Thermodynamic Control of Anvil Cloud Amount

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Thanks to

Tim Cronin (MIT) & **Allison Wing** (Columbia)

International Space Station, NASA, http://eol.jsc.nasa.gov

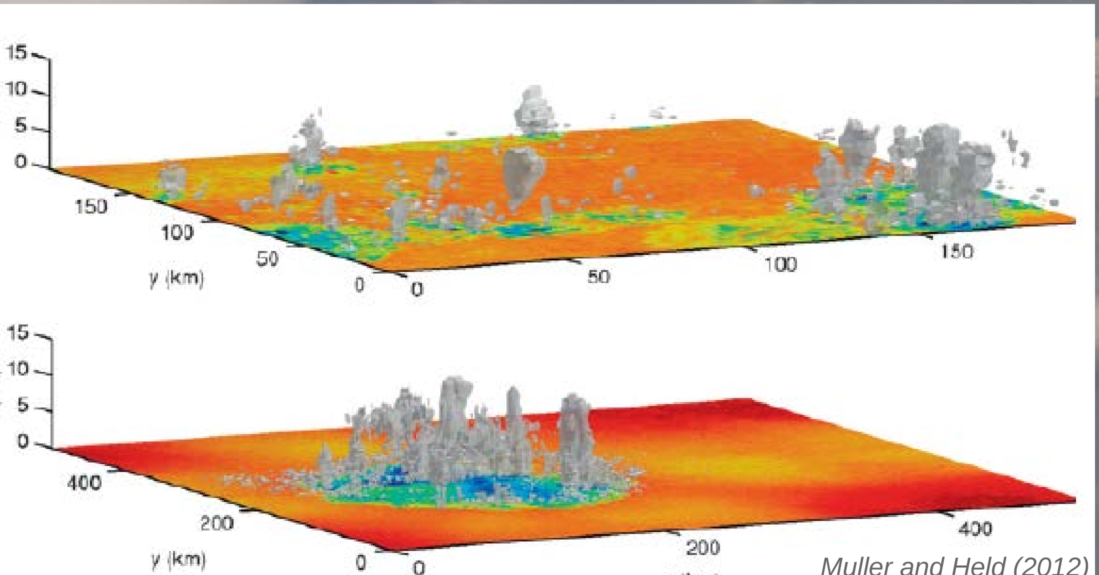
Model Hierarchy Workshop,Princeton Univ, 2-4 Nov 2016

Controls of the anvil cloud amount

- Surface temperature?

International Space Station, NASA, http://eol.jsc.nasa.gov

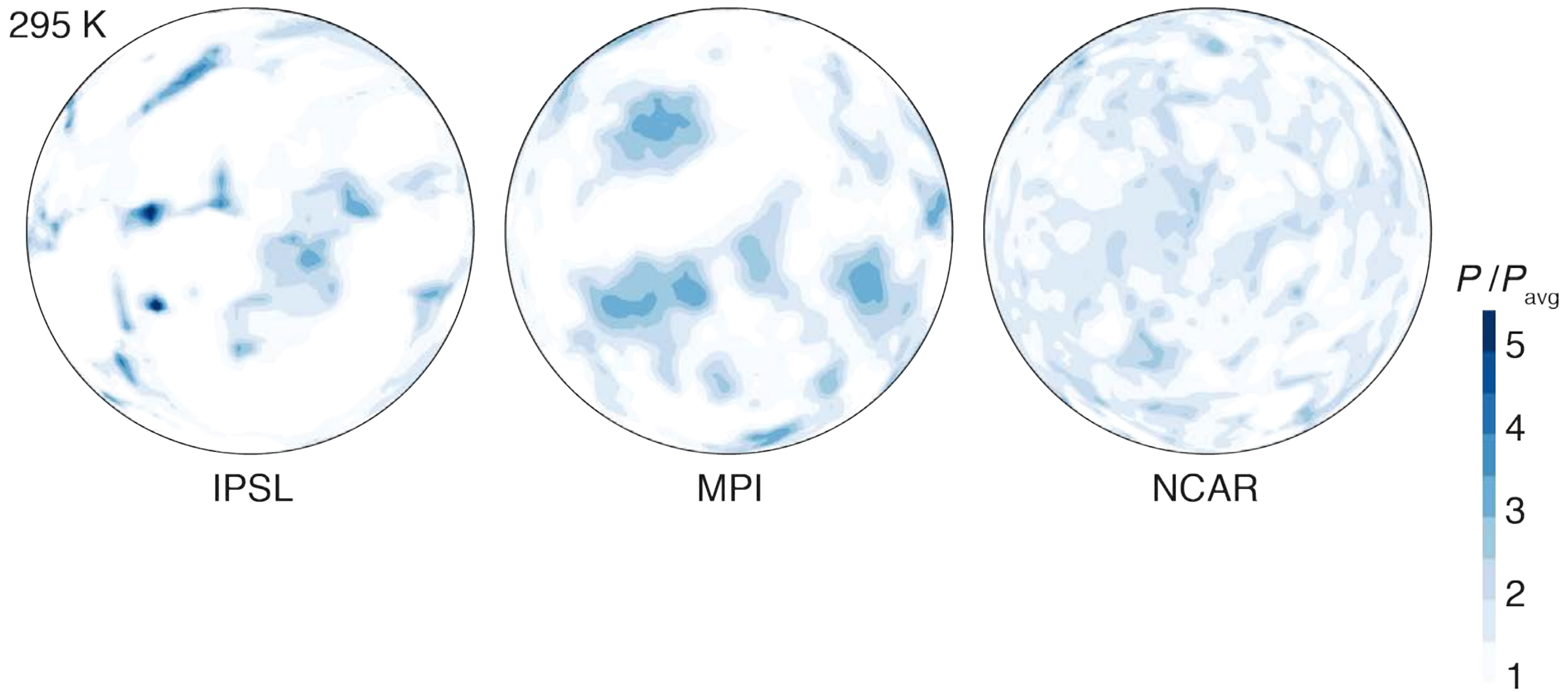
Controls of the anvil cloud amount



Muller and Held (2012)

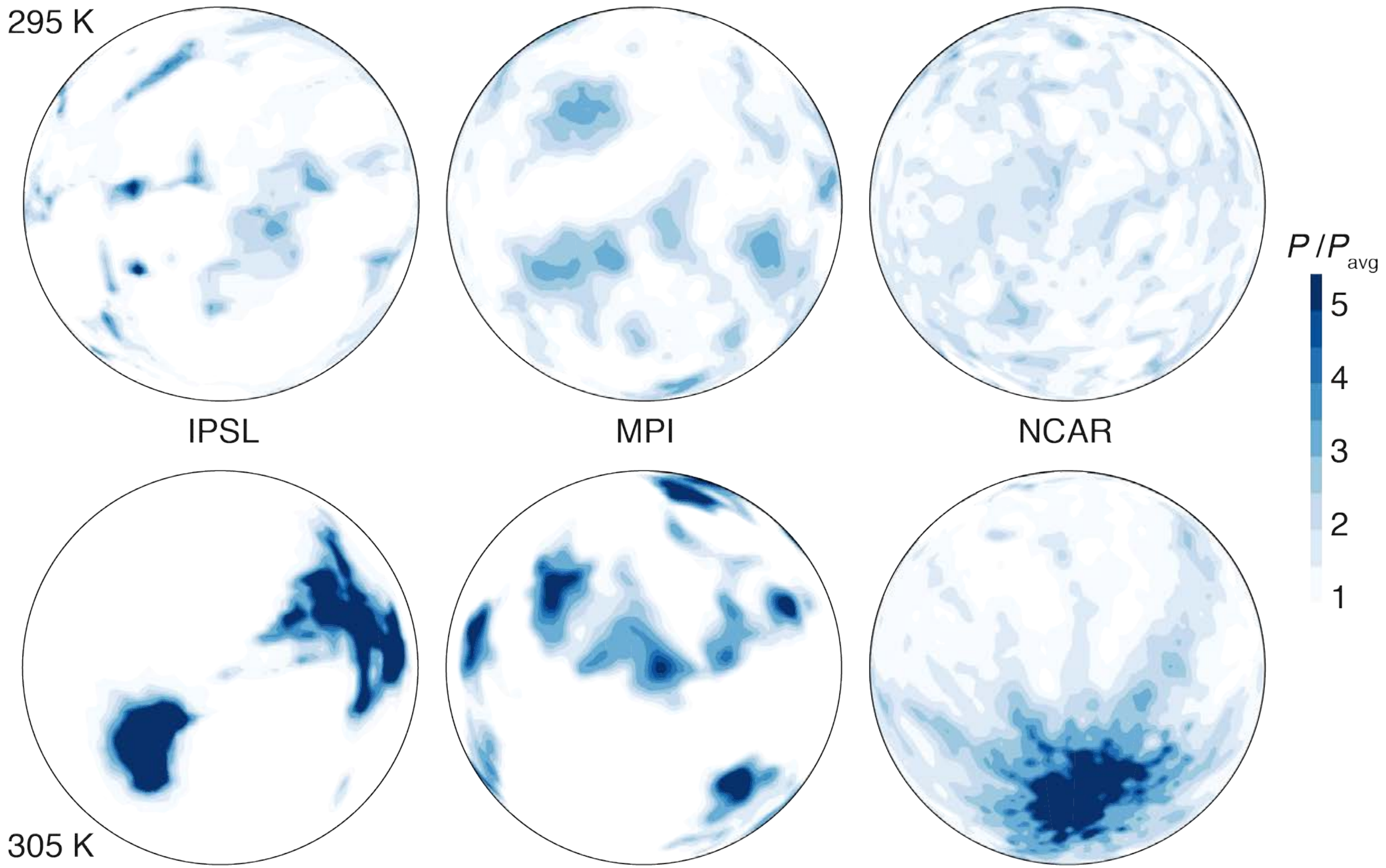
- Surface temperature?
- Clustering of convection?
- Combination of both?

