The Habitability of Frozen Worlds

Adiv Paradise – University of Toronto

ERES III – Yale – June 12, 2017

Astronomy & Astrophysics
UNIVERSITY OF TORONTO

CPS

What is a “habitable planet”?

What is a “habitable planet”?

This is not so simple.

Photo by CEphoto, Uwe Aranas, via Wikimedia Commons

Photo by user brewbooks, via Wikimedia Commons

Photo by Paxton Woelber, via Wikimedia Commons

What is a “habitable planet”?

Liquid water on the surface

What is a “habitable planet”?

Liquid water on the surface

The Habitable Zone:

Inner edge: Transition to Venus: all water is vapor; water loss ensues.

Outer edge: Too cold to avoid total glaciation—adding CO_2 decreases temperature further

What is a “habitable planet”?

- Liquid water on the surface

The Habitable Zone:

Warm edge:	Transition to Venus: all water is vapor; water loss ensues.
Cold edge:	Too cold to avoid total glaciation—adding CO_2 decreases temperature further

We use these constraints to define the Habitable Zone in multiple dimensions of parameter space

Climate Stability in the Habitable Zone

- **Thermal stability**: Energy in = Energy out; Surface temperatures more or less stable on decade timescales.

- **Weathering stability**: CO_2 in = CO_2 out; Greenhouse effect stable on kyr-Myr timescales.

Climate Stability in the Habitable Zone

- Carbon-silicate cycle: CO2 drawdown through weathering processes; outgassing via volcanic processes

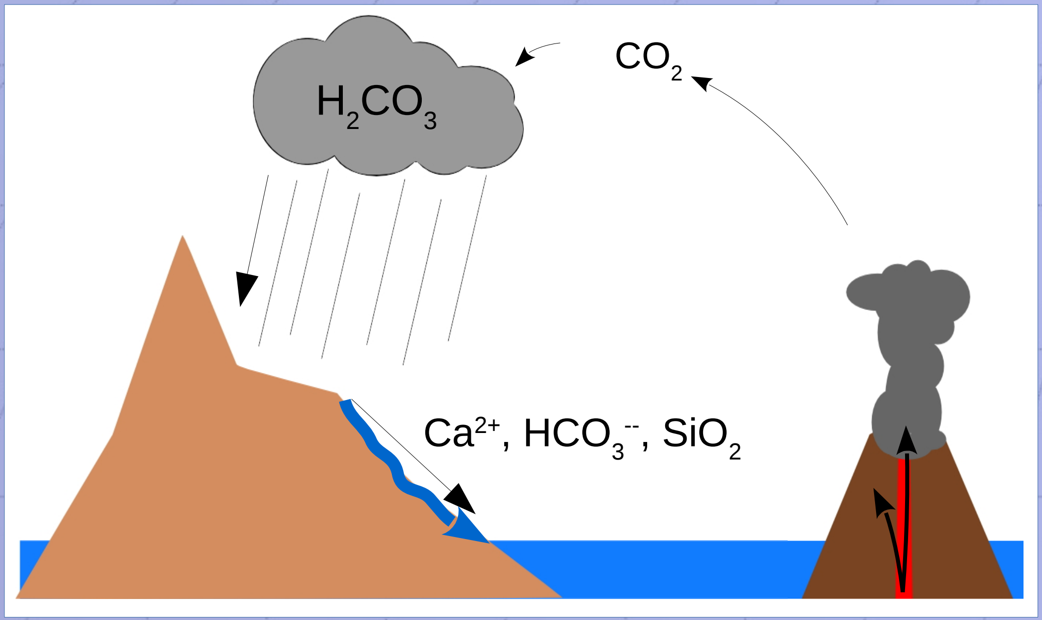
$$\frac{\Delta pCO_2}{\Delta t} = \text{Outgassing - Weathering}$$

Equilibrium when $\frac{\Delta pCO_2}{\Delta t} = 0$

$$W = (pCO_2)^{\beta} \times (P)^{\alpha} \times \exp[k_{act} * (T_s - T_0)]$$

T_s > 273.15 K

- Carbon-silicate cycle: CO2 drawdown through weathering processes; outgassing via volcanic processes



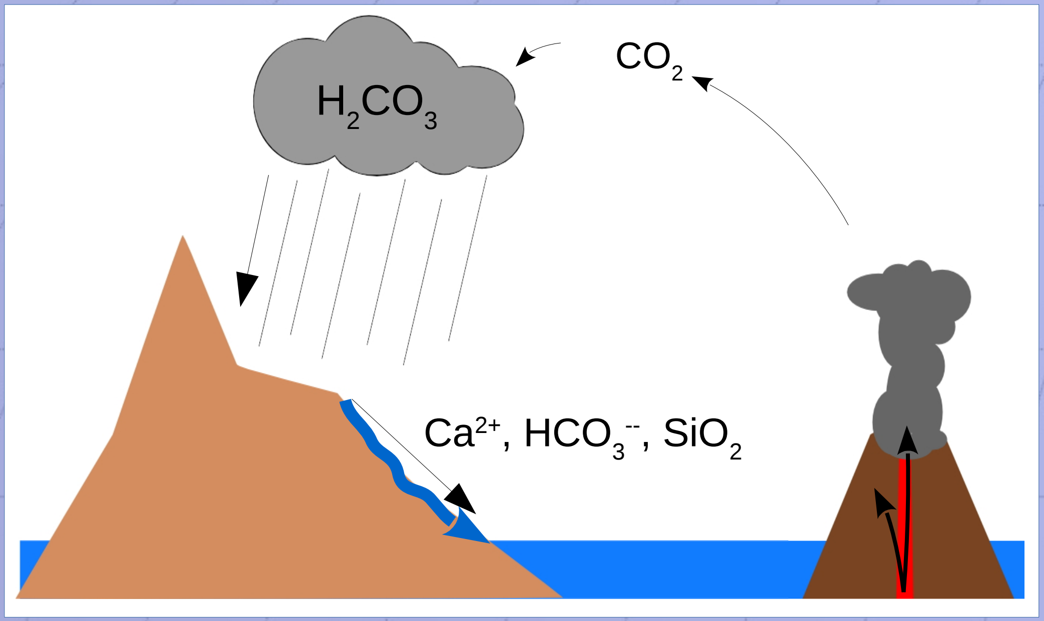
Ingredients:

- Chemical Reaction:
  - **Temperature**
  - CO_2 Supply
- Delivery: Rainfall
- Burial:
  - Liquid surface water
  - Exposed land

$$W = (pCO_2)^{\beta} \times (P)^{\alpha} \times \boxed{\exp[k_{act} * (T_s - T_0)]}$$

$T_s > 273.15$ K

- Carbon-silicate cycle: CO2 drawdown through weathering processes; outgassing via volcanic processes



Ingredients:

- Chemical Reaction:
  - Temperature
  - **CO_2 Supply**
- Delivery: Rainfall
- Burial:
  - Liquid surface water
  - Exposed land

$$W = \left(pCO_2\right)^{\beta} \times (P)^{\alpha} \times \exp\left[k_{act} * \left(T_s - T_0\right)\right]$$

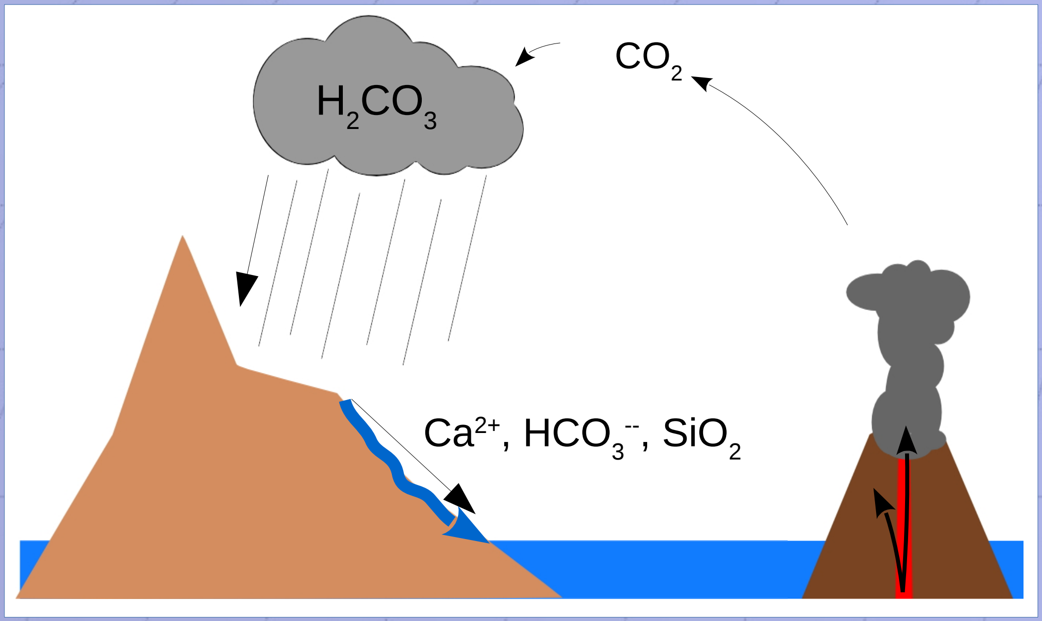
$T_s > 273.15$ K

Astronomy & Astrophysics
UNIVERSITY OF TORONTO

CPS

Climate Stability in the Habitable Zone

- Carbon-silicate cycle: CO2 drawdown through weathering processes; outgassing via volcanic processes



Ingredients:

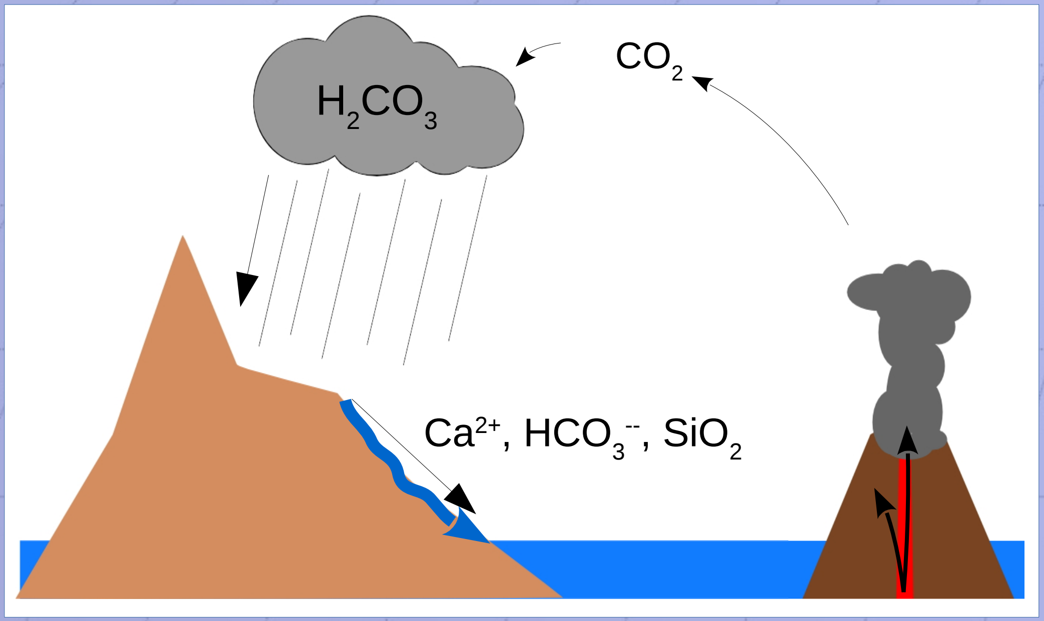
- Chemical Reaction:
  - Temperature
  - CO_2 Supply
- Delivery: **Rainfall**
- Burial:
  - Liquid surface water
  - Exposed land

$$W = (pCO_2)^{\beta} \times (P)^{\alpha} \times \exp[k_{act} * (T_s - T_0)]$$

$T_s > 273.15$ K

Climate Stability in the Habitable Zone

- Carbon-silicate cycle: CO2 drawdown through weathering processes; outgassing via volcanic processes



Ingredients:

- Chemical Reaction:
  - Temperature
  - CO_2 Supply
- Delivery: Rainfall
- Burial:
  - **Liquid surface water**
  - Exposed land

$$W = (pCO_2)^{\beta} \times (P)^{\alpha} \times \exp[k_{act} * (T_s - T_0)]$$

T_s > 273.15 K

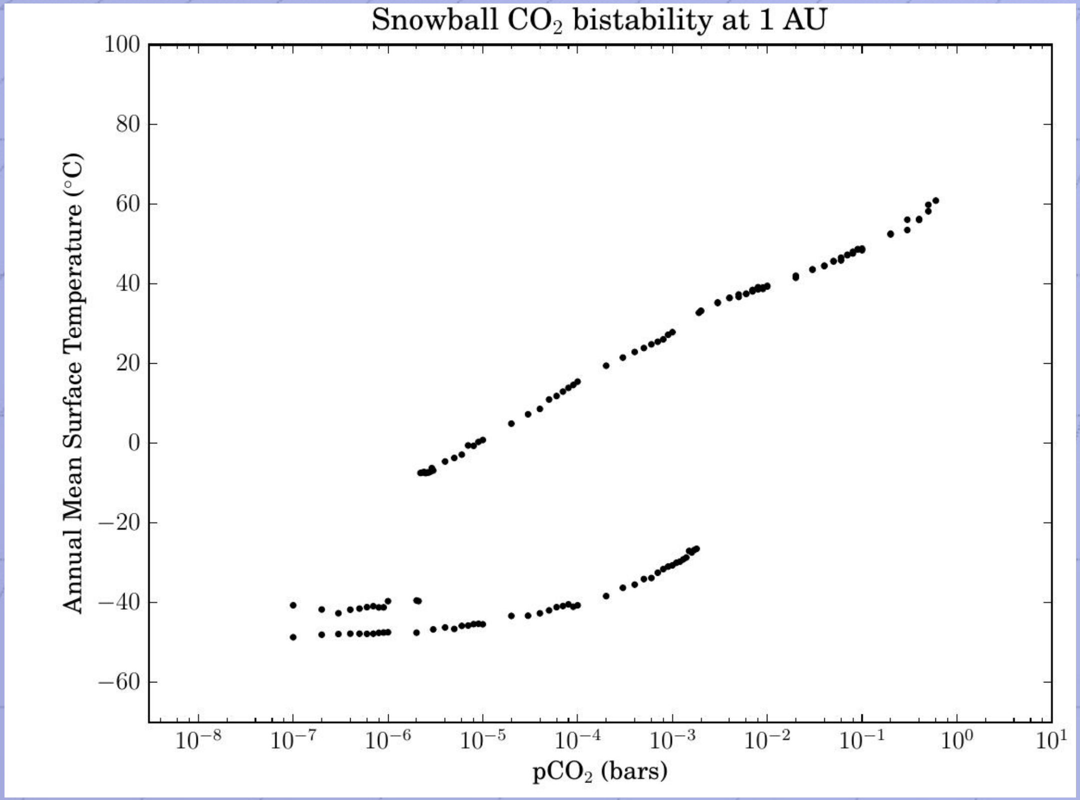
PlaSim: 3D climate model for simulating Earth-like planets

