Snow-free land surfaces allow for refugia on Snowball Earth

Artist's impression of Snowball Earth

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Motivation: how could eukaryotic, photosynthetic life survive on the surface in a snowball climate?

1. Paleobiology – during the Neoproterozoic era, two snowball events occurred on Earth (720-630 Ma), and fossil evidence shows eukaryotic life survived (Hoffman et al. 2009, Kirschvink 1992, MacDonald et al. 2010).

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2. Astrobiology – the snowball climate is energetically stable for an Earth-like planet (Budyko 1969, Sellers 1969).

Snowball climate: global oceans freeze to the equator.

In a theoretical snowball climate, the global oceans would become covered in ice hundreds of meters thick, even at the tropics.

This ice, flowing like an ice shelf but not dependent on continental glaciation, is called a **sea glacier** (Warren et al., 2002).

Photo by Stephen Warren on a blue-ice area in Antarctica in 1992.

How can you maintain sunlit liquid water in a snowball climate?

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- *Modern analogs of sea-glaciers have albedo ~ 0.57-0.80 under clear sky, and even higher under cloudy sky (Dadic et al., 2013)*
- *Braun et al. (2022) found the waterbelt to be unviable, even with sea-glacier albedo as low as 0.45.*

How can you maintain sunlit liquid water in a snowball climate?

4. **Ice surface:** Microbial sea-ice communities thrive both in surface meltwater pools and in brine pockets on Arctic and Antarctic sea ice and ice shelves (Vincent and Howard-Williams, 2000; Vincent et al., 2000).

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5. **Narrow bay:** When flowing into a narrow bay, nearly enclosed by dry land, ice flow is slowed by friction with the side walls, so that the invading ice can lose mass by sublimation faster than it is replaced by inflow (Campbell et al., 2011).

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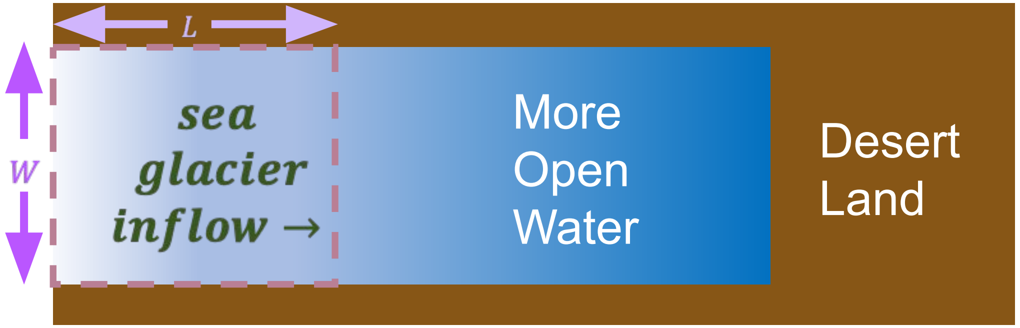
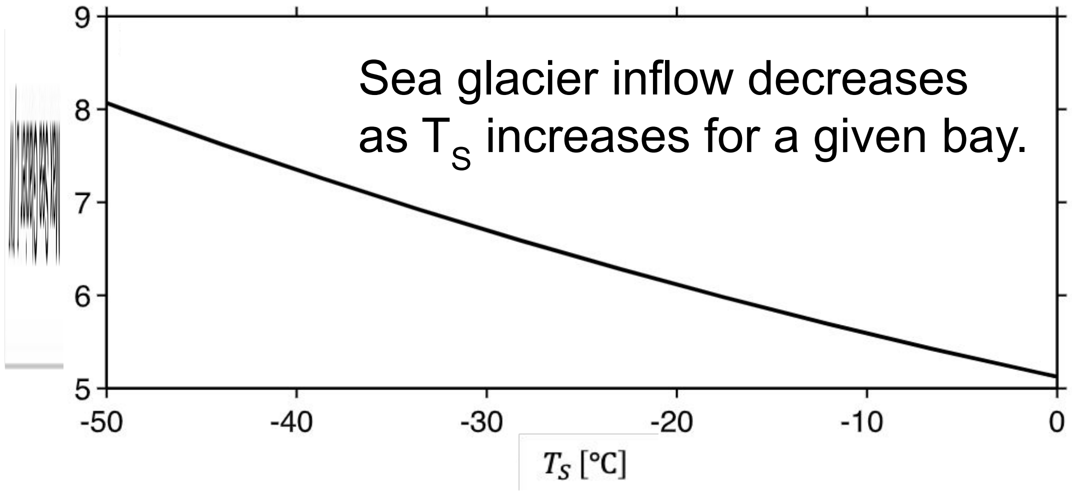
Campbell et al. (2011) show refugia on land could exist if ocean water could be sourced (without inflow of sea glaciers).

If ocean-sourced water flowing from below the ice could find its way to the end of the narrow bay, it would be safe from sea glaciers.

If the surrounding land were net-evaporative (i.e., potential sublimation outpaces precipitation), this place would be safe from land glaciers as well.





Sea glacier inflow decreases as T_S increases for a given bay.

Research Questions

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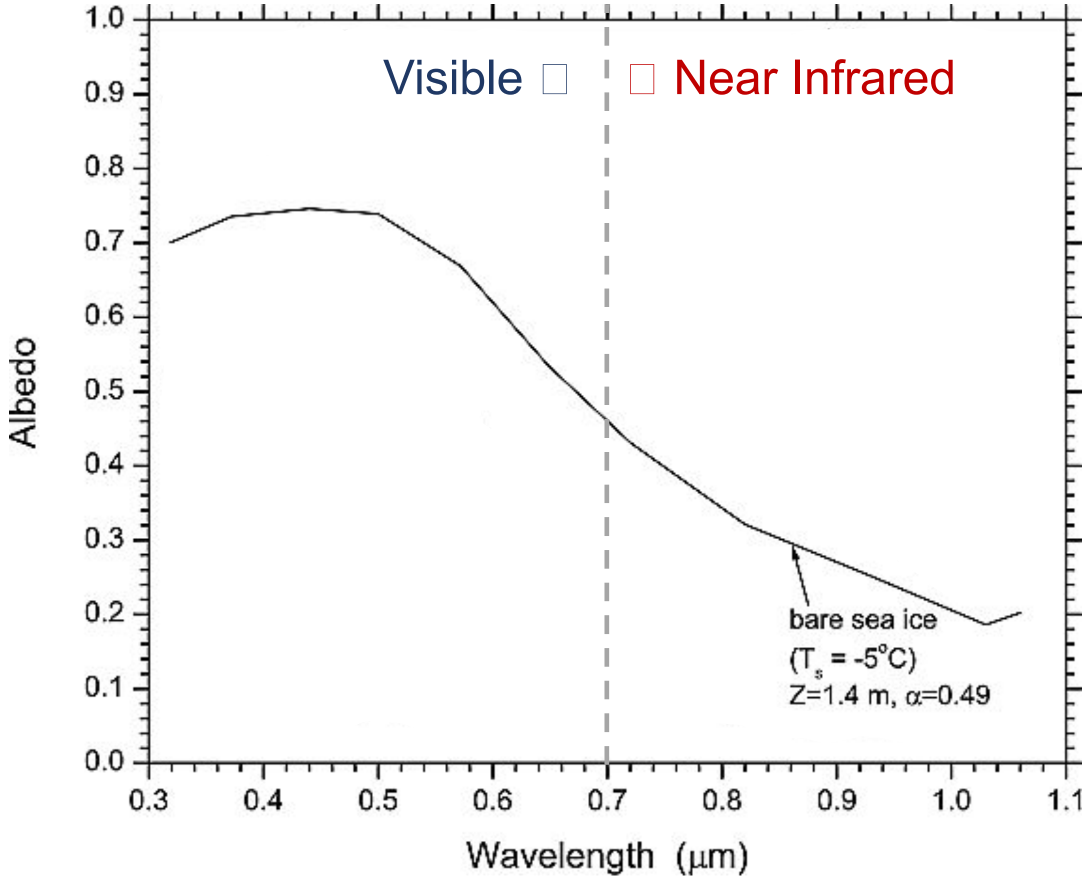
   >> Use CESM to simulate hardest bottleneck for life in snowball climate – fully frozen ocean, low CO_2*, high albedo sea ice.*

Ice on the oceans would form through the compaction of snow, leading to brighter albedos.



Warren et al. 2002

Sea ice: 0.49 (0.68 vis, 0.34 nir)

Brandt et al. 2005

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Taku Glacier, Juneau Icefield

Blue ice: 0.6 (0.85 v, .41 nir)
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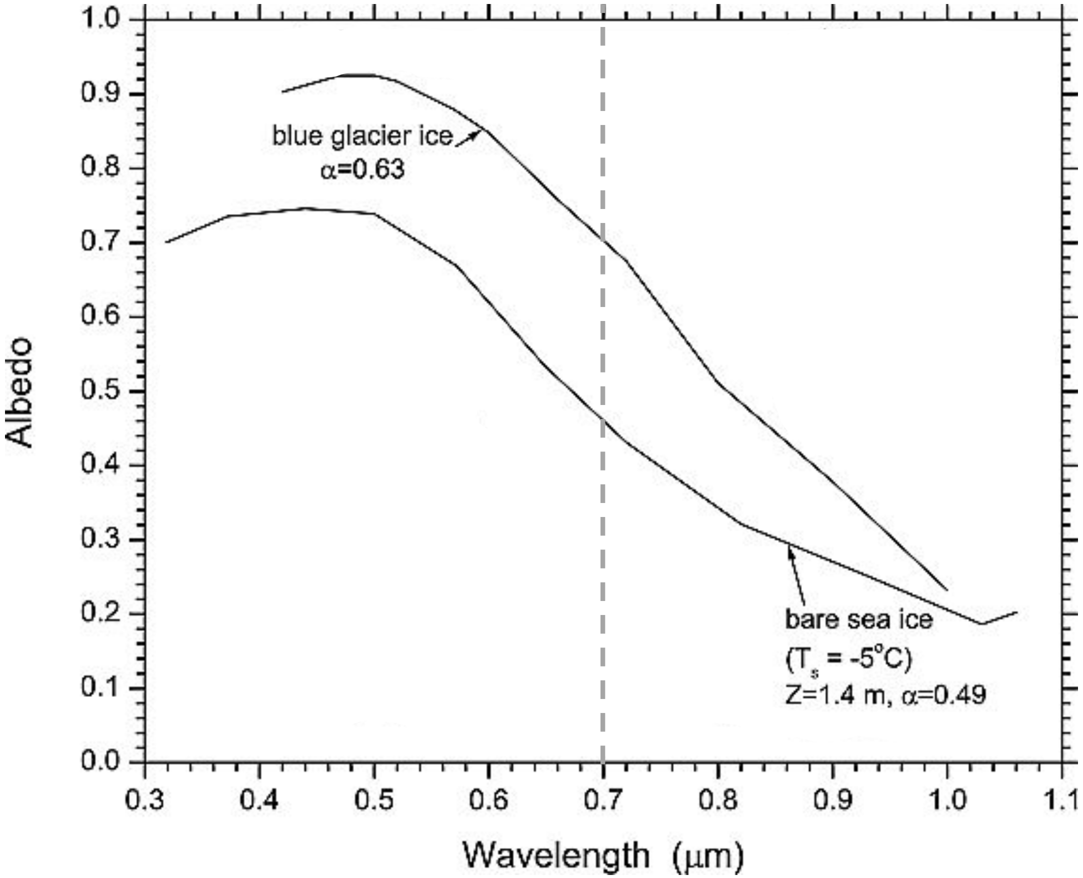

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The surface of the glacier ice:

Firn ice: 0.67 (0.94 v, .44 nir)

Dadic et al. 2013

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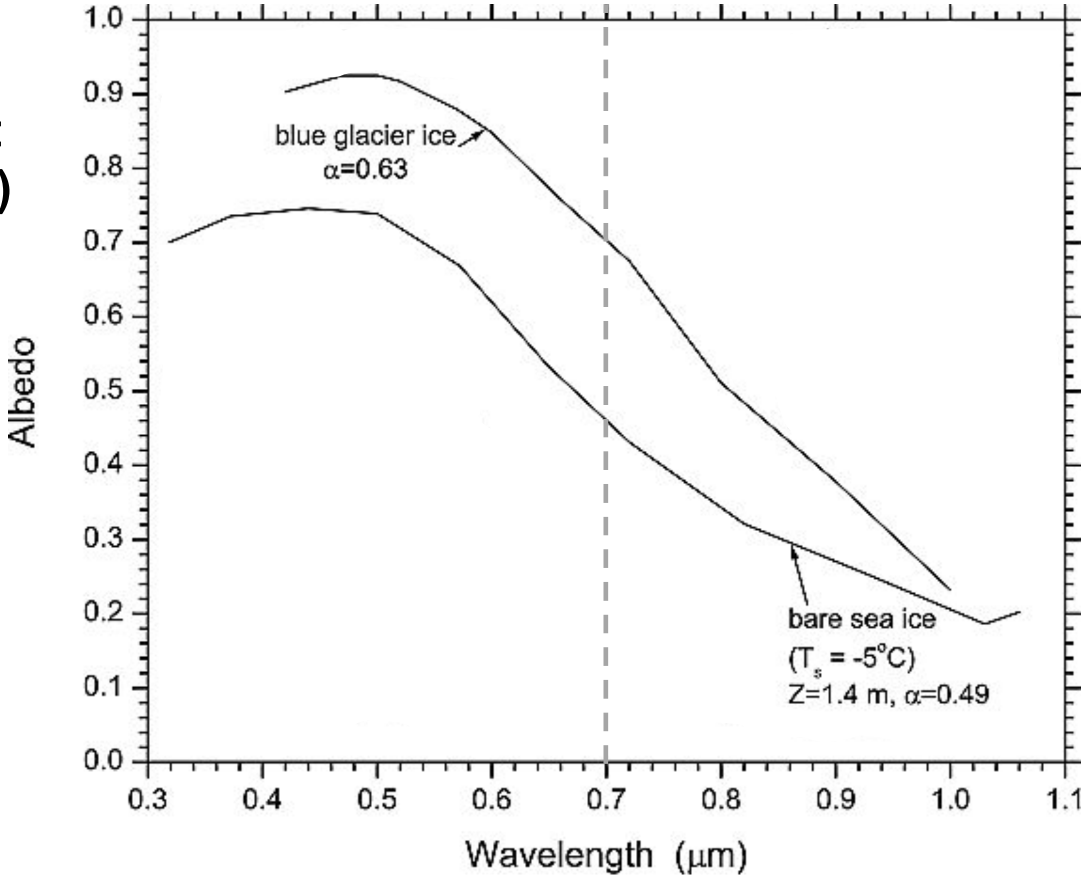

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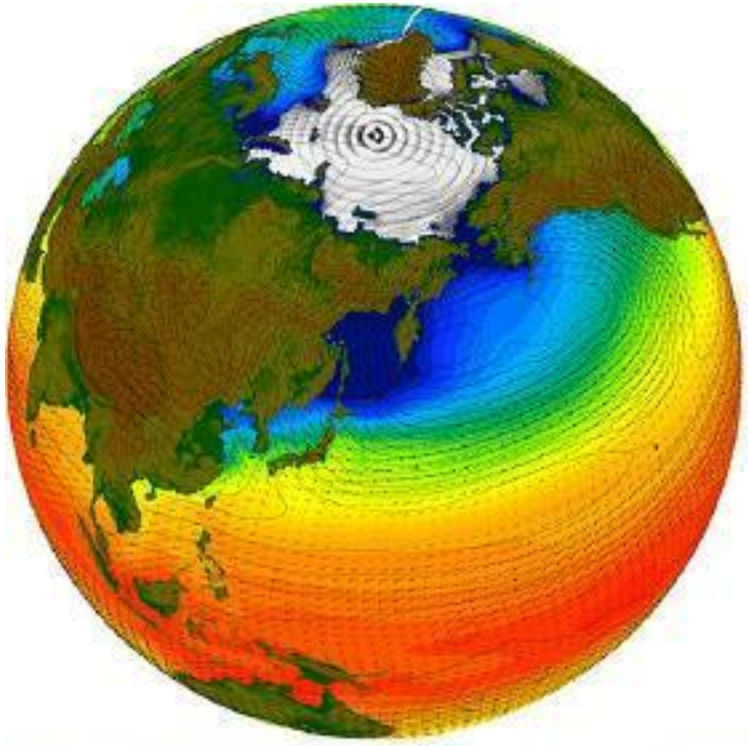
Approach: Simulate Snowball Earth climate in CESM.



Atmosphere Model

CAM 5 (Community Atmosphere Model)

- Lower solar constant (91%)
- CO_2 = 100 ppm

Land Model

SLIM (Simple Land Interface Model)

- Uniform albedo: 0.4
- Uniform evaporative resistance (100 s m^{-1})
- Uniform roughness (0.1 m)

Sea Ice & Ocean

CICE 5 (Los Alamos Sea Ice)

- Bitz & Lipscomb thermo-only
- Prescribed ice albedo (CCSM3)

Slab Ocean with no lateral heat flow in ocean

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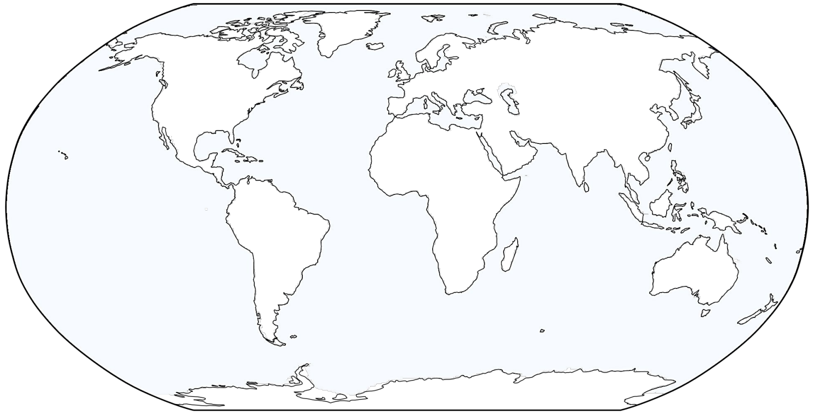

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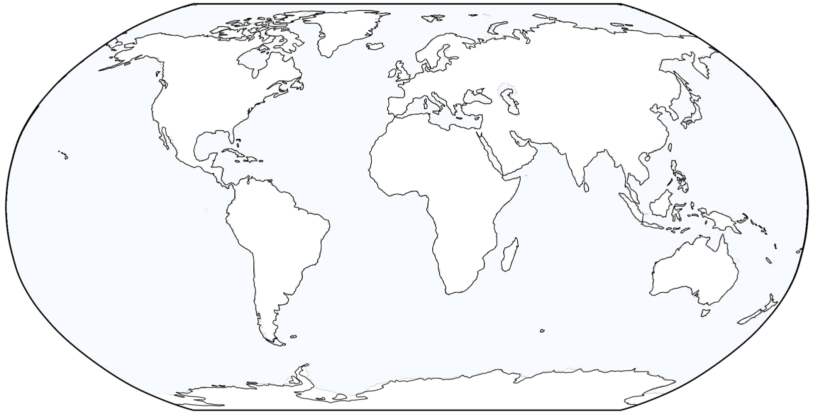

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Thank you to David Bailey for helping me get this unconventional experimental setup to work!

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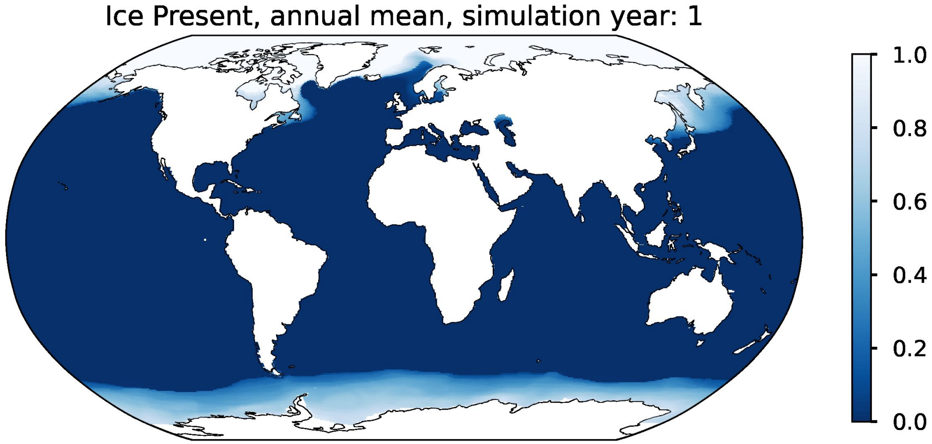

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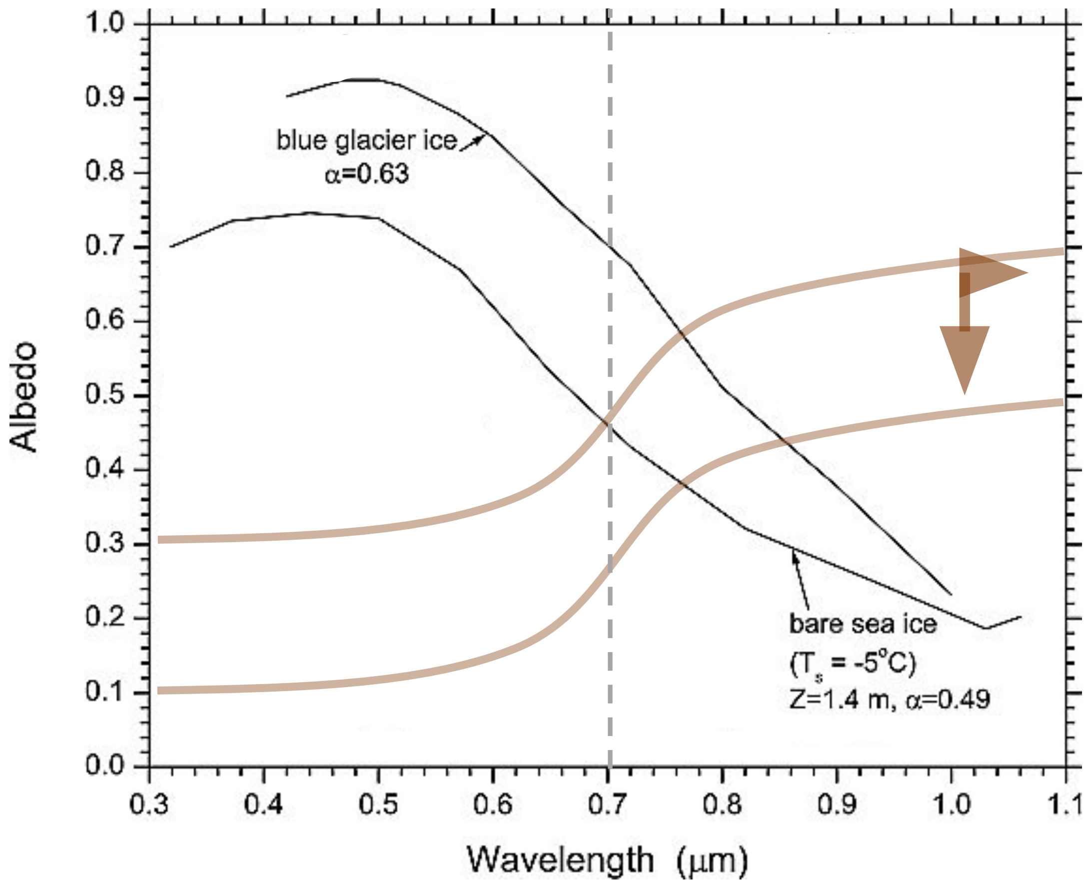
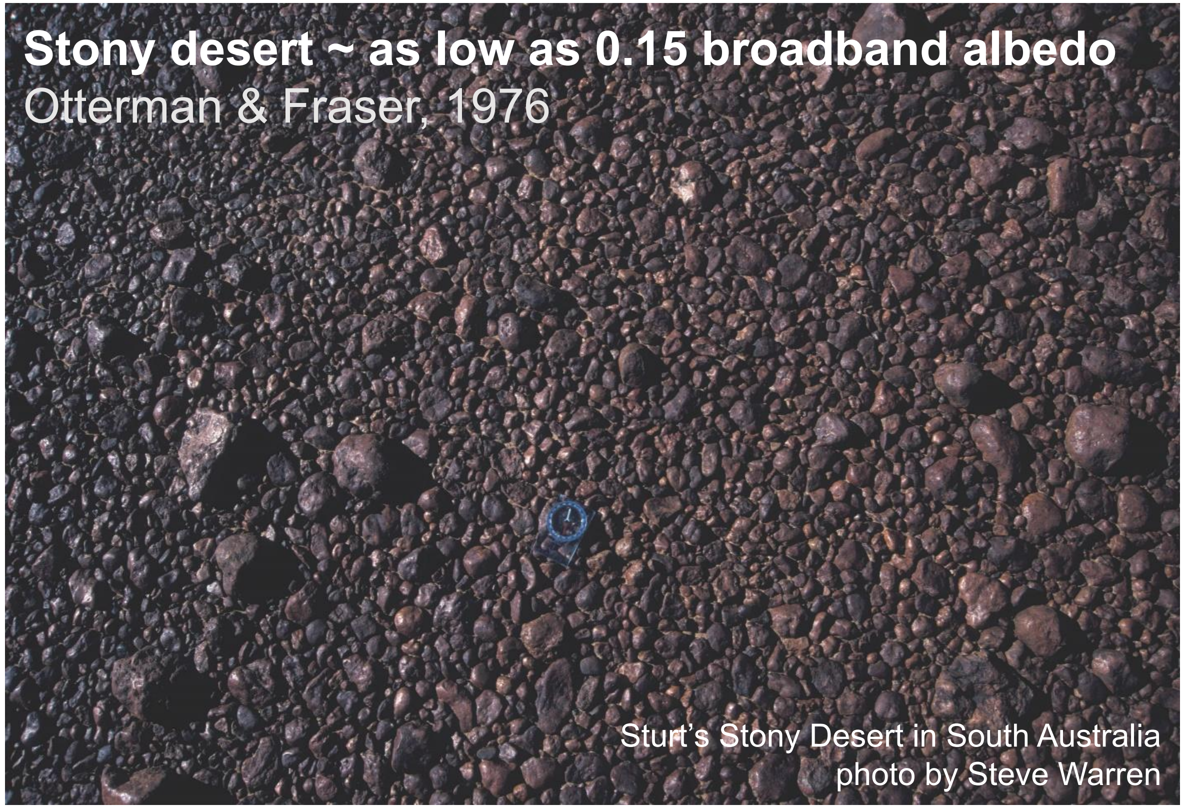
2. What controls the existence of these refugia?

