Hydrostatic and Non-hydrostatic Convective Self-aggregation in E3SM

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Clustered convection

Clustered convection is ubiquitous in the atmosphere, often organized as

- Gregarious cumulus towers
- Squall lines
- Mesoscale convective complexes
- Tropical cyclones (TCs)
- Convectively coupled equatorial waves
- Madden-Julian Oscillation (MJO)

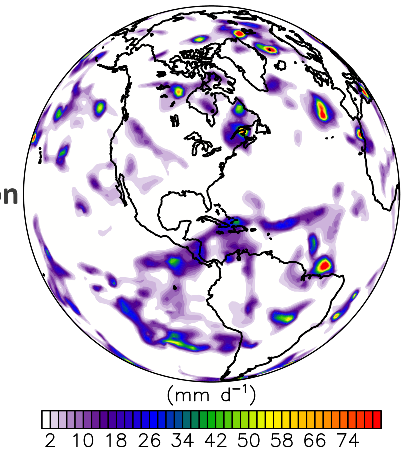
NASA

Understanding convective organization is essential for understanding its implications on weather and climate.

Using E3SM, we developed a new compset to study convective self-aggregation under Radiative-Convective Equilibrium (RCE).

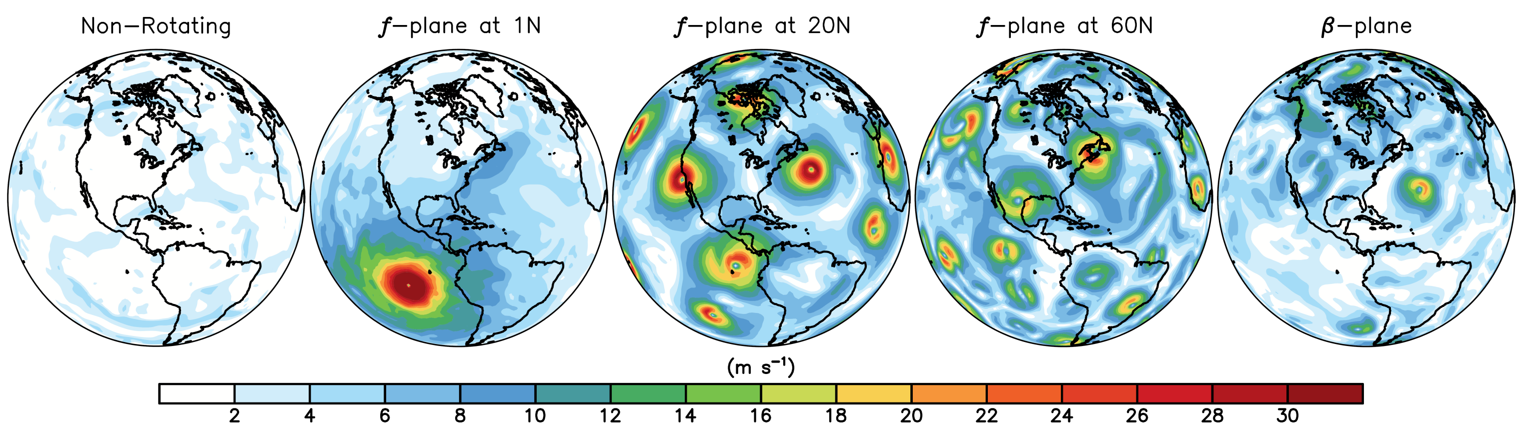
The E3SM RCE compset

