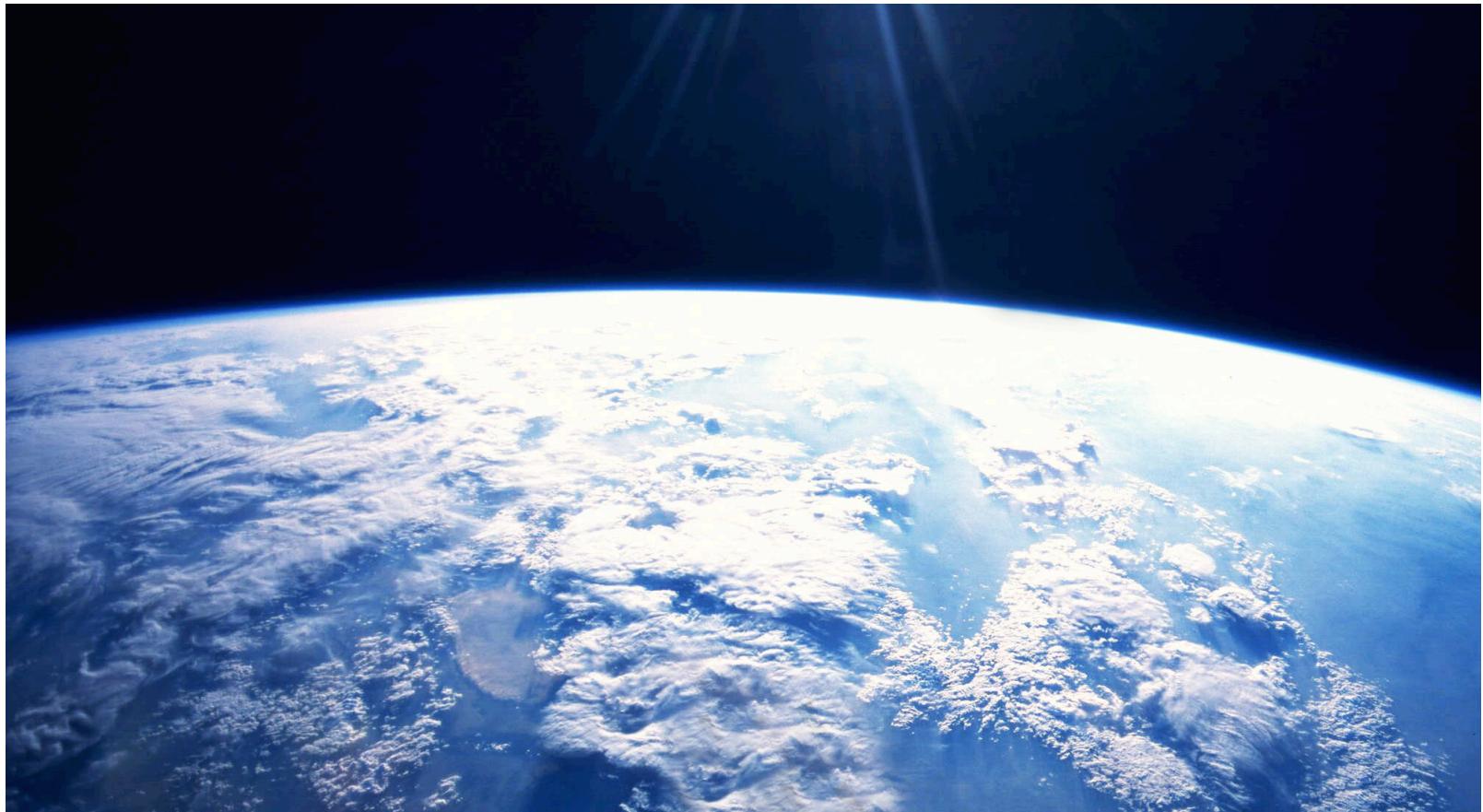


# Clouds in Wacky Climates



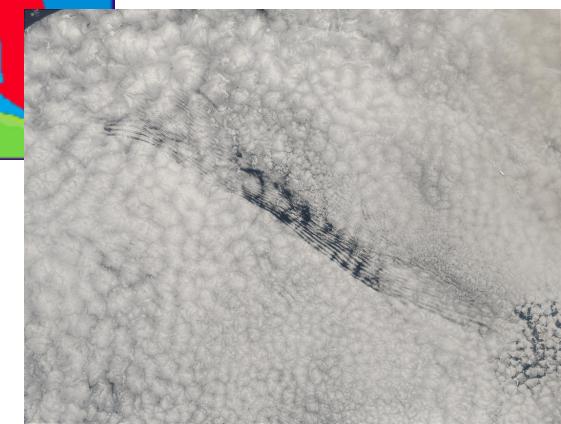
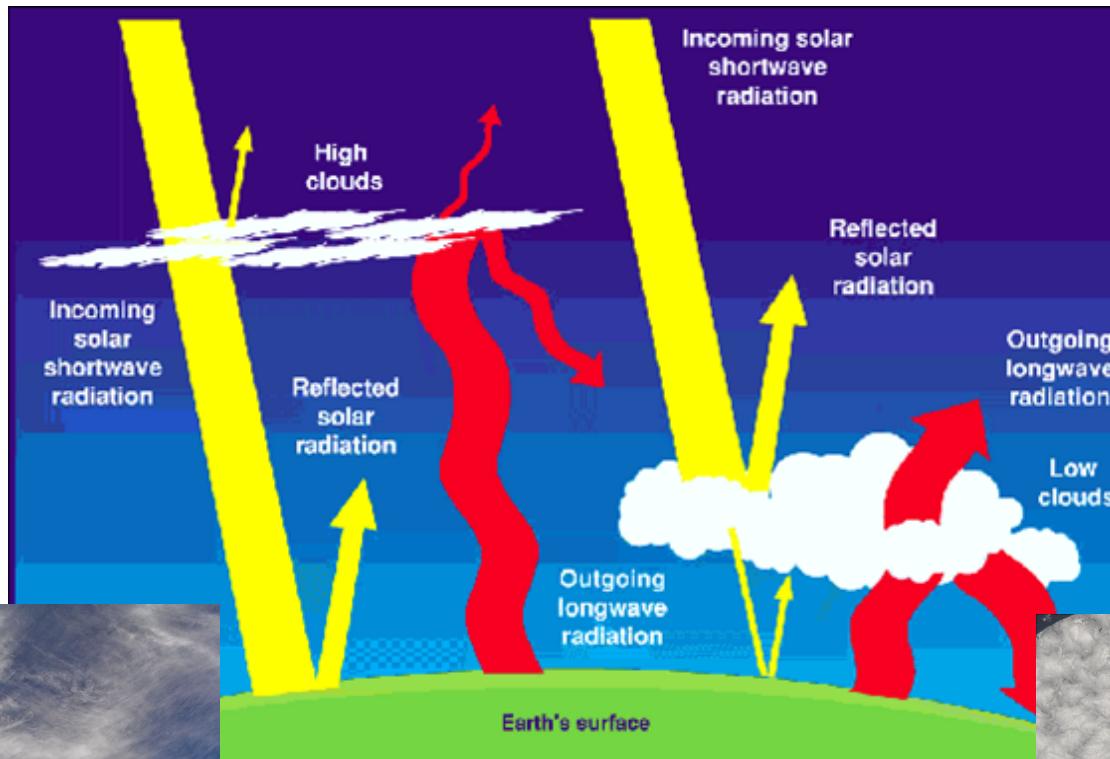
Dorian S. Abbot