   >> Sample land albedo and CO_2 *values in CESM to assess relative radiative influence on habitability.*

Land surfaces could have been stony deserts (no plant roots to break up rocks) leading to dark land albedos.

Albedo of sandy desert land varies by moisture content and **grain size:**





Stony desert ~ as low as 0.15 broadband albedo

Otterman & Fraser, 1976

Sturt's Stony Desert in South Australia
photo by Steve Warren

Sampling range of land surface albedo and CO_2 values

- After reaching equilibrium Snowball state, we sample land surface albedo and CO_2 levels
- Initialize sea ice:
  - 20 m depth at all latitudes
  - Set sea ice albedo (higher) firn albedo
- Snow albedo masks land albedo at 1 cm water-equivalent (~10 cm snow)

	Increasing CO2 concentration (ppm) □					
		10	*25*	*50*	*100*	*200*
Decreasing land albedo □	*0.4*	🟩		🟩		🟩
	0.35			🟩		
	0.3	🟩	🟩	🟩	🟩	🟩
	0.25			🟩		
	0.2	🟩		🟩		🟩

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Decreasing land albedo □	*0.4*	-38°C		-36°C		-34°C
	0.35			-35°C		
	0.3	-37°C	-35°C	-35°C	-34°C	-34°C
	0.25			-34°C		
	0.2	-35°C		-34°C		-33°C

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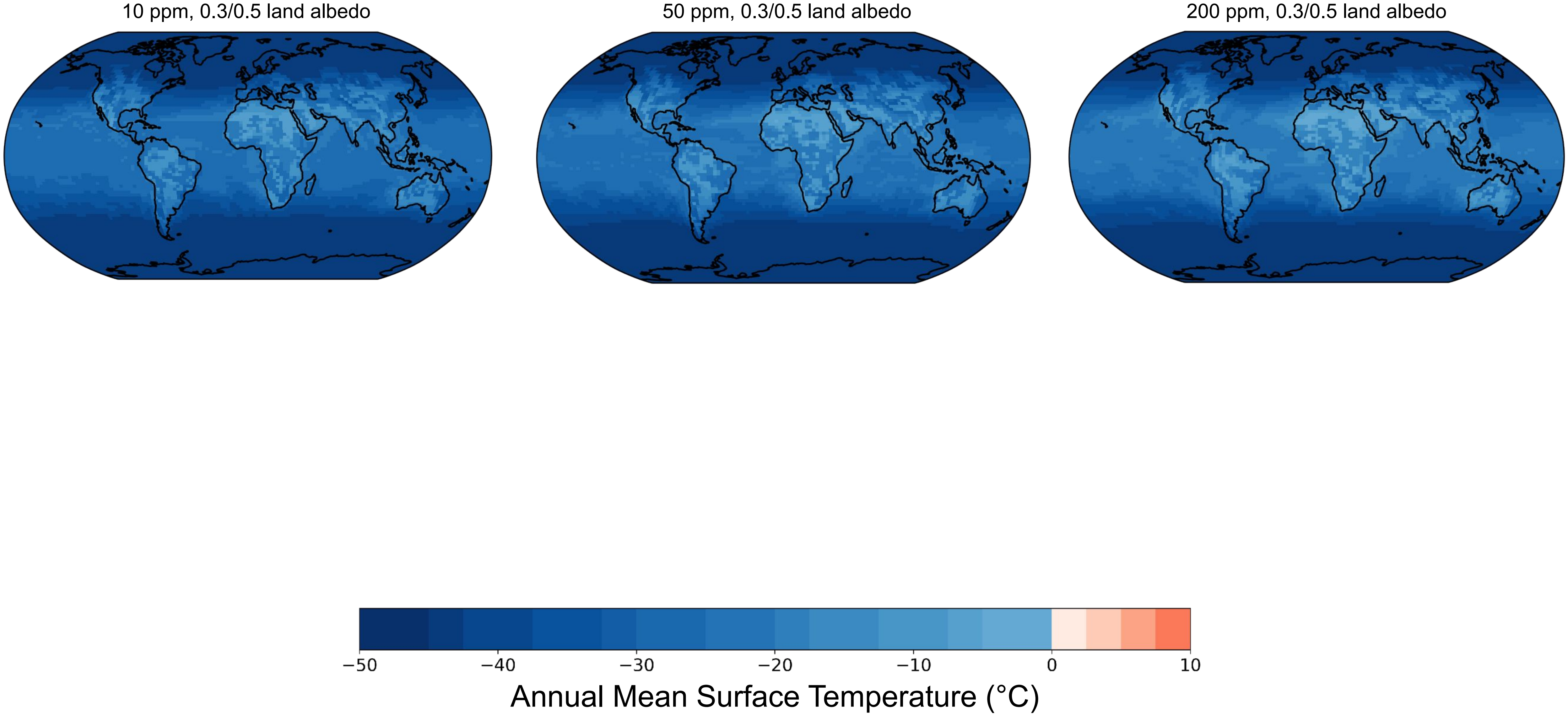
	0.2	-35°C		-34°C		-33°C

5.1 Wm^{-2}

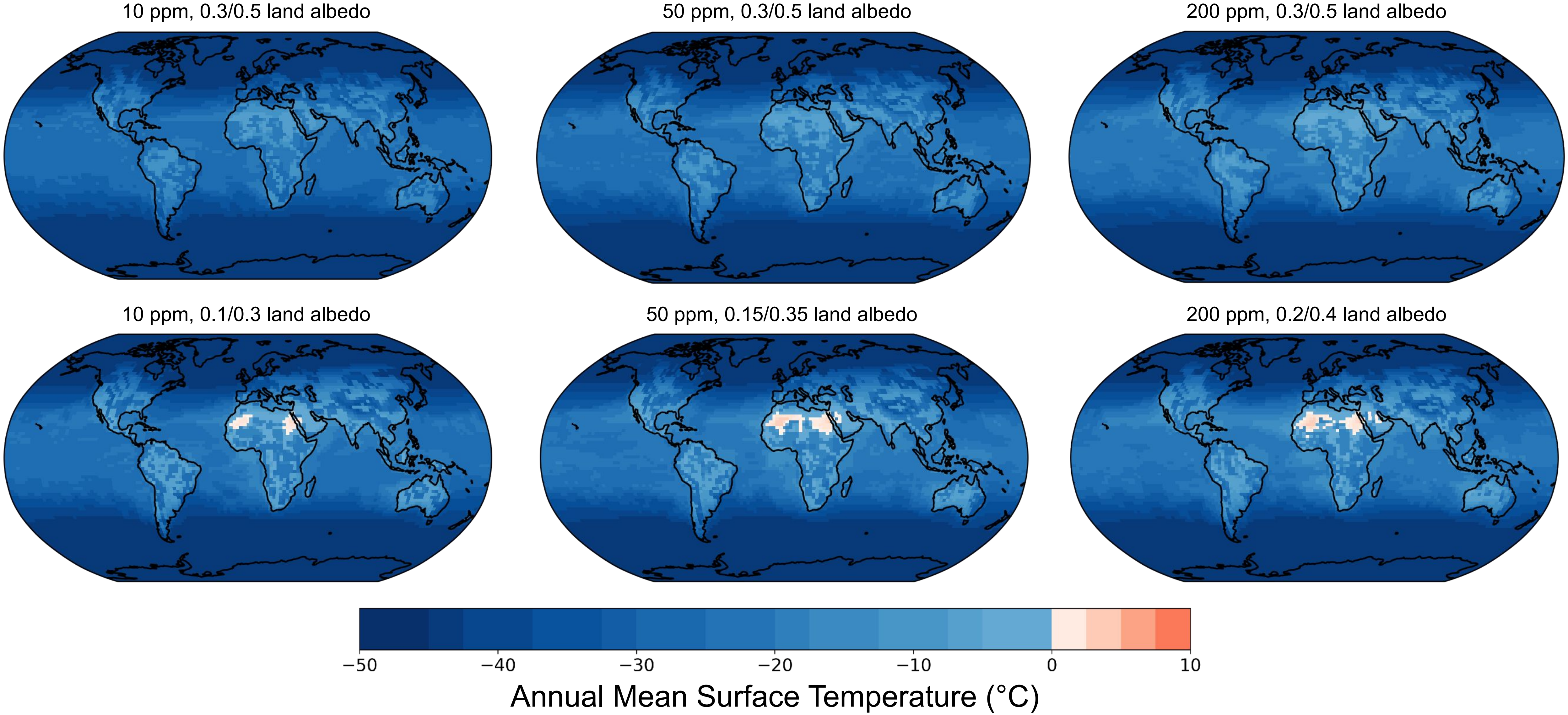
8.4 Wm^{-2}

Radiative forcing (W/m^2) as estimated by CAM's Portable Offline Radiation Tool (PORT)

At high land albedos, nowhere has mean annual surface temperatures that can maintain liquid water.



At lower albedos and higher CO_2, mean annual land surface T reaches above freezing, allowing “open-water” refugia near coasts.



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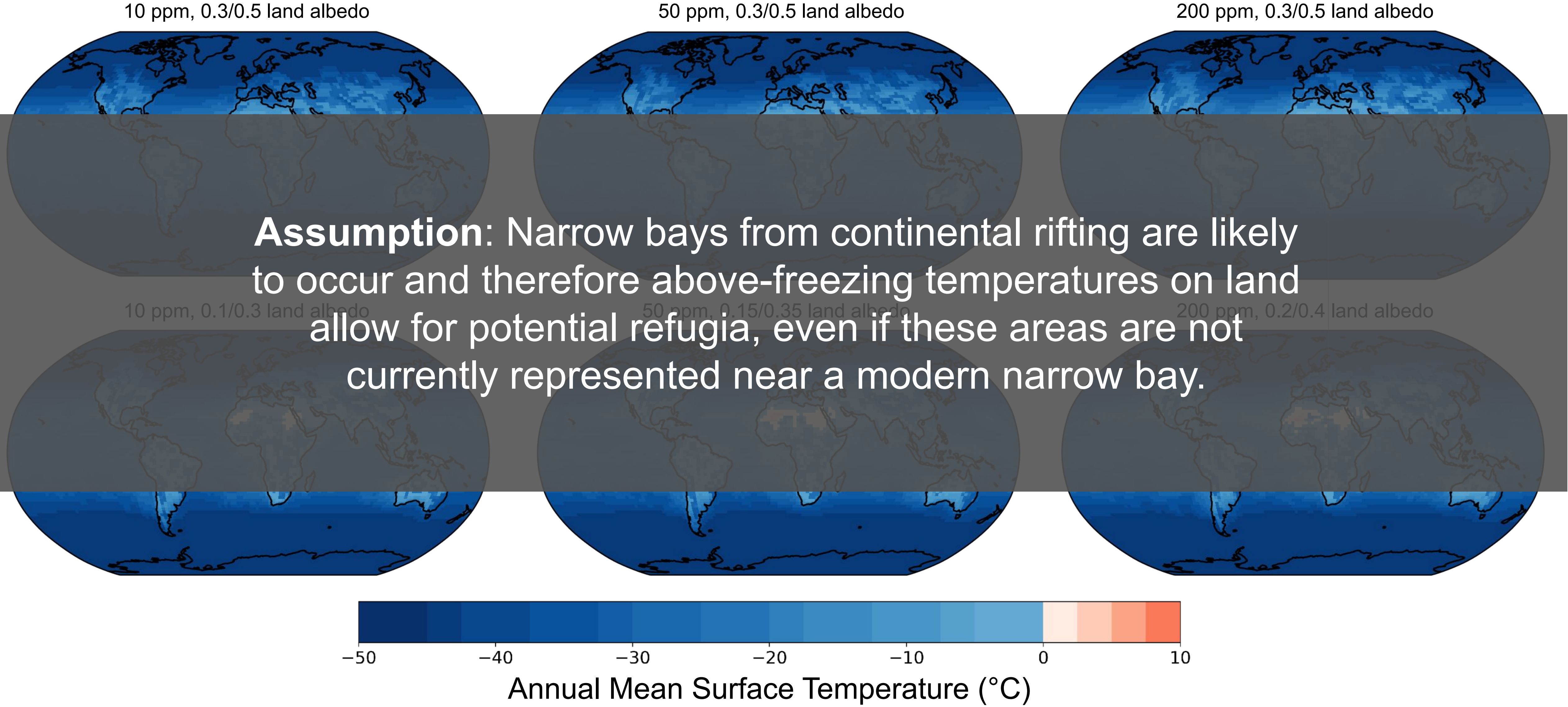
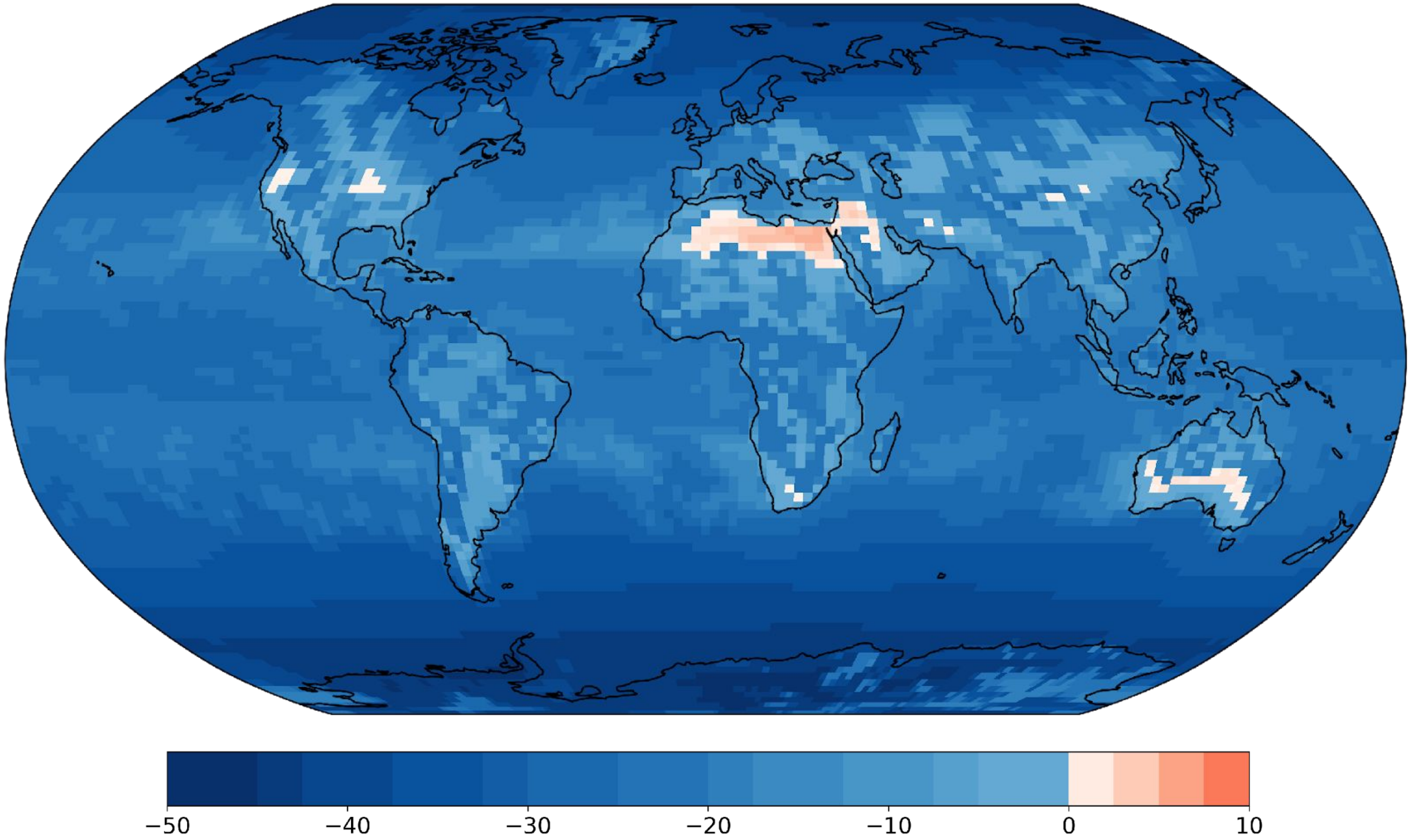


Assumption: Narrow bays from continental rifting are likely to occur and therefore above-freezing temperatures on land allow for potential refugia, even if these areas are not currently represented near a modern narrow bay.

Even in the coldest conditions, land surfaces reach above-freezing temperatures seasonally, allowing for “ice-surface" refugia.



Annual Max Surface Temperature (°C)
lowest CO_2, highest bare land albedo

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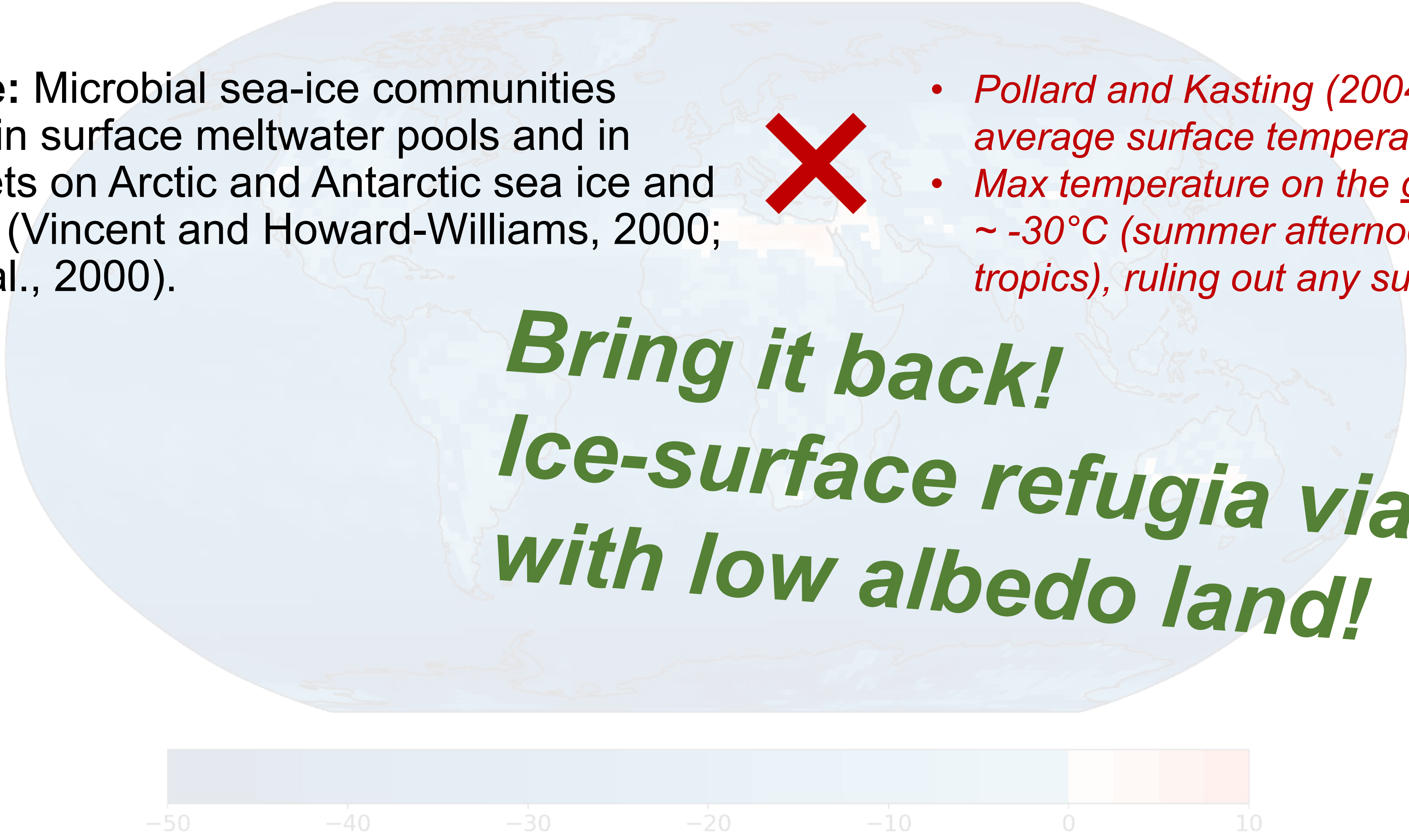
Bring it back!

Ice-surface refugia viable with low albedo land!