GCMs run in Radiative-Convective Equilibrium (RCE)



- IPSL-CM5A-LR, ECHAM6 and CAM5 GCMs
- Non-rotating aqua-planet configuration
- Spatially uniform insolation, prescribed surface temperature
- Convective self-aggregation occurs

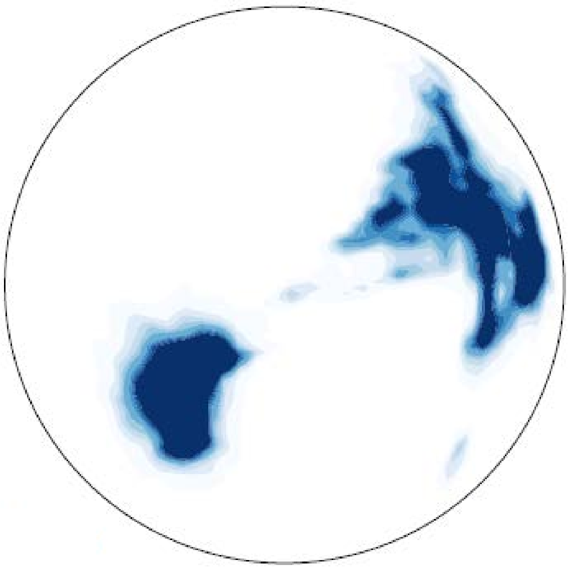
GCMs run in Radiative-Convective Equilibrium (RCE)

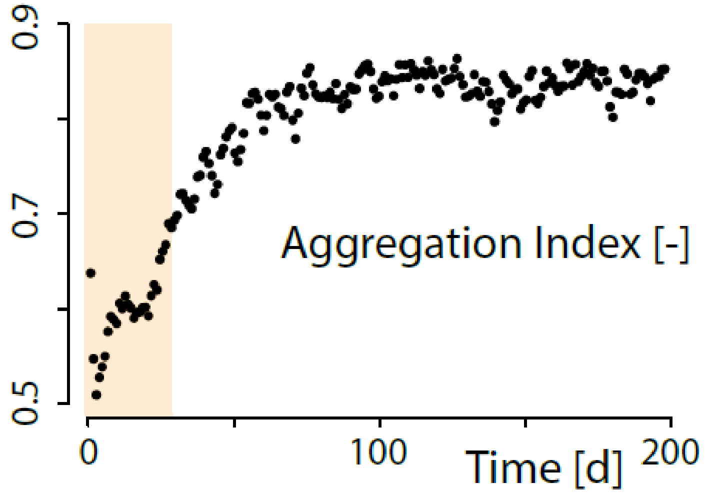


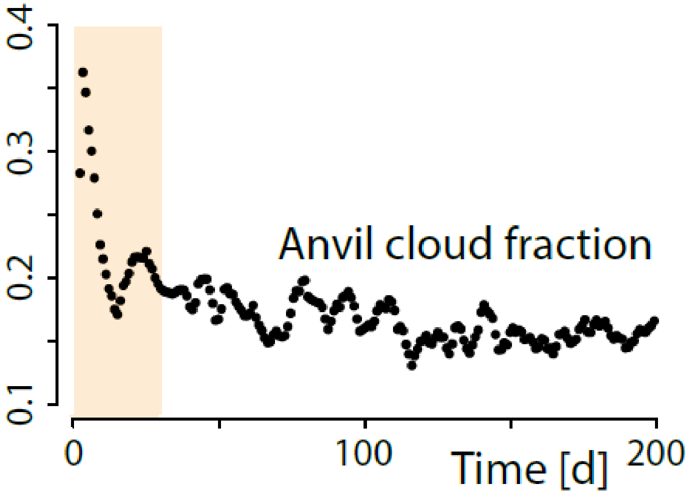
Increasingly so at high surface temperature

The clustering of convection reduces the anvil-cloud amount

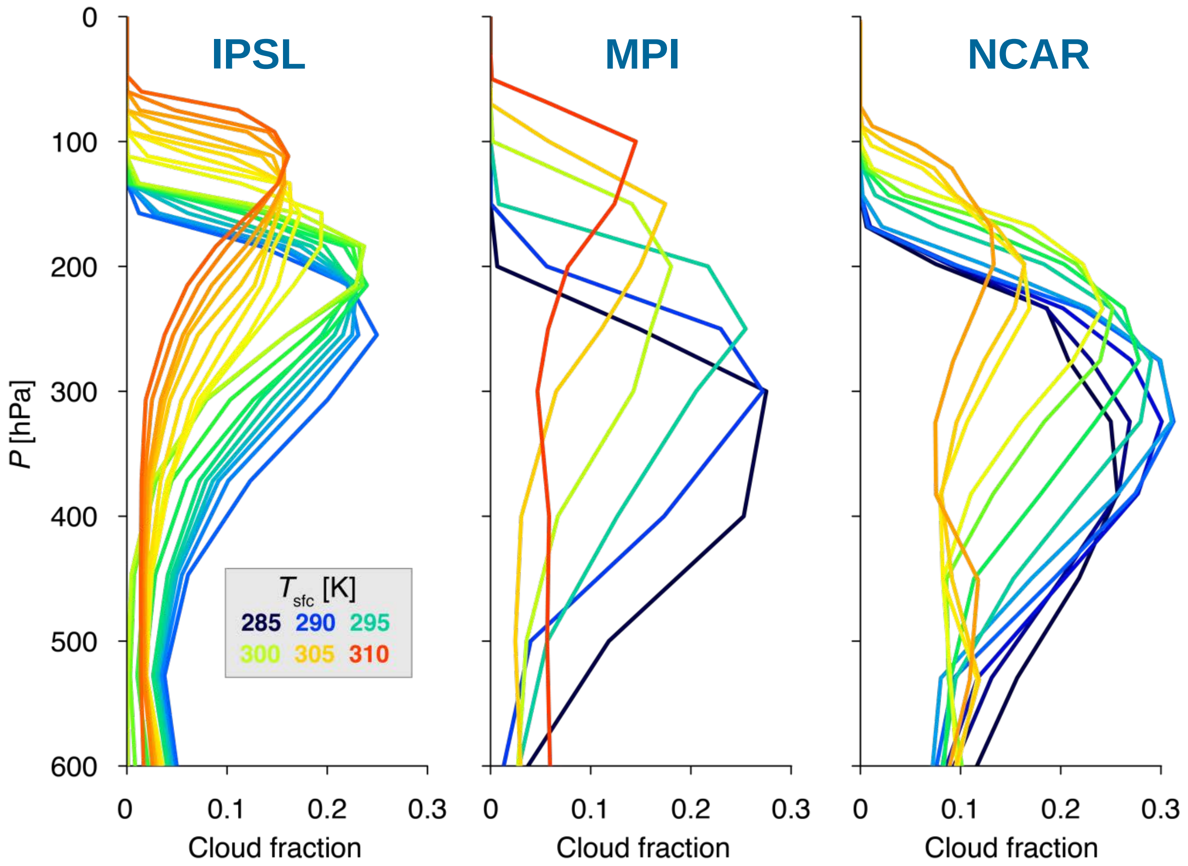
- IPSL climate model
- Non-rotating Radiative-Convective Equilibrium
- Uniform prescribed SST (here: 305K)