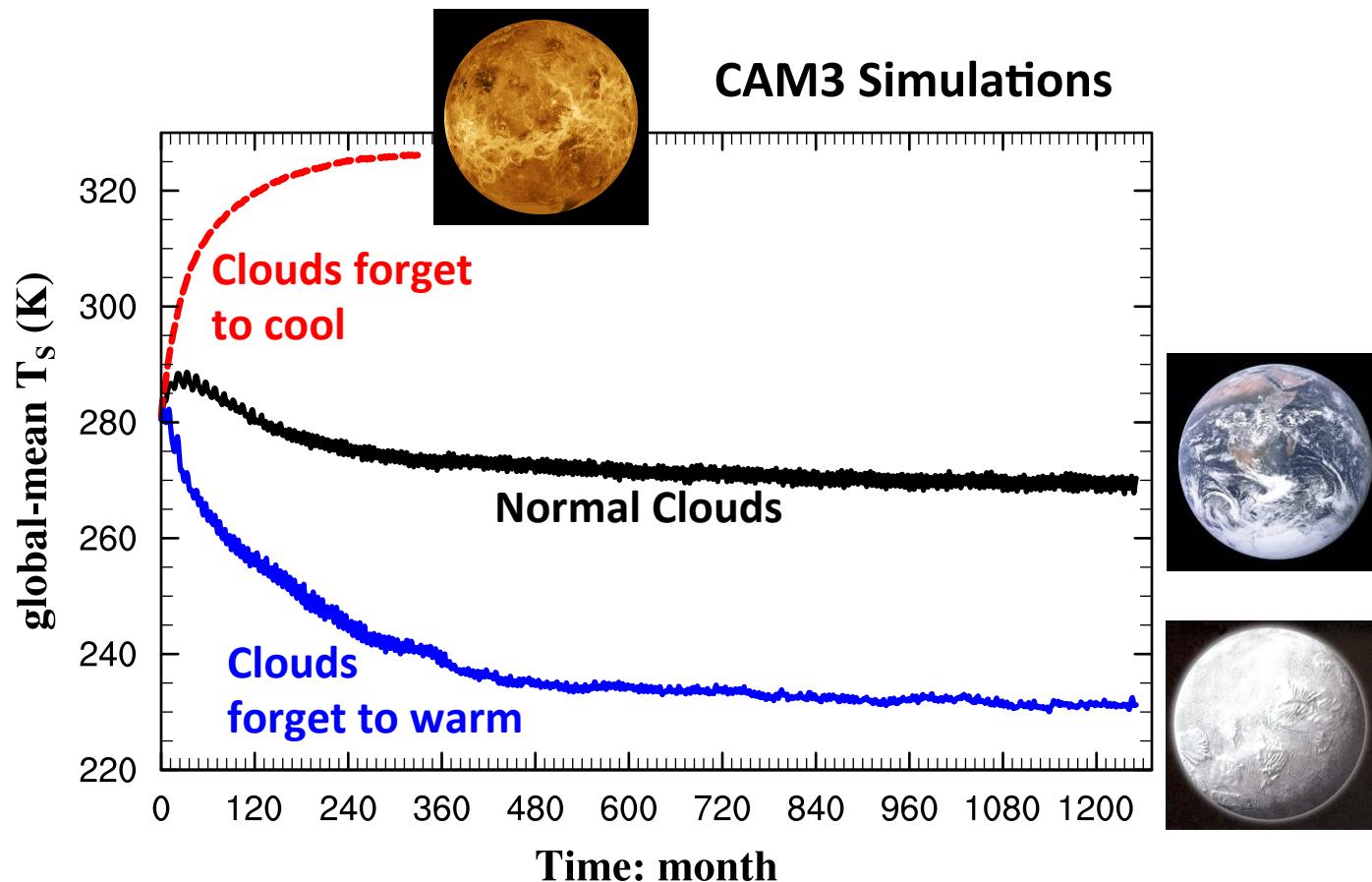
Clouds both reflect solar radiation (cooling a planet) and absorb escaping planetary radiation (warming a planet).

High clouds tend to warm modern Earth

Low clouds tend to cool modern Earth

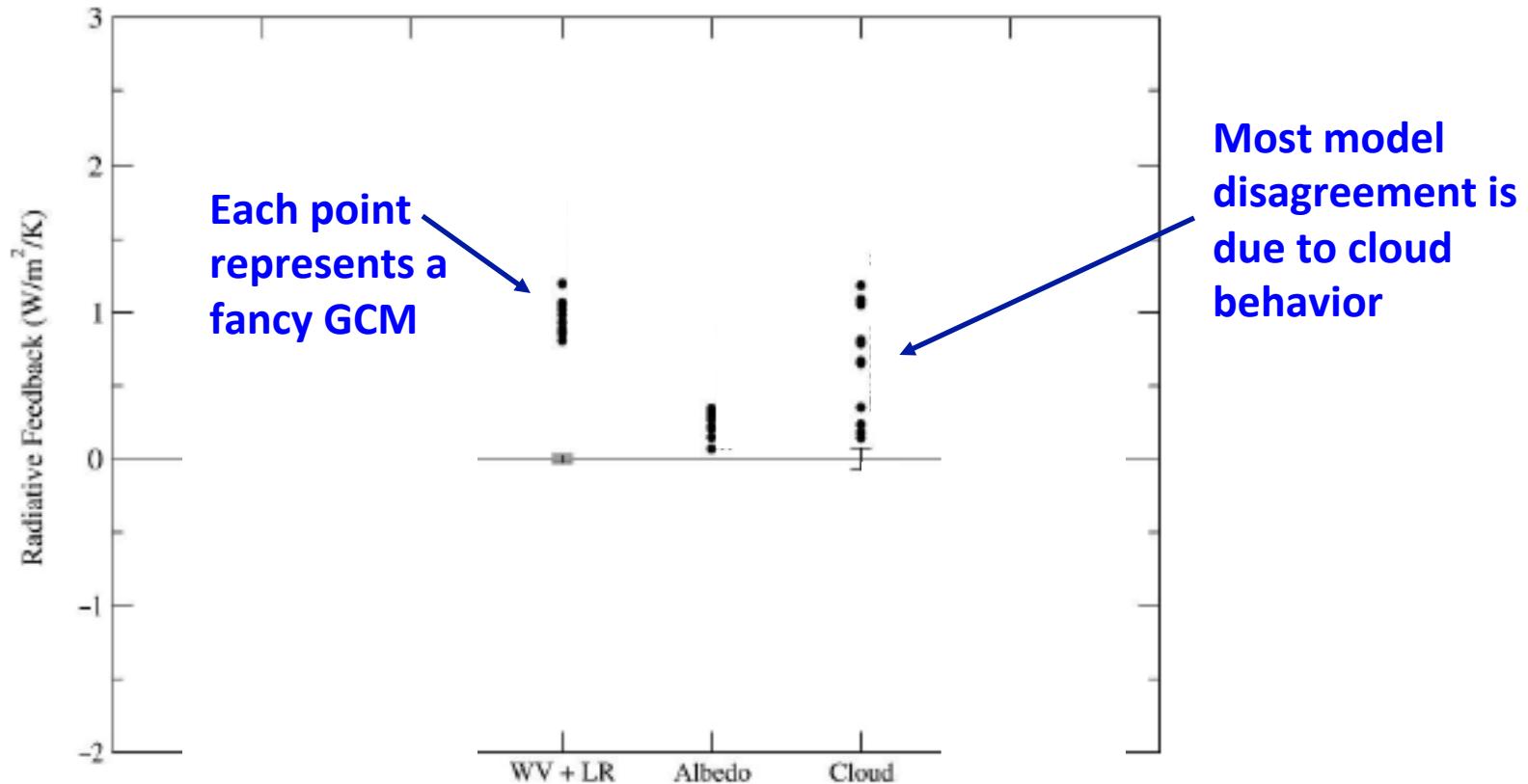


Cloud shortwave reflection and infrared absorption are critical for determining planetary climate.

