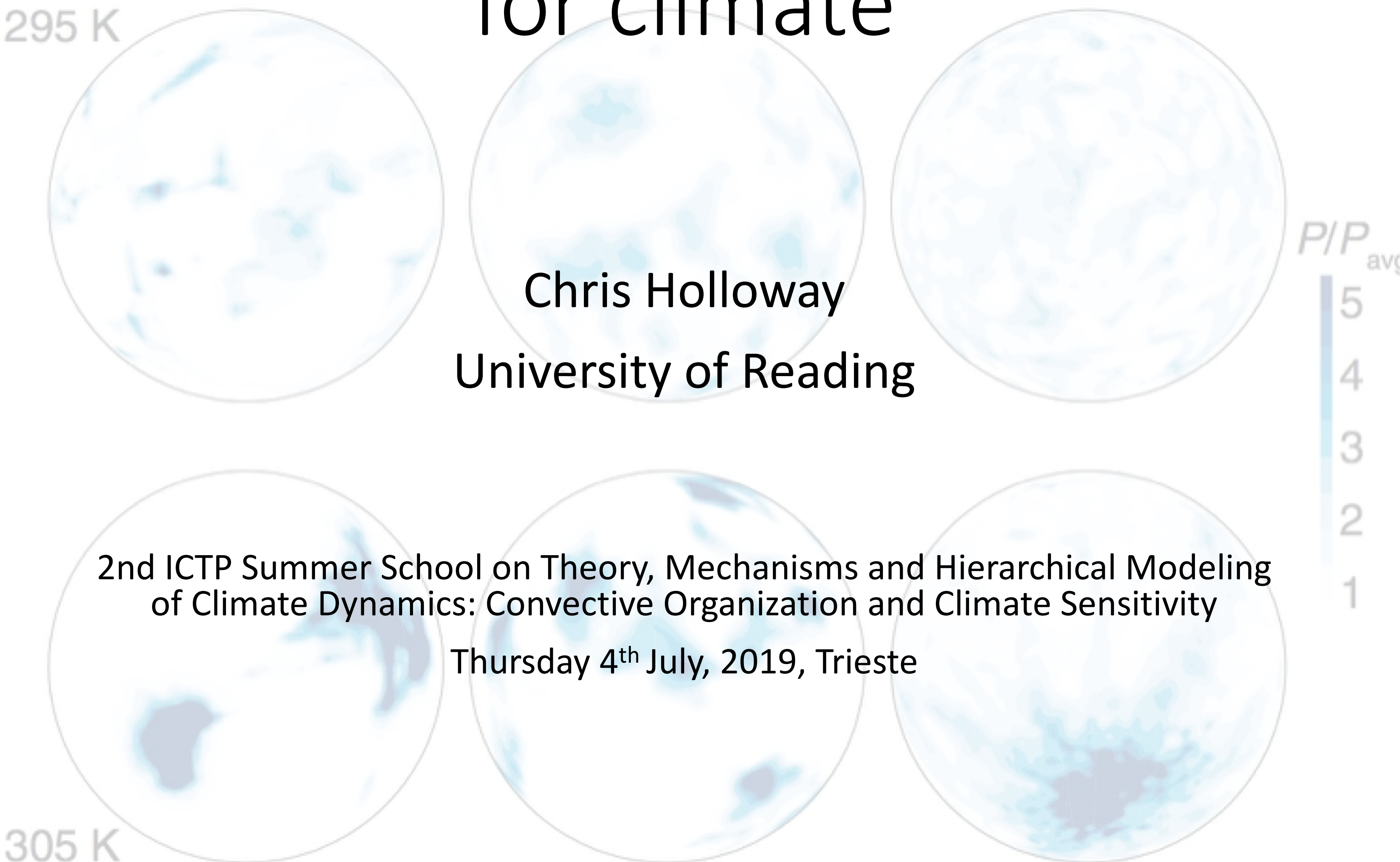
Implications of aggregation for climate



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

Thursday 4th July, 2019, Trieste

Outline

1. Concepts of feedbacks in the climate system
2. Main climate feedbacks (Planck, water vapour, lapse rate, surface albedo and cloud)
3. Cloud feedbacks in more detail
4. SST dependence of aggregation
5. Anvil cloud changes with warming
6. Potential for organisation to act as an iris
7. Issues
8. Questions

Feedbacks in the climate system

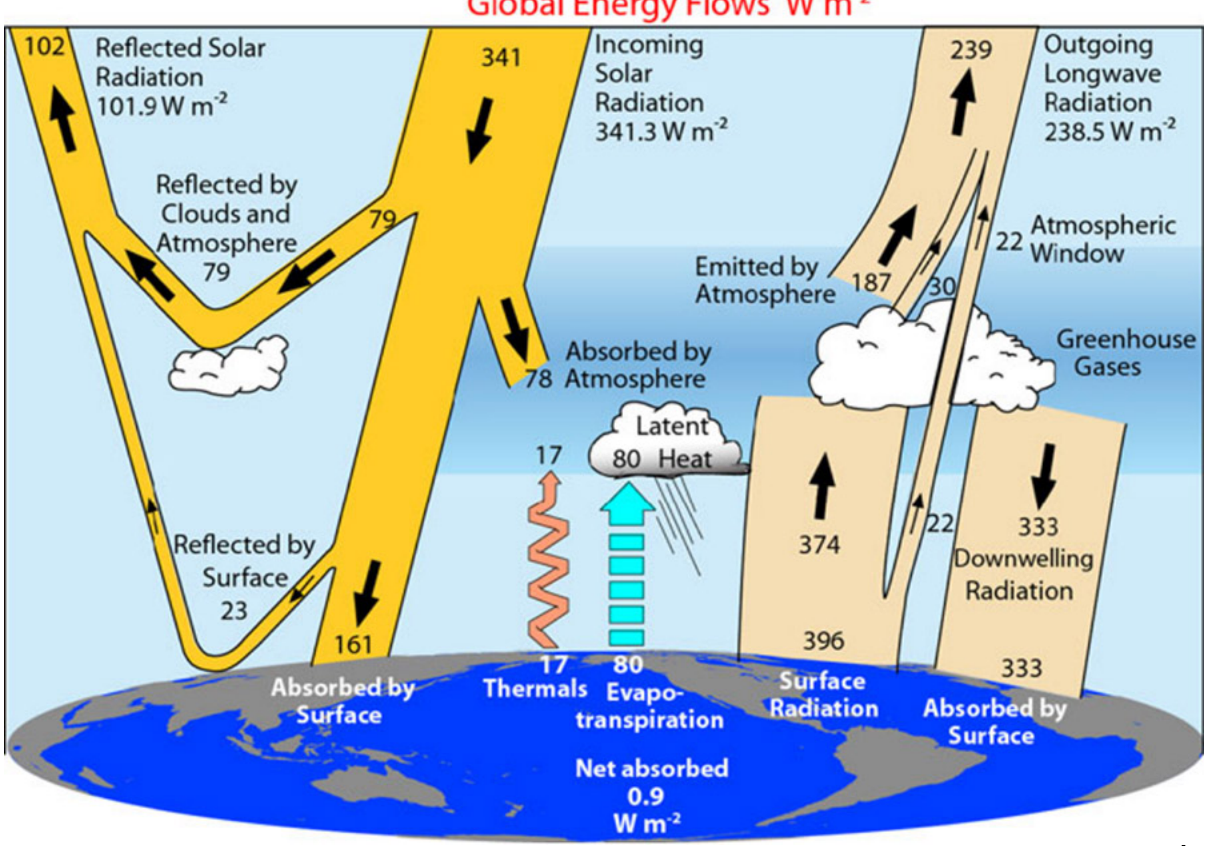
Basic energy flows

Shortwave radiation (SW)

Longwave radiation (LW)

Total albedo = 102/341 = 0.3

Surface albedo = 23/161 = 0.14



341 – 102 = 239

Very little LW escapes directly from surface to space: *greenhouse effect*

Trenberth et al. 2009

Feedbacks in the climate system

- Basic feedback equation (cf. Ceppi et al. 2017)
- $N = F + \lambda \Delta T$
    - ***N*** is the net (downward) energy flux imbalance at the top of atmosphere (TOA).
    - ***F*** is the (downward) radiative forcing, which is positive for greenhouse gas increases.
    - $\boldsymbol{\Delta T}$ is the global-mean surface warming.
    - $\boldsymbol{\lambda}$ is the total climate feedback parameter (in $W\ m^{-2}\ K^{-1}$), which measures how effectively warming (ΔT) re-establishes radiative balance.
    - For a positive F, warming must induce a negative radiative response to restore balance, so $\lambda < 0$.
    - At new steady state, $N = 0$, and thus final warming is determined by both forcing and feedback, $\boldsymbol{\Delta T = -F/\lambda}$.
    - A more positive (less negative) feedback $\lambda \longrightarrow$ more warming.
    - *Equilibrium Climate Sensitivity (ECS)*: ΔT for an F from $2 \times CO_2$