E3SM RCE Precipitation Snapshot



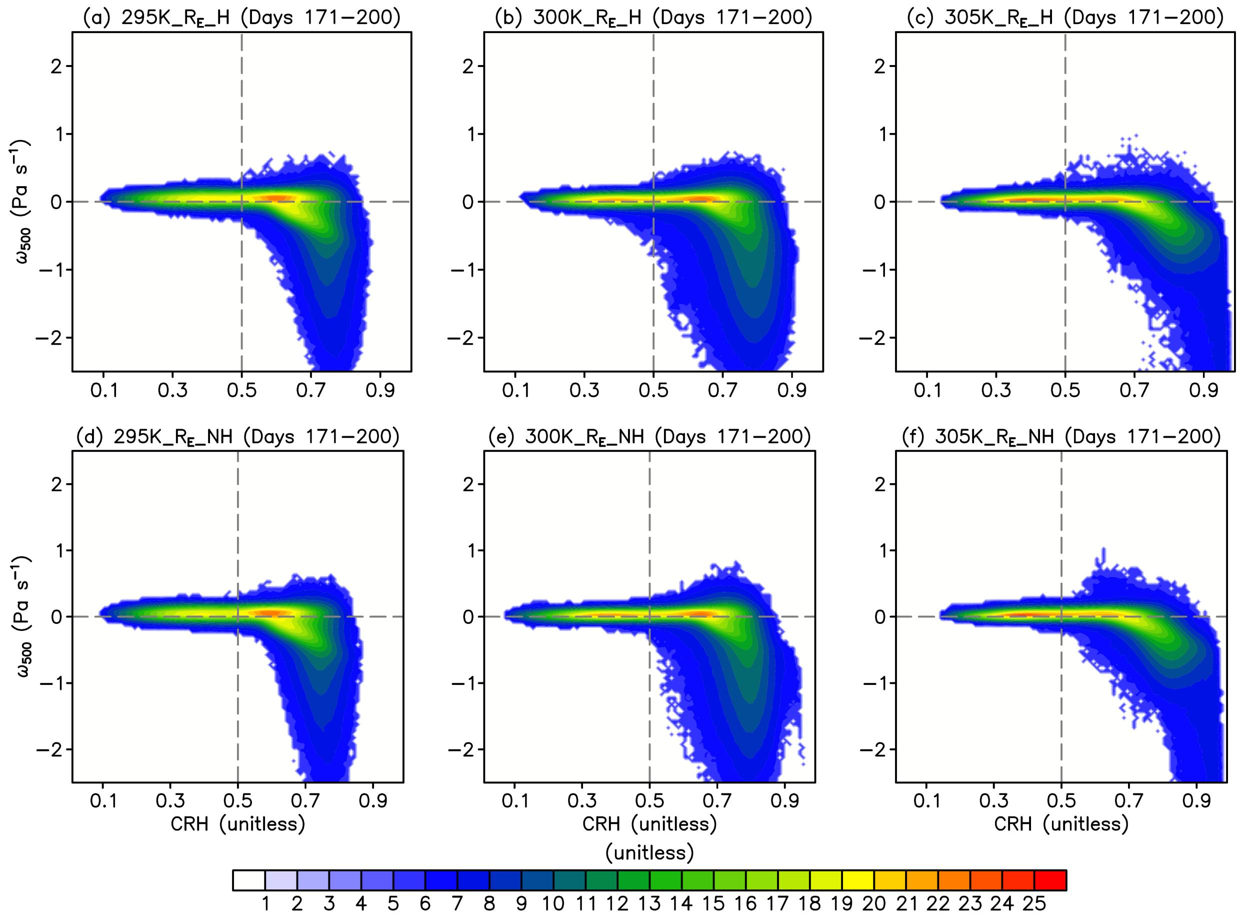
Solar insolation is globally uniform
Direct aerosol radiative effect is removed
Minimum surface layer gustiness is implemented
Model constants are consistent with RCEMIP
Thermal seed is introduced at initialization
IC is derived from single column E3SM runs following RCEMIP

Coriolis effect is deactivated for non-rotating RCE
Rotating *f*-plane and β-plane approximations are available



E3SM RCE Surface Wind: Rotating RCE simulations with *f*-plane approximation reproduce the scaling theory of TC-like vortices ($R \sim 1/f$). Under β-plane approximation, TC-like vortices are displaced toward the polar regions (R denotes the size of TC-like vortices and f is the Coriolis parameter).