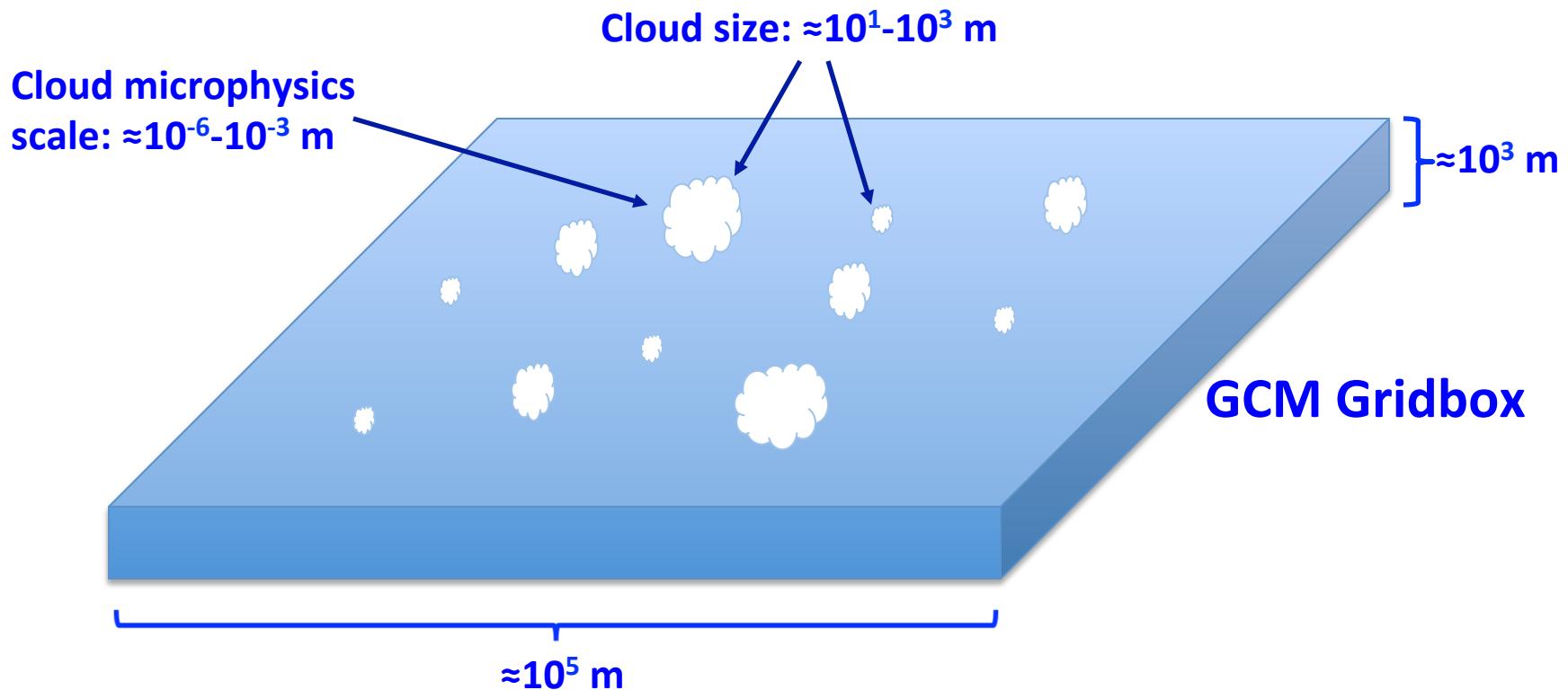


Thanks to Jun Yang

# Cloud feedback dominates climate uncertainty in Global Climate Models (GCMs).



Cloud processes are not resolved by GCMs, and therefore require parameterization in terms of resolved variables.



There are ways to find robust behavior and make progress modeling clouds despite the difficulty of the problem.

