Monday July 8, 2019

What is convective self-aggregation and how can we measure it?

Allison Wing

Assistant Professor
Department of Earth, Ocean and Atmospheric Science
Florida State University

2nd ICTP Summer School on Theory, Mechanisms and Hierarchical Modeling of Climate Dynamics: Convective Organization and Climate Sensitivity

Outline

1. What is self-aggregation?
    - Length scale
    - Time scale
    - Mechanisms
    - Impacts on large-scale

2. How can we measure self-aggregation?

Wing, A.A., K. Emanuel, C.E. Holloway, and C. Muller 2017: Convective self-aggregation in numerical simulations: A review, *Surveys in Geophysics*,38, 1173-1197, doi:10.1007/s10712-017-9408-4.

Wing, A.A. 2019: Self-aggregation of deep convection and its implications for climate, *Curr. Clim. Change Rep.,* doi:10.007/s40641-019-00120-3.

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

Occurs in a wide range of model configurations

2D CRMs: Held et al 1993, Grabowski and Moncrieff 2001, Grabowski and Moncreiff 2002, Stephens et al 2008, Yang 2018a, Yang 2018b, Brenowitz et al 2018

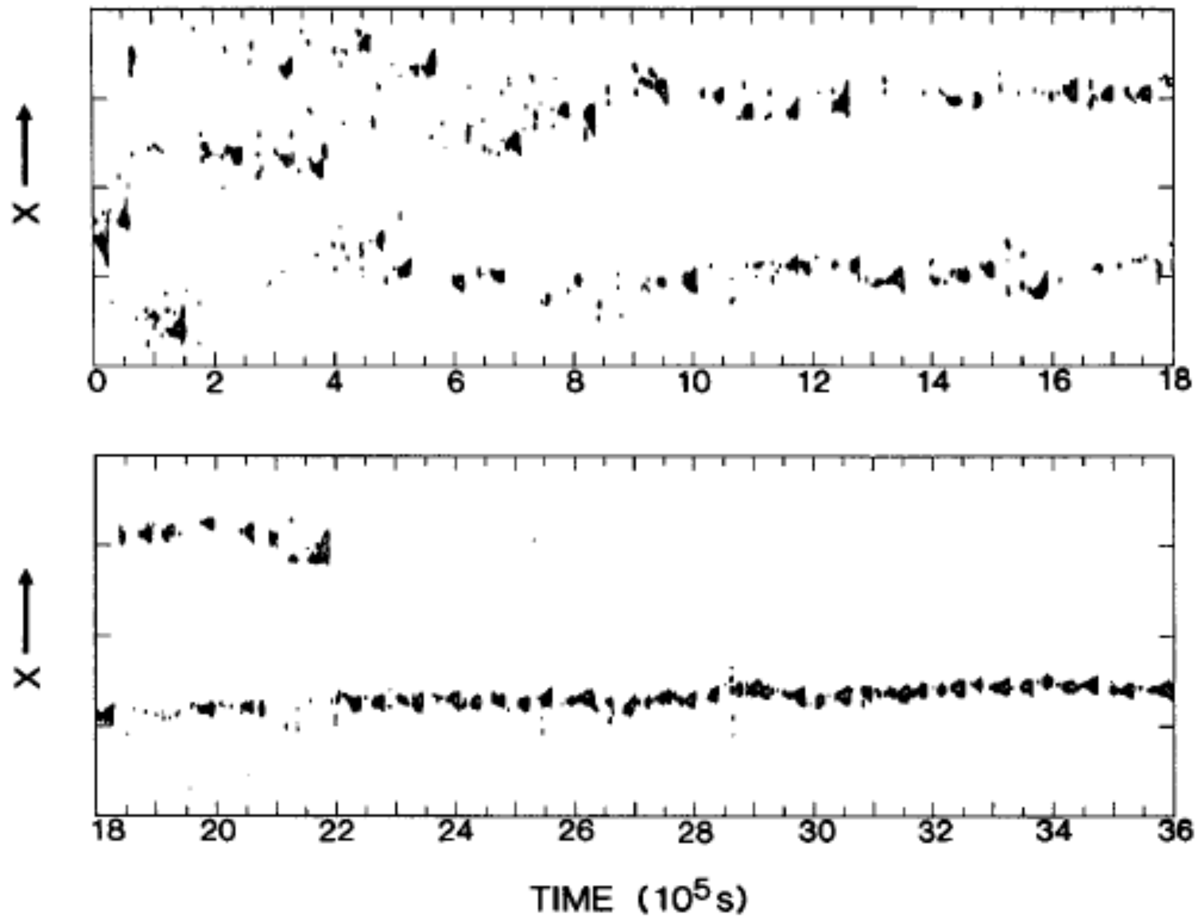

FIG. 4. Precipitation as a function of time and x in the case in which the mean wind is constrained to vanish.

Held et al (1993)

Occurs in a wide range of model configurations

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Small-domain square 3D CRMs: Tompkins and Craig 1998, Bretherton et al 2005, Khairoutdinov and Emanuel 2010, Muller and Held 2012, Jeevanjee and Romps 2013, Wing and Emanuel 2014, Abbot 2014, Muller and Bony 2015, Holloway and Woolnough 2016, Hohenegger and Stevens 2016, Tompkins and Semie 2017, Hohenegger and Stevens 2018, Becker et al. 2018, Bao and Sherwood 2018, Ruppert and Hohenegger 2018, Colin et al 2019

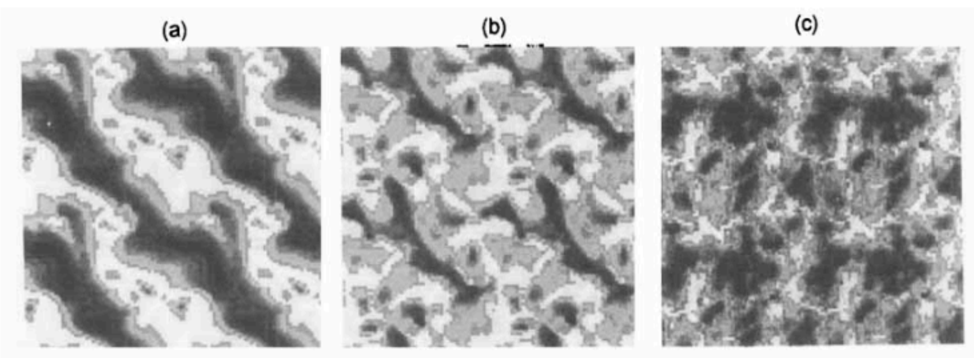
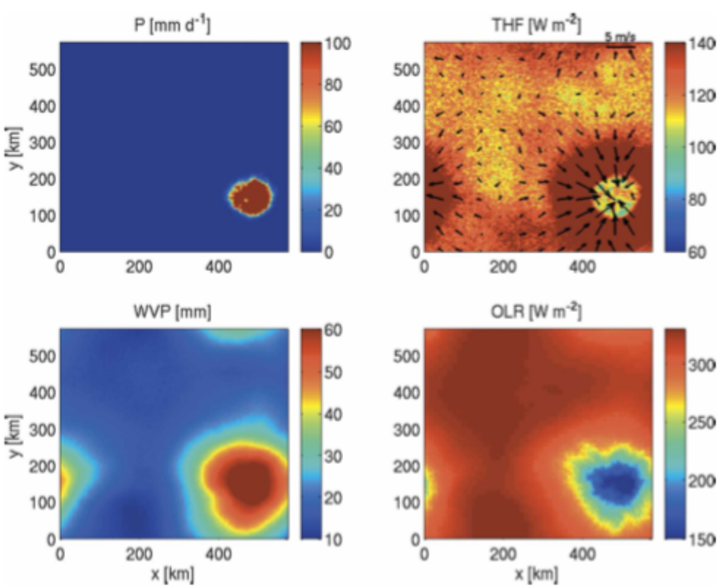


Figure 7. Water-vapour mixing ratio in the bottom model layer for: (a) day 70 of the control run using interactive radiation + wind-sensitive surface fluxes, (b) after 4 days simulation with interactive radiation + wind-insensitive surface fluxes and (c) after 4 days simulation using non-interactive radiation and wind-sensitive surface fluxes. Runs (b) and (c) were initialized using the organized state shown in (a). The domain is repeated twice in each direction for clarity. The colour scale is as for Figure 6.

Tompkins and Craig (1998)



Bretherton et al (2005)

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Elongated channel 3D CRMs: Tompkins 2001 ,Posselt et al 2008, Posselt et al 2012, Stephens et al 2008, Wing and Cronin 2016, Cronin and Wing 2017, Wing et al 2018, Beydoun and Hoose 2019

Wing and Cronin (2016)

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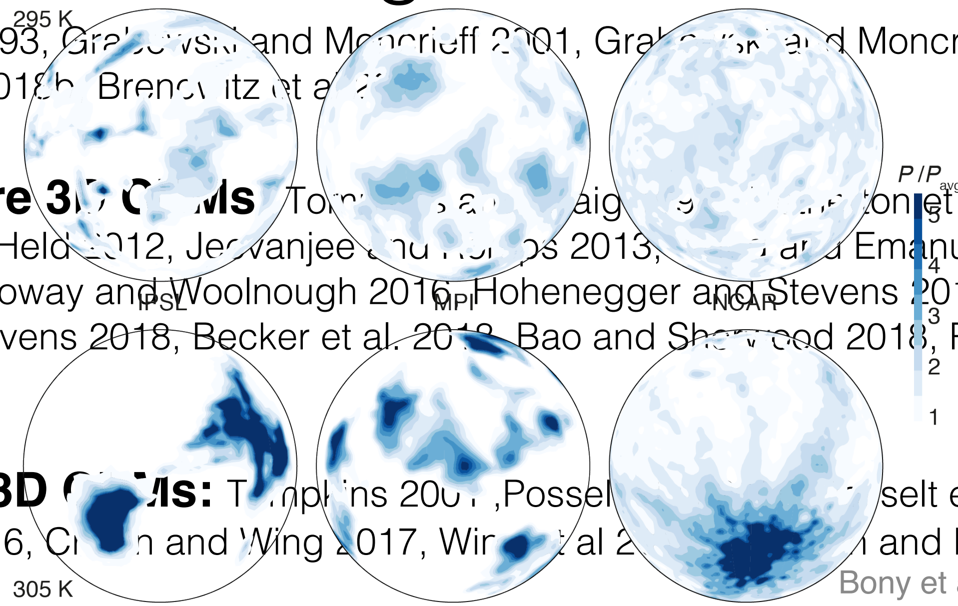
Small-domain square 3D CRMs: To[illegible] [illegible]aig [illegible] [illegible]ton et al 2005, Khairoutdinov and Emanuel 2010, Muller and Held 2012, Jeevanjee and Romps 2013, [illegible] and Emanuel 2014, Abbot 2014, Muller and Bony 2015, Holloway and Woolnough 2016, Hohenegger and Stevens 2016, Tompkins and Semie 2017, Hohenegger and Stevens 2018, Becker et al. 2018, Bao and Sherwood 2018, Ruppert and Hohenegger 2018, Colin et al 2019