Annual Max Surface Temperature (°C)
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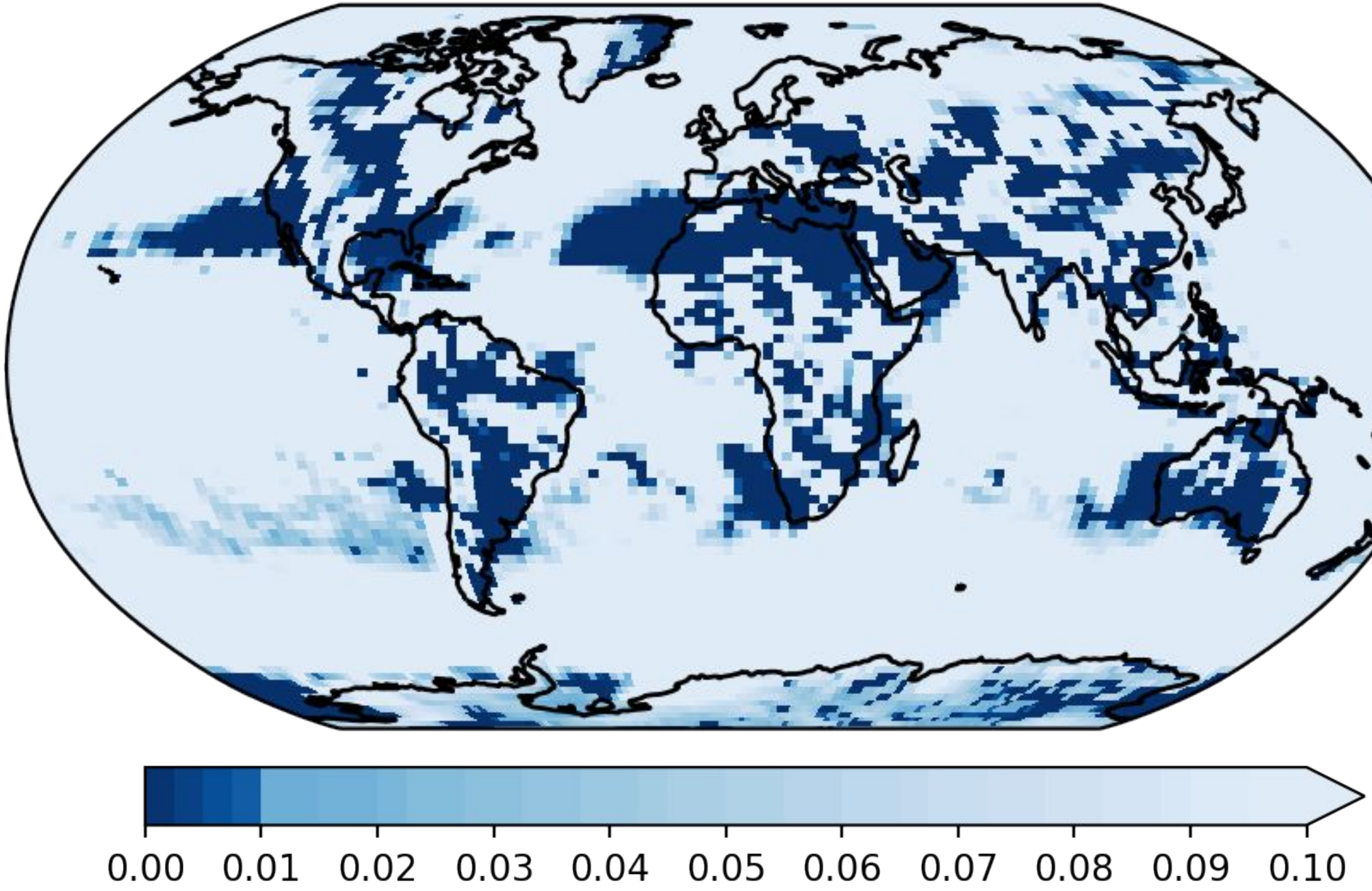
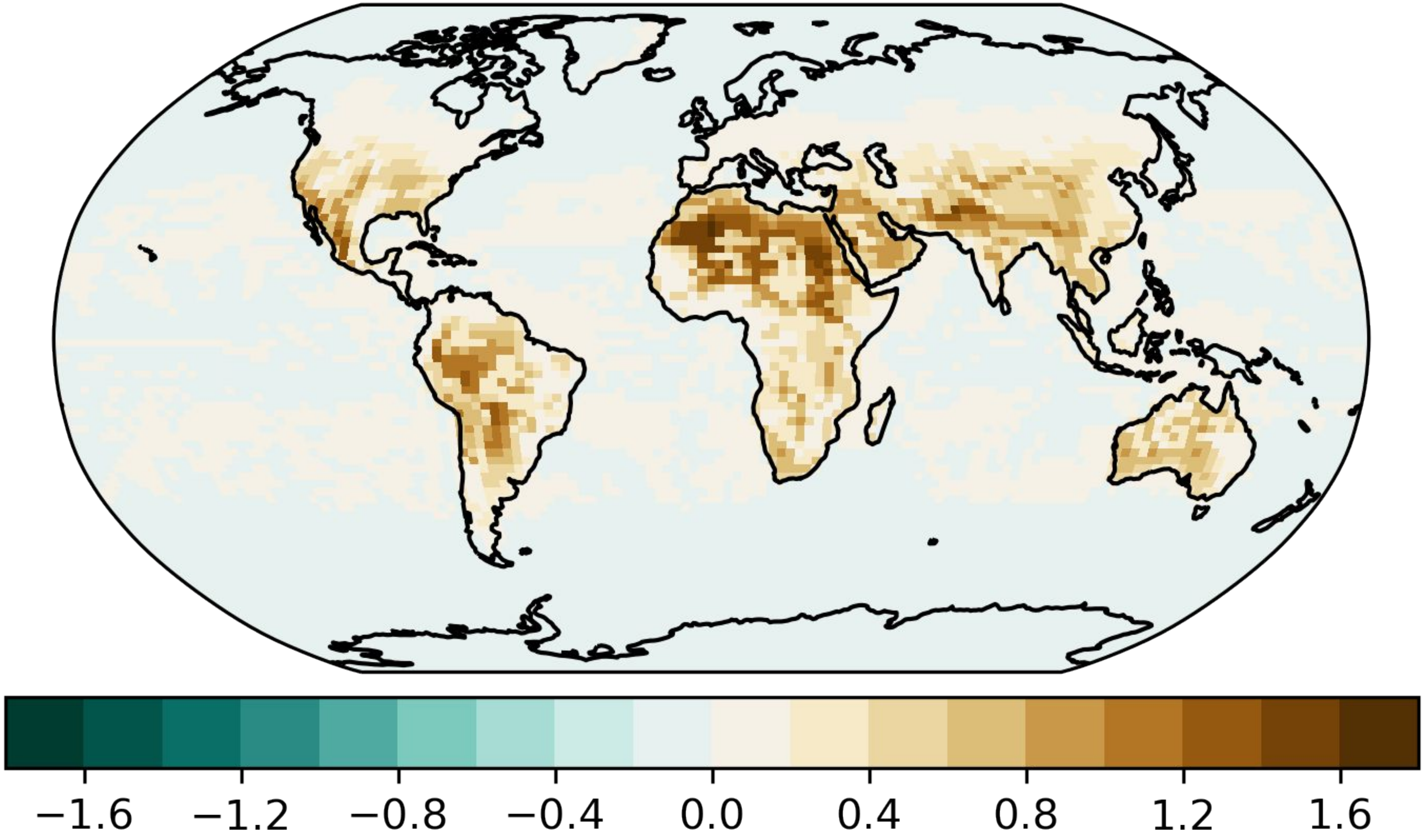
Widespread snow-free land exposes dark land surface albedo.



Annual Min Water Equivalent Snow Depth (m)
lowest CO_2, highest bare land albedo

Frozen ocean leads to very dry atmosphere, most of land is net-sublimating, PE > P.



Annual Mean Potential Evaporation – Precipitation (mm/day)
lowest CO_2, highest bare land albedo

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   - “Open water” refugia possible at low land albedo, high CO_2
   - “Ice-surface” refugia in narrow bays are possible even at low CO_2 and bright bare ground.
2. What controls the existence of these refugia?

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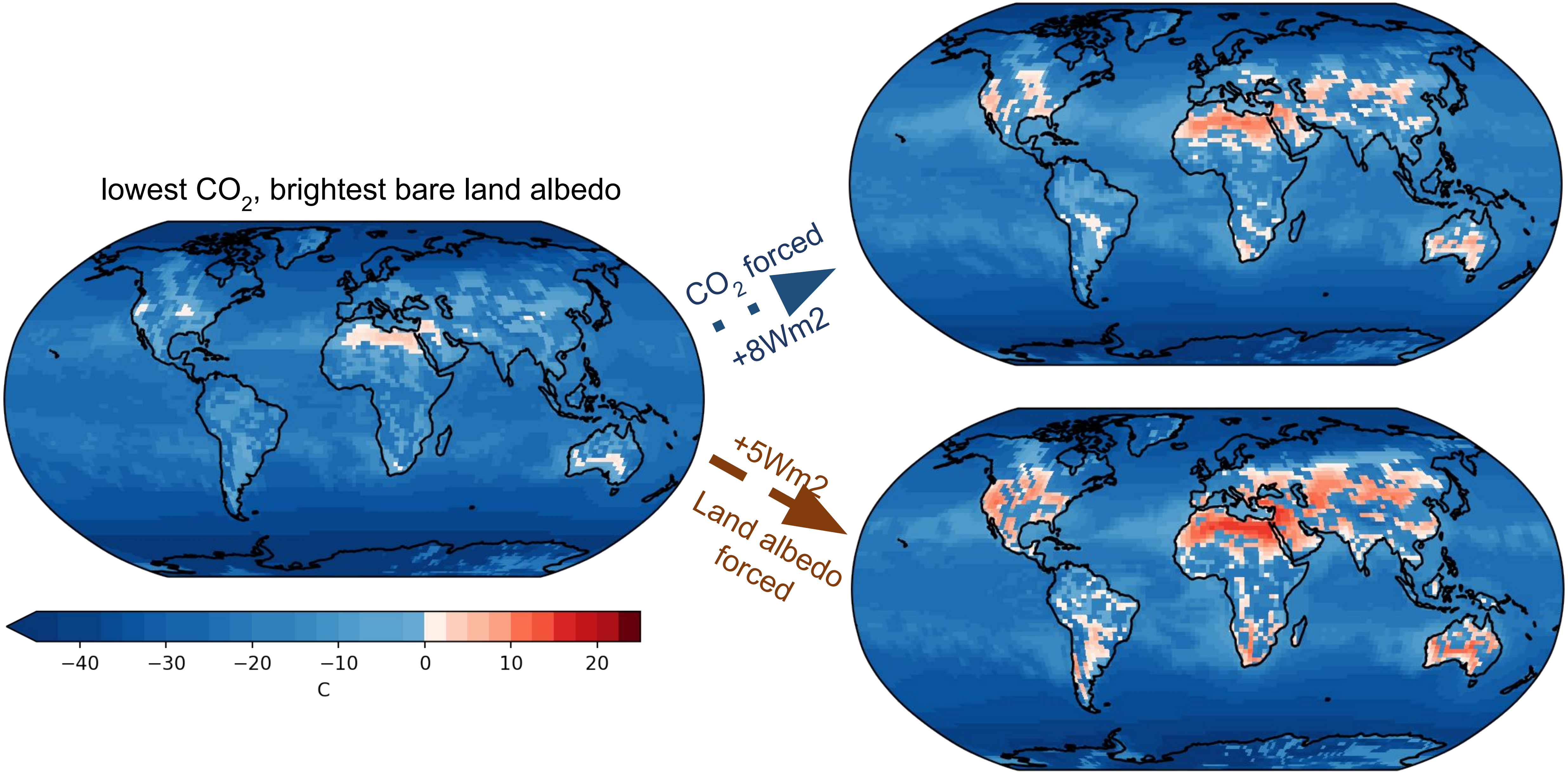
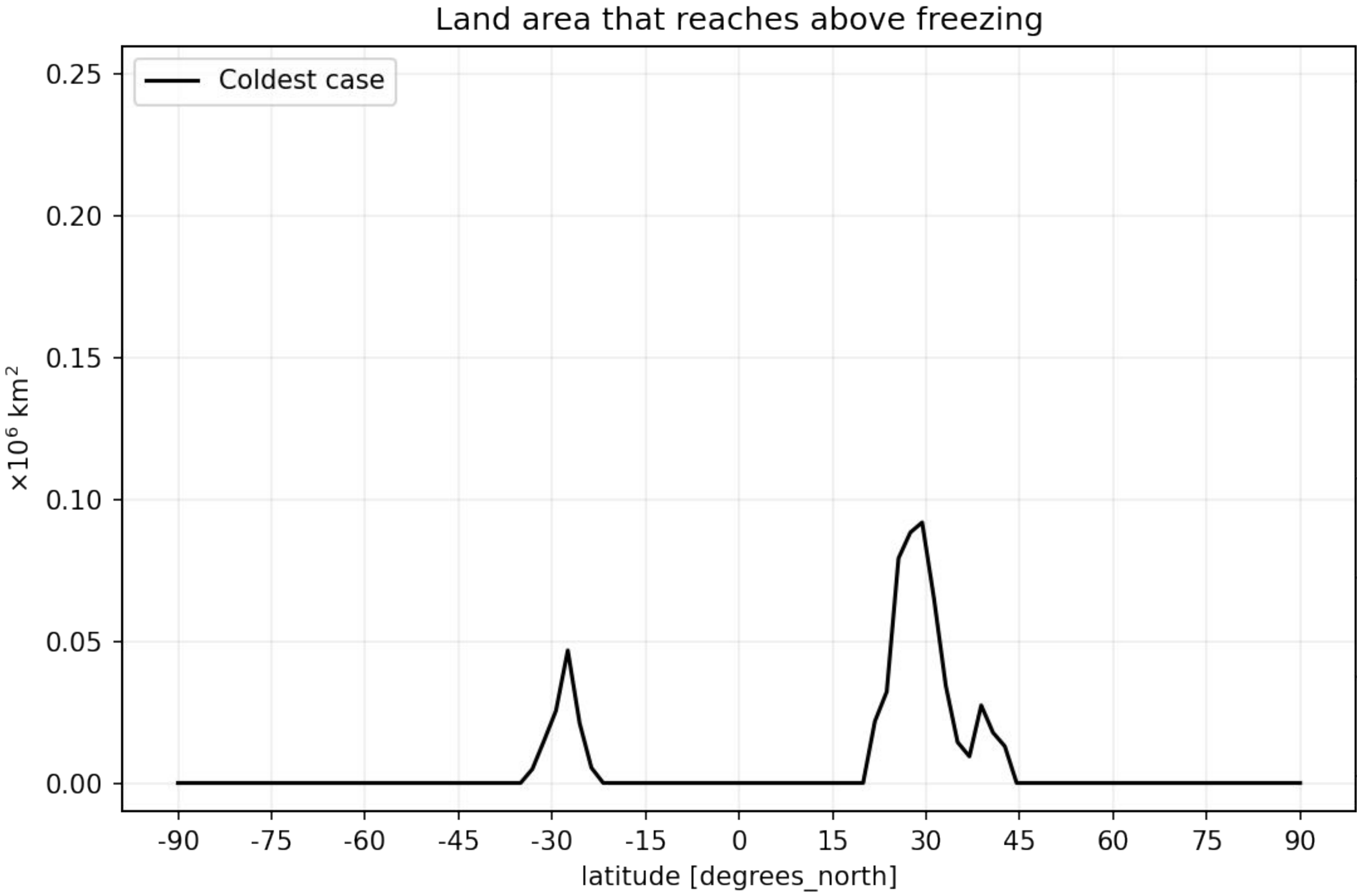
>> Sample land albedo and CO_2 *values in CESM to assess relative radiative influence on habitability.*

More habitable land produced through albedo forcing.



Result: Decreasing albedo leads to stronger temperature increases over land since much of land is snow-free.



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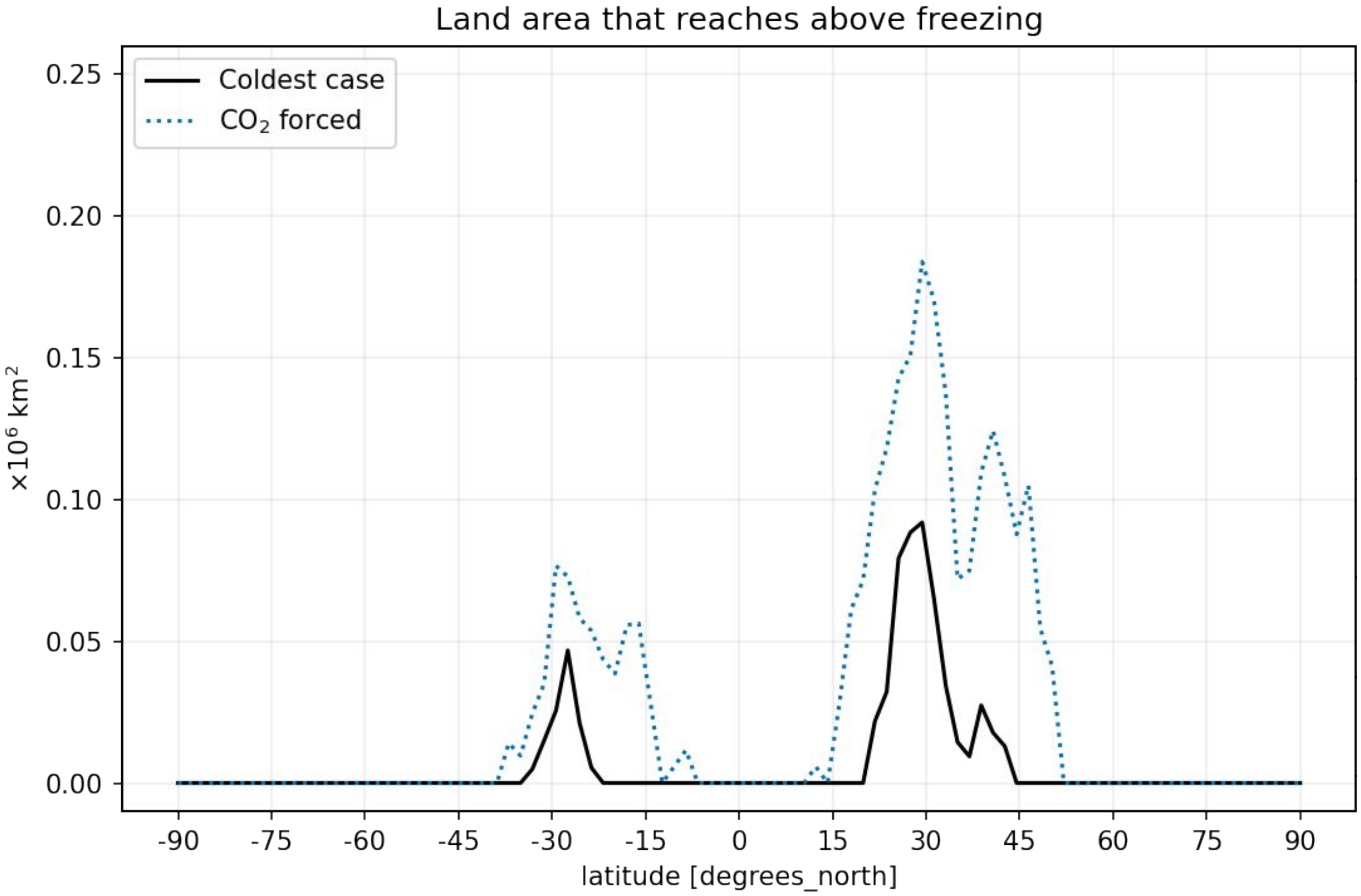

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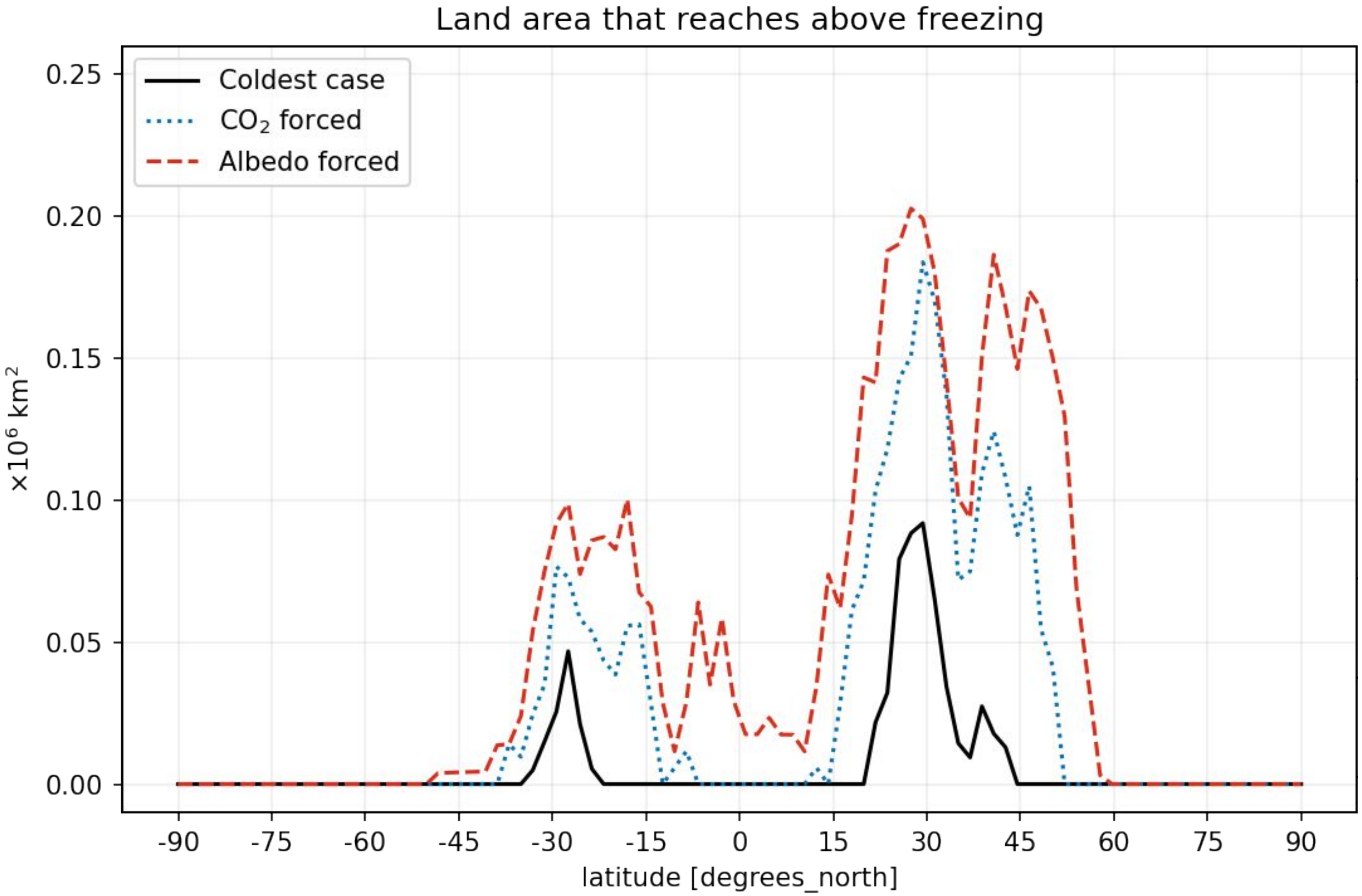
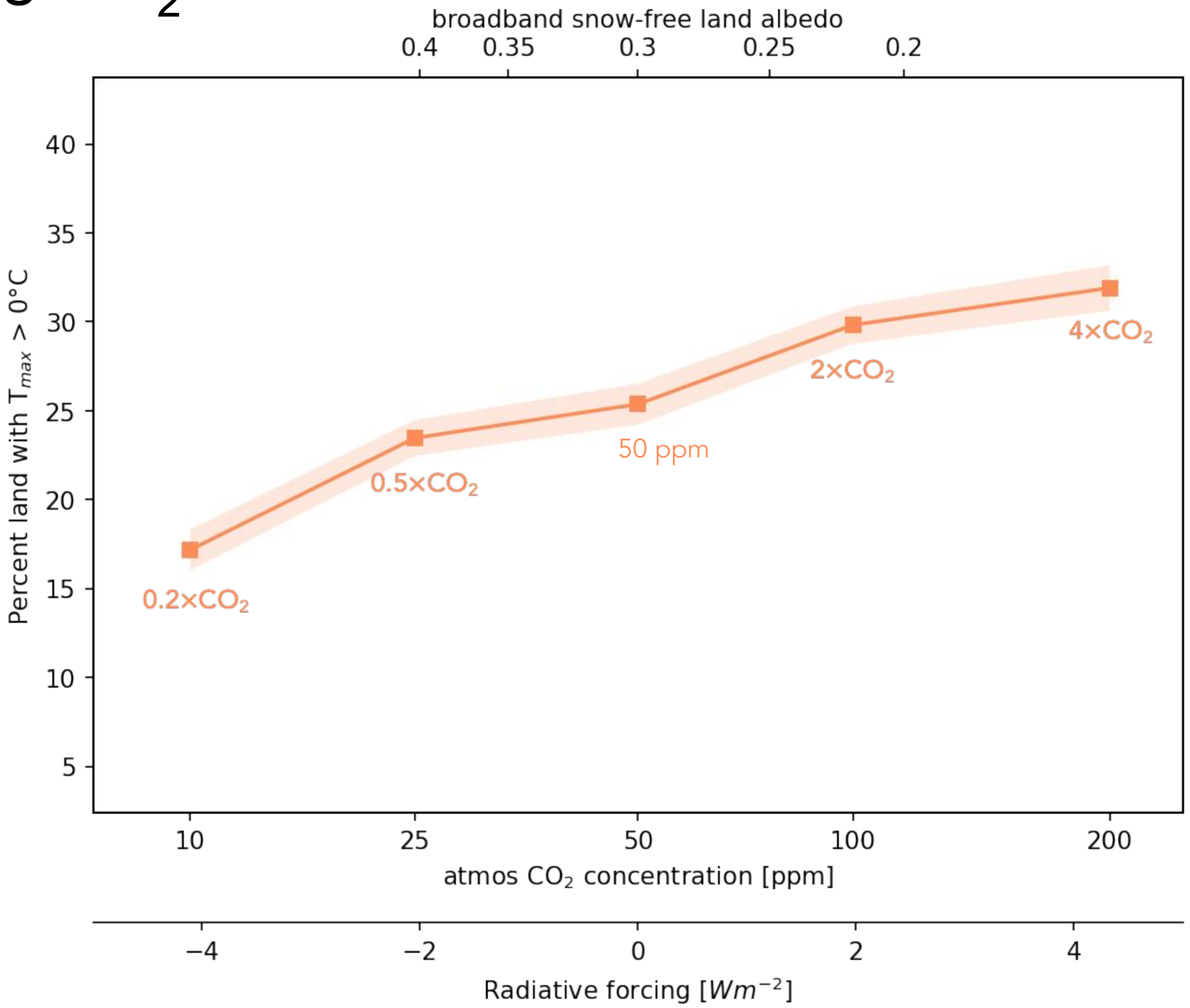


Lowering land albedo increases surface temperatures more strongly than increasing CO_2.



