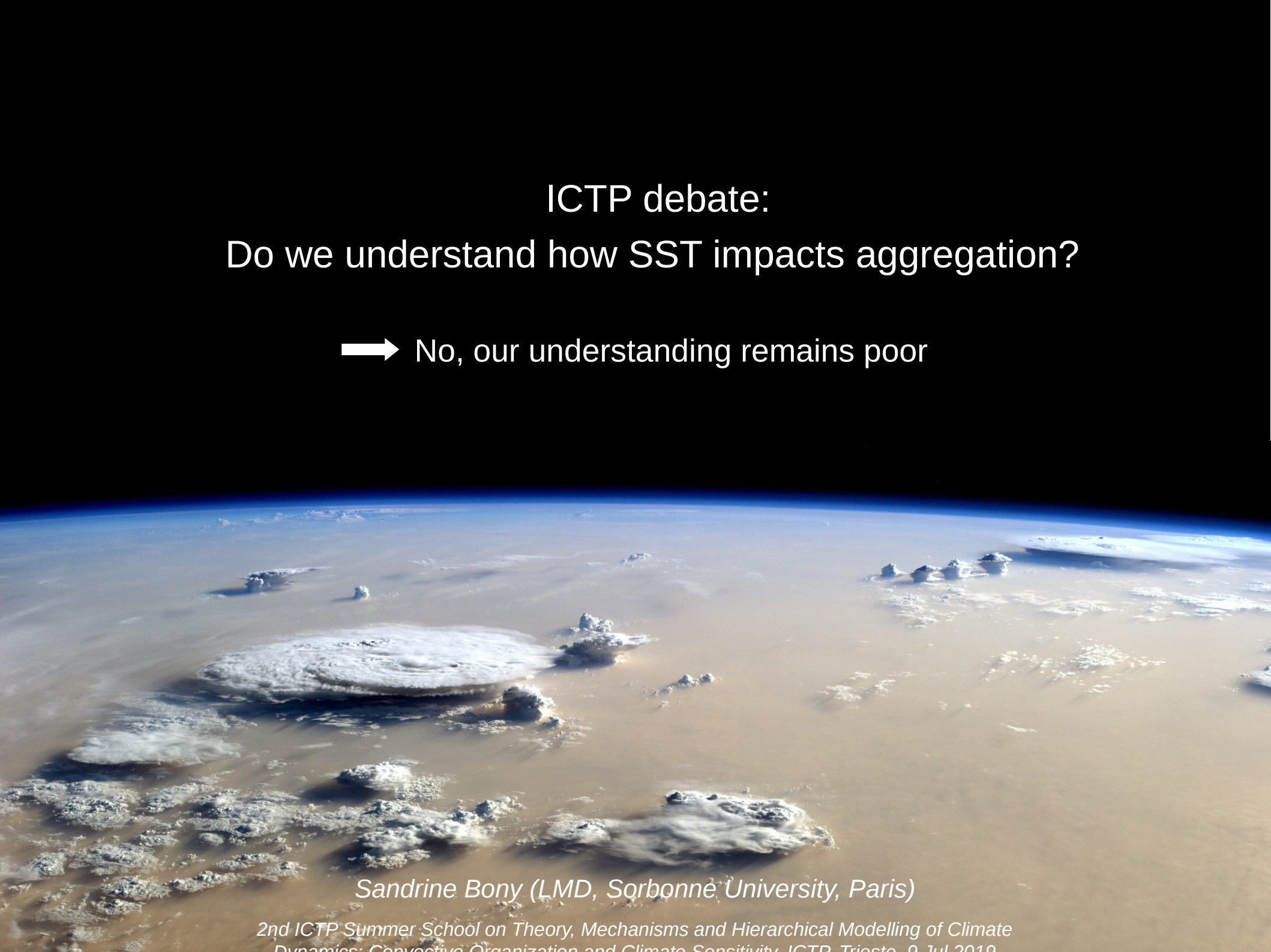
ICTP debate:
Do we understand how SST impacts aggregation?

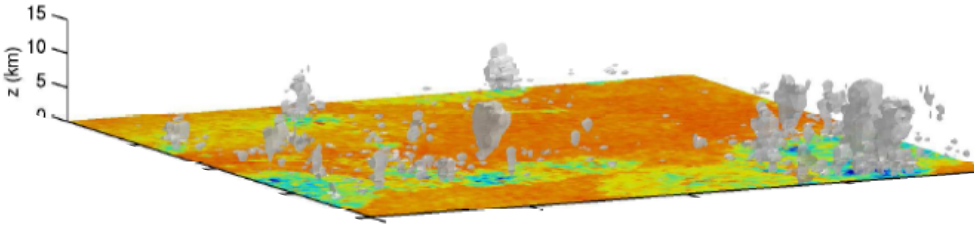
➞ No, our understanding remains poor



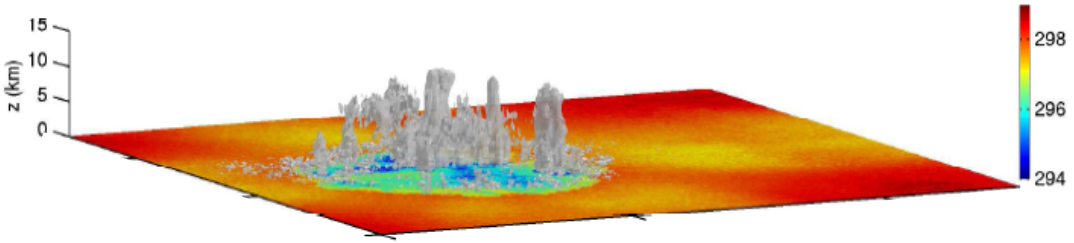
Sandrine Bony (LMD, Sorbonne University, Paris)

2nd ICTP Summer School on Theory, Mechanisms and Hierarchical Modelling of Climate Dynamics: Convective Organization and Climate Sensitivity, ICTP, Trieste, 9 Jul 2019

How does SST impact convective aggregation? Key question



low SST

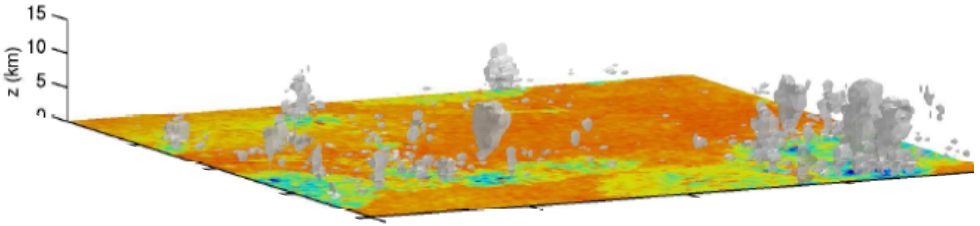


high SST

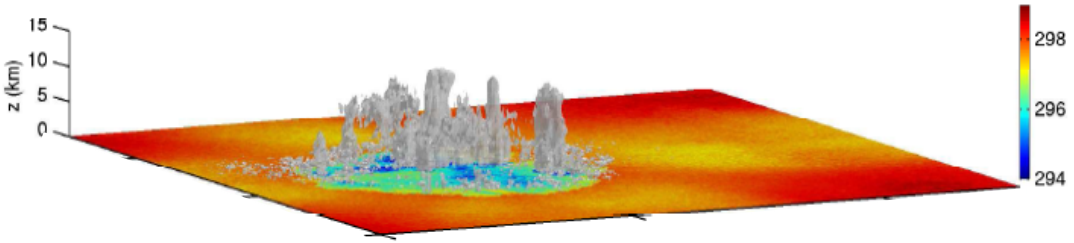
More convective aggregation at high temperatures → Atmospheric drying and enhanced OLR → Impact on Climate Sensitivity and Hydrological Sensitivity?

Khairoutdinov and Emanuel, AMS (2010); Khairoutdinov and Emanuel, JAMES (2013); Wing and Emanuel, JAMES (2014); Emanuel et al., JAMES (2014); Wing and Cronin, QJRMS (2015); Coppin and Bony, JAMES (2015); Bony et al. (2016); Mauritsen and Stevens (2015); Fig adapted from Muller and Held, J. Climate (2012)

How does SST impact convective aggregation? TWO questions



low SST



high SST

More convective aggregation at high temperatures → Atmospheric drying and enhanced OLR → Impact on Climate Sensitivity and Hydrological Sensitivity?

1. How does SST impact convective self-aggregation?

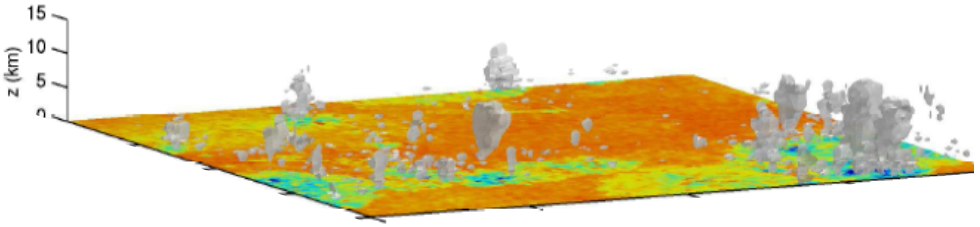
2. How does SST impact convection aggregation once it is established?

My position in this debate:

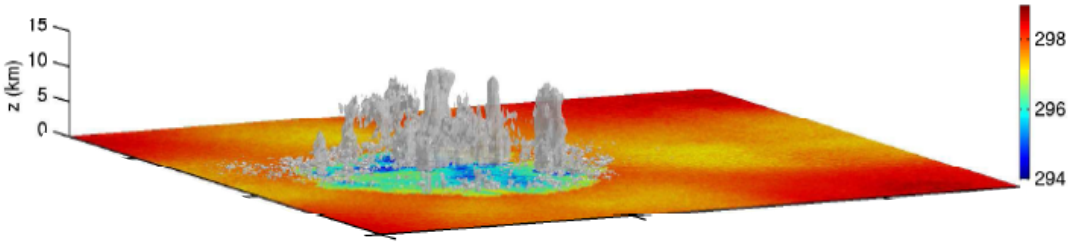
→ Our understanding of each issue is poor (inconsistent, non-robust or limited evidence

→ Highlight issues to be clarified

How does SST impact convective aggregation? TWO questions



low SST



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Our understanding of how SST impact convective self-aggregation?