Elongated channel 3D CRMs: T[illegible]mpkins 200[illegible], Possel[illegible] [illegible]selt et al 2012, Stephens et al 2008, Wing and Cronin 2016, Cr[illegible]n and Wing 2017, Wi[illegible]t al 2[illegible] [illegible]n and Hoose 2019

Bony et al (2016)

Regional/global models with parameterized convection: Su et al 2000, Held et al 2007, Popke et al 2013, Becker and Stevens 2014, Reed et al 2015, Arnold and Randall 2015, Reed and Medeiros 2016, Coppin and Bony 2015, Silvers et al 2016, Hohenegger and Stevens 2016, Bony et al 2016, Pendergrass et al 2016, Becker et al 2017, Coppin and Bony 2017, Arnold and Putnam 2018, Coppin and Bony 2018, Wing et al 2018

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Region ... 007, Popke et a ... leiros 2016, Cop ... dergrass et al 2016 ... 3, Wing et al 2018

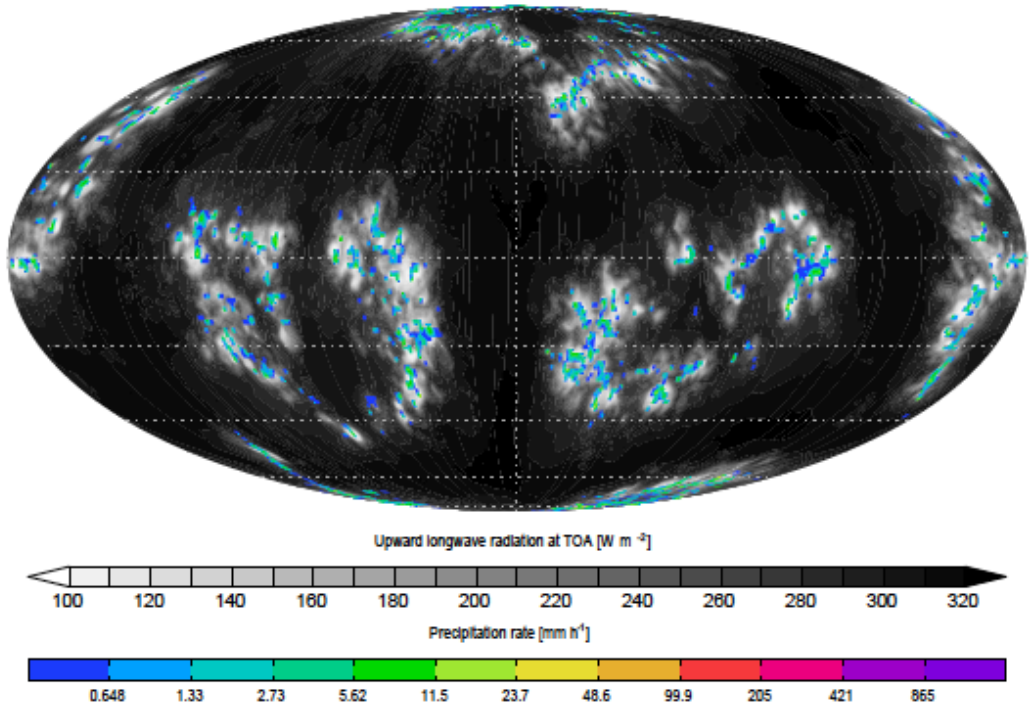

Figure 8. Hourly-averaged OLR at the top of atmosphere (gray shading) and precipitation rate (color shading) in a NICAM simulation at $T_s = 300$ K. Note that several parameters do not precisely follow the RCEMIP protocol.

Wing et al (2018)

Global models with explicit convection: Satoh and Matsuda 2009, Satoh et al 2016, Ohno and Satoh 2018, Wing et al 2018

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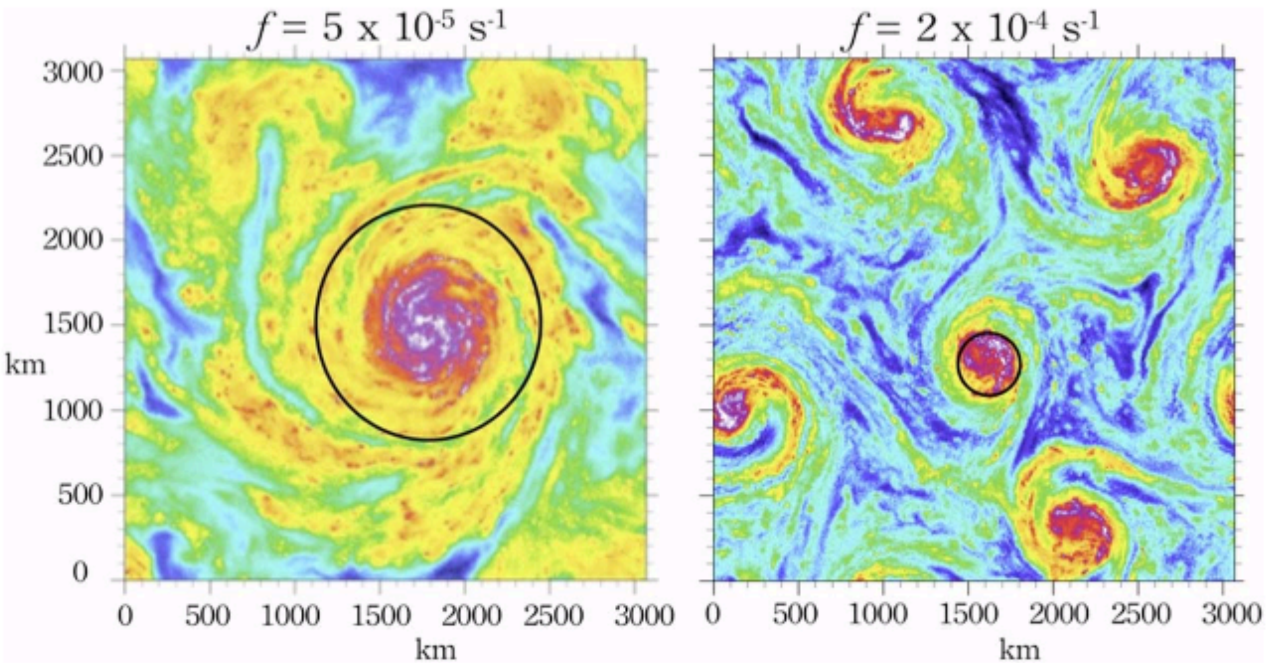


Figure 1. Tropical cyclones for two different values of the Coriolis parameter in otherwise identical RCE simulations (precipitable water is shown; warm colors represent higher values). The black circles on the foreground have diameters computed from formula (1).

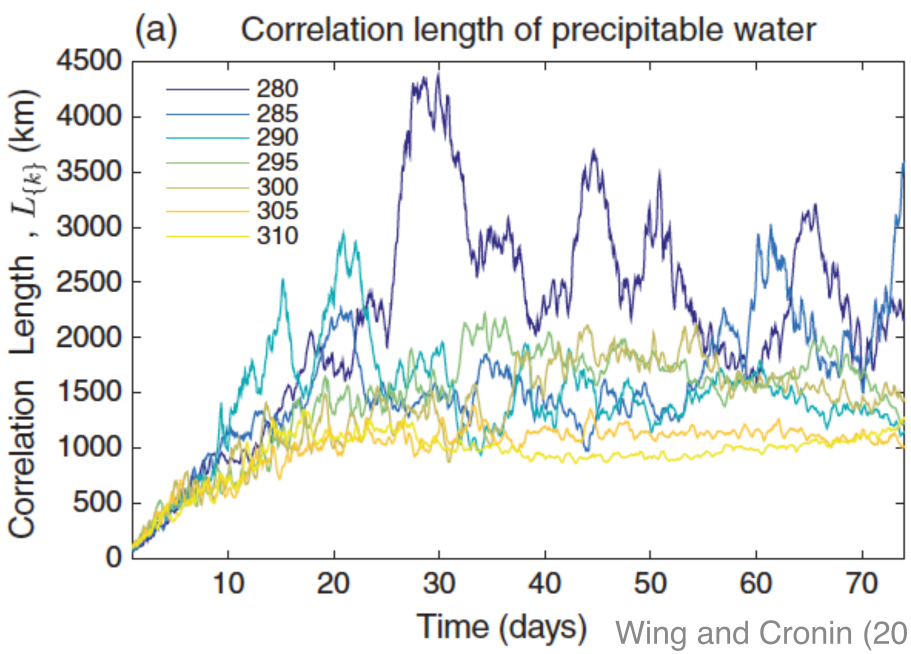
Khairoutdinov and Emanuel (2013)

Global models with explicit convection: Satoh and Matsuda 2009, Satoh et al 2016, Ohno and Satoh 2018, Wing et al 2018

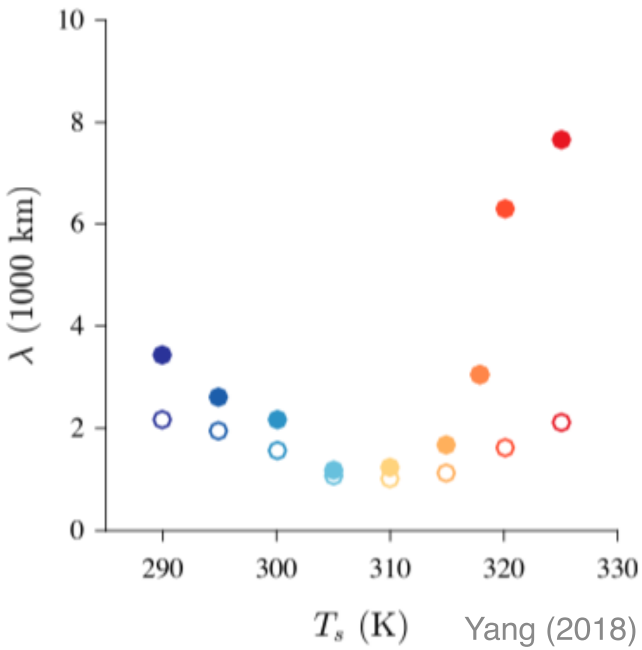
Rotating RCE: Bretherton et al 2005, Nolan et al 2007, Khairoutdinov and Emanuel 2013, Shi and Bretherton 2014, Zhou et al 2014, Boos et al 2016, Reed and Chavas 2015, Davis 2015, Wing et al 2016, Merlis et al 2016, Zhou et al 2017, Muller and Romps 2018, Khairoutdinov and Emanuel 2018