The main climate feedbacks

- $\Delta T = -F/\lambda$ (at new steady state)
- $\lambda = \lambda_{\text{Planck}} + \lambda_{\text{Water Vapour}} + \lambda_{\text{Lapse Rate}} + \lambda_{\text{Albedo}} + \lambda_{\text{Cloud}}$
    - **Planck**: largest feedback, negative because emitted longwave radiation $\propto \sigma T^4$
    - **Water Vapour**: large, positive: $T\uparrow \rightarrow q_s \uparrow \rightarrow$ (for roughly constant RH) $q_v \uparrow \rightarrow$ greenhouse warming $\uparrow \rightarrow T \uparrow$ …*
    - **Lapse rate**: negative: upper levels warm more than surface, so relatively more upward LW
    - **Albedo (surface)**: changes in surface ice, snow, (sometimes vegetation), generally positive since $T\uparrow \rightarrow$ melting $\rightarrow$ albedo $\downarrow \rightarrow T\uparrow$ …
    - **Cloud**: Can be positive or negative since clouds have both SW and LW effects (more later)

* (where q_v is specific humidity and q_s is saturation specific humidity)

Feedbacks in the climate system

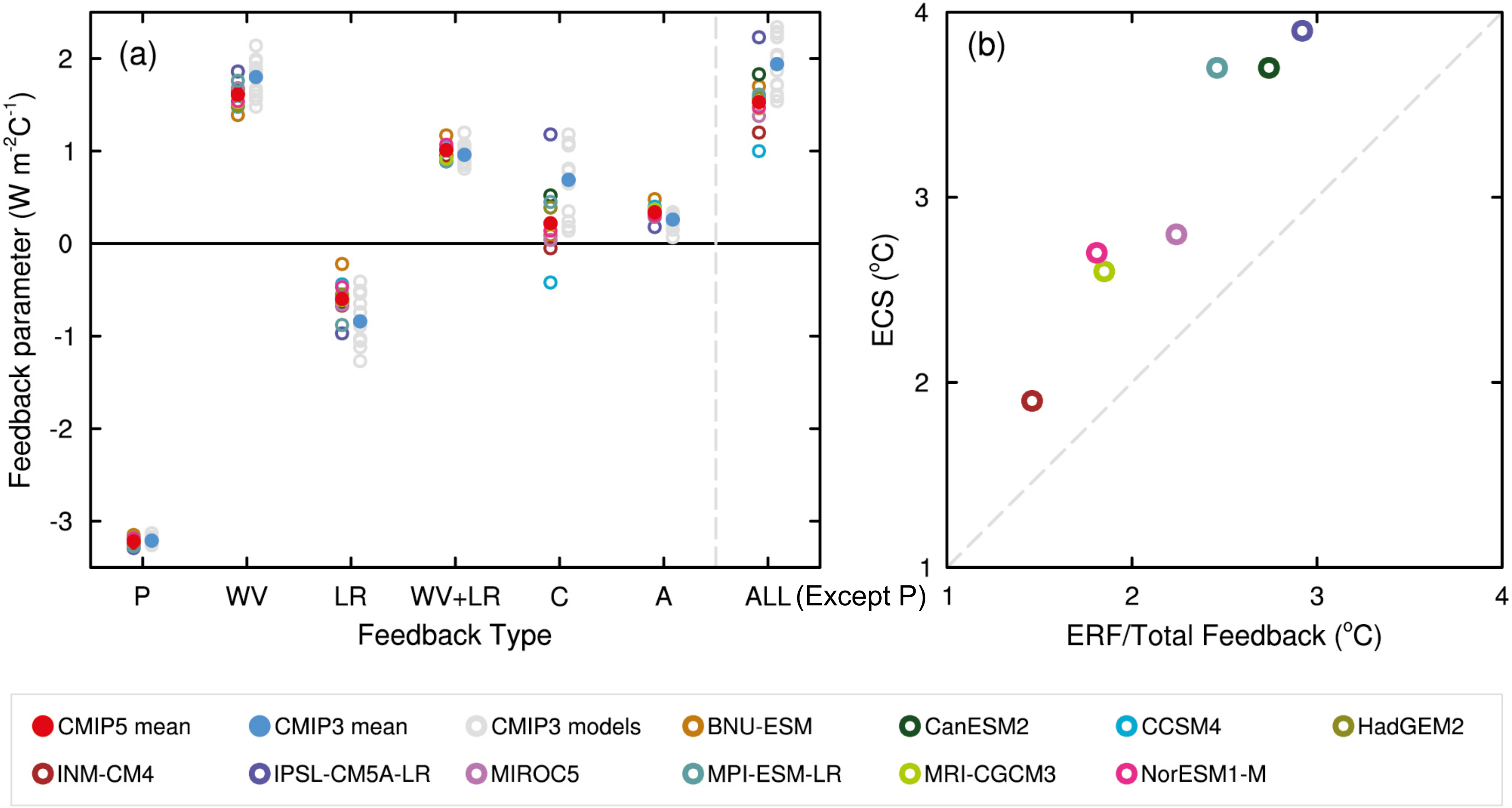
- Some issues/complications:
  - assumption of linearity ($\lambda = \lambda_0 + \lambda_1 + \ldots$) not perfect, since feedbacks can interact
  - fast versus slow feedbacks: the fast (a few days to months) response of atmospheric temperature and clouds to greenhouse gas perturbations can be included as part of forcing (*F)*
  - non-stationarity of feedbacks over time: for example, GCMs have a transient climate response (*TCR*) which is smaller than their corresponding *ECS* because ocean heat uptake delays surface warming*;* also, GCM "effective" climate sensitivity tends to become larger over time
  - For observed recent climate change, there are uncertainties in both λ and *F* (due especially to uncertainty in aerosol forcing)

The main climate feedbacks

- Lapse rate and water vapour – model differences largely compensate for these two combined, so often shown as one combined feedback
- Largest uncertainty in total feedback in CMIP GCMs comes from cloud feedback

