Climate Modeling Challenges Related to Global Cloud Feedbacks

Stephen Klein[1]

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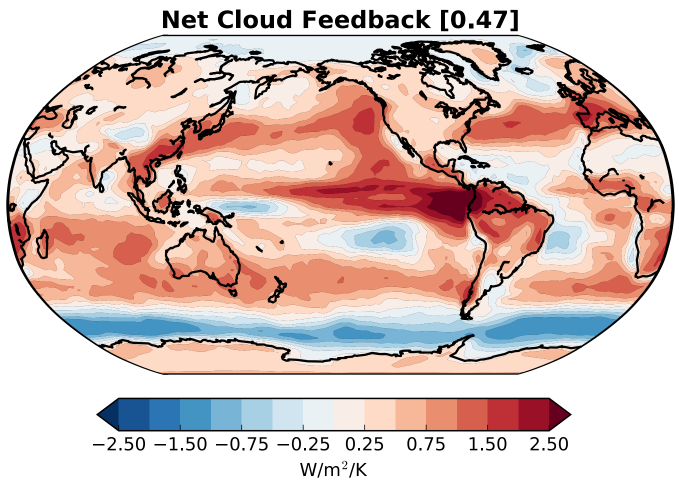
Average climate model cloud feedback



Zelinka et al. (2016)

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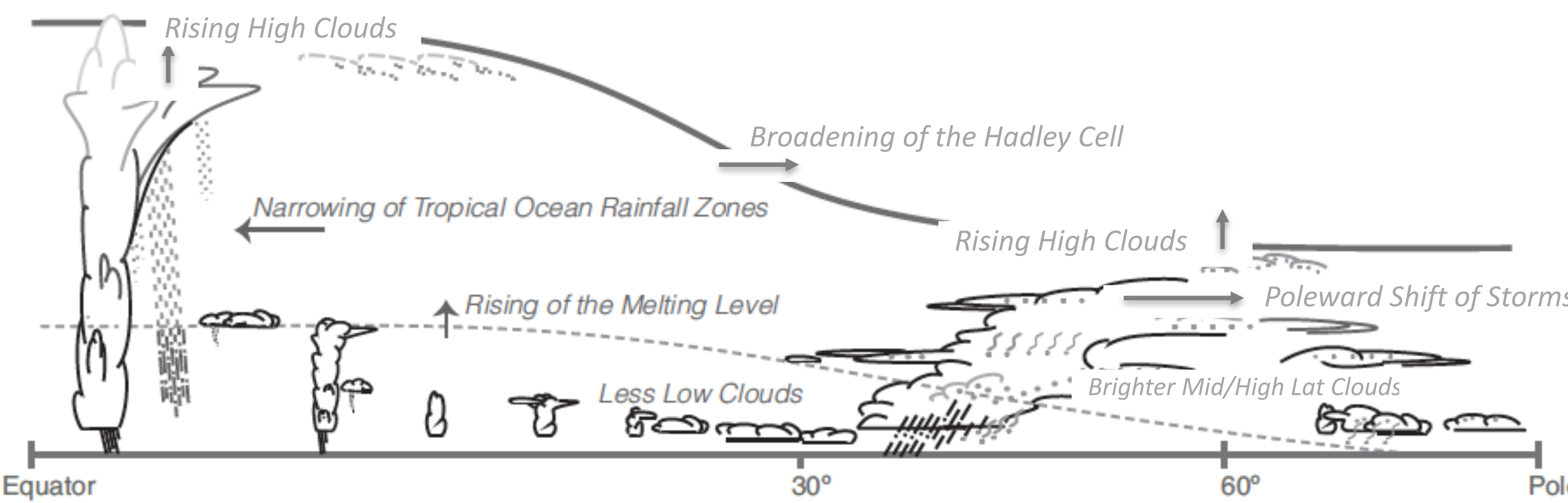
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-PRES-732907

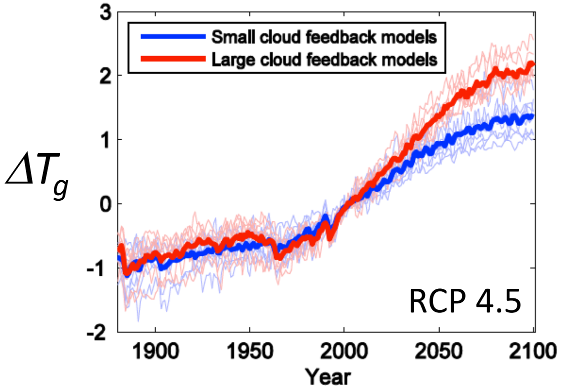
- Introduction
- Cloud Feedbacks for
  - Tropical Low Clouds
  - Extra-tropical Low Clouds
- Summary

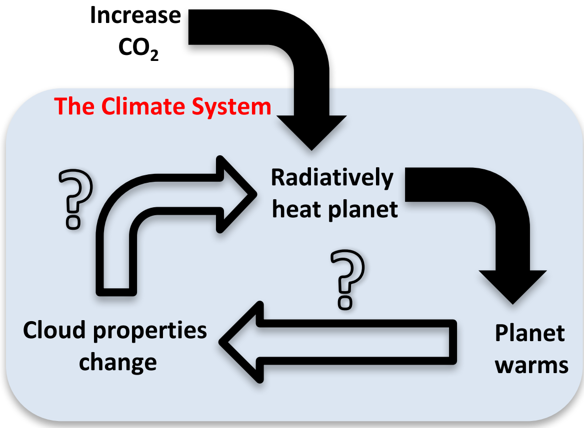


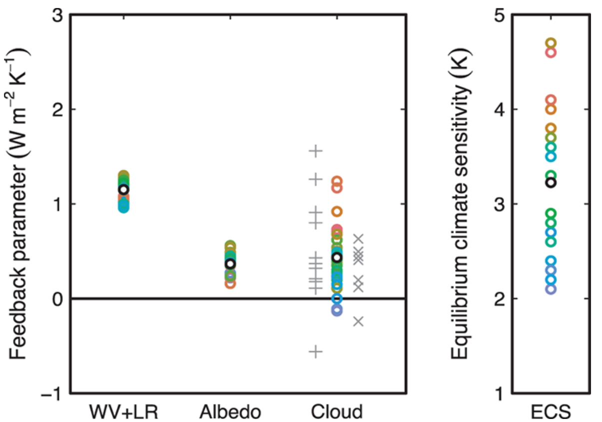
Modified from IPCC AR5, Figure 7.11

Cloud Feedbacks (intro.)

- Cloud feedbacks → Climate Sensitivity
- Do cloud changes **increase** or **decrease** the planet's radiation imbalance?
  - Increase ➔ Positive cloud feedback
  - Decrease ➔ Negative cloud feedback
- Cloud Feedback → $\frac{dR}{dT_g}$ (W/m²/K)
- Model cloud feedbacks vary widely
  - Other feedbacks have less spread (uncertainty?)