⟹ **Excellent!**

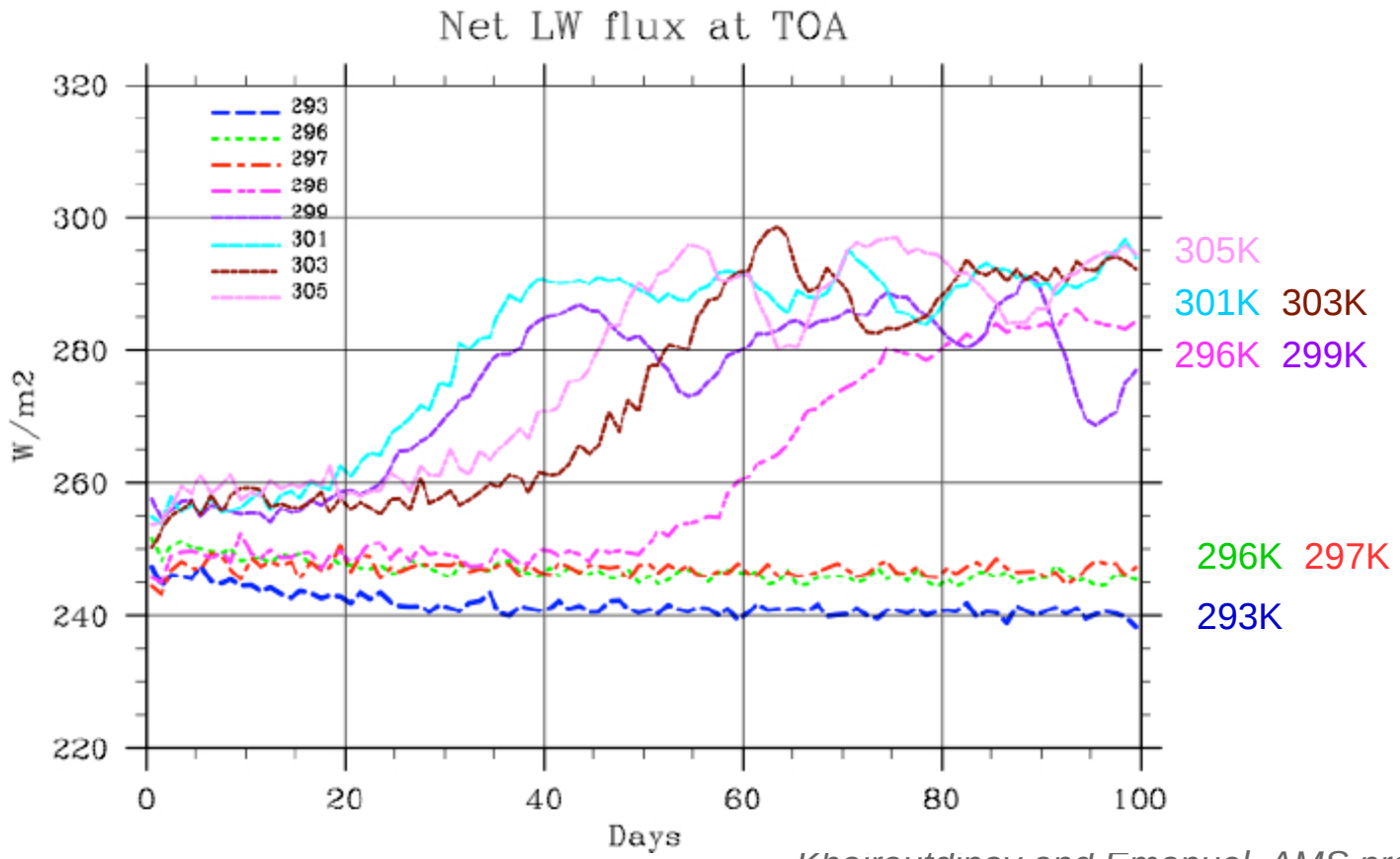
Our understanding of how SST impact convective self-aggregation?

⟹ **Excellent!….until 2014**

Our understanding of how SST impact convective self-aggregation?

➡ **Excellent!….until 2014**

1. Strong evidence that self-aggregation depends on SST



Khairoutdinov and Emanuel, AMS proceedings (2010)

Our understanding of how SST impact convective self-aggregation?

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2. Self-aggregation results from an instability of RCE

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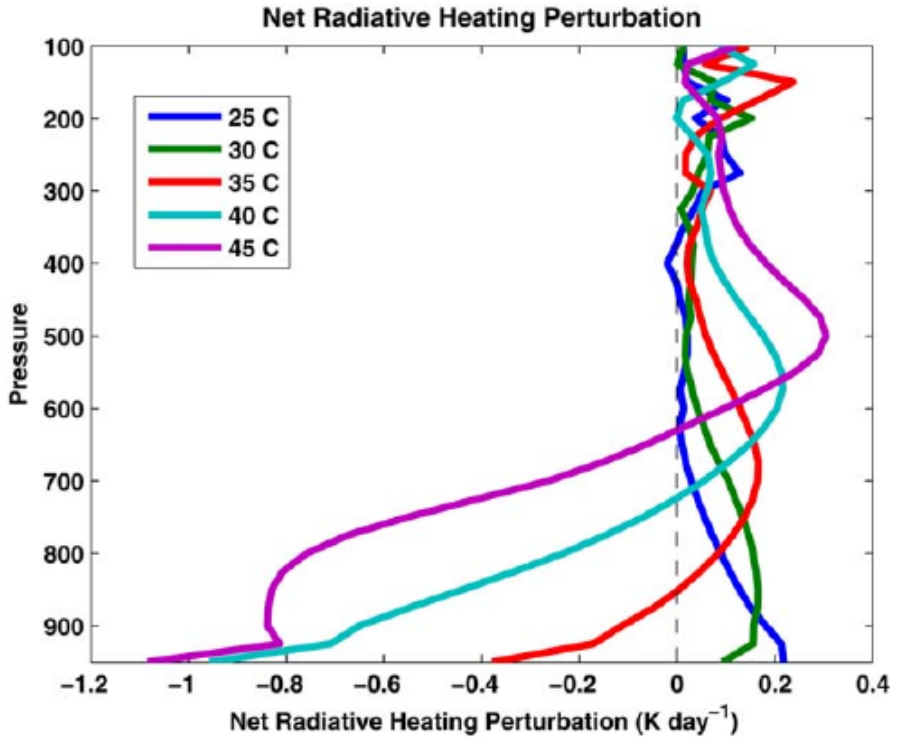
3. The mechanism of instability manifests itself above a critical SST value close to 300-303K



Perturbation net radiative heating rates in response to an instantaneous reduction of specific humidity of 20% from the RCE states for SSTs ranging from 25 to 45°C

Above a critical SST, the clear-sky IR opacity of the lower troposphere becomes so large that the radiative cooling of the lower-troposphere is governed principally by upper tropospheric water vapor
→ RCE becomes unstable to large-scale overturning circulations; Critical SST: 303K or more?

Emanuel et al., JAMES (2014)

Our understanding of how SST impact convective self-aggregation?

➟ **Excellent!….until 2014**

1. Strong evidence that self-aggregation depends on SST
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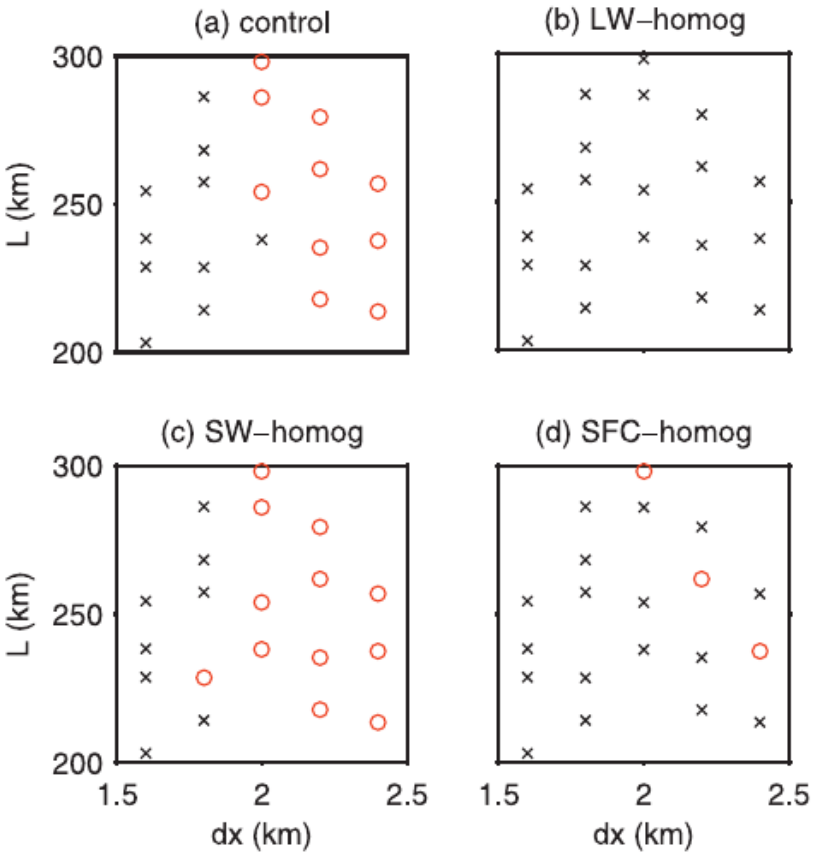
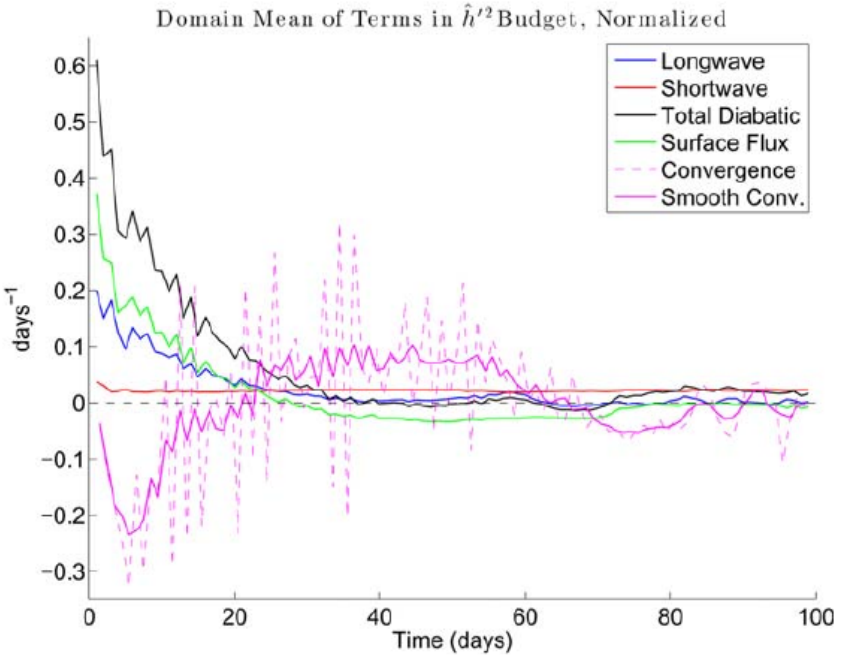