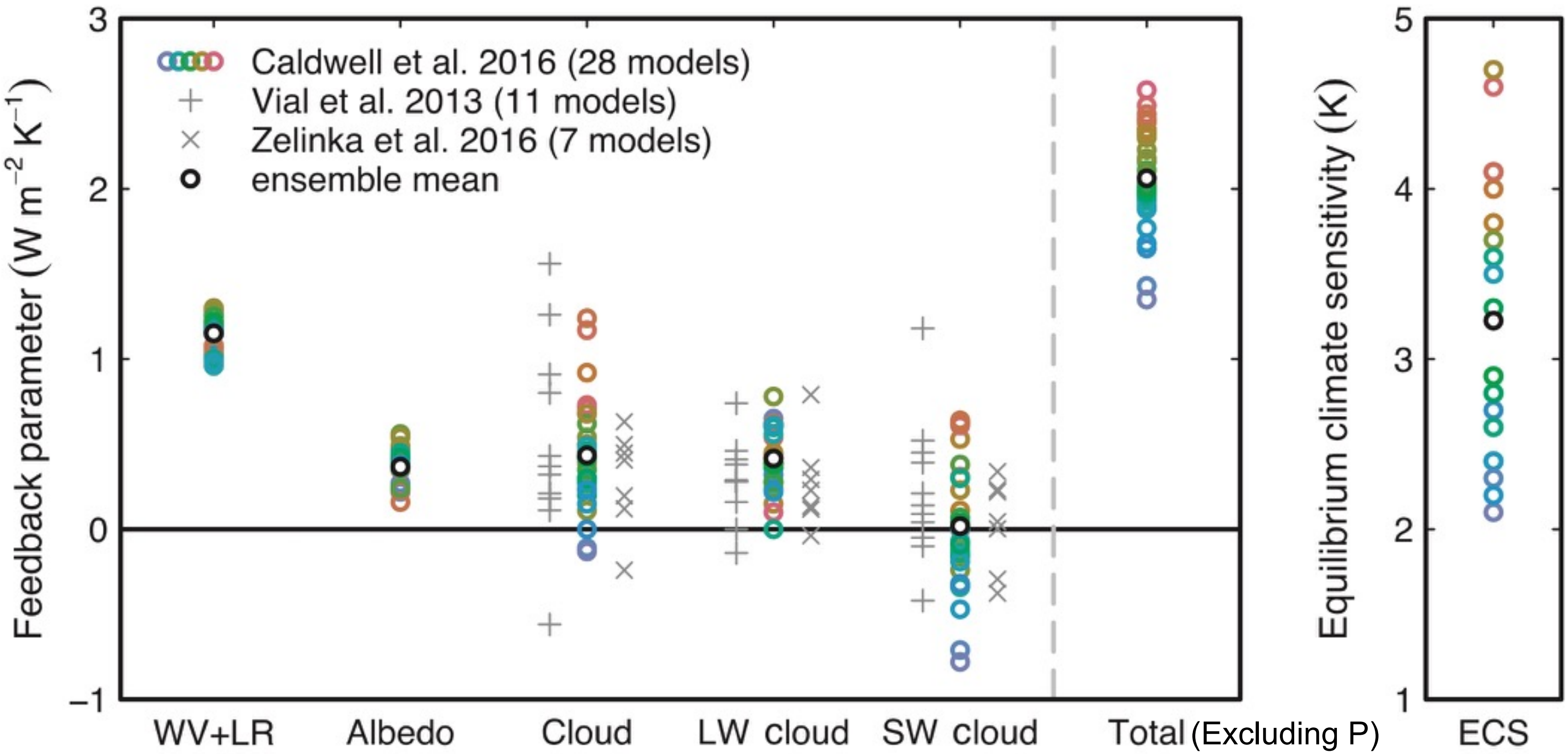
The main climate feedbacks

IPCC AR5 report figure showing different feedbacks



The main climate feedbacks (CMIP5)

Ceppi et al. 2017: breaking Cloud into LW and SW



Ceppi et al. 2017

Cloud feedbacks

- Main types of cloud feedback and their contributions to LW and SW feedback, as well as uncertainties:
  - Cloud top altitude feedback: FAT (Fixed Anvil Temperature) or PHAT (Proportionately Higher Anvil Temperature)
    - Cloud tops become higher, so they emit relatively less upward LW compared to surface (positive feedback, models agree on sign but some uncertainty on magnitude)
  - Low cloud feedback (tropical and sub-tropical)
    - Cloud fraction usually goes down, so less reflected SW (positive or slightly negative, large uncertainty)
  - Low cloud mixed phase feedback
    - Clouds in middle and high latitudes are warmer and so have more liquid and are brighter, so more reflected SW (negative, large uncertainty)

Cloud feedbacks: FAT

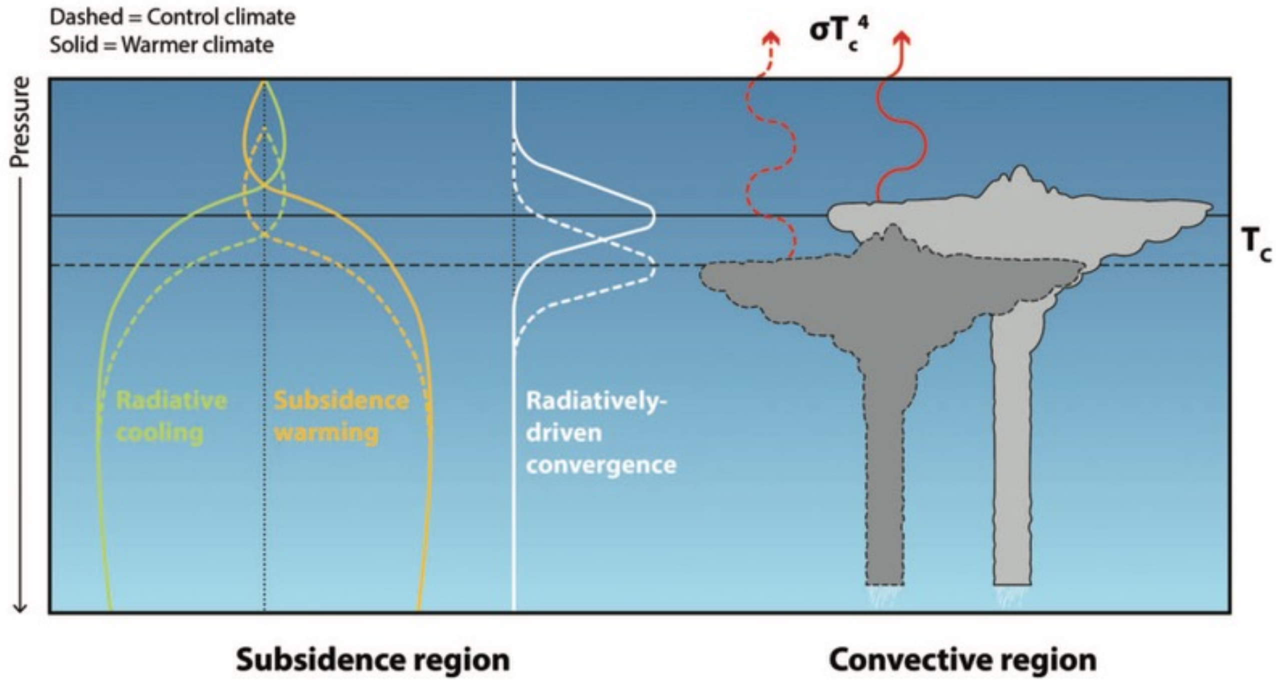
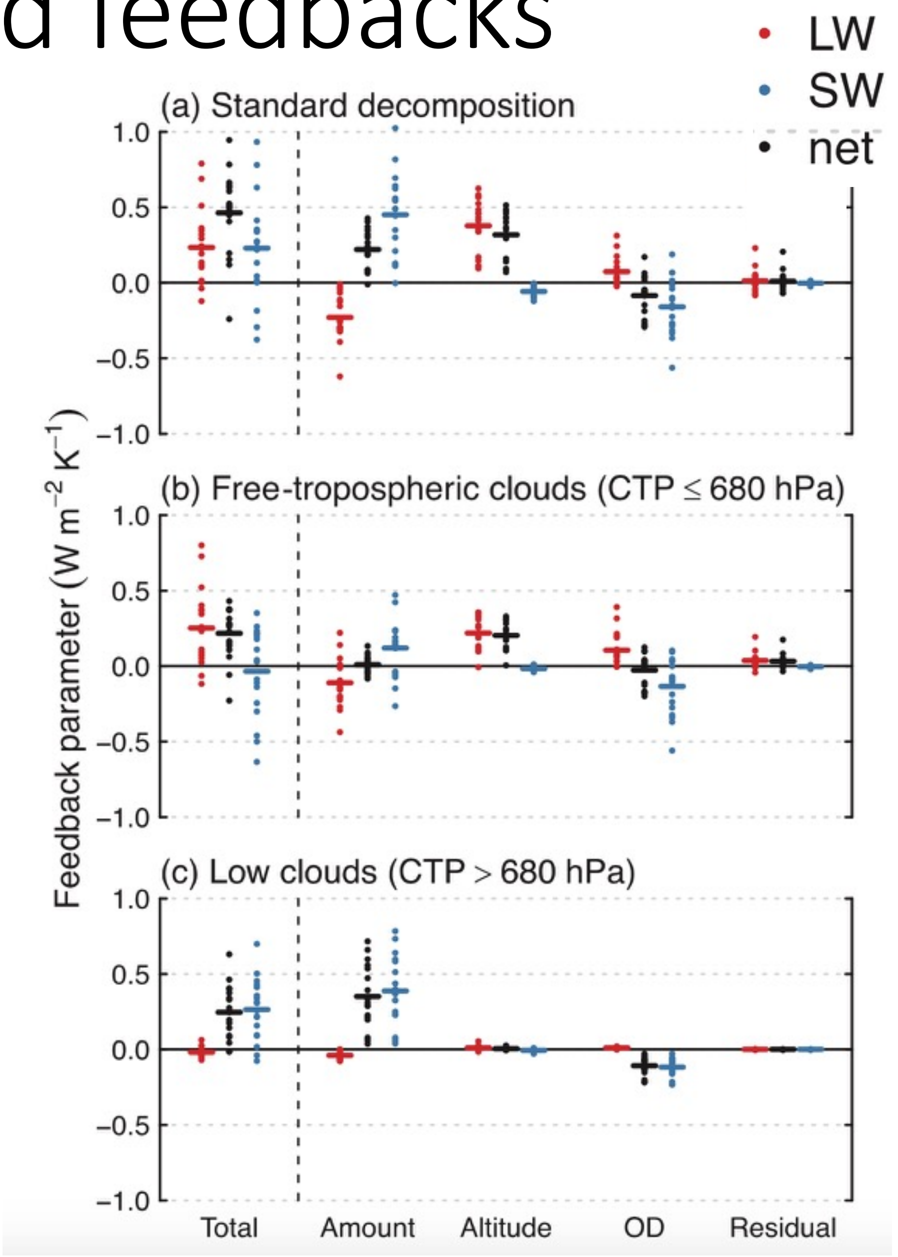


FIGURE 5 | Schematic of the relationship between clear-sky radiative cooling, subsidence warming, radiatively-driven convergence, and altitude of anvil clouds in the tropics in a control and warm climate, as articulated in the fixed anvil temperature hypothesis. Upon warming, radiative cooling by water vapor increases in the upper troposphere, which must be balanced by enhanced subsidence in clear-sky regions. This implies that the level of peak radiatively-driven convergence and the attendant anvil cloud coverage must shift upward. T_C denotes the anvil cloud top temperature isotherm.