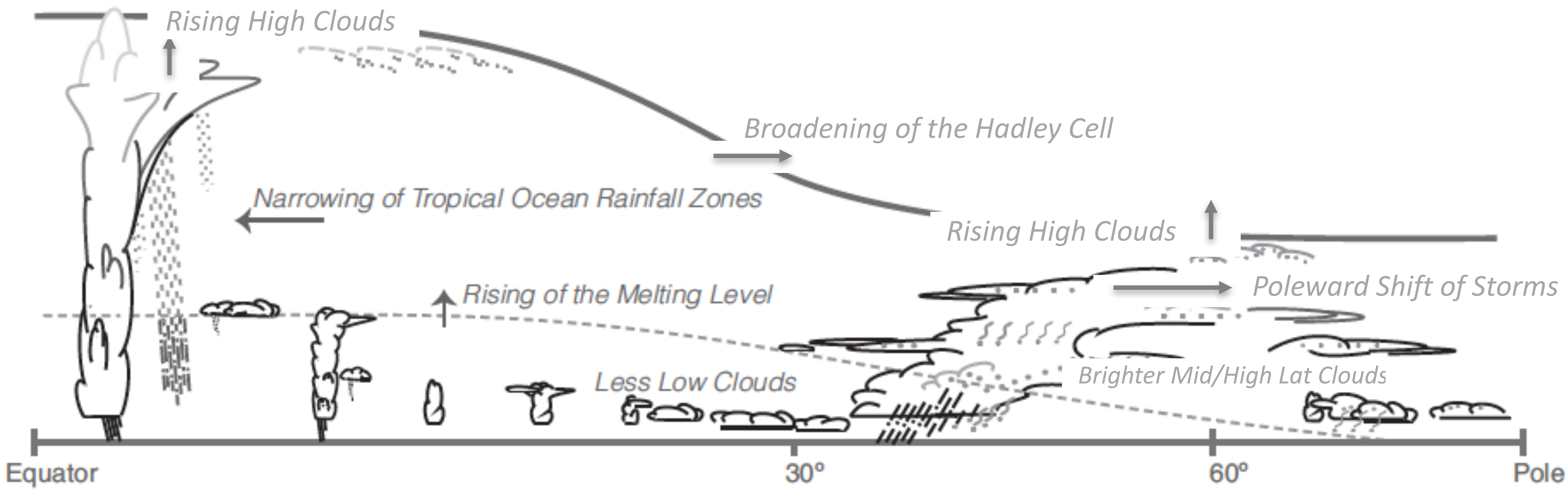






Ceppi et al. (2017)

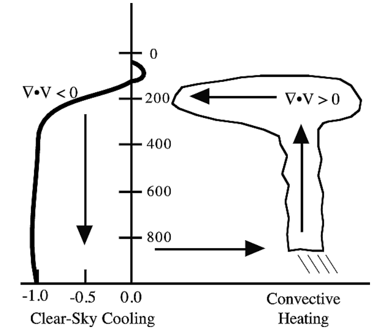
Cloud Responses to Warming



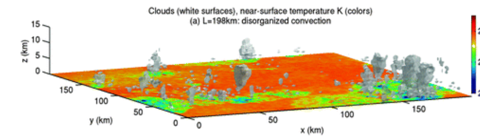
Modified from IPCC AR5, Figure 7.11

Response of **ALL** radiatively important clouds matters

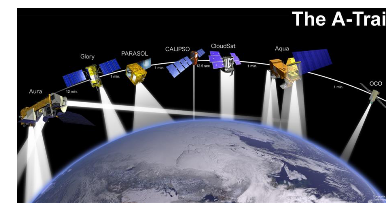
Significant Progress from:



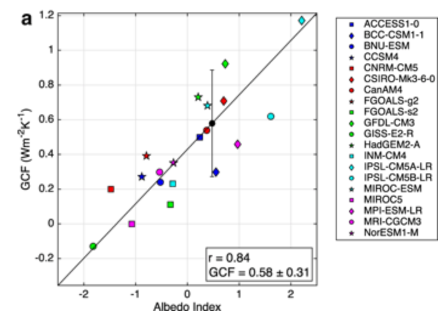
- Theoretical understanding



- Fine-scale models

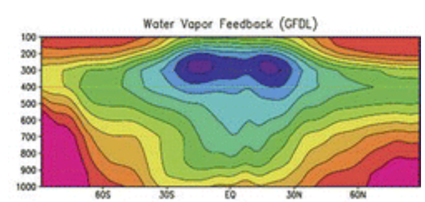


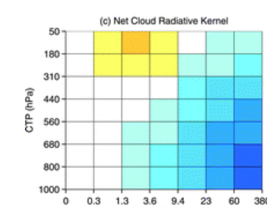
- New observations and their use in emergent constraints



- Advanced diagnostic tools and creative analysis applied to model simulations of climate change (CMIP)

$$\overline{R(w_A+\delta\overline{w}, T_A, c_A, a_A)} - \overline{R(w_A, T_A, c_A, a_A)} \approx \sum_i \overline{\frac{\partial R}{\partial w_i}}\,\delta\overline{w}_i \equiv \sum_i K_i^w\,\delta\overline{w}_i.$$





Robust Cloud Feedbacks: Recent Advances

Feedback Type	Supported by:			Feedback Sign	Does the average GCM do this?
	Theory	High-Resolution Models	Observations		
High clouds everywhere will rise	✓	✓	✓	+	✓
Tropical high cloud extent will decrease	✓	✓	✓	0	✓
Tropical low cloud extent will decrease	✓	✓	✓	+	✓
Extra-tropical low cloud brightening will be small			✓	0	✗
Cloud and other feedbacks not constant in time				+	✓

- With this talk, I will discuss:
  - Some of what we know (but there's still a lot we don't know)
  - Present observational targets for model simulations that are relevant for cloud feedbacks (so called "emergent constraints")
  - Possible pathways for climate models to simulate these targets

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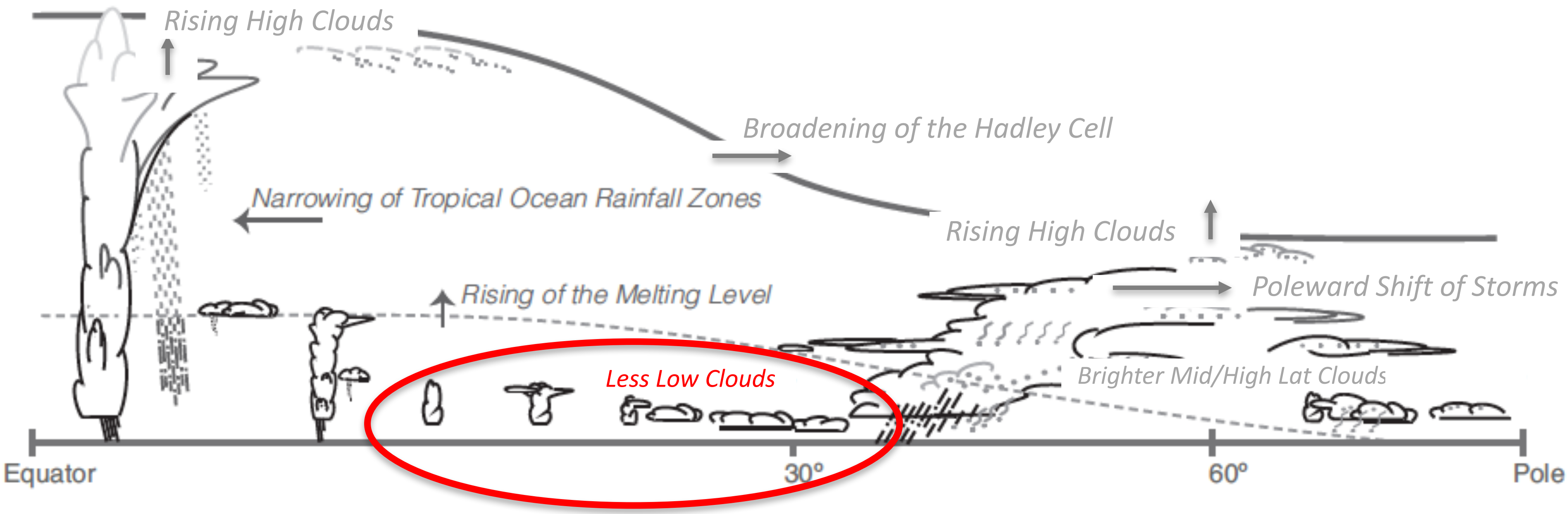
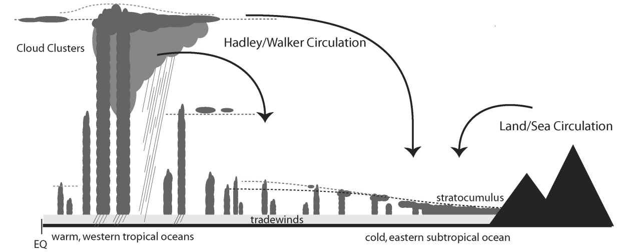