Global warming as well



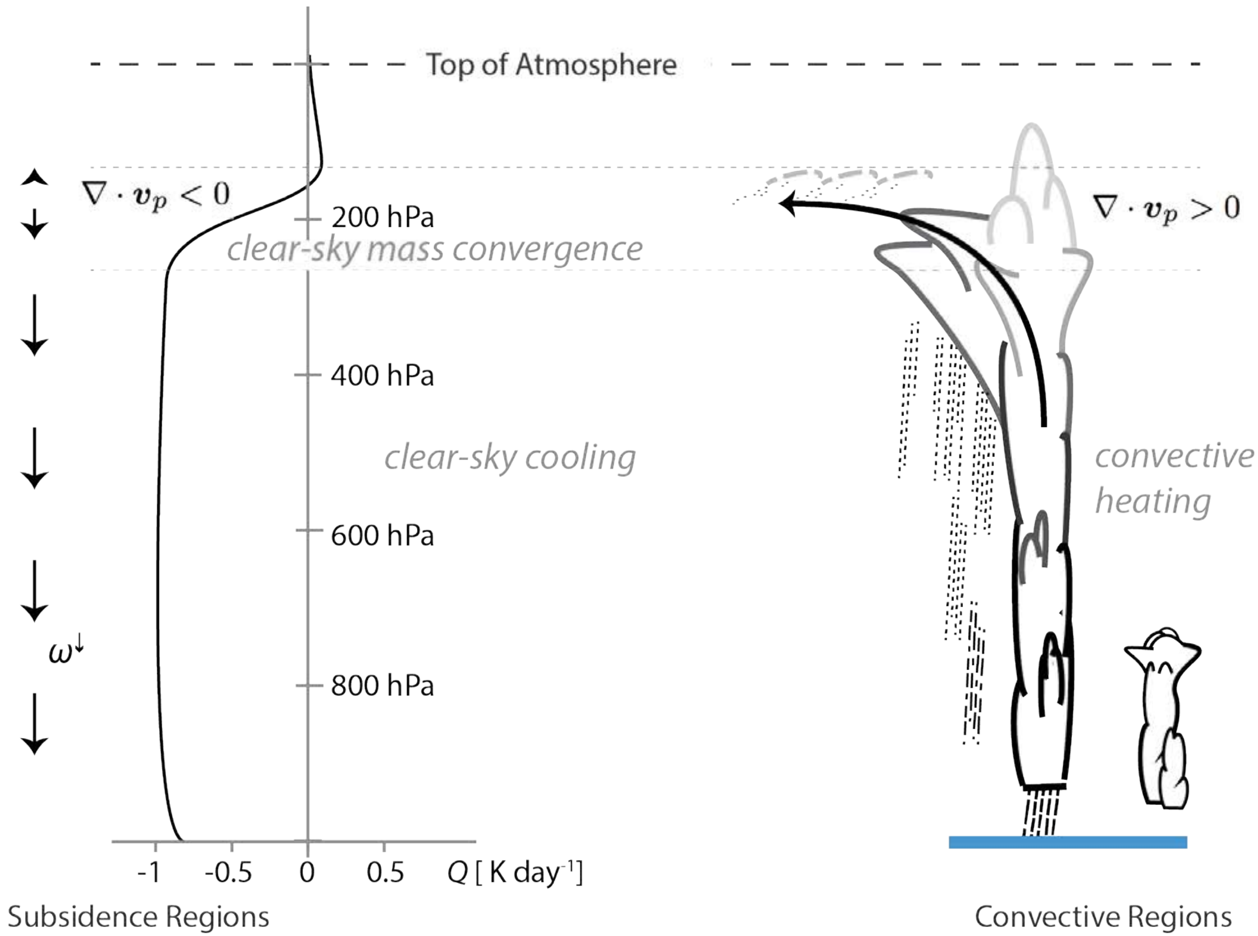
- As the climate warms: anvil clouds rise... and their coverage falls.
- A consequence of convective aggregation or global warming?

→ Both, but primarily global warming. Mechanism?

Constraints on upper-level cloudiness

The altitude of tropical anvil clouds is well constrained by upper-tropospheric convergence computed from the mass and energy budget of the clear-sky atmosphere

$$D_\mathrm{r} = \frac{\partial \omega}{\partial P} \quad \text{with} \quad \omega = -\frac{Q_\mathrm{r}}{S} \qquad\qquad S = -\frac{T}{\theta}\frac{\partial \theta}{\partial P} = \left(\frac{R_\mathrm{d}}{c_\mathrm{pd}}\right)\frac{T}{P}(1-\gamma)$$

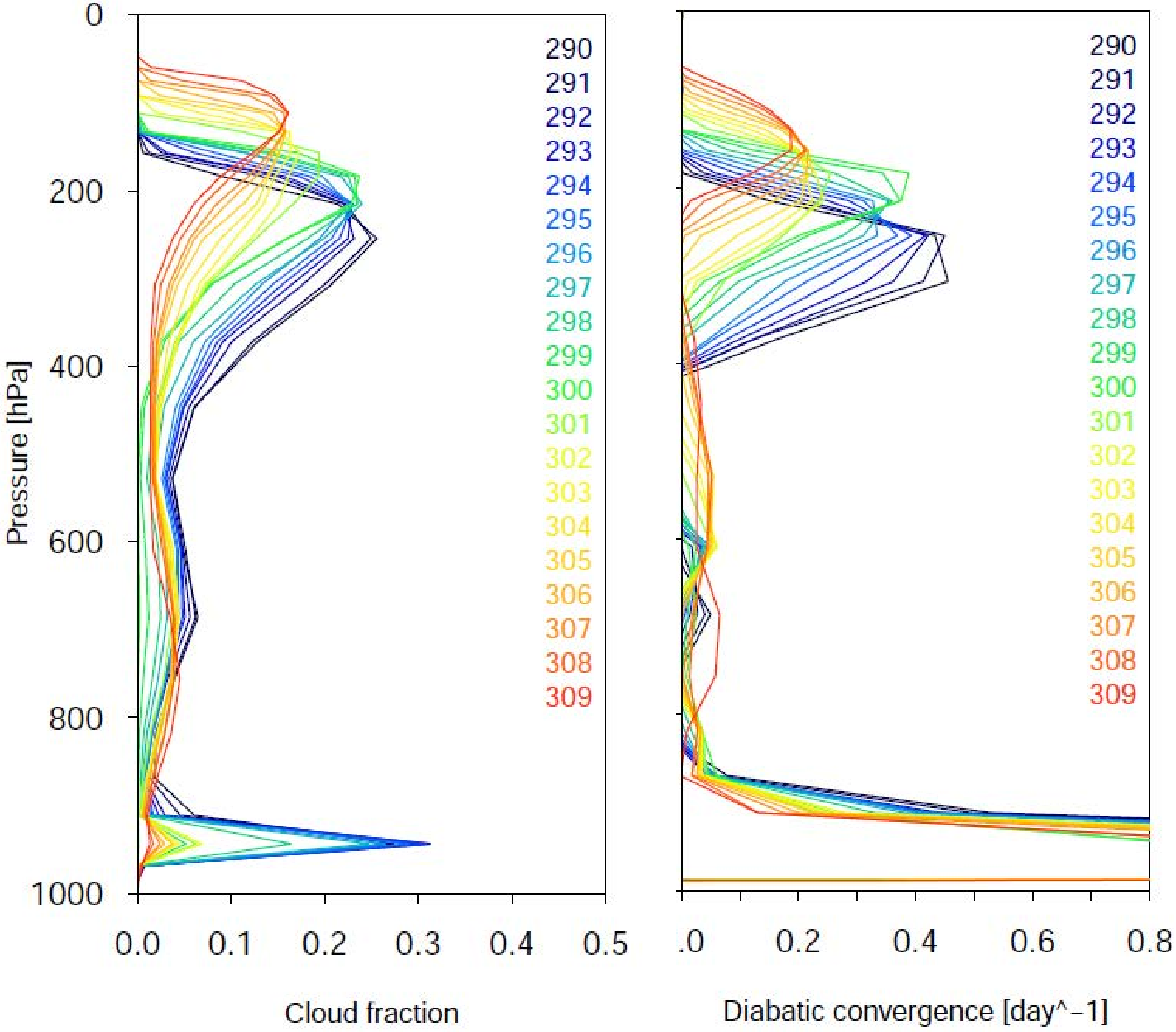


Hartmann and Larson, GRL (2002); Zelinka and Hartmann, JGR (2010)

Radiative-Convective Equilibrium simulations

cloud fraction

Radiatively-driven mass convergence in clear-sky areas (or divergence in moist areas)

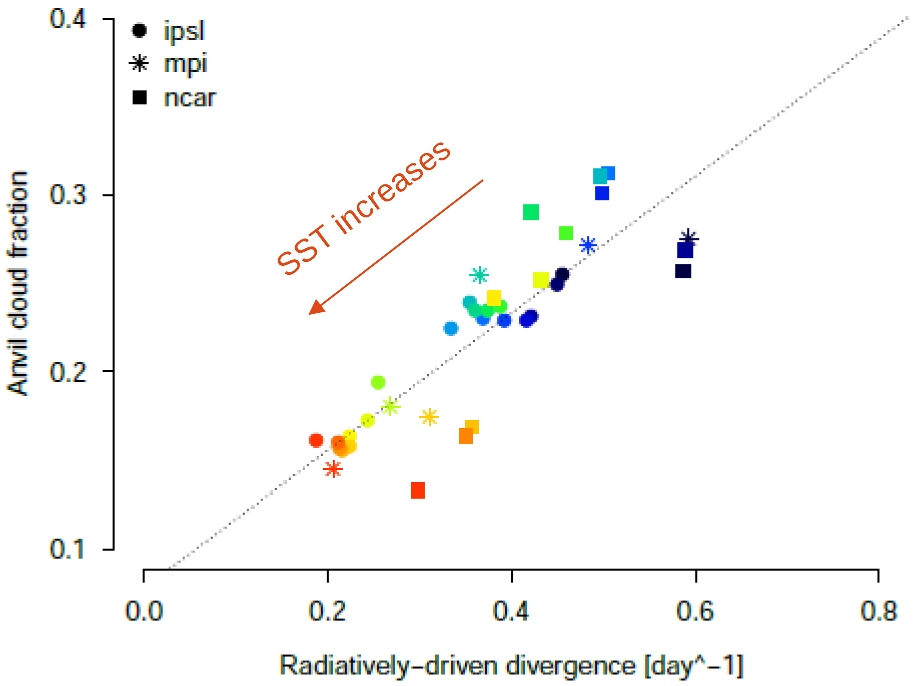


The altitude of anvil clouds is well constrained by upper-tropospheric convergence diagnosed from the mass and energy budget of the clear-sky atmosphere *(Hartmann and Larson 2002, Zelinka and Hartmann 2010)*.

