A budget for the size of convective self-aggregation

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Abstract

There is no consensus on the physical mechanisms controlling the scale at which convective activity organizes near the Equator, where the Coriolis parameter is small. High resolution cloud-permitting simulations of non-rotating convection show the emergence of a dominant length scale, which has been referred to as convective self-aggregation. Furthermore, simulations in an elongated domain of size 12228km x 192km with a 3km horizontal resolution equilibrate to a wave-like pattern in the elongated direction, where the cluster size becomes independent of the domain size. These recent findings suggest that the size of convective aggregation may be regulated by physical mechanisms, rather than artifacts of the model configuration, and thus within the reach of physical understanding. We introduce a diagnostic framework relating the evolution of the length scale of convective aggregation to the net radiative heating, the surface enthalpy flux, and horizontal energy transport. We evaluate these length scale tendencies of convective aggregation in twenty high-resolution cloud-permitting simulations of radiative-convective equilibrium. While both radiative fluxes contribute to convective aggregation, the net longwave radiative flux operates at large scales (1000-5000 km) and stretches the size of moist and dry regions, while the net shortwave flux operates at smaller scales (500-2000 km) and shrinks it. The surface flux length scale tendency is dominated by convective gustiness, which acts to aggregate convective activity at smaller scales (500-3000 km). We further investigate the scale-by-scale radiative tendencies in a suite of nine mechanism denial experiments, in which different aspects of cloud radiation are homogenized or removed across the horizontal domain, and find that liquid and ice cloud radiation can individually aggregate convection. However, only ice cloud radiation can drive the convective cluster to scales exceeding 5000 km, because of the high optical thickness of ice, and the increase in coherence between water vapor and deep convection with horizontal scale. The framework presented here focuses on the length scale tendencies rather than a static aggregated state, which is a step towards diagnosing clustering feedbacks in the real world. Overall, our work underscores the need to observe and simulate surface fluxes, radiative and advective fluxes across the 1km-1000km range of scales to better understand the characteristics of turbulent moist convection.

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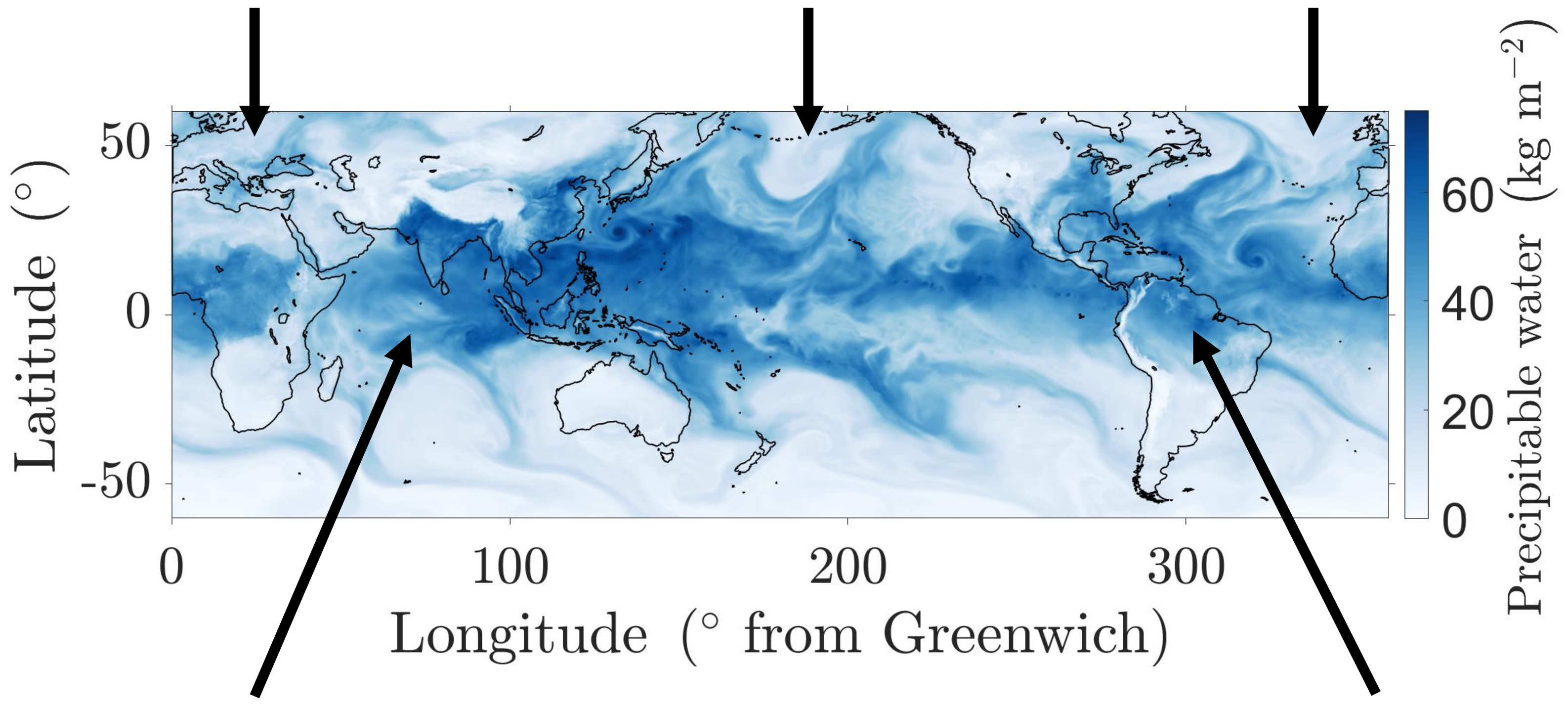
Motivation