Modified from IPCC AR5, Figure 7.11

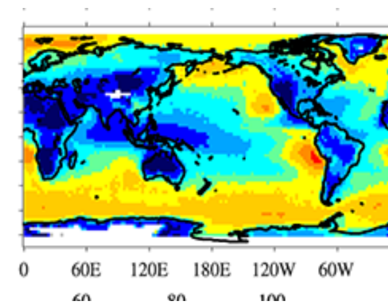
Tropical Low Clouds in Observations & Models



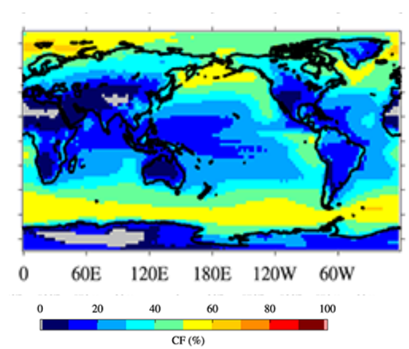
Stevens (2005)

- Climate models typically underestimate low clouds
- Usually "too few - too bright"
- Problematic to represent a thin (~100-300 m) stratiform cloud under trade inversion
- Clouds have improved a lot in some models

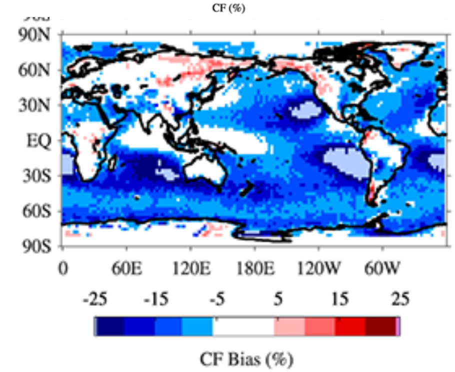
Calipso Satellite Observations



Climate Models (w/Calipso simulator)



Models Minus Observations

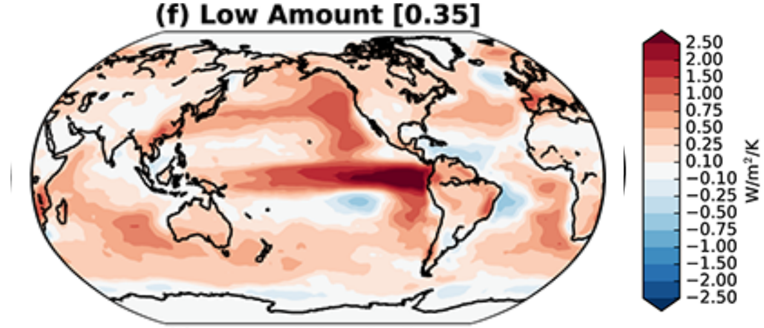


Cesana and Waliser (2016)

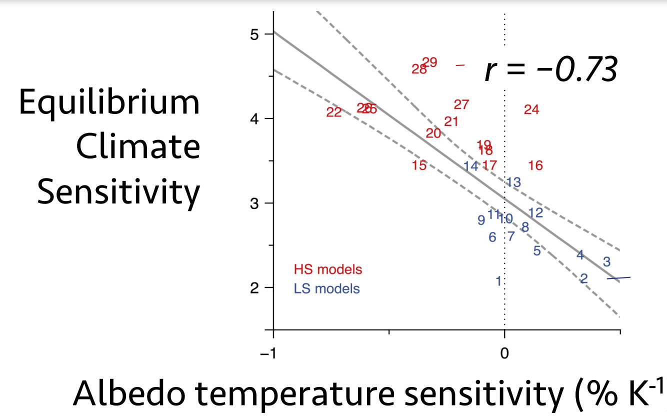
Tropical Low Cloud Feedbacks

- Climate models predict low-cloud amount to decrease on average
  - Largest single feedback on average
- The response of tropical low clouds to warming is the single cloud type with the strongest correlation to equilibrium climate sensitivity
  - Due to albedo changes not compensated by longwave radiation trapping changes
- Observations and high-resolution modeling agree that tropical low cloud feedbacks should be positive

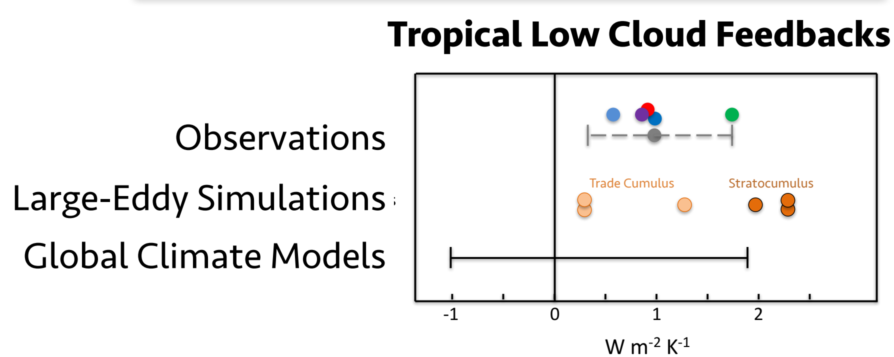
Average Low Cloud Amount Feedback in Climate Models



Zelinka et al. (2016)



Brient and Schneider (2016)



Klein et al. (submitted)

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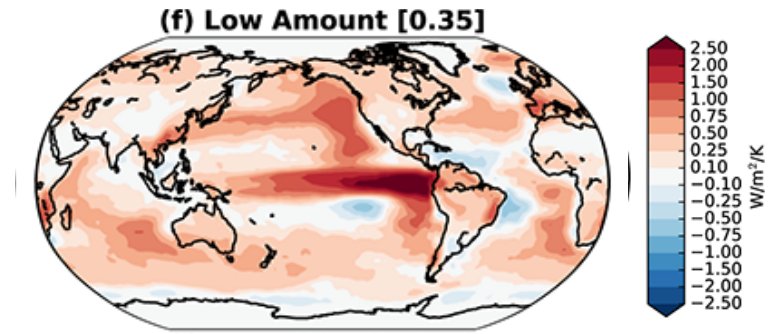

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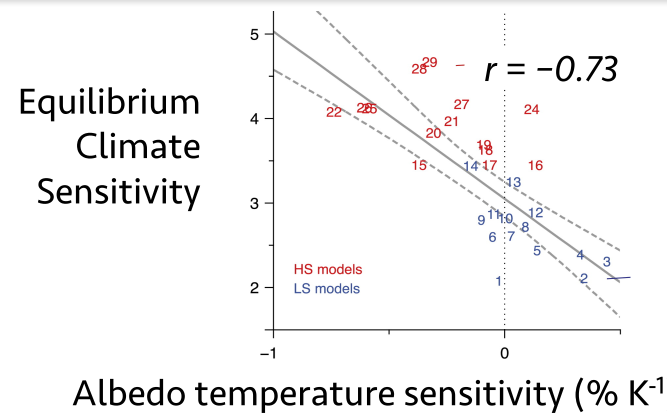