Perturb Physics



Multiple GCMs



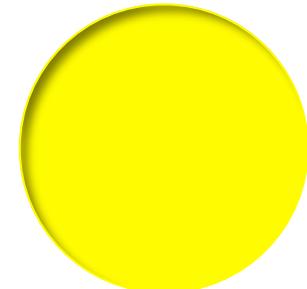
GCM



Check with  
fancy model

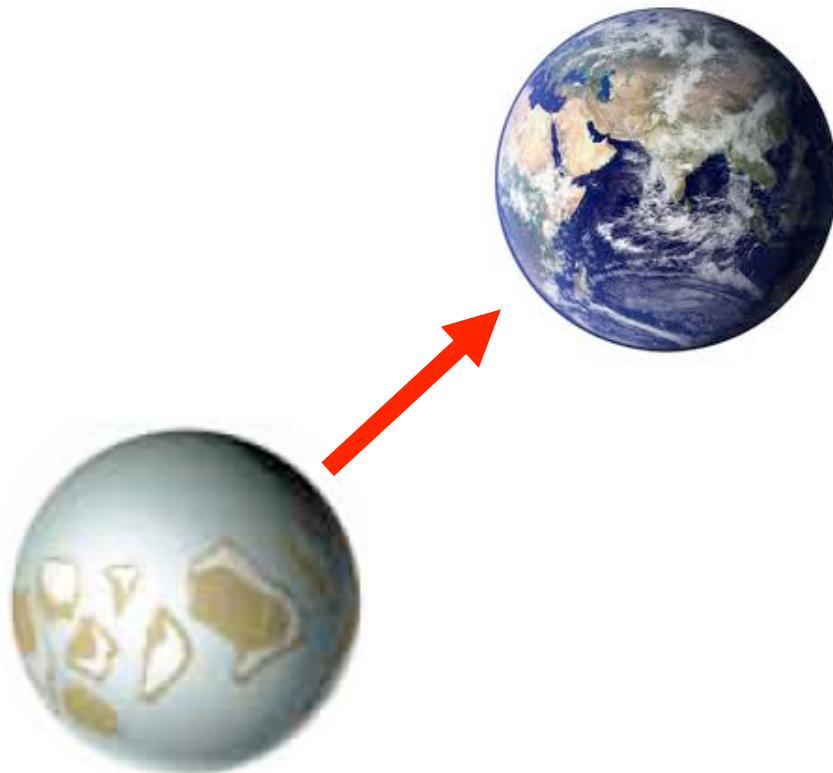


Find a simple  
story/physics



# Snowball Deglaciation

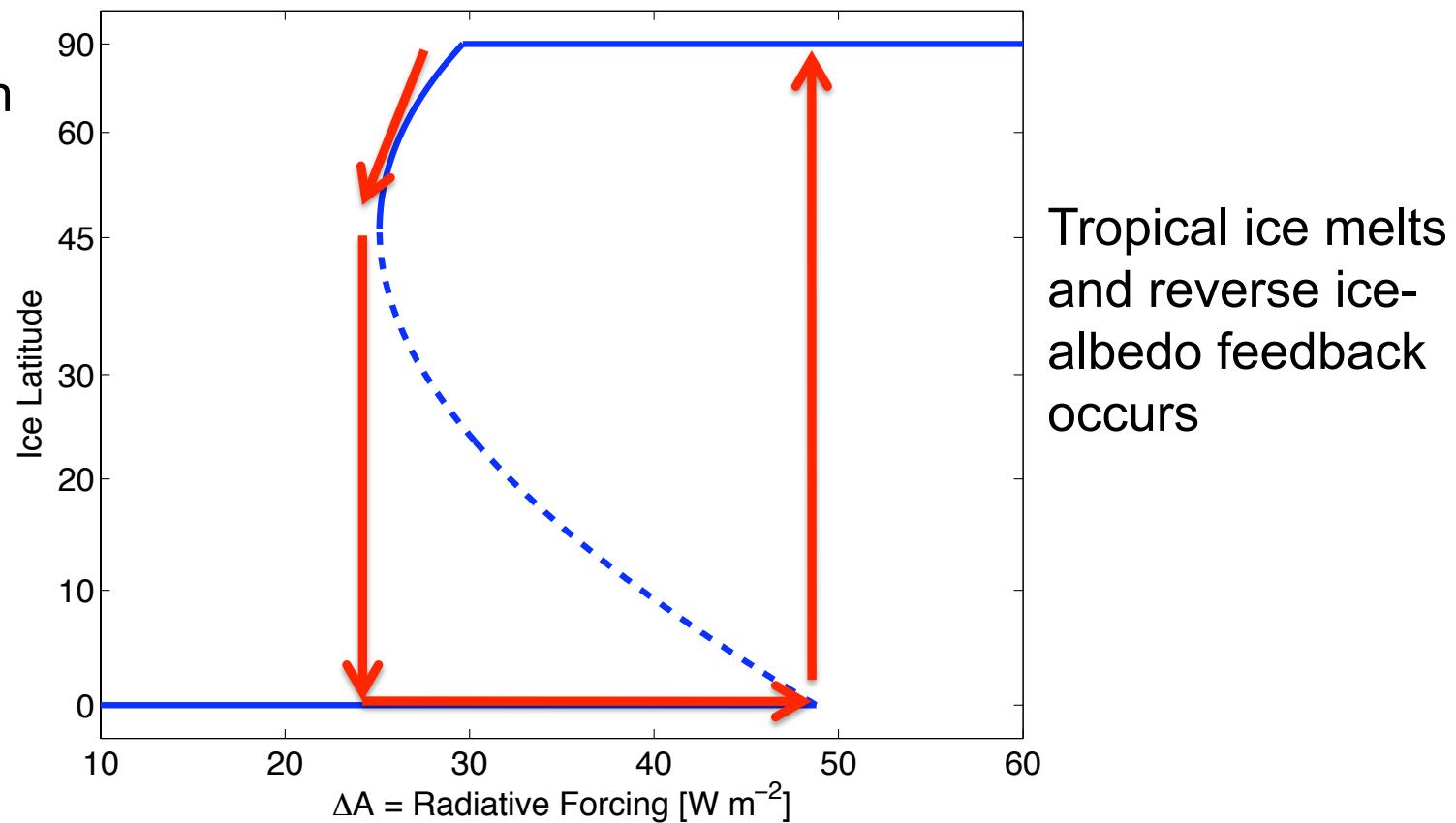
Abbot et al., “Clouds and Snowball Earth Deglaciation,” *Geophysical Research Letters*, 2012



The Snowball Earth hypothesis tries to explain various times when low-latitude glaciation has occurred on Earth.

CO<sub>2</sub> draw down

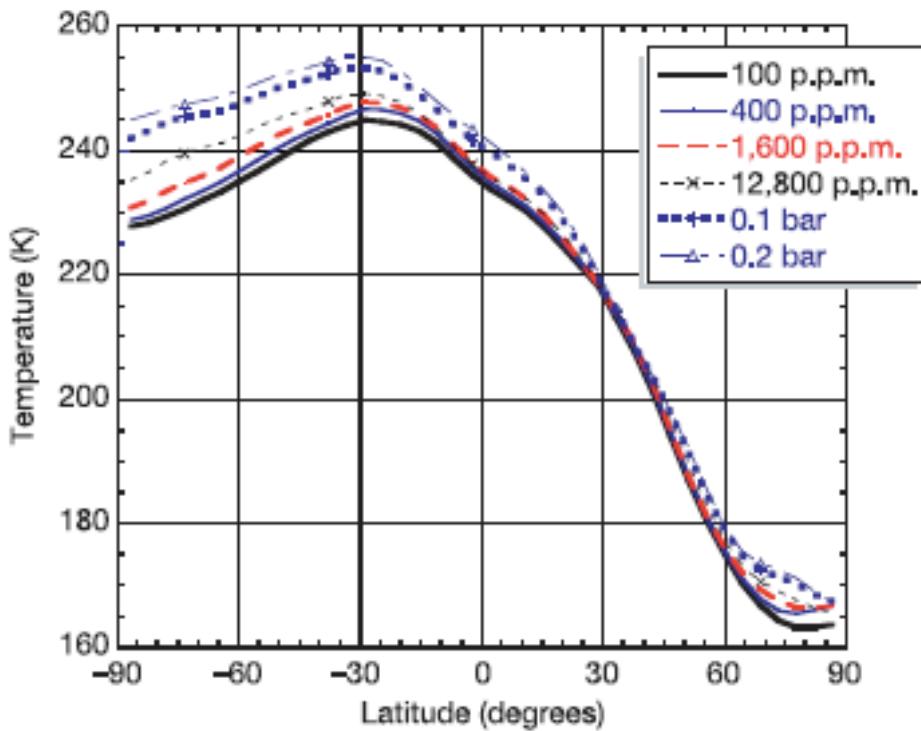
Runaway  
ice-albedo  
feedback



Very low weathering allows CO<sub>2</sub> to build up to ~10% of atmosphere over 1-10 million years

Pioneering FOAM results indicated that >>20% CO<sub>2</sub> might be needed to deglaciate a Snowball.

### January Surface Air Temperature



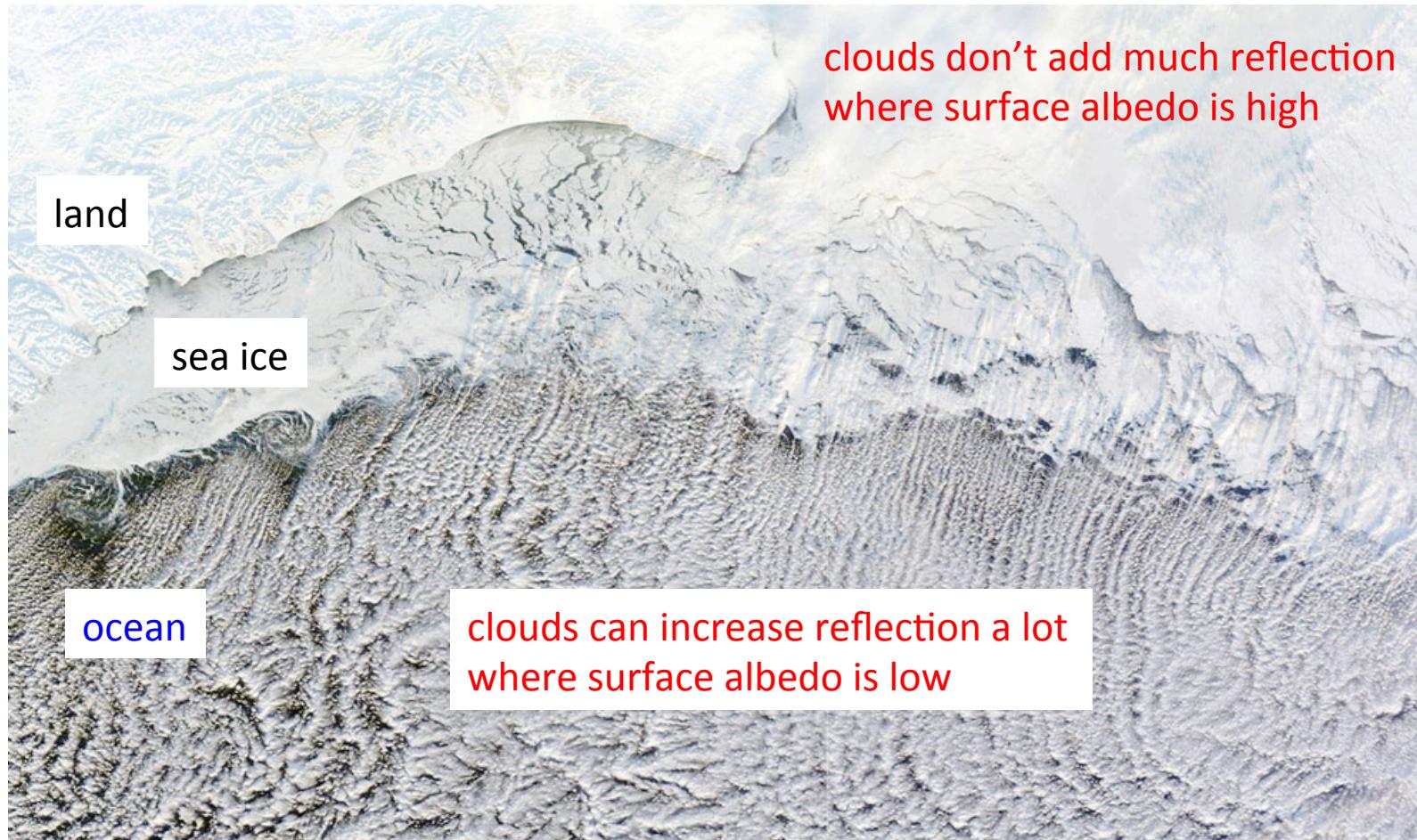
[Pierrehumbert, 04,05]

But geological observations seem to indicate the maximum CO<sub>2</sub> was 1-8%

[Bao et al., 08,09]

Cloud reflection is low over ice and snow, which emphasizes cloud warming in a Snowball Earth.