- Uses spectral transforms to solve for vorticity, temperature, divergence, and pressure
- T21 resolution: 64 longitudes x 32 latitudes (~5.6° at equator)
- 10 vertical pressure levels
- 50-meter mixed-layer slab ocean model
- Thermodynamic sea ice
- Bucket model + runoff for soil hydrology
- Convection, clouds, and precipitation
- Longwave and shortwave radiative transfer

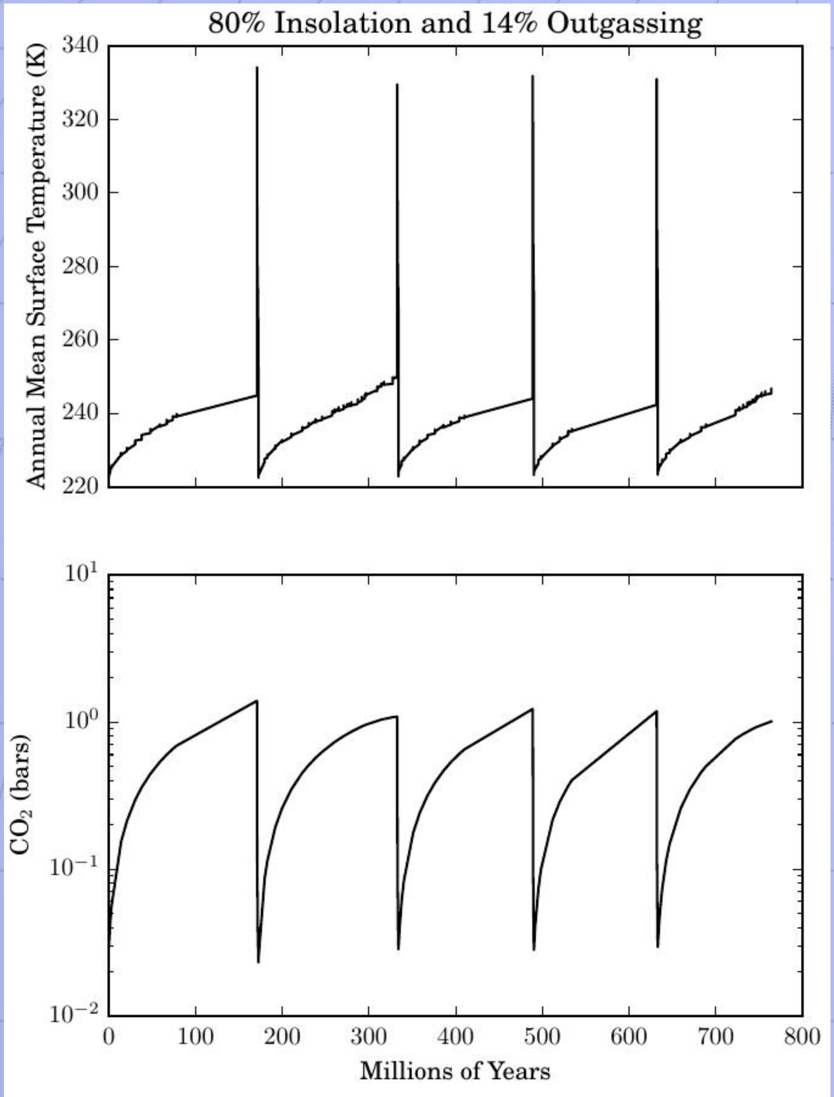
Fraedrich, et al (2005)

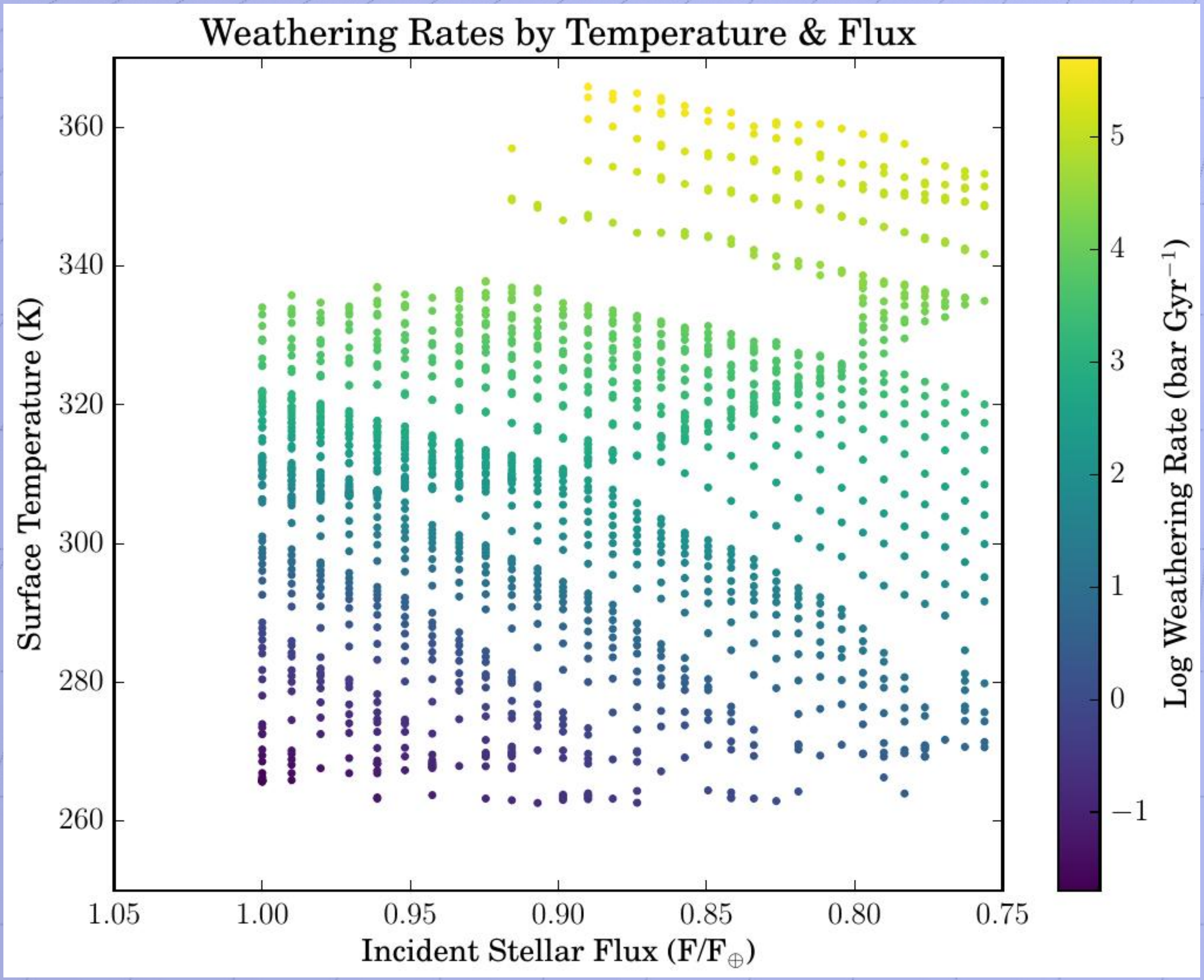
http://edilbert.github.io/PLASIM/

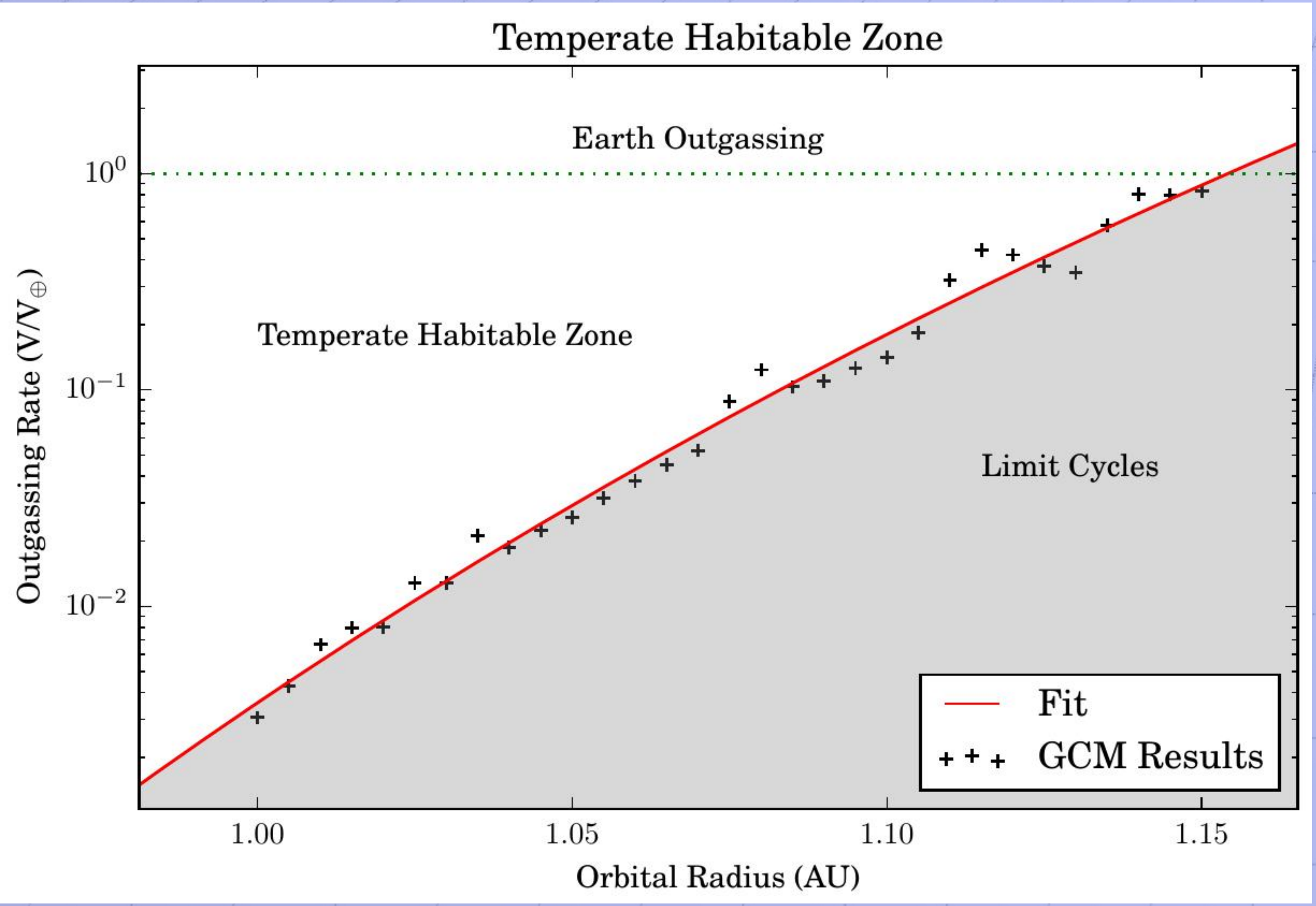
Thermal Stability



Weathering Instability



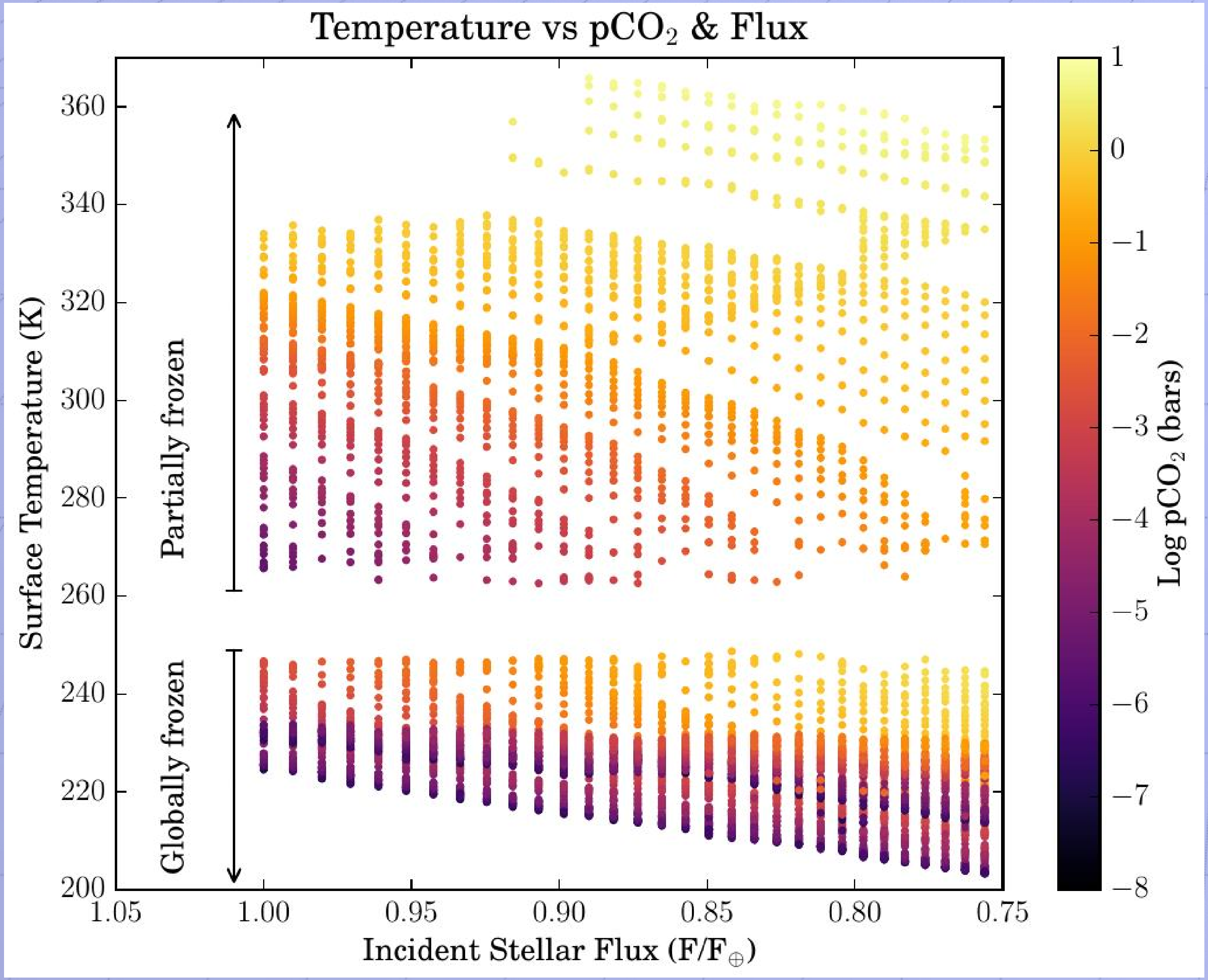

Weathering Rates by Temperature & Flux
Surface Temperature (K)
360
340
320
300
280
260
1.05
1.00
0.95
0.90
0.85
0.80
0.75
Incident Stellar Flux ($F/F_\oplus$)
Log Weathering Rate (bar Gyr^{-1})
5
4
3
2
1
0
−1