The anvil cloud amount too

Thermodynamic control on anvil-cloud amount

$$D_r = \frac{\partial \omega}{\partial P} \quad \text{with} \quad \omega = -\frac{Q_r}{S}$$

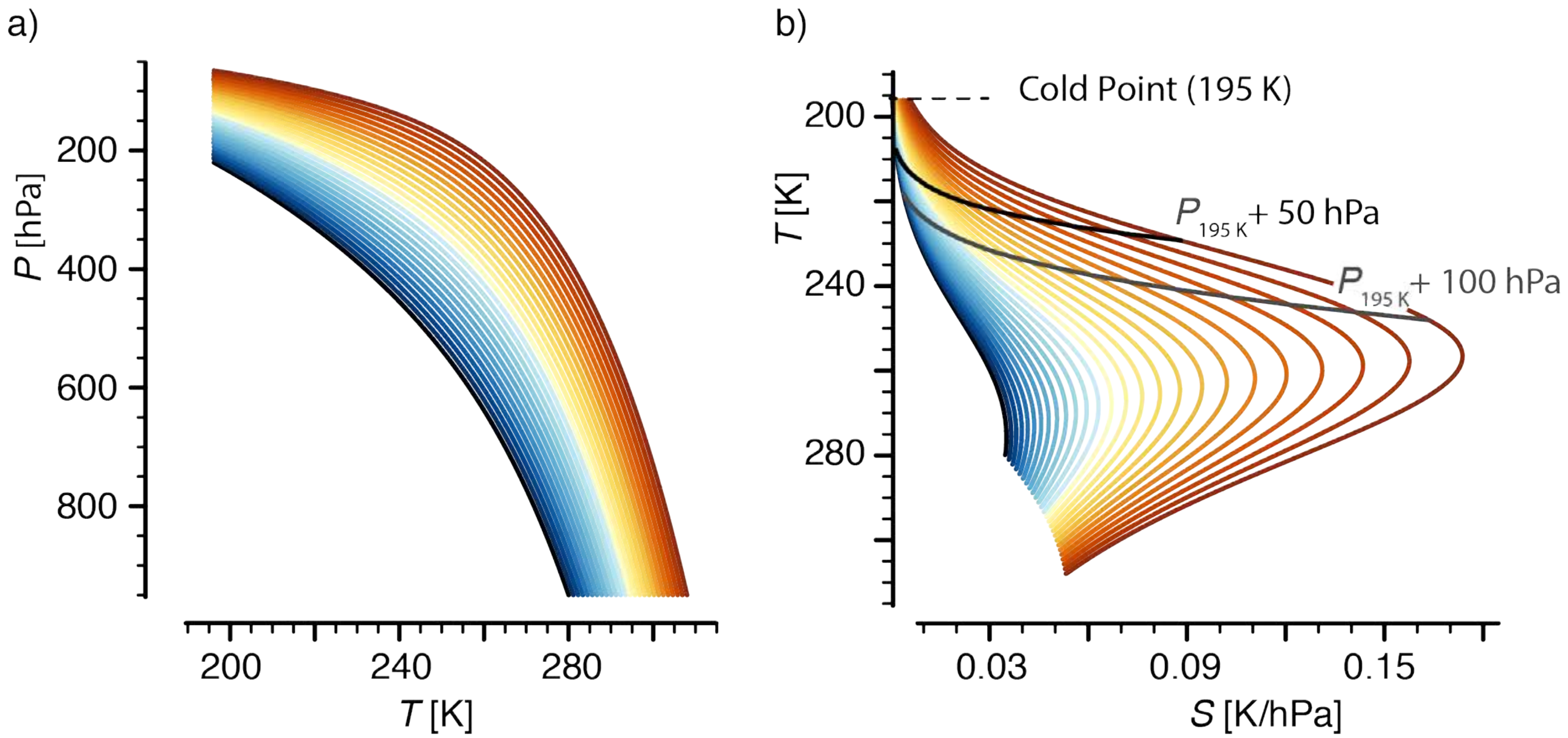


- The anvil-cloud fraction varies linearly with the upper-level mass divergence D_r (convective outflow).
- As the climate warms, the upper-level mass divergence decreases (even in the absence of convective aggregation).
- Results from changes in upper-tropospheric static stability

A mechanism rooted in basic thermodynamics (moist adiabats)

Moist adiabatic temperature profiles associated with different cloud-base temperatures:

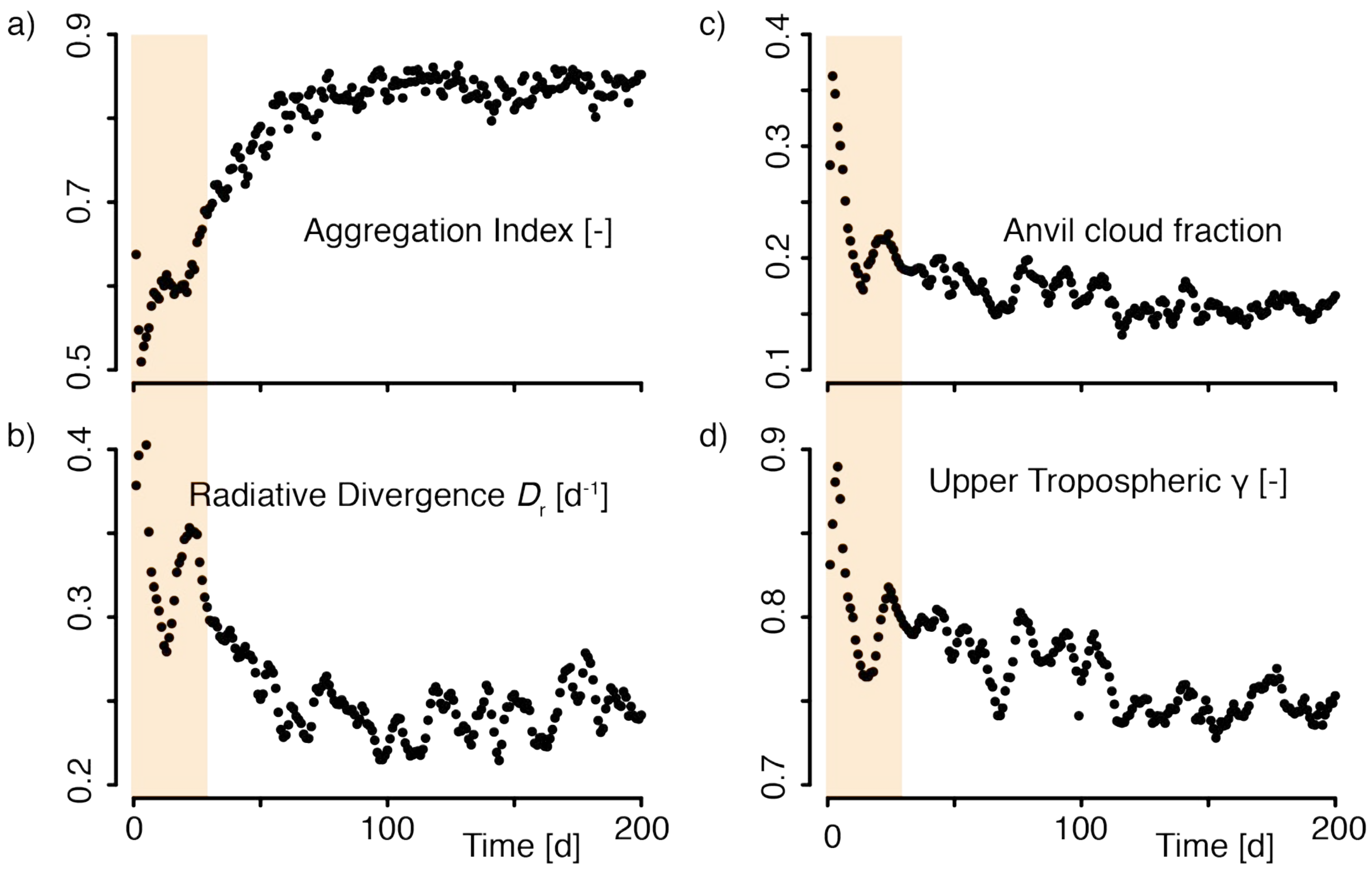
Static stability: $$S = -\frac{T}{\theta}\frac{\partial \theta}{\partial P} = \left(\frac{R_{\mathrm{d}}}{c_{p\mathrm{d}}}\right)\frac{T}{P}(1-\gamma)$$



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.**

Also explains the variation of the anvil cloud amount with convective aggregation



As convective aggregation increases, convective cloud-base MSE increases, which warms the troposphere, increases upper-tropospheric static stability and decreases the radiatively-driven mass divergence in the upper troposphere, leading to a smaller anvil cloud amount.

Robustness of this mechanism across a hierarchy of models?