Length Scale of Self-Aggregation

- Coarsening explains upscale growth of moist and dry regions (Craig and Mack 2013, Windmiller and Craig 2019)
- Density currents in “radiatively-driven cold pools” export humidity out of dry regions and increase their size (Coppin and Bony 2015)
- Scale of aggregation decreases with warming (Wing and Cronin 2016, Yang 2018)



Wing and Cronin (2016)



Yang (2018)

Length Scale of Self-Aggregation

- Scale dependence of self-aggregation feedbacks (Bretherton and Khairoutdinov 2015, Beucler and Cronin 2018)
- No accepted theory for what sets the scale – several relating to boundary layer processes proposed
  - Boundary layer remoistening (Wing and Cronin 2016)
  - Boundary layer height and buoyancy (Yang 2018): Maintenance of BL winds limits size to ~4000 km (Arnold and Putnam 2018)

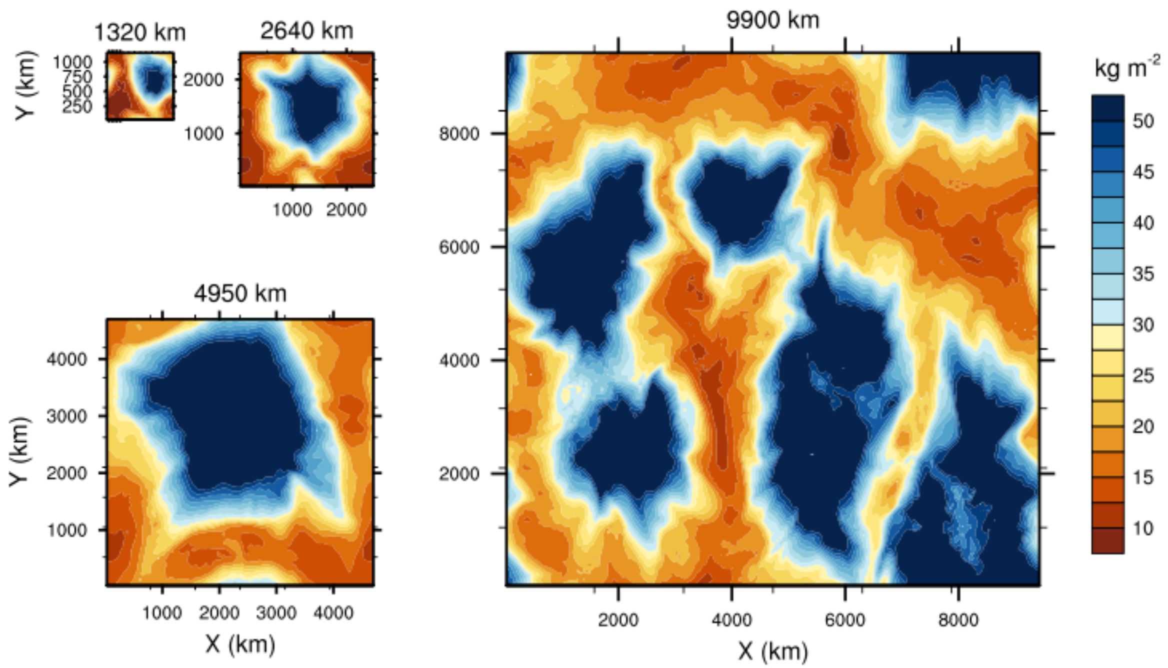


Figure 10. Snapshots of column water vapor in simulations with 55 km grid spacing and varying domain size. Days 120, 150, 180, and 300 are shown for the cases in increasing size.

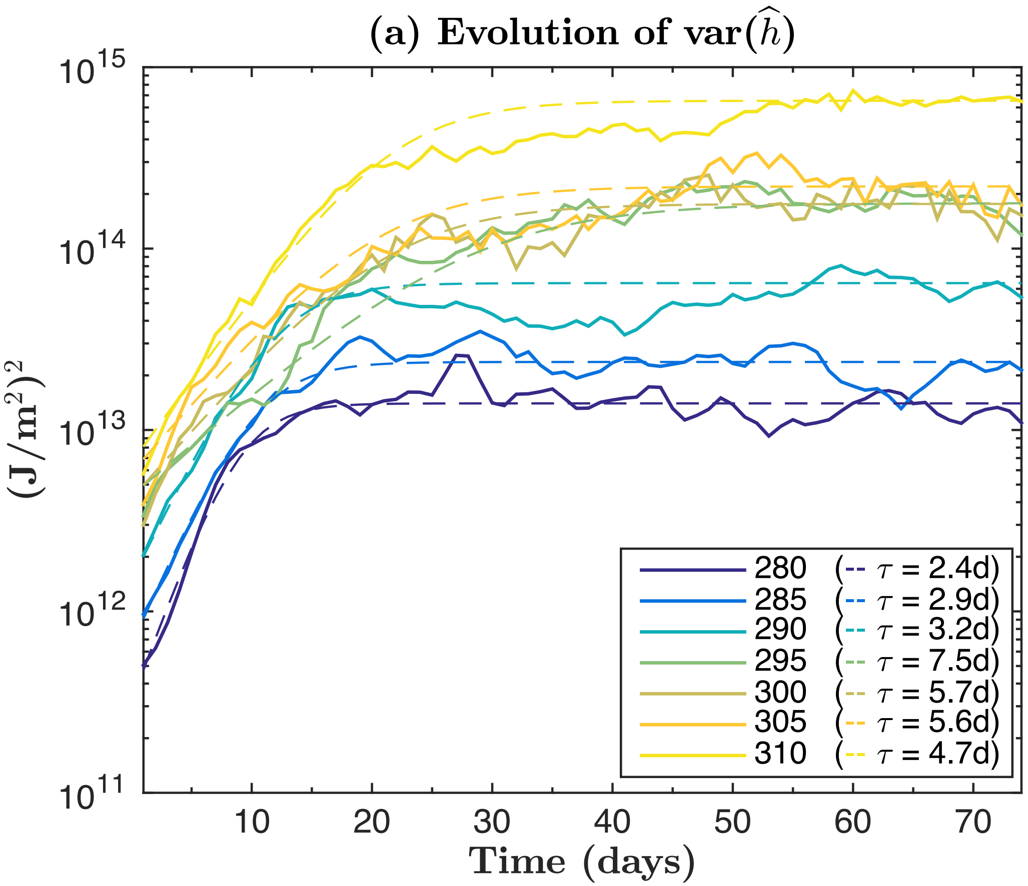
Arnold and Putnam (2018)

Time Scale of Self-Aggregation

- Time from homogeneous → stable, self-aggregated state is ~10s of days, but varies
  - 40 days (Bretherton et al 2005)
  - 20-25+ days (Muller and Held 2012)
  - 60 days (Wing and Emanuel 2014)
  - 16 days (Holloway and Woolnough 2016)
  - 15-50 days (Wing and Cronin 2016)

- e-folding time for growth of humidity variance
  - 9 days (Bretherton et al 2005)
  - 11-13 days (Wing 2014)
  - 2-6 days (Wing and Cronin 2016)

Increase in FMSE variance with aggregation



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

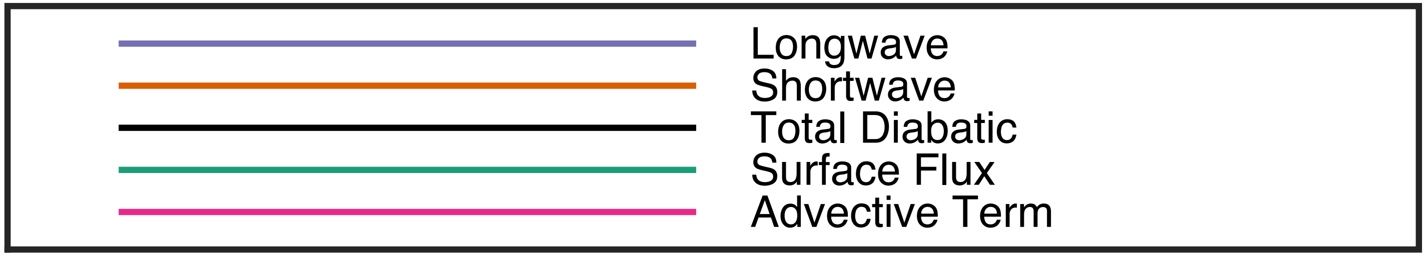
FMSE conserved, column integral unchanged by convection

Large increase in column FMSE variance with aggregation

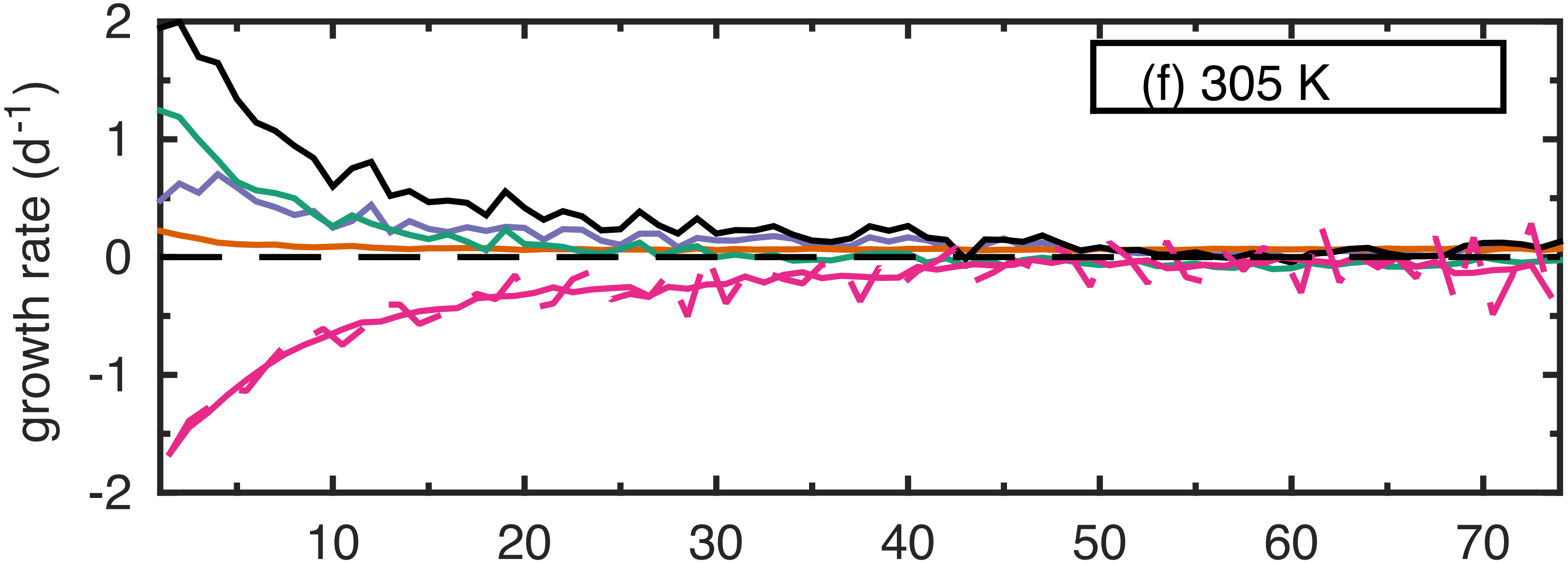
→Processes that increase var(h) favor self-aggregation