Satellite picture of Bering Sea



We tested a variety of models in a consistent configuration at  $\text{CO}_2=10^{-4}$  and  $\text{CO}_2=0.1$ .

Participating Models:

**FOAM   GENESIS   ECHAM   LMDz   CAM   SP-CAM**

Less parameterized cloud scheme 

Simulation Specifications:

Solar Constant 94% of modern

Obliquity=23.5°

Eccentricity=0°

Uniform surface albedo of 0.6

Land surface type “glacier” everywhere

Zero aerosol

Zero ozone

All GHG except  $\text{CO}_2$  and  $\text{H}_2\text{O}$  set to zero

Aiko Voigt



MAX-PLANCK-GESELLSCHAFT

Mark Branson



Raymond T. Pierrehumbert



David Pollard



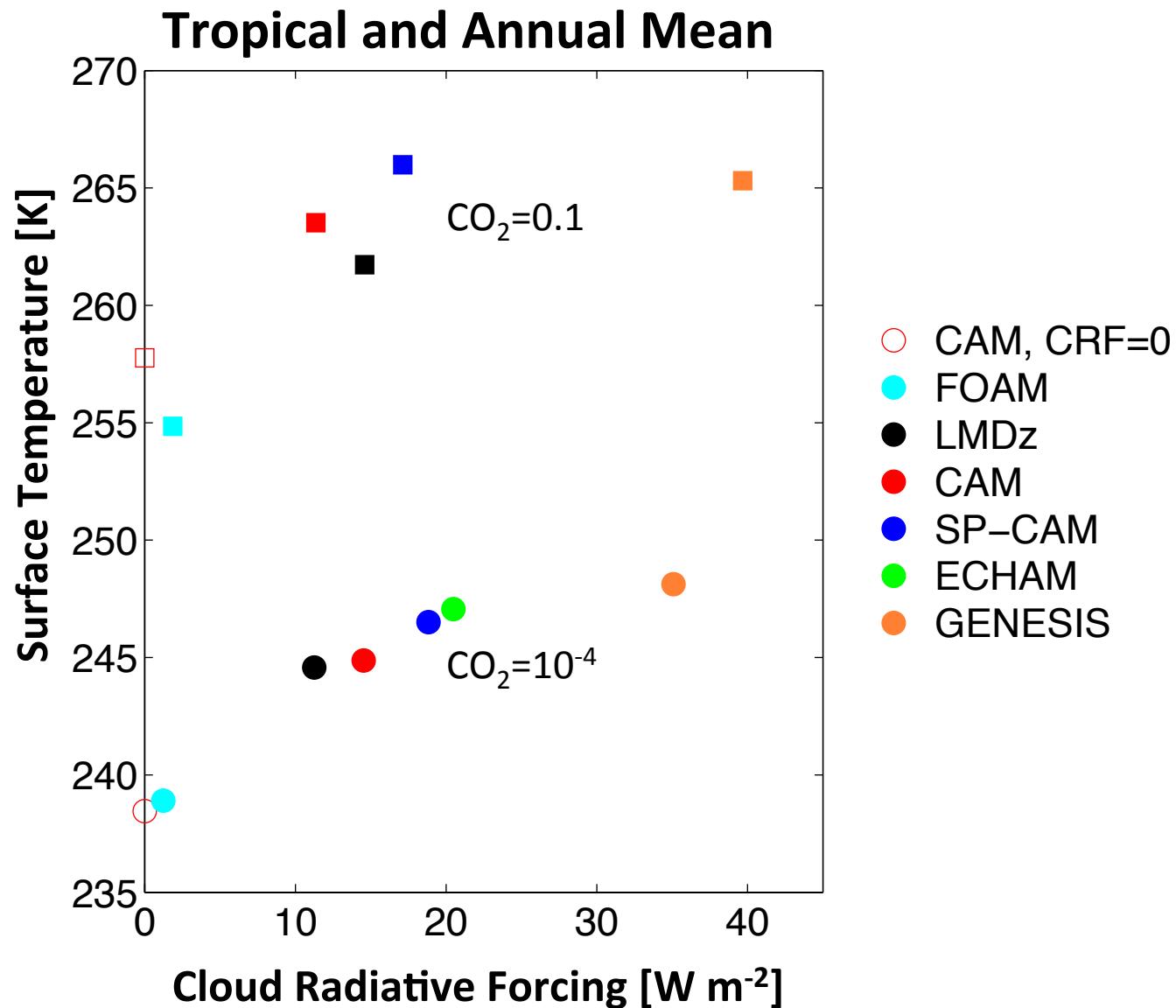
Guillaume Le Hir



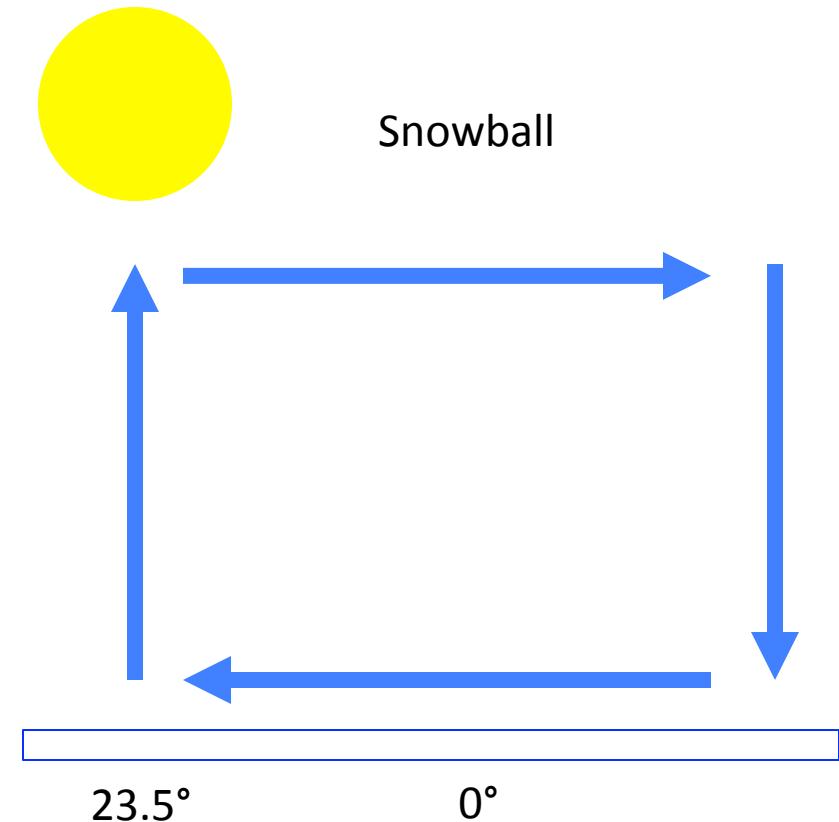
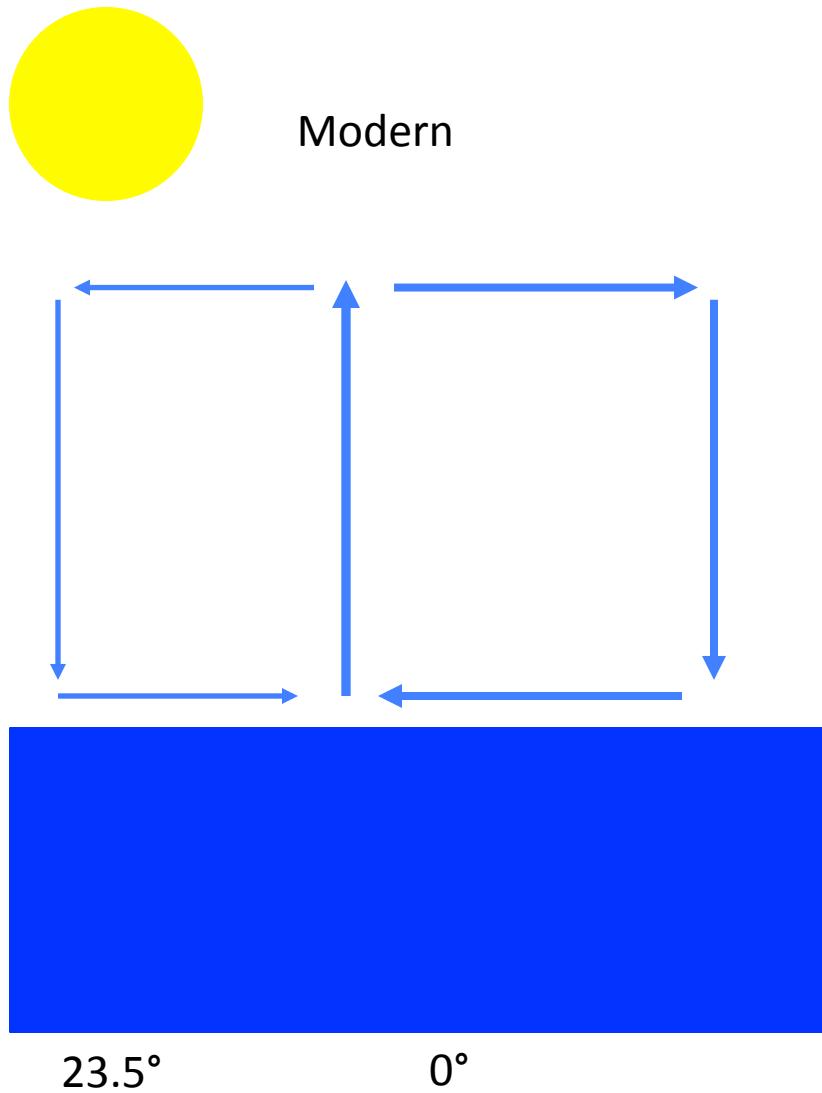
Daniel Koll



CRF $\approx$ 0 in FOAM, causing 7-11K cooler tropics, which is equivalent to decreasing CO<sub>2</sub> by a factor of 10-100.



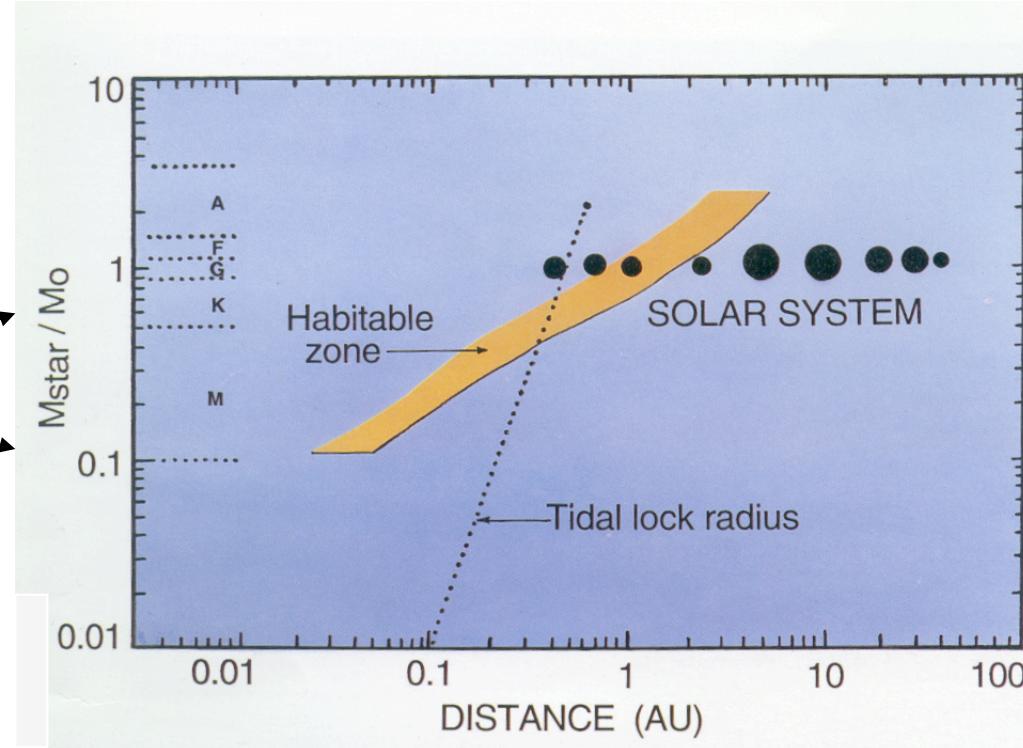
Clouds form in the Snowball because of uplift associated with an extremely strong Hadley circulation.



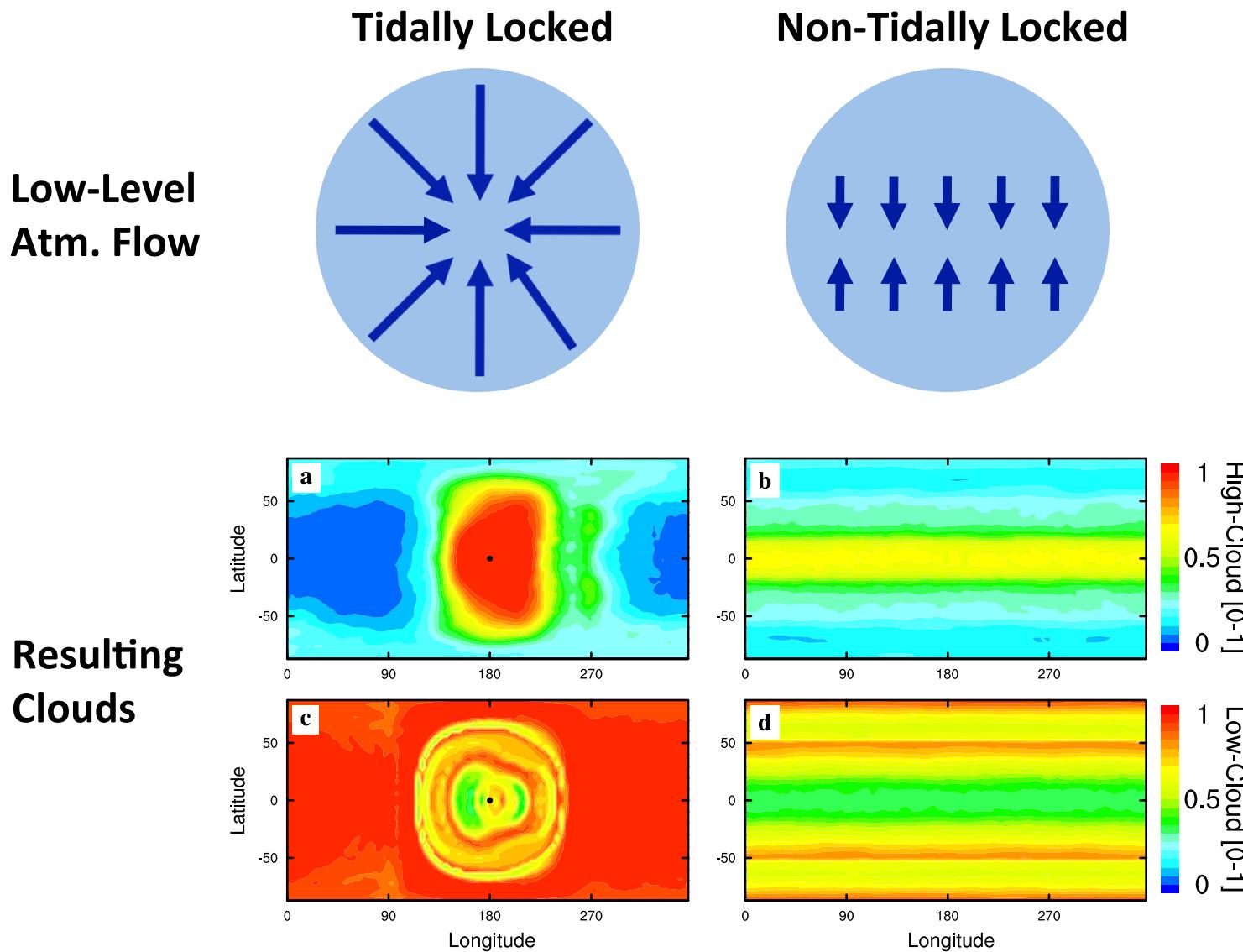
# Stabilizing cloud feedback for tidally locked planets