Astronomy & Astrophysics
UNIVERSITY OF TORONTO

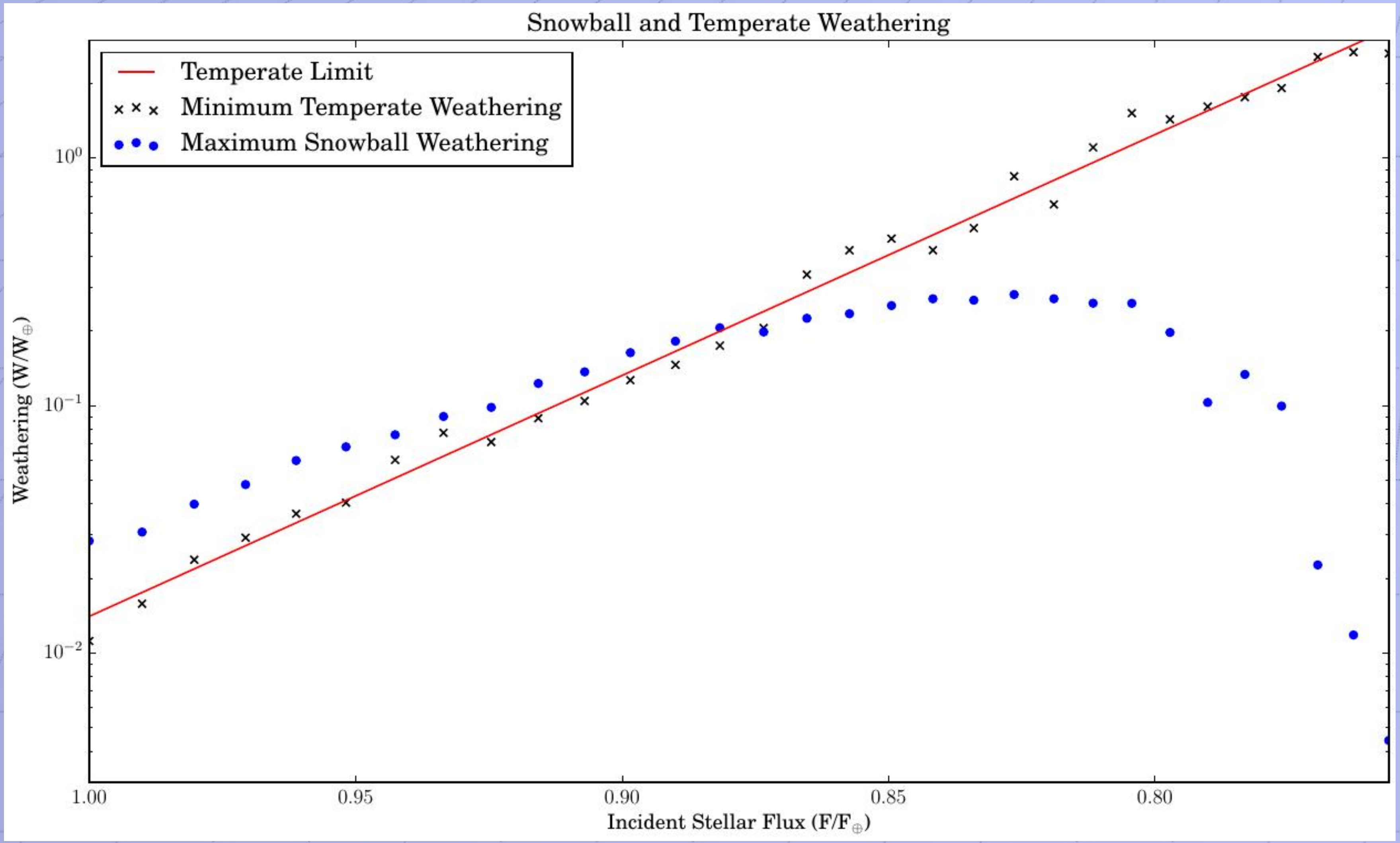
CPS

What if weathering happens even during snowball?



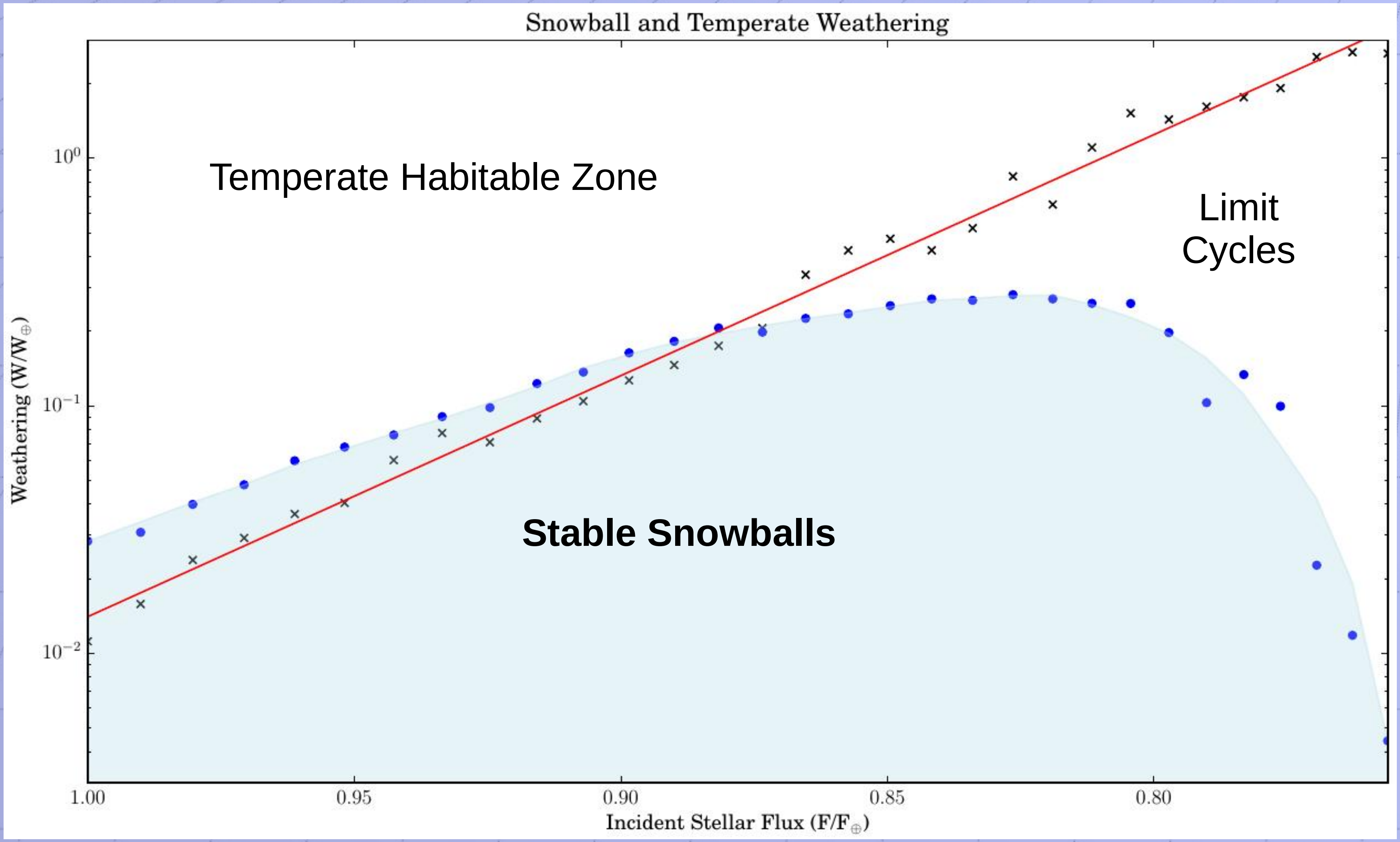
Astronomy & Astrophysics
UNIVERSITY OF TORONTO

CPS



Astronomy & Astrophysics
UNIVERSITY OF TORONTO

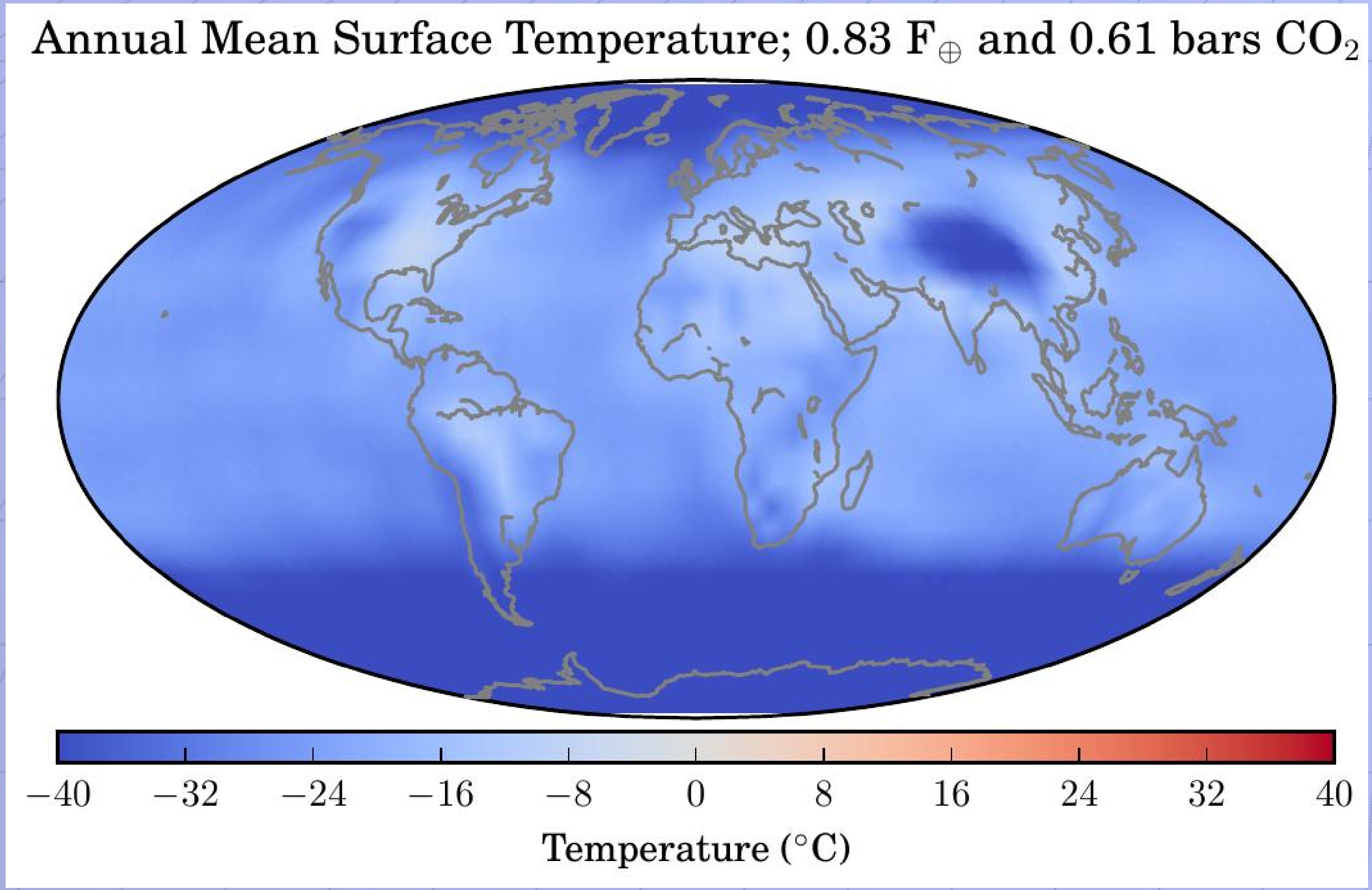
CPS


Snowball and Temperate Weathering
Temperate Habitable Zone
Limit Cycles
Stable Snowballs
Weathering ($W/W_\oplus$)
10^0
10^{-1}
10^{-2}
1.00
0.95
0.90
0.85
0.80
Incident Stellar Flux ($F/F_\oplus$)