The E3SM non-hydrostatic dynamical core

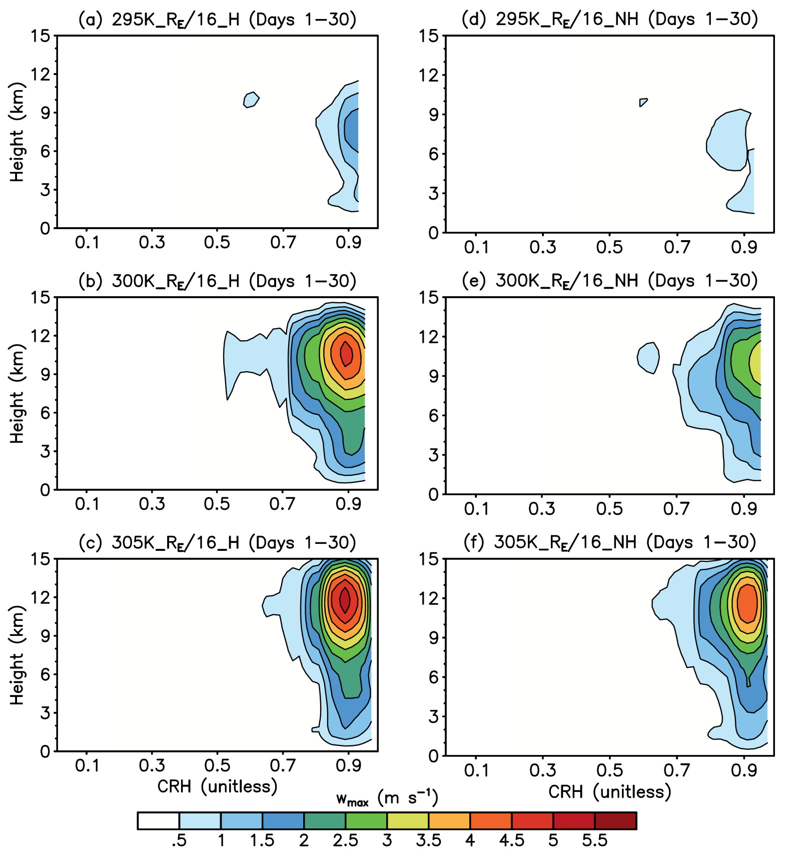


Joint Histograms: Coarse-resolution hydrostatic (top) and non-hydrostatic (bottom)

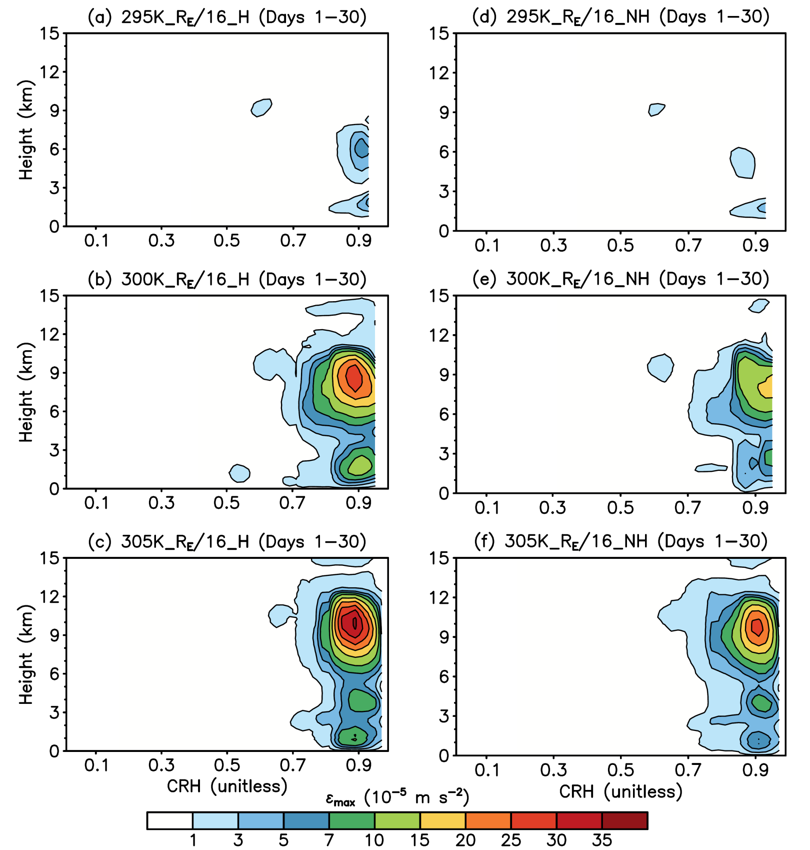
In ***coarse-resolution*** non-rotating RCE simulations at fixed 295, 300, and 305 K SSTs, the non-hydrostatic Dycore developed at the Sandia National Lab. (Taylor et al. 2020) behaves similarly as the hydrostatic counterpart in terms of both climatological mean and extremes as expected, lending confidence to the new E3SM non-hydrostatic Dycore.

