ICTP summer school, 17 July 2024

WHAT DO OBSERVATIONS REVEAL ABOUT THE INFLUENCE OF CONVECTIVE ORGANIZATION ON CLIMATE?

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OUTLINE

- Different ways to think about “convective organization”, and how it may affect climate, from an observational perspective (more general than “aggregation”)
- Moist Static Energy (MSE) spatial variance budget (and self-aggregation)
- Self-aggregation of shallow convection
- Convective aggregation in observations
- Spatial Scales of self-aggregation processes
- MJO
- Rotating RCE and tropical cyclones
- ITCZ
- Aggregation in a warming world
- Conclusions and possible areas for future research
- **Note:** some of this is my own (and my collaborators’) work, but largely a review of others’ work – this is not intended to be comprehensive and there are many other interesting papers and topics I didn’t have time to talk about.

DIFFERENT CLOUD TYPES (RELATED TO CIRCULATIONS)

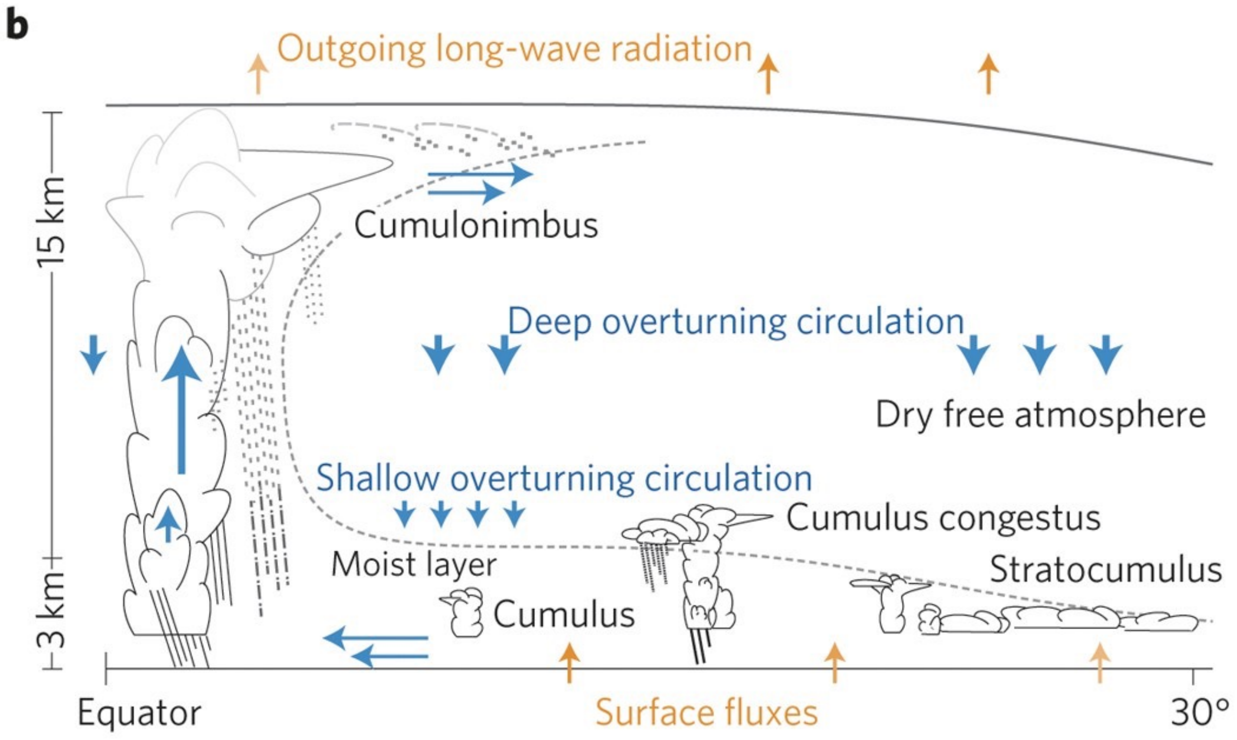


Fig. from Bony et al 2015, *Nat. Geosci.*

- The whole tropical-subtropical circulation is “organized” into large overturning circulations (Hadley, Walker) which interact with convection.
- Changes in these circulations are associated with changes in the frequency, coverage, location and optical depth of different cloud types.
- These changes in cloud types and cloud properties can have large effects on radiative fluxes and therefore climate.

DIFFERENT CLOUD TYPES (AND CLOUD FEEDBACKS)

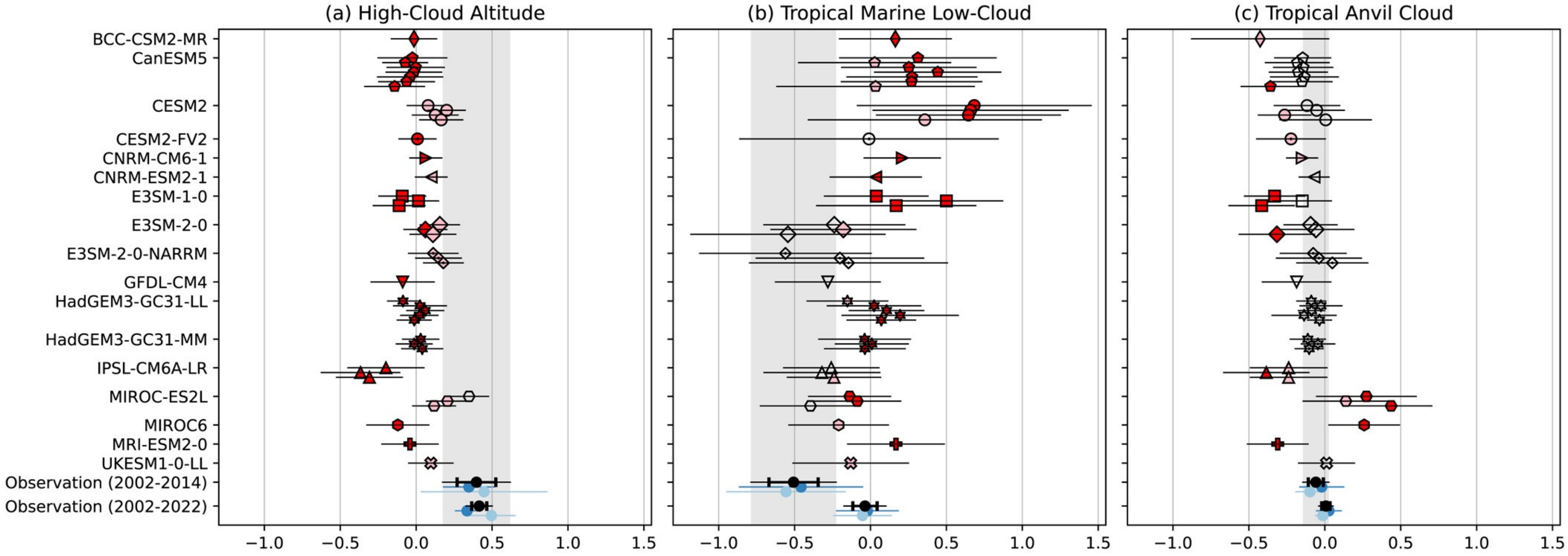
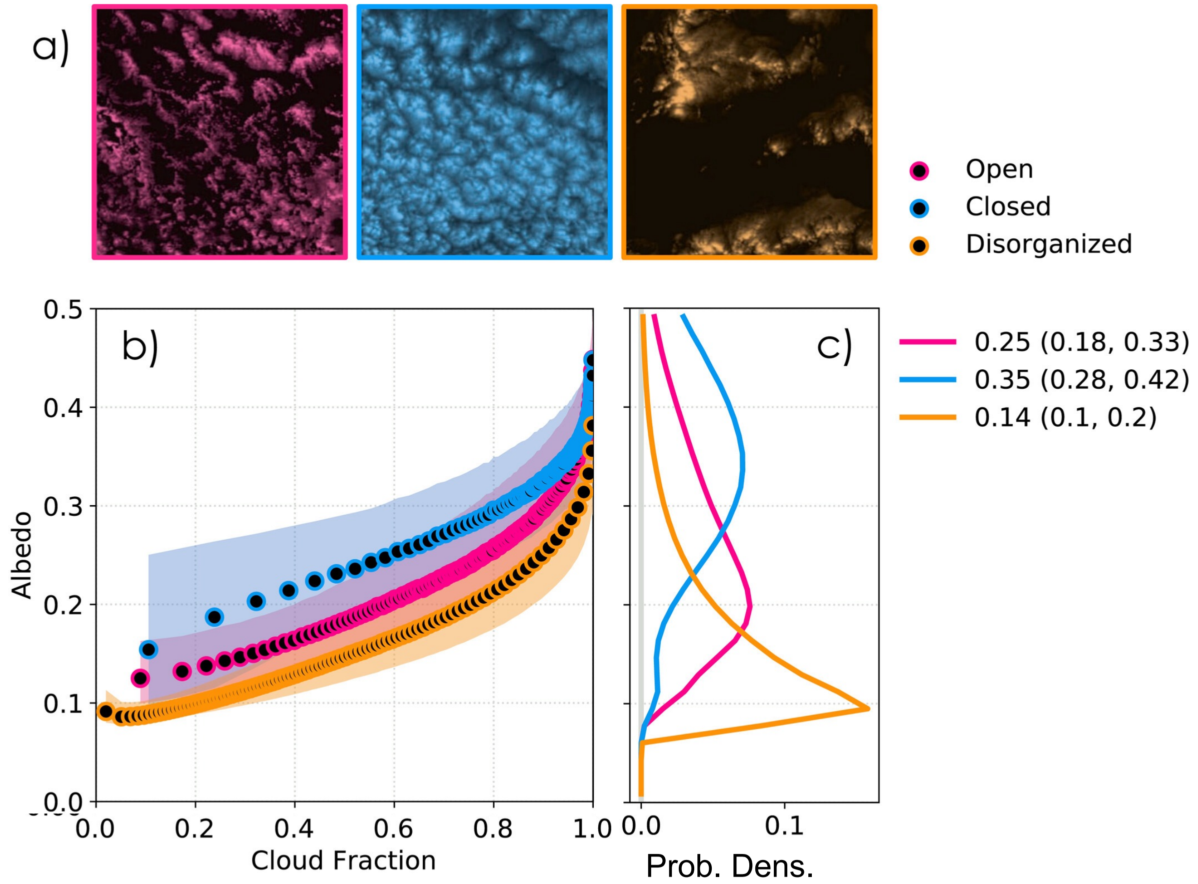


Fig. from Chao et al 2024, *JGR Atmos.*

Obs. from CERES and MODIS satellite products.

- Cloud feedbacks over short (here, interannual) time scales in models can be compared to observational estimates of these feedbacks – possible insight for longer (climate change) time scales.
- Changes in convective circulations contribute toward these feedbacks – these are less important than “thermodynamic” effects (change in temperature, humidity etc. for a given circulation regime) in GCMs (Byrne and Schneider 2018, *J. Clim.*) but can be substantial in RCEMIP CRMs (Mackie and Byrne 2024, *JAMES*).

DIFFERENT MORPHOLOGIES OF SHALLOW CONVECTION



- For the same cloud fraction, different morphologies of shallow cloud (open cells, closed cells, and disorganized) have quite different albedo.
- The relative frequency of these morphologies may change with climate change (e.g. due to local SST changes).
- This study uses estimates of environmentally driven cloud morphology changes in optical depth to calculate a shortwave feedback of 0.04–0.07 W m^{-2} K^{-1}.