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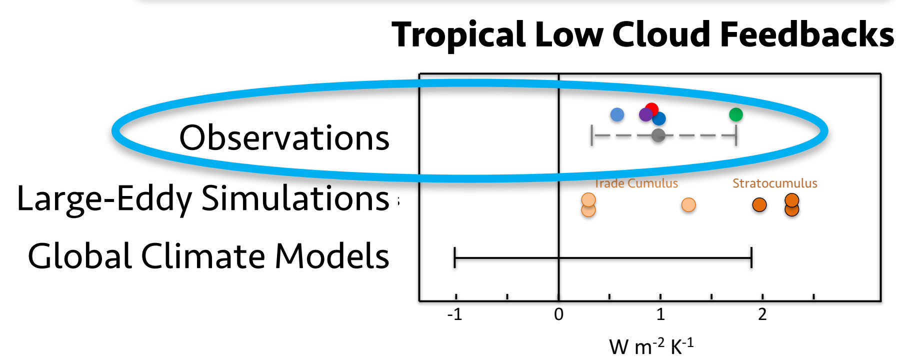


Klein et al. (submitted)

Low Cloud Feedbacks from Cloud-Controlling Factors

- Low clouds are a fast (~hours-days) response to "cloud-controlling factors" (CCF) of the environment *(Stevens and Brenguier 2009)*
- If we assume that these cloud sensitivities are "time-scale invariant", and we know how CCF change, then we can predict the cloud feedback:

Cloud Sensitivity to CCF (x_i) ← **from Observations (Usually inter-annual variability)**

$$\frac{dC}{dT_g} = \sum_i \frac{\partial C}{\partial x_i} \frac{dx_i}{dT_g}$$

$x_i \in$ *{ SST, EIS, ω, RH_{tropo}, temperature advection}*

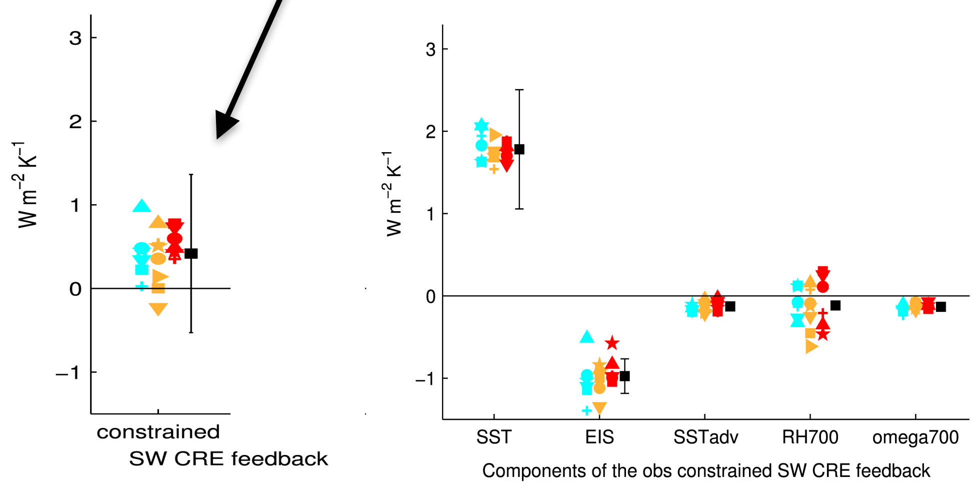
Low Cloud Feedback

Climate Change in CCF ← **from Climate Models**

Qu et al. (2014, 2015), Zhai et al. (2015), Zhou et al. (2015), Myers and Norris (2016), Brient and Schneider (2016), and McCoy et al. (2017)

Low Cloud Feedbacks from Cloud-Controlling Factors

$$\frac{dC}{dT_g} = \sum_i \frac{\partial C}{\partial x_i}\frac{dx_i}{dT_g}$$



Observed cloud sensitivity with CCF change from good, average, or poor models

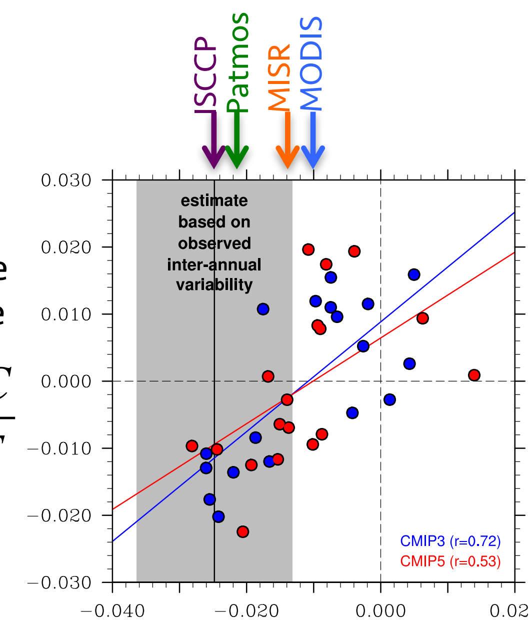
Observed cloud sensitivity and its error bars with average climate model CCF change

Myers and Norris (2016)

Climate Change

$$\frac{\Delta LCC}{\Delta SST}$$

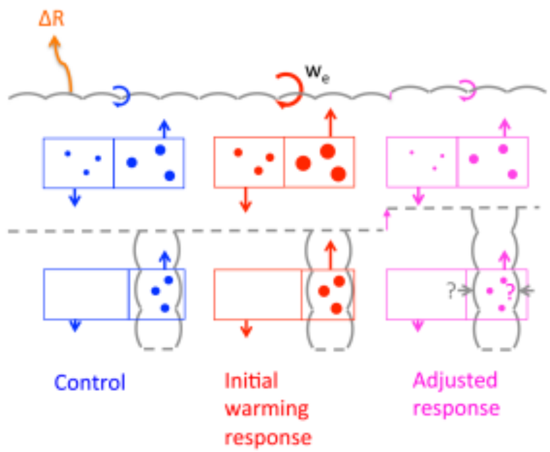
(K^{-1})



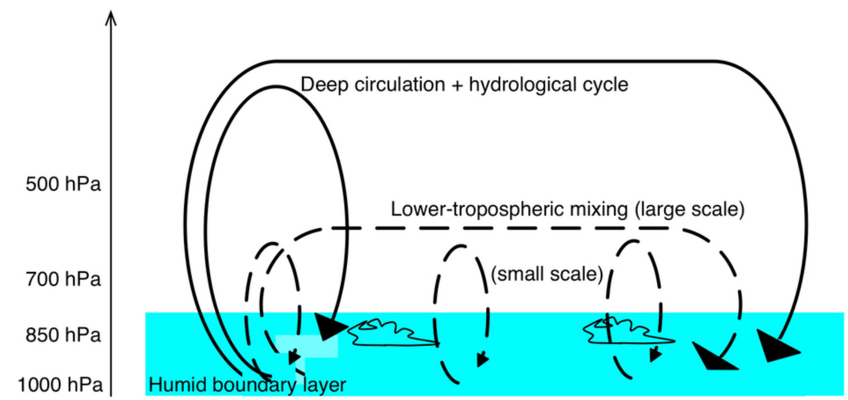
Sensitivity from Natural Variability $\left.\frac{\partial LCC}{\partial SST}\right|_{EIS}$ (K^{-1})

Qu et al. (2014, 2015)

Physical Basis for Cloud Sensitivities



Bretherton and Blossey (2014)



Sherwood et al. (2014)

- Increased vertical moisture flux in a warmer world promotes more efficient entrainment drying of the boundary layer ["entrainment liquid-flux adjustment"] *(Bretherton and Blossey 2014, Rieck et al. 2012)*

- Increased vertical moisture gradient in a warmer world increases the amount entrainment drying of the boundary layer *(Sherwood et al. 2014)*