Ceppi et al. 2017

Cloud feedbacks

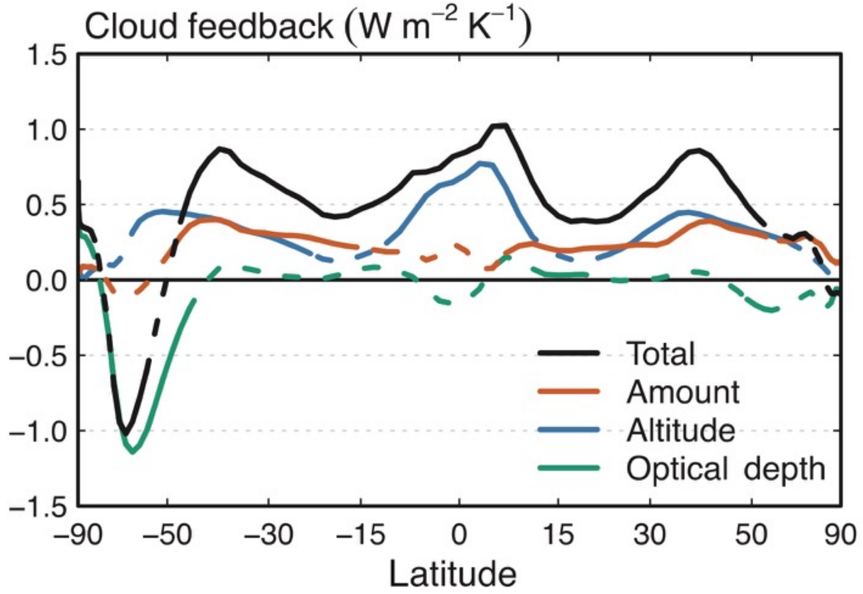


multimodel-mean LW feedback is similar to just the altitude feedback of rising free-tropospheric clouds (Figure 2(b)).

SW cloud feedback is due to changes in low cloud amount and optical depth (Figure 2(c)).

Zelinka et al. 2016

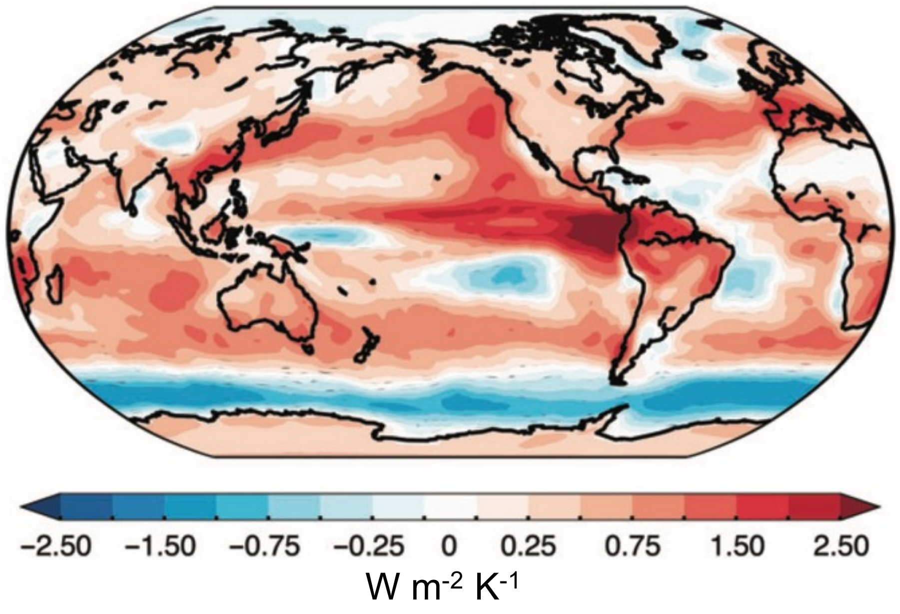
Cloud feedbacks



Zonal-, annual-, and multimodel-mean net cloud feedbacks in a set of 11 CMIP3 and 7 CMIP5 models.

Solid: ≥ 75% models agree on the sign of the feedback

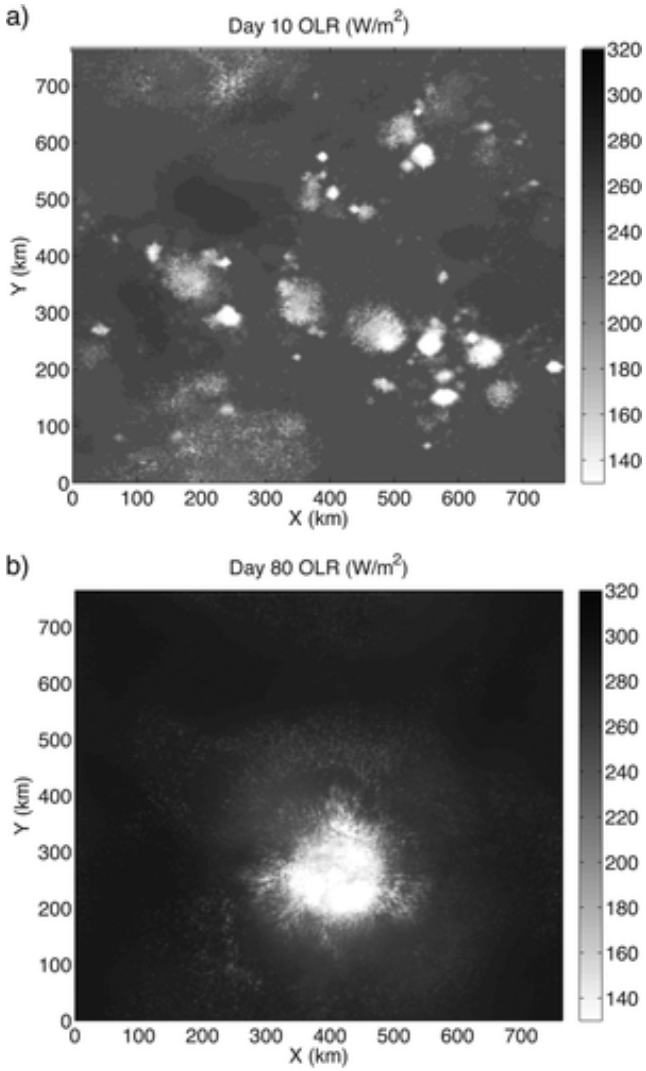
Dashed: < 75% models agree on sign



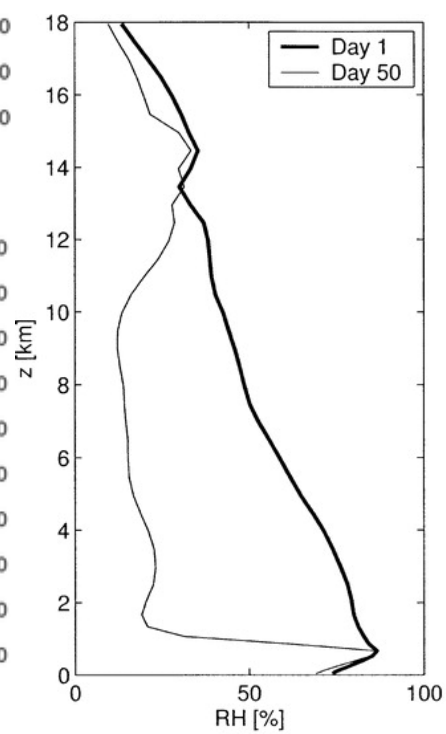
Spatial distribution of the multimodel-mean net cloud feedback in a set of 11 CMIP3 and 7 CMIP5 models with abrupt CO_2 increase

Zelinka et al. 2016

Reminder: aggregation affects mean state



Self-aggregation...
increases atmospheric radiative cooling,
warms and dries mean state,
reduces high clouds,
enhances dryness of dry regions.



