Mixed-Phase Clouds & Their Role in a Changing Climate

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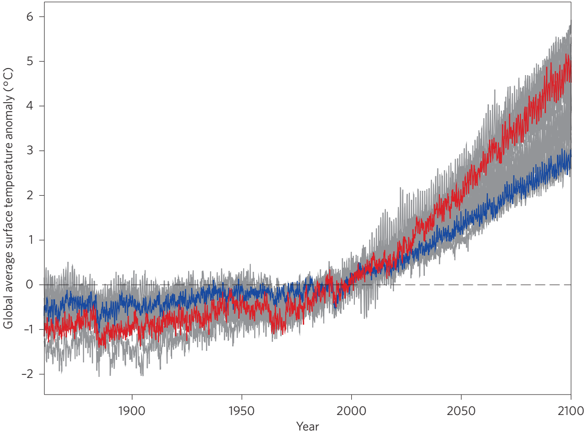
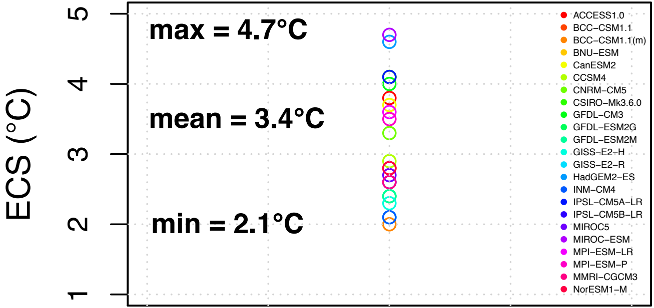
How much will Earth warm in response to CO_2 emissions?



Zelinka *et al.* (2017), Nature Clim. Change

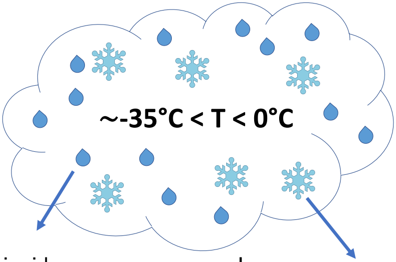
Equilibrium Climate Sensitivity (ECS):
The ultimate increase in global mean surface air temperature in response to a doubling of atmospheric $\mathrm{CO_2}$ concentrations.



- Cloud feedback — the surface-temperature mediated response of clouds to global warming, is the main cause of the large spread in ECS (IPCC AR5)

Mixed-Phase Clouds

- Composed of liquid droplets and ice crystals.
- Ubiquitous — found at all latitudes



Liquid:
is supercooled

Ice:
forms via ice nucleation

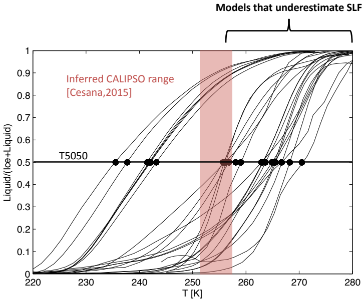
Partitioning of liquid & ice in mixed-phase clouds

— a challenging problem for models

- Models fail to maintain enough liquid in their mixed-phase clouds.

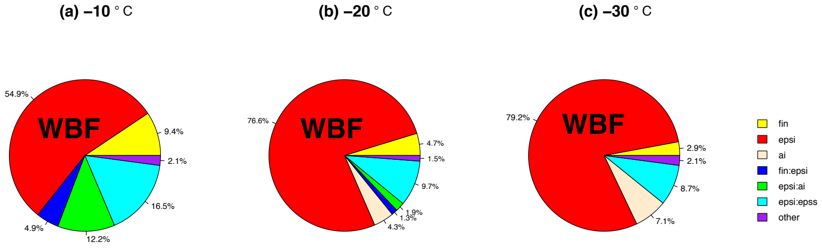
Define $$SLF = \frac{x_{liq}}{x_{liq} + x_{ice}},$$

e.g. x = water content, number concentration, mixing ratio



Adapted from D. T. McCoy, I. Tan *et al.* (2016), *J. Adv. Mod. Earth Sys.*

Why can't models maintain supercooled liquid?



Tan & Storelvmo (2016), *J. Atmos. Sci.*

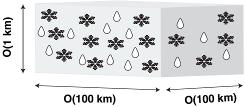
- The Wegener-Bergeron-Findeisen process for ice is generally most important for SLF.

The Wegener-Bergeron-Findeisen (WBF) Process

- Ice crystals grow at the expense of surrounding liquid droplets
- Happens as a consequence of the fact that saturation vapour pressure over ice (e_i) is less than that over liquid (e_l)
- Happens when $e_i <$ in-cloud vapour pressure $<$e$_l$

Importance of the WBF process for SLF

1. Efficient WBF process (more liquid-to-ice conversion $\Rightarrow$ rapid glaciation) $\rightarrow$ Uniformly mixed liquid droplets & ice crystals (this is what mixed-phase clouds in **climate models** look like)



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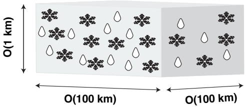
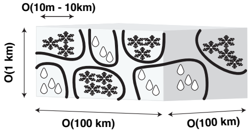


2. Inefficient WBF process (less liquid-to-ice conversion $\Rightarrow$ slow glaciation) $\rightarrow$ Patches of liquid droplets & ice crystals (this is what mixed-phase clouds are actually like in **observations**)