If snowballs are totally glaciated,

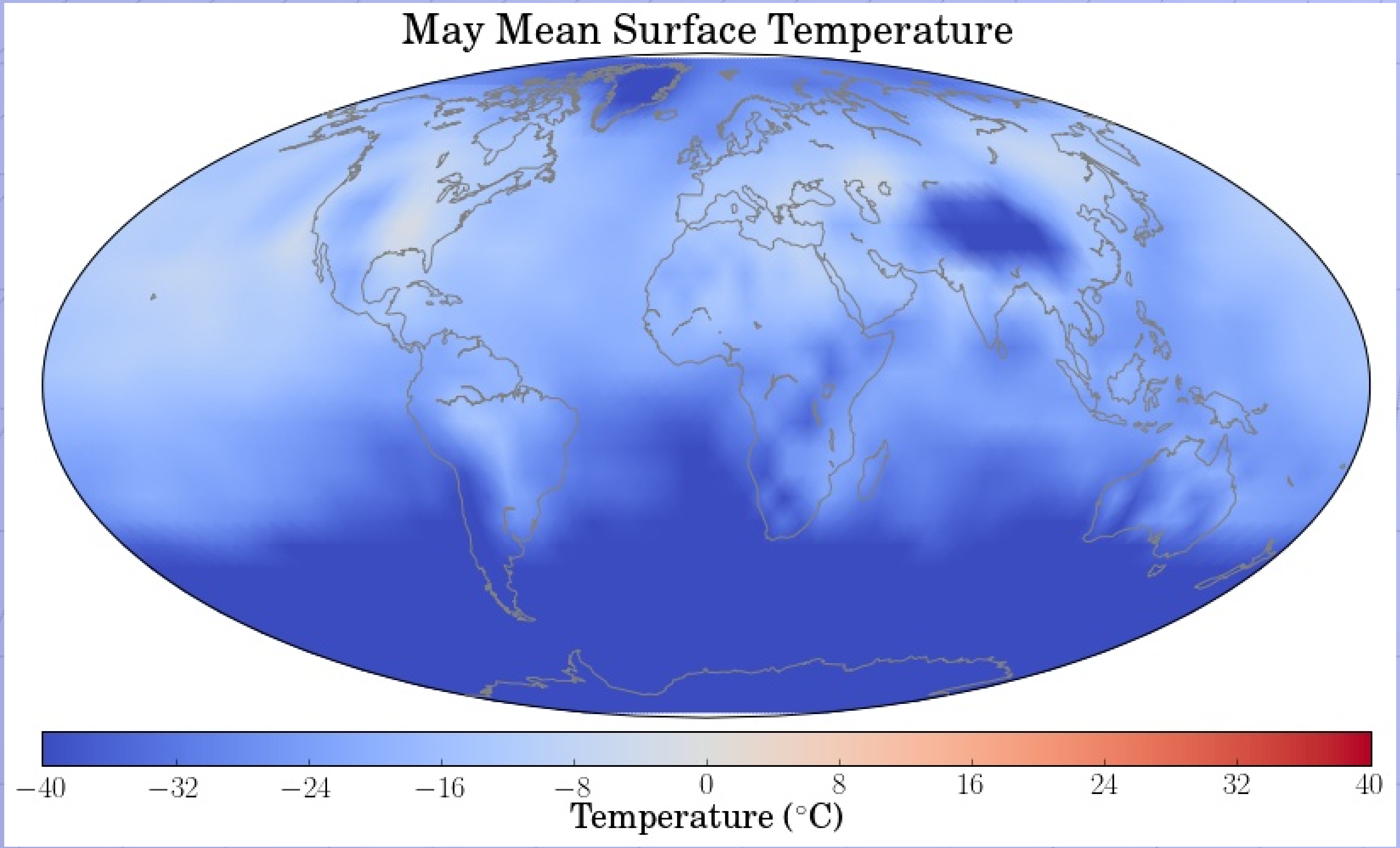
and weathering requires Ts > 273.15 K,

how can this be?



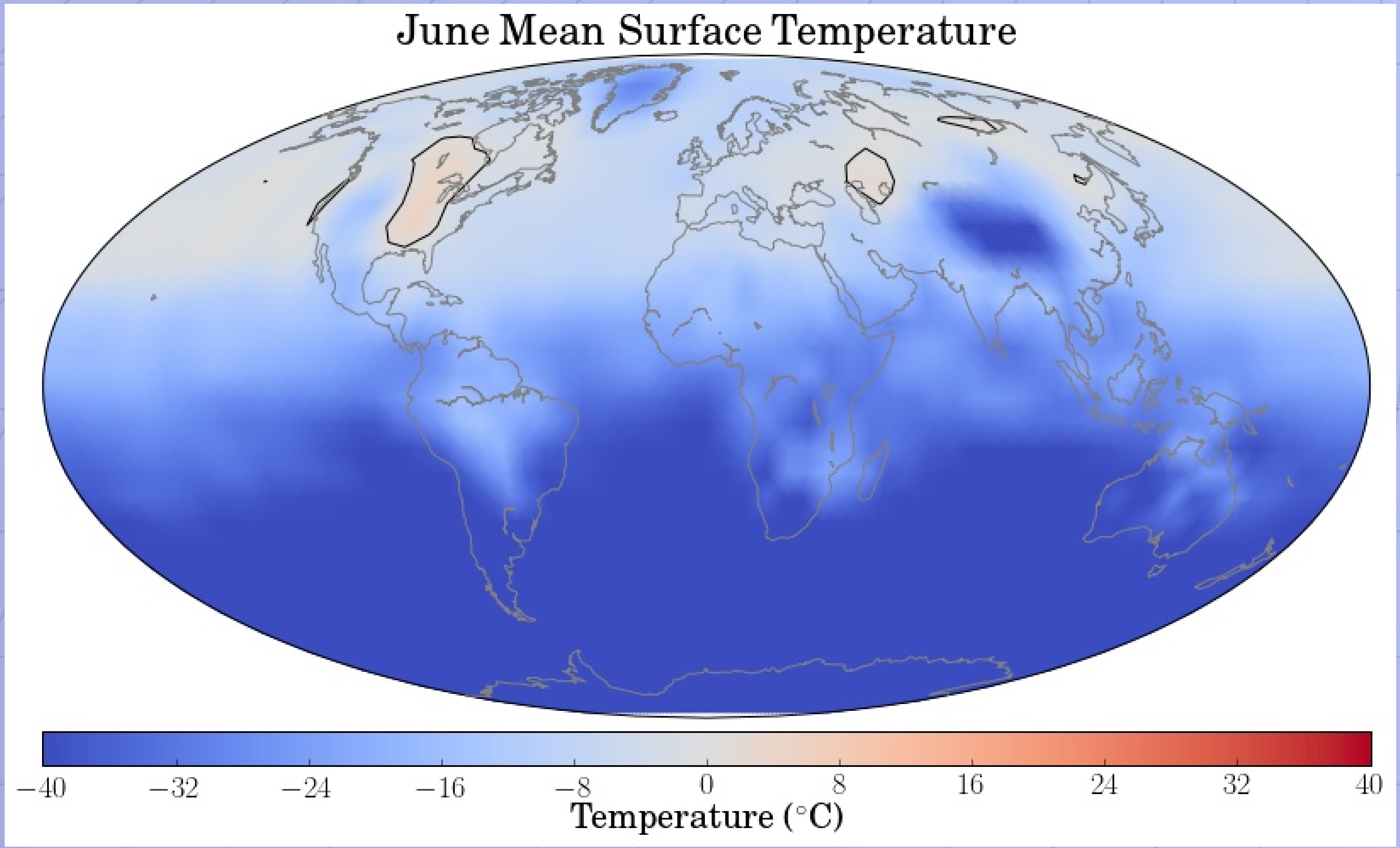
Astronomy & Astrophysics
UNIVERSITY OF TORONTO