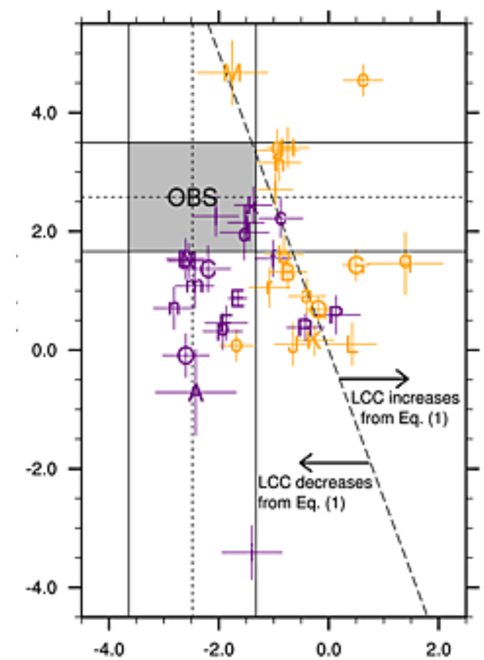
- Physical bases for cloud sensitivities to *EIS*, ω, RH_{tropo}, and *temperature advection* are well established

Climate Modeling Challenge #1

- Models should better simulate $\frac{\partial C}{\partial x_i}$
  - Low-cloud sensitivities in stratocumulus regions are highly variable and rarely correct *(Qu et al. 2015)*
  - Trade cumulus cloud sensitivities are just as problematic *(Nuijens et al. 2015)*

- How to improve models?
  - Obviously, mixing parameterizations matter a lot *(Brient et al. 2015)*
  - Vertical resolution still important
  - Cloud fraction parameterizations tied to EIS explained some of the negative low cloud feedbacks found in (older) models *(Qu et al. 2014, Geoffroy et al. 2017)*

$\frac{\partial C}{\partial EIS}$ (% K^{-1})



$\frac{\partial C}{\partial SST}$ (% K^{-1})

Qu et al. (2015)

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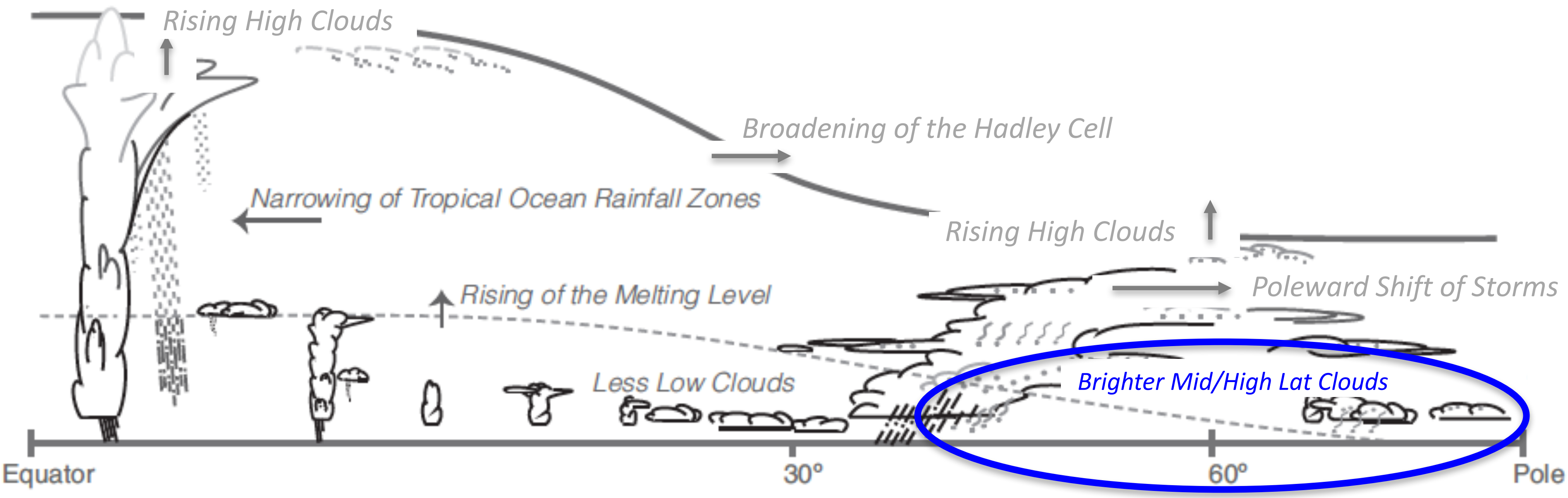
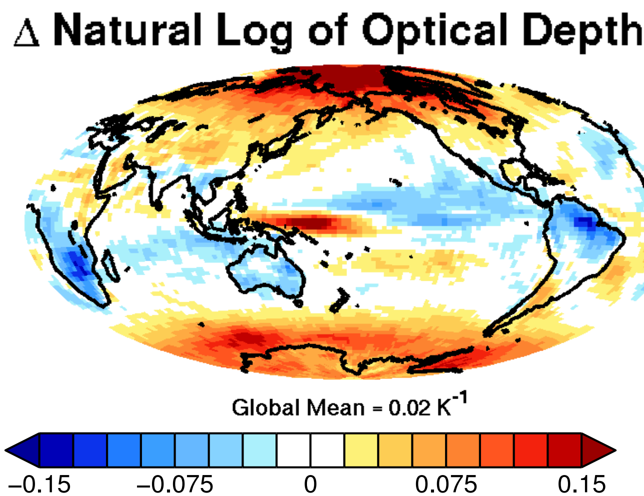
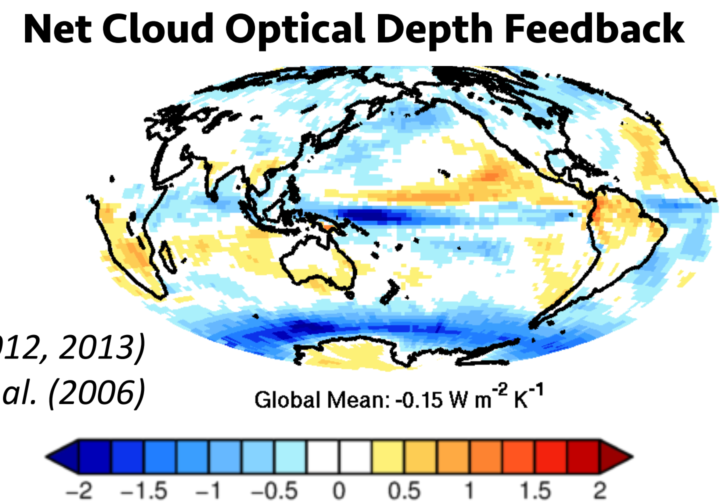


Modified from IPCC AR5, Figure 7.11

- Clouds get brighter at mid/high latitudes



Zelinka et al. (2012, 2013)
also Tsushima et al. (2006)

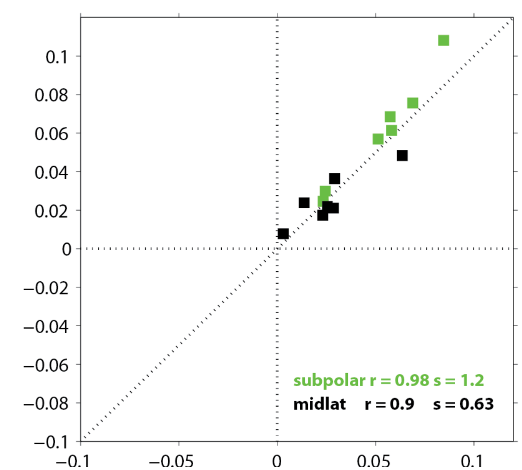


- The temperature sensitivity of low-cloud optical depth exhibits time-scale invariance

Climate Change

$$\frac{\Delta ln(\tau)}{\Delta T_G}$$

(K^{-1})



Sensitivity from Natural Variability $\frac{\partial ln(\tau)}{\partial T_L} \frac{\Delta T_L}{\Delta T_G}$ (K^{-1})

(Terai et al. 2016, Gordon and Klein 2014)