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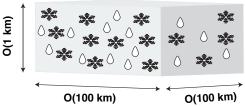

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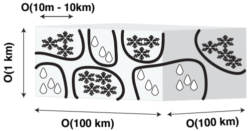


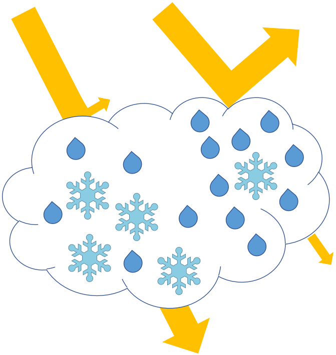
- **Models don't represent subgrid variability of liquid/ice $\Rightarrow$ WBF is too efficient $\Rightarrow$ they fail to maintain liquid i.e. underestimate SLF!**

SLF affects Earth's radiation budget

Lower SLF (more ice):

- ice less abundant
- ice larger in size

→ optically thinner
→ reflects less sunlight



Higher SLF (more liquid):

- liquid more abundant
- liquid smaller in size

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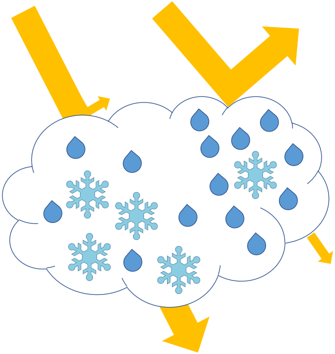

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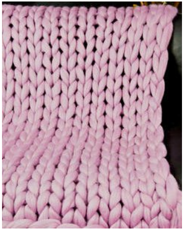
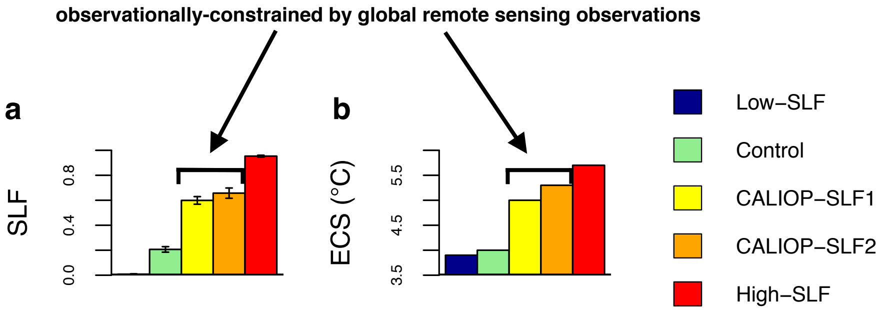


vs.

Link between SLF and ECS



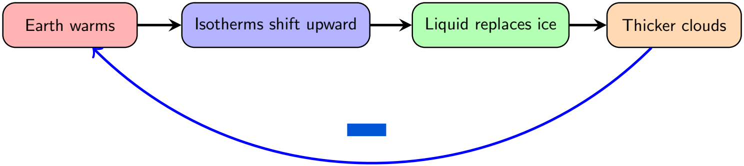
R=0.98, p=0.0025

Tan *et al.* (2016), *Science*

- The observationally-constrained simulations have ECS values that are 1.0–1.3°C greater than that of the control simulation
- Recall: ECS range of CMIP5 models: 2.1 to 4.7°C, mean = 3.4°C

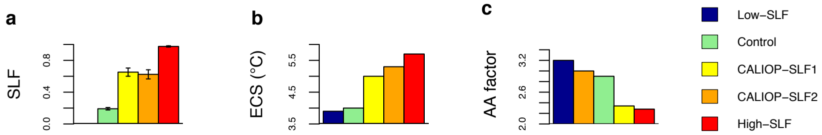
Cloud Phase Feedback

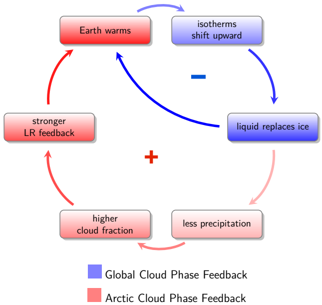
- A negative feedback, where as the atmosphere warms, isotherms shift upward in altitude, leaving behind liquid at the altitude where ice was previously present
- The resulting optically thicker liquid clouds act to lower surface temperatures by reflecting more sunlight back to space, thereby counteracting the initial warming



- Higher SLF clouds have less potential for ice-to-liquid replacement and therefore a weaker cloud phase feedback.

Arctic Impact — Opposing LW Effect

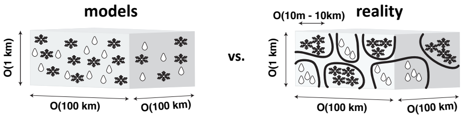




Tan & Storelvmo (2019), *Geophys. Rev. Lett.*

Summary

1. **Outstanding bias of climate models:**
   - They fail to maintain liquid in their mixed-phase clouds (underestimate SLF compared to remote sensing observations)
   - Culprit: lack of subgrid variability in cloud liquid & ice which causes an overly efficient WBF process



2. **Why it matters:**
   - Correcting for this bias increases ECS and decreases AA
   - Caveat: the impact on AA is sensitive to cloud microphysics.

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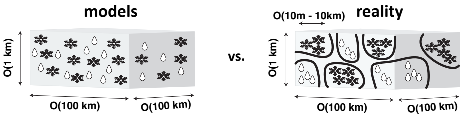

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