Wing and Cronin (2016)

Contributions to growth rate of $\mathrm{var}(\widehat{h})$



$$\frac{1}{2}\frac{\partial \hat{h}'^2}{\partial t} = \hat{h}'\mathrm{SEF}' + \hat{h}'\mathrm{NetSW}' + \hat{h}'\mathrm{NetLW}' - \hat{h}'\nabla_h \cdot \widehat{\vec{u}h}$$

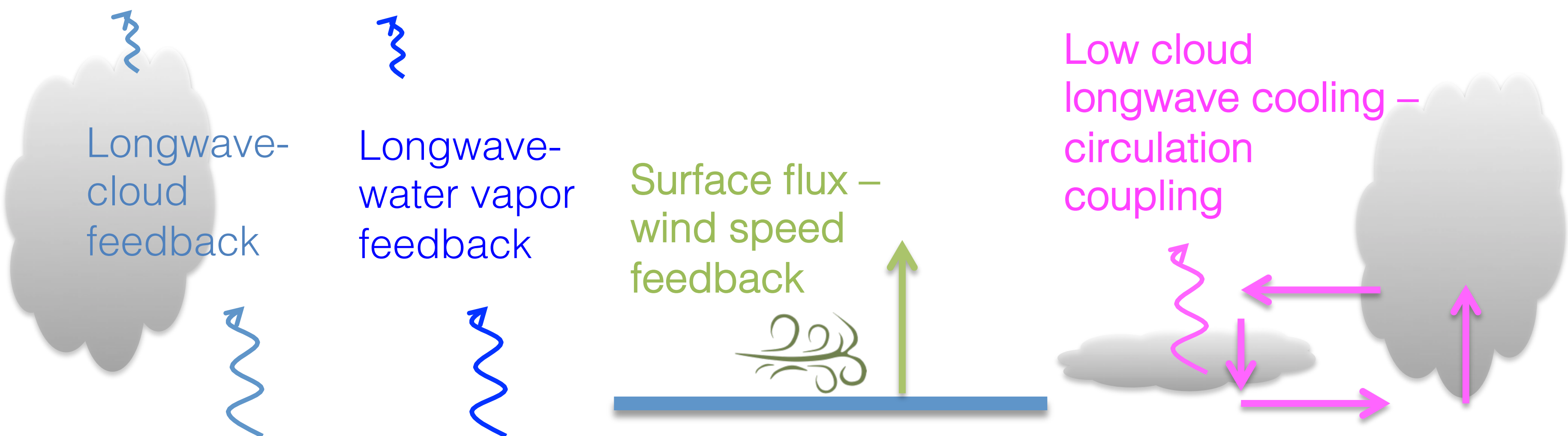


Longwave and surface flux feedbacks drive initial development of aggregation

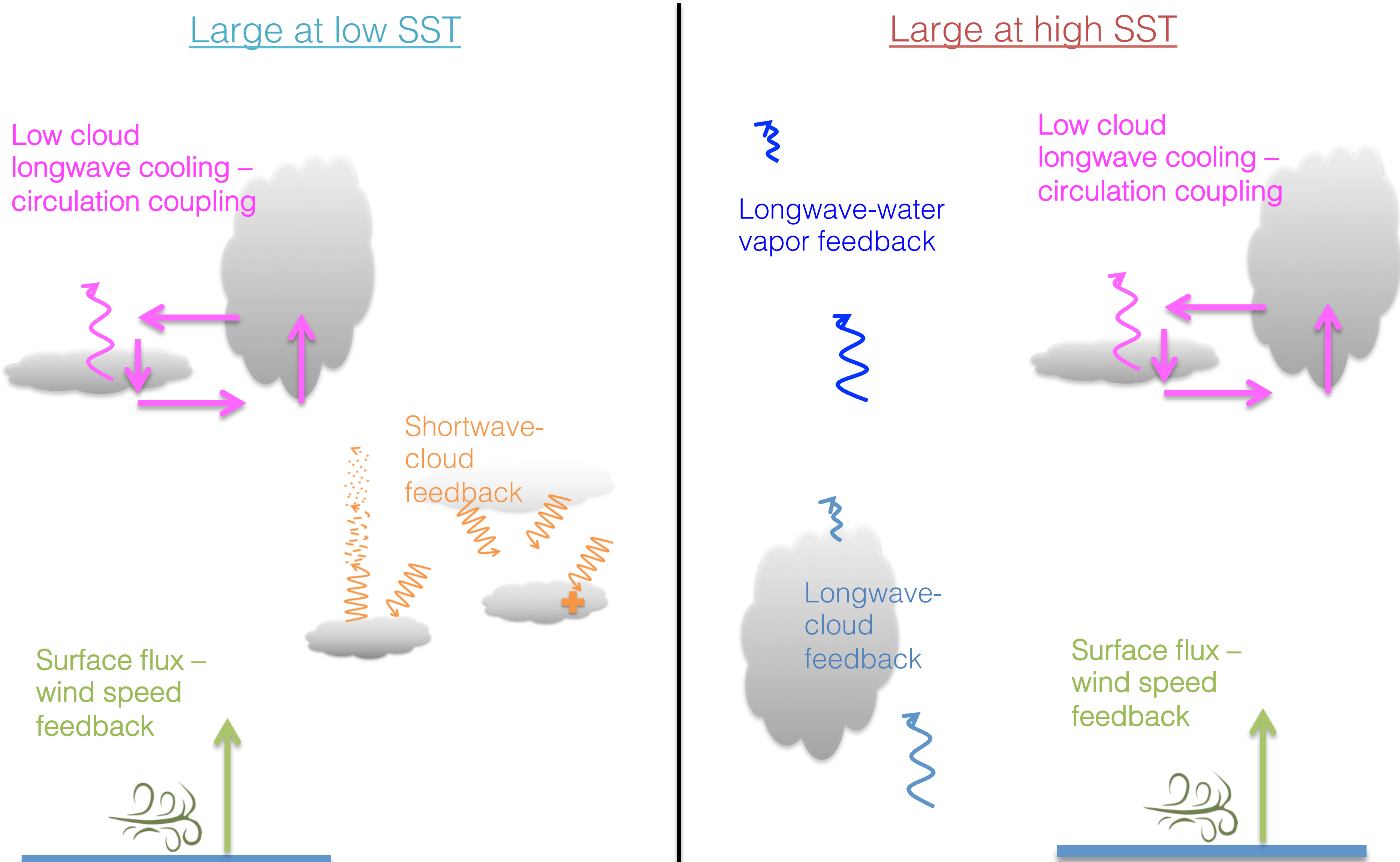
Wing and Cronin (2016)

Processes that favor self-aggregation

- Longwave – water vapor feedback (Wing and Emanuel 2014, Emanuel et al., 2014)
- Longwave – cloud feedback (Bretherton et al., 2005, Posselt et al. 2012, Wing and Emanuel 2014, Muller and Bony 2015, Wing and Cronin 2016, Arnold and Randall 2015, Holloway and Woolnough 2016)
- Low cloud longwave cooling – circulation (Muller and Held 2012, Coppin and Bony 2015, Muller and Bony 2015)
- Surface flux – wind speed feedback (Bretherton et al., 2005, Wing and Emanuel 2014, Wing and Cronin 2016, Coppin and Bony 2015)
- Moisture-convection feedback (Tompkins 2001, Craig and Mack 2013, Muller and Bony 2015, Holloway and Woolnough 2016)



Feedbacks depend on temperature!



Emanuel et al (2014), Wing and Cronin (2016), Holloway and Woolnough (2016), Coppin and Bony (2015), Becker et al (2017)

Mechanisms of self-aggregation:

Feedbacks between longwave radiation and clouds/water vapor are essential (Tompkins and Craig 1998, Bretherton et al 2005, Muller and Held 2012, Posselt et al 2012, Wing and Emanuel 2014, Abbot 2014, Muller and Bony 2015, Wing and Cronin 2016, Holloway and Woolnough 2016, Yang 2018, Coppin and Bony 2015, Arnold and Putnam 2018, Arnold and Randall 2015, Emanuel et al 2014, Beucler and Cronin 2016, Beucler and Cronin 2018)