Question: Can you explain how self-aggregation might:

1. Dry the mean state?
2. Warm the mean state?
3. Reduce high clouds?
4. Enhance dryness in dry regions?

Wing and Emanuel (2014) Bretherton et al. (2005)

SST dependence of aggregation

Khairoutdinov and Emanuel 2010: aggregation only occurs above an SST threshold of 298 K:

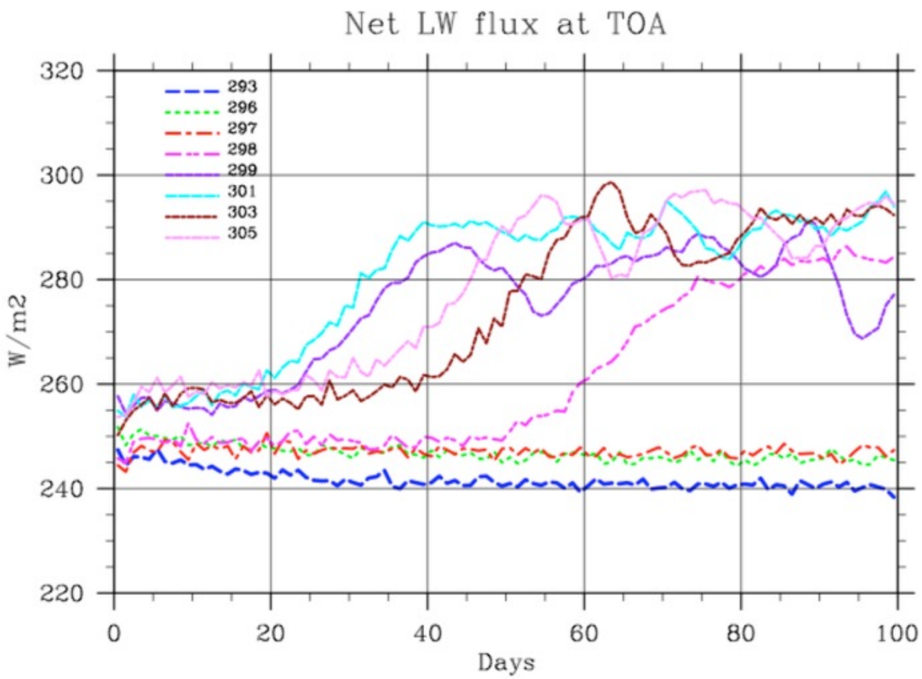


Figure 3 Net outgoing longwave flux averaged over top of the model domain, as a function of time, for eight values of the surface temperature using the CRM.

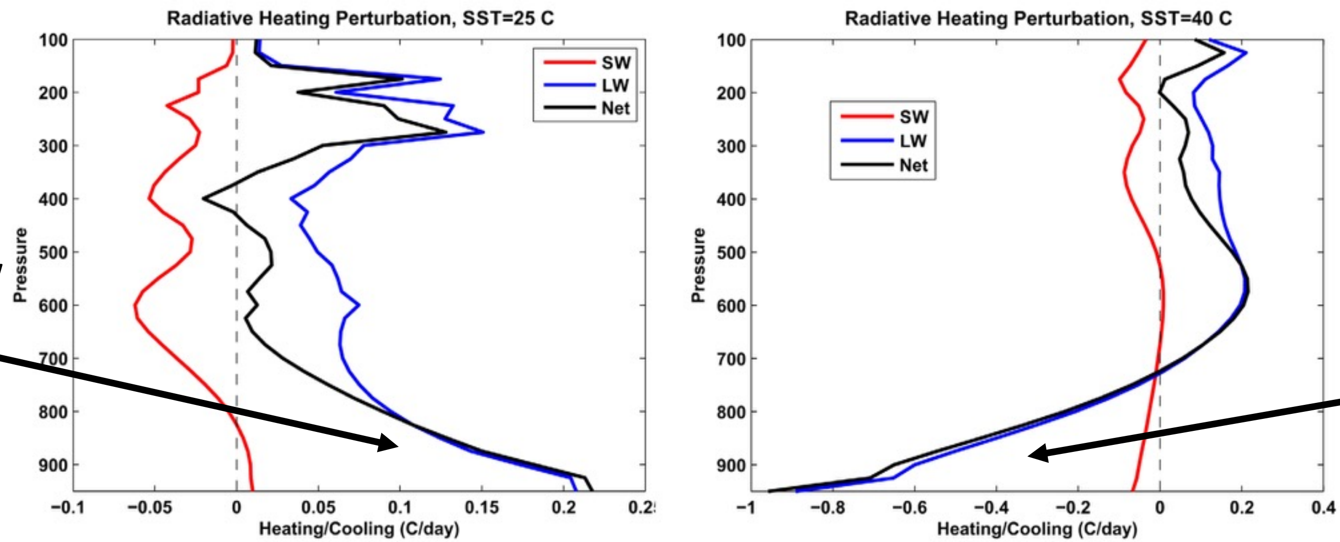
Proposed a hypothesis of self-organized criticality where:
higher SSTs -> agg. -> larger OLR -> lower SSTs -> disagg. -> lower OLR -> higher SSTs and so on.

So aggregation would act to maintain tropical SSTs in main convective regions around a critical value around 300 K, similar to observed current climate.

SST dependence of aggregation

Emanuel et al. 2014 present a possible mechanism to explain this SST threshold for self-aggregation:

Low SST: drying causes clear-sky LW *warming*



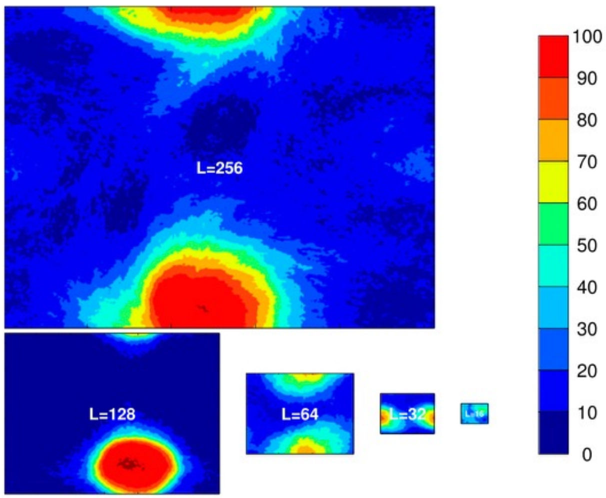
High SST: drying causes clear-sky LW *cooling*

Figure 5. Perturbation shortwave (red), longwave (blue), and net (black) radiative heating rates in response to an instantaneous reduction of specific humidity of 20% from the RCE states for (left) SST = 25°C and (right) 40°C. Note the different scales on the abscissas.

And low-level cooling in dry subsidence regions is a critical mechanism for early stages of self-aggregation (Muller and Held 2012, Muller and Bony 2015)

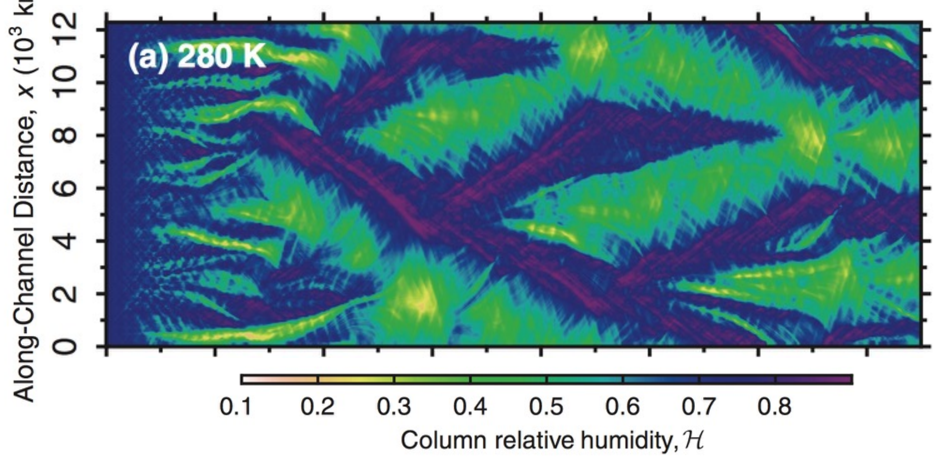
But some complications …

Abbot 2014 (~**250 K**)

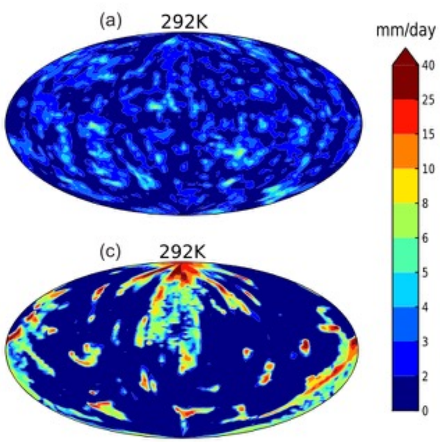


Several studies later show that self-aggregation can occur at SSTs that are much lower than 298 K:

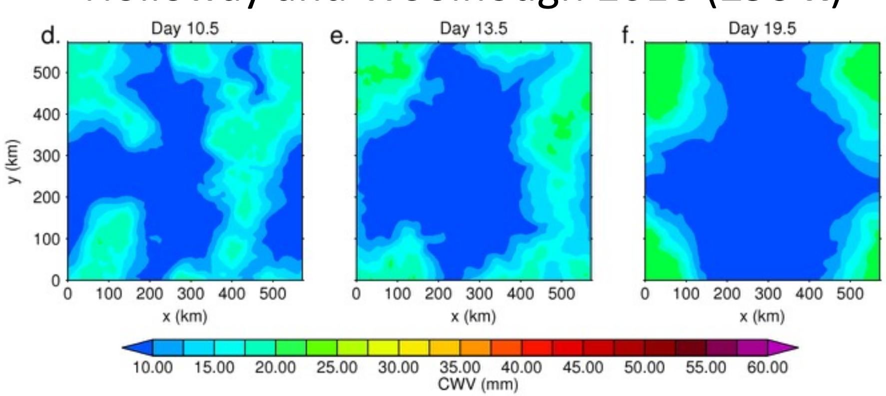
Wing and Cronin 2016 (**280 K**)



Coppin and Bony 2015 (**292 K**)



Holloway and Woolnough 2016 (**290 K**)



But some complications …

- Although observational studies agree that OLR increases with increased organisation/aggregation, they are not conclusive on the change in *total surface forcing* (including SW radiation and turbulent fluxes) that is associated with increased aggregation (Tobin et al. 2012, 2013)
- The Emanuel et al. (2014) mechanism is valid for clear sky radiation, but low clouds play an important role in radiative cooling in dry subsidence regions that helps early stages of self-aggregation (including in low-SST simulations): (Muller and Held 2012, Wing and Cronin 2016, Holloway and Woolnough 2016)
- There is some evidence of self-aggregation not occurring *above* a high enough SST threshold, although this may be due to domain-size limitations (Wing and Emanuel 2014)

Ocean coupling

Most studies of self-aggregation use atmosphere-only simulations with prescribed SST. However, ocean coupling is highly relevant for climate implications.

Hohenegger and Stevens (2016) show that shallow slab oceans lead to reduced self-aggregation due to cloud shading, which cools the surface beneath convective clusters:

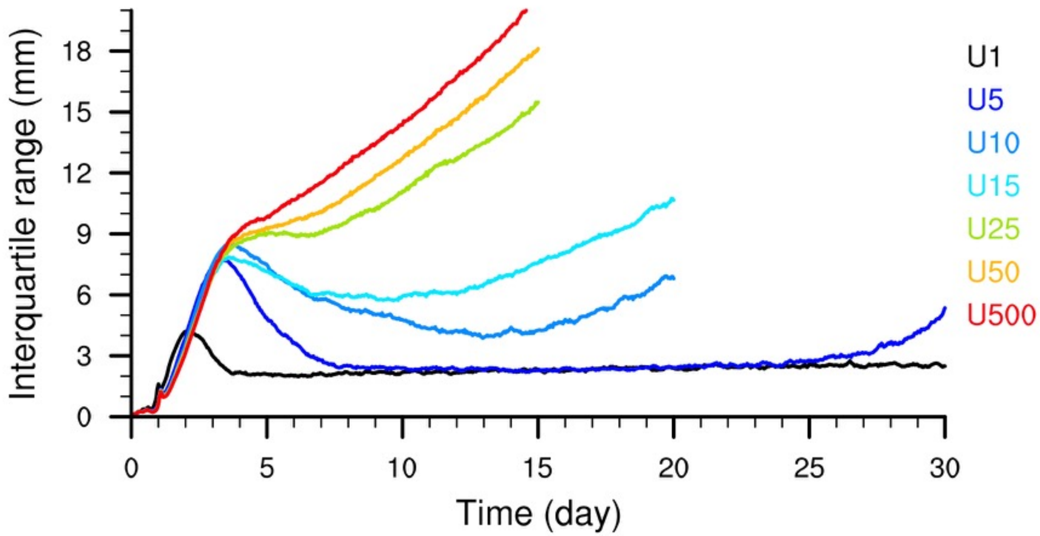
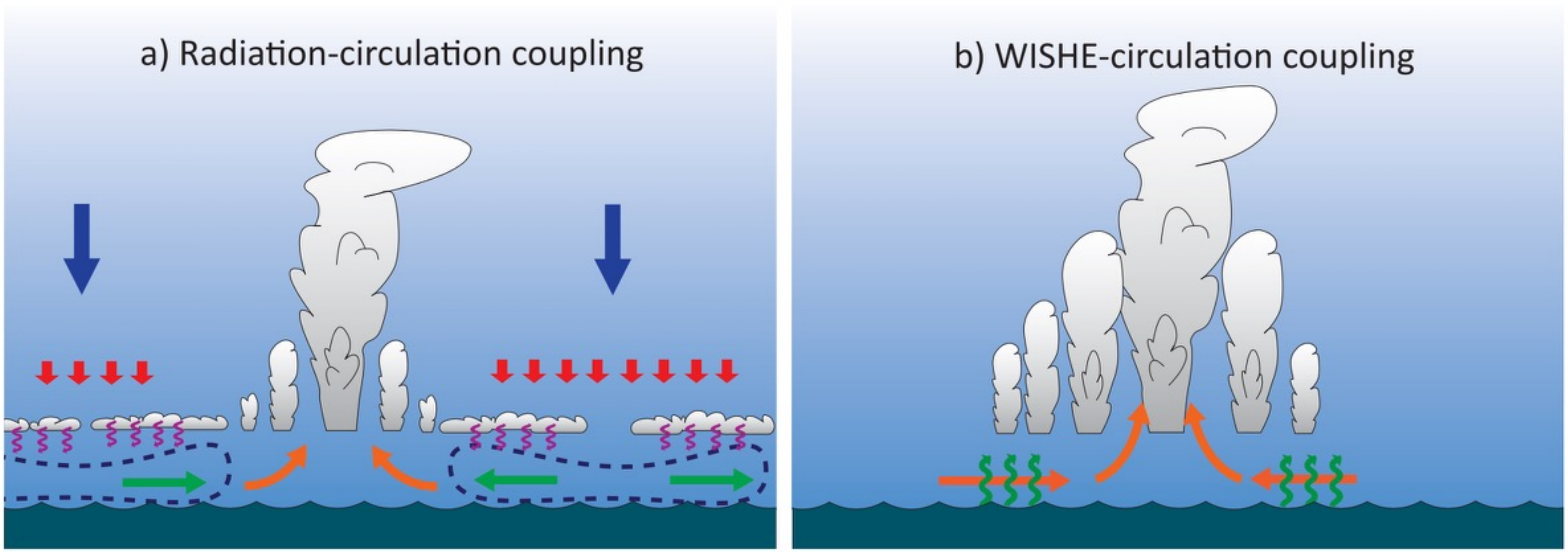


Figure 3. Interquartile range (75th minus 25th percentile) in total column water I_q (mm) for the simulations with different ocean heat capacity (through different *d*). The curves are stopped after 15, 20, or 30 days depending on when self-aggregation begins.

Hohenegger and Stevens (2016) also found that aggregation stabilised climate and that convection permitting simulations had very different climate sensitivity compared to parameterised convection simulations.

Different mechanisms for different SSTs?