- To first order, the size of extra-tropical storms is set by the Rossby radius of deformation, proportional to the atmospheric stratification divided by the Coriolis parameter.



- However, what sets the scale L at which convective activity organizes near the Equator, where the Coriolis parameter is small, remains an open question.
- Previous theories [1-4] predict the order of magnitude of L and some of its dependencies (surface temperature, boundary layer properties) by assuming a dominant mechanism.
- Here, we take an alternative approach by (1) formulating a budget for L and diagnosing contributions to its evolution from different processes in (2-3) 3D cloud-permitting sim. with interactive rad., surface fluxes & large-scale dyn. and (4) reanalysis data [5], satellite observations [6] & global cloud-permitting sim. [7-8].

How do radiation, surface enthalpy fluxes and advection contribute to the emergence and evolution of a dominant size for convective aggregation?

1. Theory

Budget for column frozen moist static energy (H)

Definition: H, a proxy for convective activity, is defined as the sum of column internal energy, potential energy and latent heat.

$$H\ [\mathrm{J\ m^{-2}}] \stackrel{\mathrm{def}}{=} \int_0^{p_s} \frac{dp}{g}\left(c_p T + gz + L_{\mathrm{vap}} q_{\mathrm{vap}} - L_{\mathrm{fus}} q_{\mathrm{ice}}\right)$$

Budget: H is conserved under vertical convective mixing and altered by the net energy flux through the col. boundaries: Longwave, shortwave, surf. fluxes & horizontal advection.

$$\frac{\partial H}{\partial t}\ [\mathrm{W\ m^{-2}}] = \dot{H}_{\mathrm{lw}} + \dot{H}_{\mathrm{sw}} + \dot{H}_{\mathrm{sf}} + \dot{H}_{\mathrm{adv}} = \sum_{\mathrm{flux=lw,sw,sf,adv}} \dot{H}_{\mathrm{flux}}$$

Budget for spatial spectrum of moist static energy (φ)

Definition: φ, a measure of the scale-by-scale variance of H, is defined as the modulus of the spatial Fourier transform $\widehat{H}$ of H.

$$\varphi\ [\mathrm{J^2\ m^{-2}}] \stackrel{\mathrm{def}}{=} \widehat{H}^* \widehat{H}$$

Budget: φ is altered by the scale-by-scale coherence between H and energy fluxes: at each scale, variance is reinforced by positive coherences & destroyed by neg. coherences.

$$\frac{\partial \varphi}{\partial t}\ [\mathrm{J^2\ m^{-2}\ s^{-1}}] = \sum_{\mathrm{flux=lw,sw,sf,adv}} 2\mathrm{Re}\left(\widehat{H}^* \widehat{\dot{H}_{\mathrm{flux}}}\right) = \sum_{\mathrm{flux=lw,sw,sf,adv}} \dot{\varphi}_{\mathrm{flux}}$$