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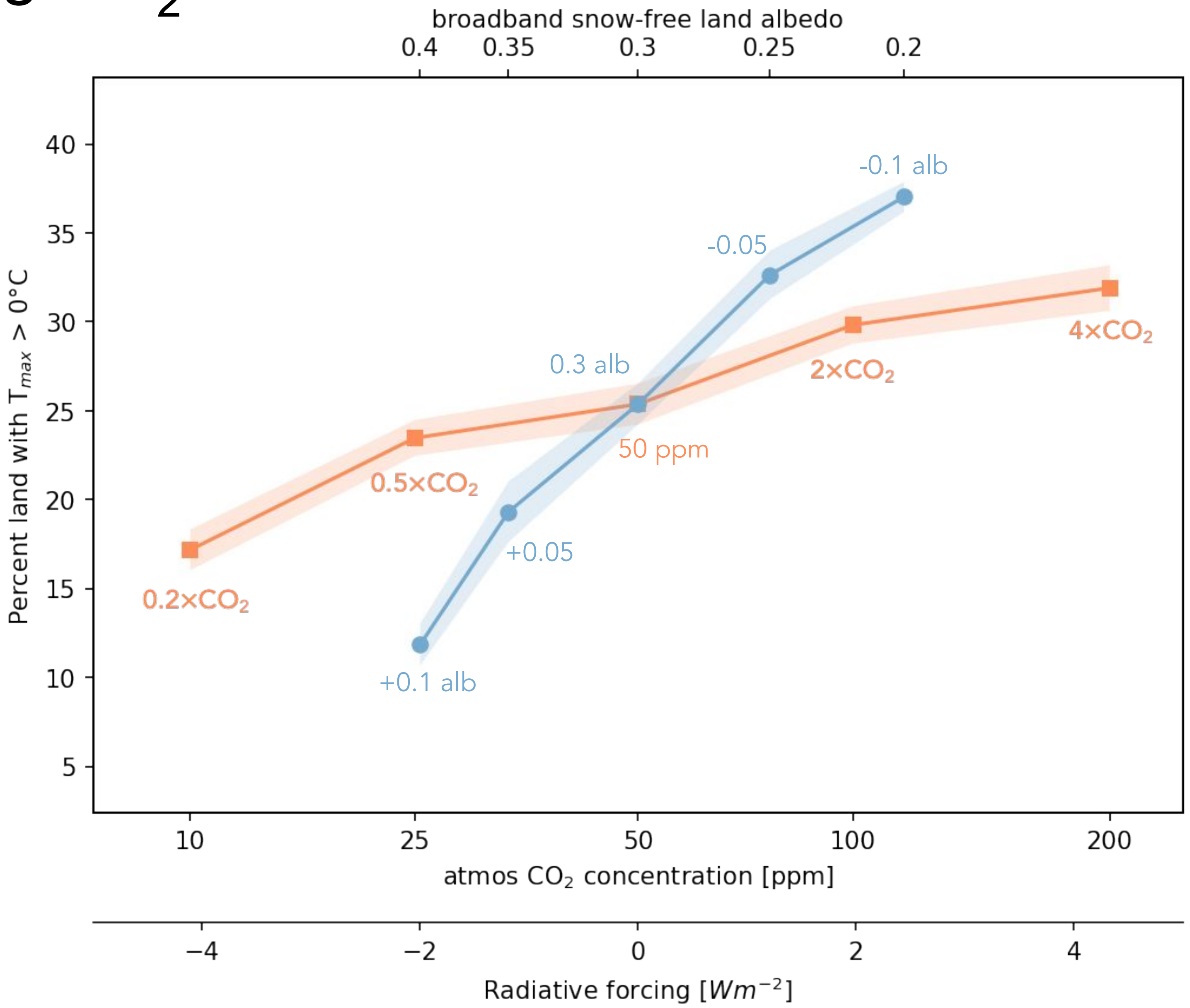

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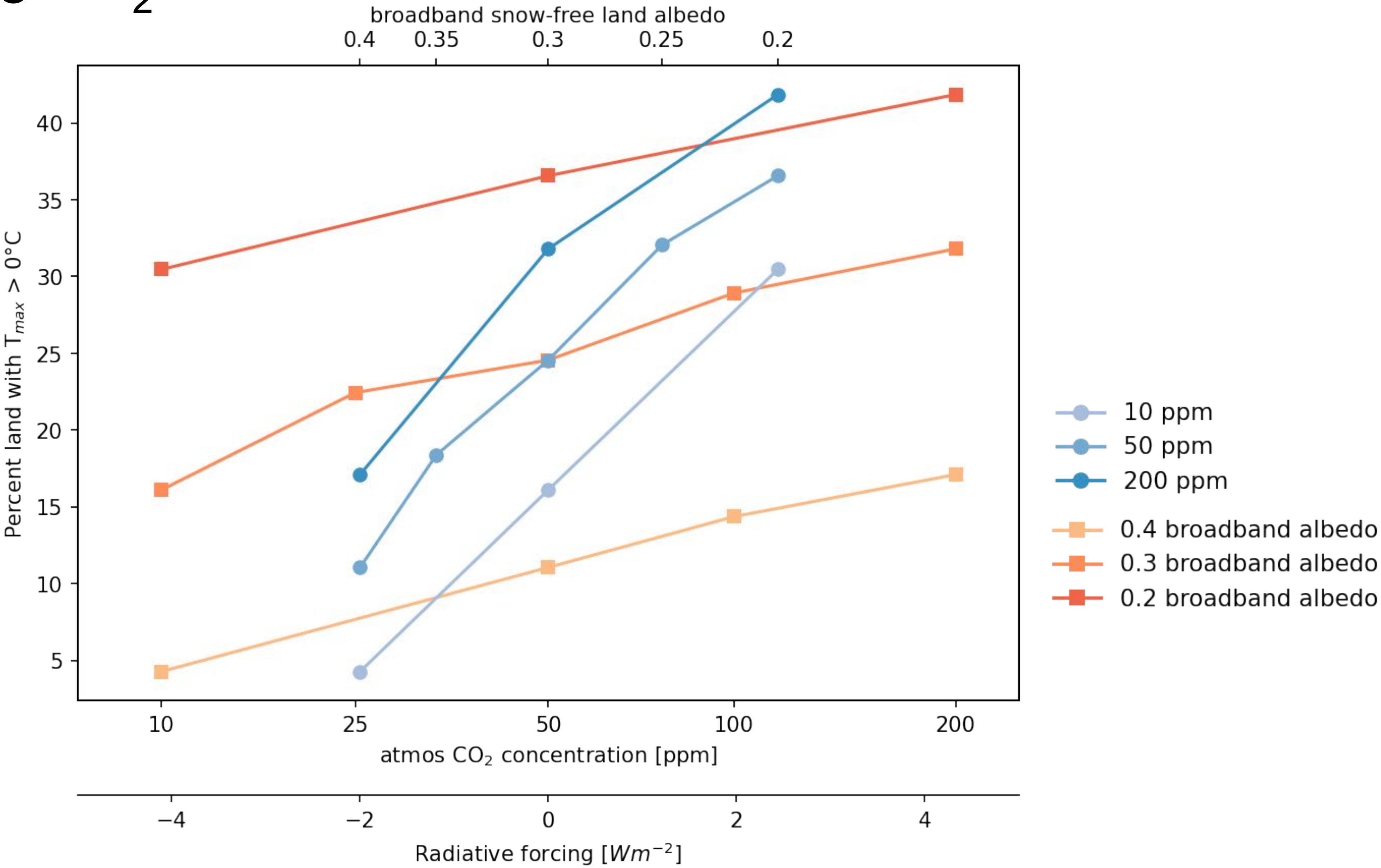

Two ways albedo forcing could outcompete CO_2 forcing:

Direct Effect:
increase net solar absorbed purely through albedo change, warm surface

Indirect Effect:
increase net solar absorbed by increasing PET – P over land, exposing more bare land, warm surface

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Direct Effect:
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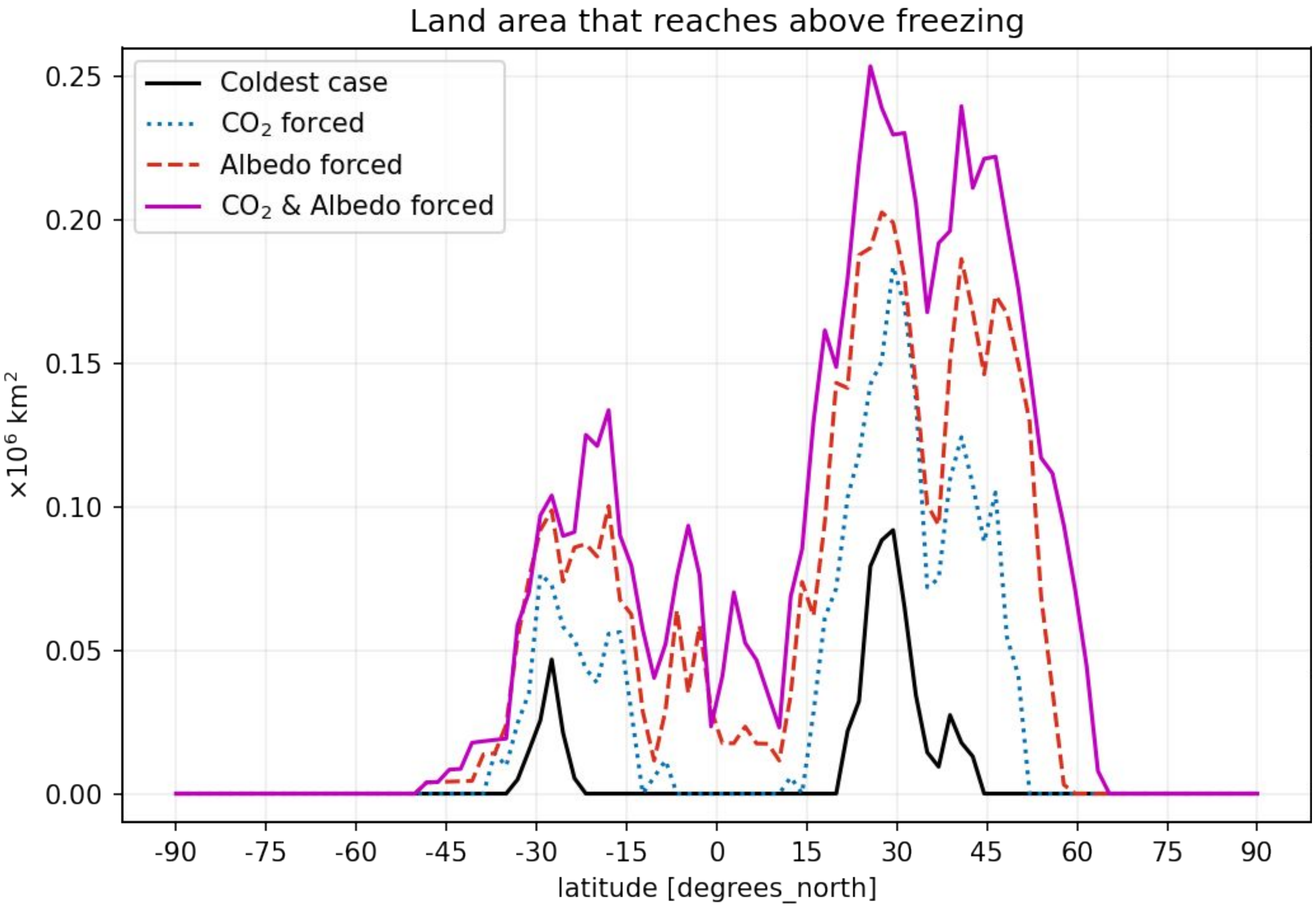
Decreasing land albedo from 0.4 □ 0.2 leads to **10%** of land to become habitable

Indirect Effect:
increase net solar absorbed by increasing PET – P over land, exposing more bare land, warm surface

Decreasing land albedo from 0.4 □ 0.2 leads to **11%** of land to become habitable

Combining the both CO_2 and albedo influences, Snowball Earth could easily host land-based refugia.



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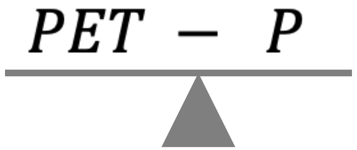
2. What controls the existence of these refugia?
   - Land surface albedo exerts a stronger control on refugia conditions (for the same global radiative forcing) than CO_2 concentration by increasing net radiation absorbed directly (albedo change) and indirectly (more snow-free land).
   - Continental configuration would influence habitability.

How can the land be snow-free? Isn’t it covered in ice sheets?

- Long-term snow height is set by long-term aridity, or the balance of evaporative demand vs moisture supply. To understand snow-height on land:



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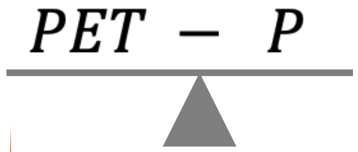


$$PET - P$$

PET calculated from Penman-Monteith Eqn as a weighted linear combination of available energy and VPD:

Penman 1984,
Monteith 1981,
Scheff & Frierson, 2014
Allen et al., 2005

$$PET = \left[\frac{\Delta\overbrace{(R_n - G)}^{\text{Available energy}} + \rho_a c_p \overbrace{e^*(T_a)(1-RH)}^{\text{Vapor pressure deficit}} C_H|u|}{\Delta + \gamma(1 - r_s C_H|u|)}\right] \Big/ L_{v/s}$$

$\Delta = de^*(T_a)/dT$
Local slope of Clausius–Clapeyron

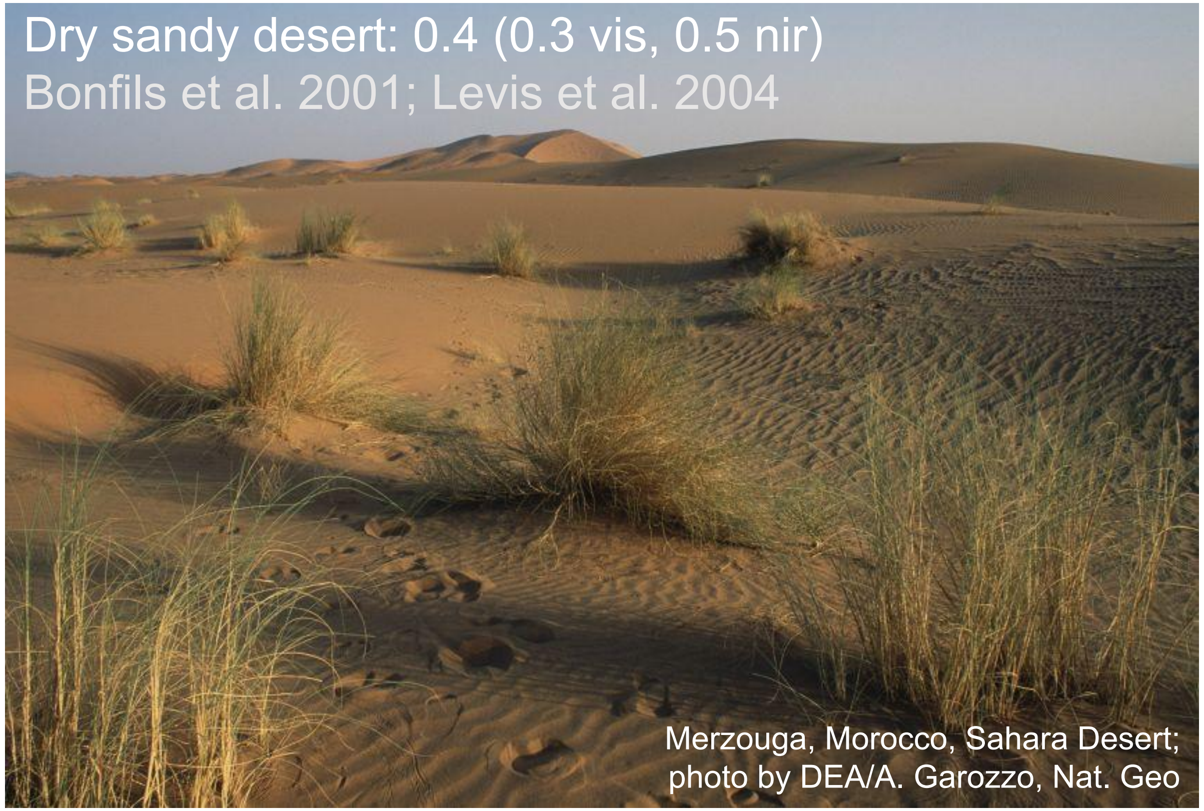
$\gamma = (c_p p_s)/(\varepsilon L)$
ε = ratio of molar masses of H_2O and dry air ~ 0.622

r_s = stomatal resistance → 0

C_H = transfer coefficient, following Monin-Obukhov, reduced because of lowered surface roughness: 4.5×10^{-3}

Land surfaces would have been stony deserts (no plant roots to break up rocks) leading to darker land albedos.

Albedo of sandy desert land varies by moisture content and **grain size:**



Dry sandy desert: 0.4 (0.3 vis, 0.5 nir)

Bonfils et al. 2001; Levis et al. 2004

Merzouga, Morocco, Sahara Desert;
photo by DEA/A. Garozzo, Nat. Geo

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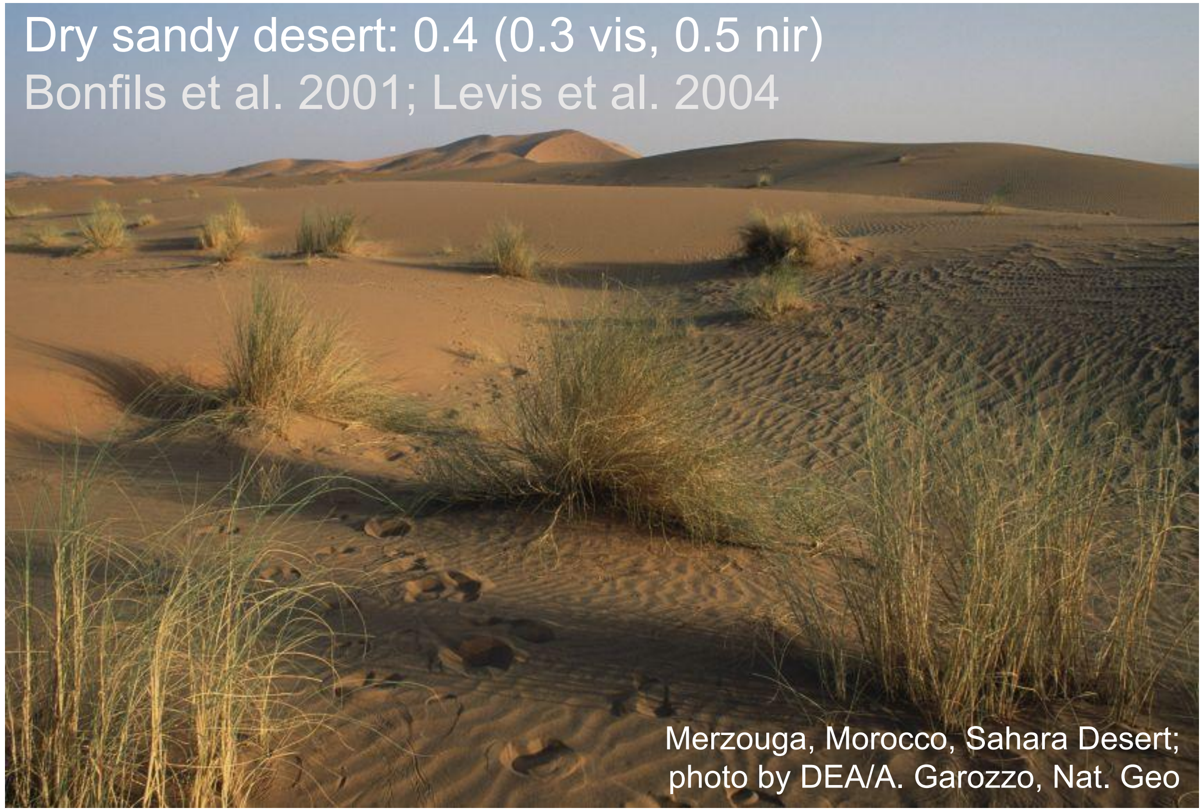