Yang, Cowan, and Abbot, “Stabilizing Cloud Feedback Dramatically Expands the HZ of Tidally Locked Planets,” *Astrophysical Journal Letters*, accepted.

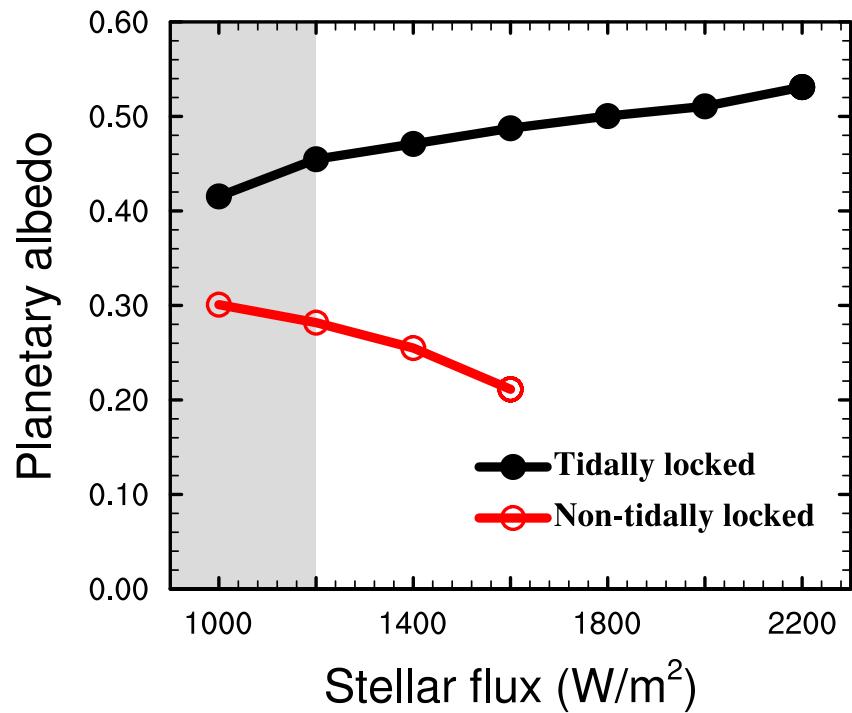
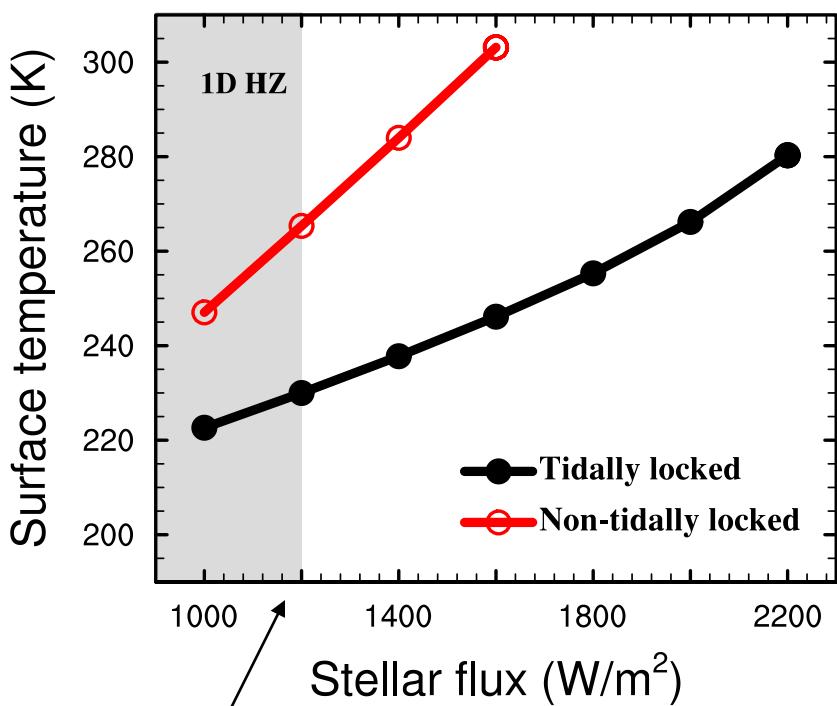
Low mass stars  
are very common



Strong low-level convergence in tidally locked configuration leads to thick dayside clouds.