(Review)



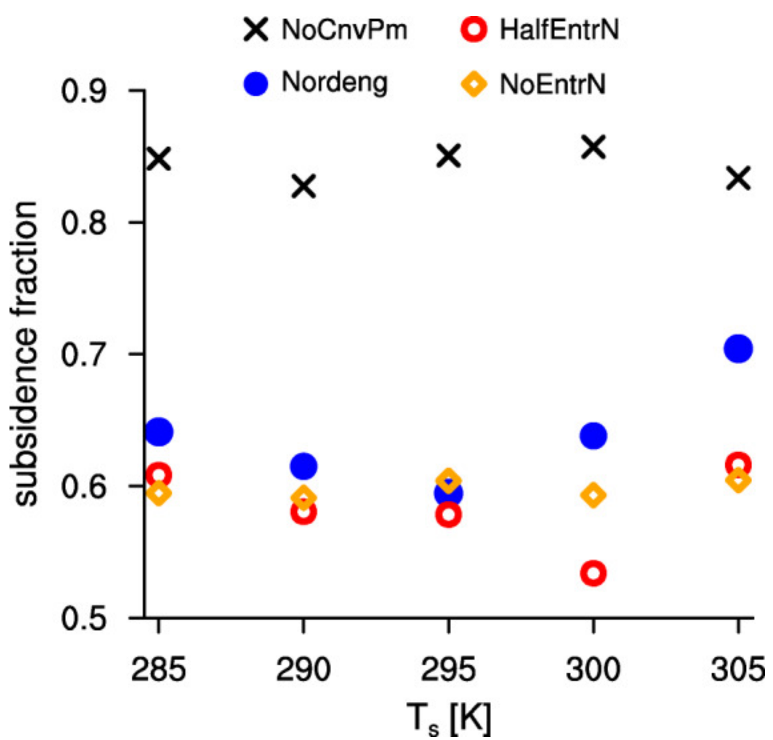
Low SST

High SST

Coppin and Bony (2015)

Dependence on convection representation and entrainment?

Review: Becker et al. (2017) find that convective parameterisation (on/off, and entrainment mixing value) affect SST dependence of aggregation in a global model:



They also find that WISHE (wind-evaporation feedback) is important at low SSTs but not at high SSTs (for parameterised convection), where evaporation is higher in dry regions. On the other hand, moisture-convection feedbacks become more important at higher SSTs because larger saturation deficits lead to more dry air dilution per mixing amount.

Anvil cloud effects

Bony et al. (2016):

- Anvil cloud tops reach higher altitude with warming (the positive cloud altitude effect), but also shrink in size

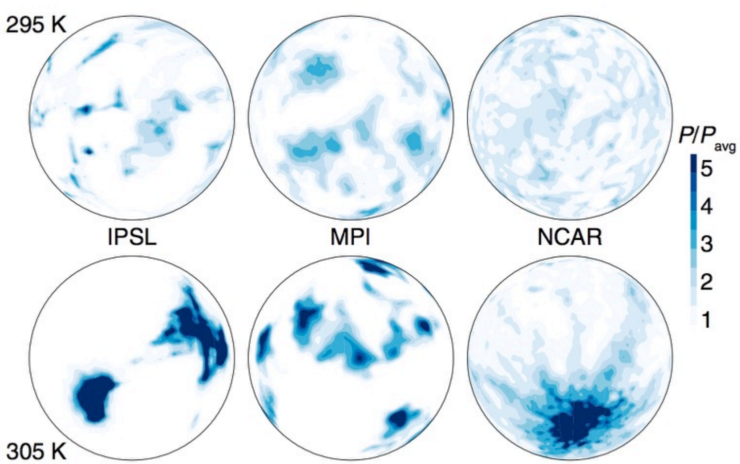
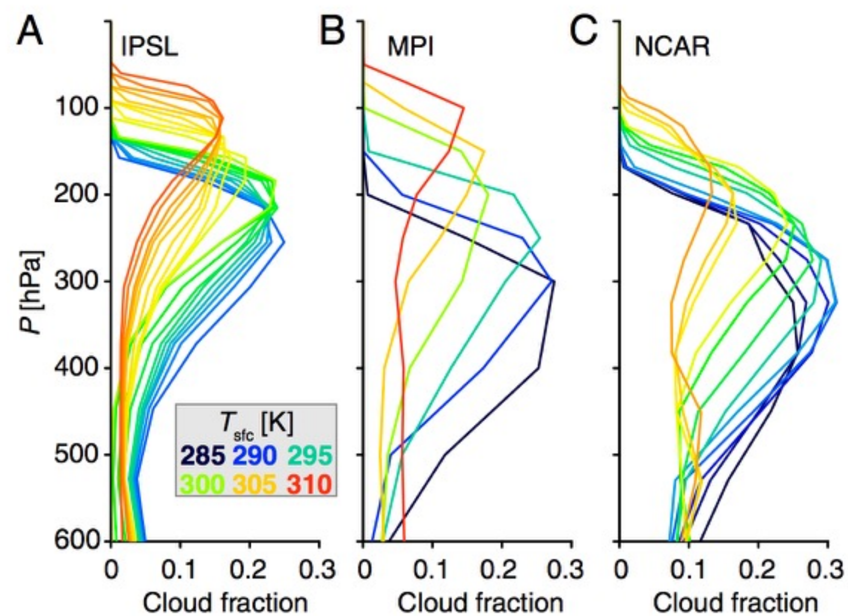


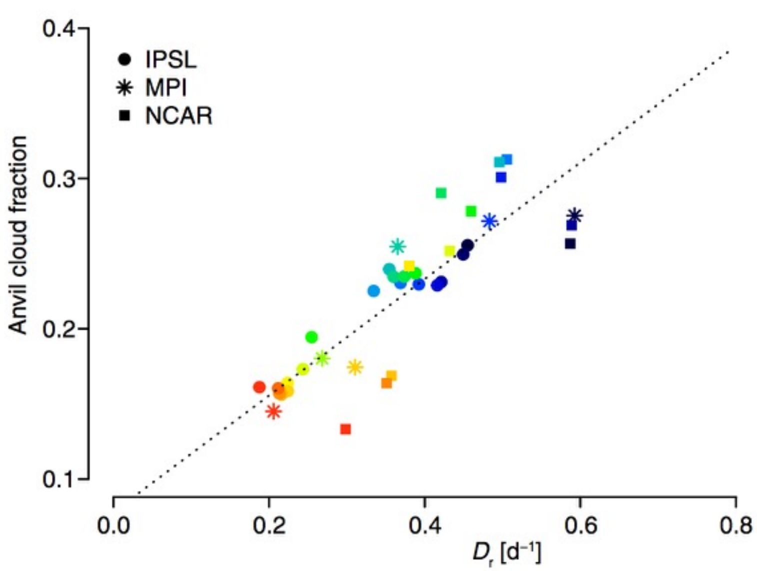
Fig. 1. Monthly precipitation (normalized by its global mean value) predicted by the IPSL, MPI, and NCAR GCMs in RCE simulations forced by an SST of (*Top*) 295 K and (*Bottom*) 305 K.



Anvil cloud effects

Bony et al. (2016):

- The shrinking is related to increased upper-level stability due to a warmer moist adiabat, which means less clear-sky subsidence per radiative cooling amount and less upper-level divergence meaning less anvil spread (a *stability-iris effect*)



Relationship between the anvil cloud fraction and the radiatively driven divergence D_r predicted by three GCMs in simulations forced by a range of SSTs (colours ranging from blue to red correspond to increasing SST, and each GCM is associated with a different marker). The dashed line represents the linear regression line across all points.

Anvil cloud effects

Bony et al. (2016):

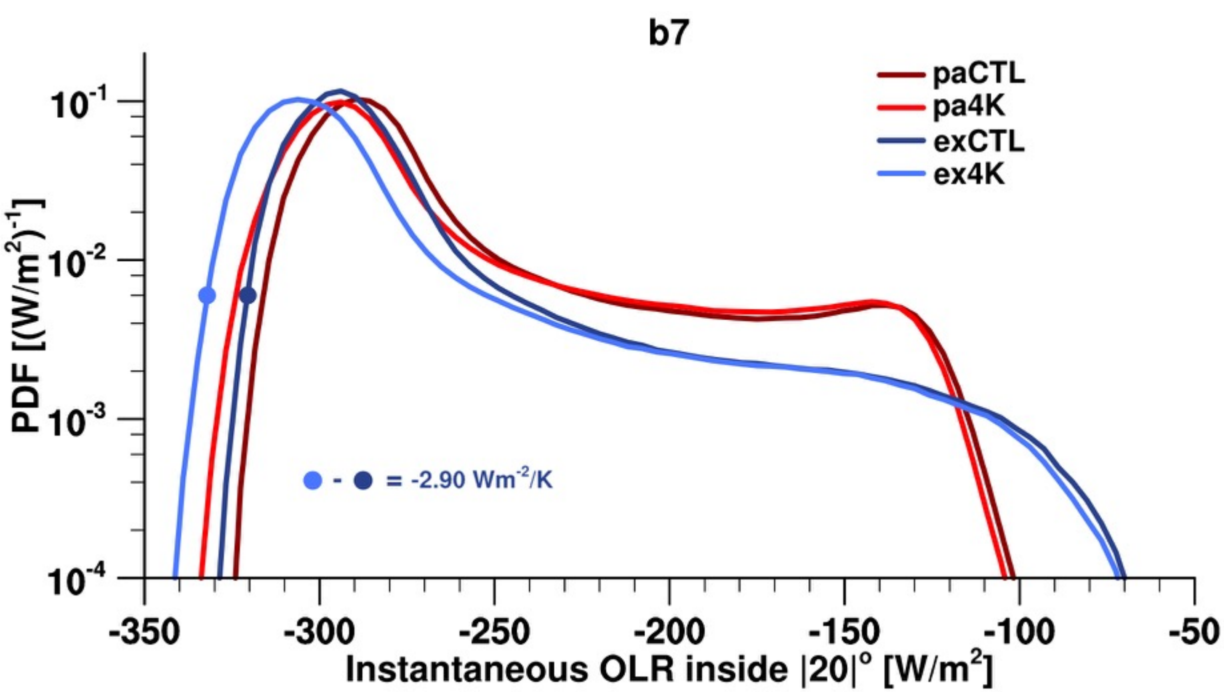
- Anvil cloud tops reach higher altitude with warming (the positive cloud altitude effect), but also shrink in size
- The shrinking is related to increased upper-level stability due to a warmer moist adiabat, which means less clear-sky subsidence per radiative cooling and less upper-level divergence meaning less anvil spread (a *stability-iris effect*)
- Increased aggregation/clustering also leads to moister low-level parcels and less dilute plumes in convecting regions -> warmer moist adiabat -> less anvil spread and less anvil fraction
- Likely leads to a narrowing of rain regions (such as ITCZ) in a warmer world
- May have small negative effect on climate sensitivity, but this needs further research