Muller and Held, JAS (2012)

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



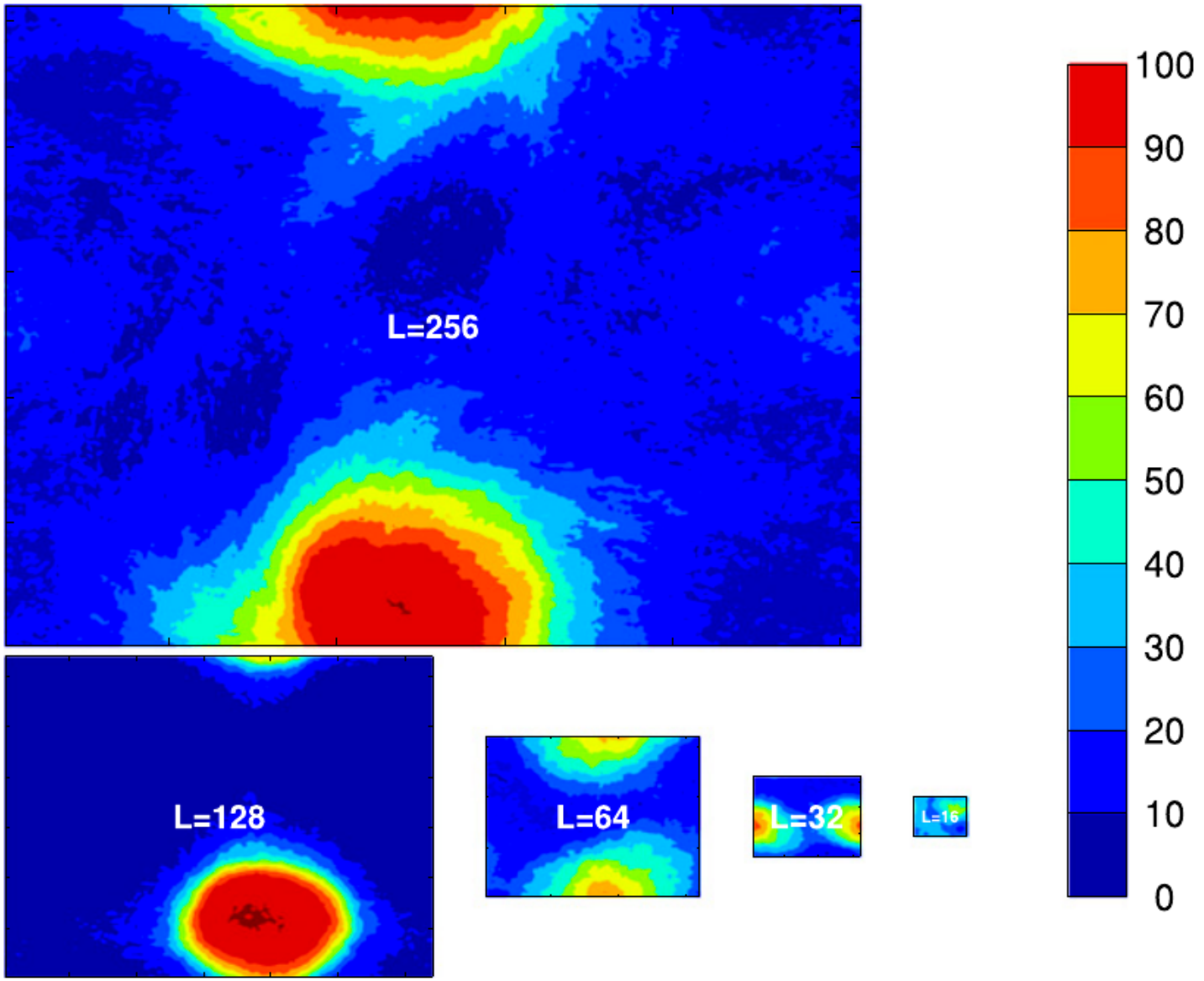
Wing and Emanuel, JAMES (2014)

Our understanding of how SST impact convective self-aggregation?

- **But then, things started to deteriorate**

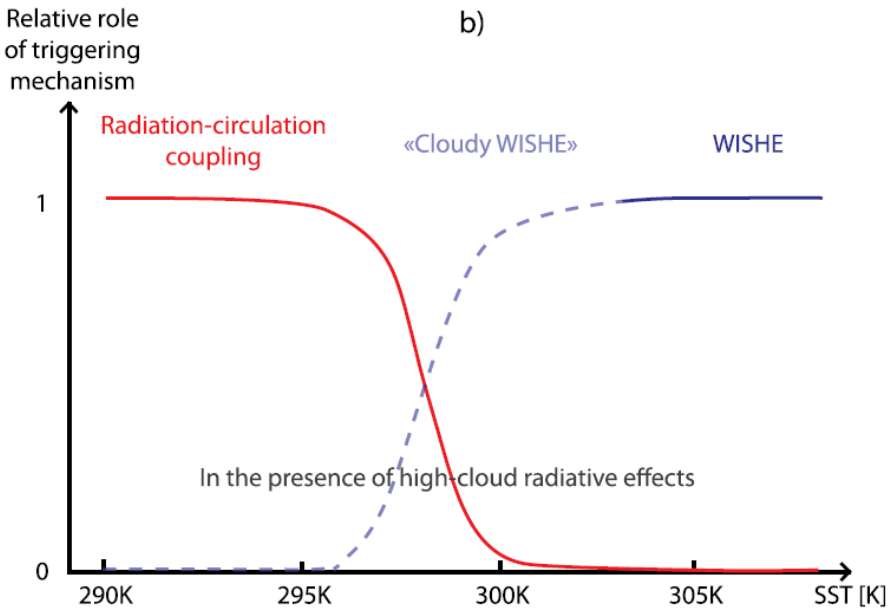
However….

Snowball simulations with a CRM (around 250 K)



Abbot., J. Climate (2014)

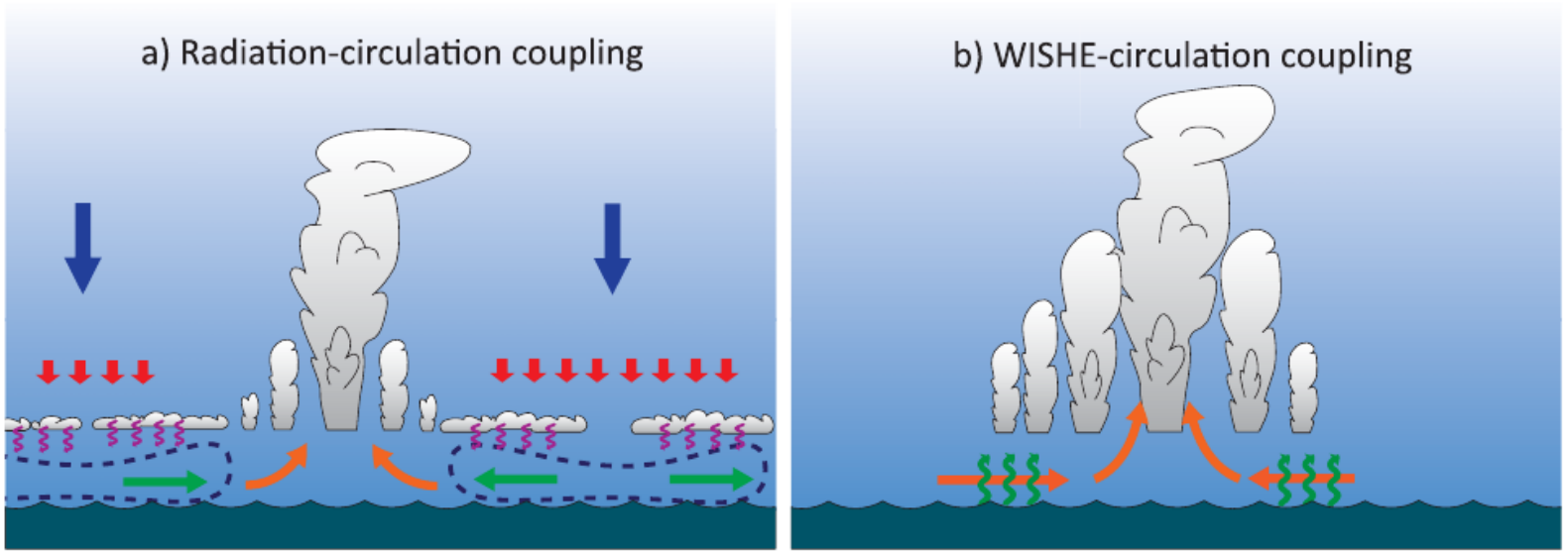
Mechanism of RCE instability?



At low T: is the instability related to a radiative feedback between low-clouds and circulation?

Yes: Muller and Bony (2015), Coppin and Bony (2015), Holloway and Woolnough (2016), Wing and Cronin (2016)

No: Becker et al. (2017)
[WISHE at low T, entrainment efficiency at high T]



Coppin and Bony, JAMES (2015)

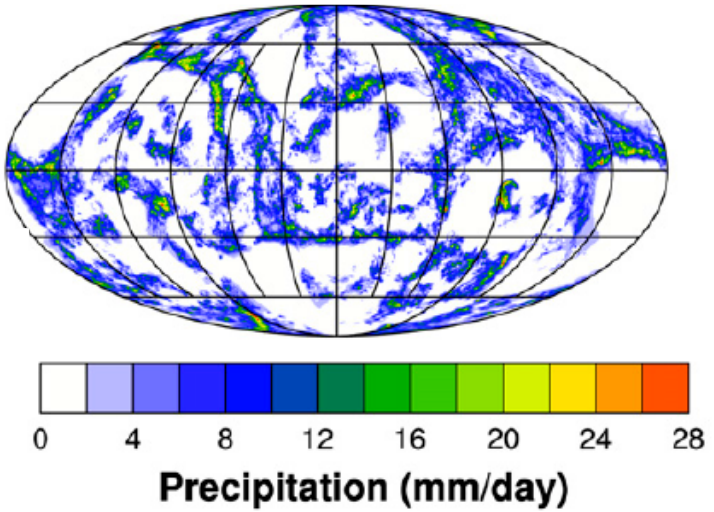
Role of ocean-atmosphere coupling?