Budget for convective-aggregation length scale (L)

Definition: L, the distance between pos. & neg. anomalies of H, is formally defined as the spectral mean of the wavelength, weighted by the spatial power spectrum φ of H.

$$L\ [\mathrm{m}] \stackrel{\mathrm{def}}{=} \frac{1}{\langle \varphi \rangle}\left\langle \frac{2\pi\sqrt{n}}{\|\boldsymbol{k}\|}\varphi \right\rangle = \frac{\langle \lambda \varphi \rangle}{\langle \varphi \rangle}$$

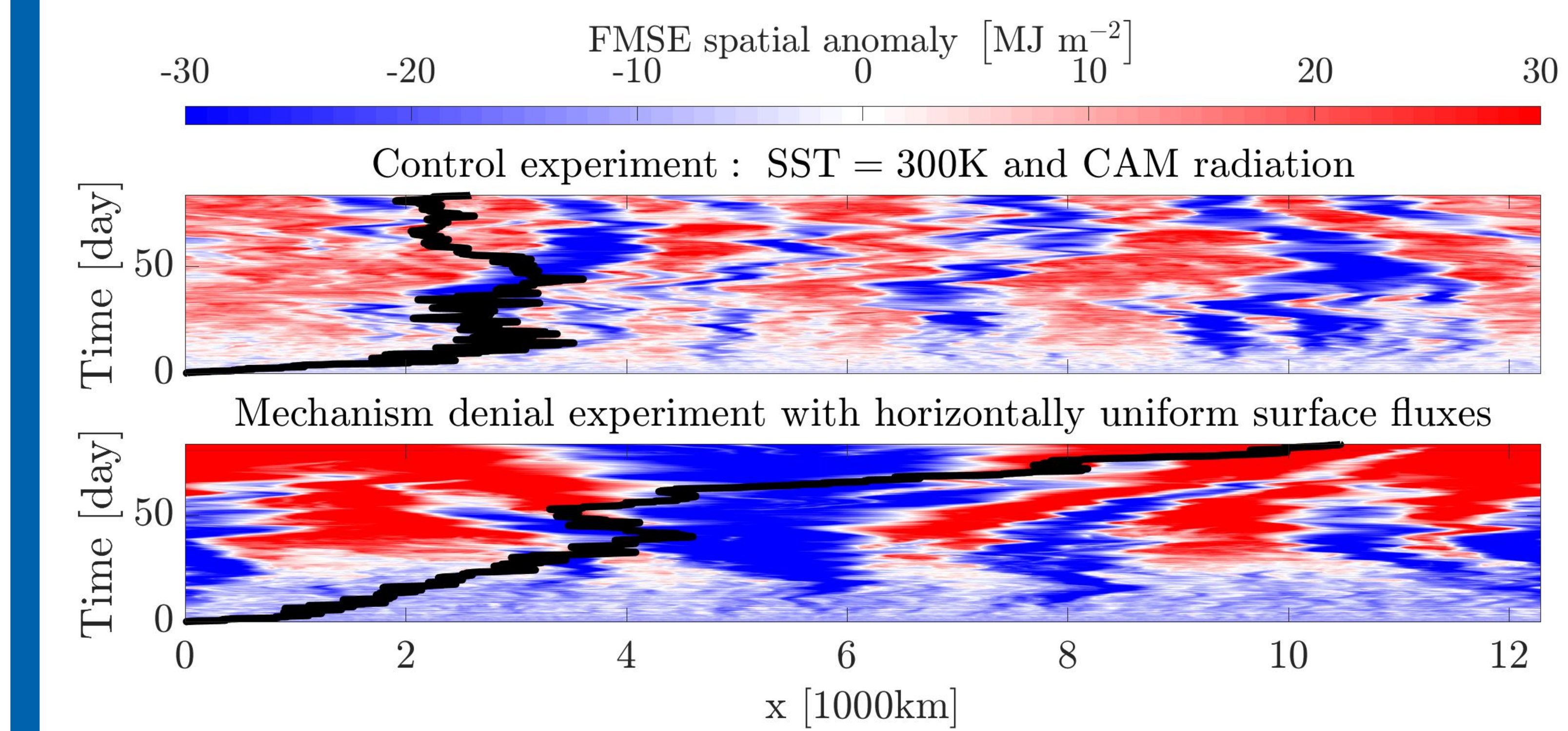
Budget: L is altered by the expansion tendency of each energy flux, given by the product of the aggregation rate and a length scale factor which vanishes if fluxes operate at the scale L.