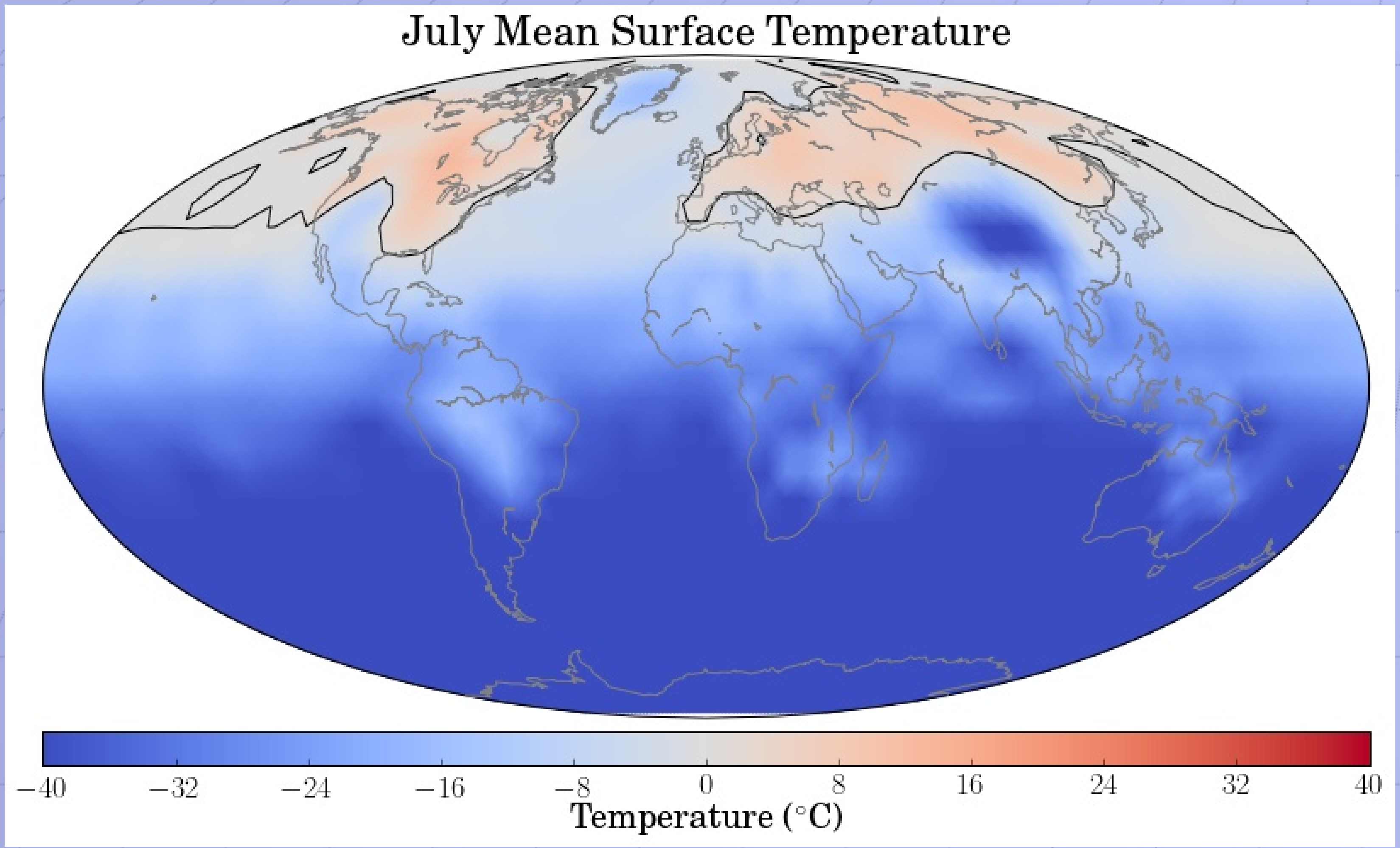
CPS

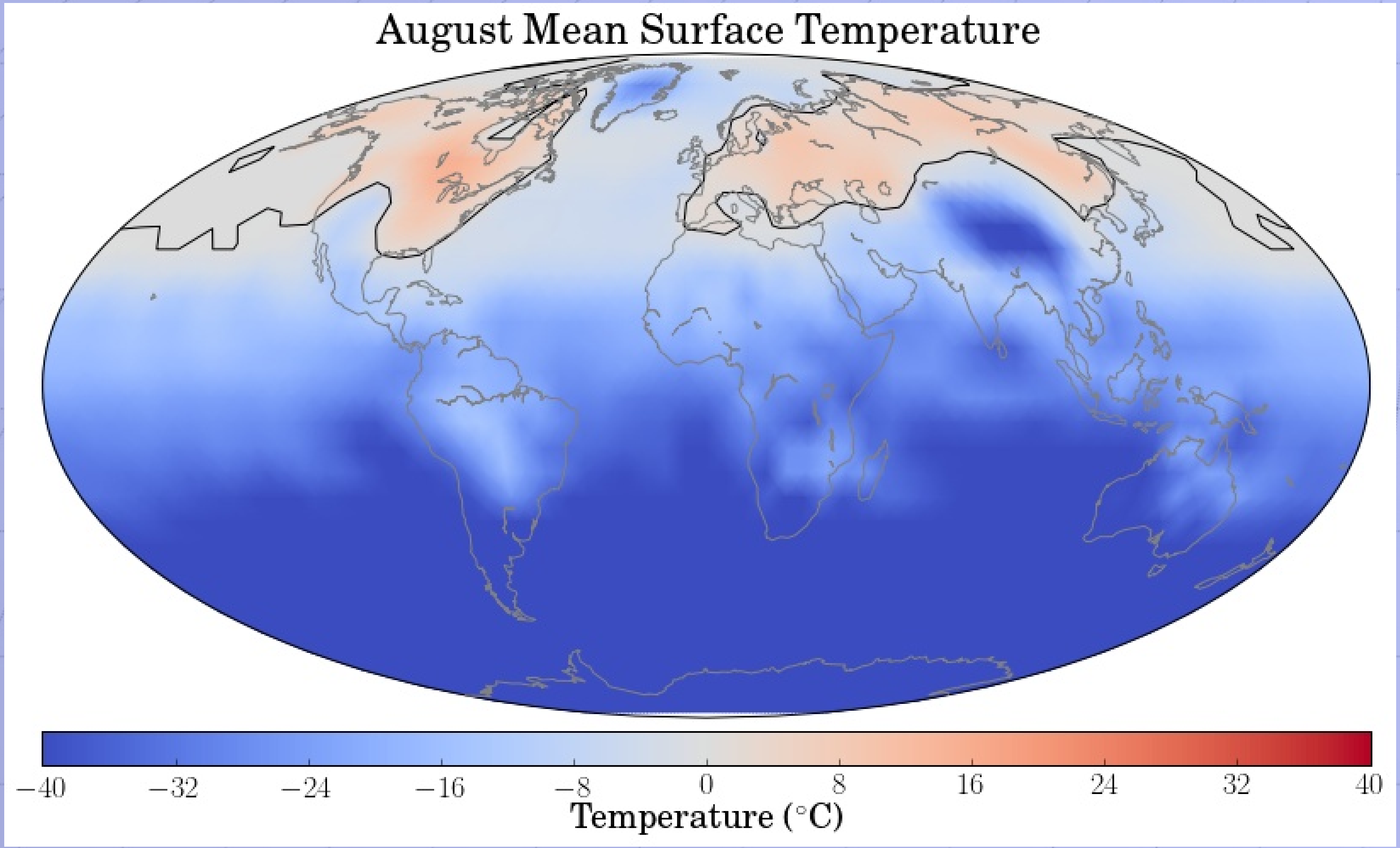


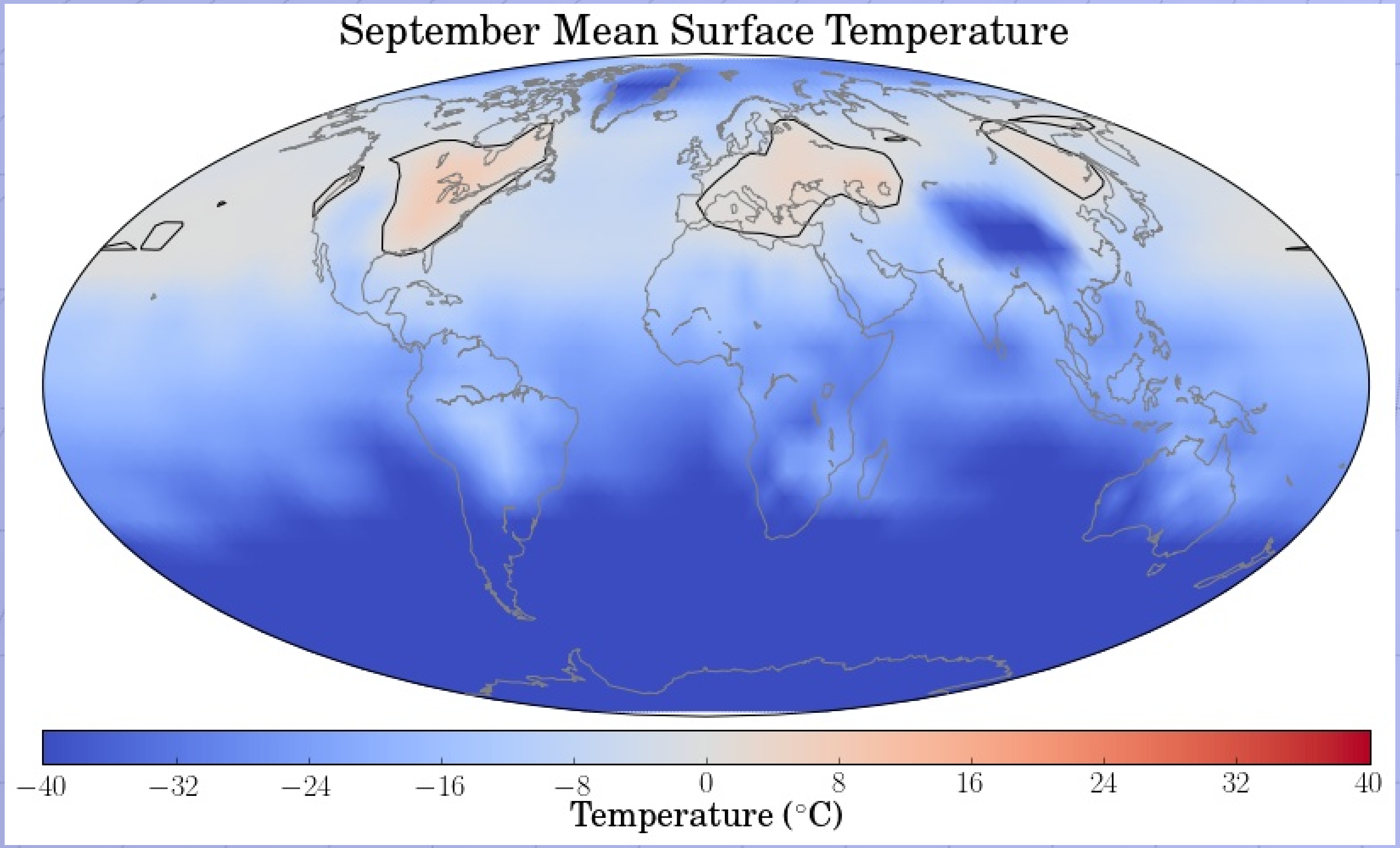
Astronomy & Astrophysics
UNIVERSITY OF TORONTO

CPS

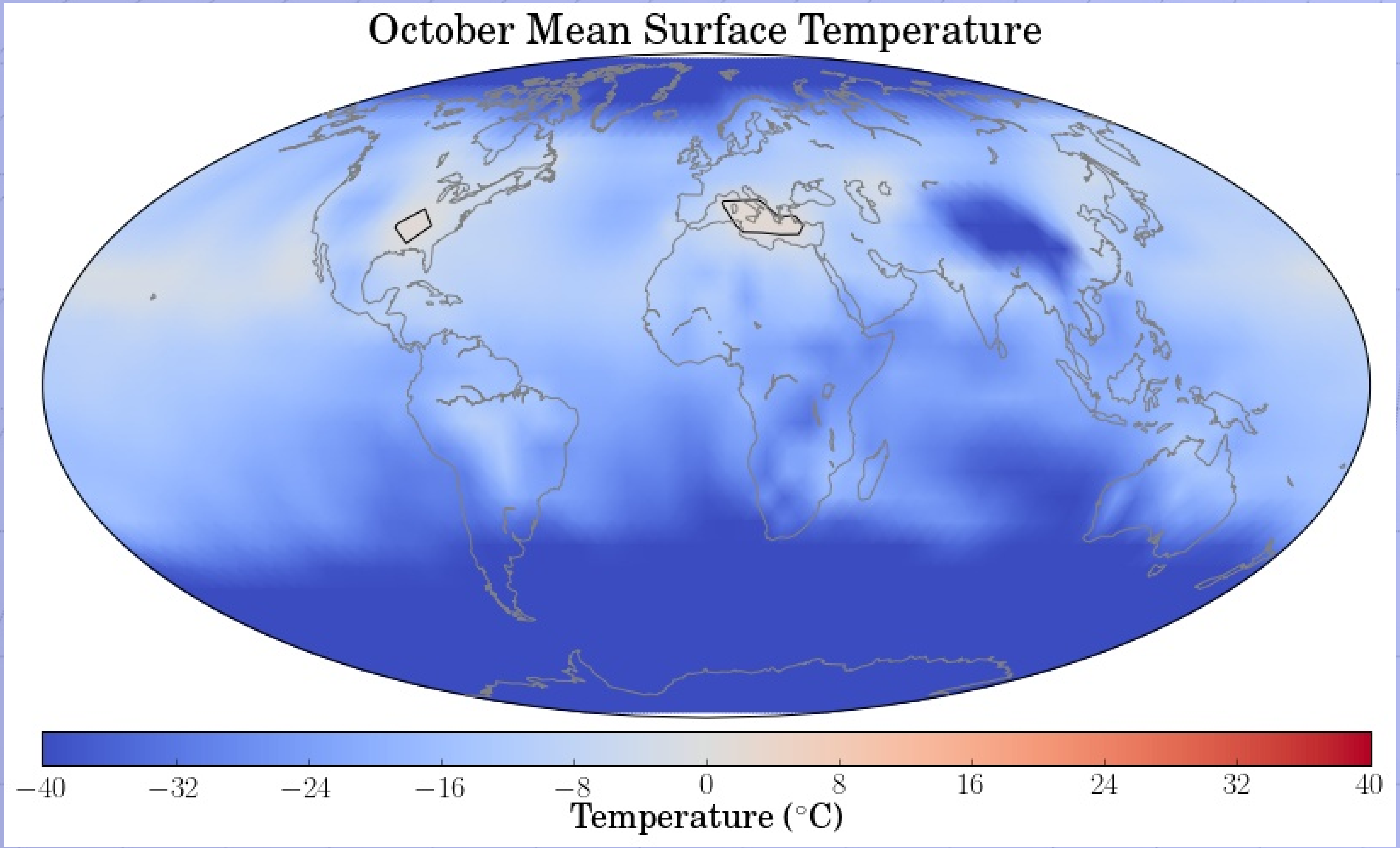

June Mean Surface Temperature
−40
−32
−24
−16
−8
0
8
16
24
32
40
Temperature (°C)


July Mean Surface Temperature
−40
−32
−24
−16
−8
0
8
16
24
32
40
Temperature (°C)


August Mean Surface Temperature
−40
−32
−24
−16
−8
0
8
16
24
32
40
Temperature (°C)

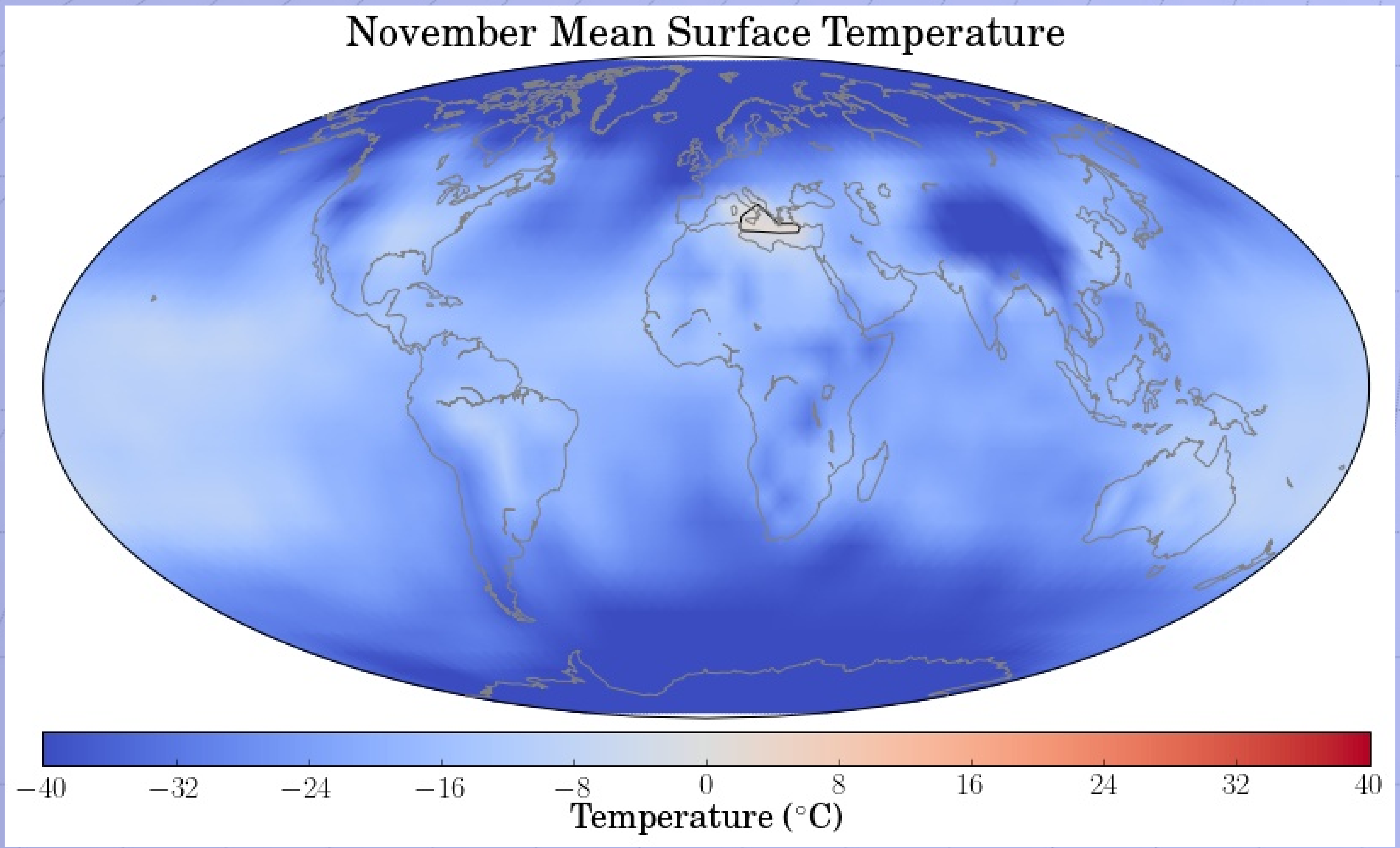


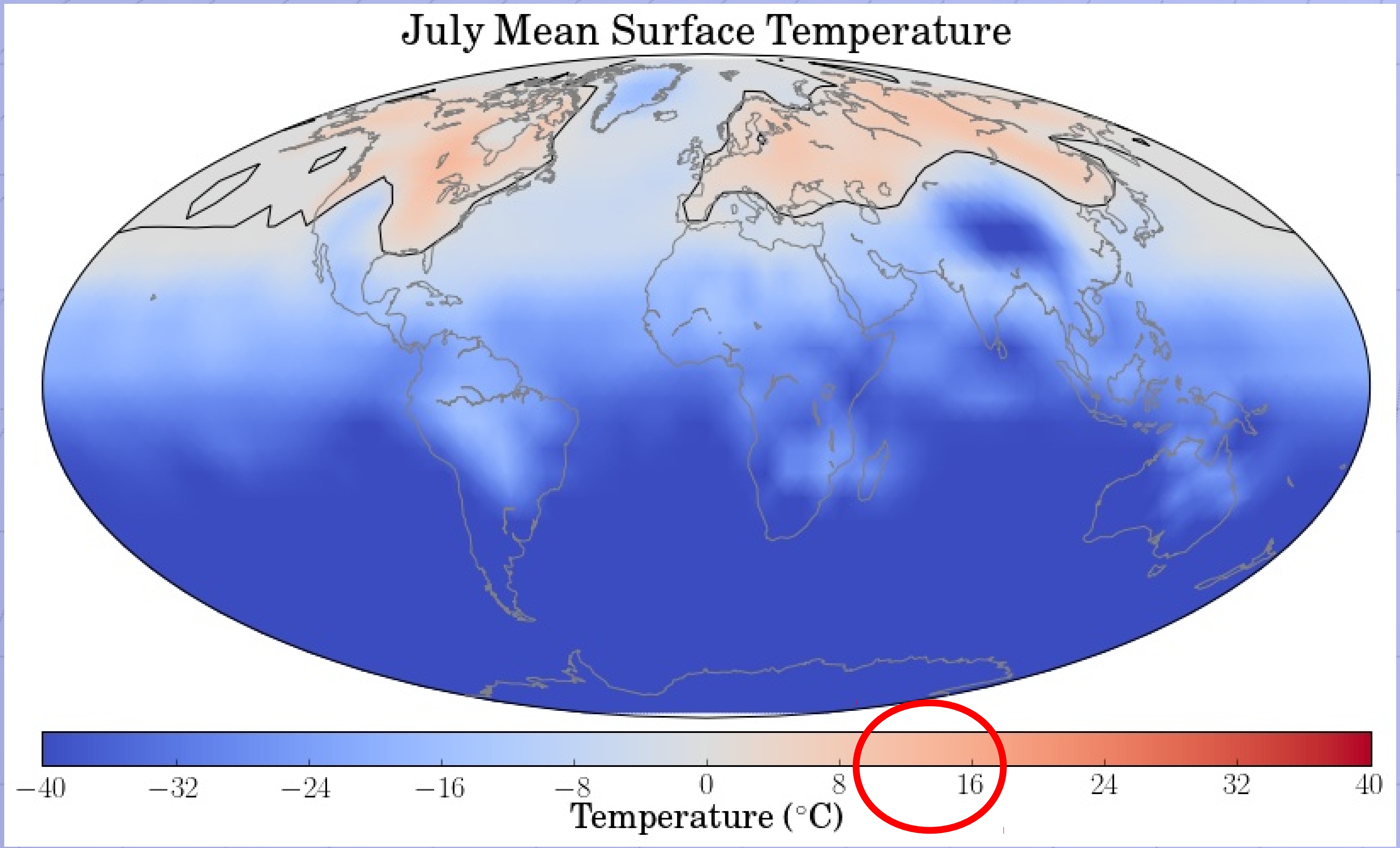
September Mean Surface Temperature
−40
−32
−24
−16
−8
0
8
16
24
32
40
Temperature (°C)