Small-earth non-rotating RCE simulations at 1/16 earth radius ($\Delta x \approx 7$ km) are thus conducted to activate non-hydrostatic effect and examine its impact on convective self-aggregation.

Non-hydrostatic effect: Vertical velocity



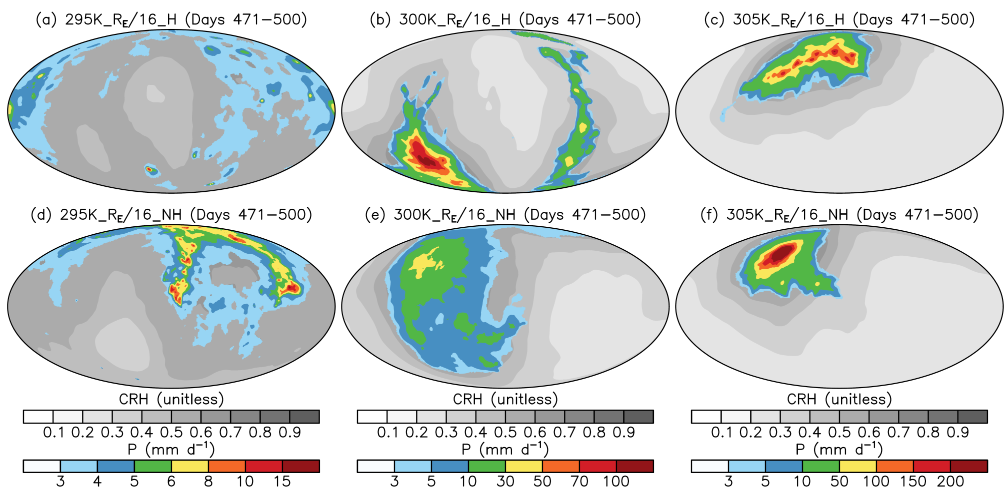
CRH Binned w_{max}: Hydrostatic (left) and non-hydrostatic (right)