$$\frac{\partial L}{\partial t}\ [\mathrm{m\ s^{-1}}] = \sum_{\mathrm{flux=lw,sw,sf,adv}} \frac{\langle \dot{\varphi}_{\mathrm{flux}} \rangle}{\langle \varphi \rangle} \times \left(\frac{\langle \lambda \dot{\varphi}_{\mathrm{flux}} \rangle}{\langle \dot{\varphi}_{\mathrm{flux}} \rangle} - L\right) = \sum_{\mathrm{flux=lw,sw,sf,adv}} \dot{L}_{\mathrm{flux}}$$

2. Long-channel simulations

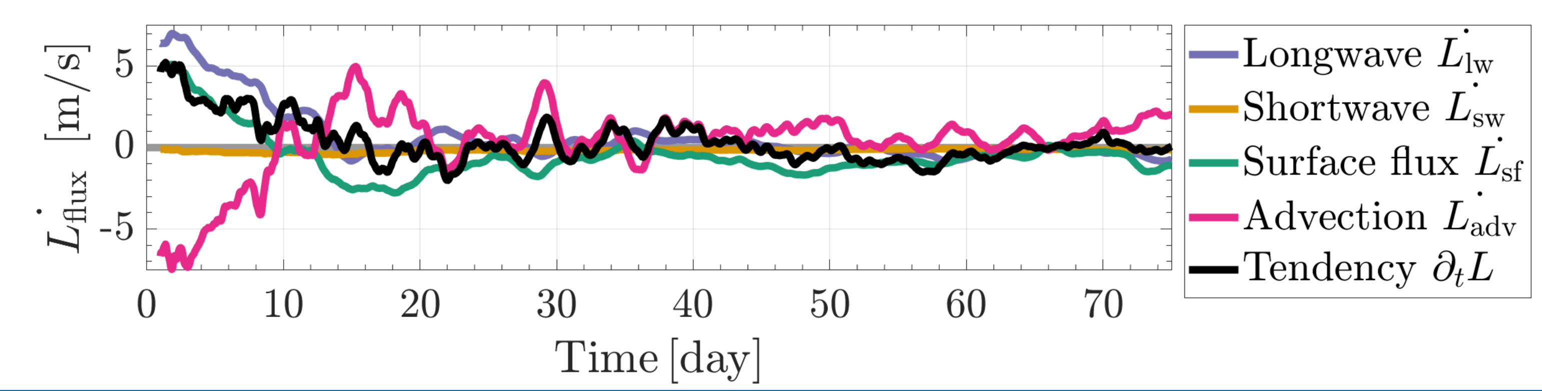
Measuring the convective-aggregation length scale (L)

Method: We simulate radiative-convective equilibrium in a long-channel domain [2] using the cloud-permitting model SAM [7] and measure the scale of West-East anomalies in time:



Understanding the evolution of L in time

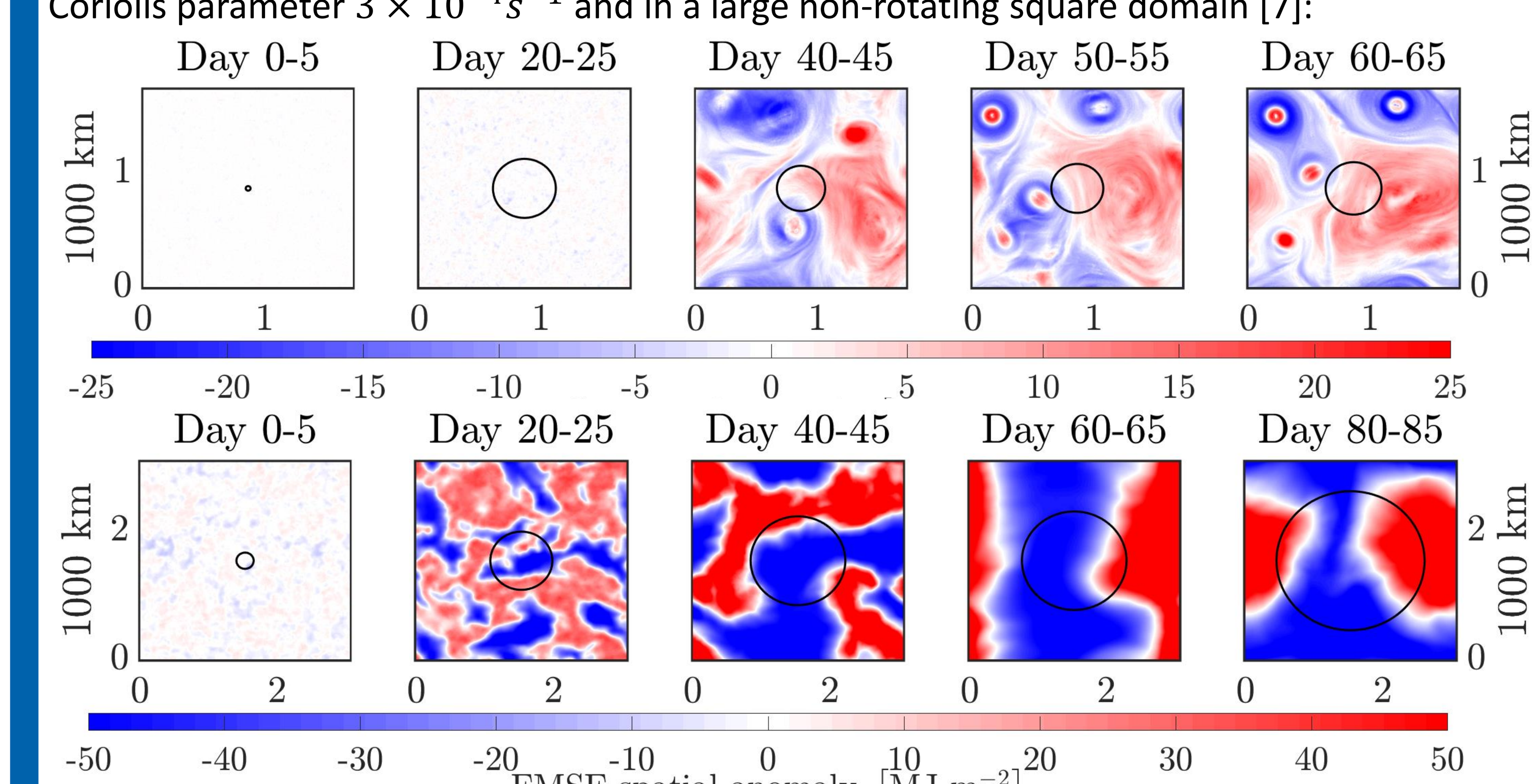
Method: We use the L budget to quantify the contribution of each flux to L's evolution:



3. Two-dimensional clusters

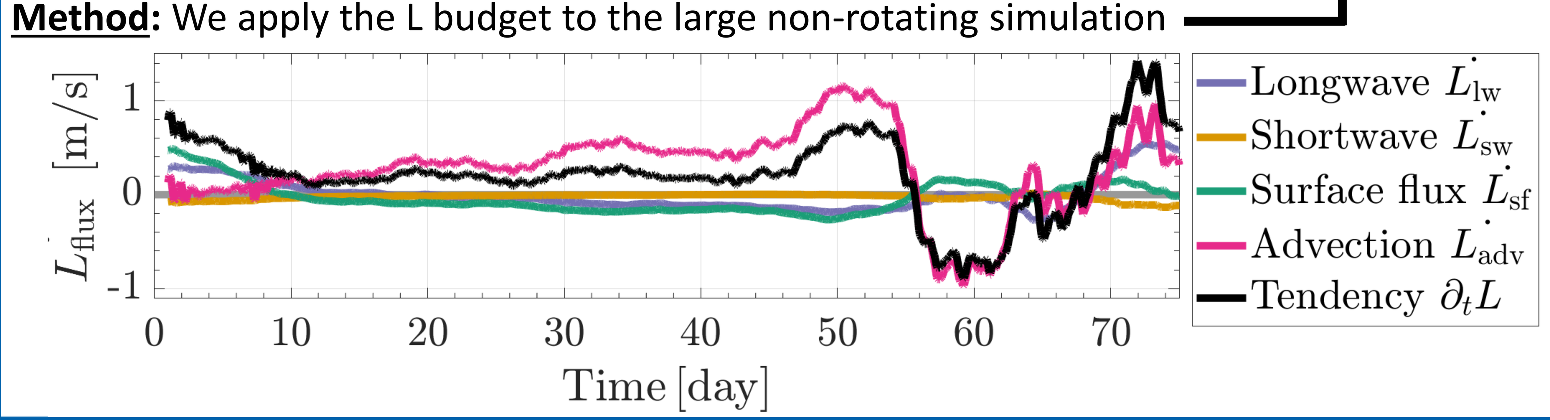
Measuring the size of convective clusters (L)