Astronomy & Astrophysics
UNIVERSITY OF TORONTO

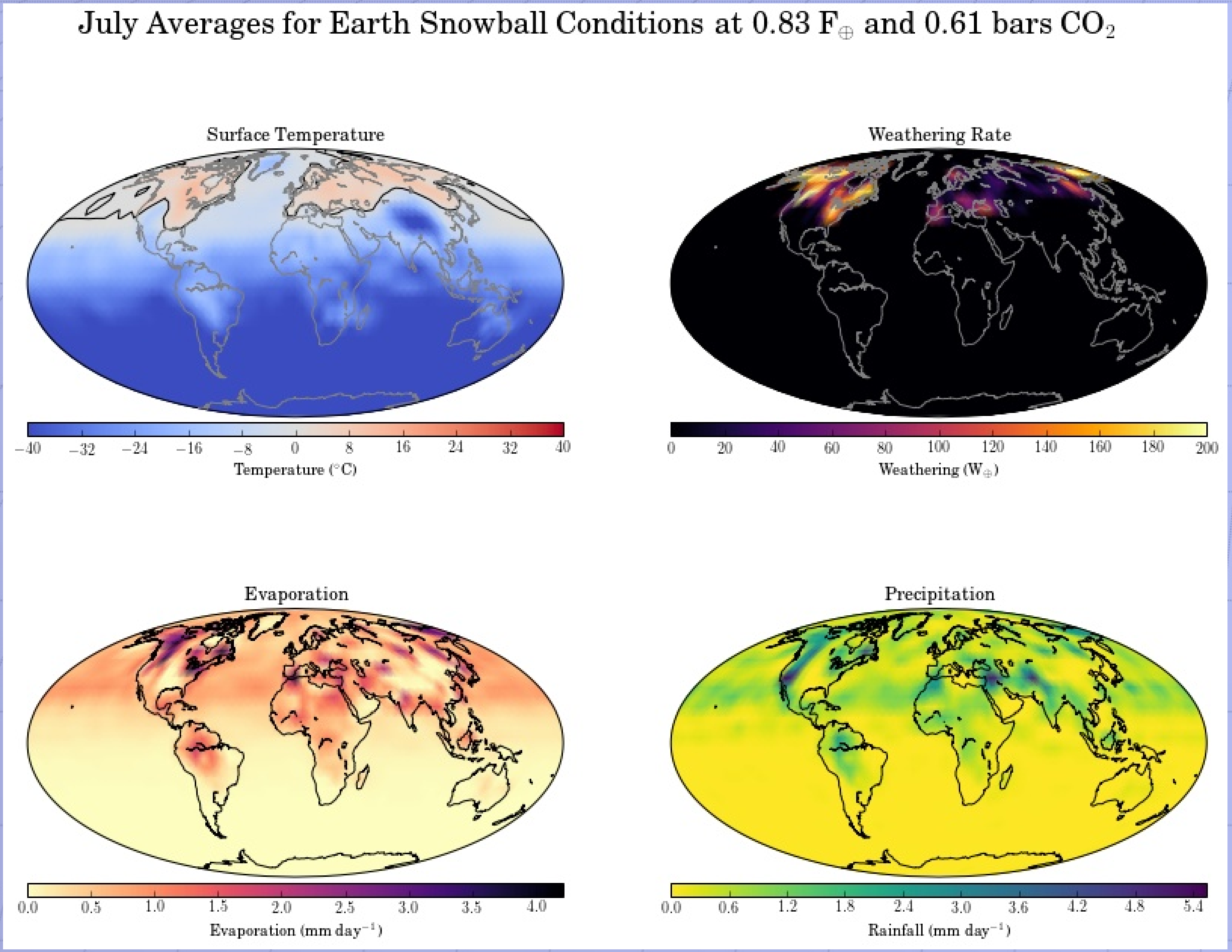
CPS


November Mean Surface Temperature
−40
−32
−24
−16
−8
0
8
16
24
32
40
Temperature (°C)



Astronomy & Astrophysics
UNIVERSITY OF TORONTO

CPS

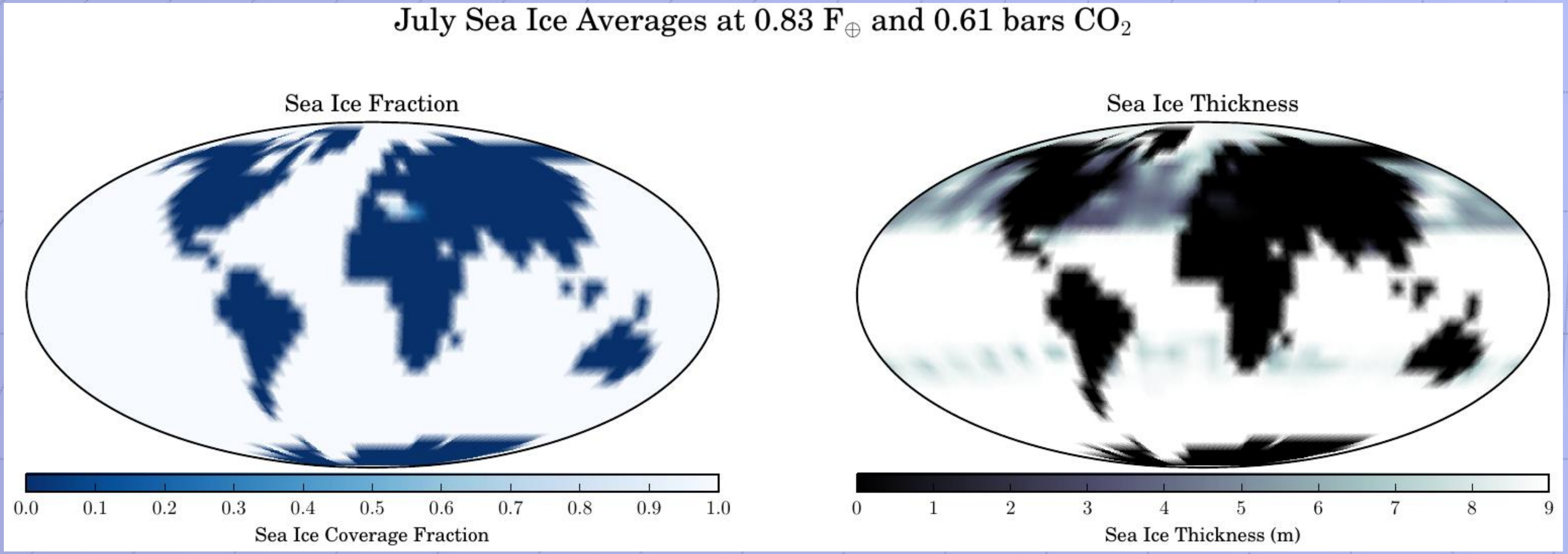


Astronomy & Astrophysics
UNIVERSITY OF TORONTO

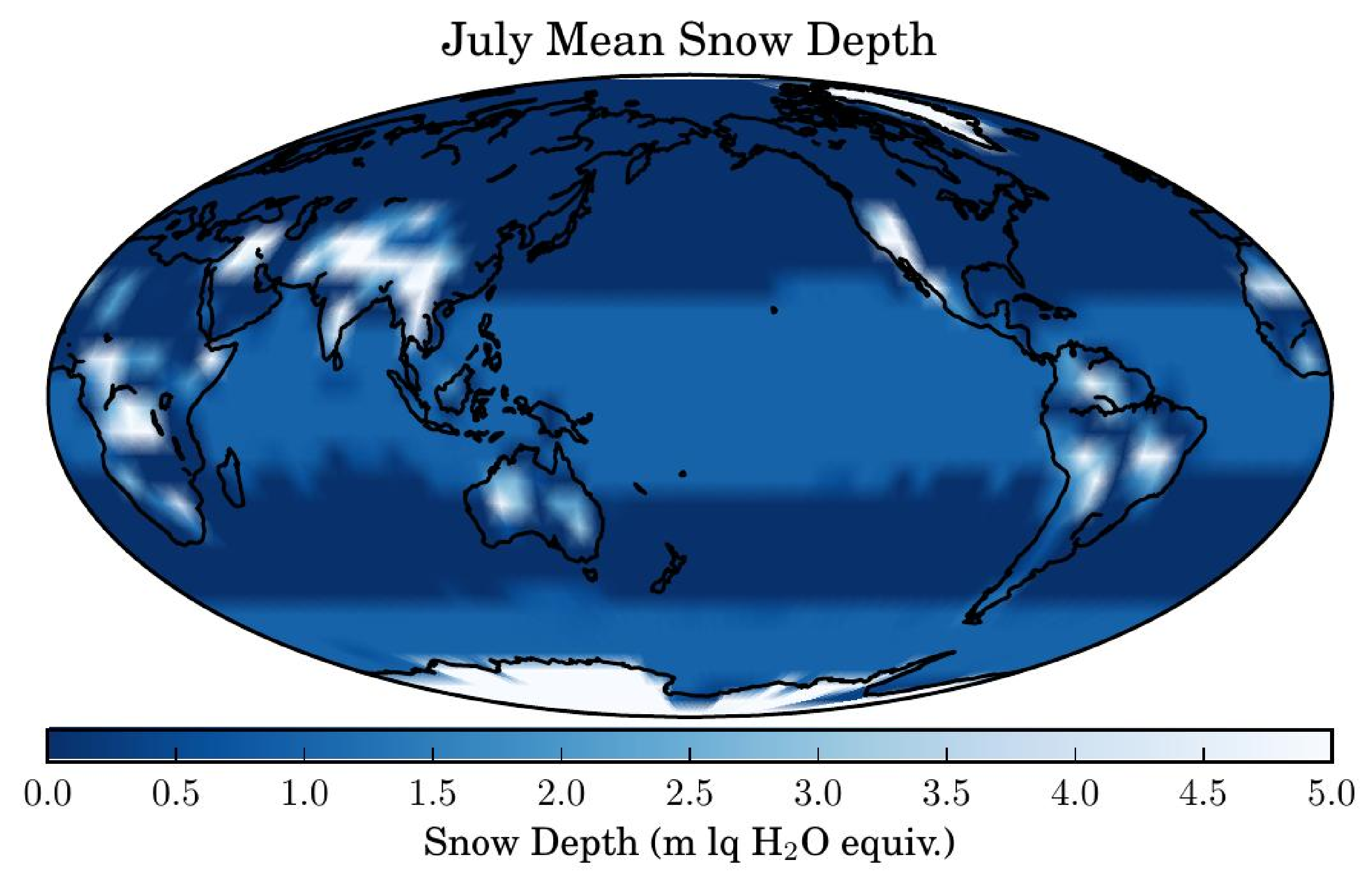
CPS

Does this make sense?

Does this make sense?



Does this make sense?