- OA coupling delays convective self-aggregation
  (Hohenegger and Stevens 2016; Coppin and Bony 2017)
- Could also affect the critical SST above which convective aggregation arises
  (Reed et al. 2015)

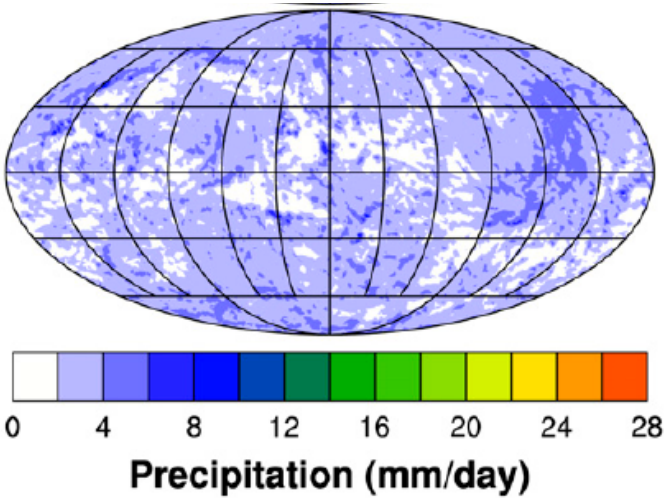
For a given global-mean SST, interactive SSTs permit self-aggregation at lower SSTs:

same global-mean SST (295 K)

Interactive SSTs



Prescribed & uniform SST



Reed et al., JAS (2015)

Recap (1): How does SST impact convective self-aggregation?

Our understanding of the SST impact on self-aggregation was good….until 2014:

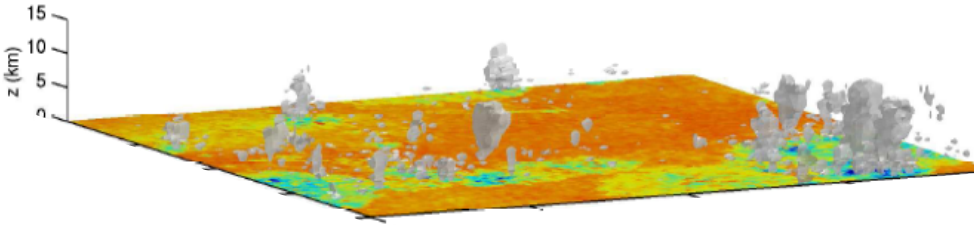
1. Strong evidence that self-aggregation depends on SST
2. Self-aggregation results from an instability of RCE
3. The mechanism of instability manifests itself above a critical SST value close to 300-303K
4. The instability mechanism is dominated by radiative processes and sfc flux feedback

Poorly understood issues:

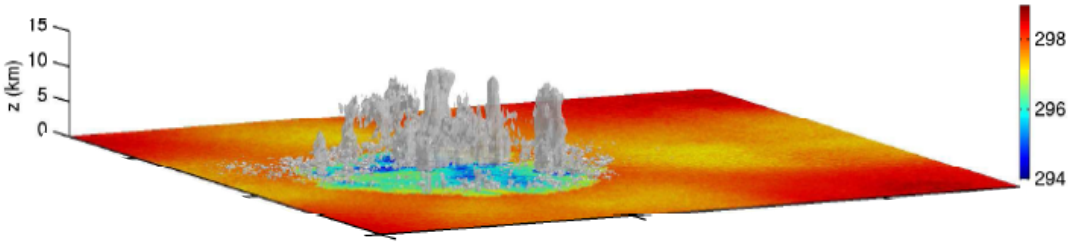
- The existence of a critical SST above which instability occurs is not so clear
  - → self-aggregation can occur at very low SSTs
  - → no absolute threshold (depends on model physics, OA coupling, etc)

- Instability mechanism:
  - → at low T: clear-sky radiative feedbacks might not be sufficient
    cloud-radiative feedbacks and/or WISHE can be more powerful
  - → what determines the relative dependence of radiative/WISHE mechanisms on T?

How does SST impact convective aggregation? TWO questions



low SST



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More convective aggregation at high temperatures → Atmospheric drying and enhanced OLR → Impact on Climate Sensitivity and Hydrological Sensitivity?

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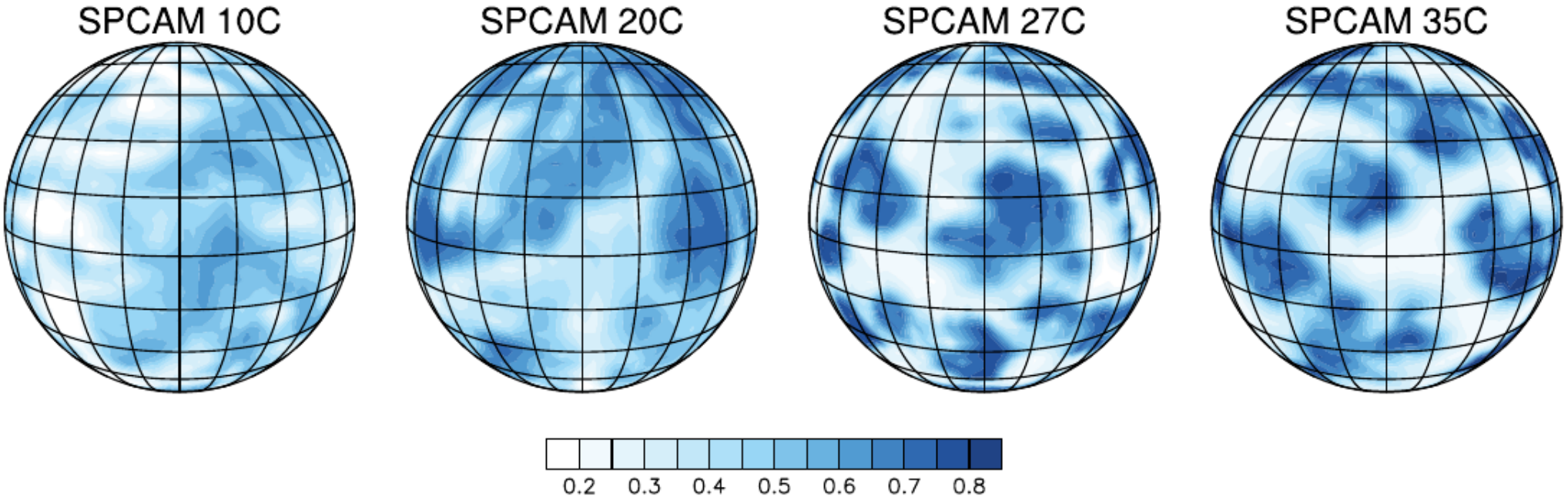
How does SST impact convective aggregation at equilibrium?

Super-parameterized GCM: aggregation becomes stronger at higher SSTs

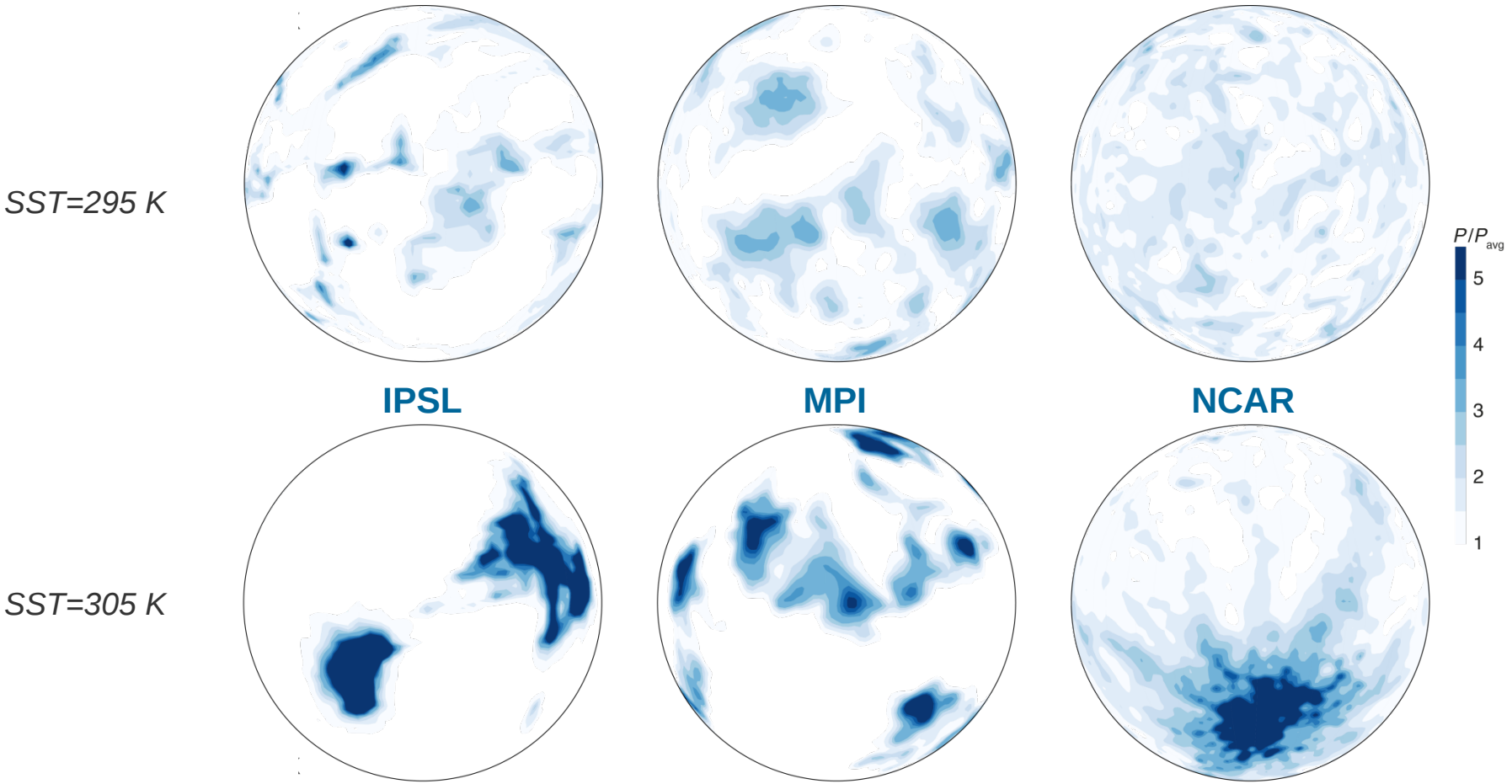


Column saturation fraction at day 120

Arnold and Randall, JAMES (2015)