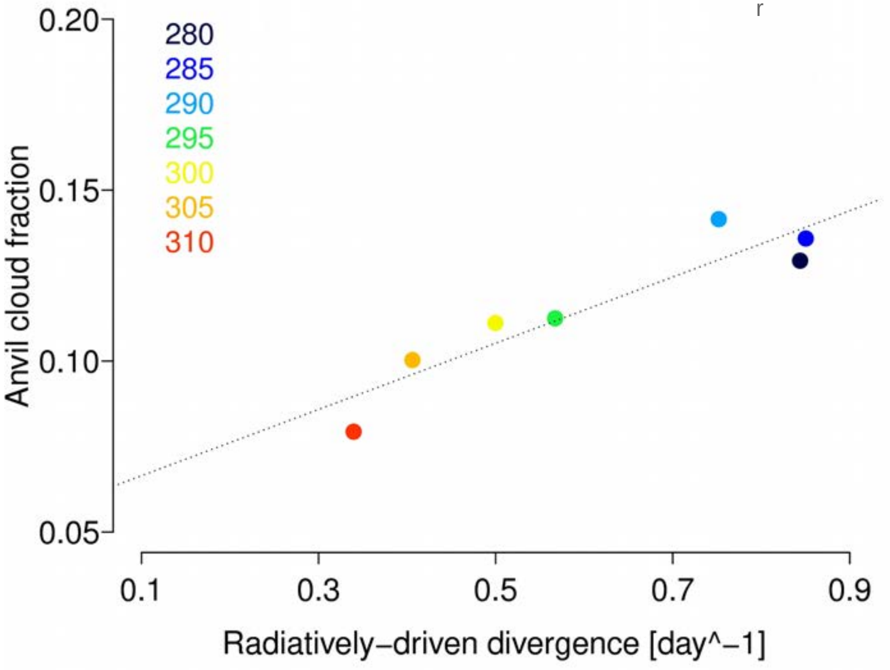
RCE simulations run with GCMs:

- IPSL, MPI and NCAR models
- with and without cloud-radiative effects
- with prescribed SSTs and with interactive SSTs
- with and without ozone radiative forcing

RCE simulations run with a CRM:

Cloud-Resolving Model simulations run over a large domain (Allison Wing and Tim Cronin 2016)

Anvil cloud amount vs D_r



Robustness of this mechanism across a hierarchy of models?

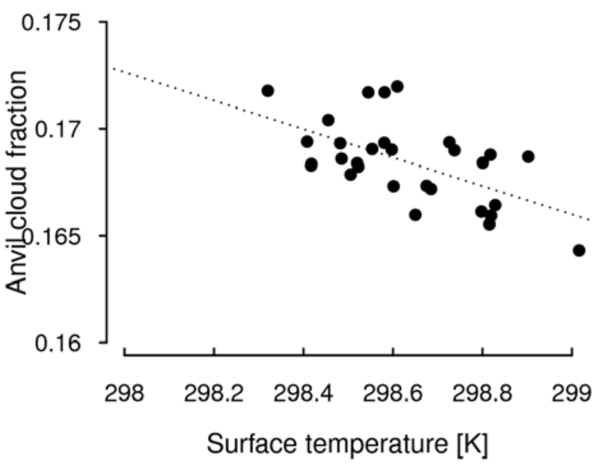
GCM simulations run in a realistic configuration:

- AMIP simulations from the same models (IPSL-CM5A, ECHAM6 and CAM5)
- with and without cloud-radiative effects (IPSL-CM5A)
- with and without convective parameterization (IPSL-CM5A)

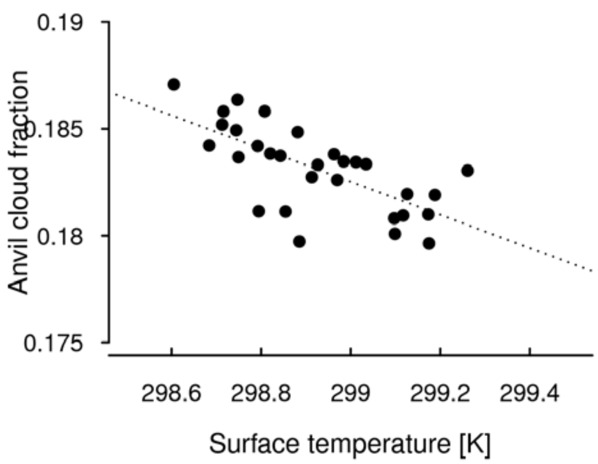
+ consistency with OAGCMs and observations (Zelinka and Hartmann 2010, 2011)

Tropically-averaged (30S-30N) anvil cloud fraction (annual means, 1979 to 2005):

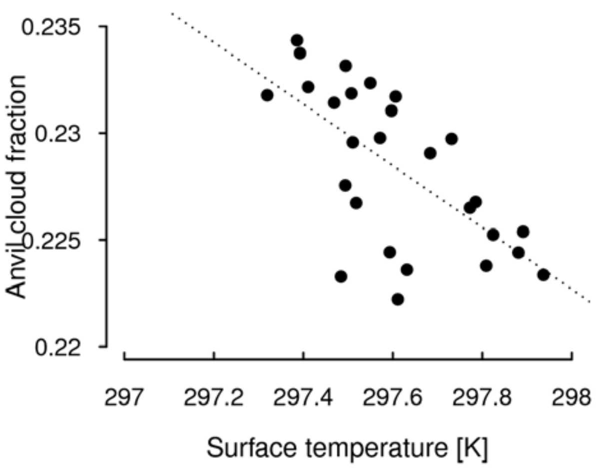
AMIP IPSL-CM5A-LR



AMIP MPI-ESM-LR



AMIP CAM5



Conclusion

- **A stability Iris mechanism:**

  The anvil cloud amount shrinks as the climate warms or when convection becomes more clustered.

  Supported by three GCMs in a hierarchy of configurations (e.g. RCE, AMIP) and a CRM.

  Appears to be consistent with observations.

  Results from basic physical mechanisms (dependence of static stability on T and P + mass/energy budget of non-convective areas).

  → Robust?

- **Implications for clouds-circulation coupling:**

  The coupling between temperature, anvil clouds, radiation and circulation exerts a positive feedback on aggregation and favors the maintenance of strongly aggregated states at high temperatures.

  Does it contribute to the narrowing of rainy areas as the climate warms?

- **Implications for climate sensitivity:**

  Whether or not the stability iris influences climate sensitivity requires further investigation.