McCoy et al 2023, *GRL*

DIFFERENT MESOSCALE PATTERNS OF SHALLOW CONVECTION

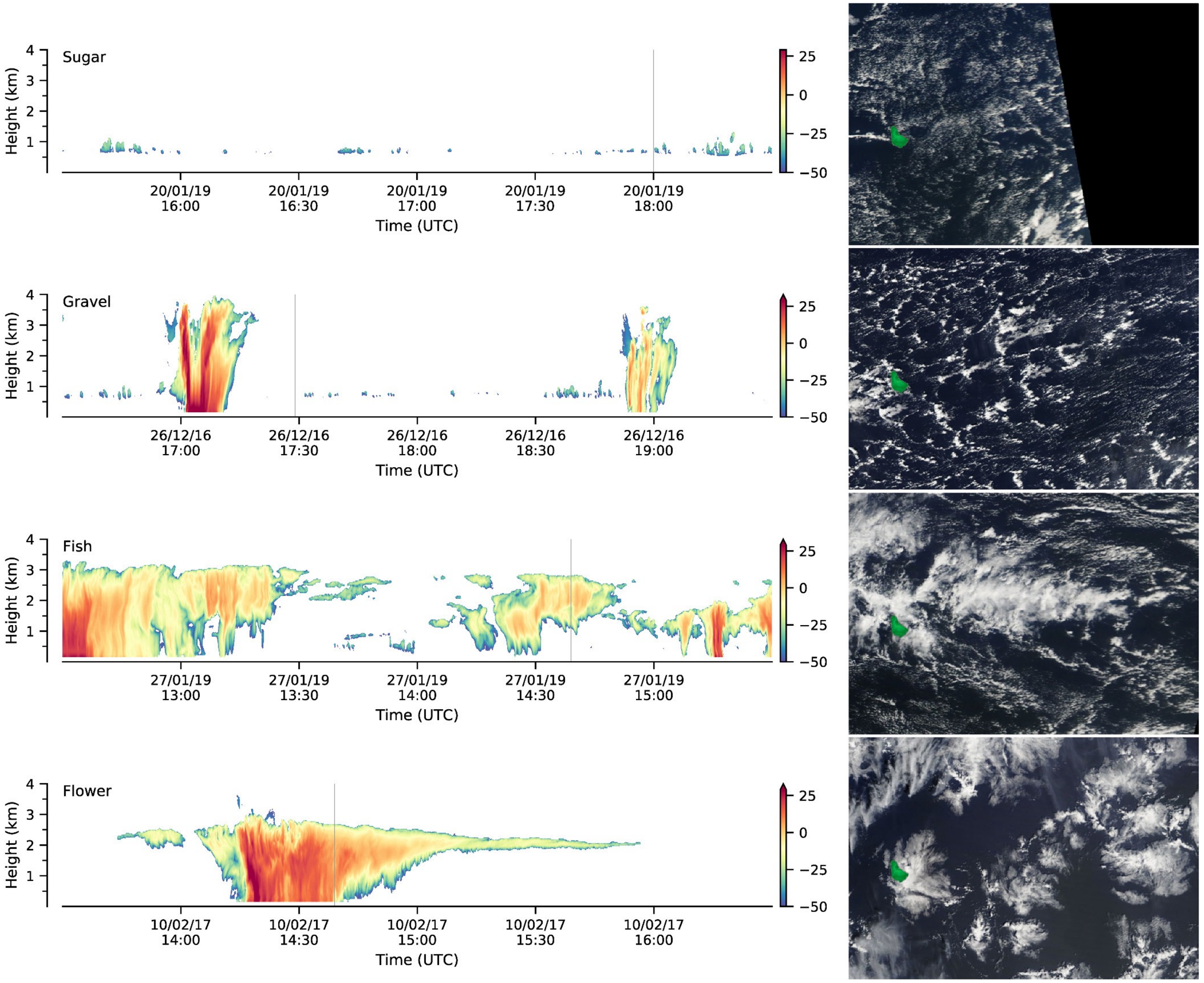


Fig. from Stevens et al 2020, *GRL*

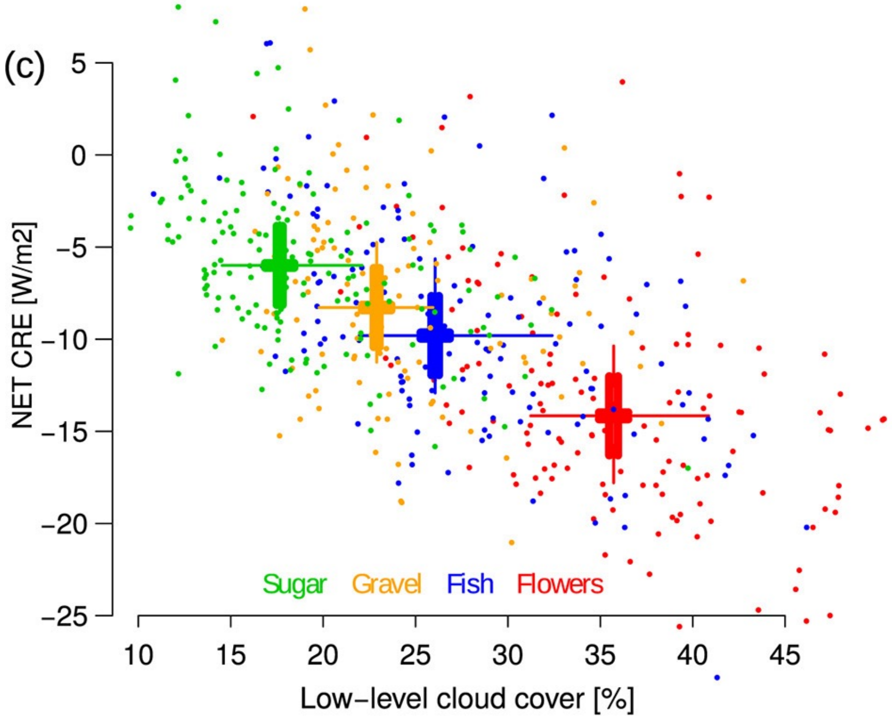
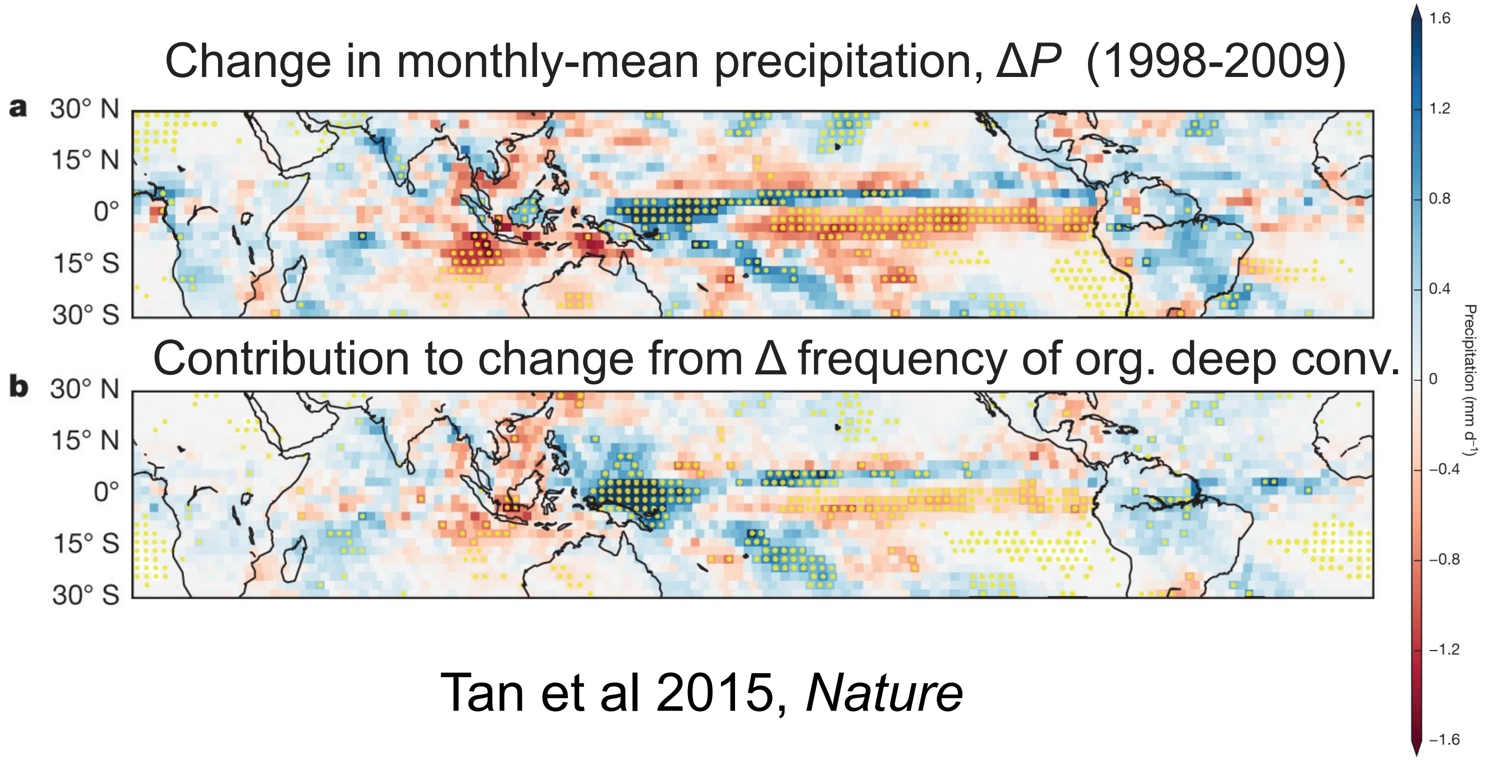


Fig. from Bony et al 2020, *GRL*

- Different shallow convection mesoscale organization patterns have different radiative properties.

PRECIP. INCREASES COME FROM MORE ORG. CONVECTION


Change in monthly-mean precipitation, Δ*P* (1998-2009)

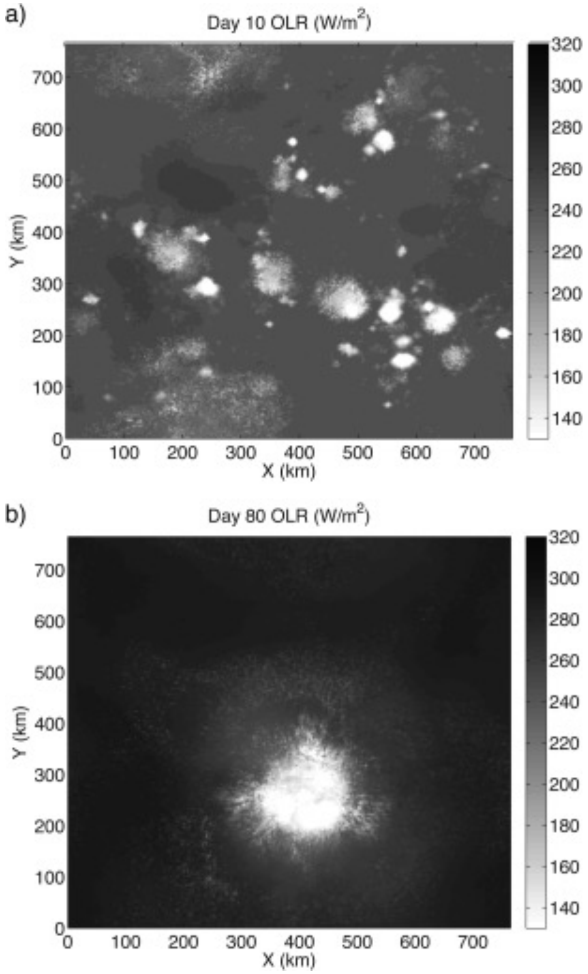
Contribution to change from Δ frequency of org. deep conv.

Tan et al 2015, *Nature*

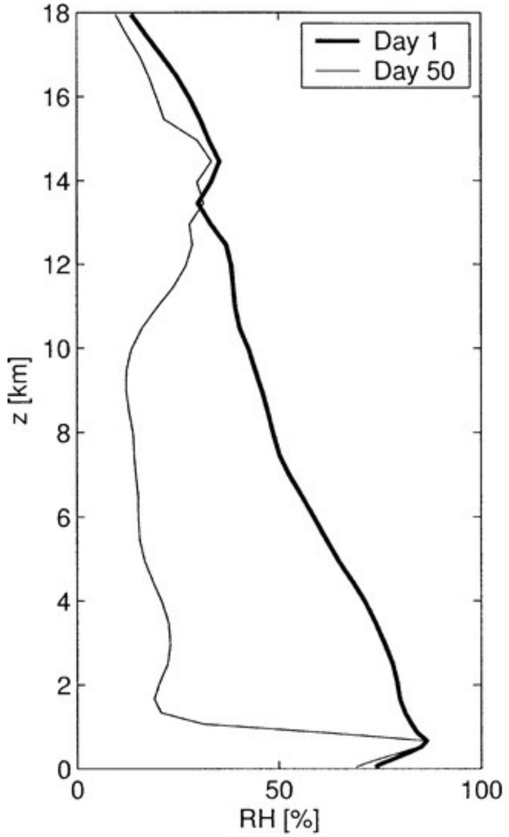
- Most of the recent observed increase in precipitation (as the climate has warmed) can be attributed to an increase in the frequency of mesoscale organized deep convection (identified by ISCPP satellite algorithm as having precipitating deep convection with widespread anvil clouds).
- Consistent with rainfall happening less often, but in more organized and intense events.

CONVECTIVE SELF-AGGREGATION IN IDEALIZED MODELS

- idealised radiative convective equilibrium (RCE): constant SST, no land, no Coriolis force (no rotation), periodic lateral boundaries. (sometimes some of these simplifications are relaxed)
- initially scattered convection becomes aggregated into one region
- linked to feedbacks between convective rainfall, tropospheric water vapor, radiation, and surface fluxes
- also previous work, e.g.: Held et al. 1993 (2D Cloud-system resolving model [CRM] aggregation); Tompkins 2001 (bands of convection in 3D CRM)



Wing and Emanuel 2014, *JAMES*



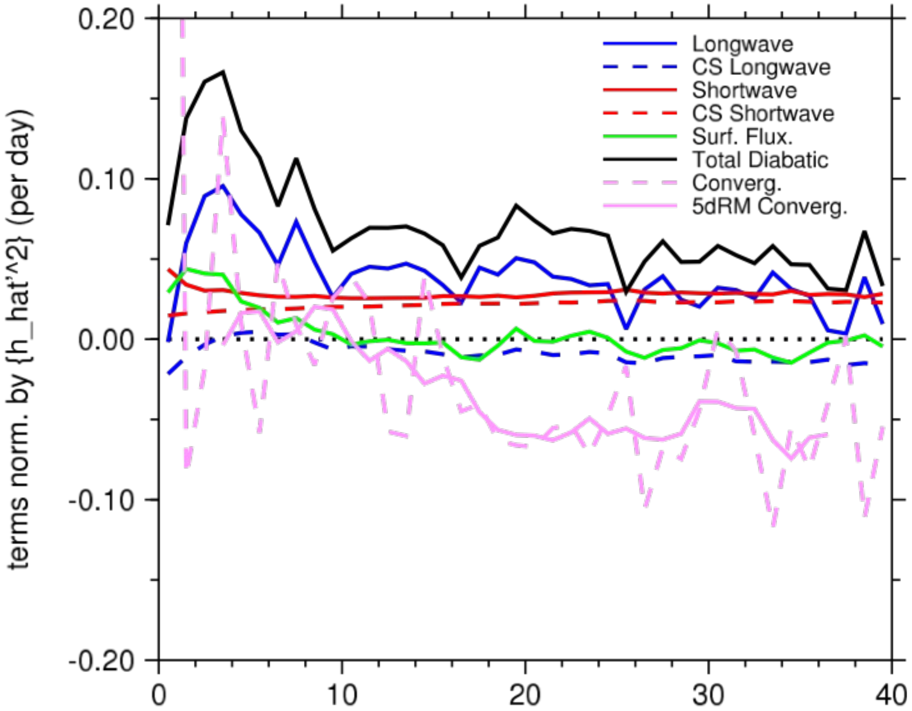
Bretherton et al. 2005, *JAS*

CONVECTIVE SELF-AGGREGATION IN IDEALIZED MODELS: MOIST STATIC ENERGY SPATIAL VARIANCE BUDGET

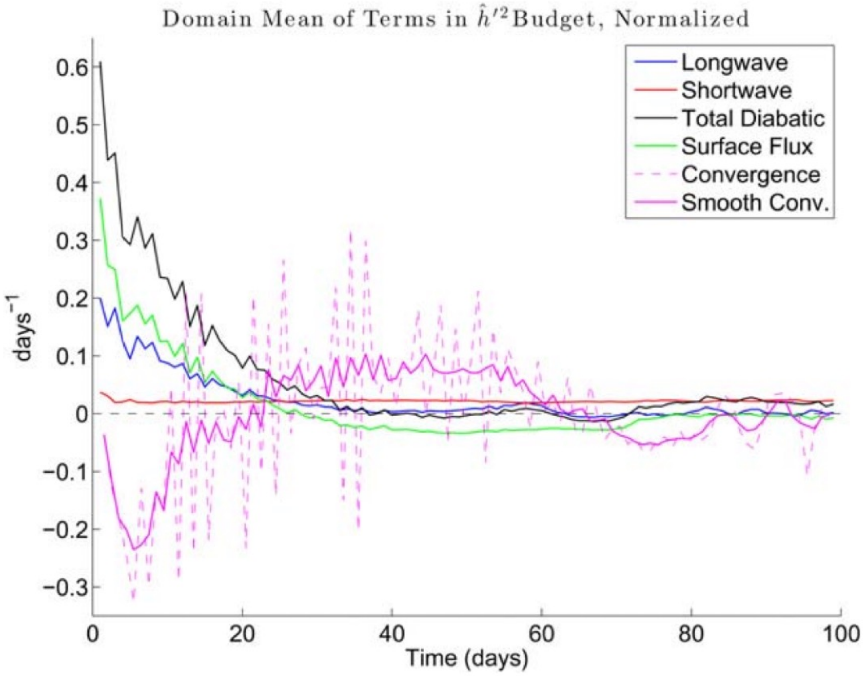
Aggregating tendency

Disaggregating tendency

Holloway and Woolnough 2016



Wing and Emanuel 2014



$$\frac{1}{2}\frac{\partial \hat{h}'^2}{\partial t} = \underbrace{\hat{h}'\mathrm{THF}' + \hat{h}'\mathrm{S\hat{W}}' + \hat{h}'\mathrm{L\hat{W}}'}_{\text{Total Diabatic}} - \hat{h}'\nabla_{\mathbf{h}}\cdot\hat{\mathbf{v}h}.$$