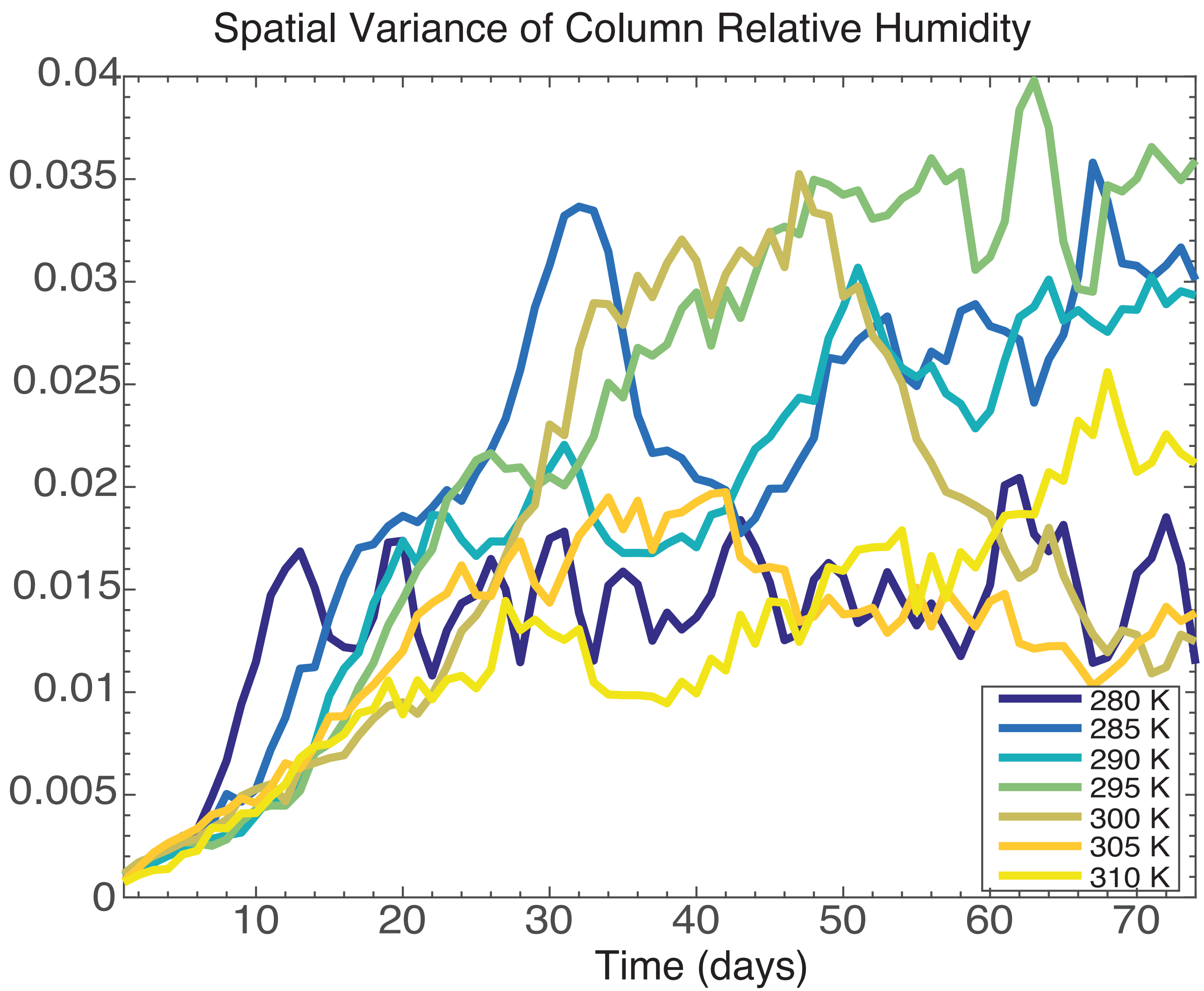
Shallow circulations & BL processes highlighted recently (Muller and Bony 2015, Hohenegger and Stevens 2018, Yang 2018a,b, Coppin and Bony 2015, Naumann et al 2017)

Relative role of energy transport by shallow circulations compared to diabatic processes in the free troposphere is debated (Bretherton et al 2005, Wing and Emanuel 2014, Wing and Cronin 2016, Coppin and Bony 2015, Arnold and Putnam 2018, Arnold and Randall 2015, Holloway and Woolnough 2016)

Self-aggregation is NOT just a spatial re-organization of the convection

Self-aggregation has a large impact on the domain-mean state

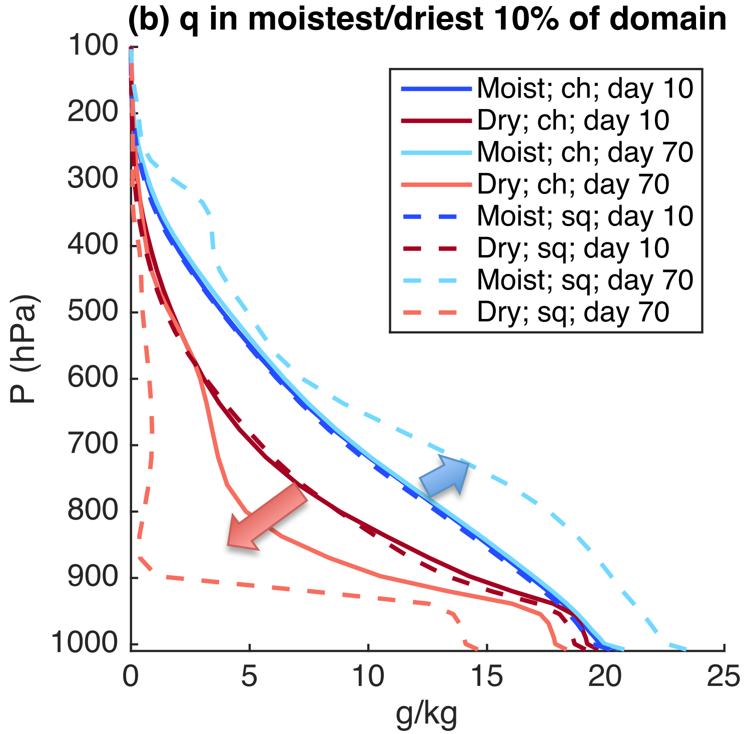
Dry regions get drier, moist regions get moister



Wing (2019)

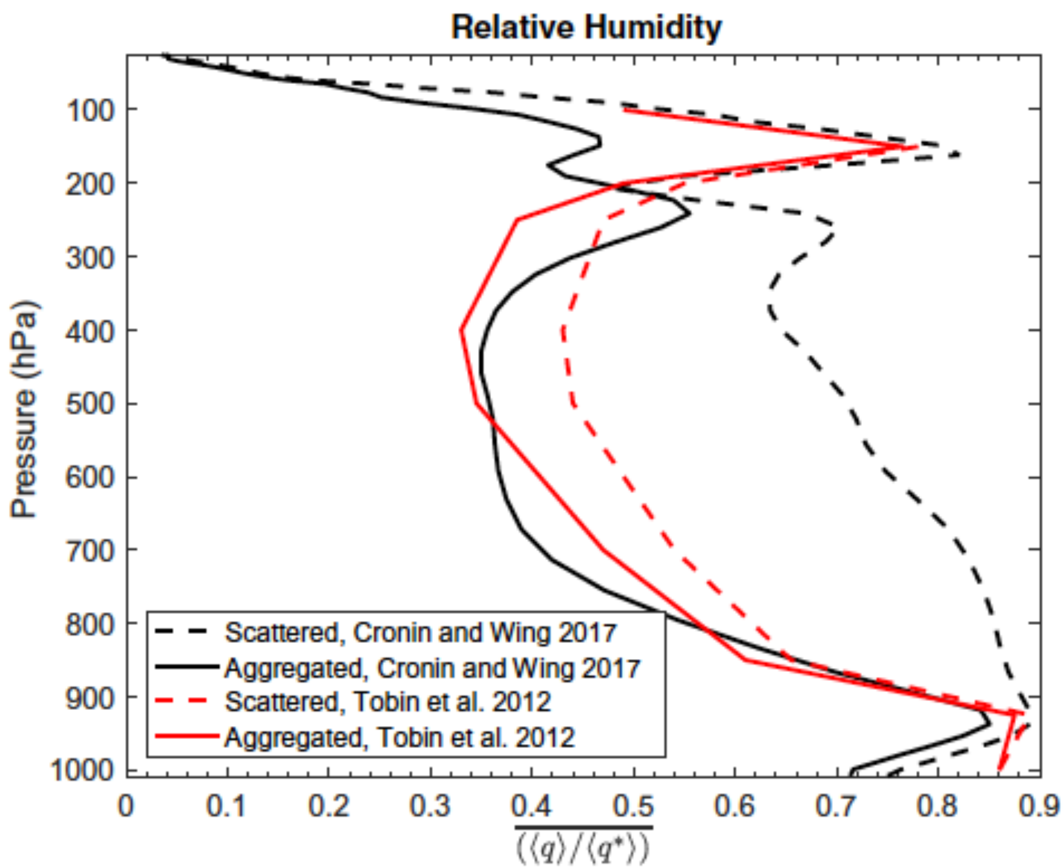
Dry regions drier at all levels

RCE Simulations



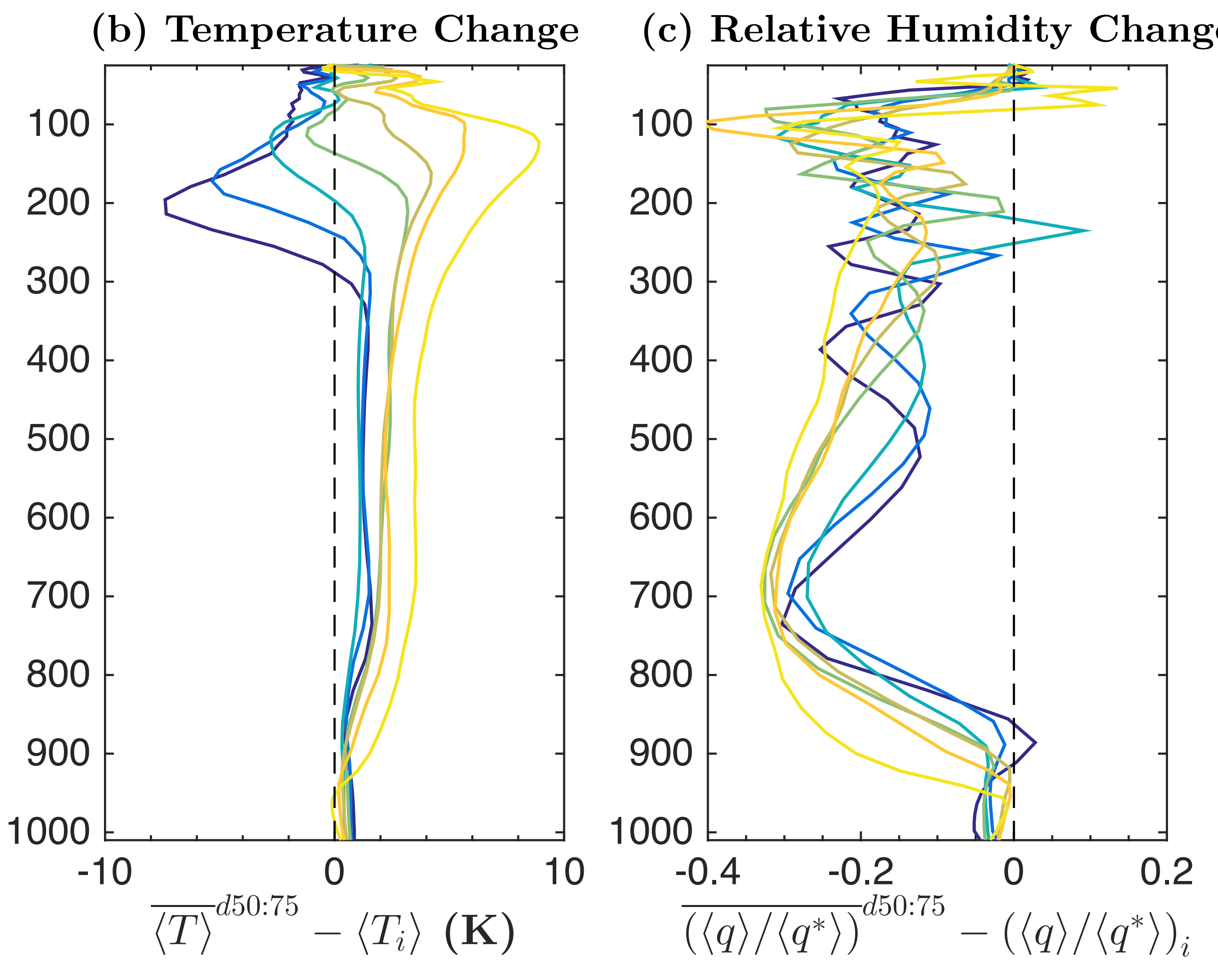
Holloway et al. (2017)