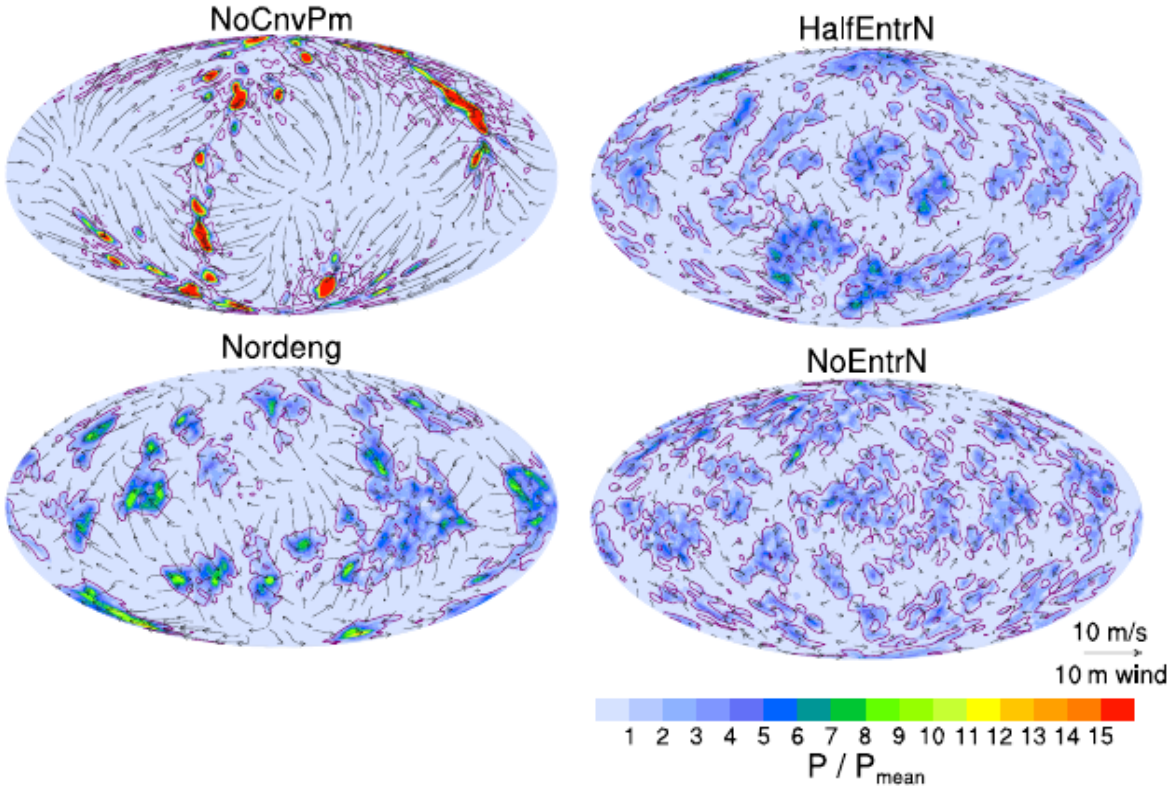
How does SST impact convective aggregation at equilibrium?

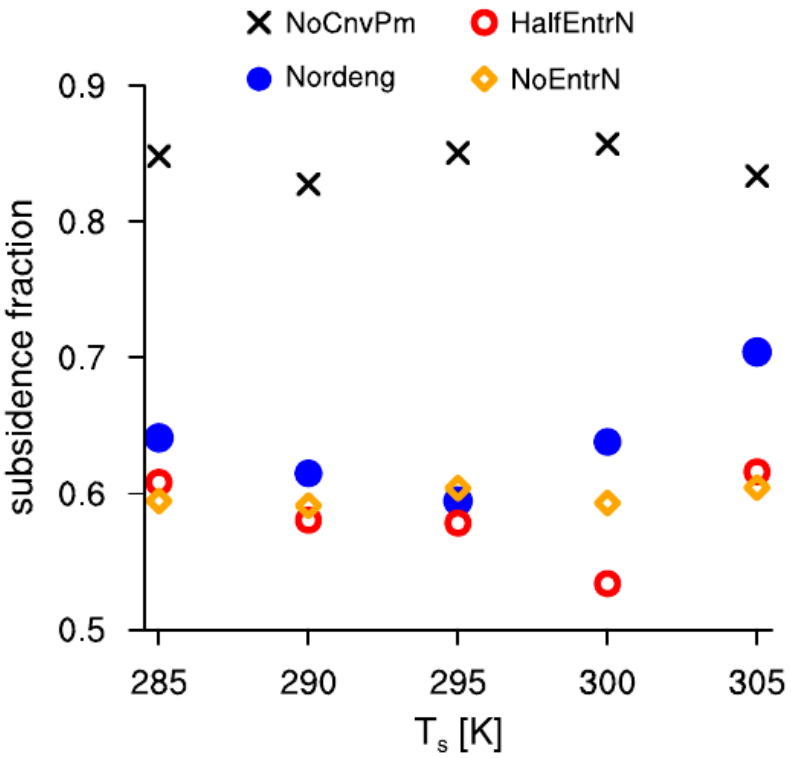
GCMs: some evidence that aggregation becomes stronger at higher SSTs



Bony et al., PNAS (2016)

But: in GCMs, aggregation depends on cumulus parameterization



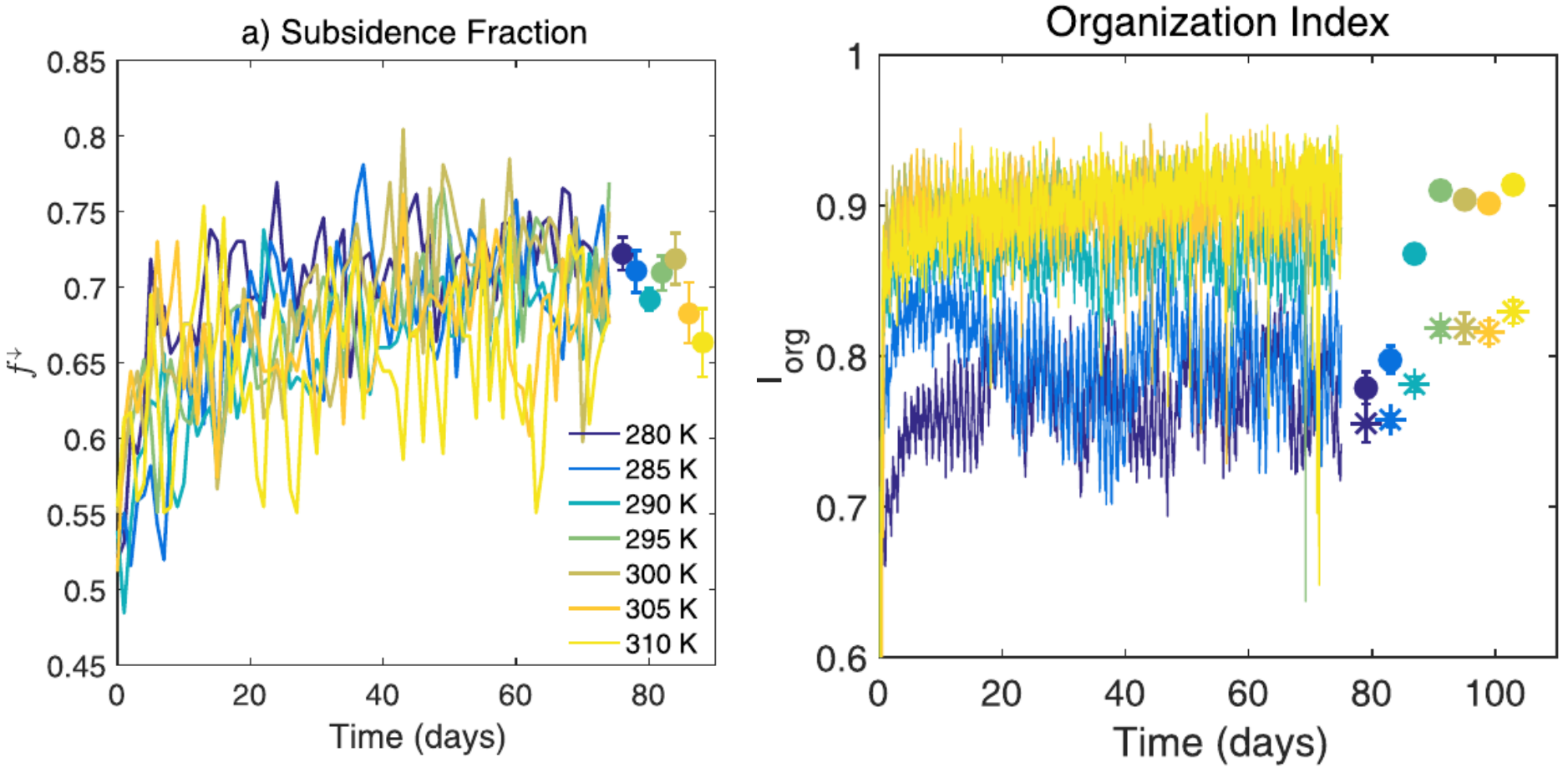


...and the dependence of aggregation on SST too

What about CRMs?

Becker et al., JAMES (2016)

How does SST impact convective aggregation at equilibrium?



In CRMs (here: long channel simulations): the impact of rising SST

- is not monotonic
- depends on the range of SST considered
- depends on the aggregation metrics considered

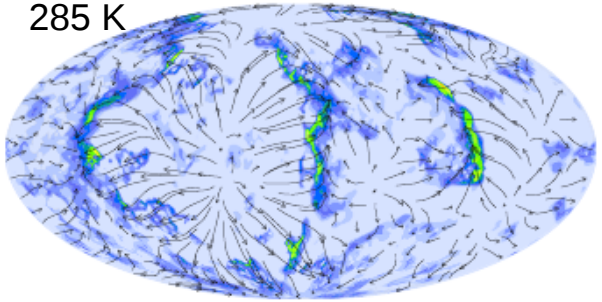
→ Does it mean that certain scales of organization are more sensitive to SST than others?