Time is ripe for an RCE intercomparison

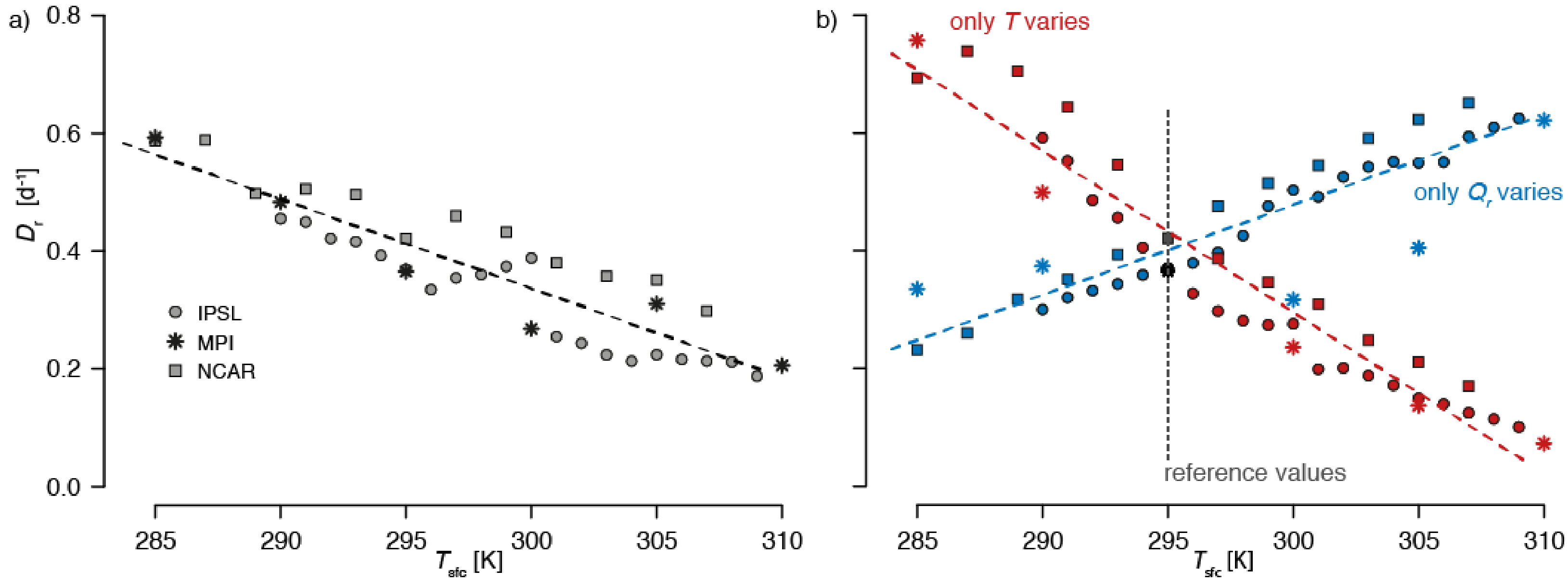
- Bridge CRMs and GCMs

- Identify robust behaviors

- Explore the links between RCE and realistic configurations

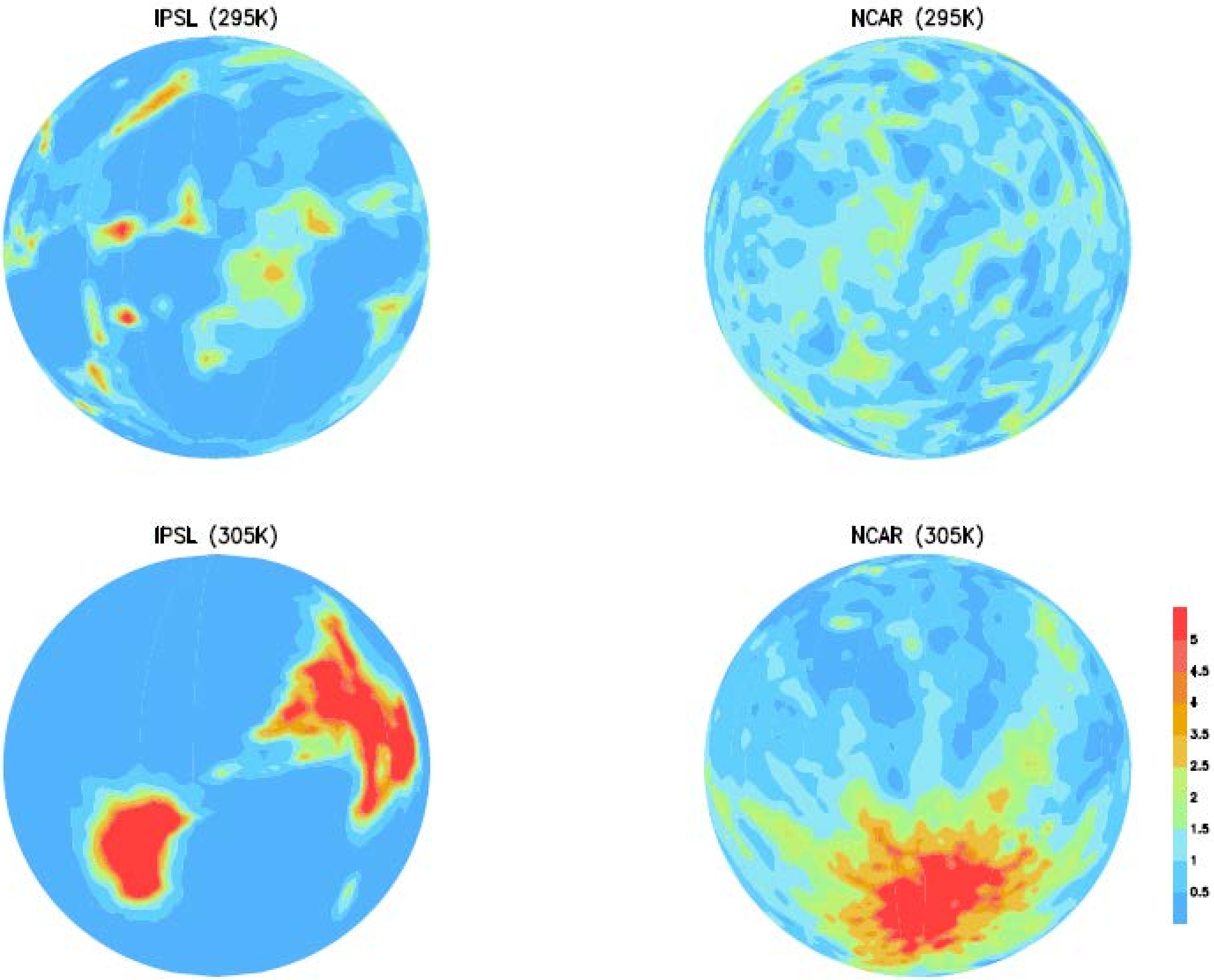

Thank You
Bony, Stevens, Coppin, Becker, Reed, Voigt and Medeiros, 2016
Proc. Natl. Acad. Sci., 113 (32), 8927–8932,
10.1073/pnas.1601472113.

Relative influence of CS radiative cooling vs stability changes



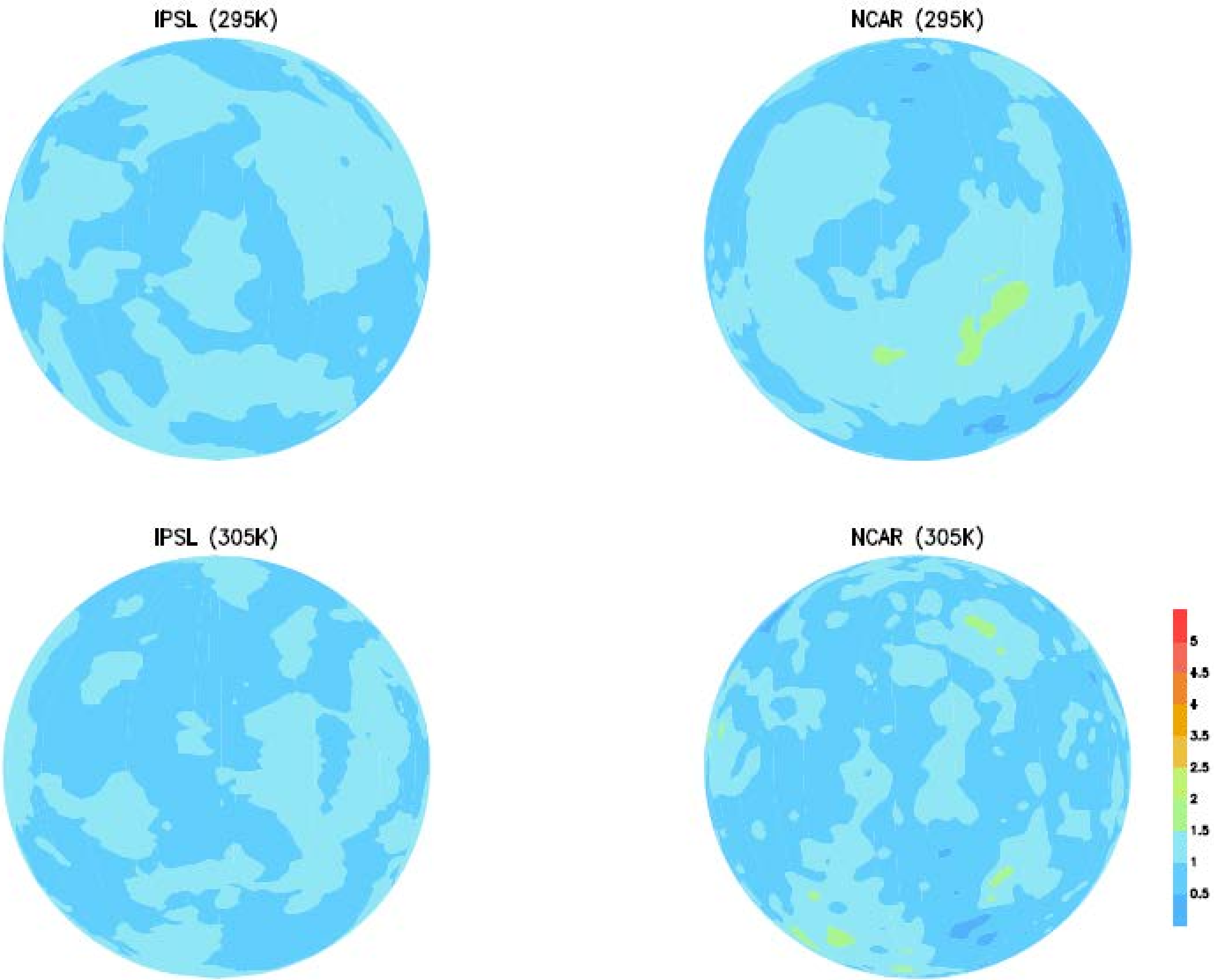
Bony, Stevens, Coppin, Becker, Reed, Voigt and Medeiros, PNAS (2016)