Drying of **mean state** under more aggregated conditions seen in self-aggregation simulations *and* observations of aggregated convection



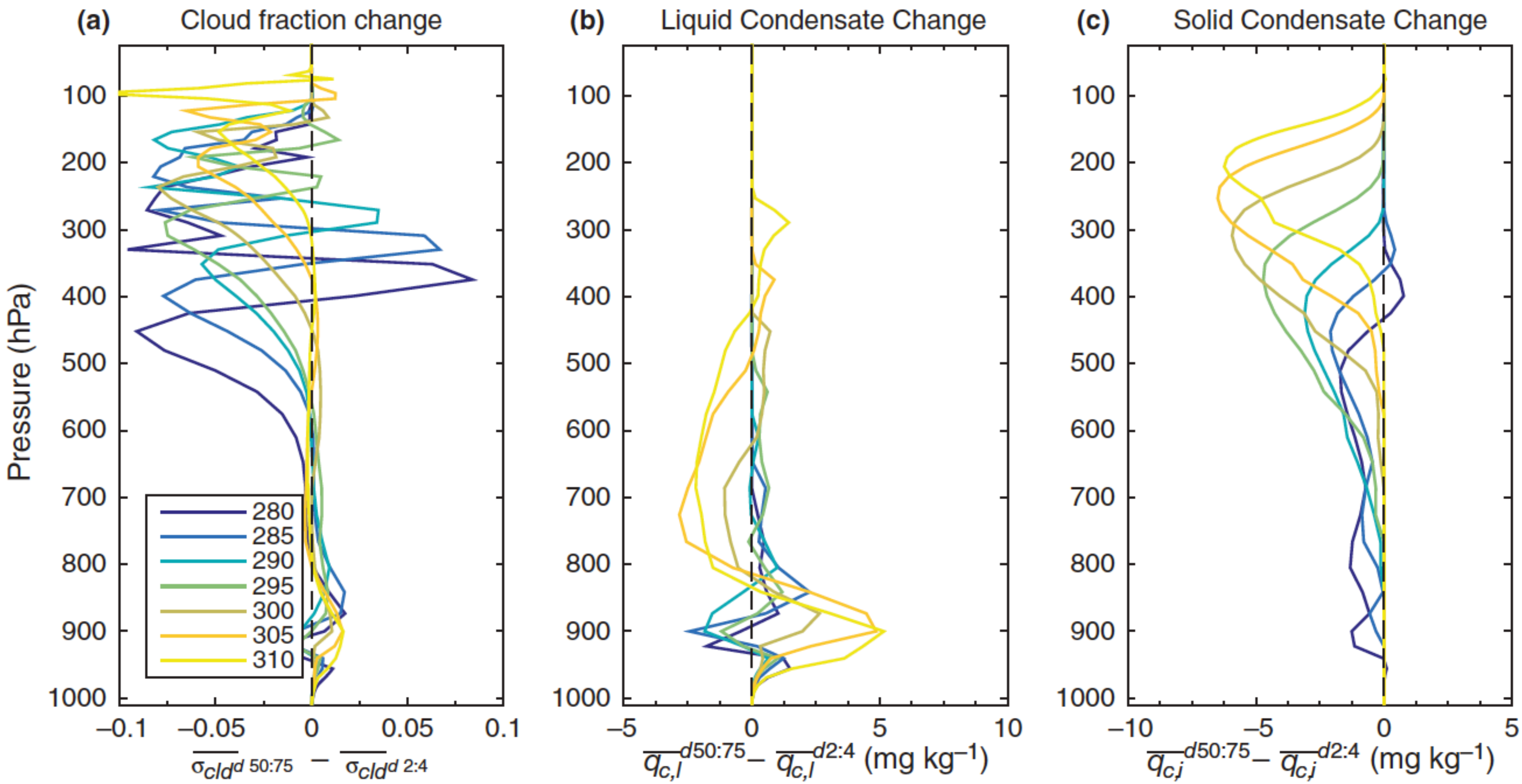
Wing (2019)

Warming and drying with aggregation



Wing and Cronin (2016)

Decrease in high clouds with aggregation



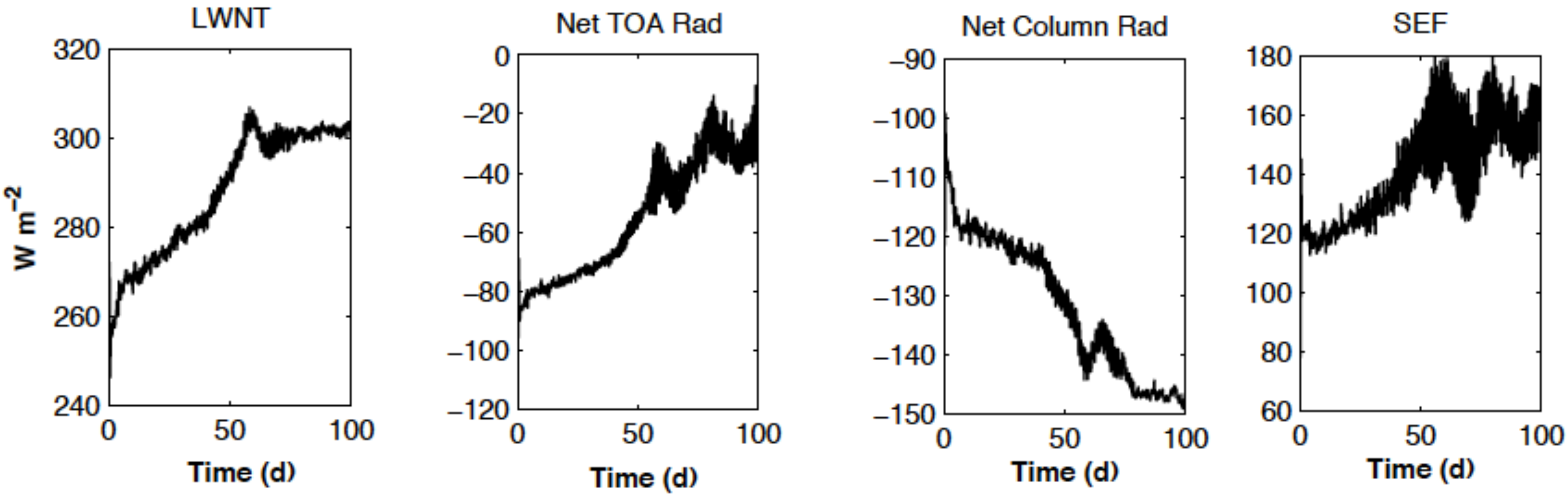
Changes in low clouds less clear

Wing and Cronin (2016)

Consequences for energy budget

With aggregation…

- Increase in OLR*
- Little change in reflected SW
- Net flux into TOA reduced
- Increase in tropospheric radiative cooling*
- Decrease in energy gain by surface
- Increase in surface enthalpy fluxes
- Increase in mean precipitation



Wing (2014), Wing and Cronin (2016)

Self-aggregation…

warms and dries mean state,
reduces high clouds,
enhances dryness of dry regions,
increases ability of atmosphere to cool to space,
might be temperature dependent

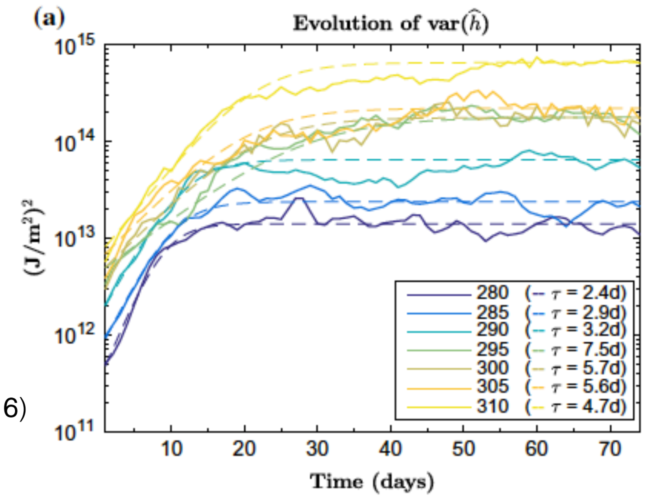
…so it might be important for climate

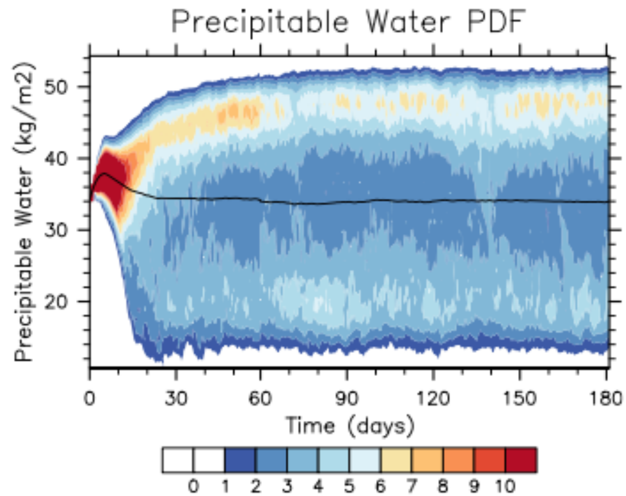
How do we diagnose and measure self-aggregation?