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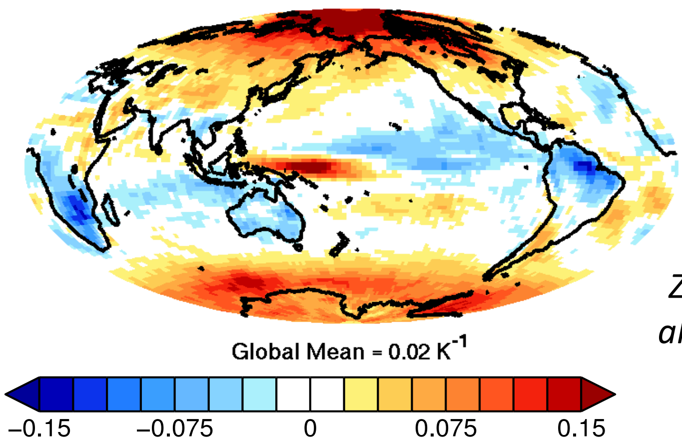
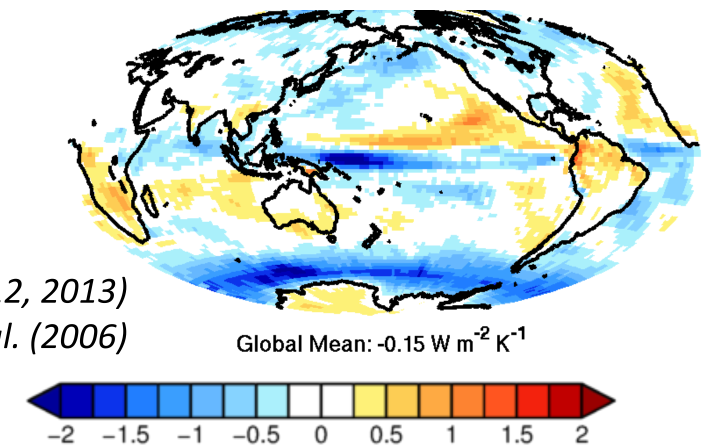
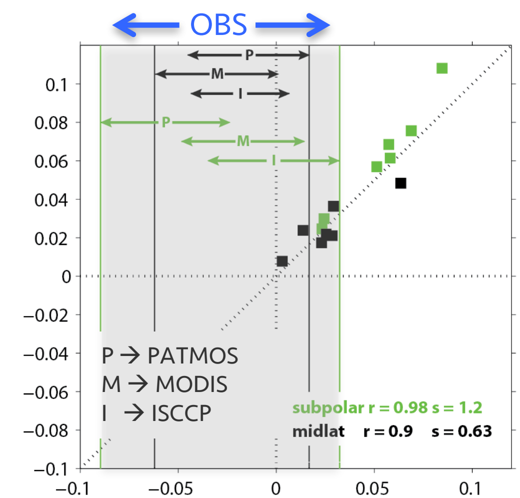




Zelinka et al. (2012, 2013)
also Tsushima et al. (2006)

- Observations suggest models exaggerate cloud brightening in natural variability
- Constraint favors less cloud brightening with climate warming

Climate Change $\frac{\Delta ln(\tau)}{\Delta T_G}$ (K^{-1})



Sensitivity from Natural Variability $\frac{\partial ln(\tau)}{\partial T_L} \frac{\Delta T_L}{\Delta T_G}$ (K^{-1})

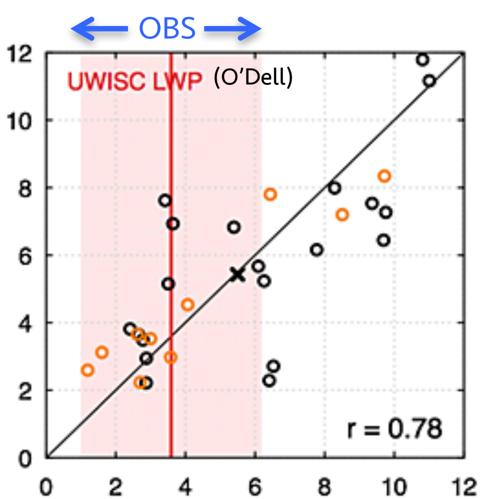
(Terai et al. 2016, Gordon and Klein 2014)

- Liquid water path sensitivities also support conclusions made with low-cloud optical depth
- Constraint would reduce southern hemisphere negative shortwave cloud feedback by 50-100% *(Terai et al. 2016)*

Climate Change

$$\frac{\Delta LWP}{\Delta T}$$

($g\ m^{-2}\ K^{-1}$)



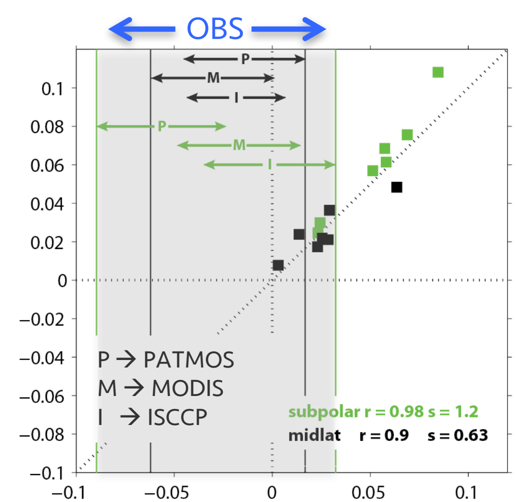
Sensitivity from Natural Variability $\frac{\partial LWP}{\partial T}$ ($g\ m^{-2}\ K^{-1}$)

Ceppi et al. (2016b)

Climate Change

$$\frac{\Delta ln(\tau)}{\Delta T_G}$$

(K^{-1})



Sensitivity from Natural Variability $\frac{\partial ln(\tau)}{\partial T_L} \frac{\Delta T_L}{\Delta T_G}$ (K^{-1})

(Terai et al. 2016, Gordon and Klein 2014)

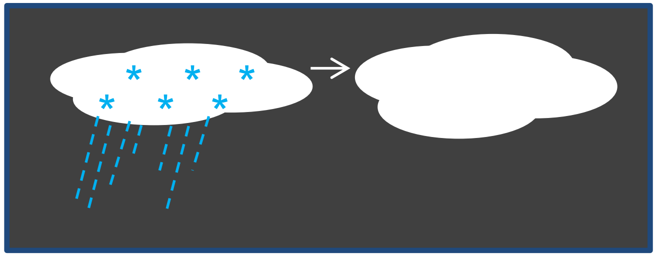
Physical Explanations

Why do clouds get brighter with warming?

- **Adiabatic Water Content** increases ~5% per Kelvin *(Somerville and Remer 1984, Betts and Harshvardhan 1987)*
- **Phase Changes**: Condensate mass is larger and particle sizes smaller when liquid replaces ice *(Shupe et al. 2008, McCoy et al. 2014, Ceppi et al. 2016)*

Why might models exaggerate cloud brightening?