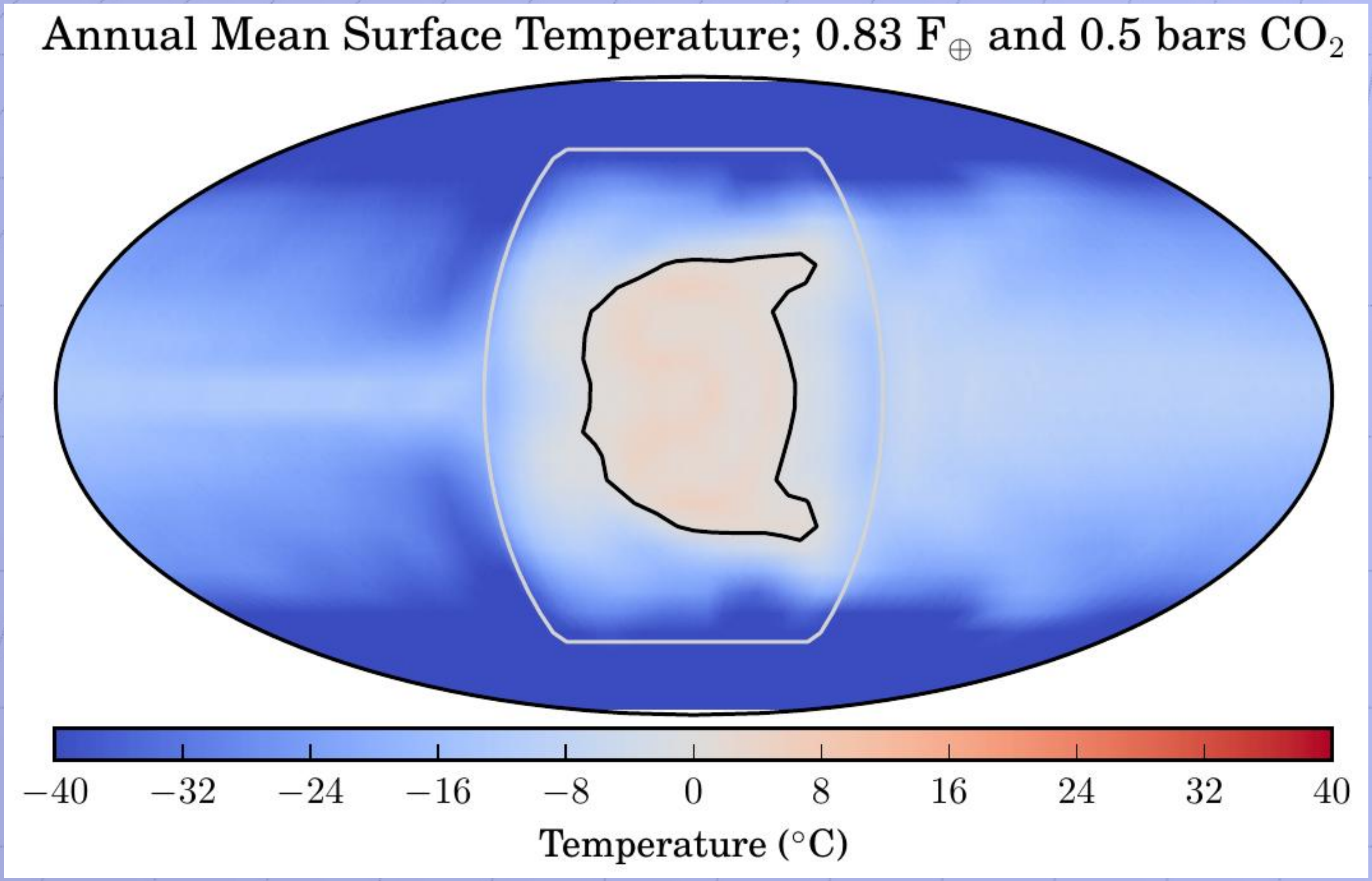


What does this imply?

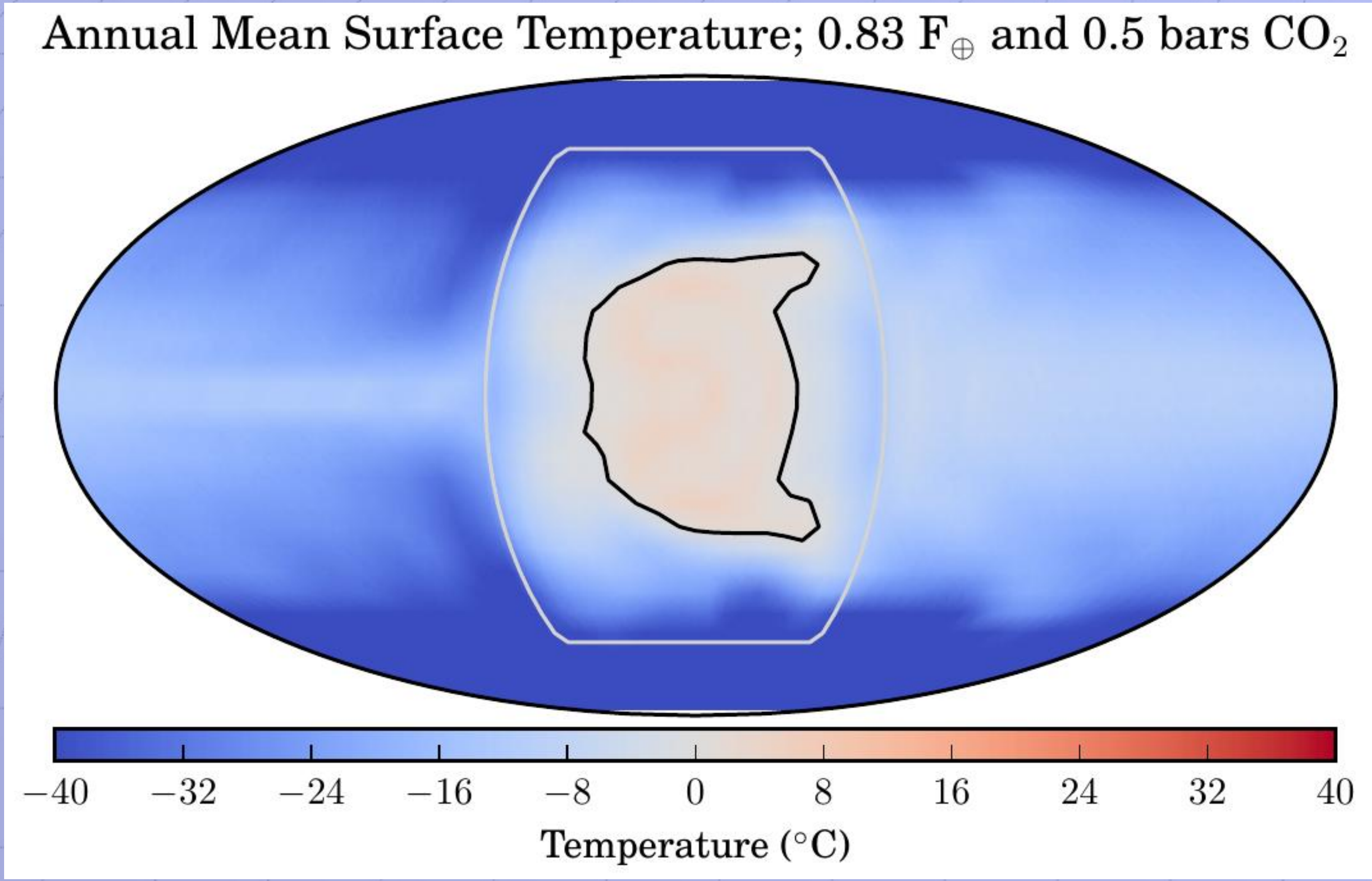
Snowball planets may have regional and seasonal habitable conditions, with rainfall and **moderate temperatures of 10 ˚C or more**

What if the obliquity were 0˚, and land was on the equator?

What if the obliquity were 0˚, and land was on the equator?



Persistent and Stable Temperate Conditions on a Snowball Planet



Conclusions

- Long-term negative feedbacks are important for characterizing the habitable zone
- Snowball conditions may be common in the habitable zone
- Snowball conditions do not preclude temperate refuges on land
- Snowball conditions are not necessarily a limit on the habitable zone

Sources

[1] CEPhoto, Uwe Aranas, via Wikimedia Commons.
https://commons.wikimedia.org/wiki/File:Papar-District_Sabah_Rainforests-of-Crocker-Mountain-Range-01.jpg

[2] User brewbrooks, via Wikimedia Commons.
https://commons.wikimedia.org/wiki/File%3ANegev_Large_Makhtesh_Crater%2C_Negev_Desert_(469181859).jpg

[3] Paxson Woelber, via Wikimedia Commons.
https://commons.wikimedia.org/wiki/File:Camping_in_Thunder_Valley._Gates_of_the_Arctic_National_Park,_Brooks_Range,_Alaska.jpg

[4] Fraedrich, K., Jansen, H., Kirk, E., Luksch, U., & Lunkeit, F. 2005, Meteorologische Zeitschrift, 14, 299

[5] Menou, K. 2015, Earth and Planetary Science Letters, 429, 20

[6] Paradise, A., & Menou, K. 2017, arXiv:1704.04535

[7] West, A. J. 2012, Geology, 40, 811

[8] Foley, B. J. 2015, The Astrophysical Journal, 812, 36

[9] Small, E. E., Anderson, R. S., Repka, J. L., & Finkel, R. 1997, Earth and Planetary Science Letters, 150, 413

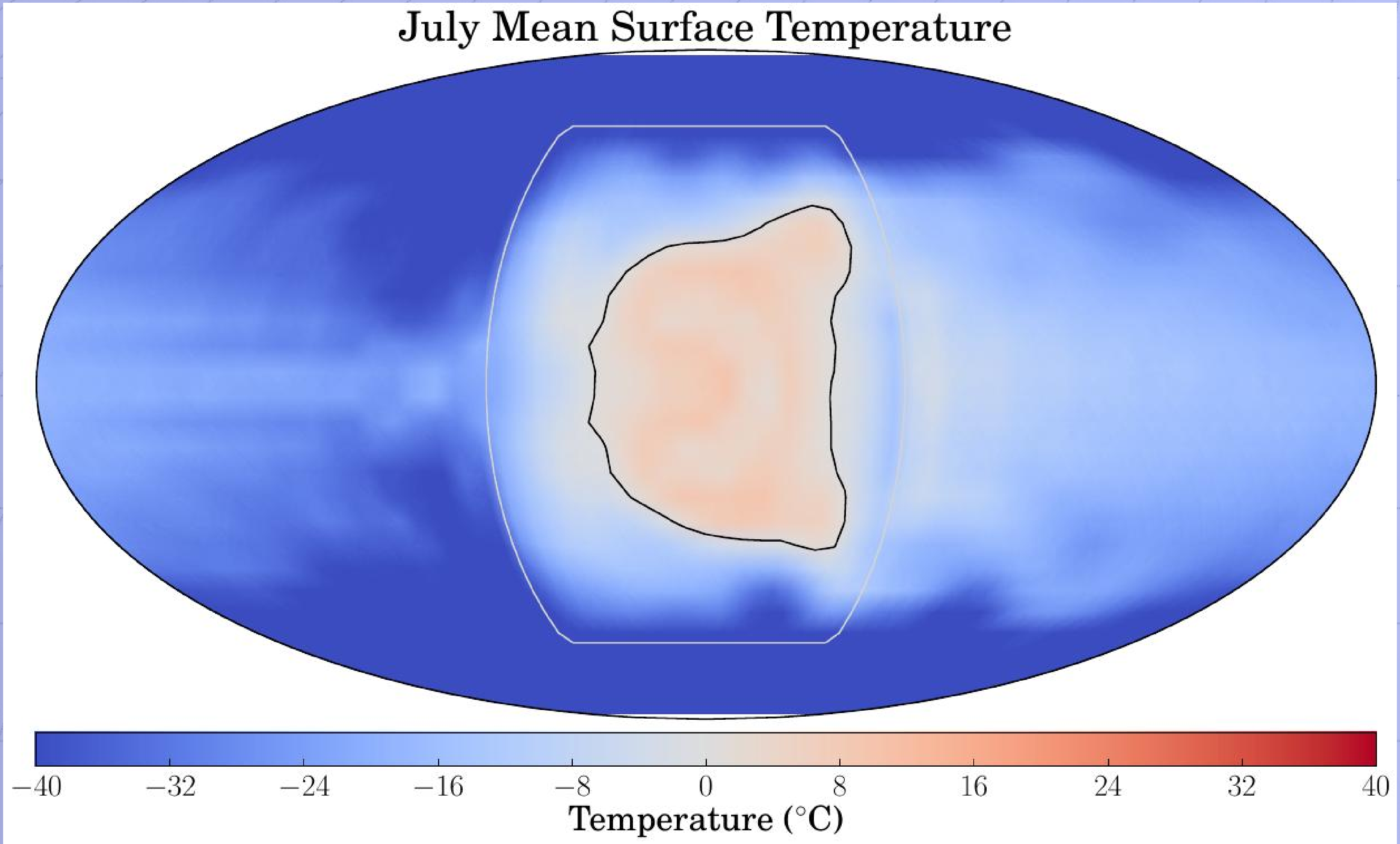
[10] Abbot, D. S. 2016, The Astrophysical Journal, 827, 117

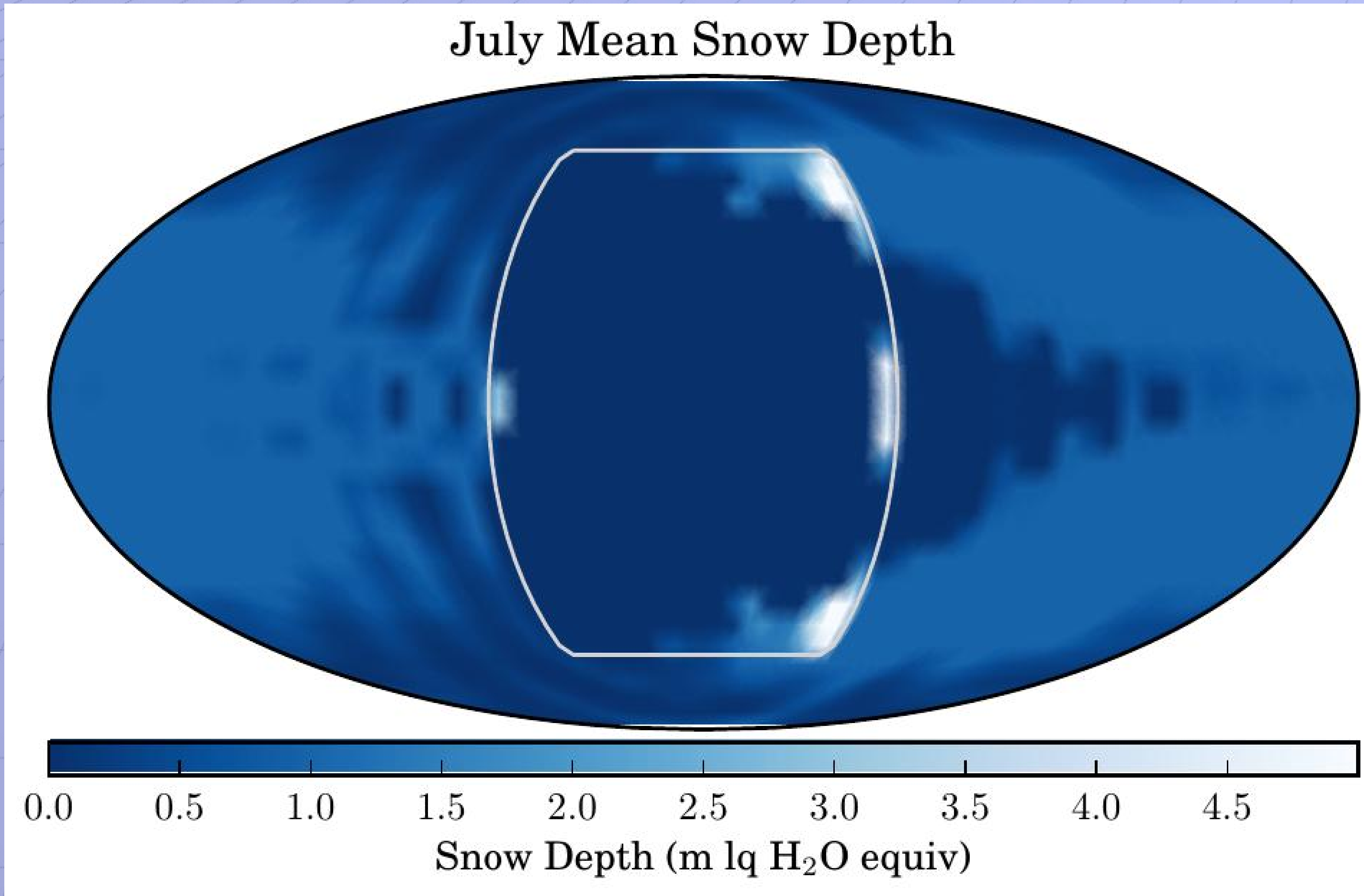
[11] Spiegel, D., Menou, K., & Scharf, C. 2008, Astrophysical Journal, 681, 1609