RCE simulations with cloud-radiative effects



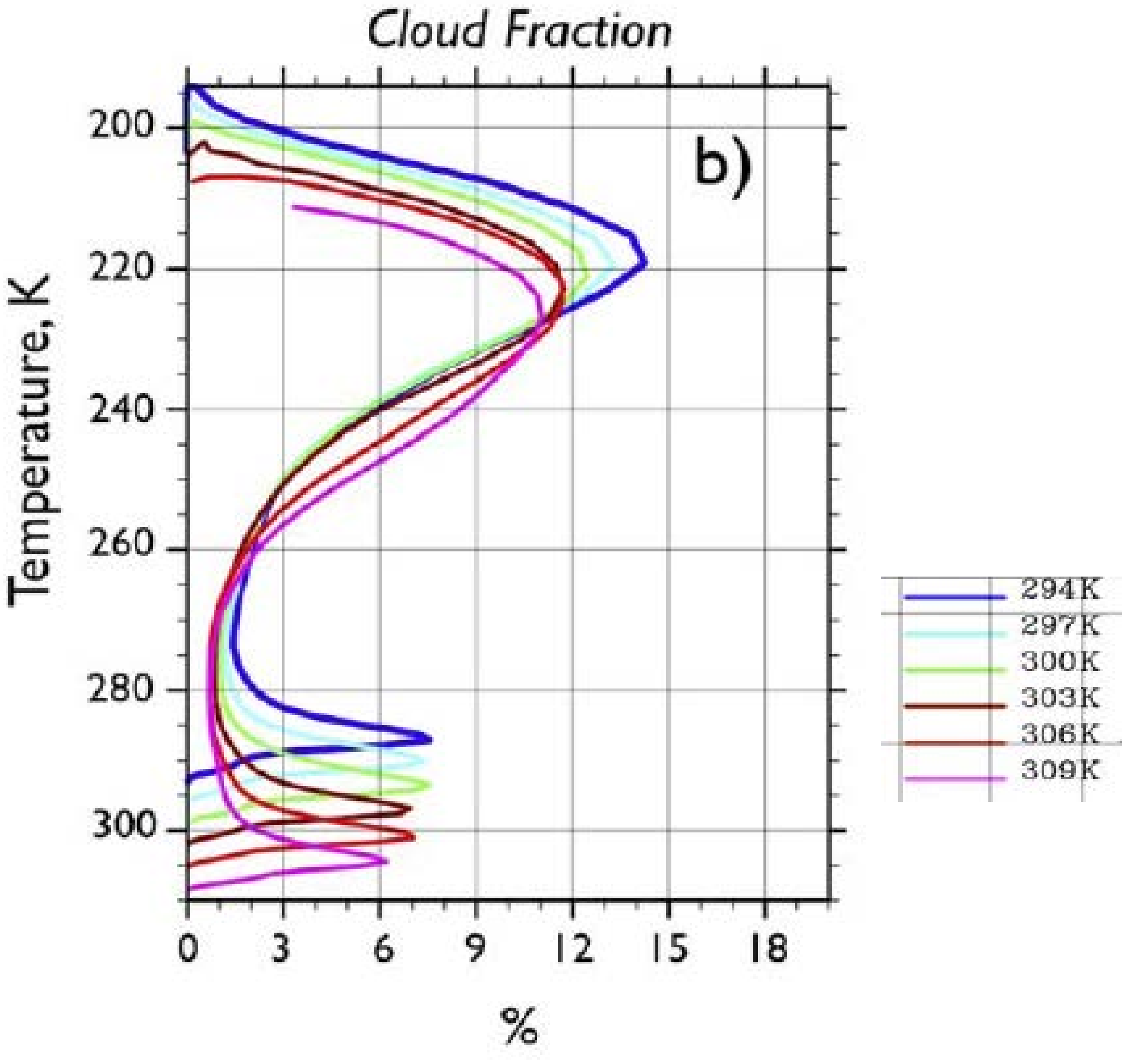
Bony, Stevens, Coppin, Becker, Reed, Voigt and Medeiros, PNAS (2016)

RCE simulations <u>without</u> cloud-radiative effects



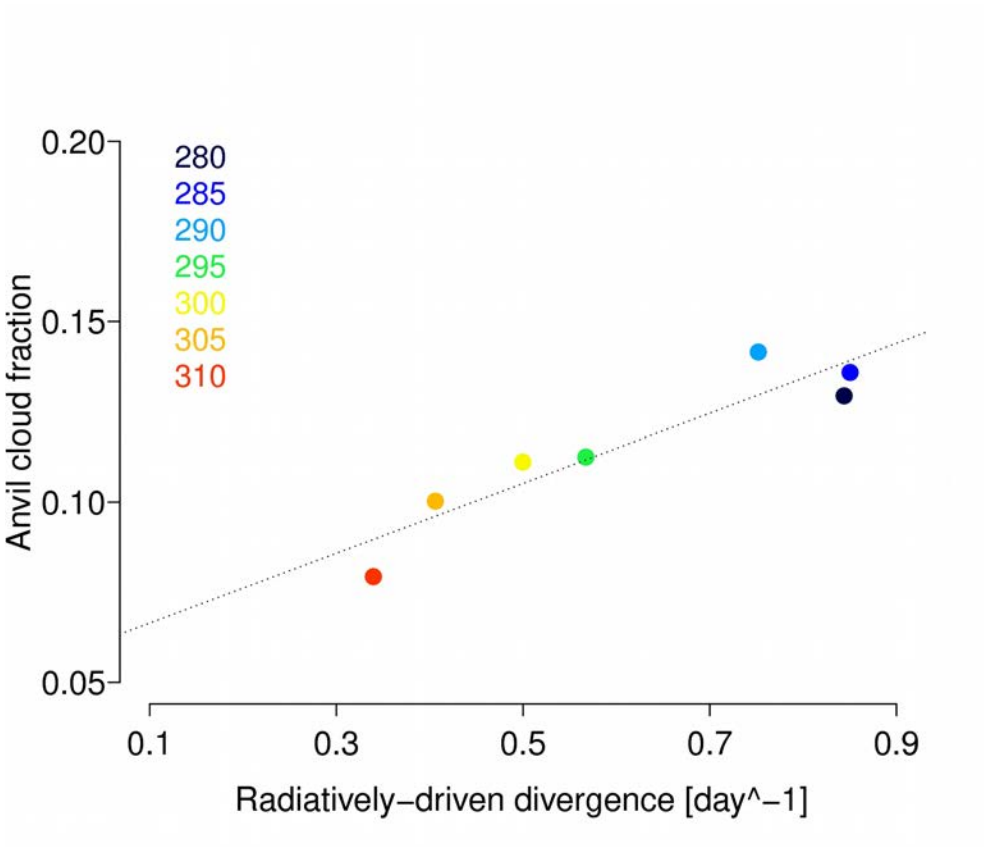
Bony, Stevens, Coppin, Becker, Reed, Voigt and Medeiros, PNAS (2016)

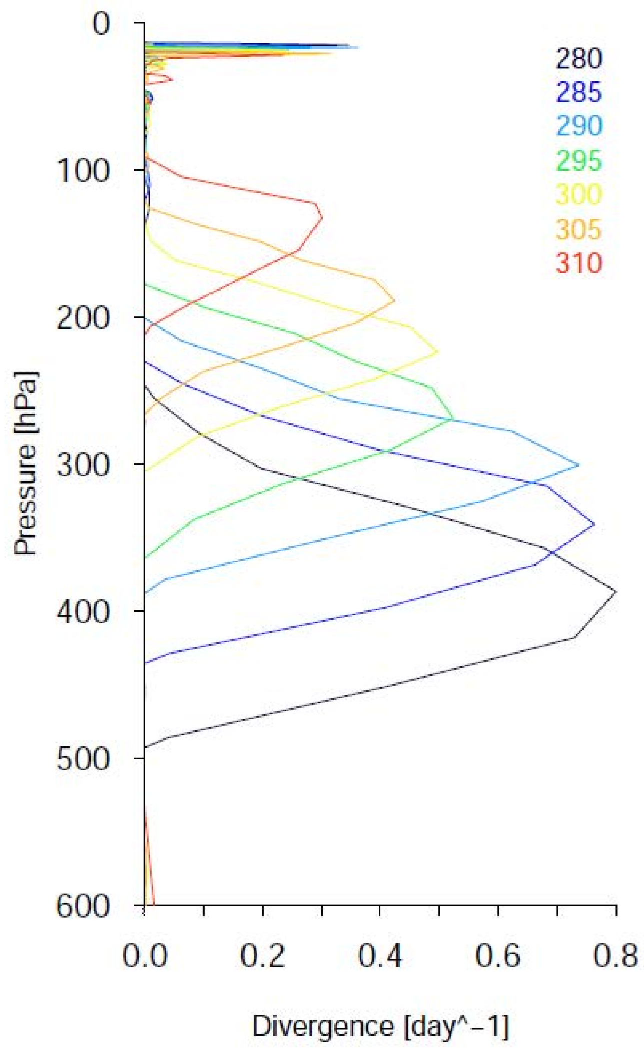
Rotating RCE simulations with a CRM



Khairoutdinov and Emanuel, JAMES (2013)