Variance
of horiz. anomaly
of vert. integ.
moist stat. energy

Surf. Flux

Shortwave

Longwave

Convergence

Total Diabatic

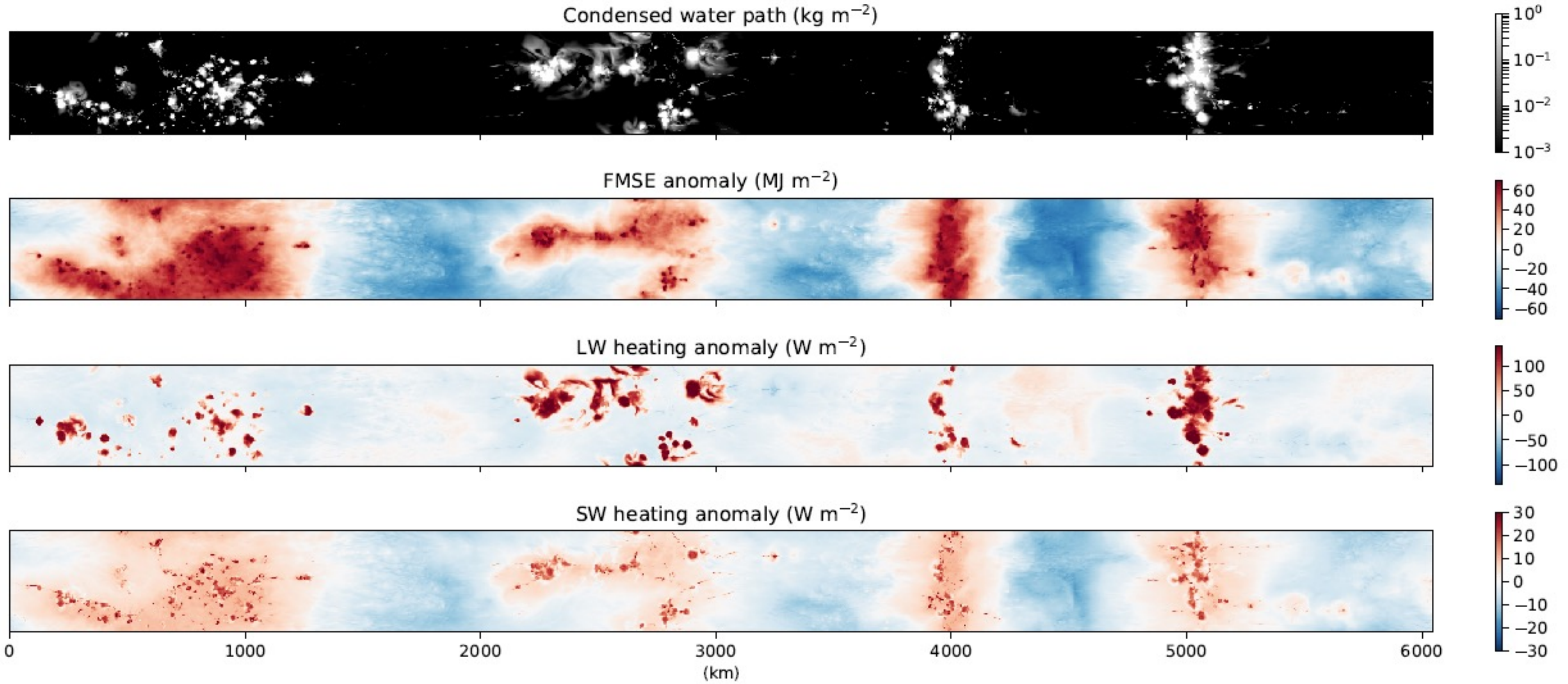
Analysis following
Wing and Emanuel 2014

THE VARIANCE OF FMSE (*h*) BUDGET

$$\underbrace{\frac{1}{2}\frac{\partial \widehat{h'^2}}{\partial t}}_{\text{Rate of change of FMSE variance}} = \underbrace{\hat{h}'LW' + \hat{h}'SW' + \hat{h}'SEF'}_{\text{Covariances between FMSE anomalies and anomalies in diabatic sources and sinks of FMSE}} - \underbrace{\hat{h}'\nabla_h.\widehat{\mathbf{u}h}}_{\text{Covariance between FMSE anomalies and FMSE advection}}$$

- Regions where radiative anomalies and FMSE anomalies have the same sign contribute to aggregation
- Clouds appear to play a dominant role in longwave anomalies
- Moisture plays a crucial role in shortwave anomalies

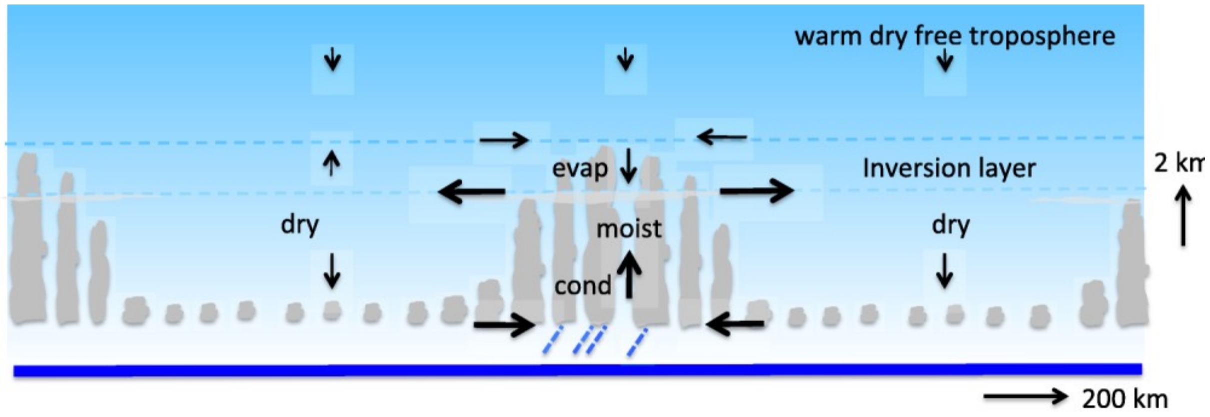
Figure by Kieran Pope



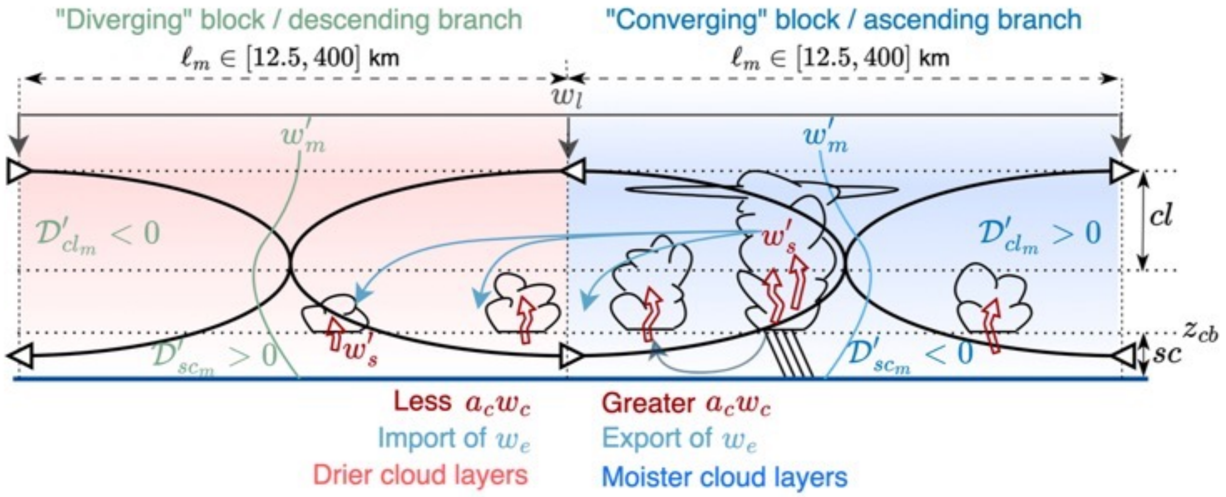
SELF-AGGREGATION OF SHALLOW CONVECTION

- LES simulations in Bretherton and Blossey (2017, *JAMES*) show that moist patches support stronger shallow convection, leading to latent heating and mesoscale ascent which in turn leads to more moistening.
- Here, radiative and surface-flux feedbacks help, but are not essential to get aggregation.

- Janssens et al. (2024 preprint, *ESS Open Archive*) use observations and LES to similarly argue that these mesoscale simulations are in approximate Weak Temperature Gradient balance, with shallow convective heating controlling the vertical motion, and growth mainly by moisture-convection feedback.



Bretherton and Blossey 2017, *JAMES*



Janssens et al. 2024, *ESS Open Archive*

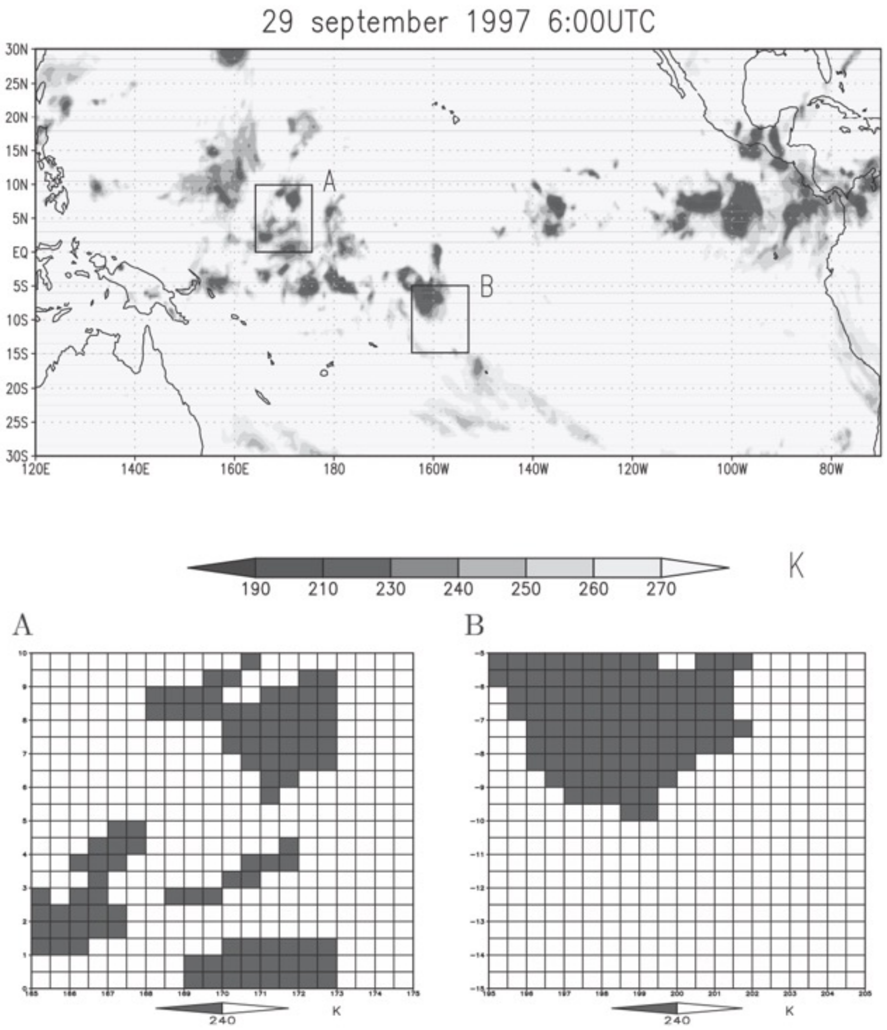
AGGREGATION IN OBSERVATIONS: EARLY OBS INDEX

- Tobin et al. 2012 (J. Climate), and Tobin et al. 2013 (JAMES) look at aggregation state in snapshots of tropical observations.
- They define a “Simple Convective Aggregation Index” (SCAI) based on clusters with IR brightness temperature below 240 K :

$$\mathrm{SCAI} = \frac{N}{\mathrm{Nmax}}\frac{D_0}{L} \times 1000 = \tilde{N}\tilde{D}_0 \times 1000.$$

where N is the number of clusters and D0 is the average geometric distance between clusters (with some constants used for normalisation). They found that N itself correlates extremely well with SCAI, and so they mostly use the smallness of N as a proxy for aggregation.

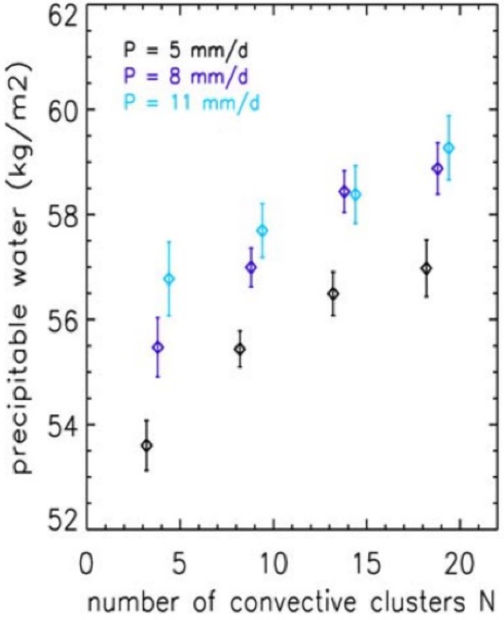
- **Low SCAI** (or **N**) means **more aggregated**.