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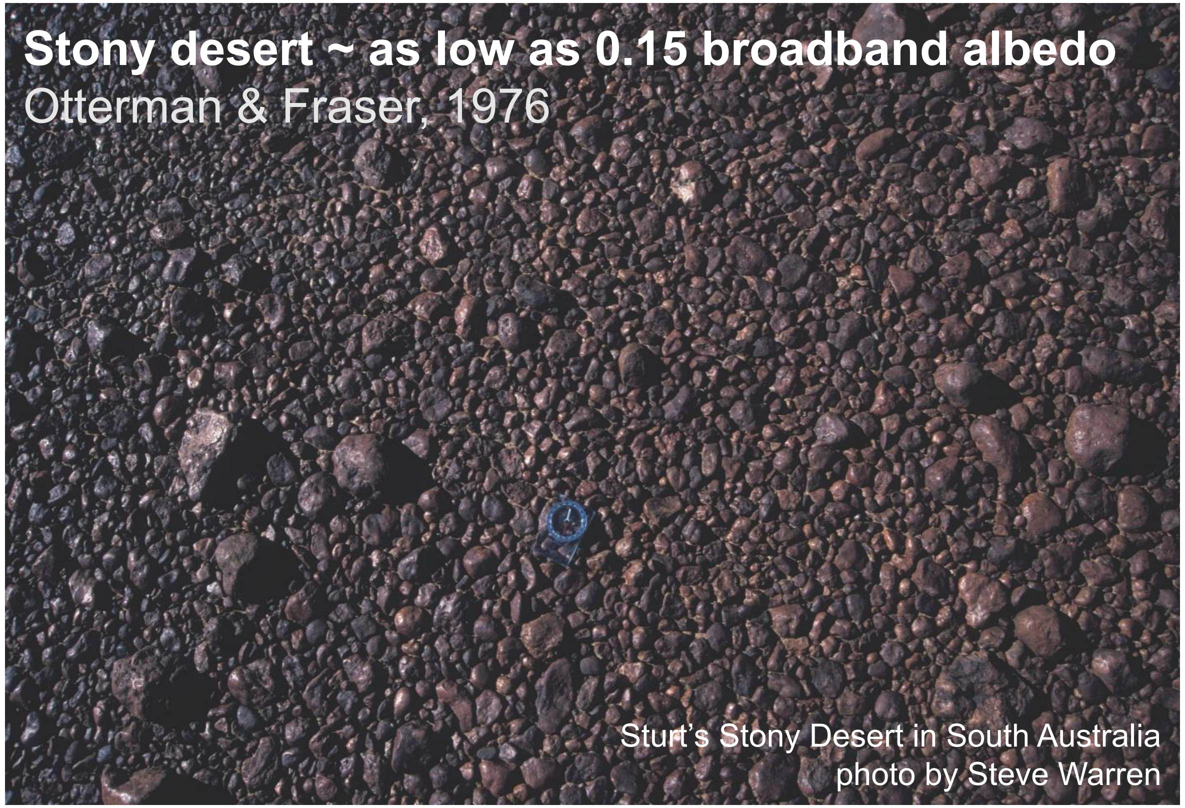
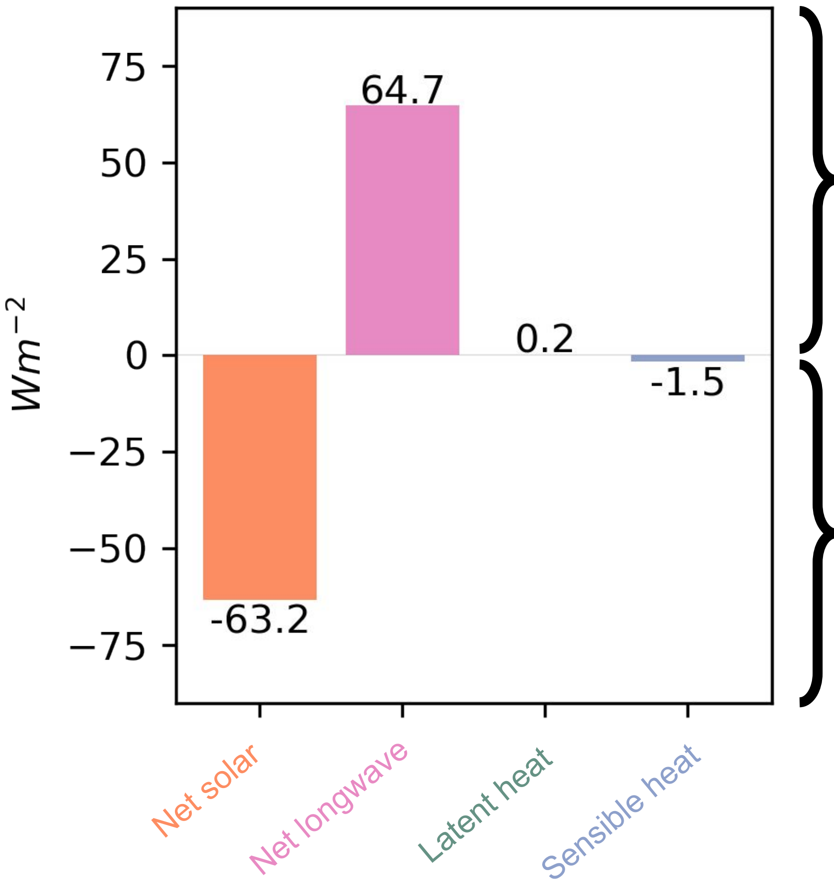


Stony desert ~ as low as 0.15 broadband albedo

Otterman & Fraser, 1976

Sturt's Stony Desert in South Australia
photo by Steve Warren

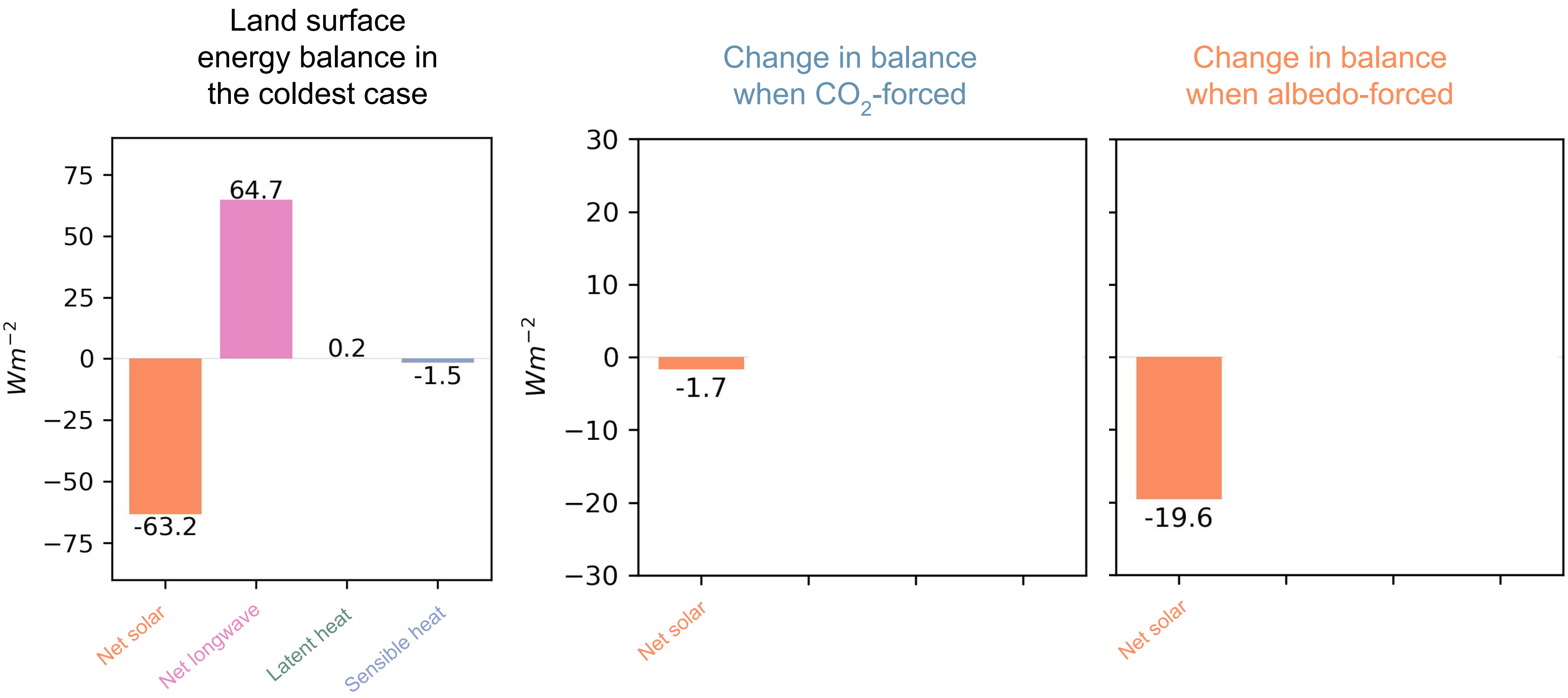
Increases in net radiation drive warmer temperatures.


Land surface energy balance in the coldest case

Positive values denote energy out of the land

Negative values denote energy going into the land

Increases in net radiation drive warmer temperatures over land



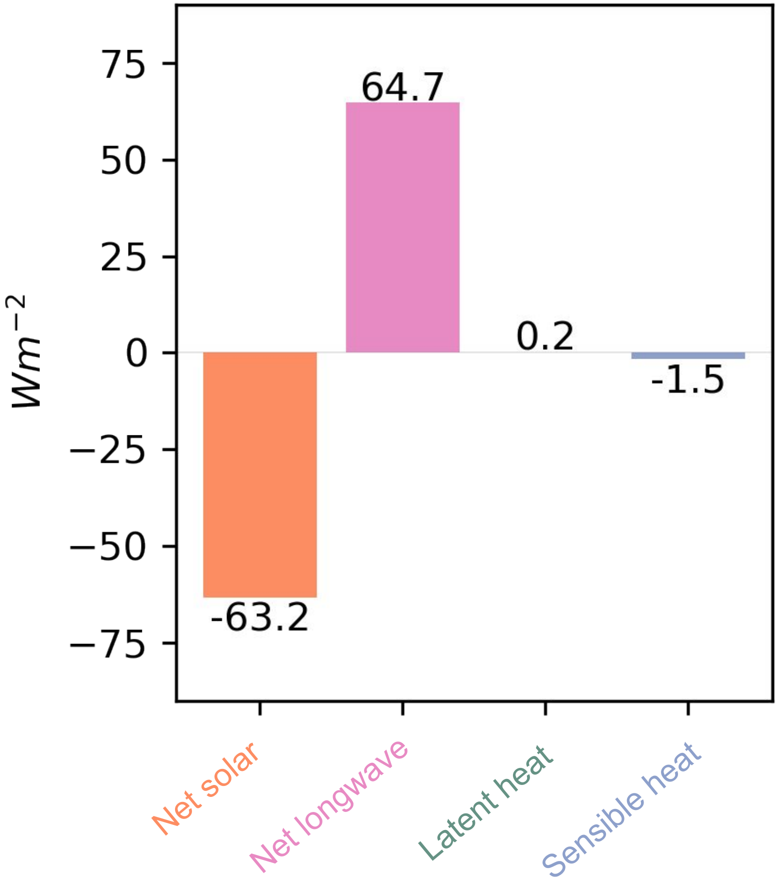
Land surface energy balance in the coldest case

Change in balance when CO_2-forced

Change in balance when albedo-forced

Increases in net radiation drive warmer temperatures over land

Land surface energy balance in the coldest case



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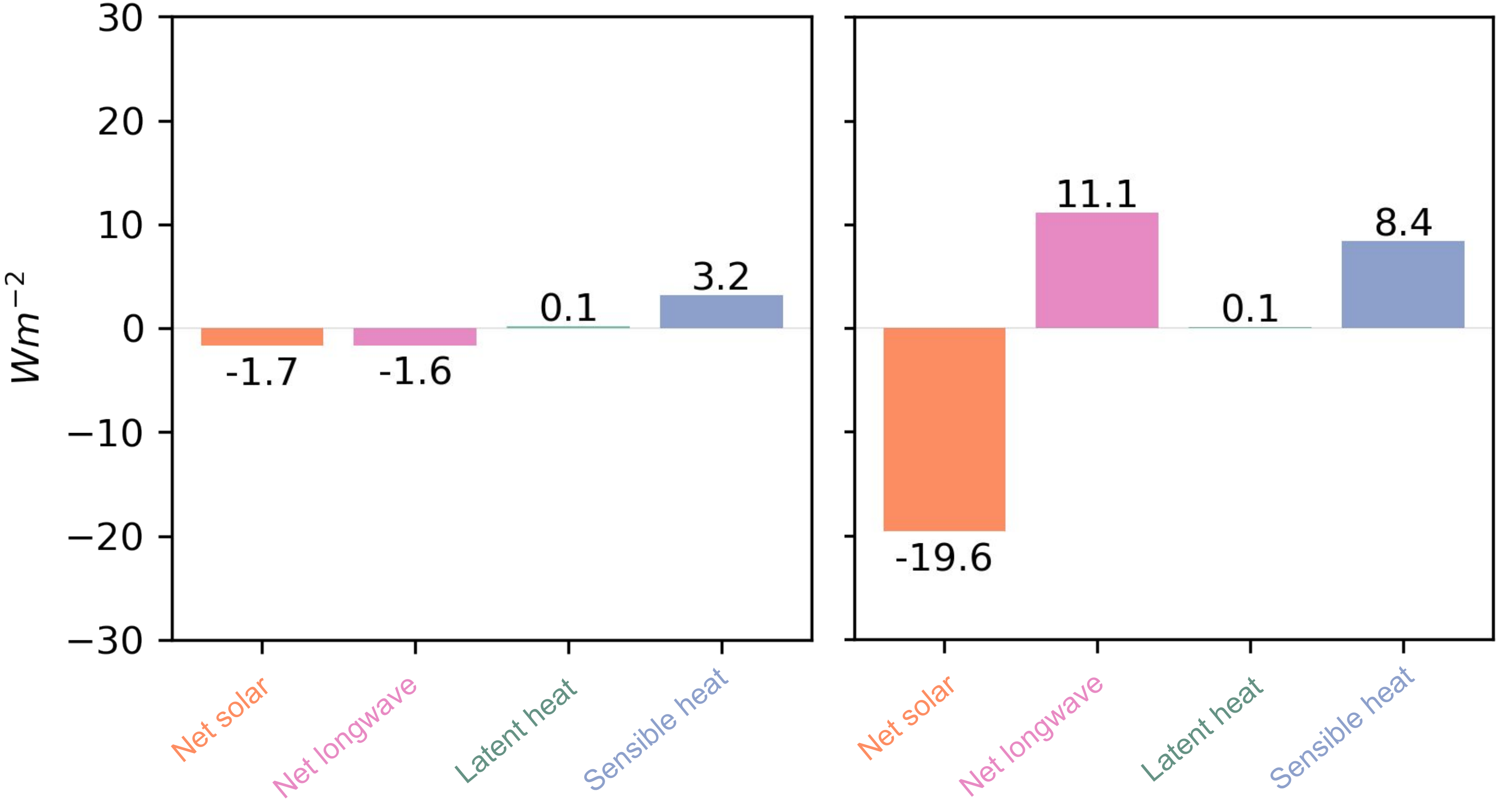
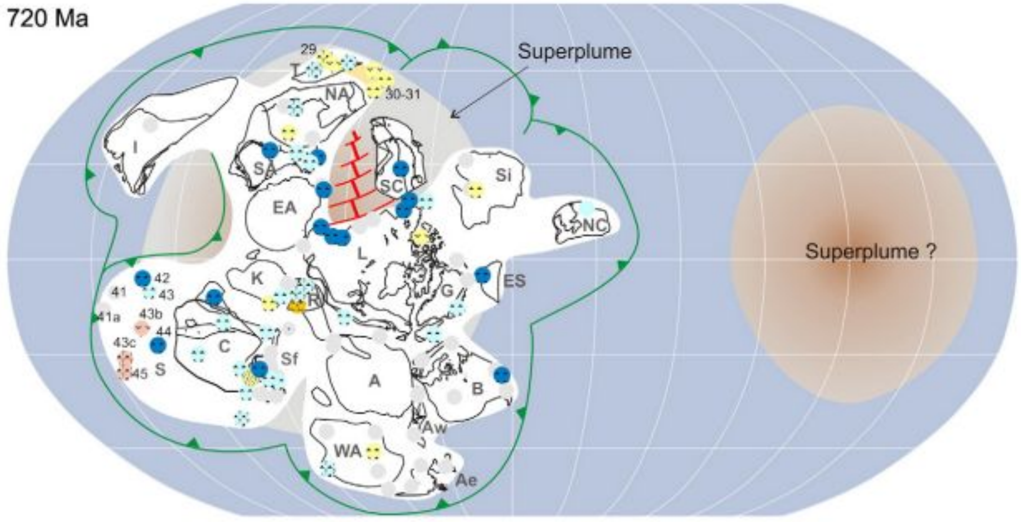


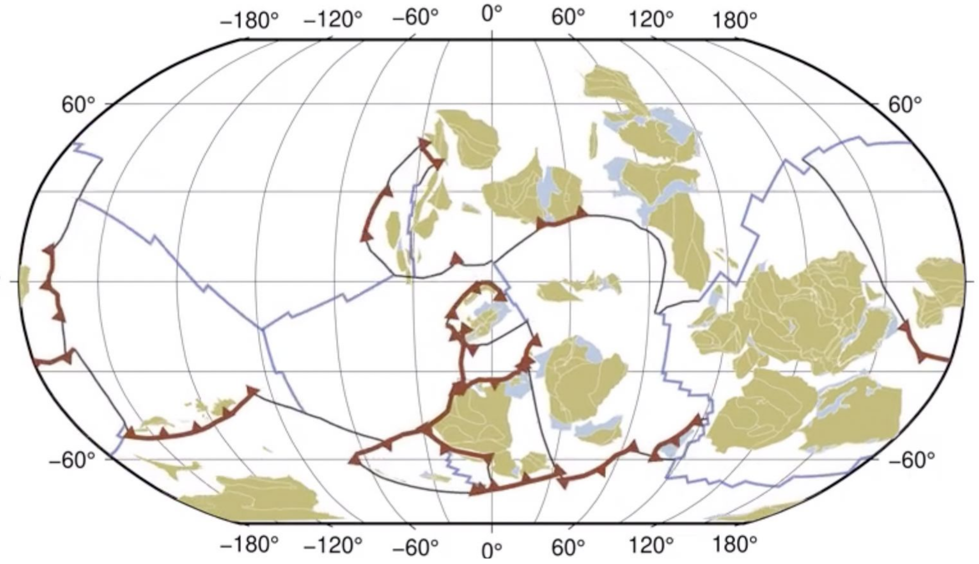
Paleogeography likely influences habitability, but is highly uncertain.

- The Sturtian Snowball event (longest known) occurred as the supercontinent, Rodinia was breaking up (780 Ma).
- **Were there large areas of concentrated land?**

  >> It’s hard to know, and recent reconstructions are inconsistent:



720 Ma, Li et al. (2013)



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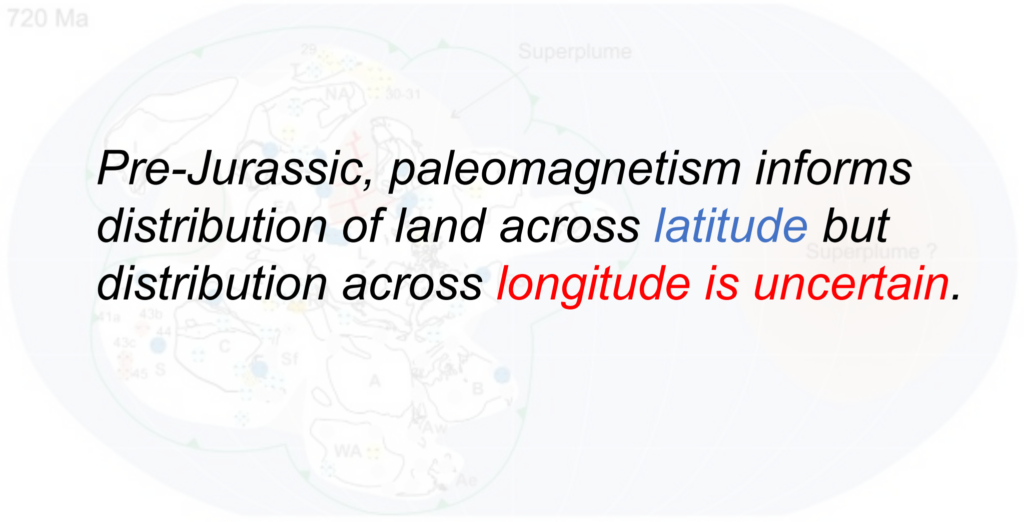
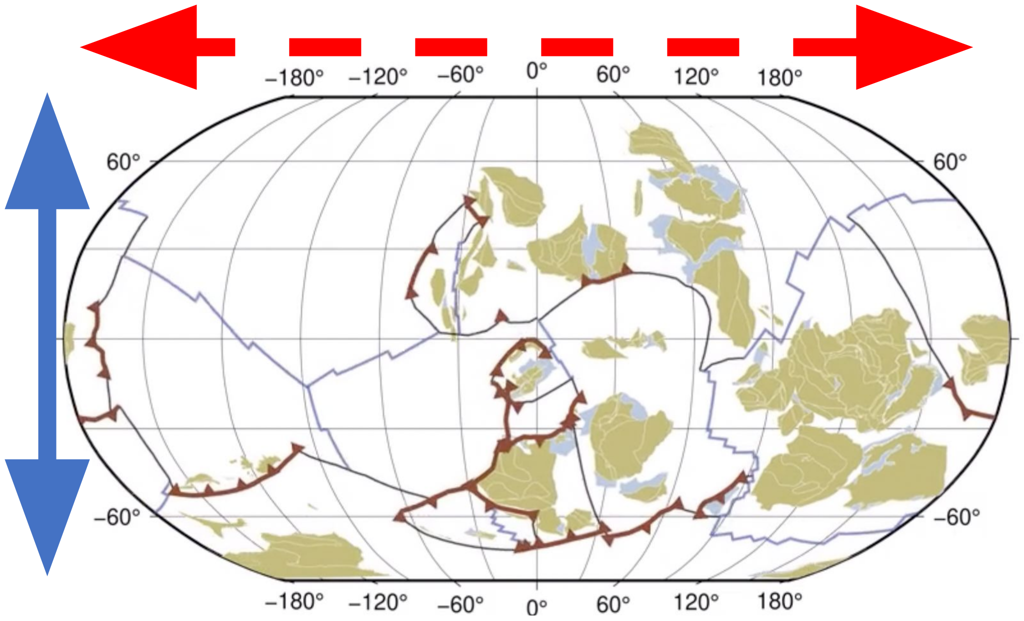


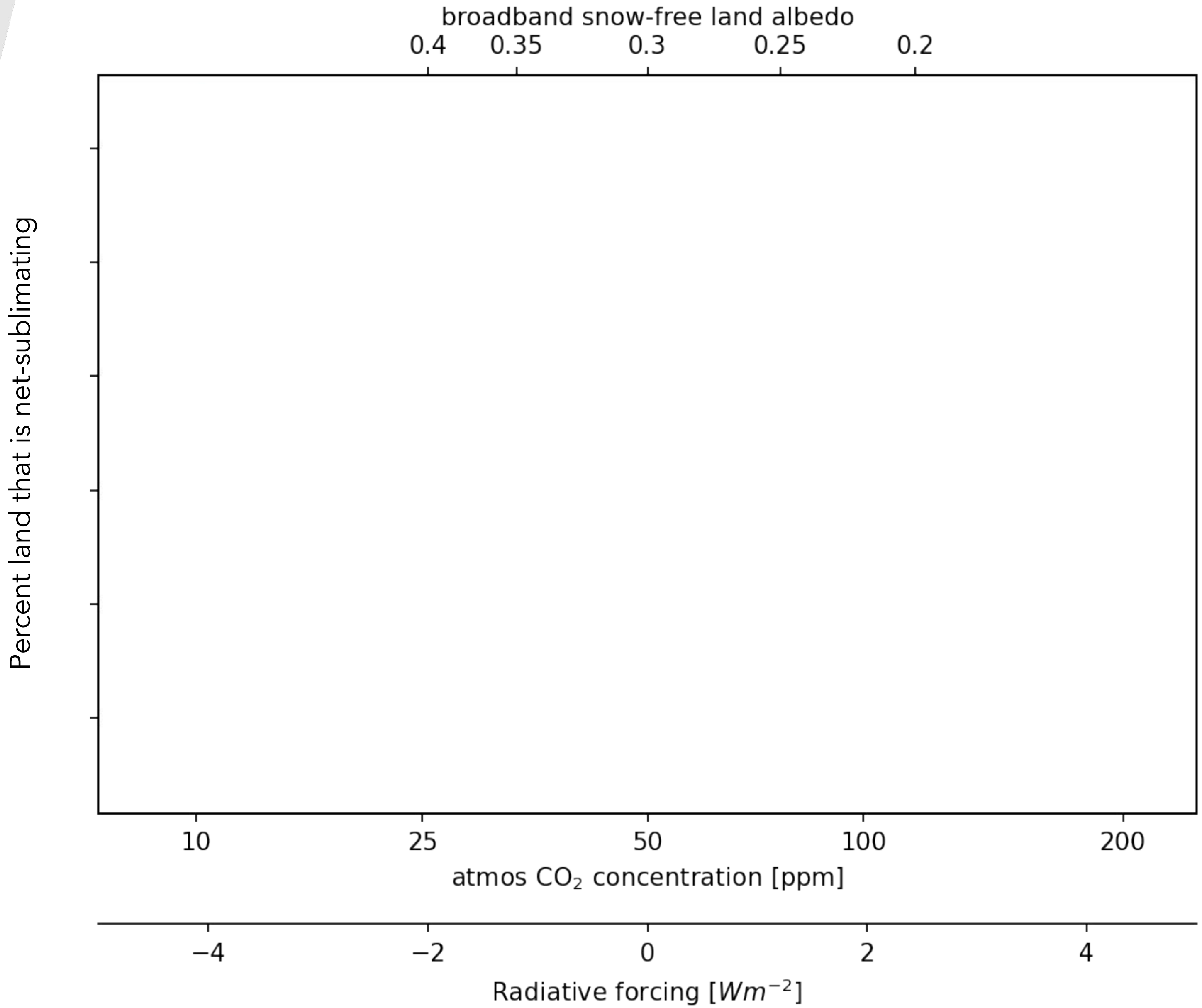
Pre-Jurassic, paleomagnetism informs distribution of land across latitude but distribution across longitude is uncertain.