1. Humidity-related indices
2. Subsidence fraction
3. Clustering metrics

Humidity-related Indices

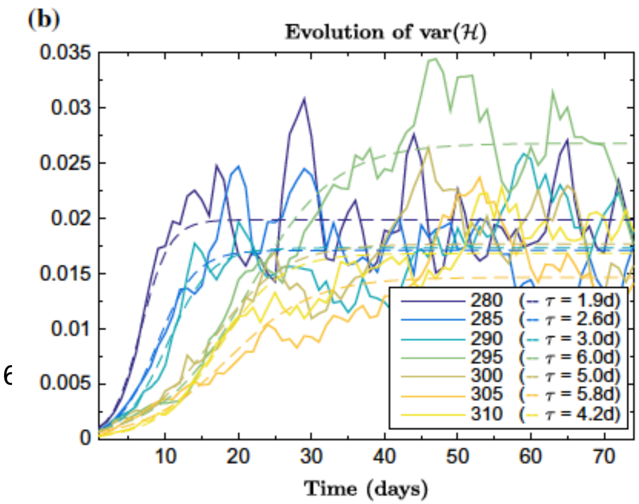
Spatial variance of column-integrated moist static energy
(Wing and Cronin 2016)

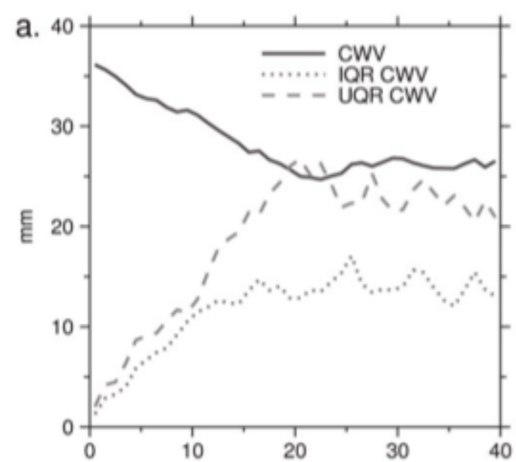




Distribution of precipitable water
(Arnold and Randall 2015)

Spatial variance of column relative humidity
(Wing and Cronin 2016)





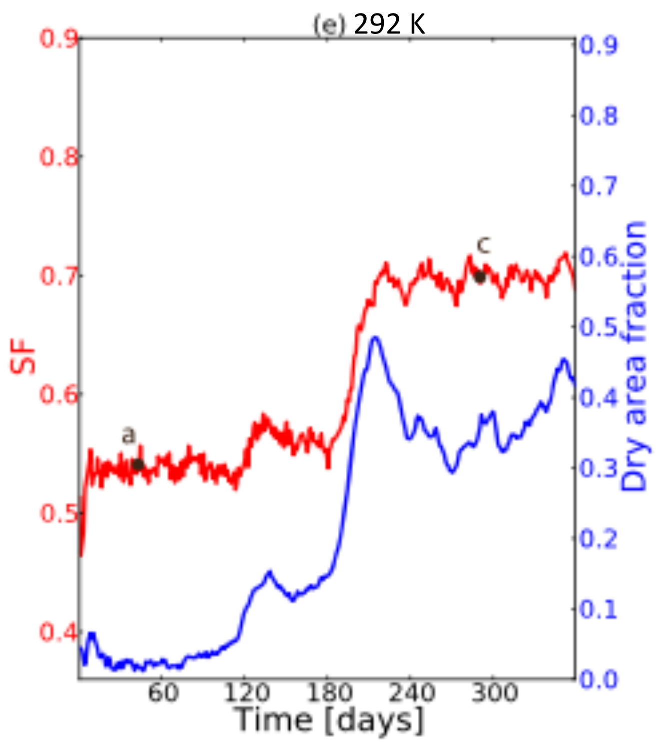
Interquartile range of column water vapor (CWV)
(Holloway and Woolnough 2016)

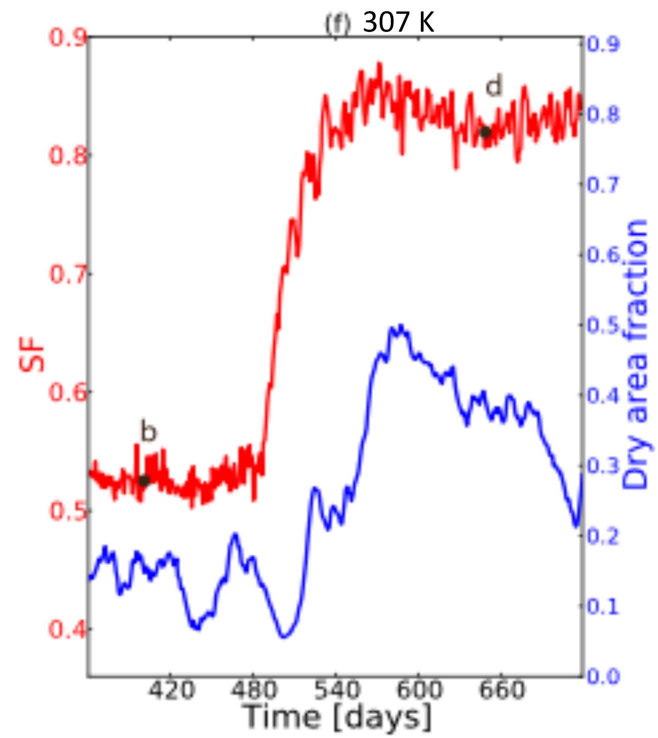
Reflect the clear signature of self-aggregation in broadening the moisture distribution

Subsidence fraction

- Fractional area of the domain covered by sinking air
- Related to transition of vertical velocity distribution to small areas of strong ascent surrounded by large areas of weak subsidence

- Use space and time-averaged mid-tropospheric vertical motion to define subsiding area

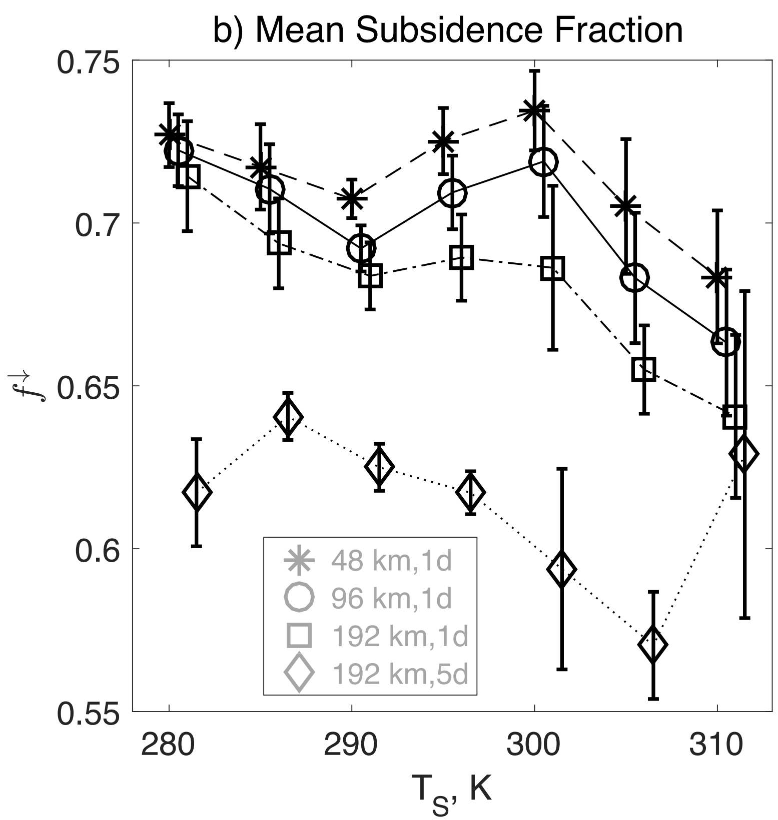




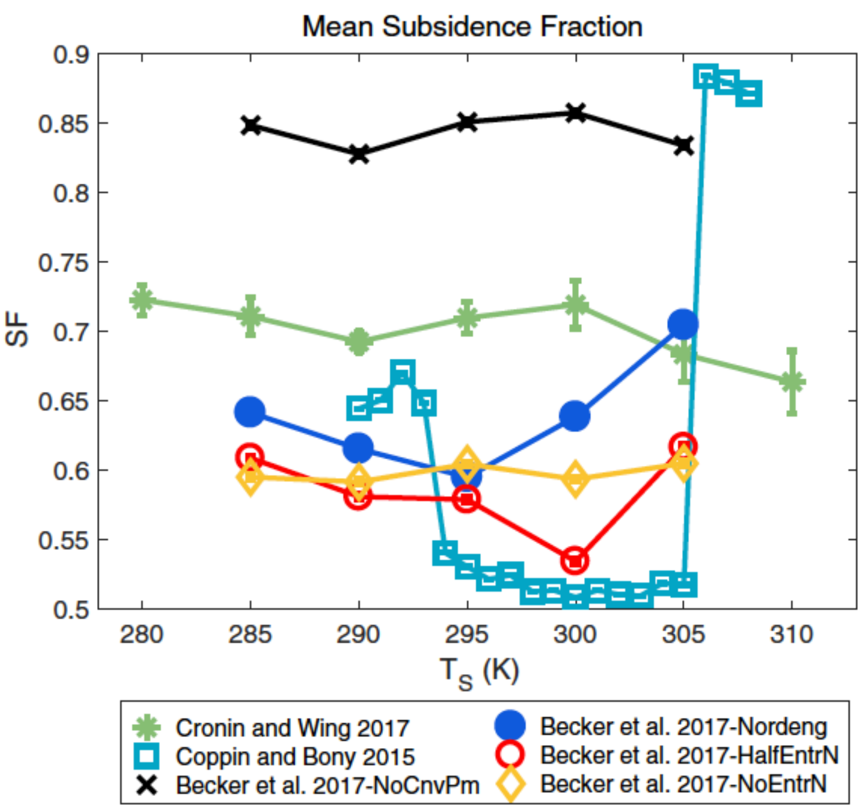
Coppin and Bony (2015)

Subsidence fraction

- Sensitive to spatiotemporal averaging scales
- Varies across studies



Cronin and Wing (2017)



Wing (2019)

Clustering metrics

- Define convective pi… …e
- SCAI: Combined me… …istance (Tobin et al 2012)
- SCAIP: Precipitation-…
- CAI: Precipitation-ce… …rporates duration (Pendergrass et al 2(…
- I_{org}: Compares neare… …ution (Tompkins and Semie 2017)

Others

- COP: Includes consi… …ite et al 2018)
- WOI: Wavelet-based… …2018)