CONVECTIVE AGGREGATION IN OBSERVATIONS

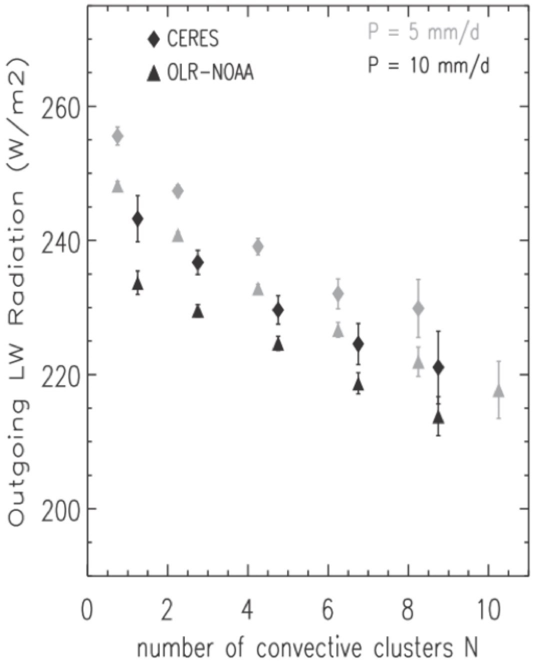
- There is agreement between models and observations that as convection becomes aggregated (clumped into fewer moist regions), the subsidence regions become drier, resulting in a drier large-scale mean environment.
- This drying, and a reduction of upper-tropospheric stratiform cloud, leads to larger OLR and stronger atmospheric cooling.

Tobin et al. 2013, *JAMES*

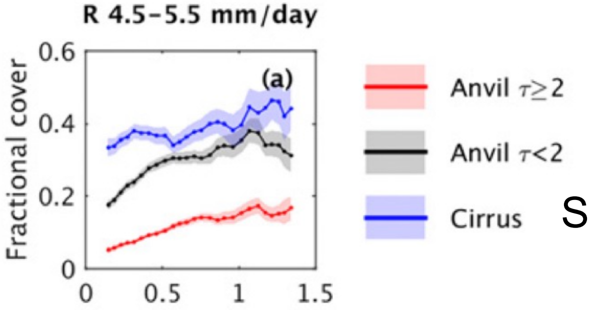


more aggregated less aggregated

Tobin et al. 2012, *J. Climate*



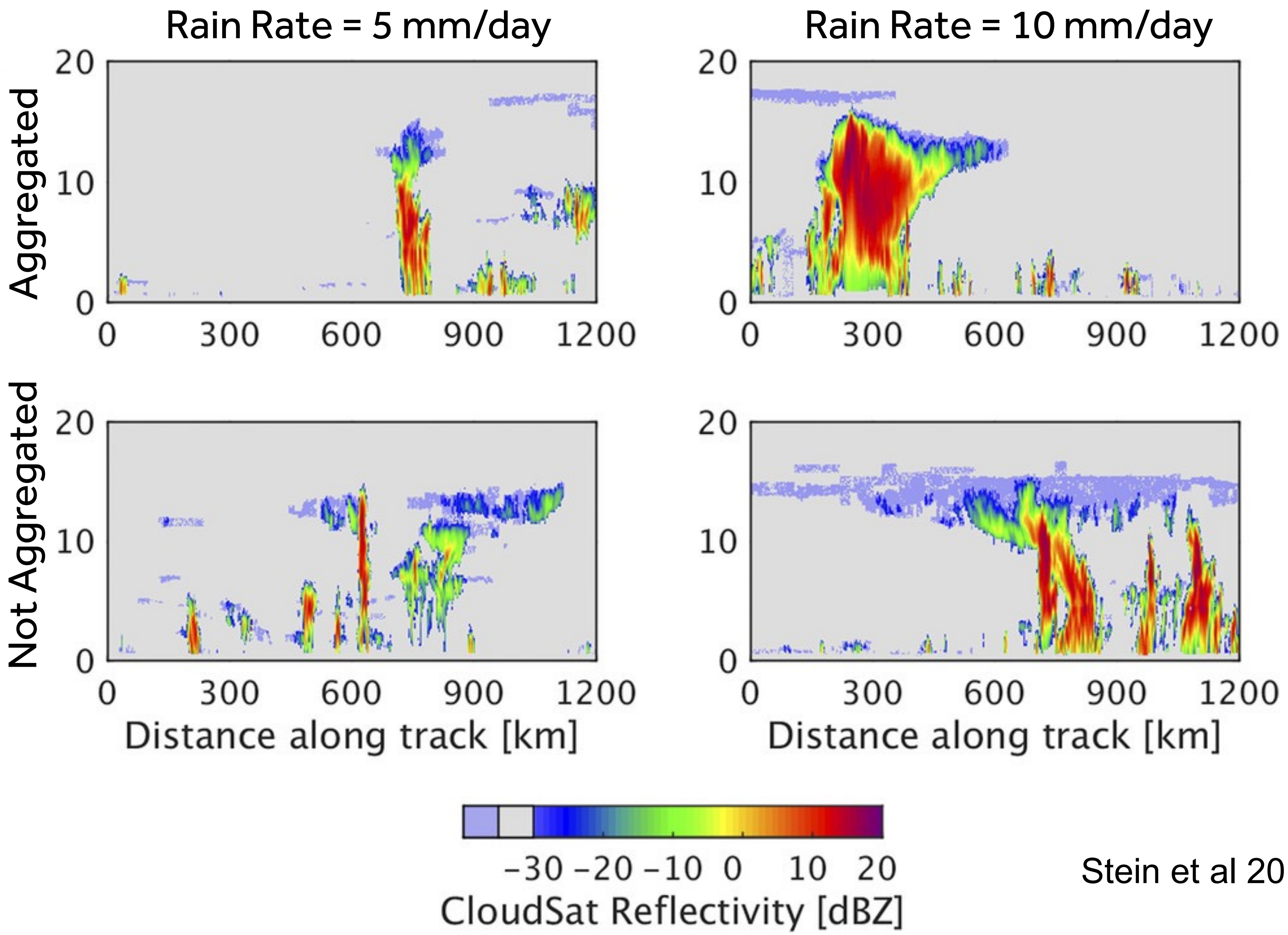
more aggregated less aggregated



Stein et al. 2017, *J. Climate*

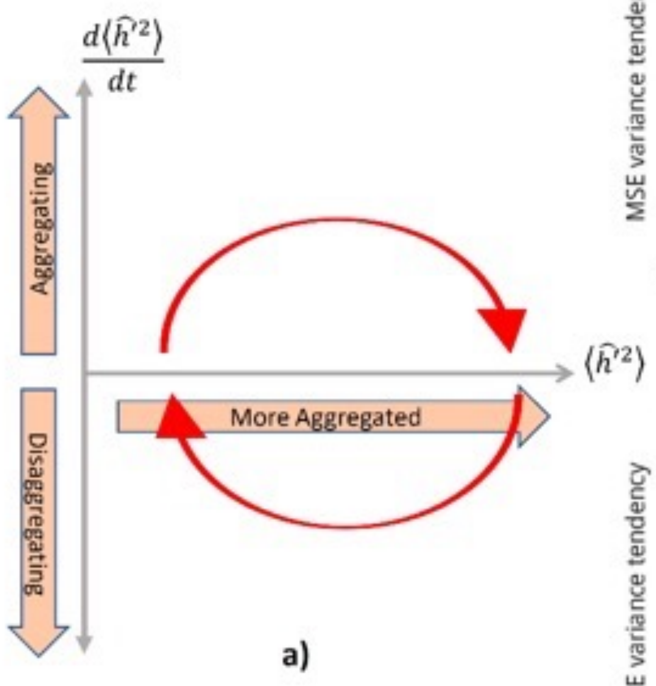
more aggregated less aggregated

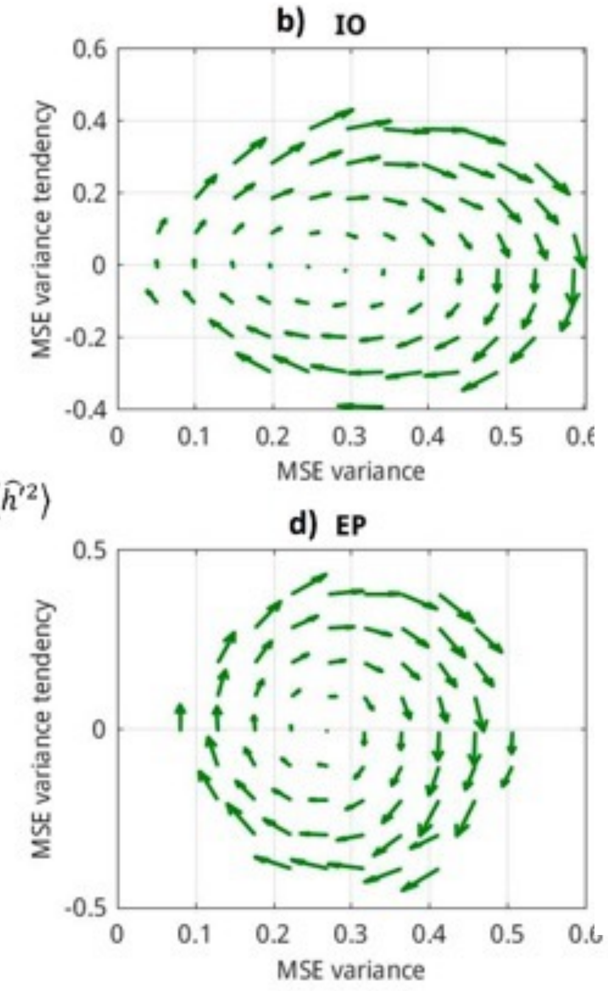
CLOUDSAT-CALIPSO EXAMPLES BY RAIN RATE AND AGG.