720 Ma, Li et al. (2013)



720 Ma, Merdith et al. (2022)

Mechanism: Is this because the atmosphere is getting dryer?



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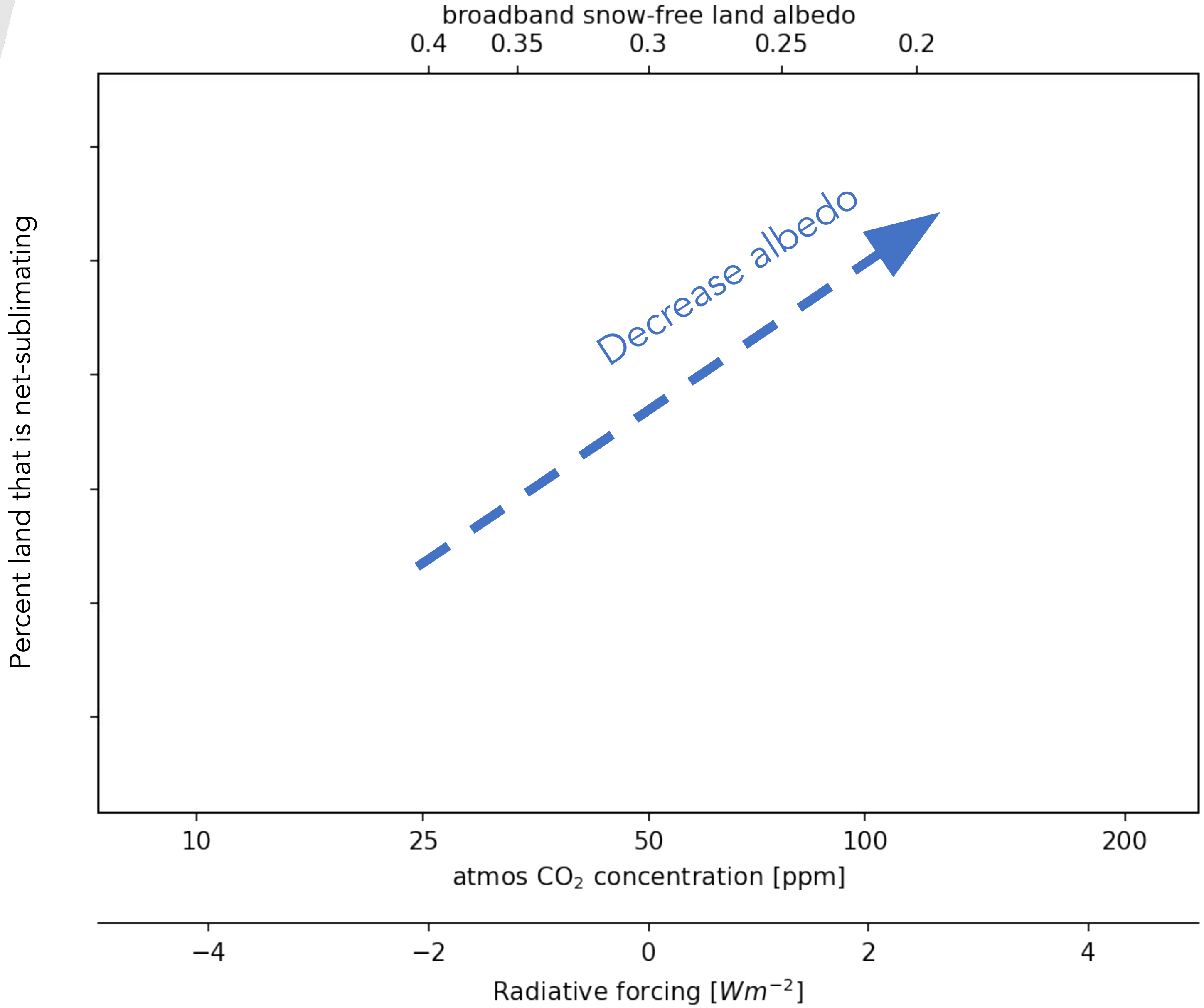

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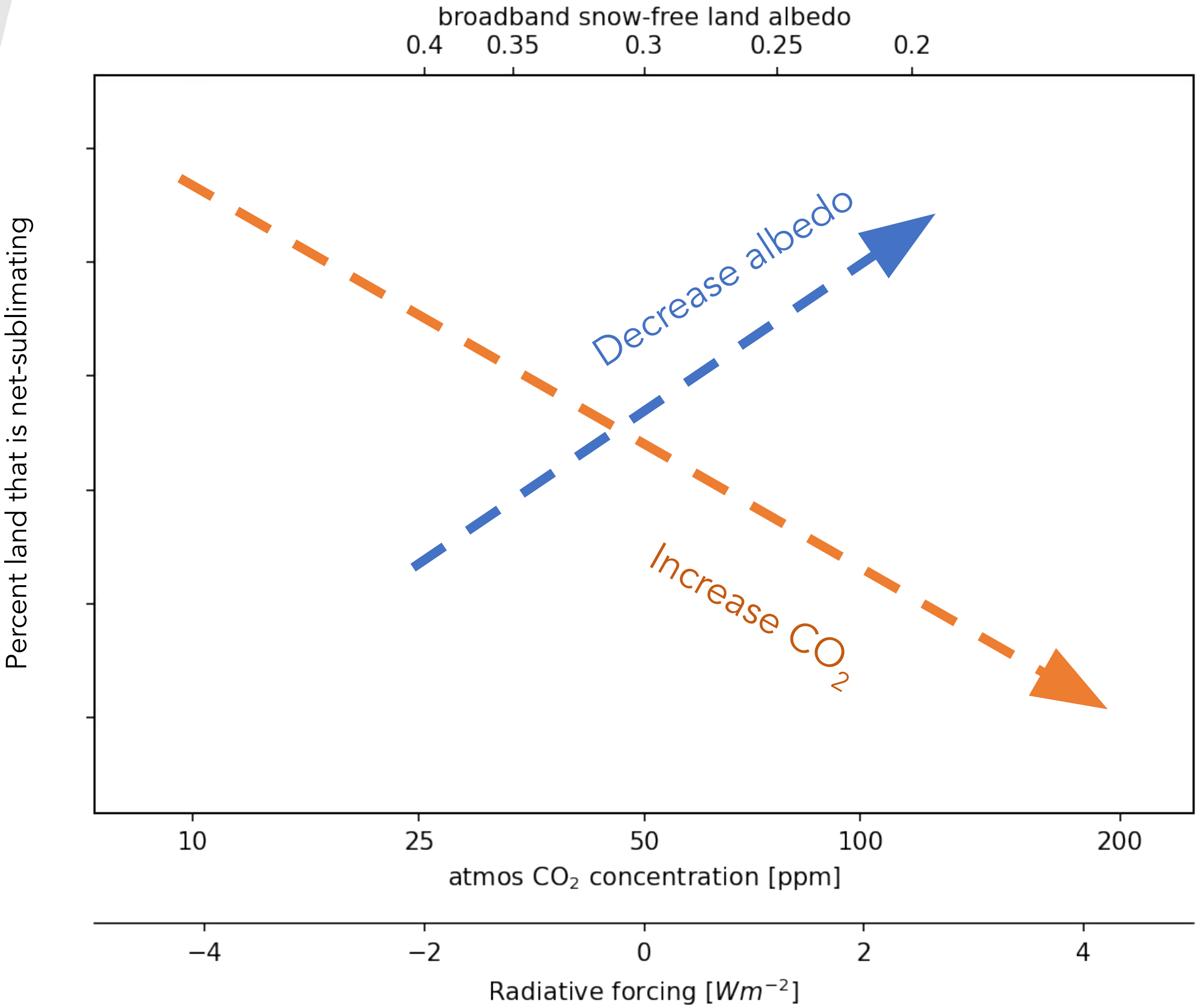
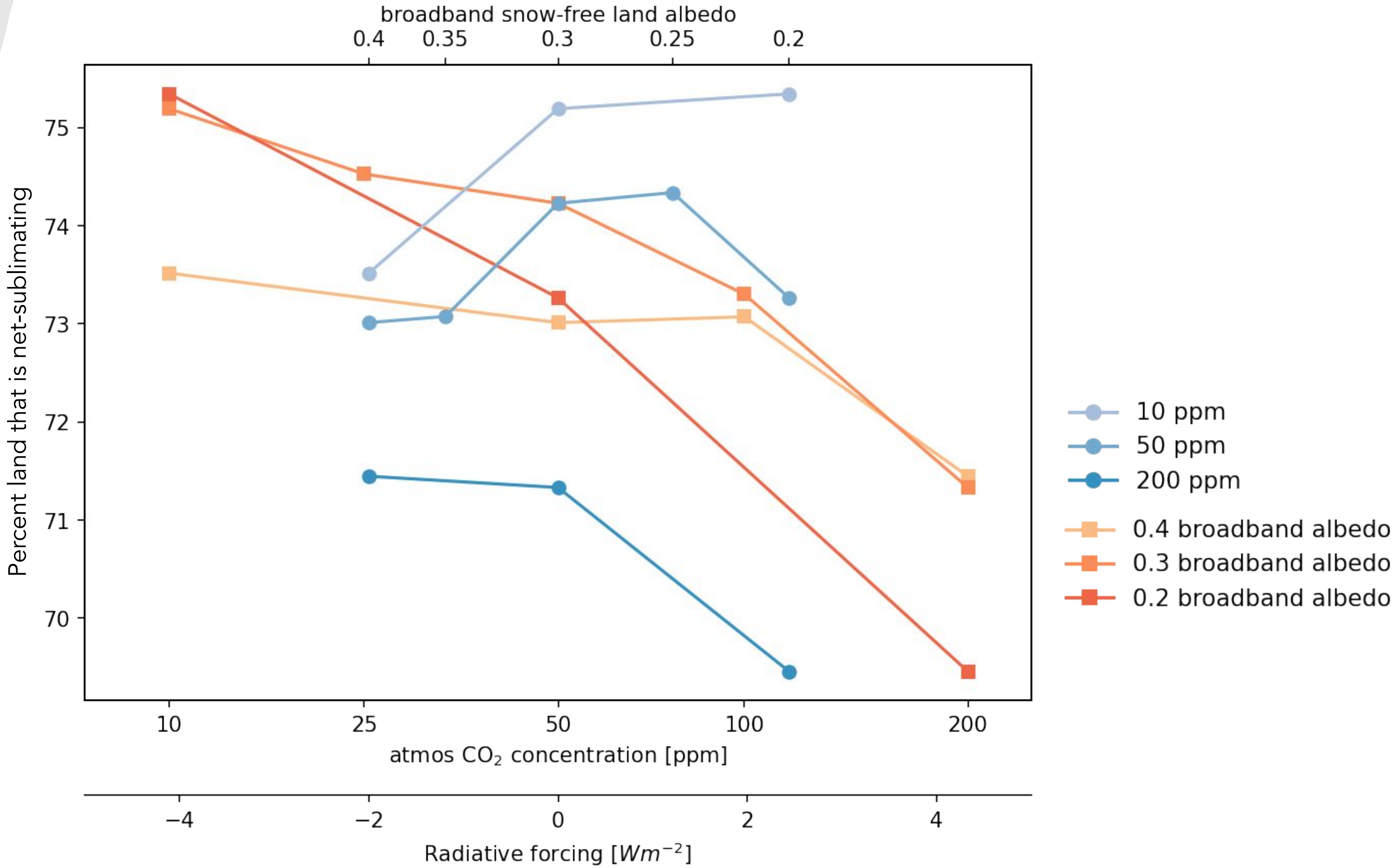


Neither forcing systematically increases area of dry land.



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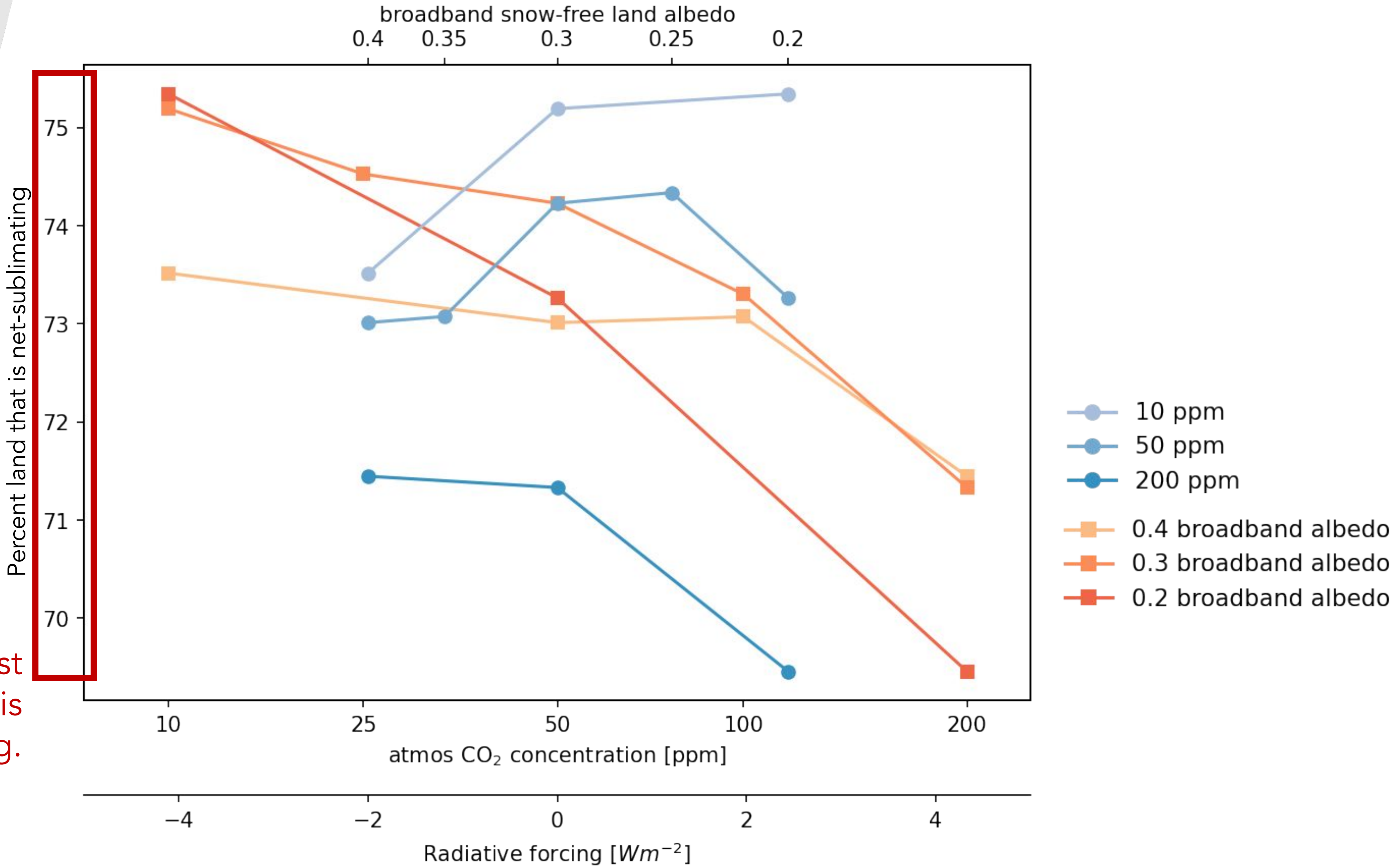
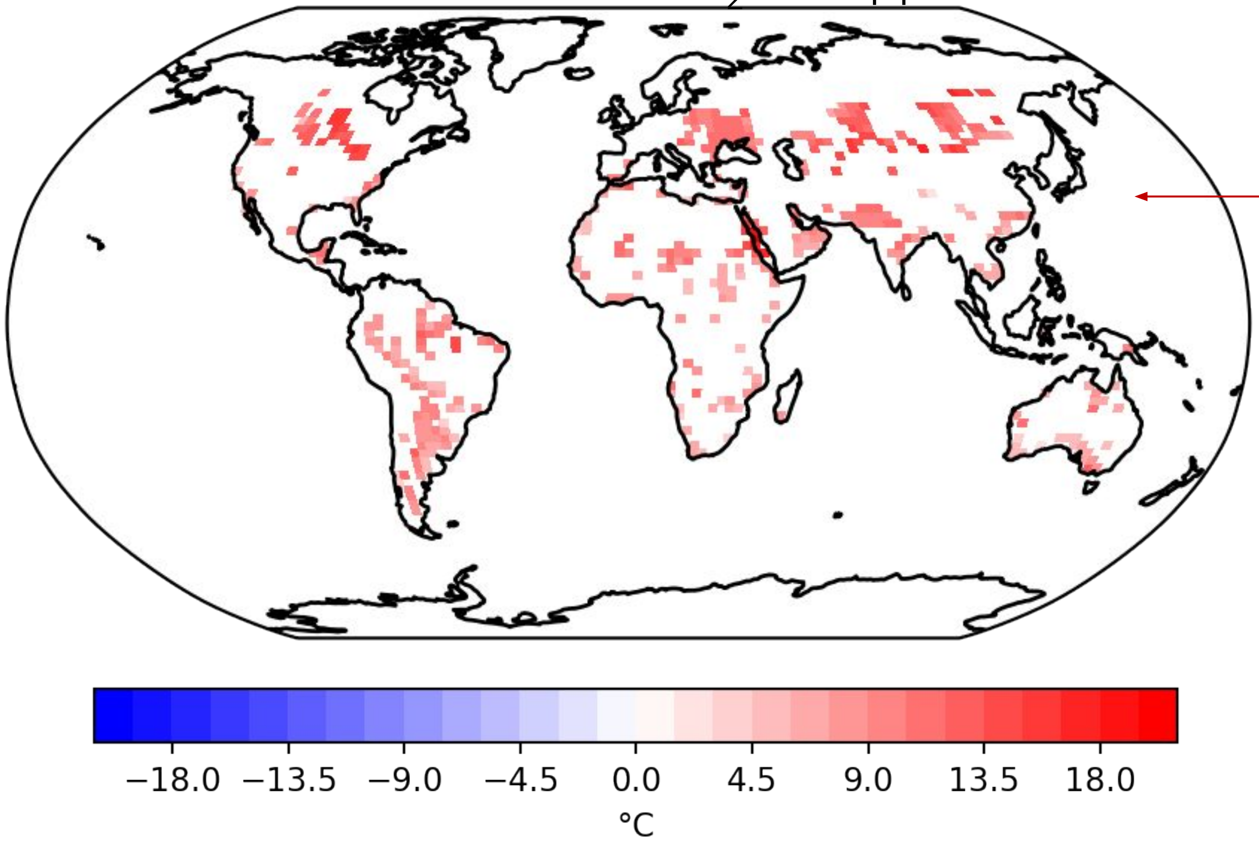


Already, the vast majority of land is net-sublimating.

Isolate places that change from below to above freezing with albedo forcing: what determines the change?

Change in annual surface T_{max} when forced by albedo (constant CO_2 = 50 ppm)



10% of land becomes potential refugia by warming bare* land.

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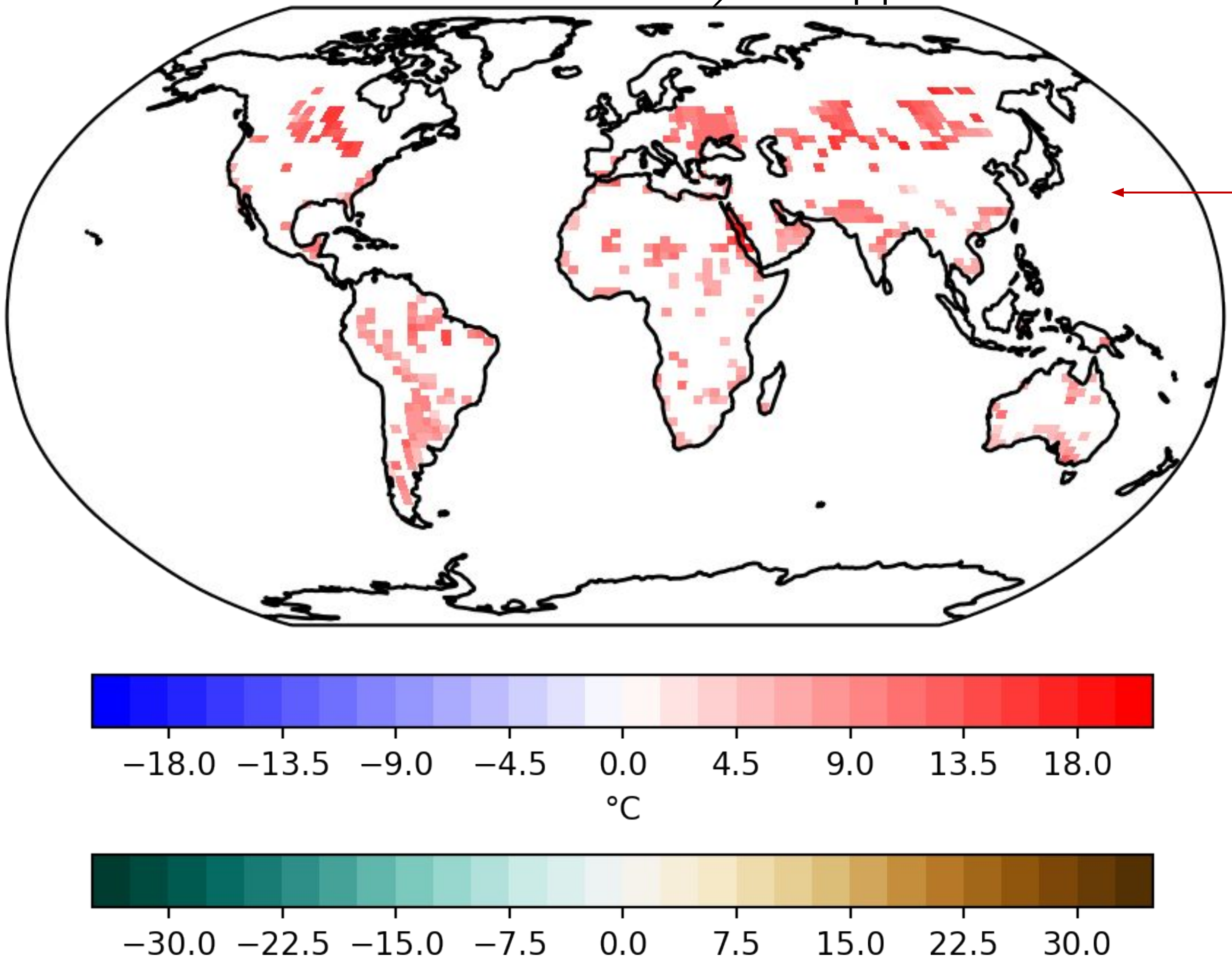