Method: We simulate radiative-convective equilibrium in a rotating square domain of Coriolis parameter $3 \times 10^{-4} s^{-1}$ and in a large non-rotating square domain [7]:



Understanding the evolution of L in time

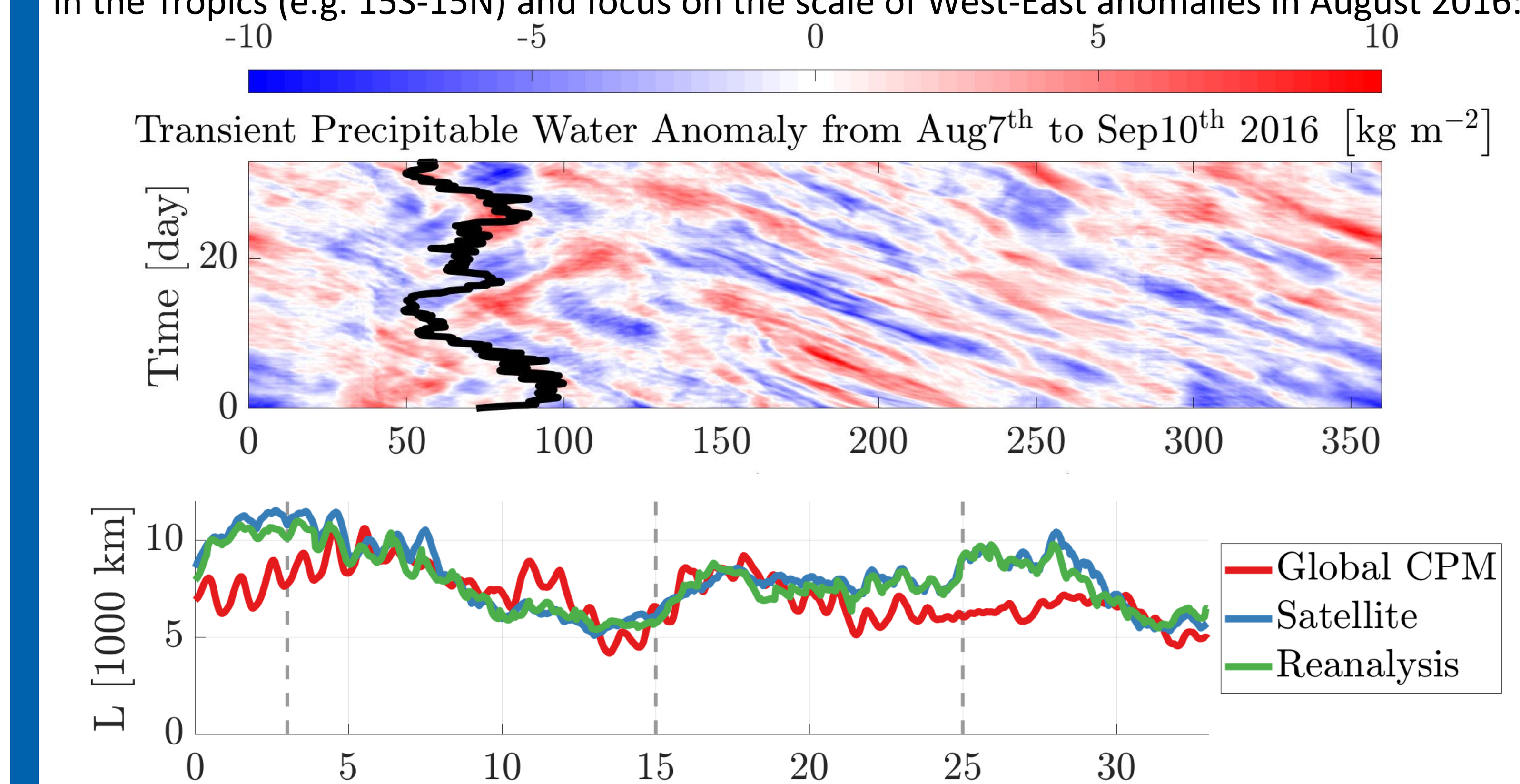
Method: We apply the L budget to the large non-rotating simulation