Cronin and Wing, JAMES (2017)

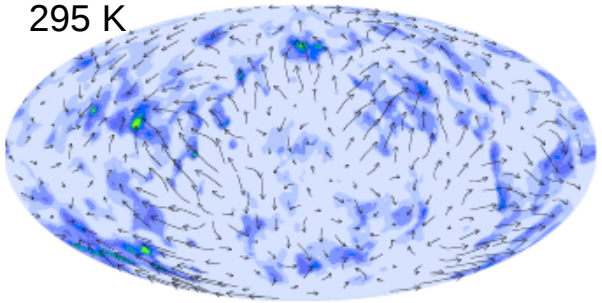
Dependence of the organization scale on SST

ECHAM 6 GCM

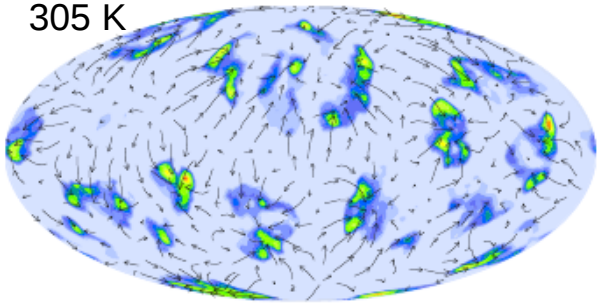
285 K



295 K

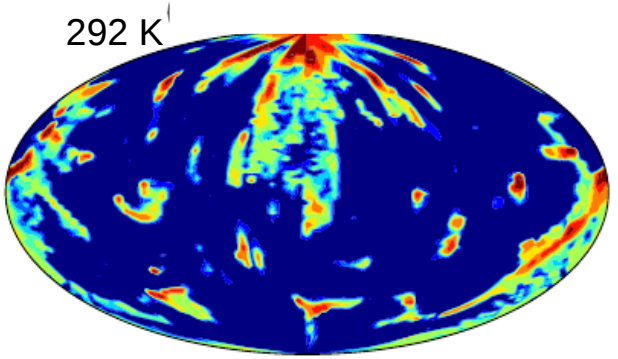


305 K

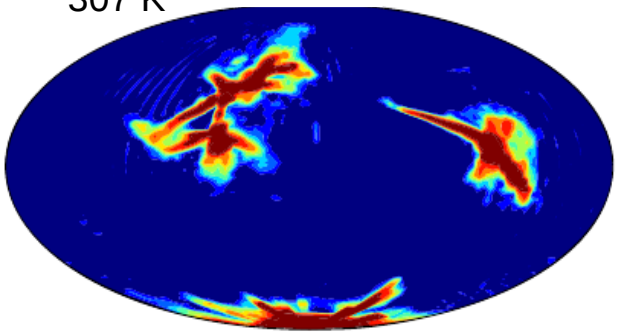


IPSL-CM5A GCM

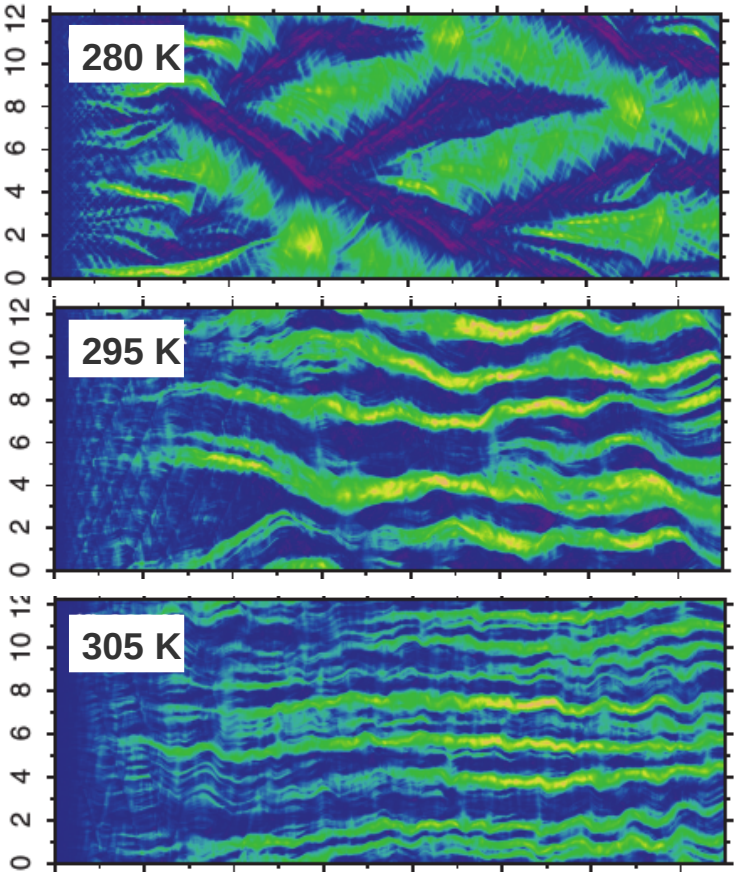
292 K



307 K



SAM CRM (long channel)



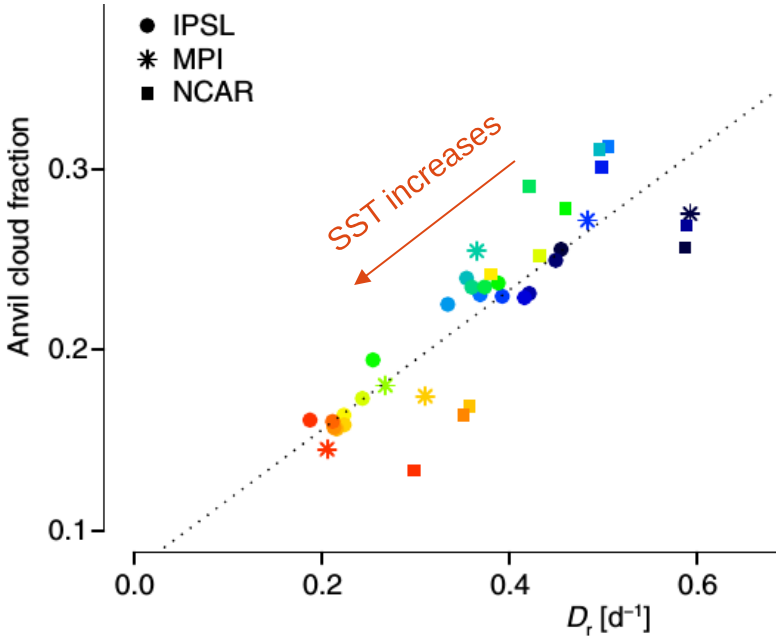
- Arcs at low SSTs vs blubs at high SSTs?
- Length-scale of aggregation?

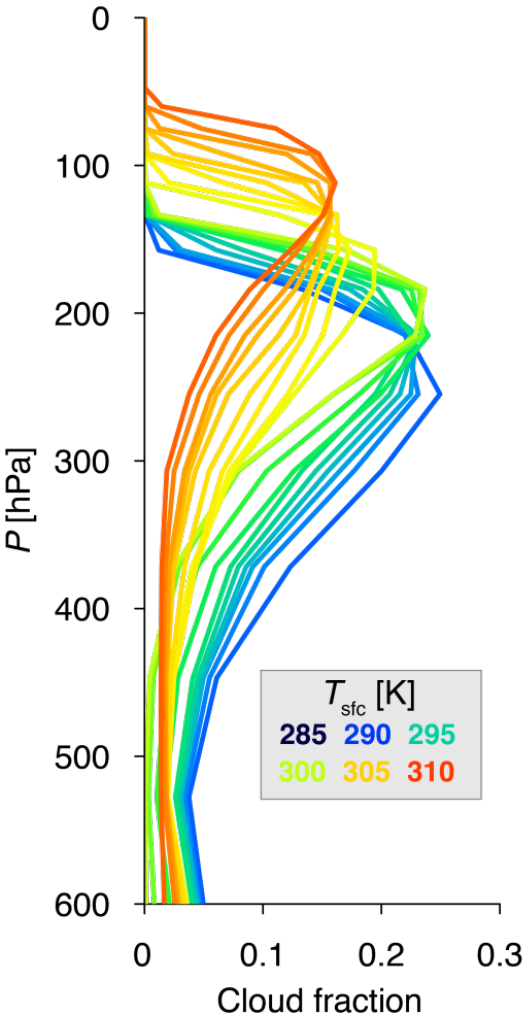
Becker et al., JAMES (2016); Coppin and Bony, JAMES (2015); Wing and Cronin, QJRMS (2016)

How to explain the dependence of mean aggregation on T?

(1) stability-Iris effect + radiative-circulation coupling ?

A thermodynamic mechanism (independent of aggregation) predicts a shrinking of the anvil cloud coverage as SST rises:





In a warmer climate, the anvil-clouds rise and remain at nearly the same temperature, but find themselves at a lower pressure and thus in a more stable atmosphere.

It reduces the convective outflow (less mass divergence required to balance the vertical gradient in radiative cooling), leading to less anvil clouds: a stability iris effect.

Bony et al., PNAS (2016)

How to explain the dependence of mean aggregation on T?

Hypothesis verified?

Stability-Iris verified by observations and at work in several GCMs and CRMs,
but not in all CRMs (e.g. Ohno and Satoh 2018).

Is the stability-Iris sufficient to influence the dependence of convective aggregation on T?

→ could maybe explain the increase of aggregation at high T, but not at low T

→ does not predict the minimum size occupied by convective areas at very high T

→ does the spread of dA/dT depends on the existence (or not) of a stability IRIS?