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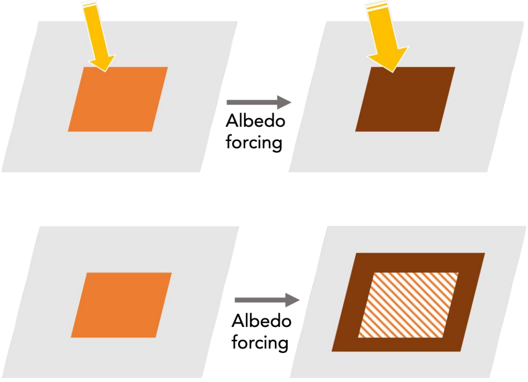
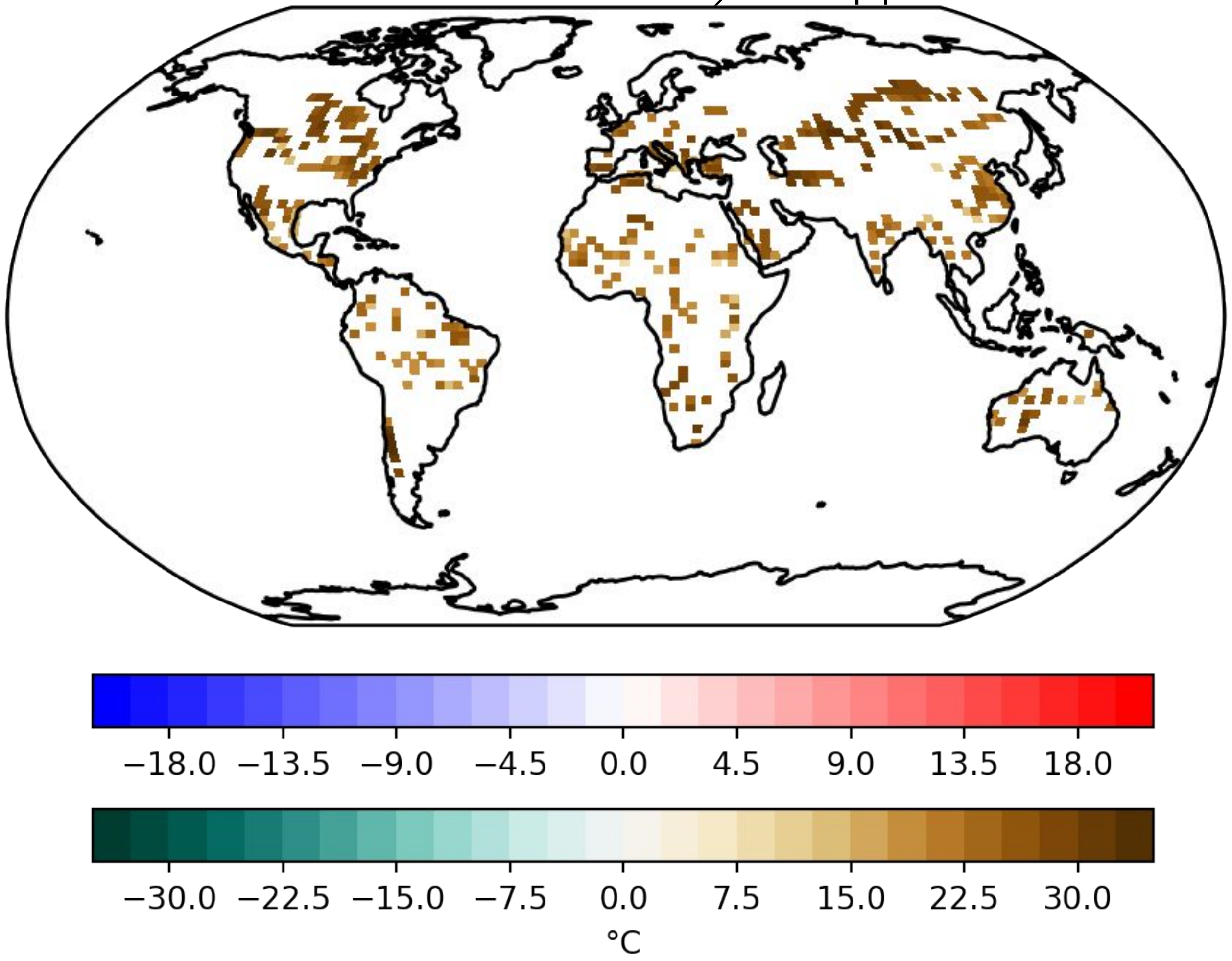


Decreasing albedo produces more potential refugia by warming bare land and by exposing new bare land that becomes warm.

Change in annual surface T_{max} when forced by albedo (constant CO_2 = 50 ppm)



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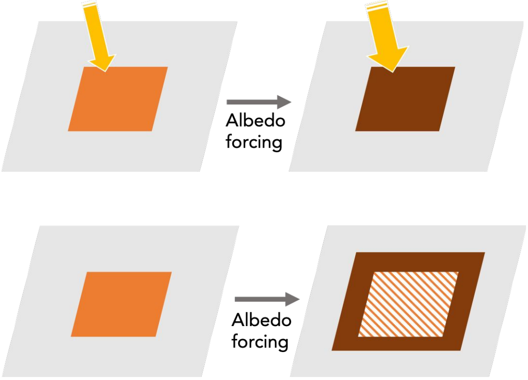
11% of land becomes potential refugia by becoming snow-free in the annual mean.



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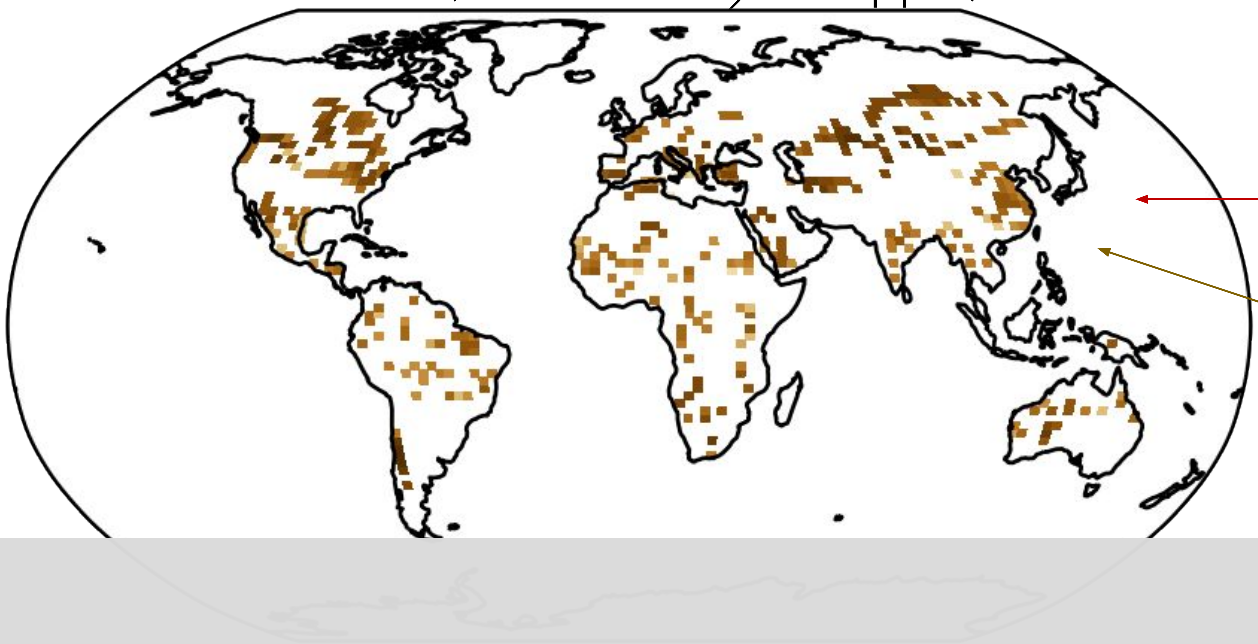


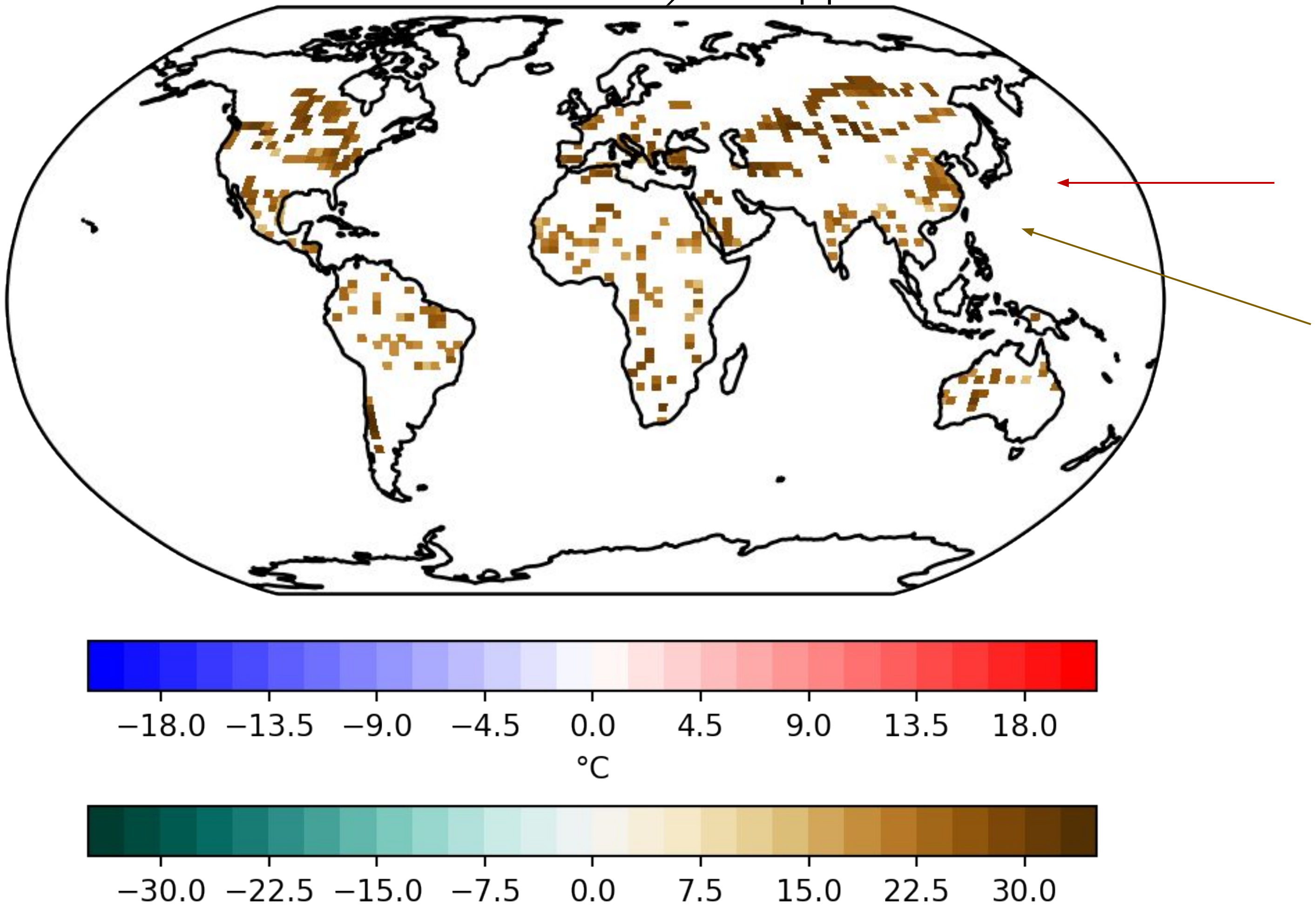
10% of land becomes potential refugia by warming bare* land.

11% of land becomes potential refugia by becoming snow-free in the annual mean.

>> Continental configurations with more large areas of connected land might yield more habitable Snowball.

Increasing albedo produces more potential refugia by warming bare land and by exposing new bare land that becomes warm.

Change in annual max $T_{surface}$ when forced by albedo (constant CO_2 = 50 ppm)



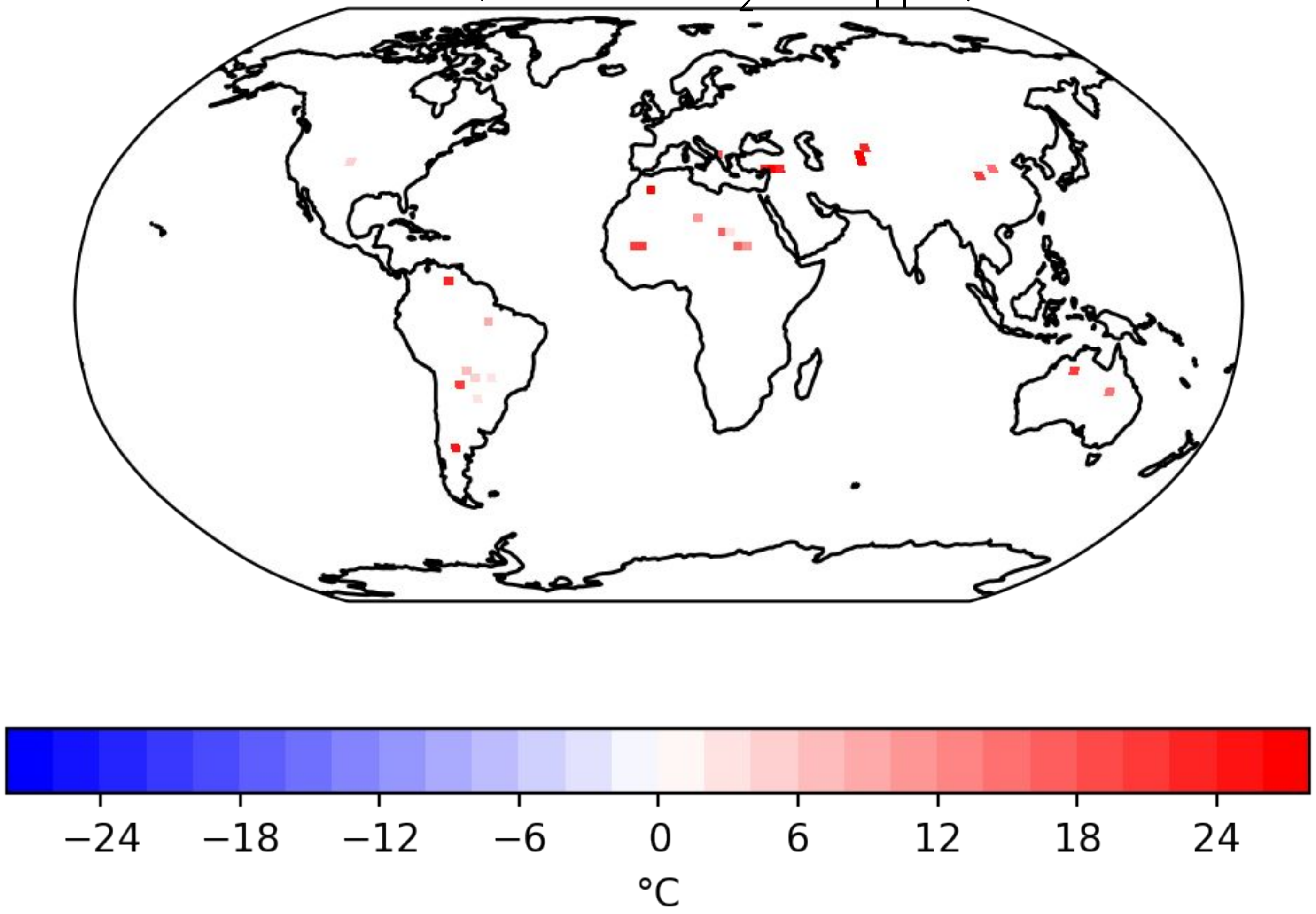
10% of land becomes potential refugia by warming bare* land.

11% of land becomes potential refugia by becoming snow-free in the annual mean.

(Only about 6% of this actually switches from net-precipitating to net-sublimating to become snow-free. Mostly albedo forcing lowers annual mean snow level to below masking threshold.)

Net-precipitating locations are never refugia, but it is possible to remain snow-covered and reach above freezing.

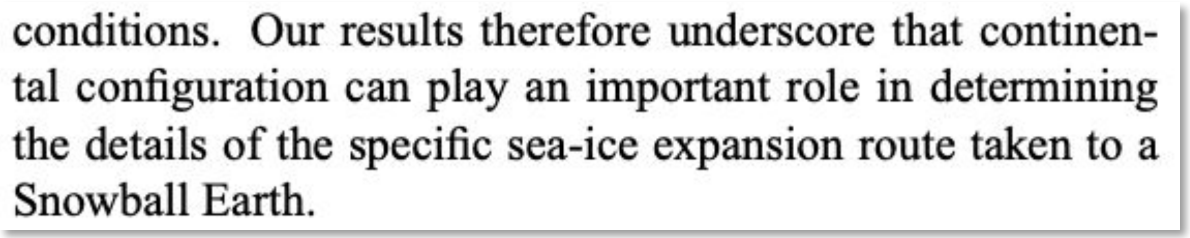
Change in annual max $T_{surface}$ when forced by albedo (constant CO_2 = 50 ppm)



There are a few places (1% of land) that reach above zero even while snow-covered.

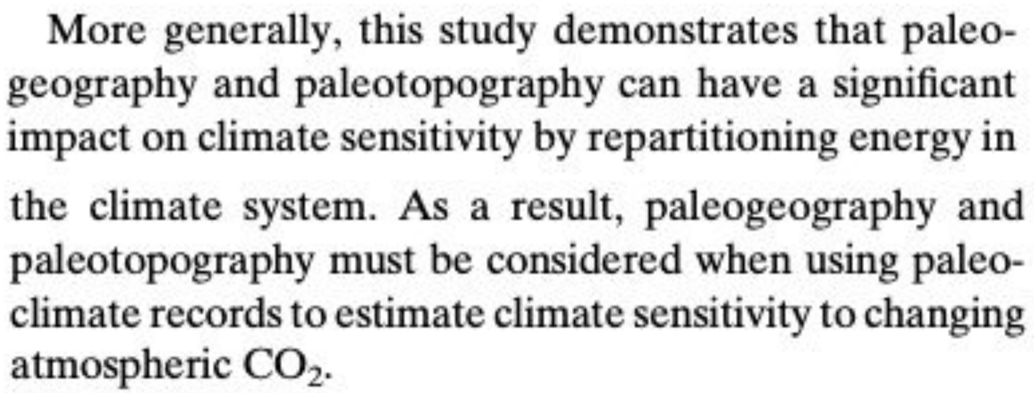
“Continental configuration would influence habitability.”

Voigt et al. (2011) showing tropical continents suppress evaporative cooling and warm the tropics:



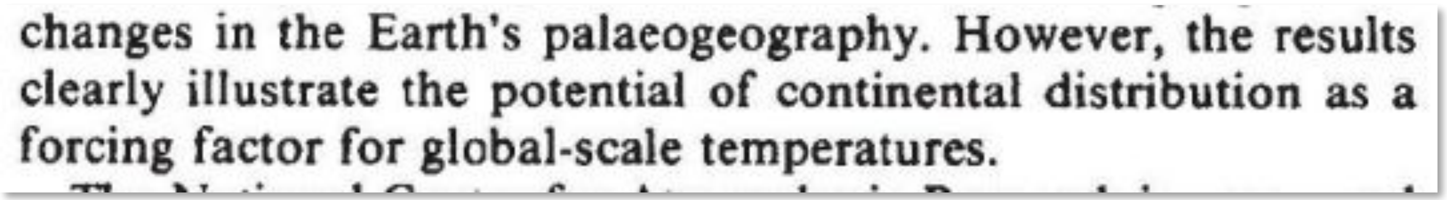
conditions. Our results therefore underscore that continental configuration can play an important role in determining the details of the specific sea-ice expansion route taken to a Snowball Earth.

Fiorella & Poulsen al. (2013) showing influence of continental distribution on TSI required to glaciate:



More generally, this study demonstrates that paleogeography and paleotopography can have a significant impact on climate sensitivity by repartitioning energy in the climate system. As a result, paleogeography and paleotopography must be considered when using paleoclimate records to estimate climate sensitivity to changing atmospheric CO_2.

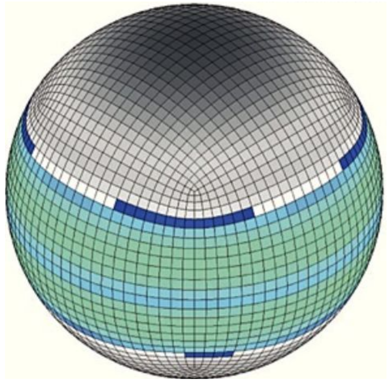
Barron et al. (1984) showing tropical continents suppress evaporative cooling and warm the tropics:



changes in the Earth's palaeogeography. However, the results clearly illustrate the potential of continental distribution as a forcing factor for global-scale temperatures.

How can you maintain liquid water in a Snowball climate?

1. "Waterbelt" where sea ice extends equatorward but does not completely close. Rose (2015) finds the waterbelt solution to be a stable climate state in coupled MITgcm in aquaplanet configuration.