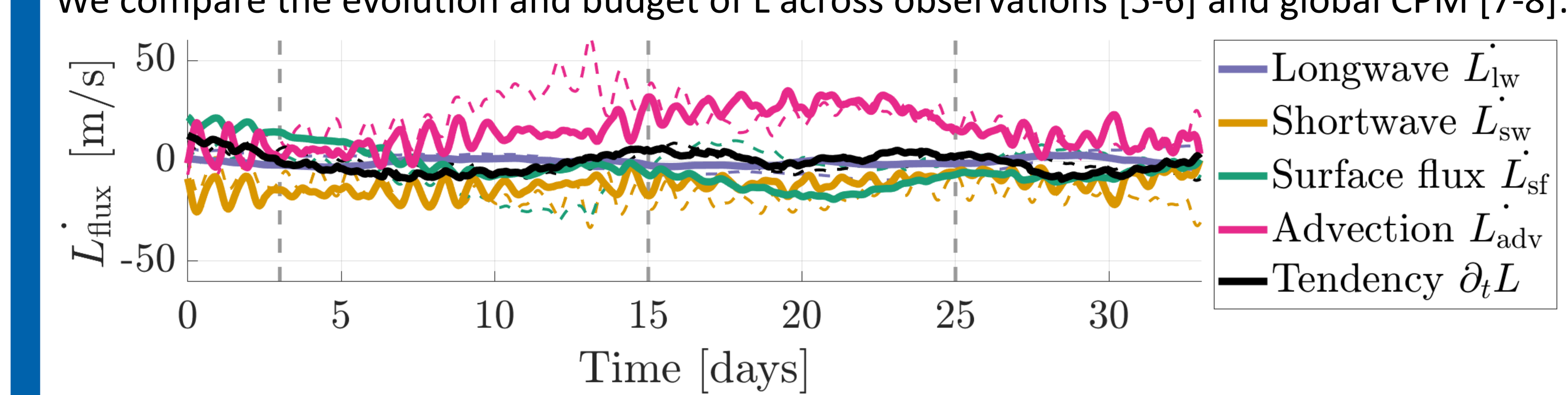
4. Observed variability in Tropics

Measuring the scale of transient precipitable water anomalies (L)

Method: We average the observed [5] transients of precipitable water from South to North in the Tropics (e.g. 15S-15N) and focus on the scale of West-East anomalies in August 2016:



We compare the evolution and budget of L across observations [5-6] and global CPM [7-8]:



Conclusions

Summary

1. We have developed a budget that relates the evolution of the convective-aggregation length scale to the vertically-integrated energy fluxes (radiative, surface, and advective).
2. Longwave cooling expands the convective-aggregation scale until convection aggregates.
3. Shortwave heating shrinks the convective-aggregation length scale.
4. Surface fluxes expand L when it is small & become main shrinking term when L is large.
5. Advection of energy expands L because it homogenizes small-scale convective anomalies.
6. We can generalize the definition and budget of L to two dimensions (n=2) and apply it to non-rotating convective clusters as well as tropical cyclones.
7. In the real Tropics, the budget can be used to understand the West-East scale of the transient zonal anomalies of precipitable water.
8. We can measure the effect of radiative and convective biases on the spatial organization of water vapor in the Tropics by comparing the L budget across models and observations.

Key References

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