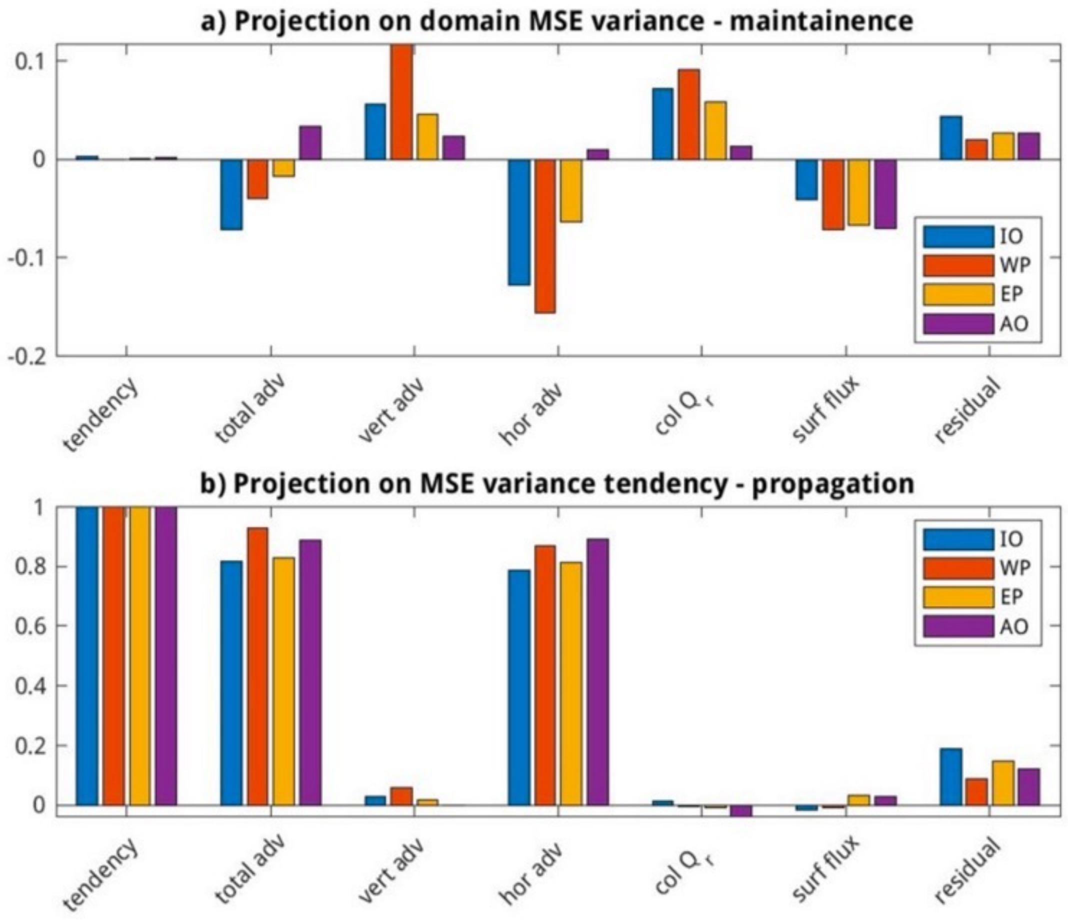


Stein et al 2017, J. Climate

AGGREGATION-DISAGGREGATION CYCLES IN ERA5



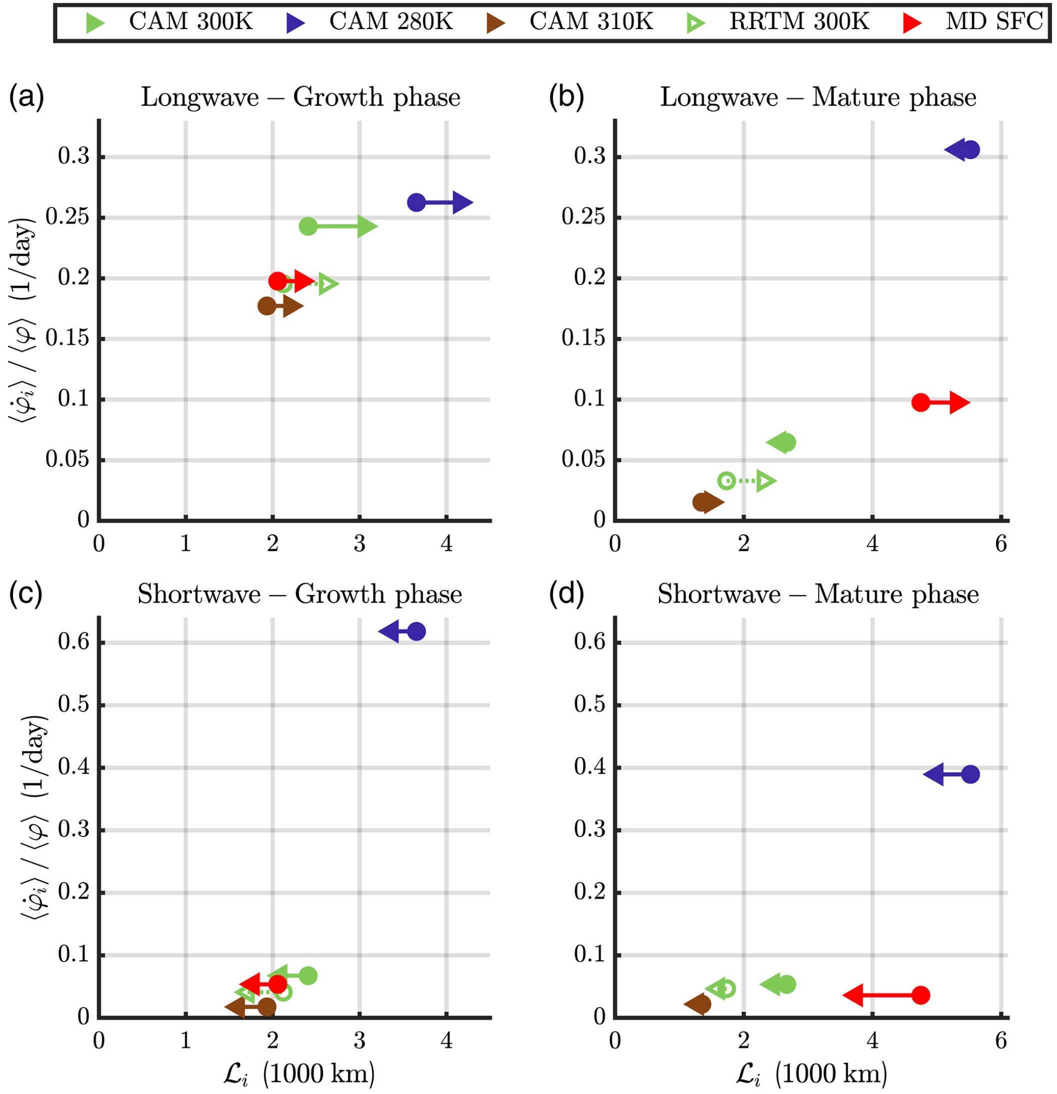




Maithel and Back 2024, submitted to *J. Climate (arXiv preprint)*

SPATIAL SCALES OF SELF-AGGREGATION PROCESSES

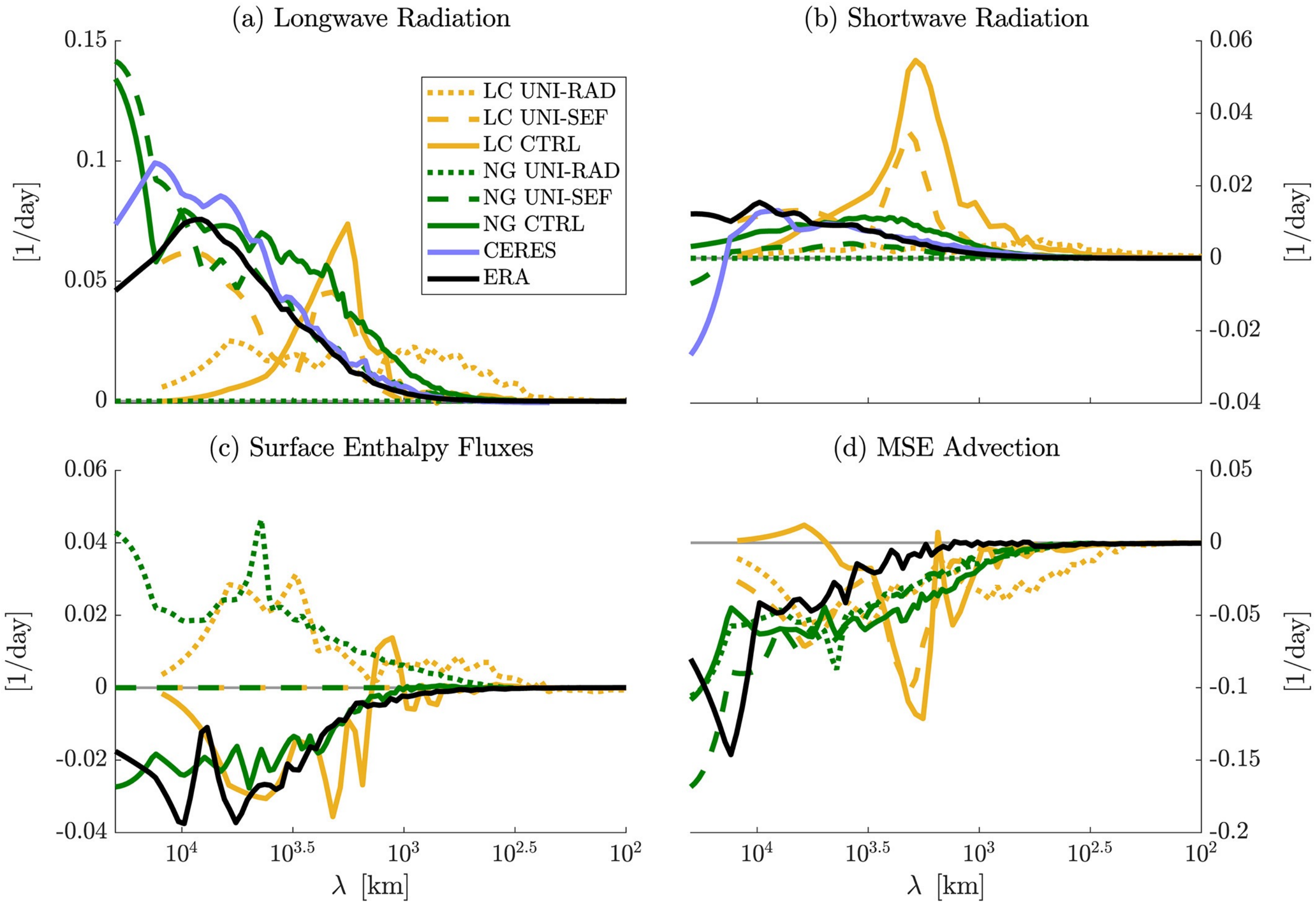
- The traditional MSE spatial variance budget does not tell us about the _scale_ of the variance (or aggregation).
- Beucler and Cronin (2019, *QJRMS*) develop a spectral diagnostic and find that, at least during the growth phase, "the net long-wave radiative flux operates at large scales (1,000–5,000 km) and stretches the size of moist and dry regions, while the net short-wave flux operates at smaller scales (500–2,000 km) and shrinks it. The surface flux expansion tendency is dominated by convective gustiness, which acts to aggregate convective activity at smaller scales (500–3,000 km)."



Beucler and Cronin (2019, *QJRMS*)

SPATIAL SCALES OF SELF-AGGREGATION PROCESSES

- Beucler et al. (2019, *GRL*) find that “The budget for the transient MSE spectrum exhibits scale-selective tendencies that hold across models and observations: Longwave radiation injects variance at the longest wavelengths, shortwave radiation injects variance at long wavelengths, MSE advection removes variance across scales, and surface enthalpy fluxes mostly remove variance between λ≈1,000 km and λ≈10,000 km.”



Beucler et al. (2019, *GRL*)

OBSERVATIONAL PERSPECTIVES ON AGGREGATION PROCESSES

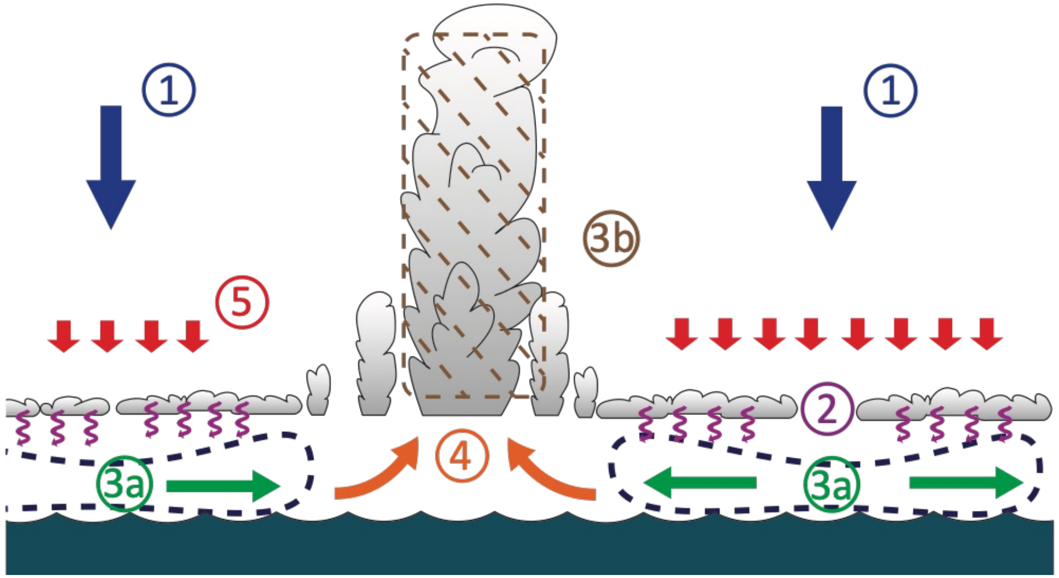


Figure adapted from Coppin and Bony 2015, *JAMES*

- Initiation processes, such as *radiatively-driven cold pools* and related shallow overturning circulations (left), are one obvious observational target.
- Maintenance processes may be easier to study in observations (already aggregated convection). Links to the *MJO, tropical cyclones*, and the *ITCZ,* with feedbacks involving convection, clouds, moisture, radiation, and surface fluxes are important.
- Further work is needed on ocean coupling effects in models and observations.

Holloway et al. 2017, *Surveys in Geophysics*

MJO MOISTURE MODE THEORY LINKS

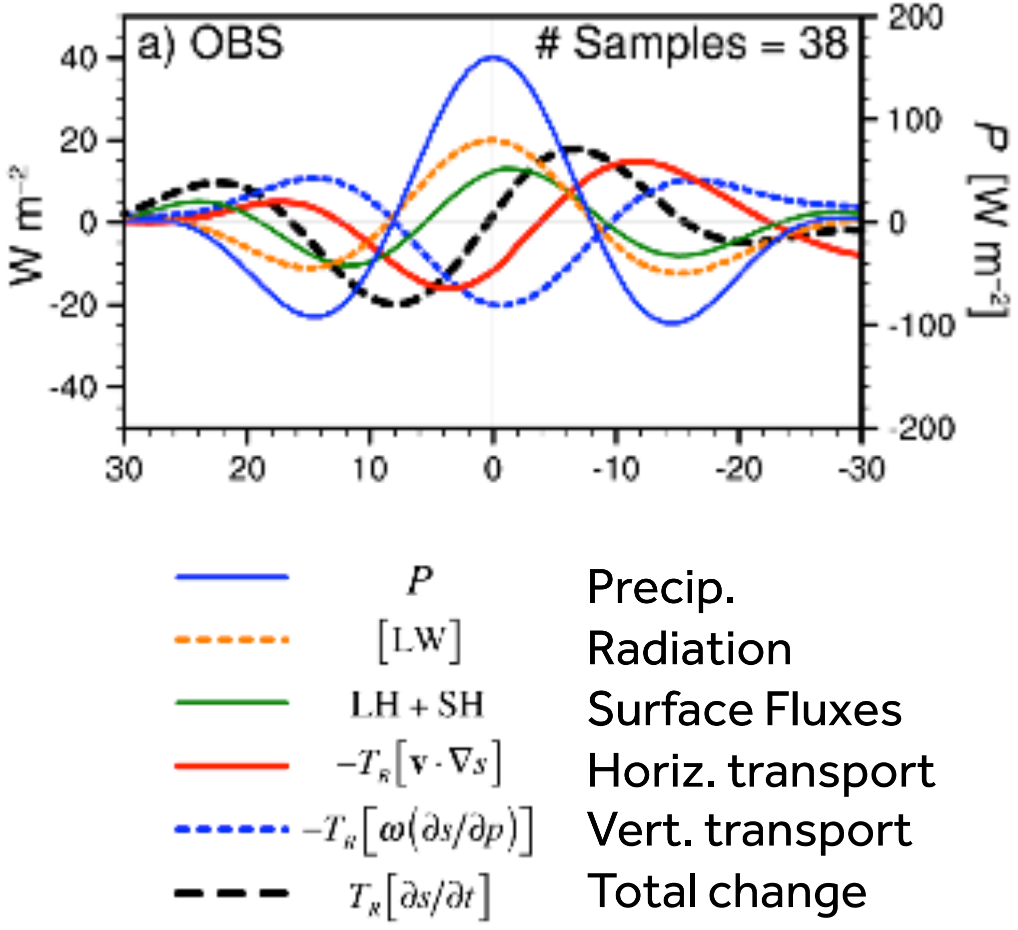
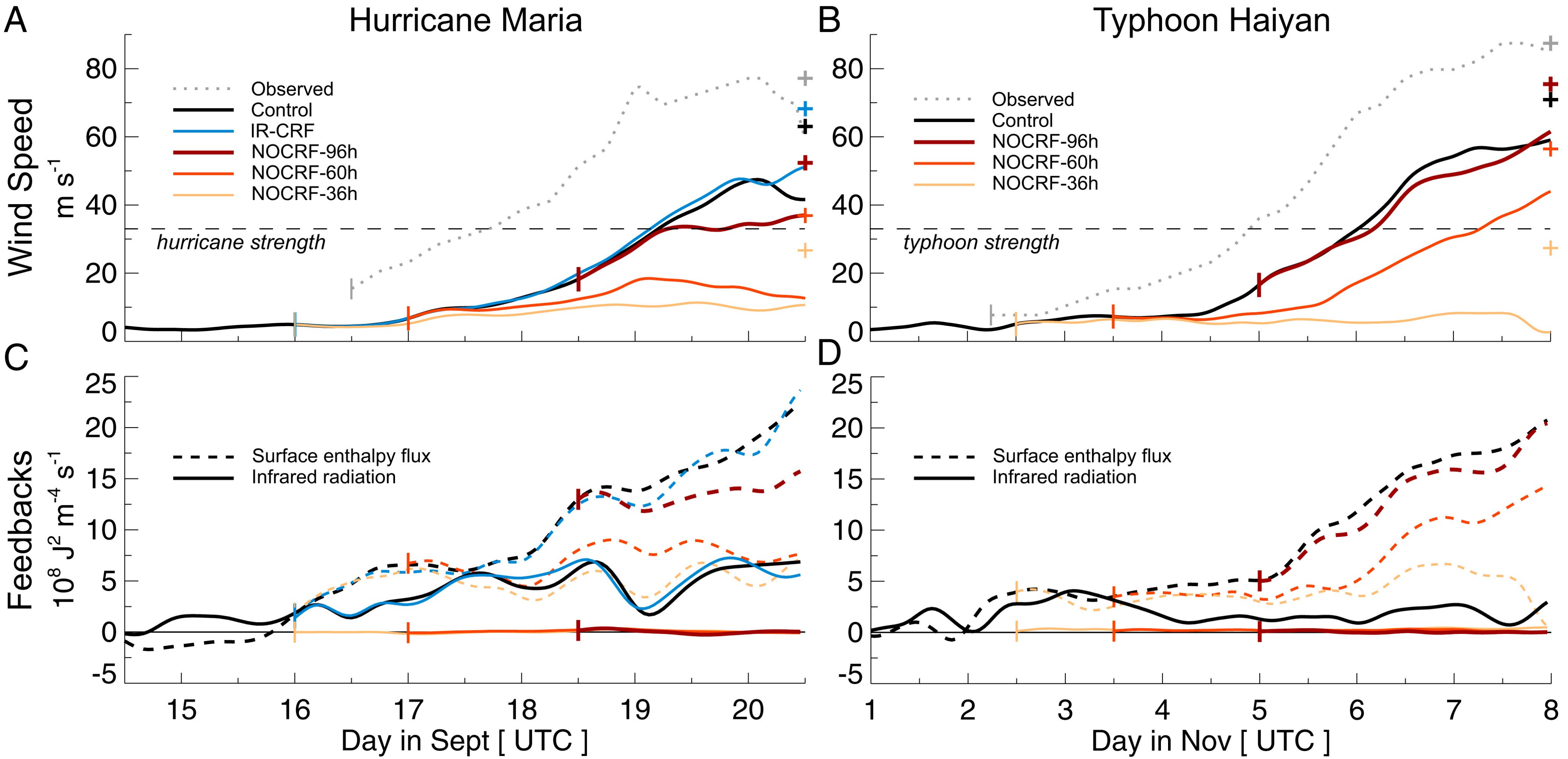