RCE simulations (Wing & Cronin 2016) from a CRM run over a large domain



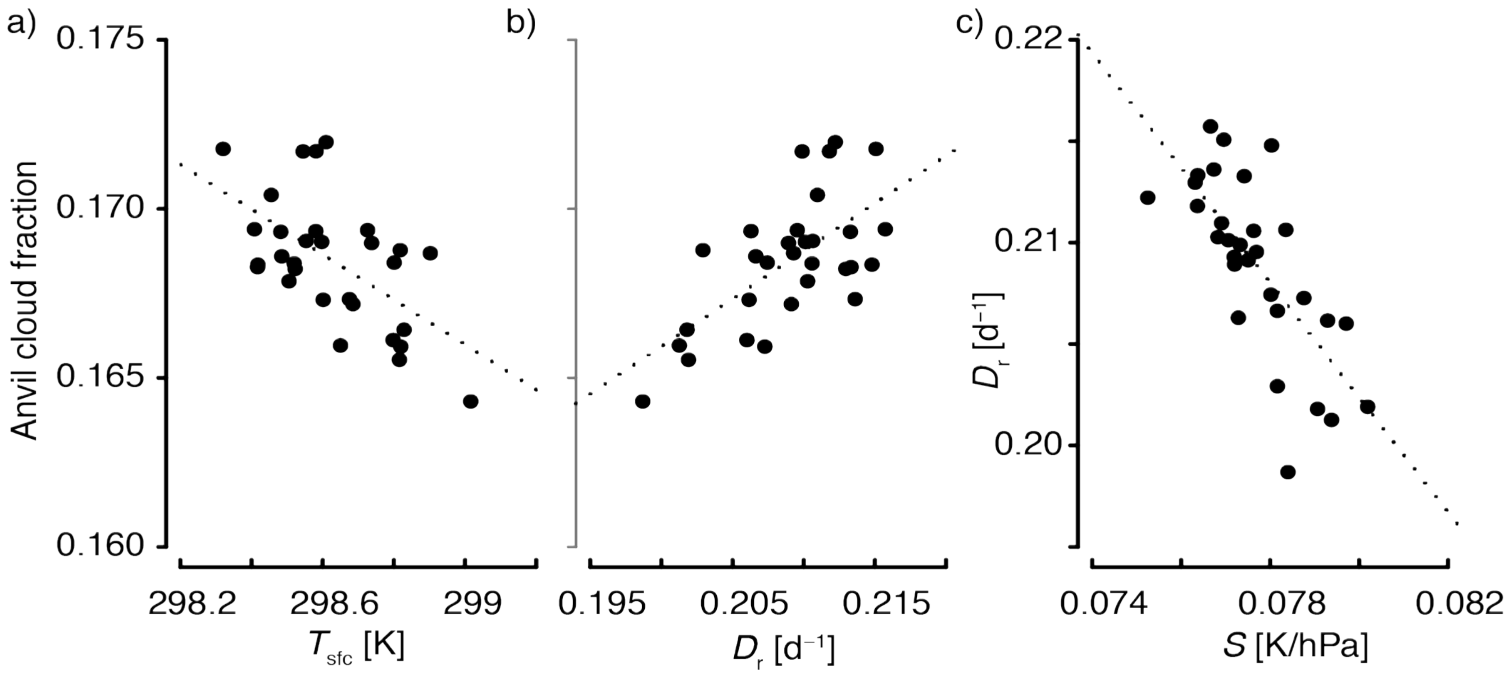


Bony, Stevens, Coppin, Becker, Reed, Voigt and Medeiros, PNAS (2016)

AMIP simulation

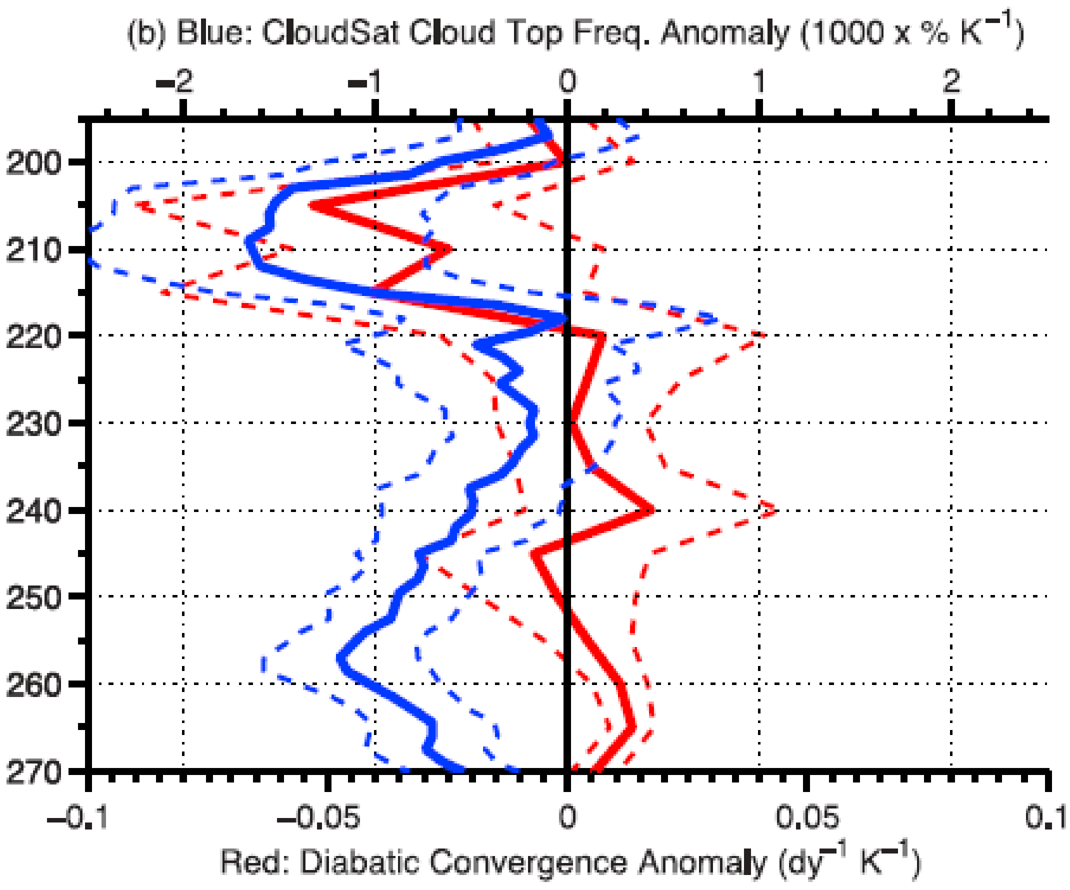
Tropically-averaged (30S-30N) anvil cloud fraction (annual means, 1979 to 2005):

IPSL-CM5A-LR



Bony, Stevens, Coppin, Becker, Reed, Voigt and Medeiros, PNAS (2016)

Observed interannual variations of the tropically-averaged anvil cloud Fraction (Zelinka and Hartmann 2011)



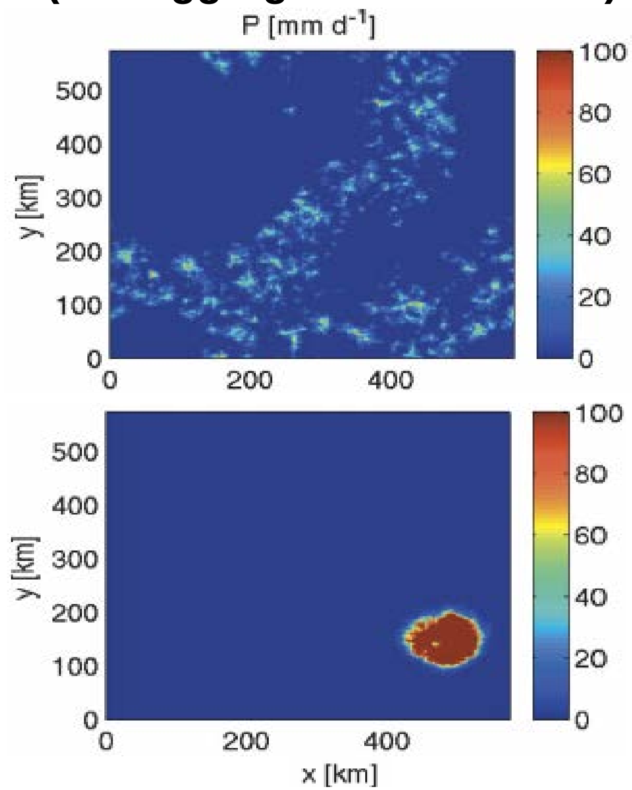
Zelinka and Hartmann, JGR (2011)

Anvil clouds & convective aggregation

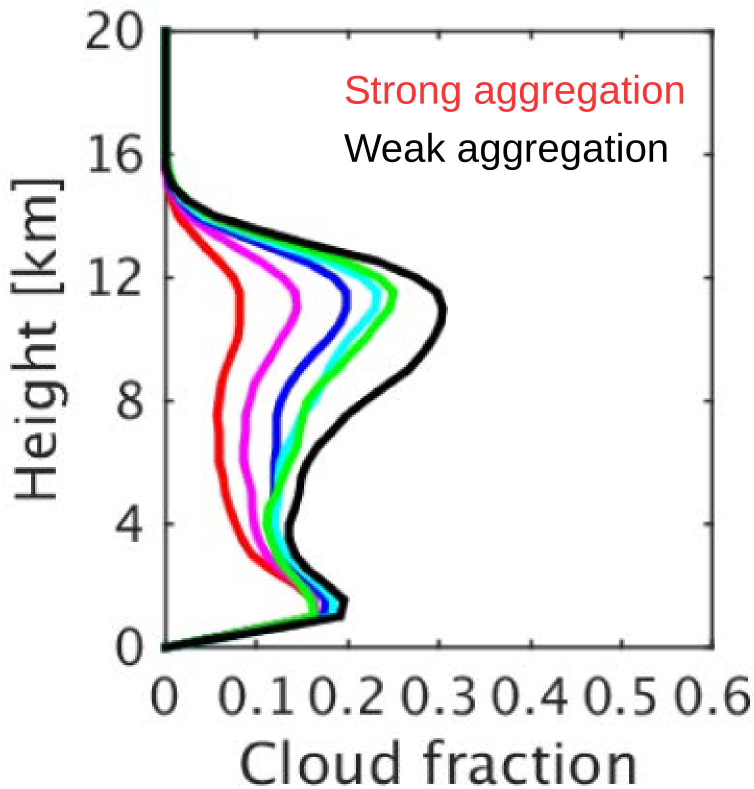
For given domain-averaged precipitation, large-scale forcings and SST :

more convective aggregation ←→ more clear-sky
less anvil clouds

CRM simulation
(self-aggregation behaviour)



Calipso/CloudSat



Bretherton, Blossey and Khairoutdinov, JAS (2005)

Stein, Holloway, Tobin and Bony (in revision)
Tobin et al., JAMES (2013)