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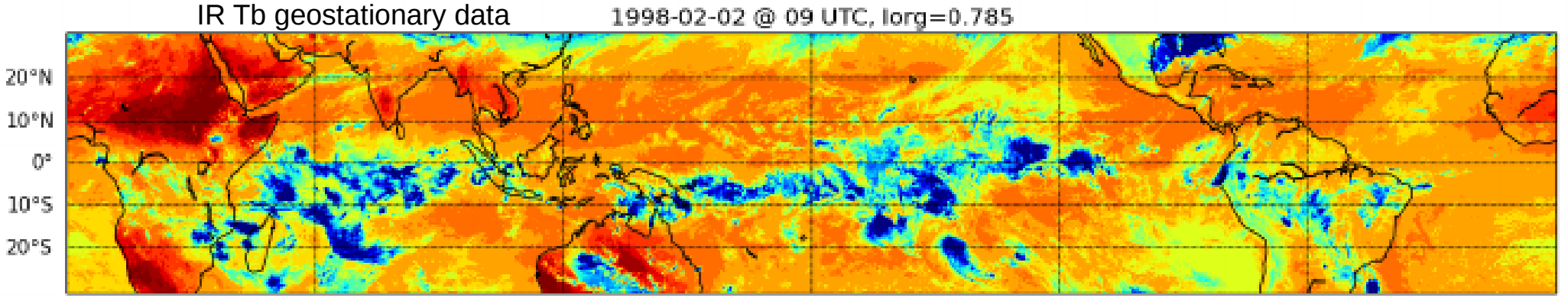
Other explanations ?

* Cronin and Wing (2017): the difference in clear-sky OLR between a moist and dry atmosphere increasingly diverges with warming

→ so robust that aggregation should increase with T in all models!...which is not the case

What do observations tell us?



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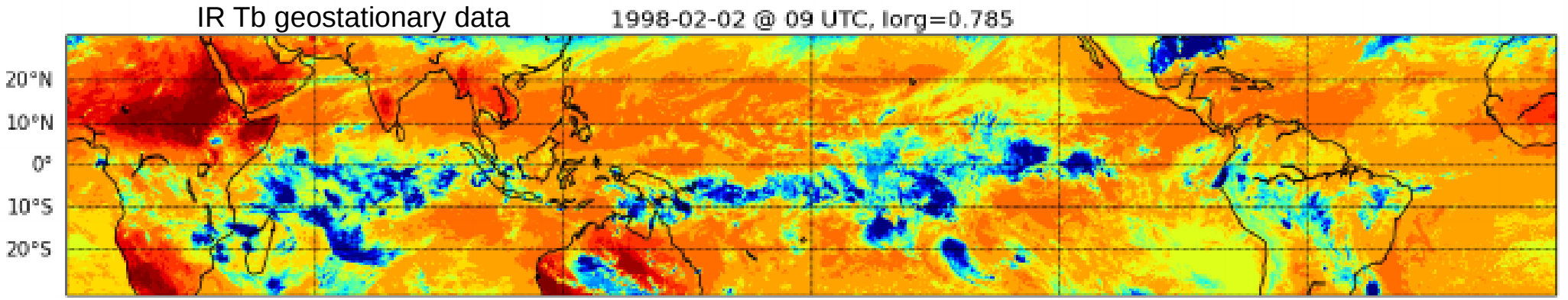
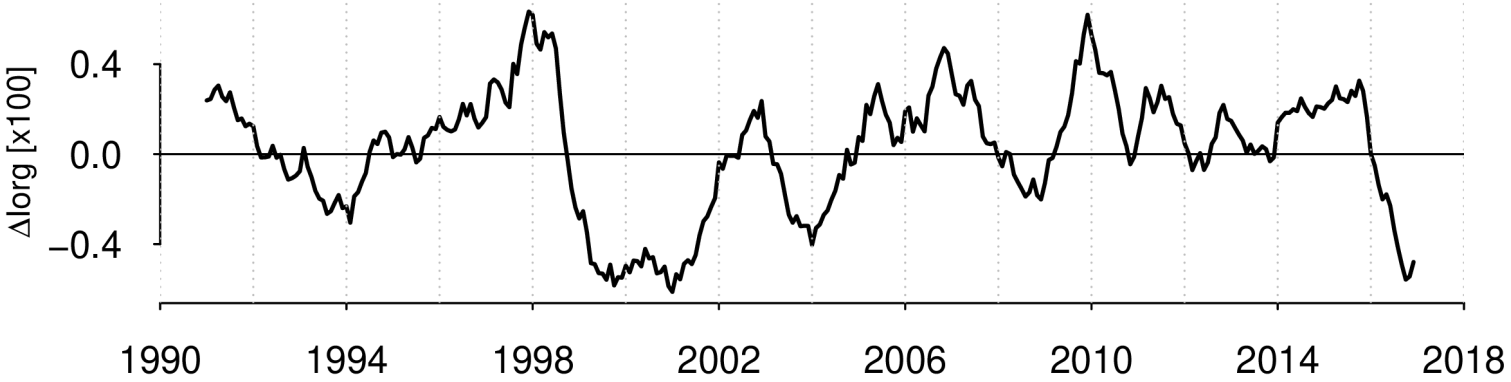


interannual variations of convective organization index:



Bony, Semie, Kramer, Soden, Tompkins and Emanuel (submitted)

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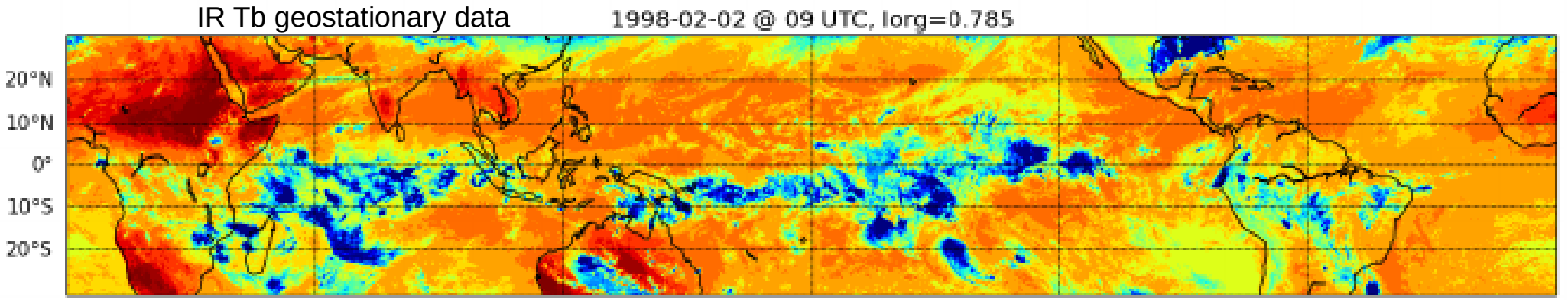

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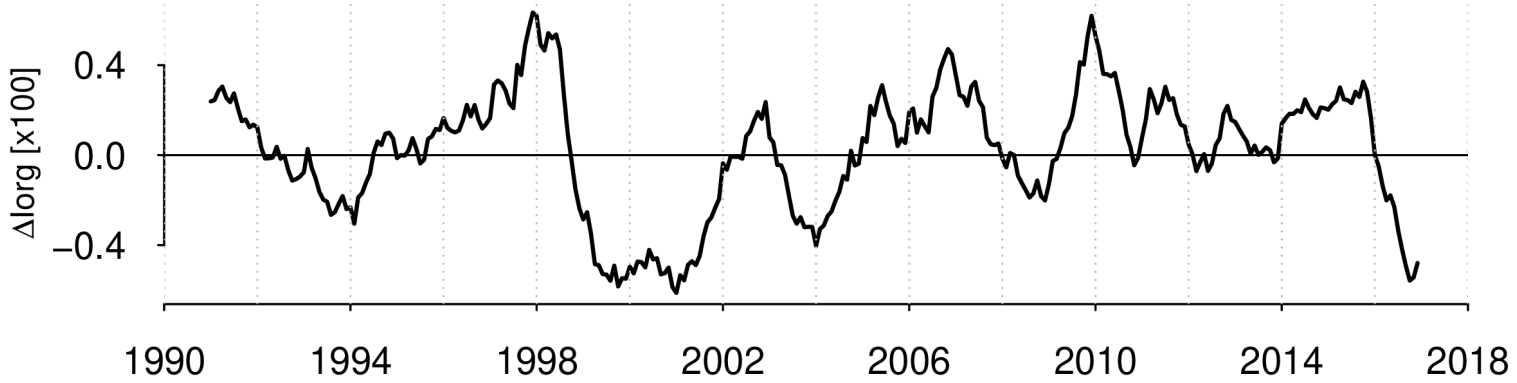

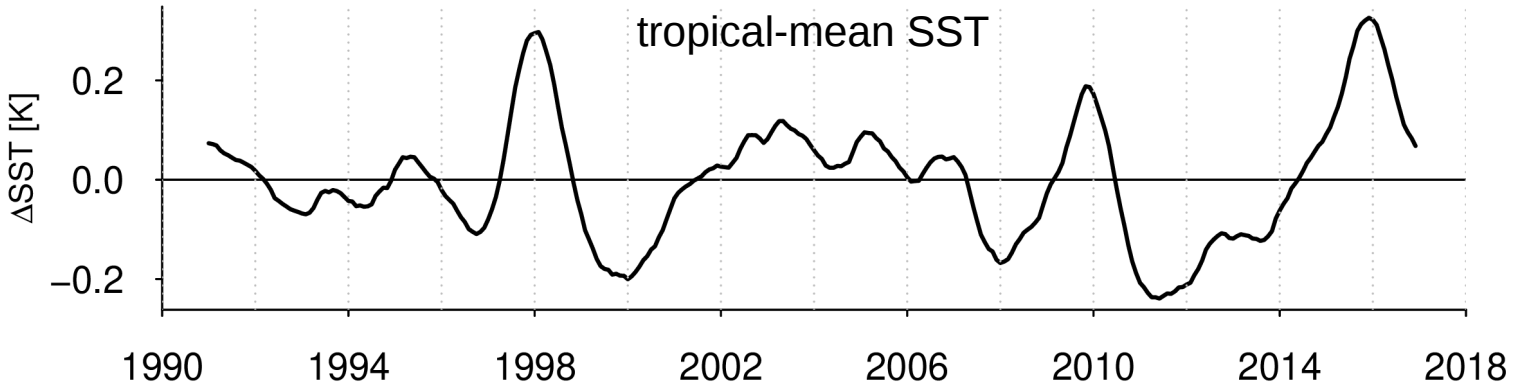

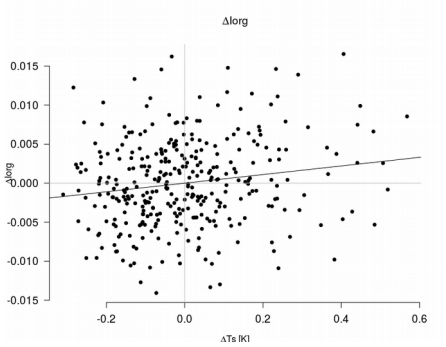

Bony, Semie, Kramer, Soden, Tompkins and Emanuel (submitted)

Does it mean that long-term changes in SST will not impact aggregation?