- **Phase Changes**: The excess of ice and lack of super-cooled liquid leads to exaggerated increases in liquid when temperature rises *(Tjernström et al. 2006, Komurcu et al. 2014, Cesana et al. 2015, Gorodetskaya et al. 2008, Tan et al. 2016, McCoy et al. 2016)*



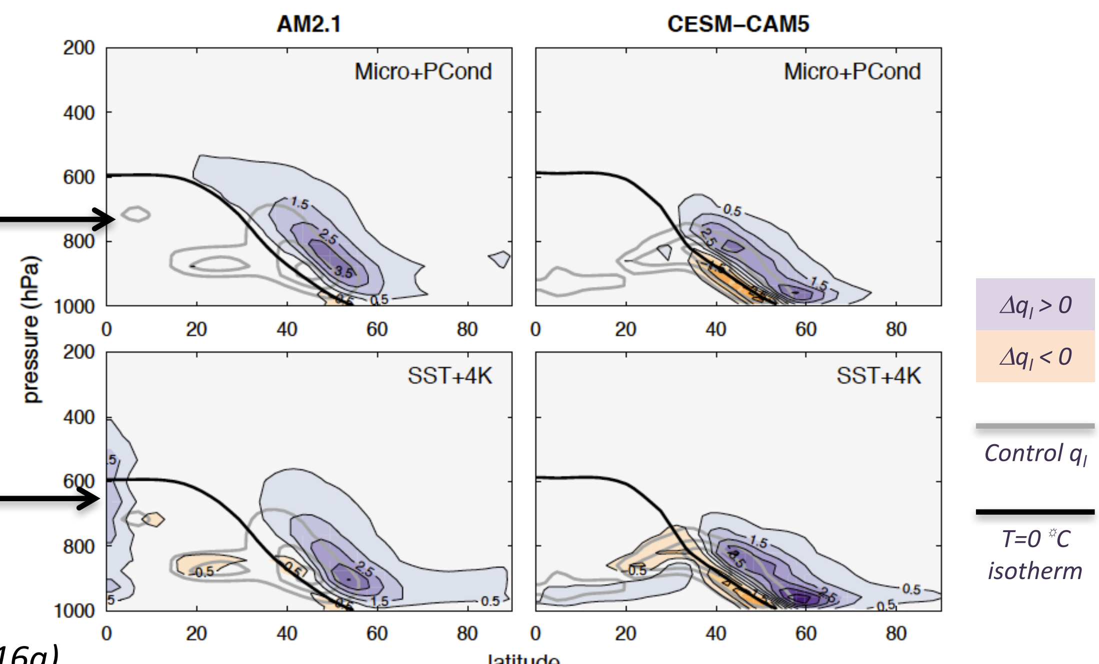
Warming →

Cloud Microphysics Drives Extra-tropical Cloud Brightening

- The climate change response of middle-latitude cloud liquid water can largely be reproduced by simply giving the cloud microphysics a temperature 4K larger than the true temperature
- Implication: Phase-transitions / temperature dependent cloud microphysics are responsible for most of the feedback

Simulations in which only the microphysics sees a 4K temperature increase

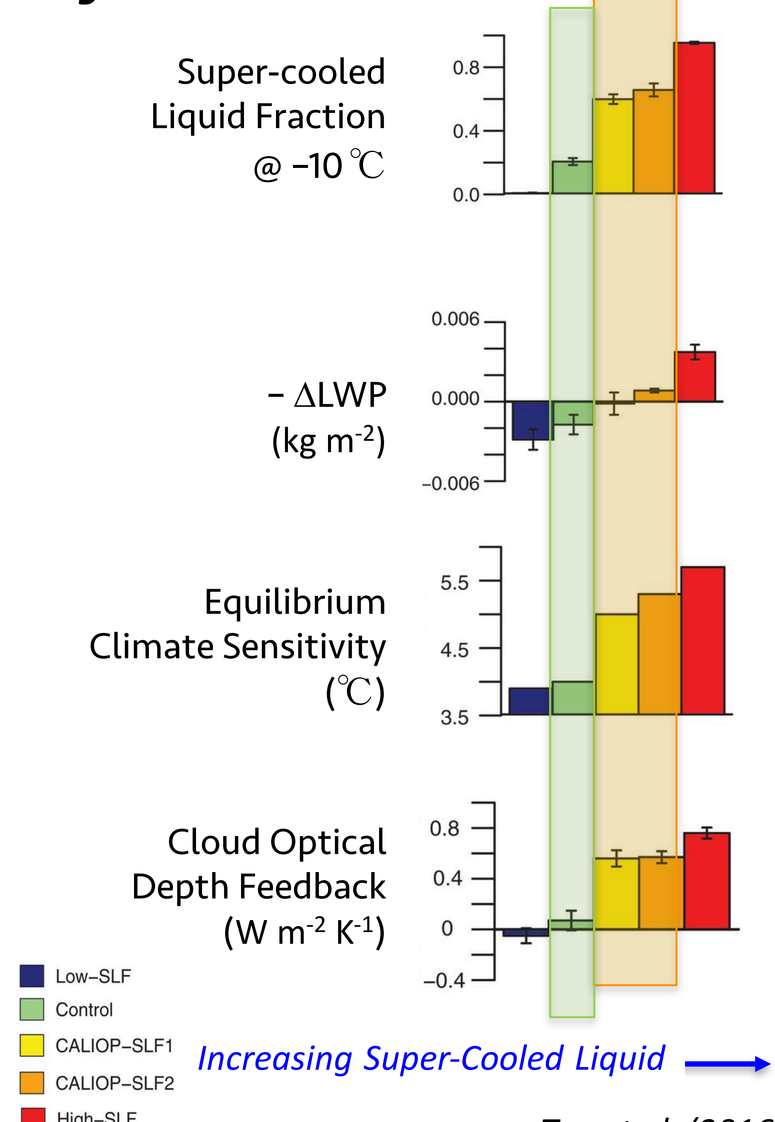
Simulations in which SST is raised by 4K



Ceppi et al. (2016a)

Increasing Super-Cooled Liquid Increases Climate Sensitivity

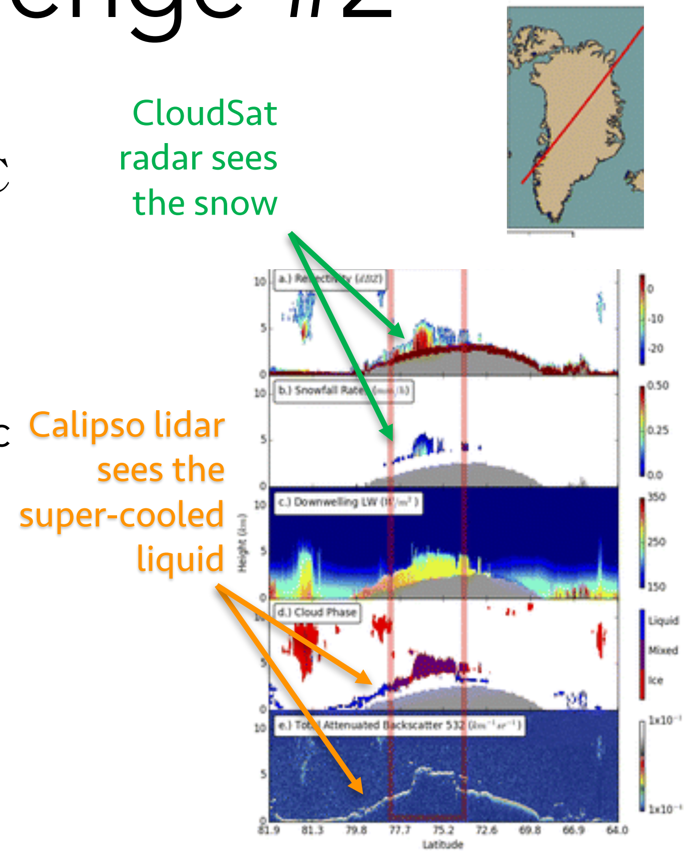
- Increasing the present-day amount of super-cooled liquid in accord with Calipso observations increases climate sensitivity markedly in one model (CESM) *(Tan et al. 2016)*
- Similar dependence on climate sensitivity upon the representation of extra-tropical cloud phase found in a much older model (HadAM) with simpler microphysics *(Mitchell et al. 1989, Senior and Mitchell 1993)*
- Multi-model analysis supports this view *(McCoy et al. 2016)*