Figure from Benedict et al. 2014, *JAS*

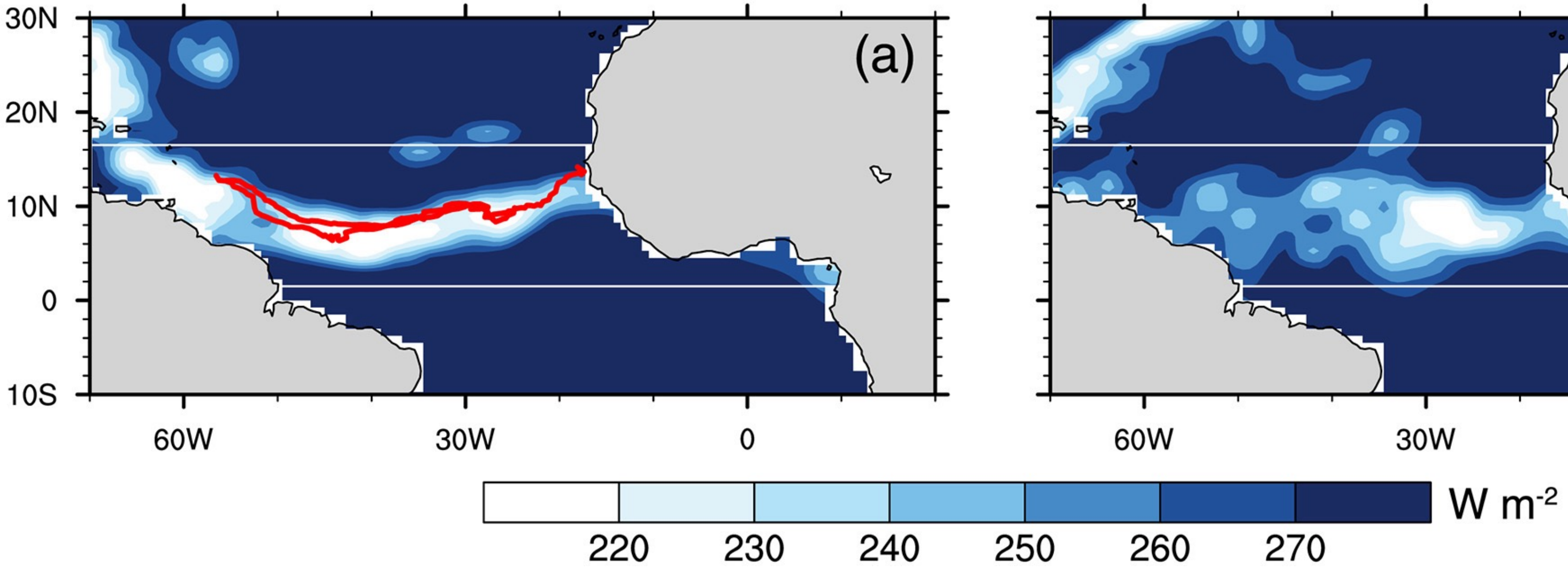
- Yu and Neelin (1994, *JAS*) first connected the MJO to a “stationary moisture mode”
- Moist static energy ($\hat{h}$) budget: terms can cause large-scale growth of $\hat{h}$ (or similarly, of moist entropy); MJO is an instability of $\hat{h}$ in this sense.
- Small-scale convective processes interact with this large-scale $\hat{h}$ instability, and feedbacks can lead to maintenance and propagation (Benedict et al 2014, *JAS*, left).
- This theory is often thought of as “convective self-aggregation on an equatorial Beta-plane.”
- See also: more recent theoretical work on moisture modes, e.g. Ahmed et al. (2021, *JAS*); Mayta and Adames Corraliza (2023, *GRL)* suggest MJO is a moisture mode only over the Indian Ocean, and a mixed moisture-gravity wave elsewhere.

RADIATIVE AND SURFACE-FLUX FEEDBACKS IN REAL TCS



Ruppert Jr. et al 2020, *PNAS*

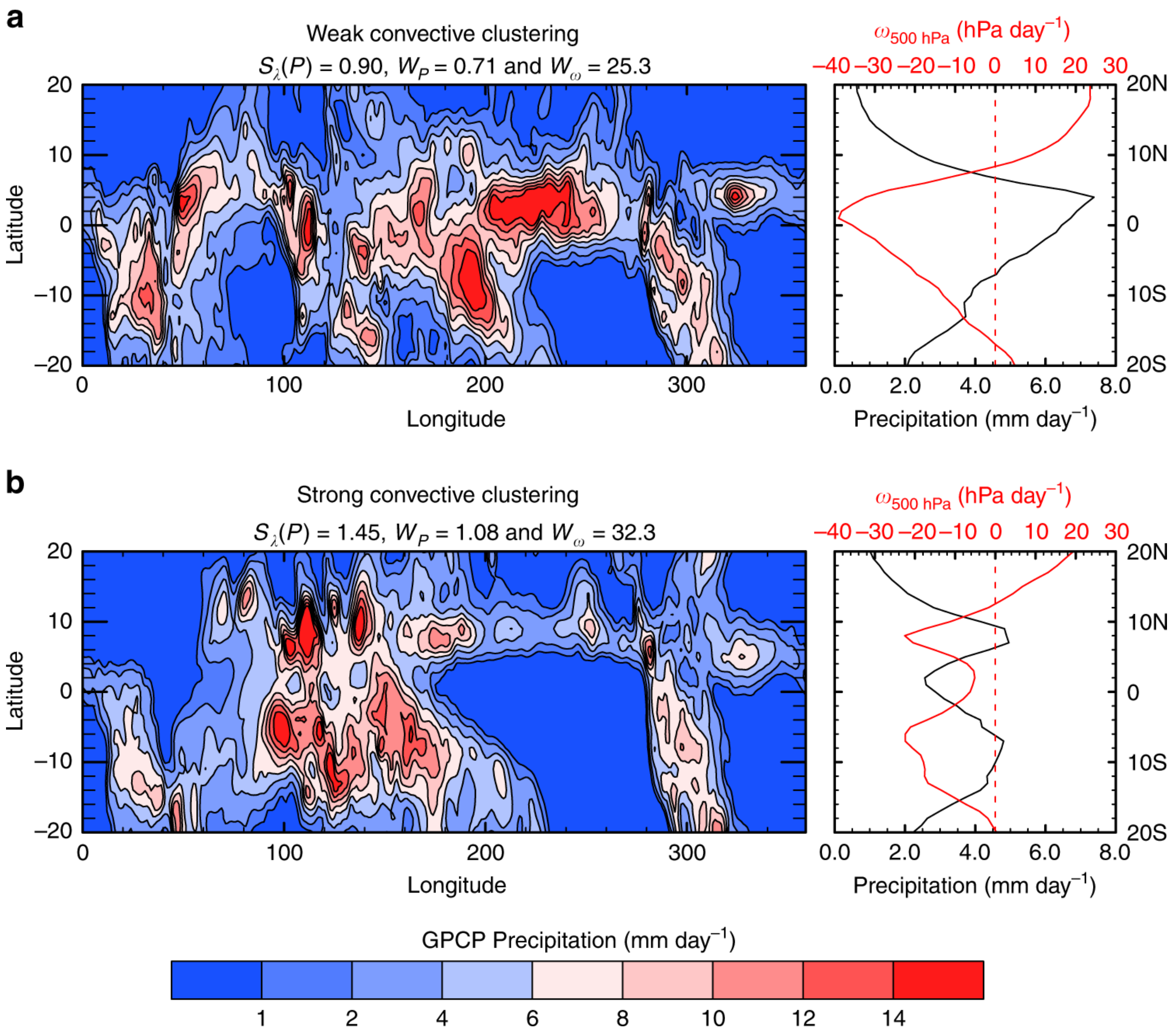
ITCZ CLUSTERING



- Using 35 years of reanalysis data, Hohenegger and Jacob (2020, *GRL*) show that years with more “organised” JJA Atlantic ITCZ (more long convergence lines per month) have a moister JJA ITCZ region and a drier subtropics.

Hohenegger and Jacob (2020), *GRL*

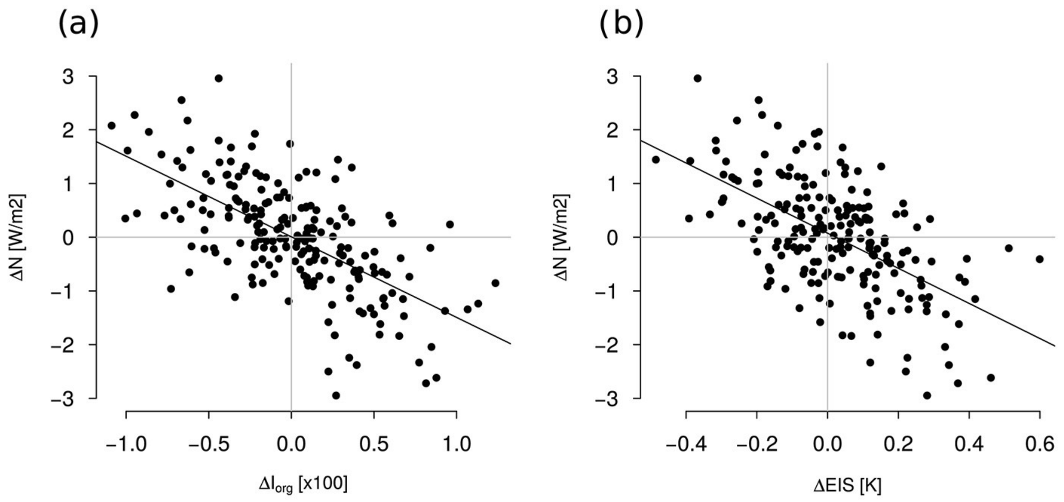
ITCZ CLUSTERING

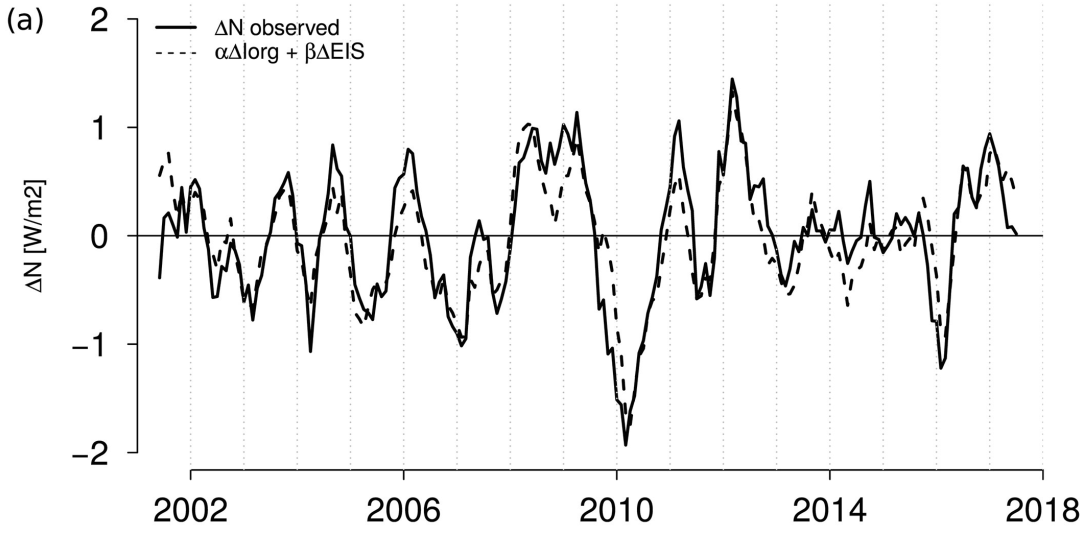


- Using GPCP rainfall data, Popp and Bony (2019, *Nature Commun.*) show that years with more zonally clustered near-equatorial rainfall (lower plot) have a wider meridional distribution of rainfall (a wider overall ITCZ).
- About half of this influence is associated with the annual cycle, the other half due to unforced climate variability.
- Observations and idealised models agree that relationship can be explained by zonal clustering alone.
- Behaviour can be explained with an energetics argument.