Not necessarily

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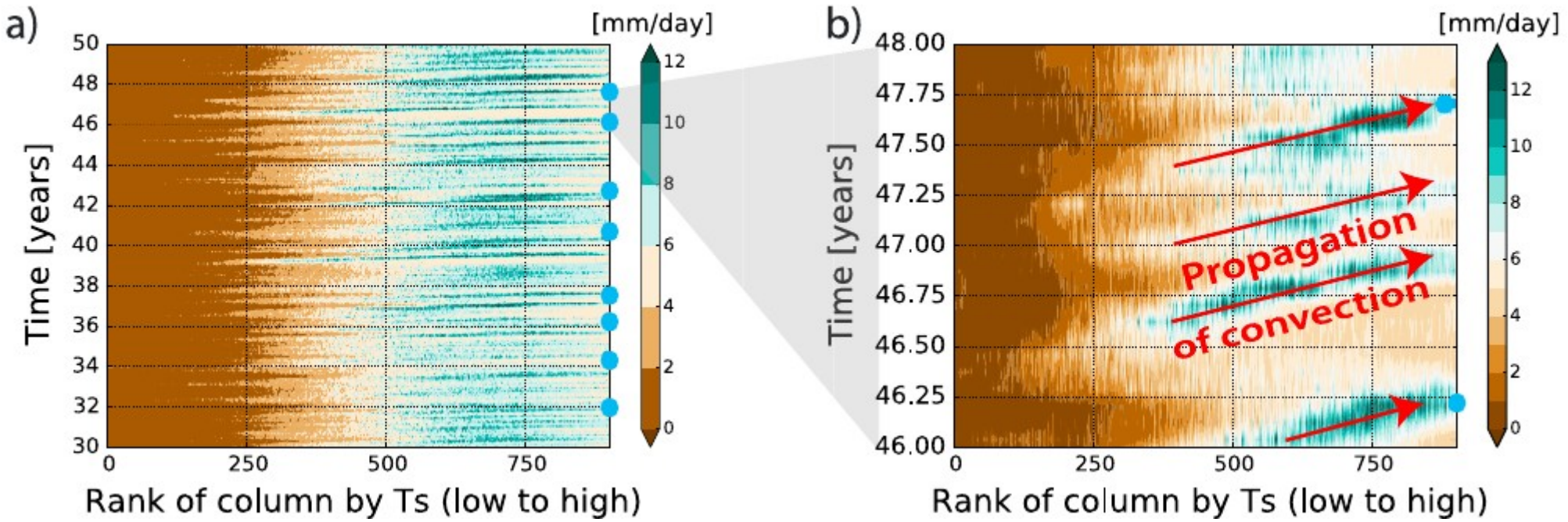
RCE simulations with interactive SSTs (GCM coupled to a slab ocean):

Strong interplay between SST gradients and convective aggregation



Coppin and Bony, GRL (2017)

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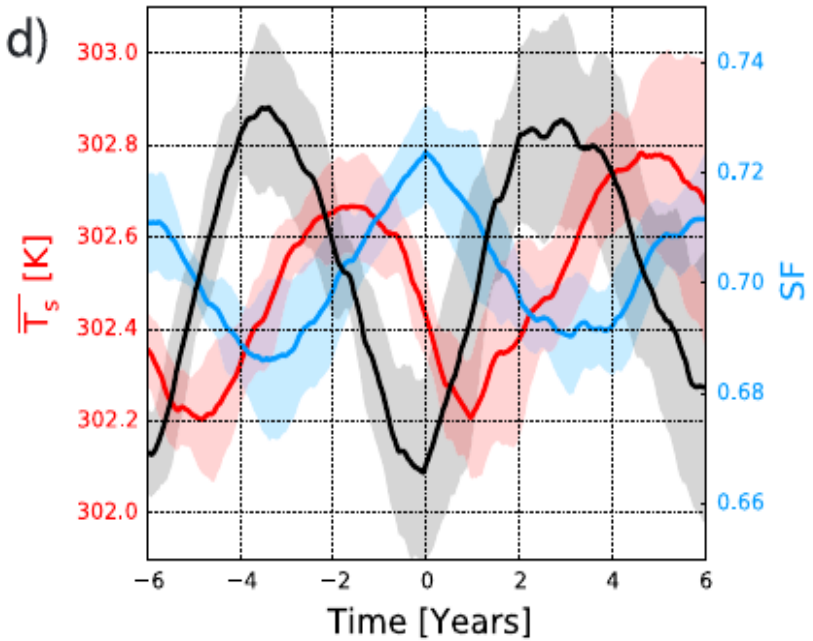
Convective aggregation
Global-mean surface temperature

Internal interannual variability



Coppin and Bony, GRL (2017) & JAMES (2018)

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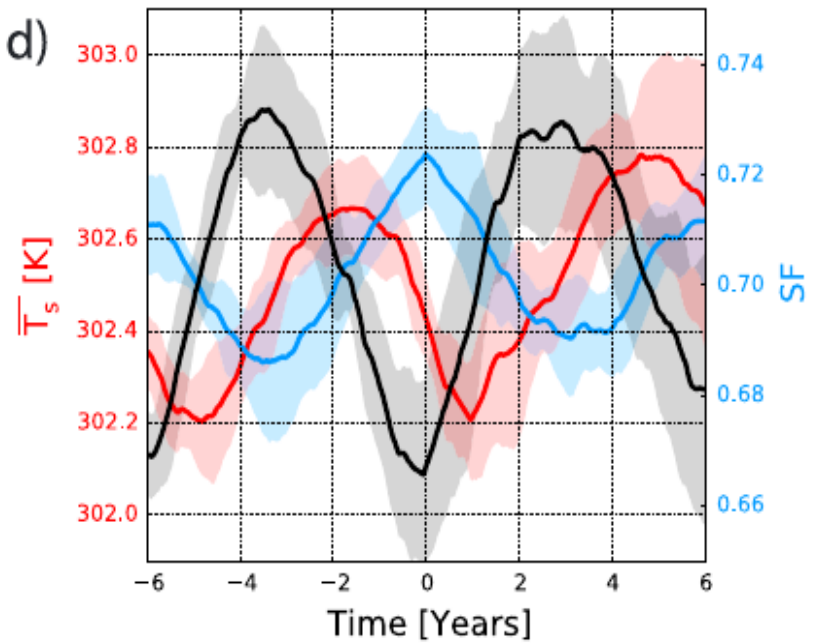
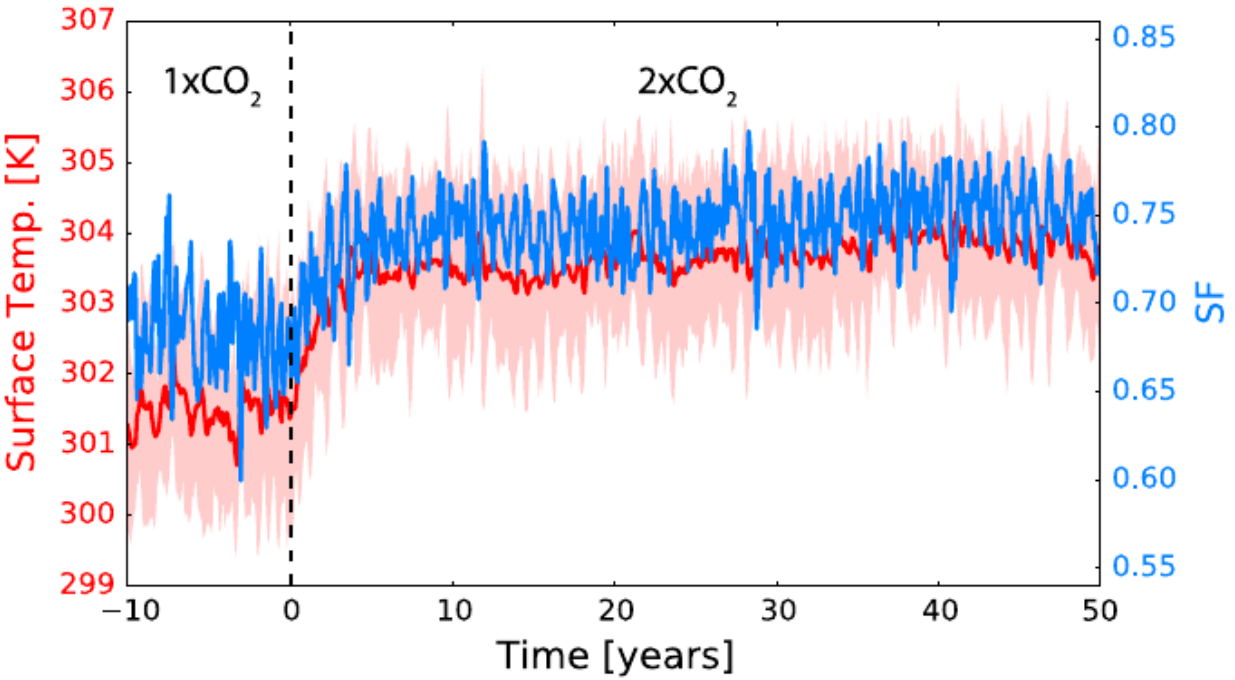


Abrupt CO2 doubling experiment



Coppin and Bony, GRL (2017) & JAMES (2018)

Recap (2):
How does SST impact equilibrium convective aggregation?

- The dependence of convective aggregation on SST is not robust across models
  - → GCMs: not monotonic, sensitivity to model physics, OA coupling, etc
  - → CRMs: not monotonic, depends on metrics and range of SST

- Observations are not more conclusive so far

- The physical mechanism underlying the dependence of aggregation on SST remains to be elucidated:
  - → role of the stability Iris remains to be demonstrated
  - → robust mechanisms are unlikely given the non-robustness of the model results

- Mean SST might not be the most relevant quantity

How does SST impact convective self-aggregation?

(1) How does SST impact convective self-aggregation?

- The existence of a critical SST above which instability occurs is not clear
  - → self-aggregation can occur at very low SSTs
  - → no absolute threshold (depends on model physics, OA coupling, etc)

- Instability mechanism:
  - → at low T: clear-sky radiative feedbacks might not be sufficient
    cloud-radiative feedbacks and/or WISHE can be more powerful
  - → what determines the relative dependence of radiative/WISHE mechanisms on T?

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The impact of SST on convective aggregation is far from being understood!

Tim: do you agree?