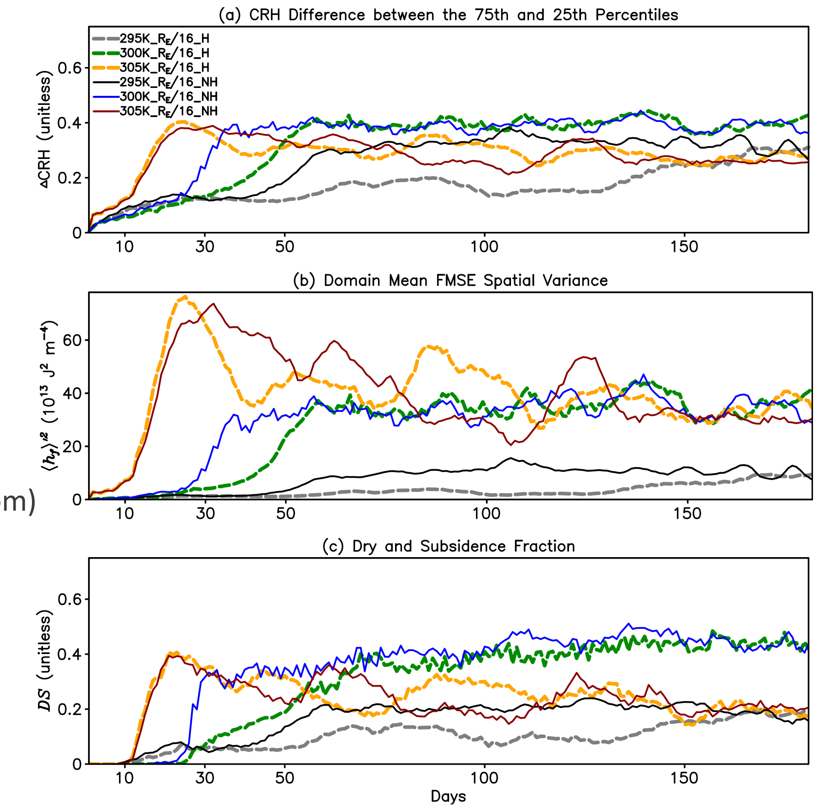
CRH Binned ε_{max}: Hydrostatic (left) and non-hydrostatic (right)

Vertical velocity change directly resulted from non-hydrostatic dynamics is primarily localized within the moist convective areas.

Non-hydrostatic effect: Convective self-aggregation



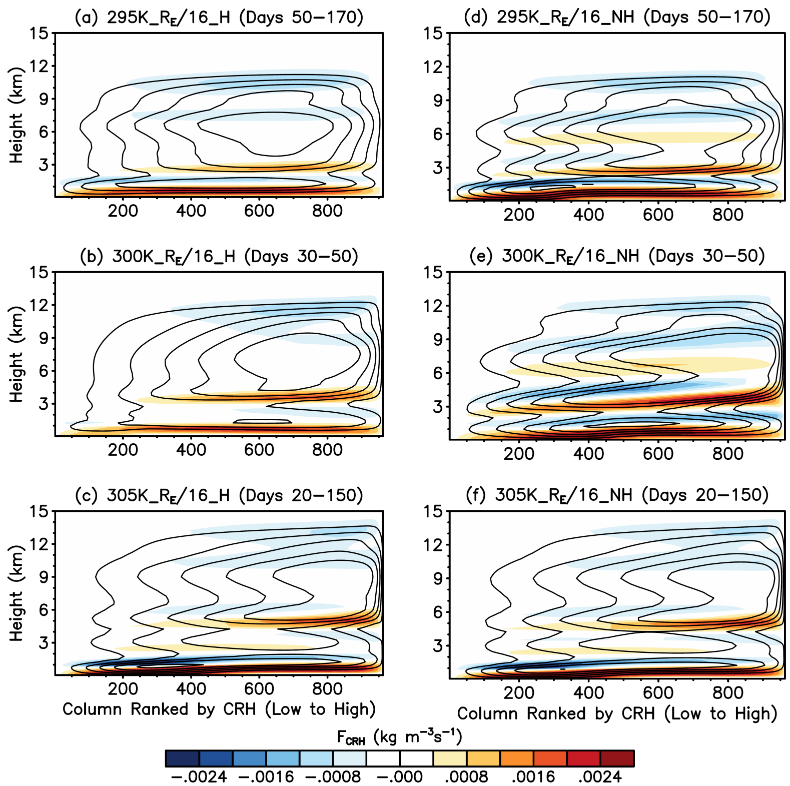
CRH (gray) and Precipitation (color): Hydrostatic (top) and non-hydrostatic (bottom)