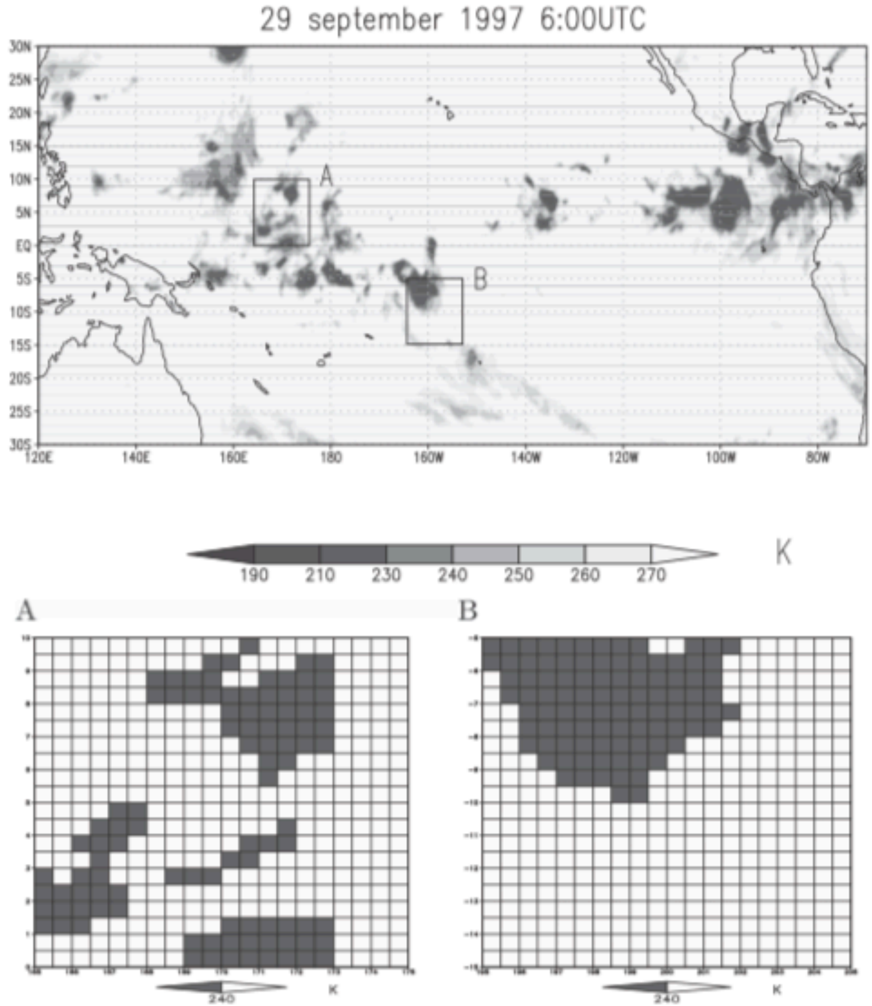
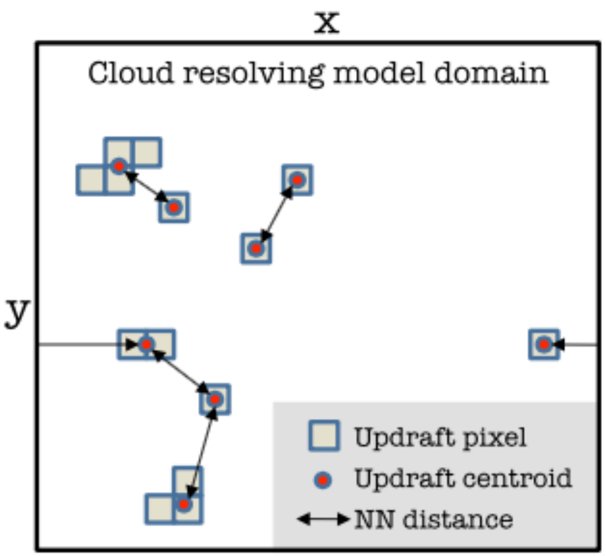
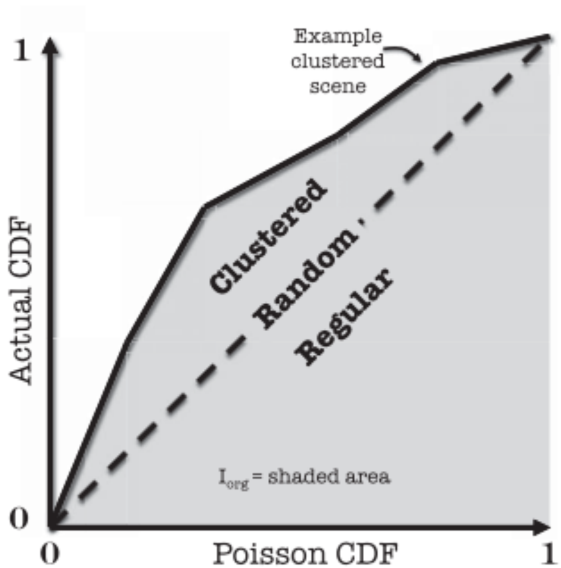


FIG. 1. (top) Snapshot of BT from CLAUS data at 0600 UTC 29 Sep 1997. The two black squares (A and B) are examples of the 10° × 10° domains under consideration in this study. (bottom) Segmentation of the domains into two parts: a deep convective region defined by the pixels with a BT colder than 240 K and the nonconvective environment (pixels warmer than 240 K). Both domains are characterized by the same domain-averaged rain rate (11 mm day^{-1}) but exhibit a different number of convective systems [A, six clusters; B, one cluster (using the four-connectivity clustering algorithm)]. Tobin et al (2012)

Organization Index (I_{org})



Identify convective pixels (w @ 500 hPa > 0.5 m/s)

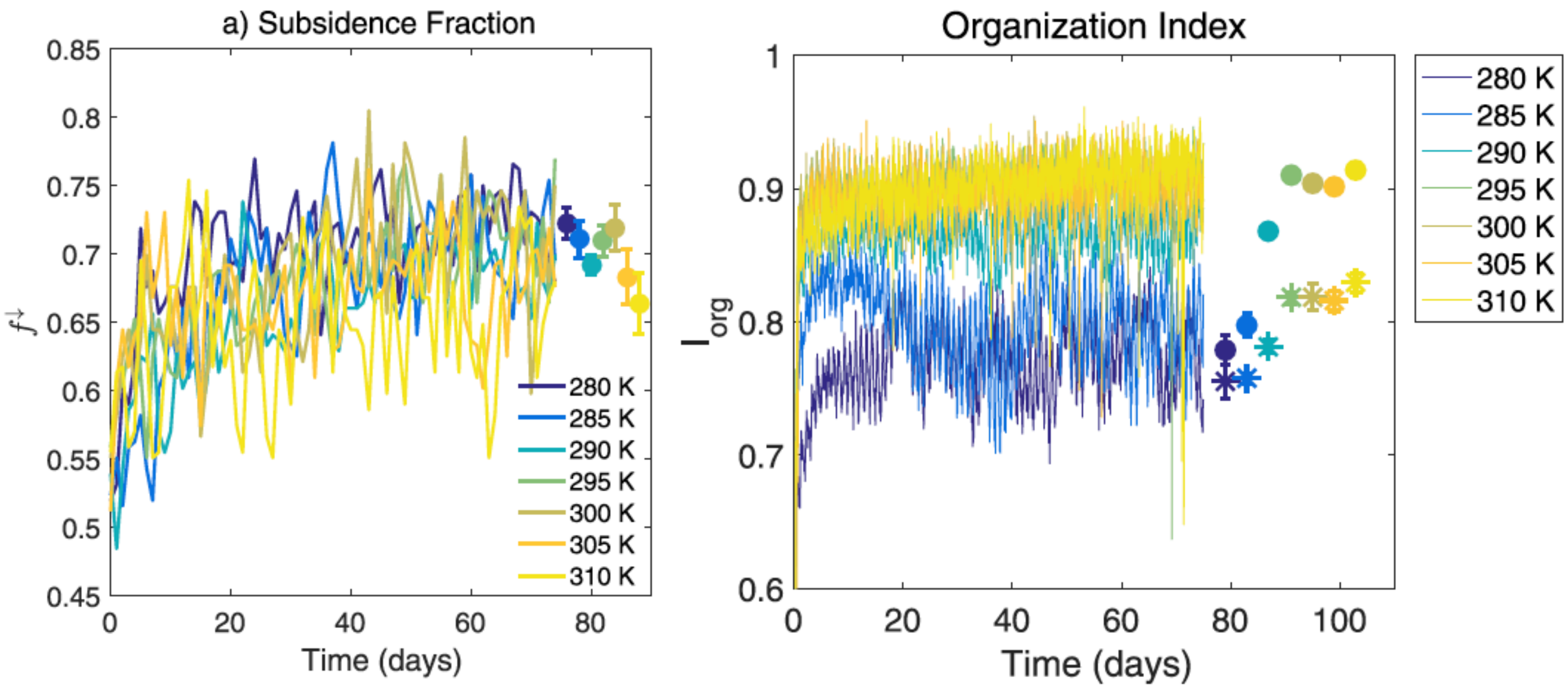


Compute nearest neighbor for each convective entity

Compare distribution to theoretical expectation from random distribution

Weger et al (1992), Tompkins and Semie (2017)

I_{org} can disagree with subsidence fraction



Cronin and Wing (2017)

Pros and Cons of Different Metrics

Metrics reflect different aspects of aggregation and can disagree!

Pros	Cons
1. Humidity-related indices	
• Reflect clear signature of aggregation • Linked to impact on climate • Simple to compute	• Quantitative value lacks physical meaning
2. Subsidence fraction	
• Reflect clear signature of aggregation • Linked to impact on climate • Simple to compute	• Quantitative value lacks physical meaning • Sensitive to spatiotemporal averaging
3. Clustering metrics	
• I_{org} has theoretical null to compare against and quantitative meaning	• I_{org} captures multiple scales of organization • Difficult to calculate

Ideal Self-Aggregation Metric

- Reflect impact of self-aggregation on the humidity distribution
- Assess temporal coherence of convection
- Transparent about scales being measured
- Applicable to CRMs with limited area domains, GCMs with parameterized convection, and observations

RCEMIP ensemble presents opportunity to test metrics across wide range of models, domain geometries, and representations of self-aggregation

What is convective self-aggregation?

Spontaneous clustering of convection in homogeneous environment driven by radiative and surface flux feedbacks

How can we measure it?

Time scale, length scale, growth rate of mechanisms, impact on mean state, humidity-related indices, subsidence fraction, clustering metrics…