Popp and Bony (2019), *Nature Commun.*

NET RADIATION AND ENV AS A FUNCTION OF IORG AND EIS

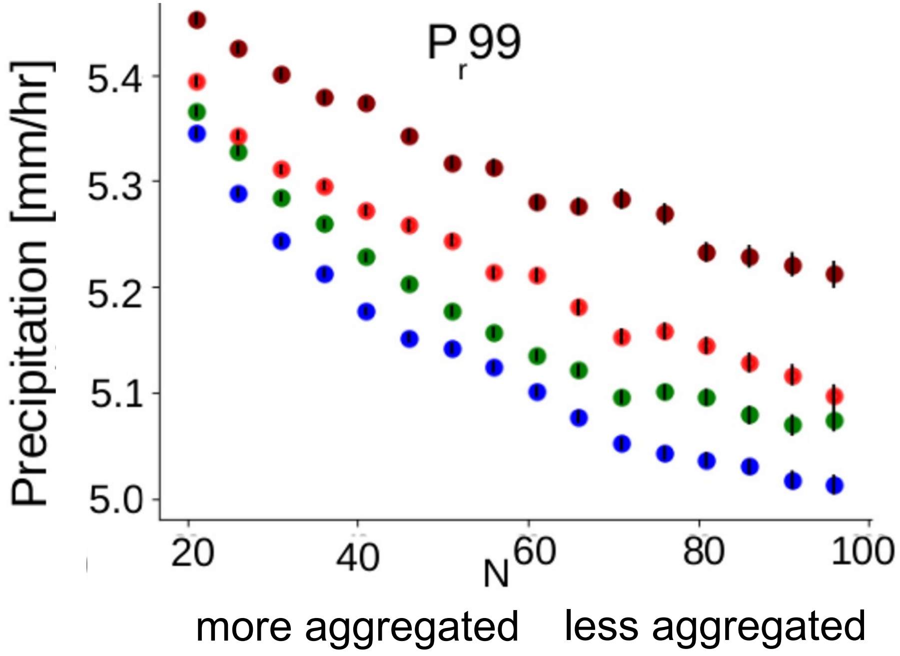




- “The monthly variability of deep convective organization in the tropics is investigated using satellite observations”
- “An enhanced organization of deep convection is associated with a drier troposphere, fewer high clouds, and a radiative cooling of the tropics”
- “Observations suggest equal and complementary modulations of the tropical radiation budget by convective organization and low-level stability”

Bony et al (2020), *AGU Adv.*

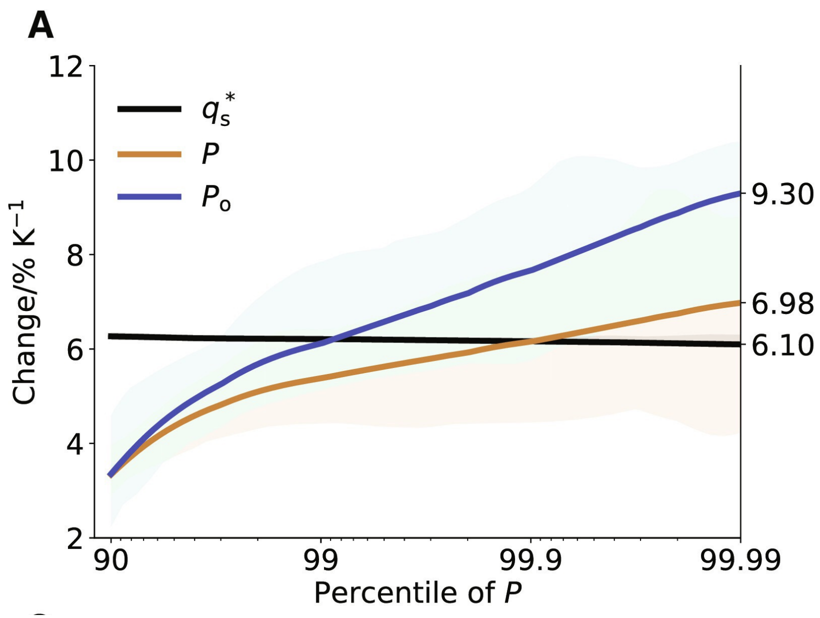
PRECIPITATION EXTREMES AND ORGANIZED CONVECTION



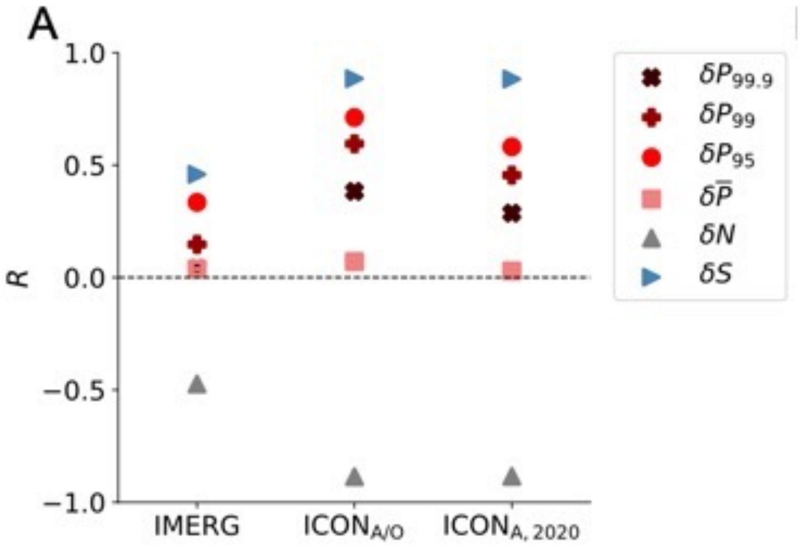
Semie and Bony 2020, *GRL*

- Semie and Bony (2020) use TRMM satellite data and geostationary data and find that extremes in 10° X 10° domain-averaged precipitation do not depend strongly on convective organization.
- However, they find that convective organization enhances extremes in local rainfall (Pr99) when convective organization is stronger (left), primarily due to larger fractions of heavy rainfall.

PRECIPITATION EXTREMES AND ORGANIZED CONVECTION



Bao et al. 2024,
Sci. Adv.



- Bao et al. (2024) find that the ICON global CRM (GCRM) simulates super-CC increase of precipitation extremes with warming over the ocean (blue line, left plot).
- The super-CC increase is linked to increased organization (higher Iorg) in the model, and a high correlation between Iorg and extreme rainfall, though IMERG observations have weaker correlation (right plot). Note that ICON also simulates smaller and more numerous convective storms compared to IMERG.
- GCRMS are a great opportunity to evaluate CRMs with observations.

AGGREGATION IN A WARMING WORLD

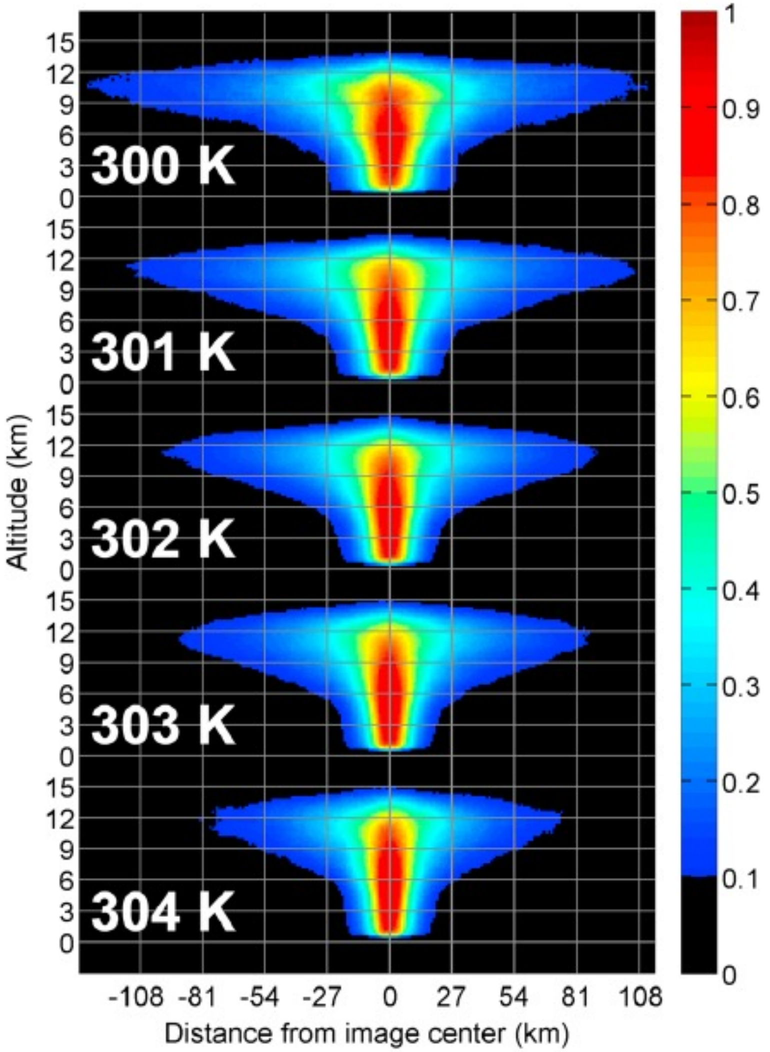


Figure from Igel et al. 2014, *JGR Atmos.*

- Recent work suggests potential sensitivity of aggregation processes to SST and climate change.
- For instance, the “stability-iris” effect (Bony et al, 2016, *PNAS*) predicts smaller anvil fractions in a warmer climate.
- Igel et al. (2014, *JGR Atmos.*) shows an observational dependence of anvil size on *local* SST (left).
- Sokol et al. (2024, Nat. Geosci.) find that RCEMIP CRMs show that changes in cloud area and opacity together act as a weakly positive feedback.
- Pope et al (2023): RCEMIP simulations show less normalised longwave aggregation feedback at warmer SSTs, mainly due to reduction of mid-high cloud area.
- Bao et al. (2024) find that global CRMs predict increasing mesoscale organ. with warming and associated super-CC increases in extreme rainfall over oceans.
- However, observational record is short, and modelling challenges include expense in high resolution as well as more complex processes such as ocean coupling.

CONCLUSIONS

- Broadly defined, convective organization can affect circulations, cloud properties, radiation fluxes, humidity, and precipitation amounts and extremes.
- The feedback processes important for idealised self-aggregation in RCE (radiation, surface flux, and circulation feedbacks) are also important for convective organisation in the real world.
- In particular, feedback between longwave radiation and anvil-stratiform clouds can be important for growth and maintenance of TCs, the MJO, and aggregated clusters of deep convection (including more organised instances of the ITCZ).
- Horizontal advection and circulation feedbacks in general can be important for the propagation of the MJO (and for propagating through large-scale aggregation-disaggregation cycles).
- Shallow tropical/subtropical mesoscale convective organisation is ubiquitous and appears to form through moisture-convection feedback (a form of shallow gross moist stability).
- Observations and models agree on spectral aspects of aggregation – e.g., longwave feedbacks act at large scales and tend to push towards larger scales of organisation.

AREAS FOR FURTHER RESEARCH

- Ocean coupling
- Better observational constraints on updraft strength, convective storm size, precipitation extremes, convective organisation, anvil cloud properties, surface fluxes, … in global (or regional) CRMs (e.g. INCUS satellite mission)
- Further work on aggregation indices including strengths and weaknesses for different observational problems (see Biagioli and Tompkins 2023, *JAS*) as well as other indices to measure convective organization/morphology
- Comparisons of aggregation/organization over land vs. ocean
- Linking theoretical work on moisture modes and moisture-convection feedbacks to aggregation studies
- More comparisons of shallow and deep convective aggregation

ADDITIONAL SLIDES

CONVECTIVE AGGREGATION IN OBSERVATIONS

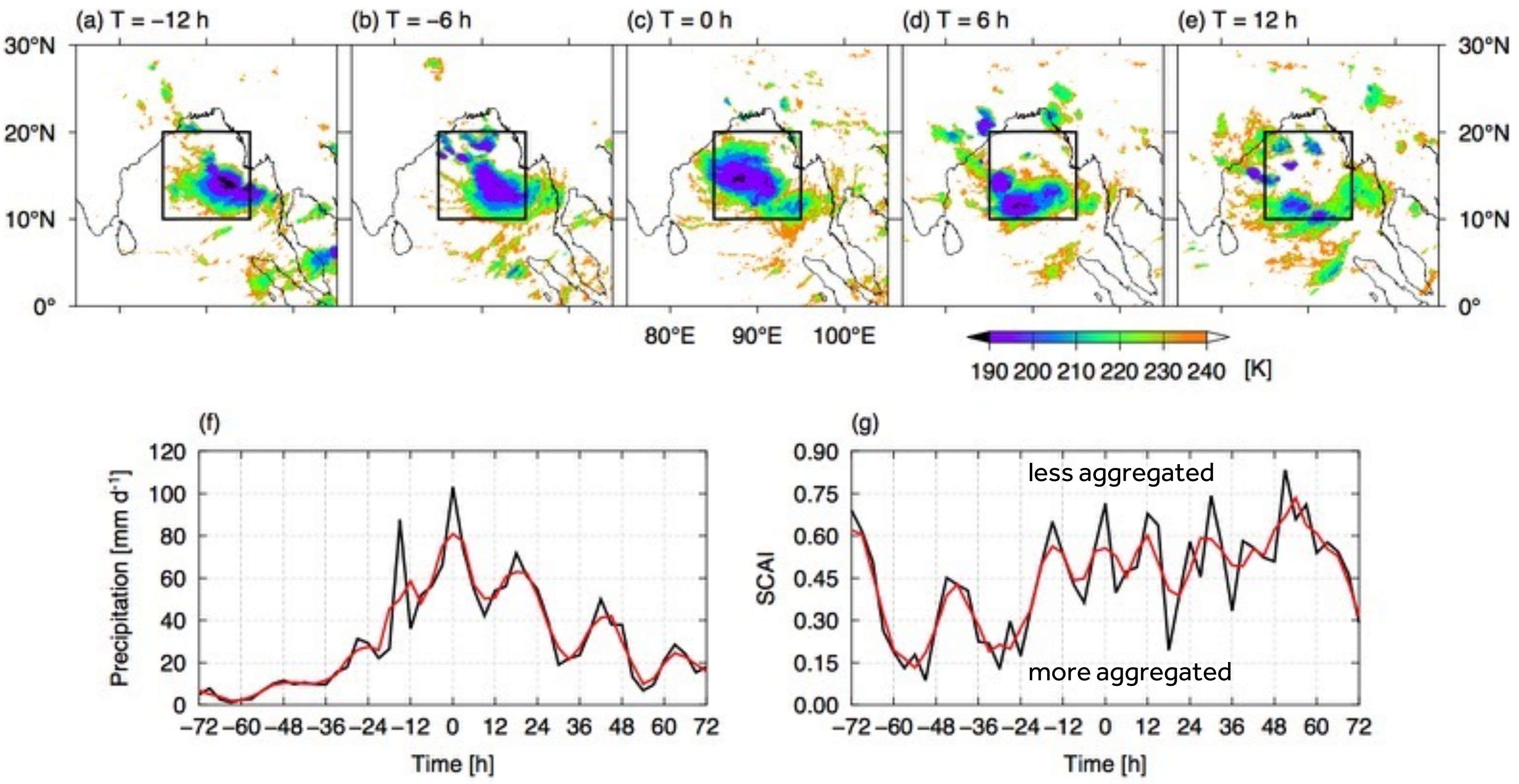


FIG. 7. As Fig. 6 but for the second largest P_0 of 103 mm d^{-1} (0900 UTC 04 June 2009).