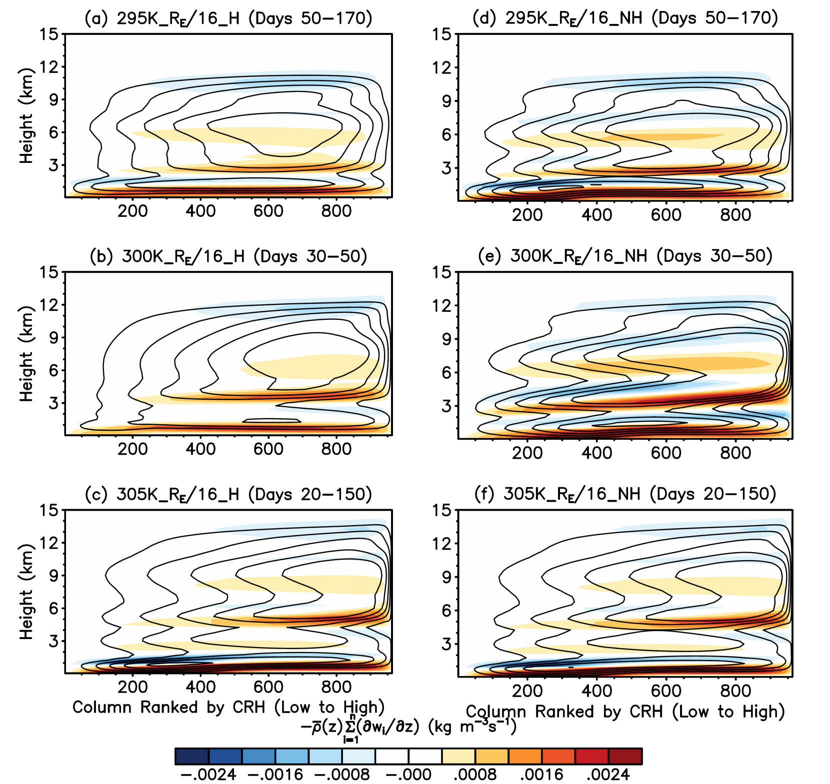


Self-aggregation Metrics

- Self-aggregation develops at all SSTs: 295, 300, and 305 K
- The size of aggregated convection varies substantially in the hydrostatic and non-hydrostatic runs at the same SST
- According the metrics of self-aggregation, it is accelerated in the non-hydrostatic simulations at relatively low SSTs