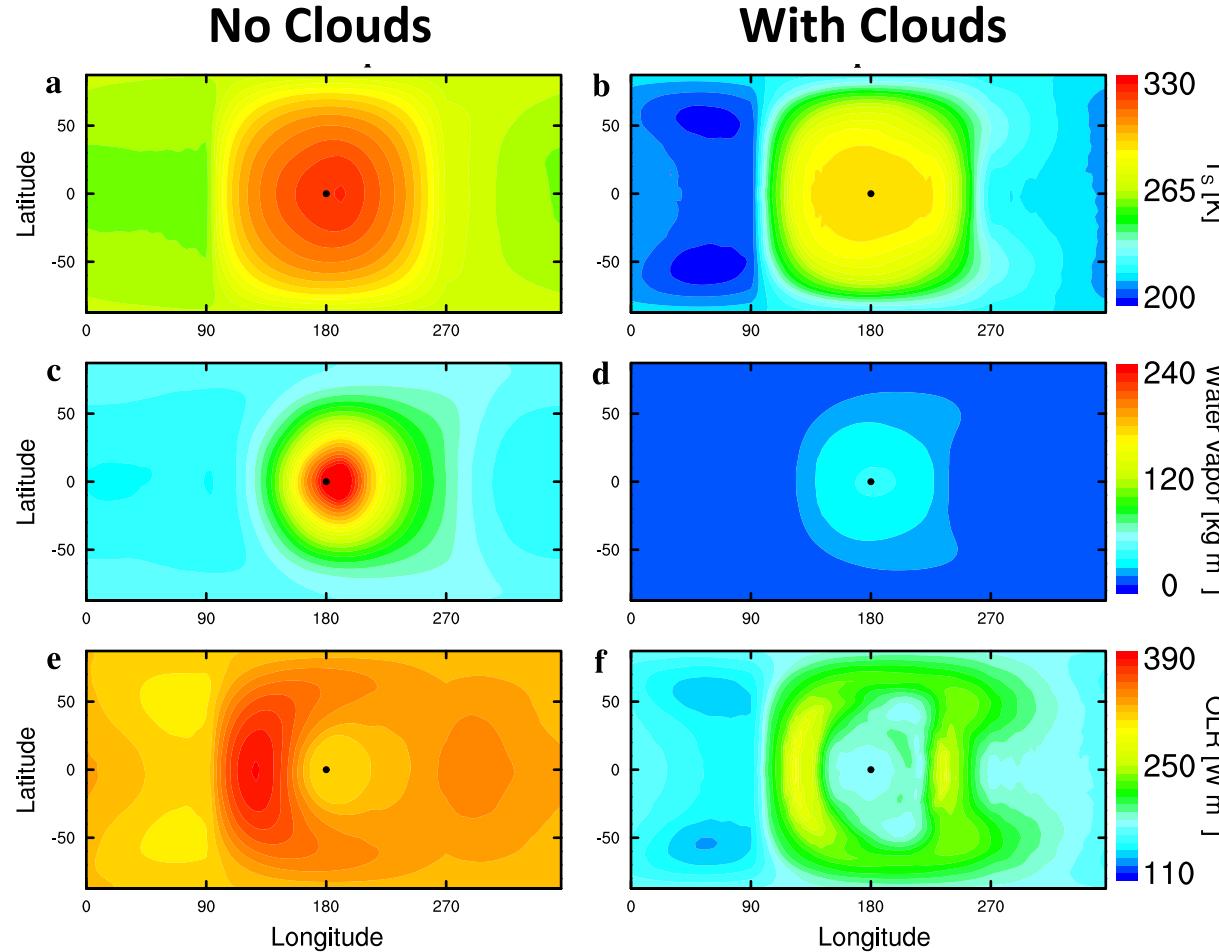


Thick dayside clouds allow 3D tidally locked simulations to stay cool at twice the stellar flux as 1D models: **bigger HZ!**

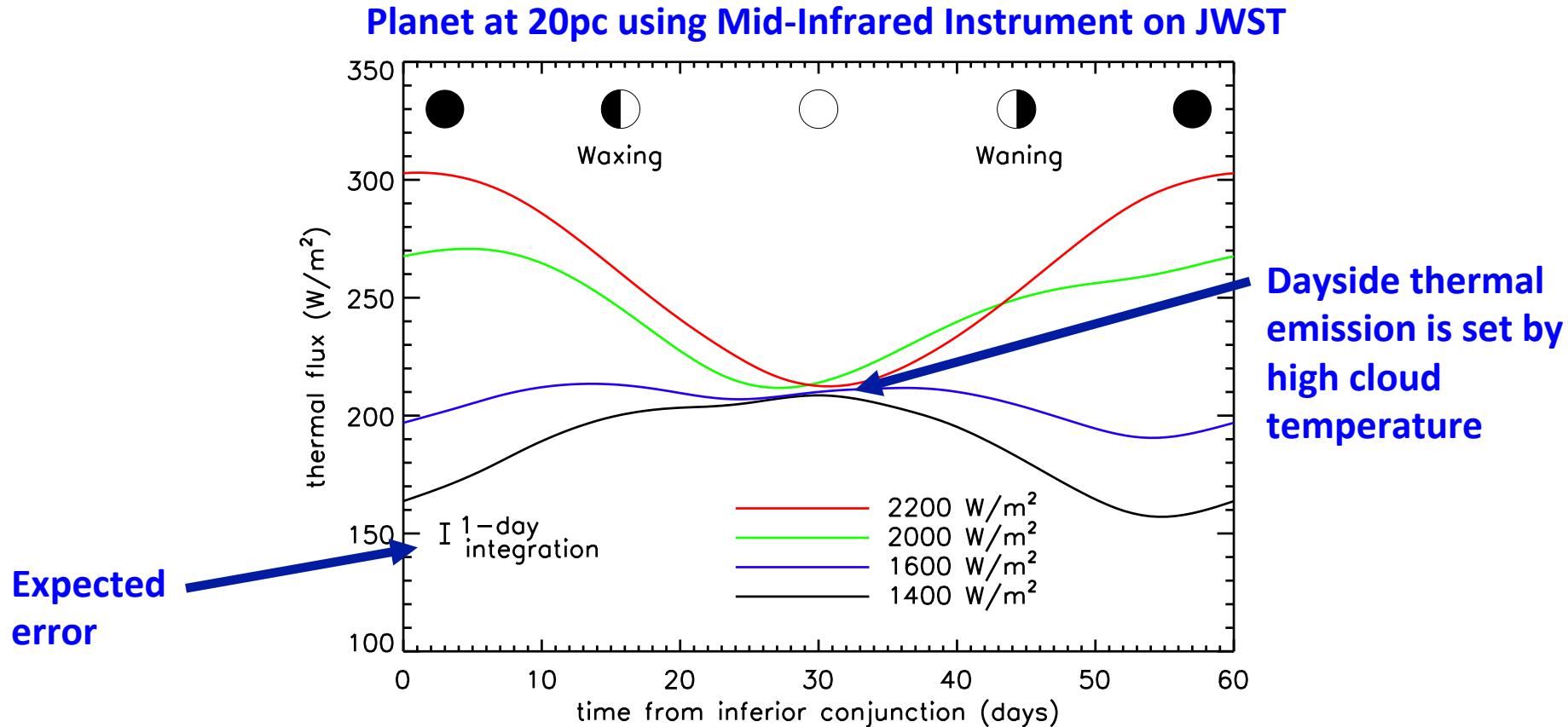


[Kopparapu et al., 13]

Moisture displaces the OLR max eastward and high clouds cause an OLR **minimum** at the substellar point.



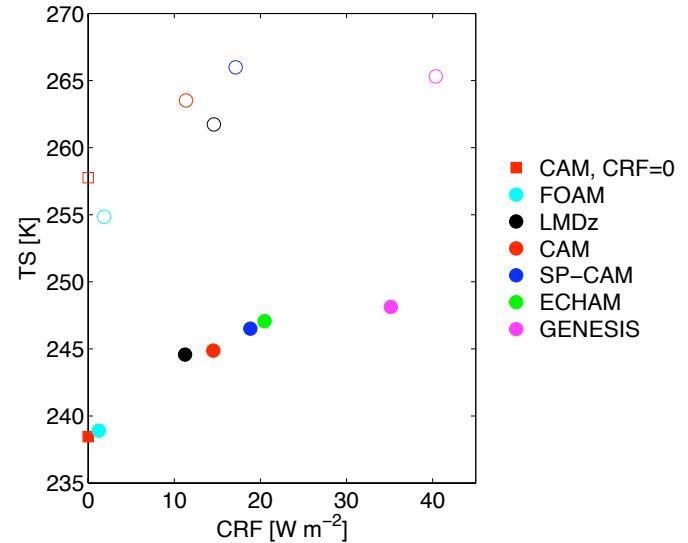
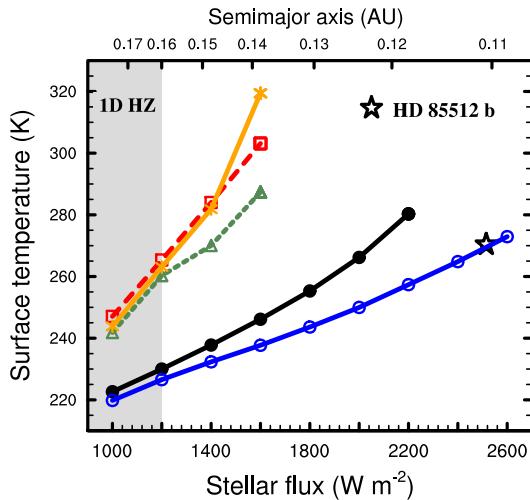
The key to confirming these ideas is that high clouds cause a reversal in the thermal phase curve pattern.



# Conclusions

Clouds are difficult to model, but we can make progress by running different GCMs, doing sensitivity tests, using models with more physical clouds schemes, and focusing only on physically robust mechanisms.

Clouds should cause  $\approx 10K$  warming in a Snowball, potentially allowing consistency with geochemical data.



A stabilizing cloud feedback for tidally locked planets allows Earth-like climates at double the stellar flux calculated by 1D models (expands the HZ).