Masunaga et al. 2021, *J. Climate*

CONVECTIVE AGGREGATION IN OBSERVATIONS

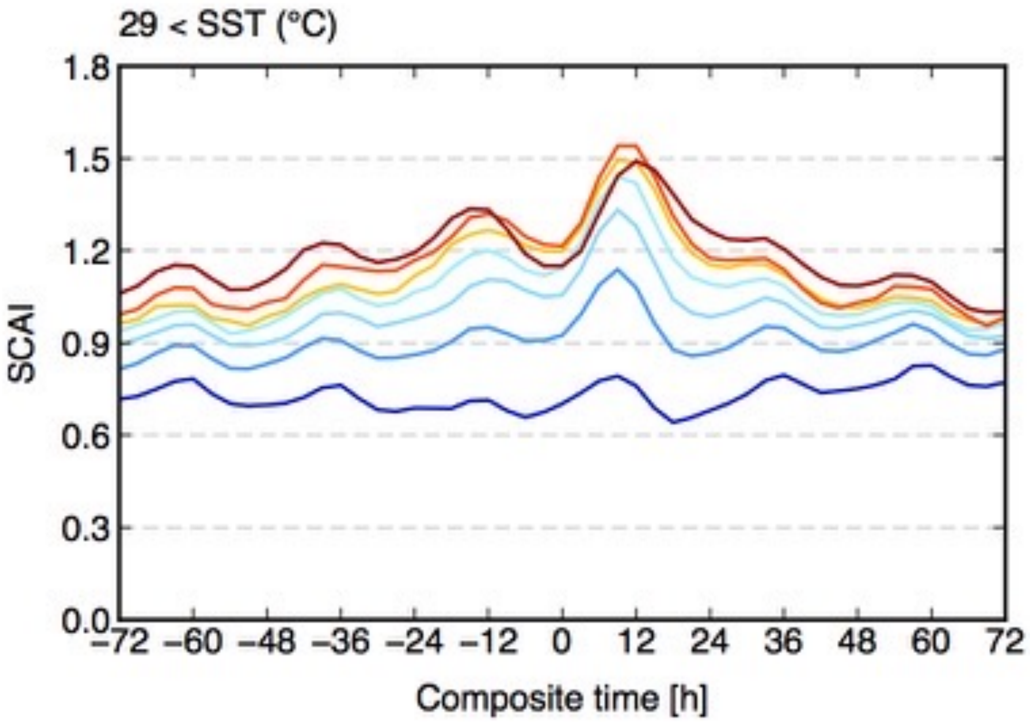


FIG. 3. Composite time series of SCAI stratified by different ranges of underlying SST

- Composites on time of maximum precipitation (time 0) show increase in aggregation just before and near that time at highest SSTs

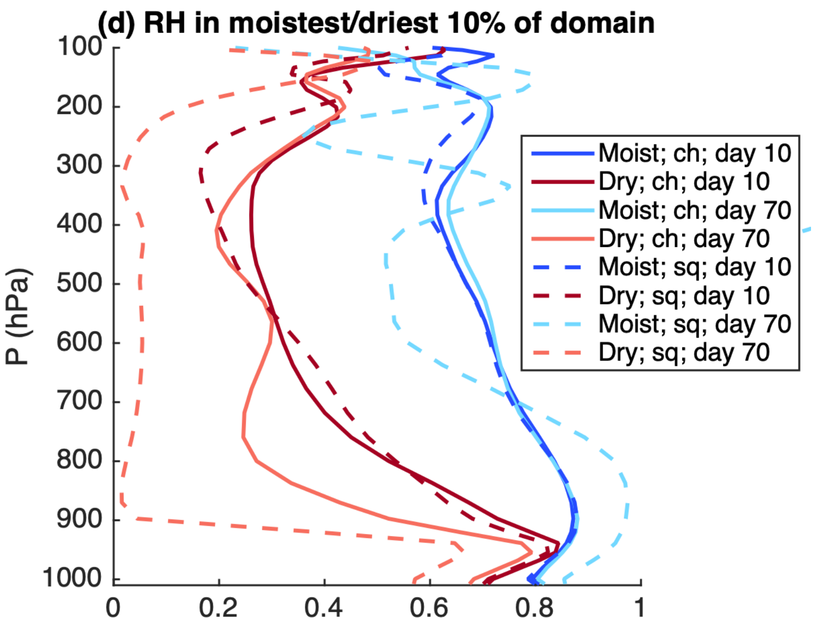
Masunaga et al. 2021, *J. Climate*

COMPARING THE IDEALIZED WORLD TO THE NATURAL WORLD

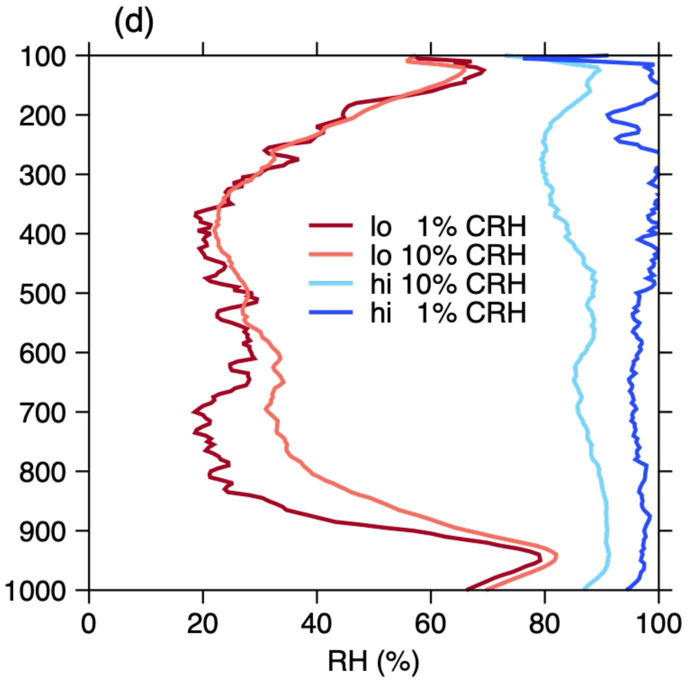
- Time scales are longer in idealized self-aggregation from homogeneous conditions than typical time scales of observed growth of organized mesoscale convection.
- However, time scales vary a lot in idealized models, and exponential growth (e-folding time 11-13 days) implies shorter effective time scales when starting from already existing organization as is often found in nature (Wing and Cronin 2016).
- Furthermore, self-aggregation processes may be favored in regions away from e.g. coastal or orographic forcing and, perhaps, on larger spatial scales (cf. near-global CRM simulations in Bretherton and Khairoutdinov 2015, *JAMES*).
- Maintenance feedbacks are also likely to be relevant in nature, since disaggregation time scales are relatively short (~10 days) when longwave radiation feedbacks are turned off in idealized simulations.

COMPARING THE IDEALIZED WORLD TO THE NATURAL WORLD

Channel (solid) and square (dash) domain



Nauru Sondes

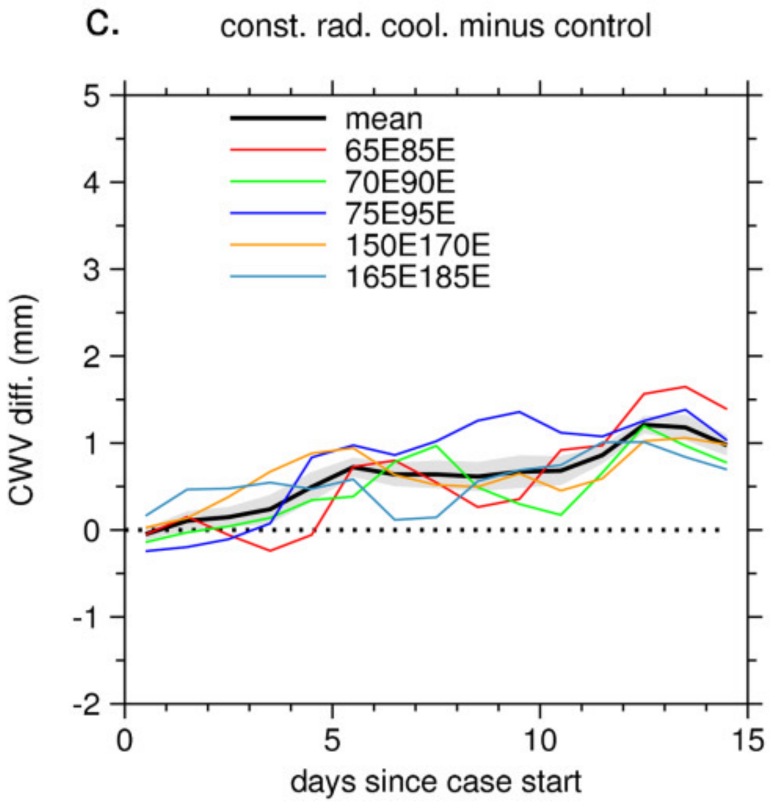


- An idealized simulation with elongated channel geometry (similar to RCEMIP I setup) has a more realistic representation of atmospheric humidity than a simulation with a square domain, which has too broad a distribution of humidity and is too dry in the driest regions when compared with radiosonde records from Nauru.

Holloway et al. 2017, *Surveys in Geophysics*

COMPARING THE IDEALIZED WORLD TO THE NATURAL WORLD

suppressed radiation feedbacks in realistic CRM runs



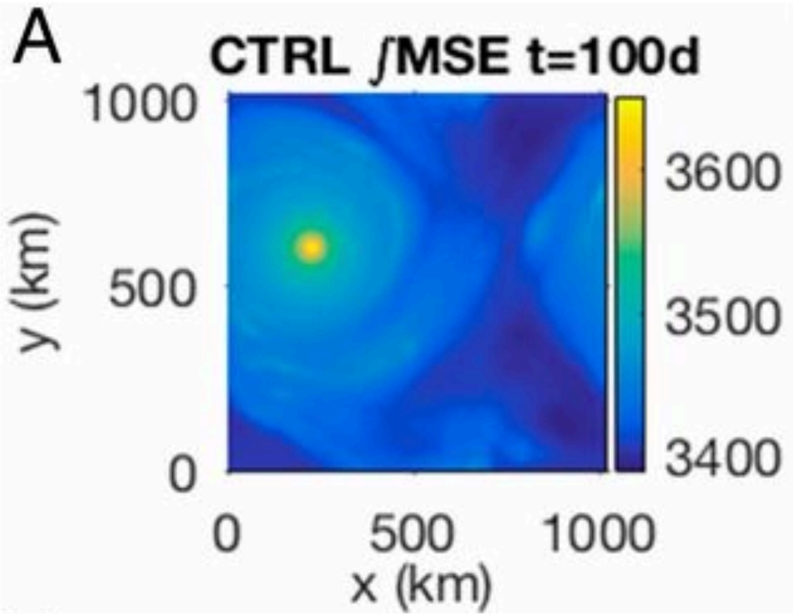
Holloway 2017, *JAMES*

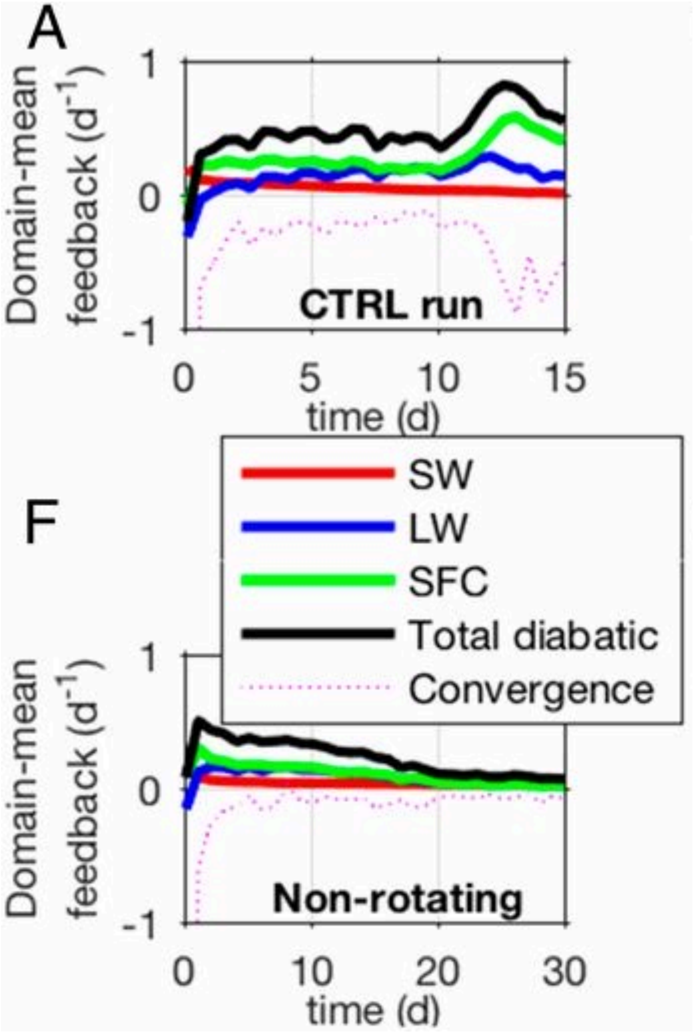
At Equilibrium:

- rate of moistening by suppressed radiation feedbacks = rate of drying by advection
- 20° X 20° box, lower tropospheric wind ~ 5 m s^{-1} ⇒ 5 days to replace air in domain
- drying rate by advection (at equilibrium 1 mm diff.) ~ 1 mm / 5 days = **0.2 mm day^{-1} = r_{norad}**

This is a similar order of magnitude to the 0.5 mm/day moistening when an idealised run is initialized with an idealised state but interactive radiation is suppressed.

ROTATING SELF-AGGREGATION (SPONTANEOUS TC GENESIS)





Muller and Romps 2018, *PNAS*

- No need for pre-existing cyclonic disturbance – aggregation-like process can lead to growth of clusters that have cyclonic vorticity (e.g. Bretherton et al. 2005 *JAS*, Nolan et al. 2007 *QJRMS*, Wing et al. 2016 *JAS*, Muller and Romps 2018 *PNAS*)
- Radiative feedbacks important, especially at early times
- Surface flux feedbacks important, especially at later times