Non-hydrostatic effect: Enhanced up-gradient FMSE transport



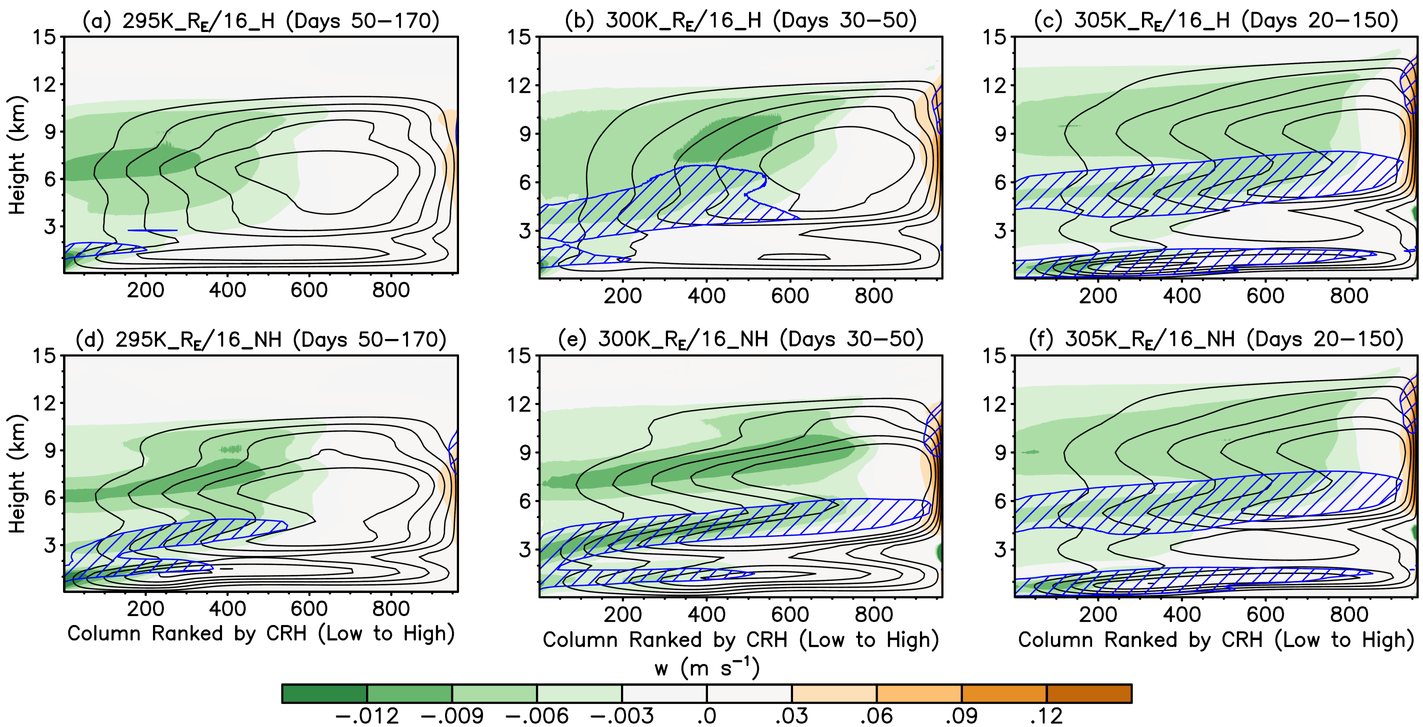


Streamfunction and F_{CRH}: Hydrostatic (left) and non-hydrostatic (right) **F_{CRH} due to $\partial w/\partial z$:** Hydrostatic (left) and non-hydrostatic (right)

At relatively low SSTs, the up-gradient FMSE transport is enhanced in the non-hydrostatic runs. Decomposition of streamfunction shows that this change is mostly related to the change of the vertical gradient of vertical velocity in the driest areas.

Non-hydrostatic effect: Radiative cooling and accelerated self-aggregation

$$w\frac{\partial \theta}{\partial z} = \frac{\theta}{c_p T}\dot{Q}_R$$



Streamfunction (contours), w (shading) and Q_R (hatching): Hydrostatic (top) and non-hydrostatic (bottom)

The non-hydrostatic dynamics induced clear-sky radiative cooling change in the driest region, which dictates vertical velocity change per thermodynamic balance, is the underlying mechanism for accelerated self-aggregation at relatively low SSTs.

Summary

- Using E3SM, a RCE compset has been developed for idealized simulations related to convective organization.
- When non-hydrostatic dynamics is included in E3SM RCE simulations, the non-hydrostatic effect varies with the underlying sea surface temperatures (SSTs).
- At relatively low SSTs, non-hydrostatic dynamics tends to accelerate convective self-aggregation by promoting up-gradient frozen moist static energy (FMSE) transport from the dry to moist regions.
- This effect, however, is not due to the vertical velocity change directly resulted from non-hydrostatic dynamics which mainly concentrates in moist convective regions, but the change of the vertical gradient of vertical velocity in the driest areas associated with non-hydrostatic dynamics induced clear-sky radiative cooling change.
- At relatively high SSTs, convective merging becomes more influential to self-aggregation and is insensitive to non-hydrostatic dynamics in E3SM, the timescale to self-aggregate is thus nearly unaltered (not shown).
- These results imply the importance of including non-hydrostatic dynamics in simulating the lifetime of clustered convection, as well as the timing of the associated intense precipitation, when running E3SM at a resolution of 10 km or finer.

References

Sun, X., B. T. Nadiga, and W. Hannah, 2020: Hydrostatic and non-hydrostatic convective self-aggregation in the DOE Energy Exscale Earth System Model (E3SM). *J. Adv. Model. Earth Syst.* (To be Submitted)