Aggregation: Iris effect?

Mauritsen and Stevens (2015): "**A controversial hypothesis suggests that the dry and clear regions of the tropical atmosphere expand in a warming climate and thereby allow more infrared radiation to escape to space. This so-called iris effect could constitute a negative feedback that is not included in climate models. … We propose that, if precipitating convective clouds are more likely to cluster into larger clouds as temperatures rise, this process could constitute a plausible physical mechanism for an iris effect.**"

“Iris” effect or reduced water vapour feedback?

Retch et al. (2019): more negative longwave feedback in explicit convection simulations due not to changes in anvil but to *changes in clear sky*: tropical subsidence regions show near-constant RH with warming, whereas parameterised simulations show increased RH in those regions:



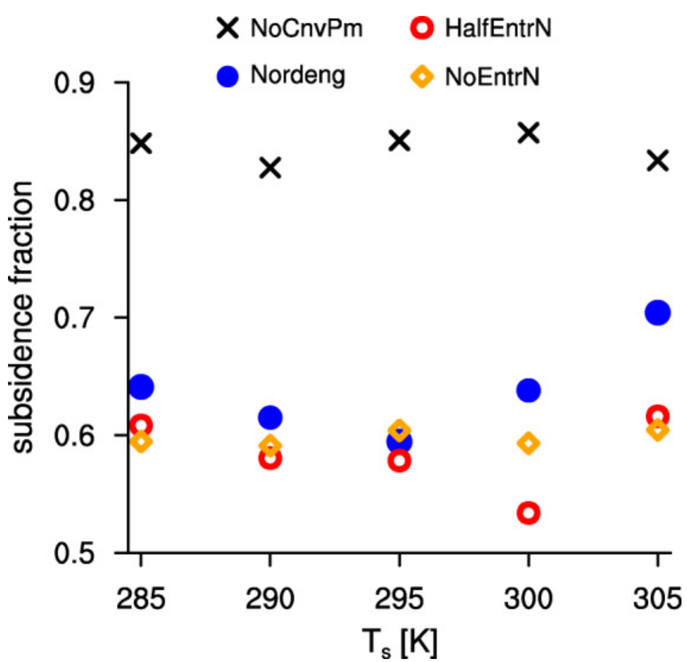
Aggregation: Climate Sensitivity

Becker et al. (2017) find that simulations with more aggregation have smaller estimated climate sensitivities (though these are fixed SST runs with variations, so should be viewed with caution):

Table 4. Top-of-Atmosphere Radiation Imbalance R_{TOA}, in W m^{-2} [a]

Simulation	285 K	290 K	295 K	300 K	305 K
NoCnvPm	−14.0	−32.7	−38.1	−58.2	−72.6
Nordeng	22.8	7.4	6.8	15.7	−8.5
HalfEntrN	26.7	11.0	16.4	23.8	4.4
NoEntrN	32.6	20.7	29.9	26.0	13.3

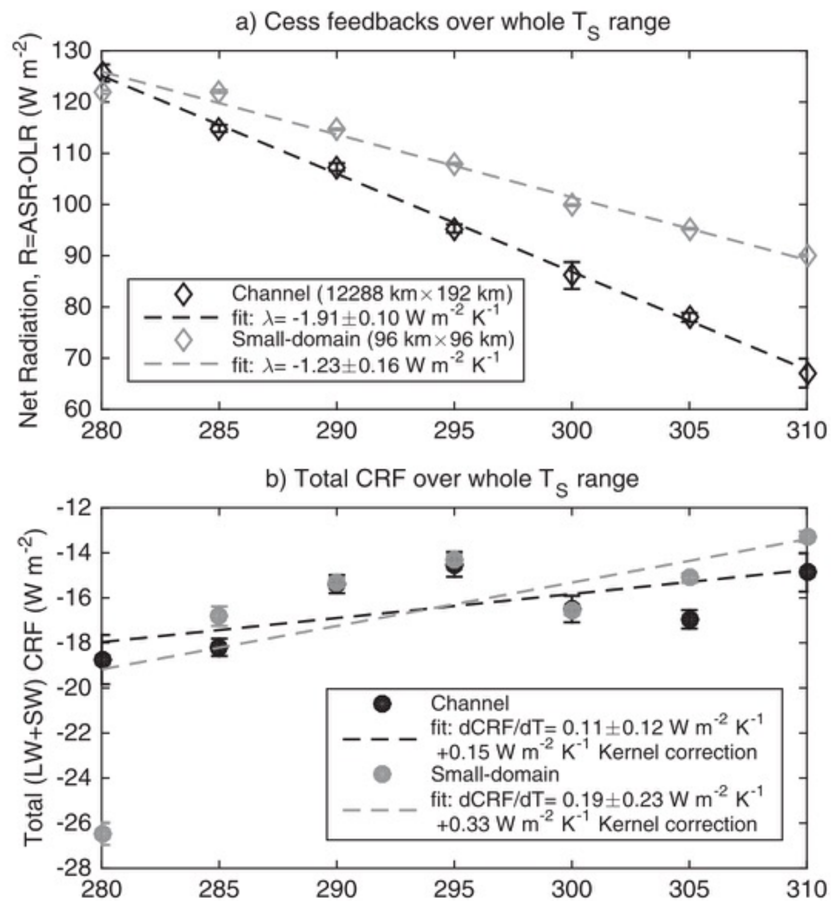
[a] A strong decrease of R_{TOA} with SST implies a small climate sensitivity.



Aggregation: Climate Sensitivity

Cronin and Wing (2017) also find indications of a modest reduction of climate sensitivity (steeper negative slope upper panel) for aggregated convection (channel simulations, dark line).

They estimate total feedbacks to be more negative by 0.68 W m^{-2} K^{-1} in the channel simulations, with contributions from both a more negative non-cloud feedback (by 0.41) and a less positive cloud feedback (by 0.27).



Issues

- Subgrid versus resolved processes?
- Estimates of uncertainty in climate sensitivity are largely based on studies using GCMs, which don’t represent convective and cloud processes directly.
- Temperature dependence of aggregation still uncertain: RCEMIP and better aggregation metrics could help (cf. Wing 2019)
- Clear-sky versus cloud feedbacks
- Effects on climate sensitivity that directly link to aggregation (convective clustering) versus other effects related to tropical circulation, cloud and water vapour
- Separate effects of LW and SW changes (even if net effects are small)

Summary

- Climate feedbacks can amplify or dampen warming: positive feedbacks enhance warming
- Largest uncertainty in GCM feedbacks is from clouds: particularly low clouds but also anvil clouds
- Aggregation/organisation of convective clouds may change with warming: e.g. expanding dry regions, narrowing rainy regions? Still uncertainty about this and its effects on climate sensitivity.
- Anvil cloud fraction is likely to reduce with warming, but effects on climate sensitivity may be small.
- Many outstanding topics of research (ocean coupling, explicit convection, subgrid processes)

Questions

- Does anyone (students or other instructors) have other points they'd like to raise about this very current research topic?
- How might unresolved or under-resolved processes change our view of uncertainty in climate sensitivity?
- How could aggregation affect low clouds?
- What real-world phenomena might be related to aggregation and might change with a warming climate?

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