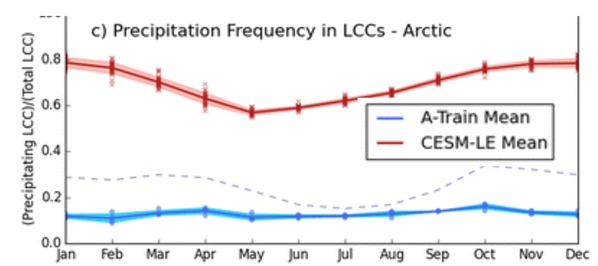


Tan et al. (2016)

Climate Modeling Challenge #2

- Models should better simulate super-cooled liquid particularly for 0 < *T* < –15 ℃
- How to improve models?
  - Bergeron process is too active
    - CloudSat and Calipso together indicate that super-cooled liquid produces snow in the Arctic very infrequently *(McIlhattan et al. 2017)*
  - But how to fix this?
    - Deposition of vapor onto ice
    - Ice nuclei
    - Fall speeds
    - Super-saturation treatment
    - Colocation of liquid and ice within a grid box
  - Also production of liquid could be under-done for non-microphysical reasons *(Forbes and Ahlgrimm 2014)*
    - thin stratocumulus layers under inversion
- Model tuning may be responsible for the fact that models with less super-cooled liquid have greater cloud amounts *(McCoy et al. 2016)*





McIlhattan et al. (2017)

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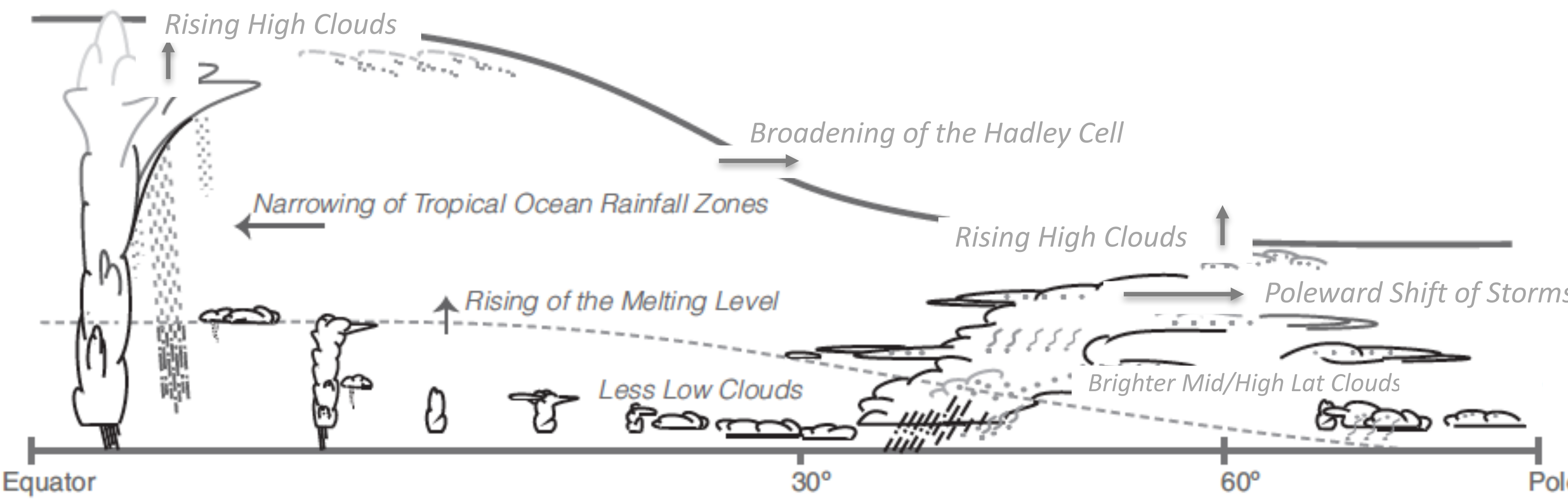


Modified from IPCC AR5, Figure 7.11

Summary (1)

- Cloud feedback science confidently predicts:
  - high clouds to rise
  - tropical high cloud amount to decrease
  - tropical low clouds to decrease
  - phase changes in extra-tropical clouds to have small radiative impact

- While uncertainties remain, current thinking suggests that
  - there are no major credible negative cloud feedbacks
  - cloud feedbacks are in the middle or upper half of model ranges
  - climate sensitivity is at least 3K

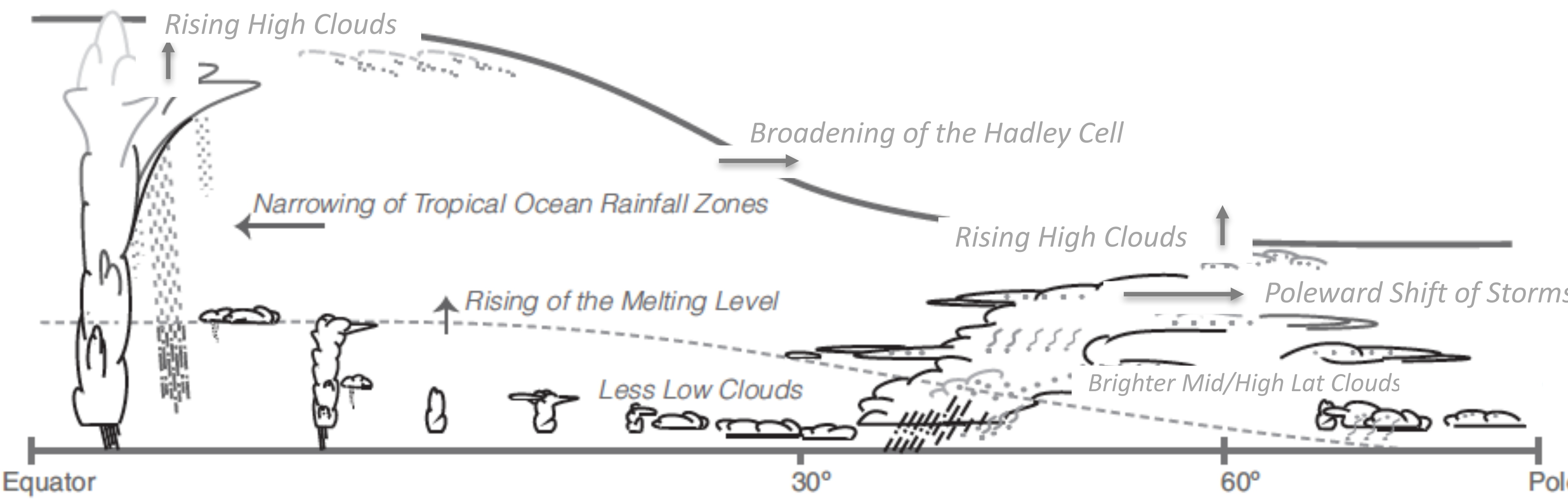
- Cloud feedback science is identifying target diagnostic quantities for climate models to match that would reduce inter-model spread in cloud feedbacks and climate sensitivity
  - Sensitivity of tropical low-clouds to environmental parameters
  - Frequency and abundance of super-cooled liquid

Summary (2)

- Improving these quantities will also improve:
  - Decadal climate fluctuations such as the IPO/AMO *(Bellomo et al. 2016, Brown et al. 2016, Yuan et al. 2016, Myers et al. 2017)*
  - Sensitivity of radiation to shifts in the middle latitude jets *(Grise and Medeiros 2017)*
  - Surface air temperature over cold season land and sea-ice *(Forbes and Ahlgrimm 2014, Pithan et al. 2014)*
  - Glacier melt *(Bennartz et al. 2013, Van Tricht et al. 2016)*

- While some of the targets may be in the range of model tuning, continued development is needed for the following parameterizations:
  - PBL turbulent mixing
  - Shallow convection
  - Mixed-phase cloud microphysics

Thank you!



Modified from IPCC AR5, Figure 7.11