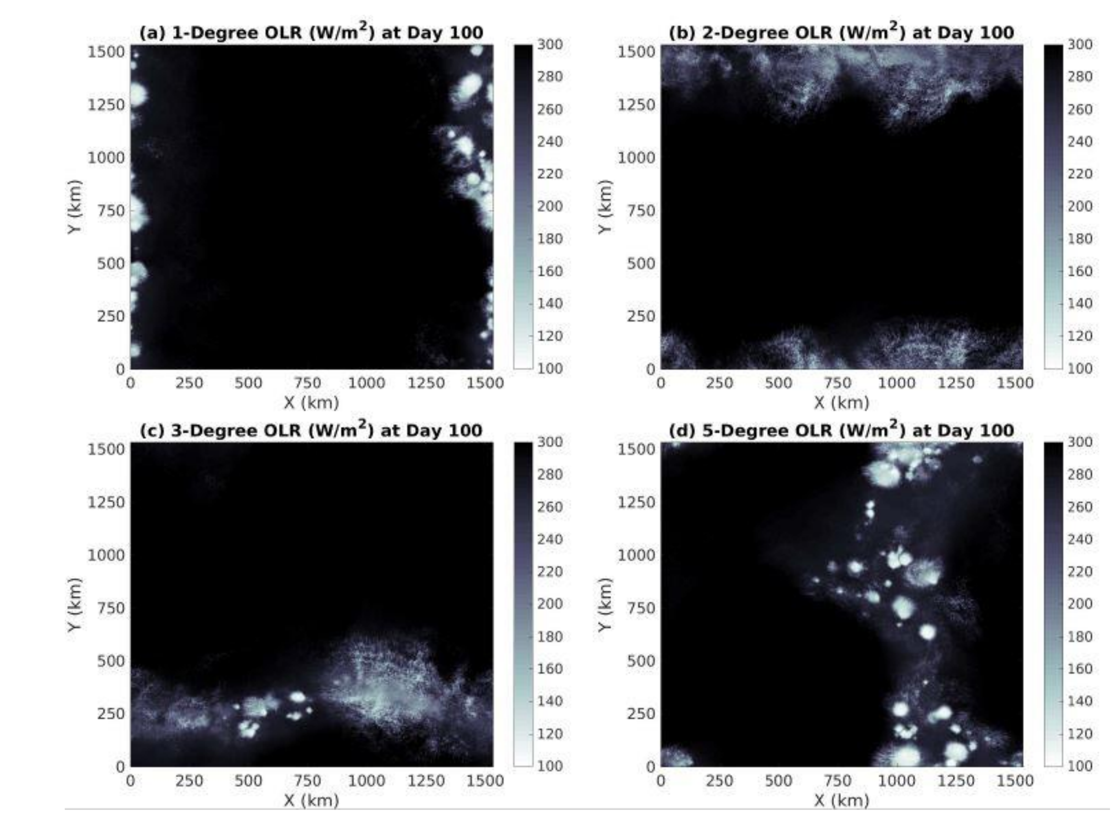


FIG. 7: Banded self-aggregated convection at day 100 of 1°, 2°, 3°, and 5° simulations.

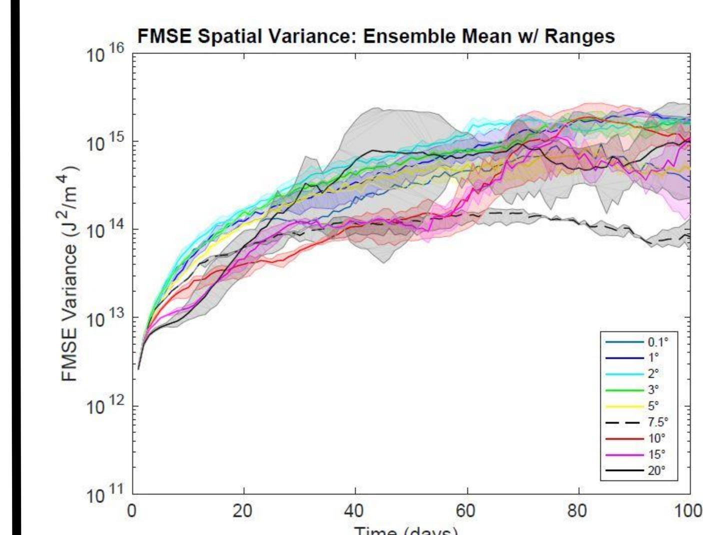


FIG. 8: Ensemble means of daily-averaged frozen moist static energy (FMSE) spatial variance, with shaded ranges.

FUTURE WORK

- Precisely quantify results/ideas presented here with vorticity, divergence, and FMSE budgets (currently in progress).
- The set of 7.5° fails to fully self-aggregate. Does this represent a transition zone between the two regimes outlined here?
- Banded vs. circular aggregation in "low-f" simulations: What separates these?

ACKNOWLEDGMENTS: High-performance computing support from Cheyenne (doi:10.5065/D6RX99HX) provided by NCAR's Computational and Information Systems Laboratory, sponsored by the National Science Foundation, and the High Performance Computing cluster at the Research Computing Center at the Florida State University. AAW acknowledges support from NSF grant 1830724. Additional acknowledgments to Marat Khairoutdinov. Robert Hart, and Jeffrey Chagnon.

[1] Wing, A.A., K. Emanuel, C.E. Holloway, & C.J. Muller (2017). Convective self-aggregation in numerical simulations: A review. *Surv. Geophys.*, **38 (6)**, 1173-1197.
[3] Muller, C.J., & D.M Romps (2018). Acceleration of tropical cyclogenesis by self-aggregation feedbacks. *Proc. Nat. Acad Sci.*, **115**, 2930-2935.
[5] Steenkamp, S.C., G. Kilroy, and R.K. Smith (2019). Tropical cyclogenesis at and near the equator. *Q. J. R. Meteorol. Soc.*, 1-19.
[2] Wing, A.A., S.J. Camargo, & A.H. Sobel (2016). Role of radiative-convective feedbacks in spontaneous tropical cyclogenesis in idealized numerical simulations. *J. Atmos. Sci.*, **73**, 2633-2642.
[4] Khairoutdinov, M.F., & D.A. Randall (2003). Cloud resolving modeling of the ARM summer 1997 IOP: Model formulation, results, uncertainties, and sensitivities. *J. Atmos. Sci.*, **60**, 607-625.