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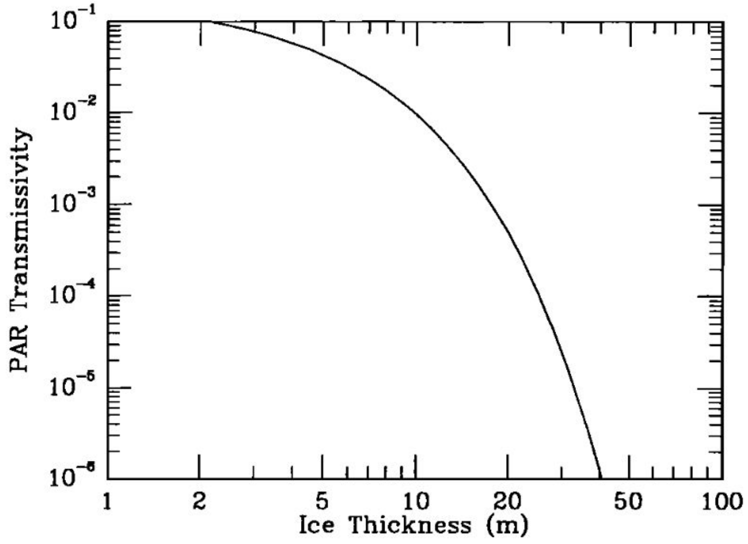

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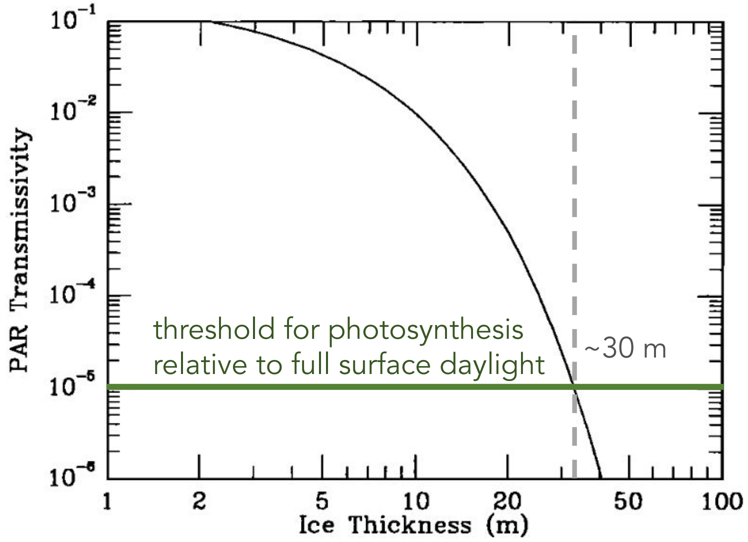

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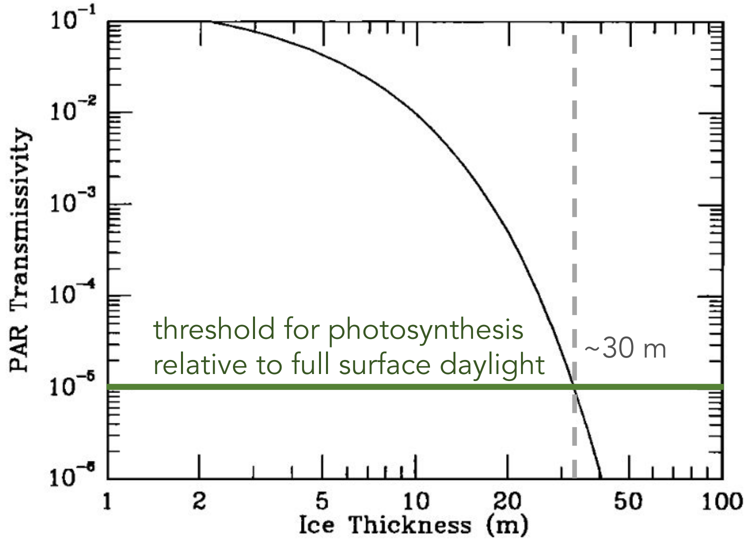

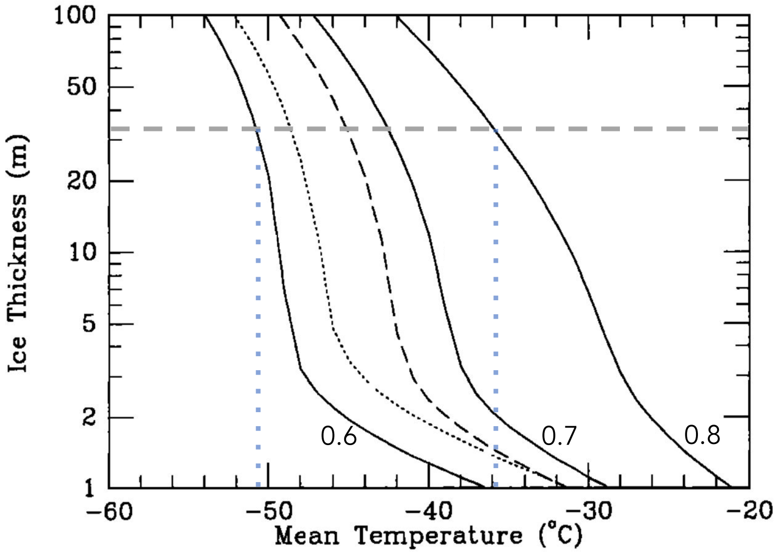

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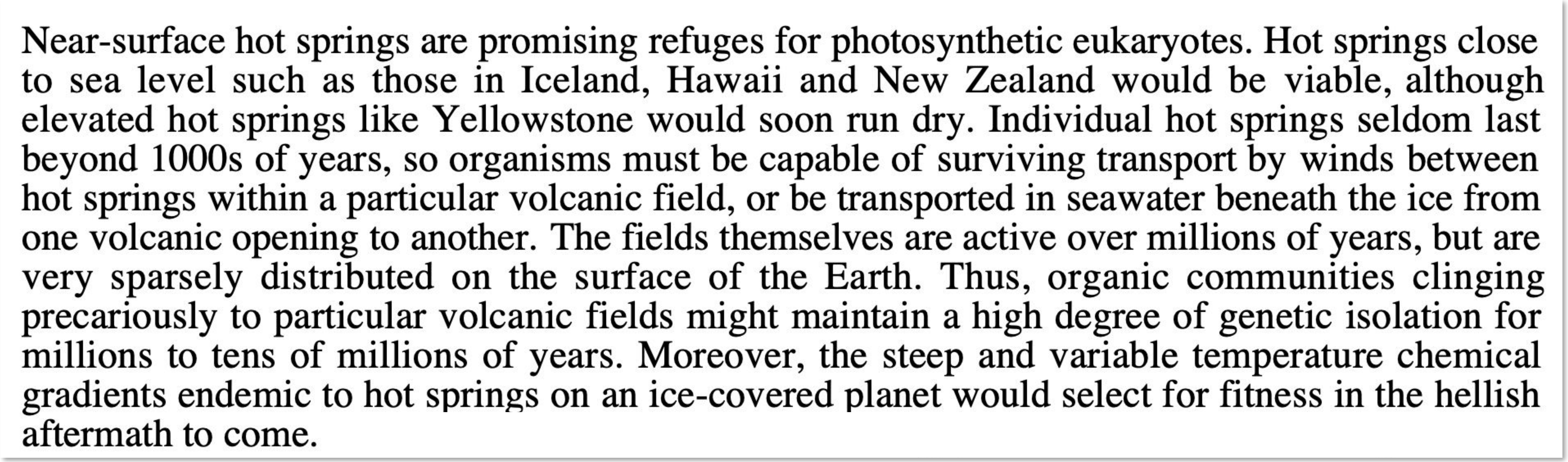
3. Hoffman and Schrag (1999, 2000) suggest volcanic hotspots could have maintained life (high risk).

How can you maintain liquid water in a Snowball climate?



Near-surface hot springs are promising refuges for photosynthetic eukaryotes. Hot springs close to sea level such as those in Iceland, Hawaii and New Zealand would be viable, although elevated hot springs like Yellowstone would soon run dry. Individual hot springs seldom last beyond 1000s of years, so organisms must be capable of surviving transport by winds between hot springs within a particular volcanic field, or be transported in seawater beneath the ice from one volcanic opening to another. The fields themselves are active over millions of years, but are very sparsely distributed on the surface of the Earth. Thus, organic communities clinging precariously to particular volcanic fields might maintain a high degree of genetic isolation for millions to tens of millions of years. Moreover, the steep and variable temperature chemical gradients endemic to hot springs on an ice-covered planet would select for fitness in the hellish aftermath to come.

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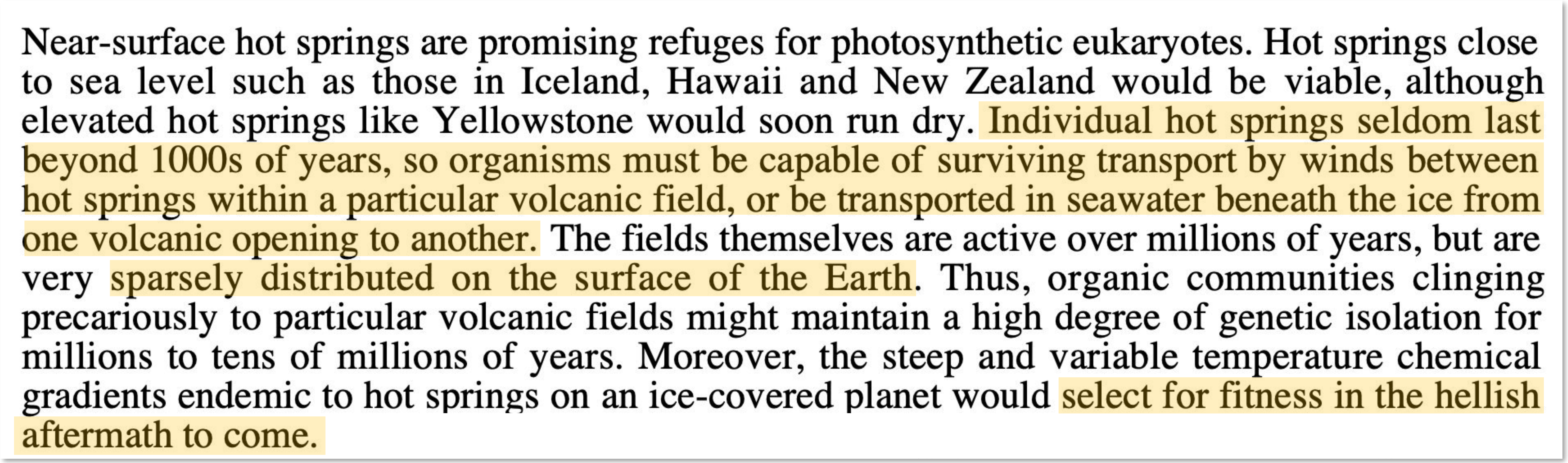

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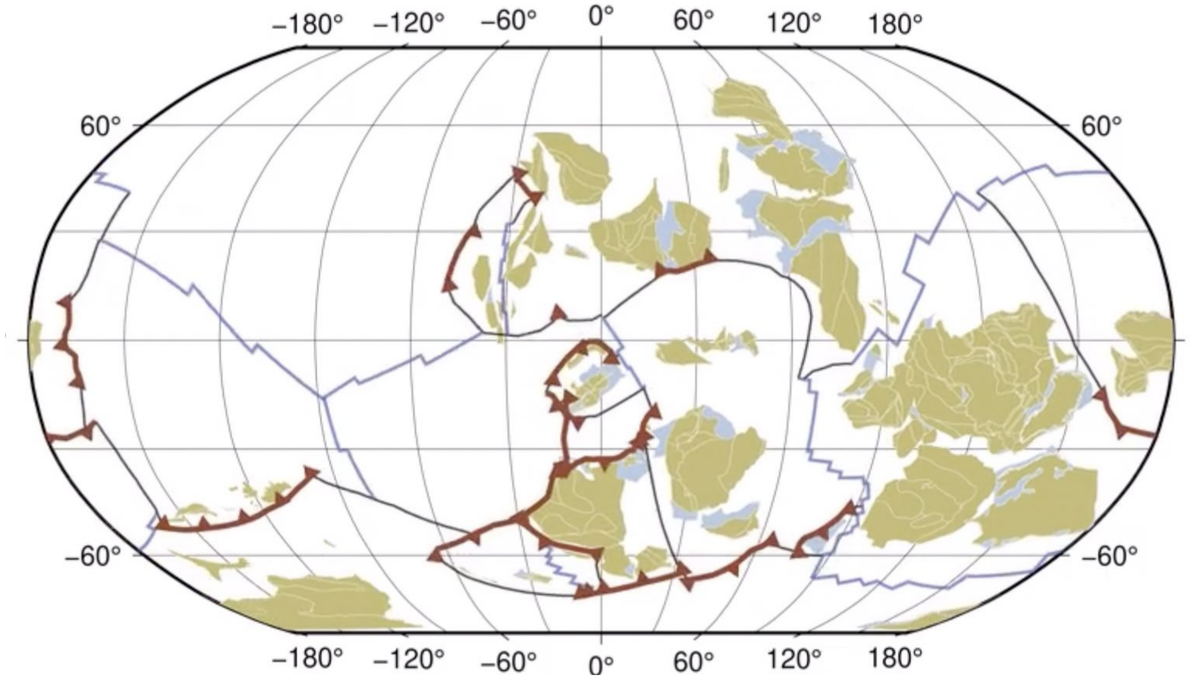
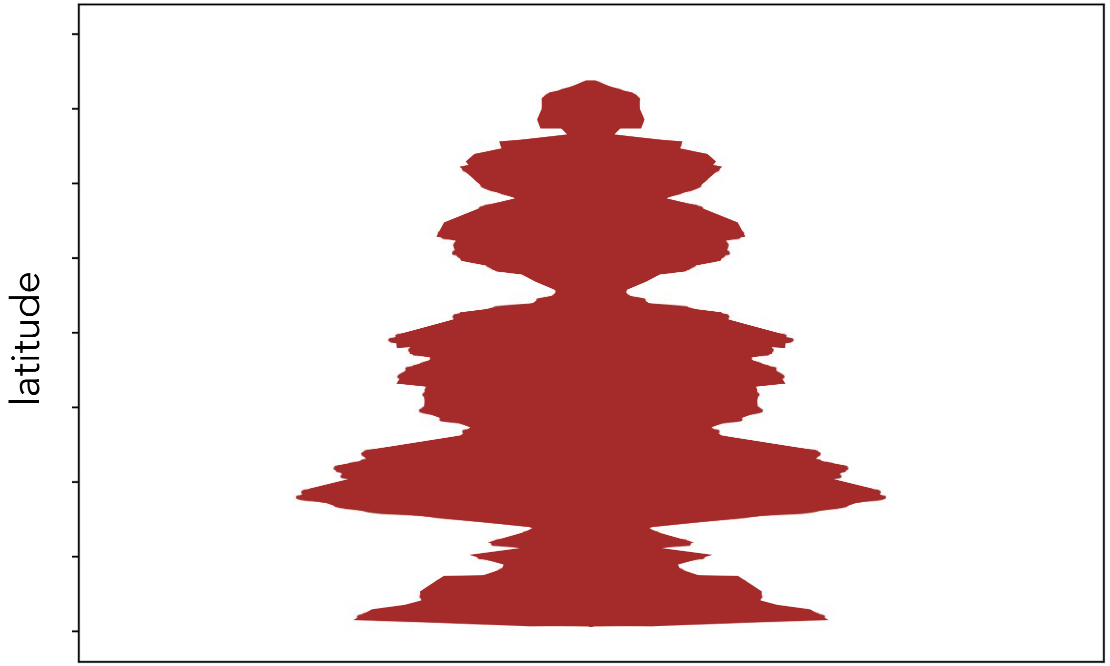
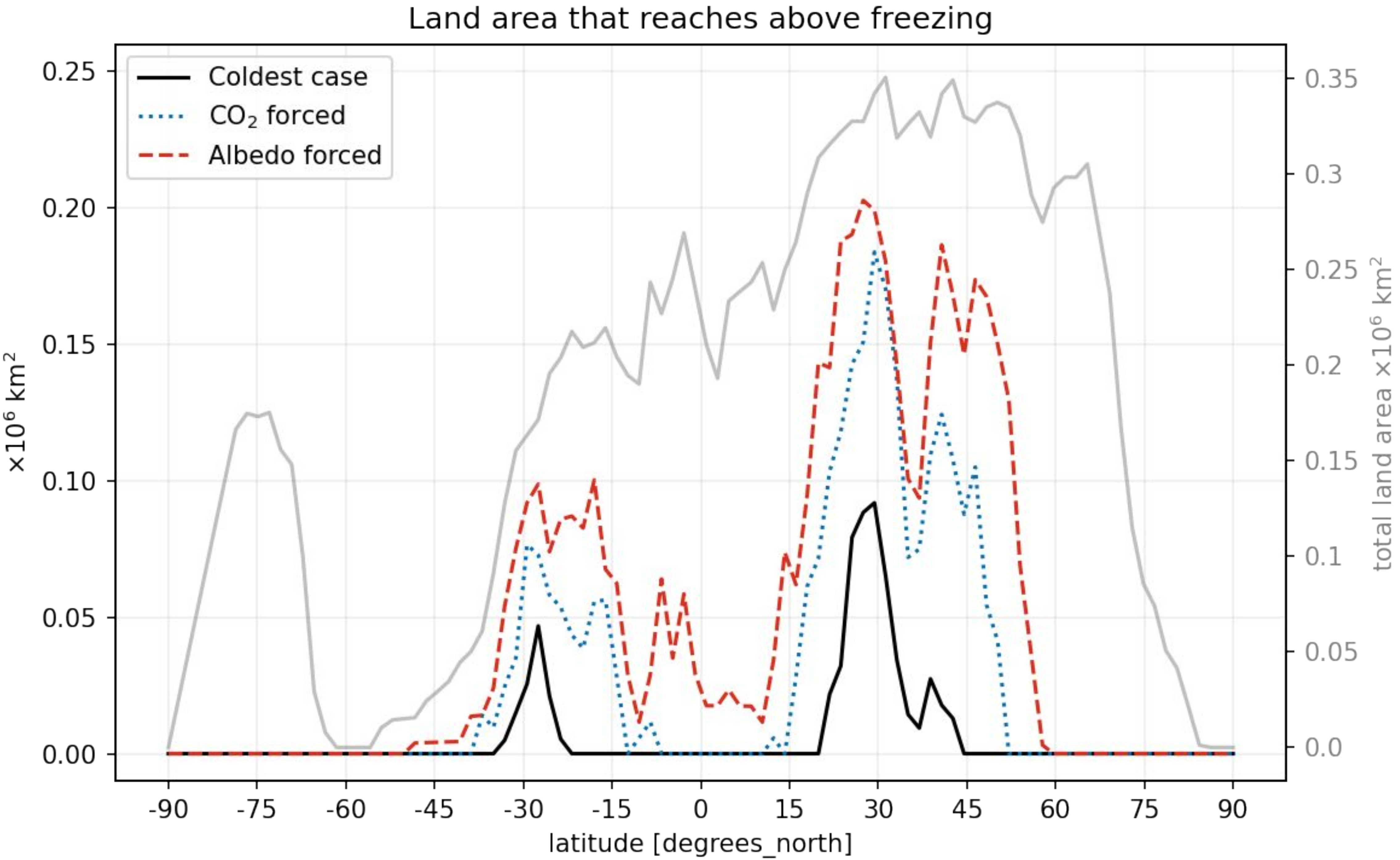
Next steps: Building experiments to quantify the influence of continental configuration on refugia:



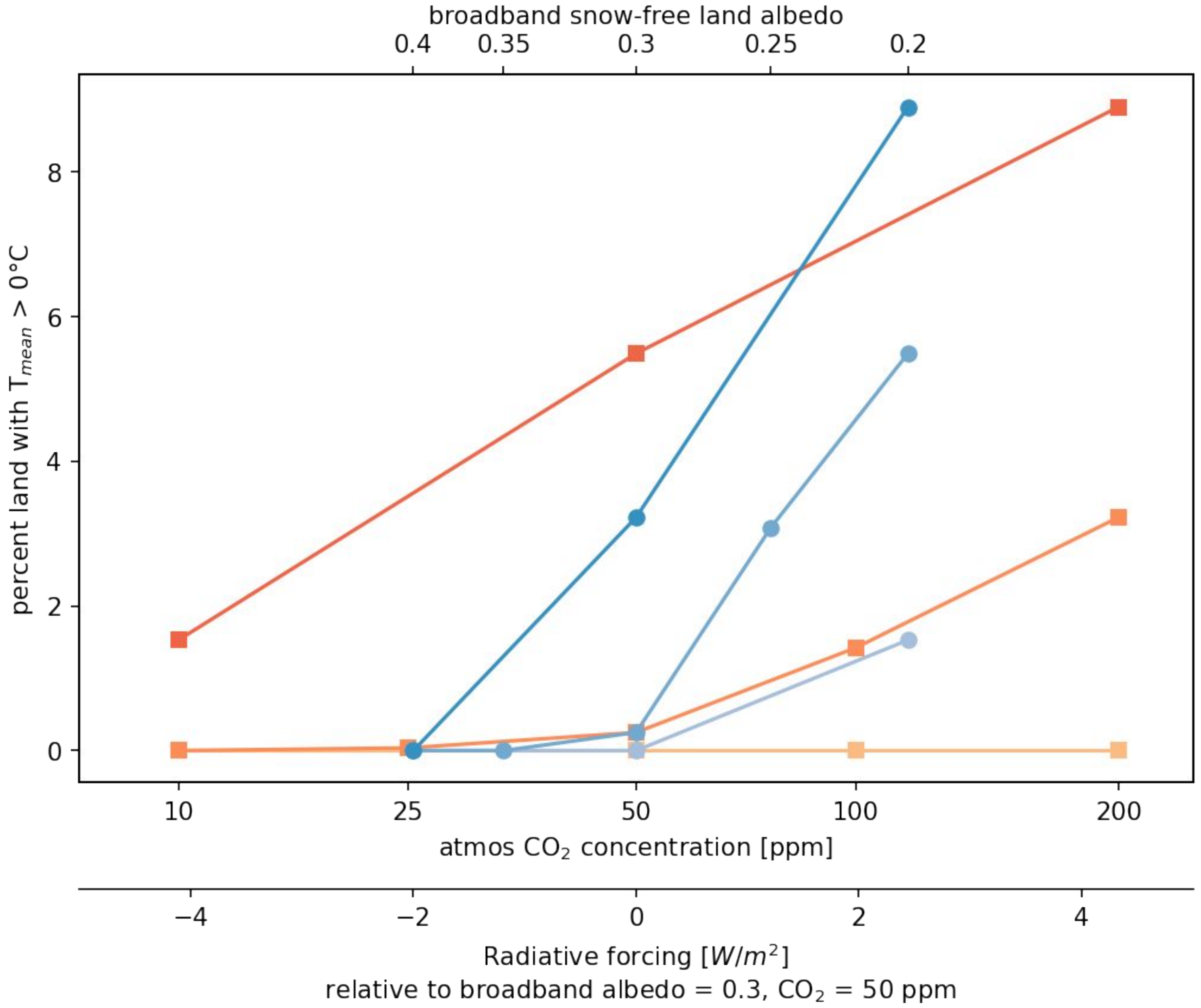


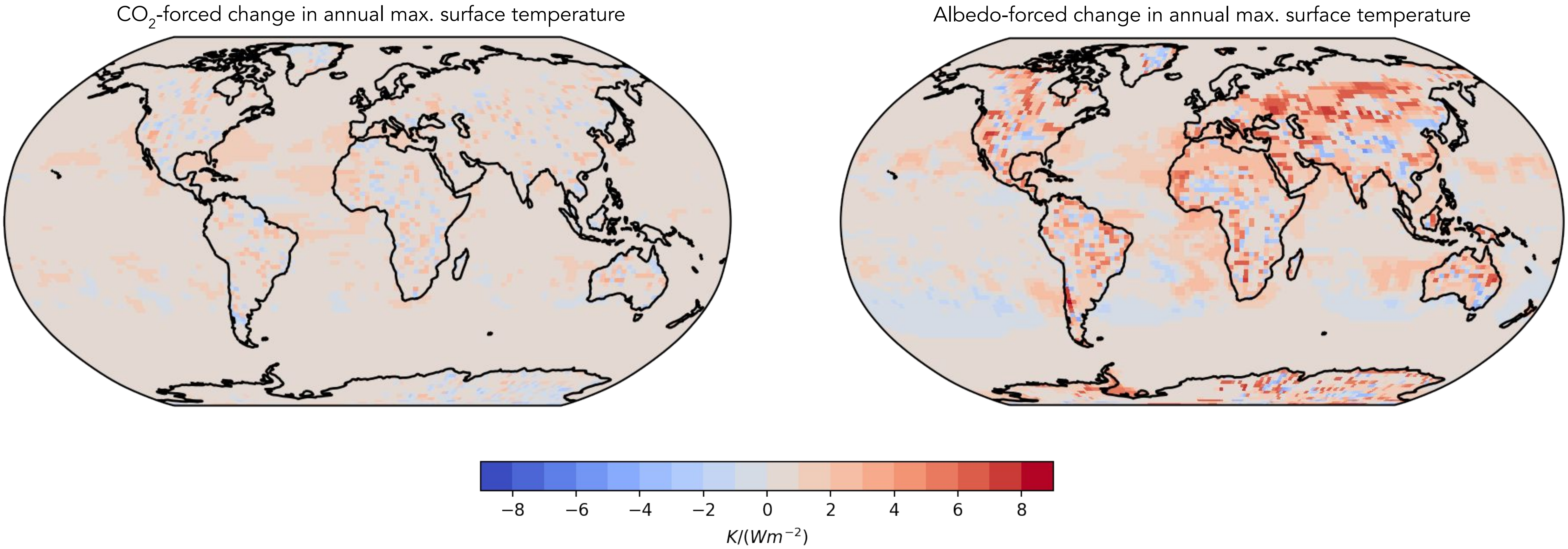
Is continental clustering better for life in a cold climate?



Land area that reaches above freezing
Coldest case
CO₂ forced
Albedo forced
×10⁶ km²
0.25
0.20
0.15
0.10
0.05
0.00
total land area ×10⁶ km²
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0.0
-90
-75
-60
-45
-30
-15
0
15
30
45
60
75
90
latitude [degrees_north]

Response of T_{mean} radiative forcing (albedo & CO_2)




CO$_2$-forced change in annual max. surface temperature

Albedo-forced change in annual max. surface temperature