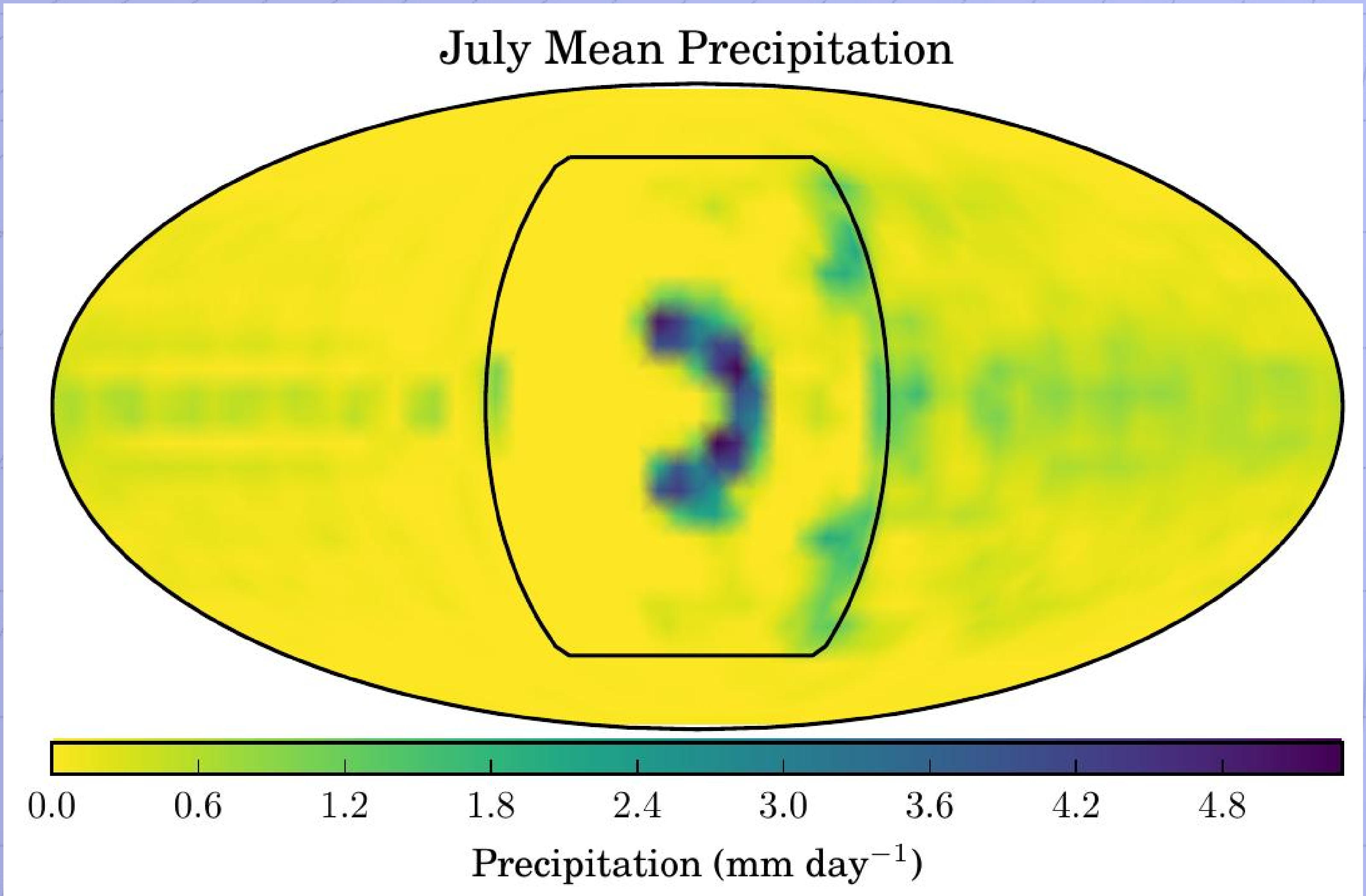
[12] Turbet, M., Forget, F., Leconte, J., Charnay, B., & Tobie, G. 2017, 1

Caveats

- PlaSim doesn't have a dynamical glacier model—snow just piles up
  - Glaciers reach thicknesses of 100s of meters to kilometers; have significant effect on atmospheric circulation and temperature
  - Sea level change due to ice buildup is ignored
- Simplified slab ocean model, rather than dynamical ocean transport model
- Neglect CO_2 condensation at high pCO_2 or in cold traps (Abbot 2016)
- Neglect feedbacks between temperature, plate speed, uplift, erosion
  - No tectonic model at all
- Lack a sophisticated model of soil type, rock properties, topography, and erosion
- Neglect weathering-albedo feedbacks—weathered basalt has a different albedo than unweathered basalt
- Neglect sea-floor weathering

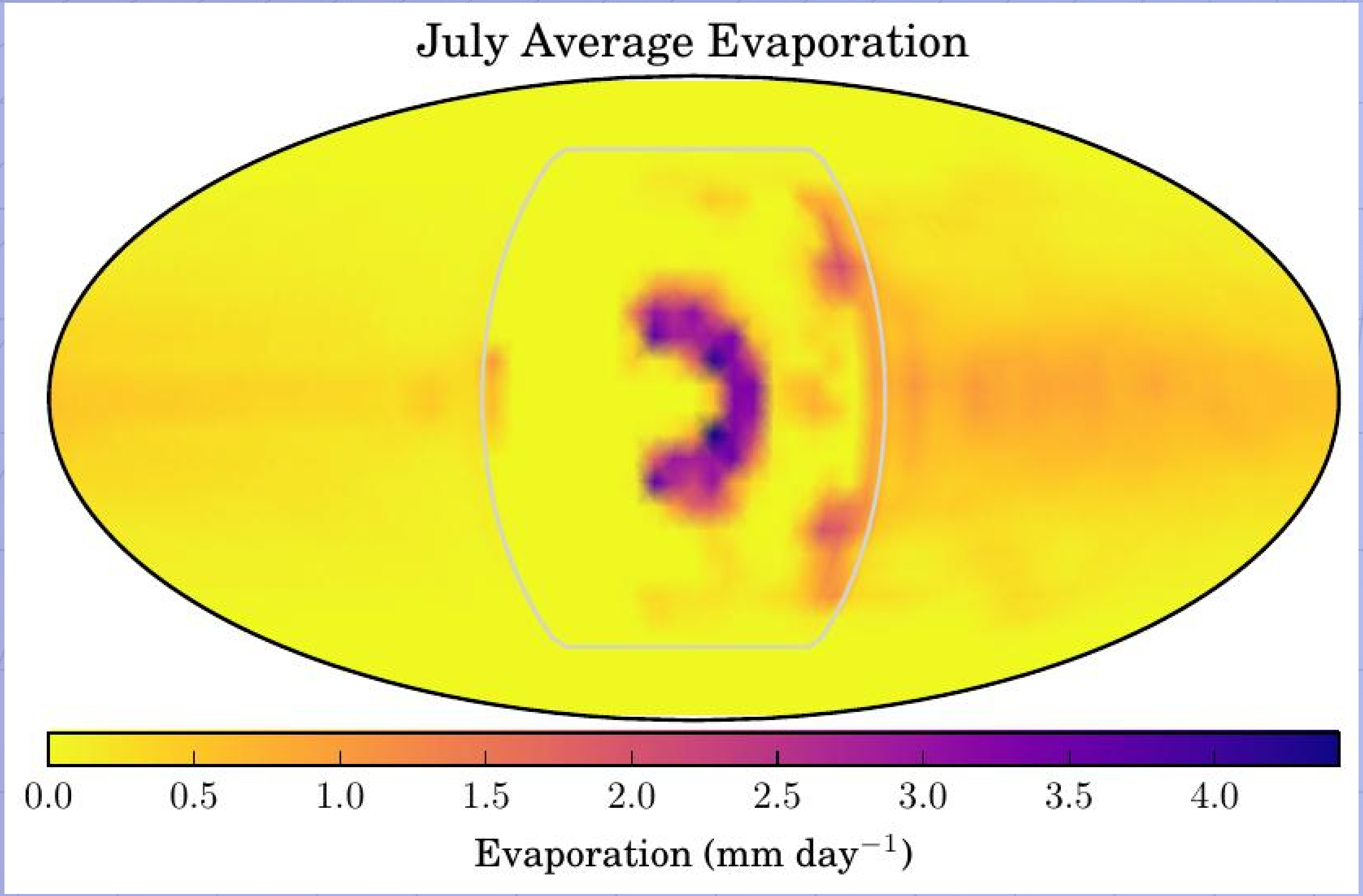

July Mean Surface Temperature
−40
−32
−24
−16
−8
0
8
16
24
32
40
Temperature (°C)


July Mean Snow Depth
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Snow Depth (m lq H_2O equiv)



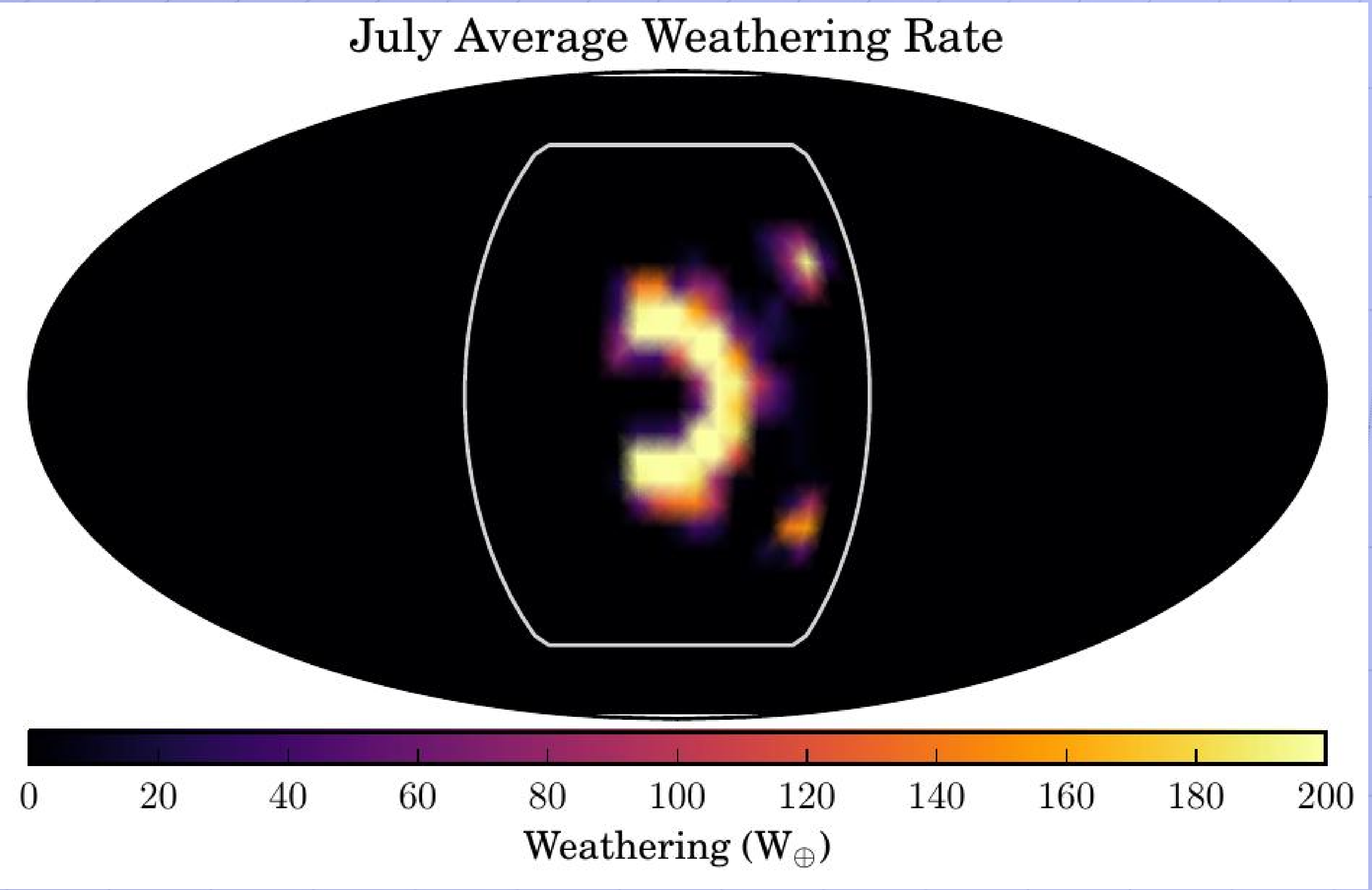
Astronomy & Astrophysics
UNIVERSITY OF TORONTO

CPS



Astronomy & Astrophysics
UNIVERSITY OF TORONTO

CPS

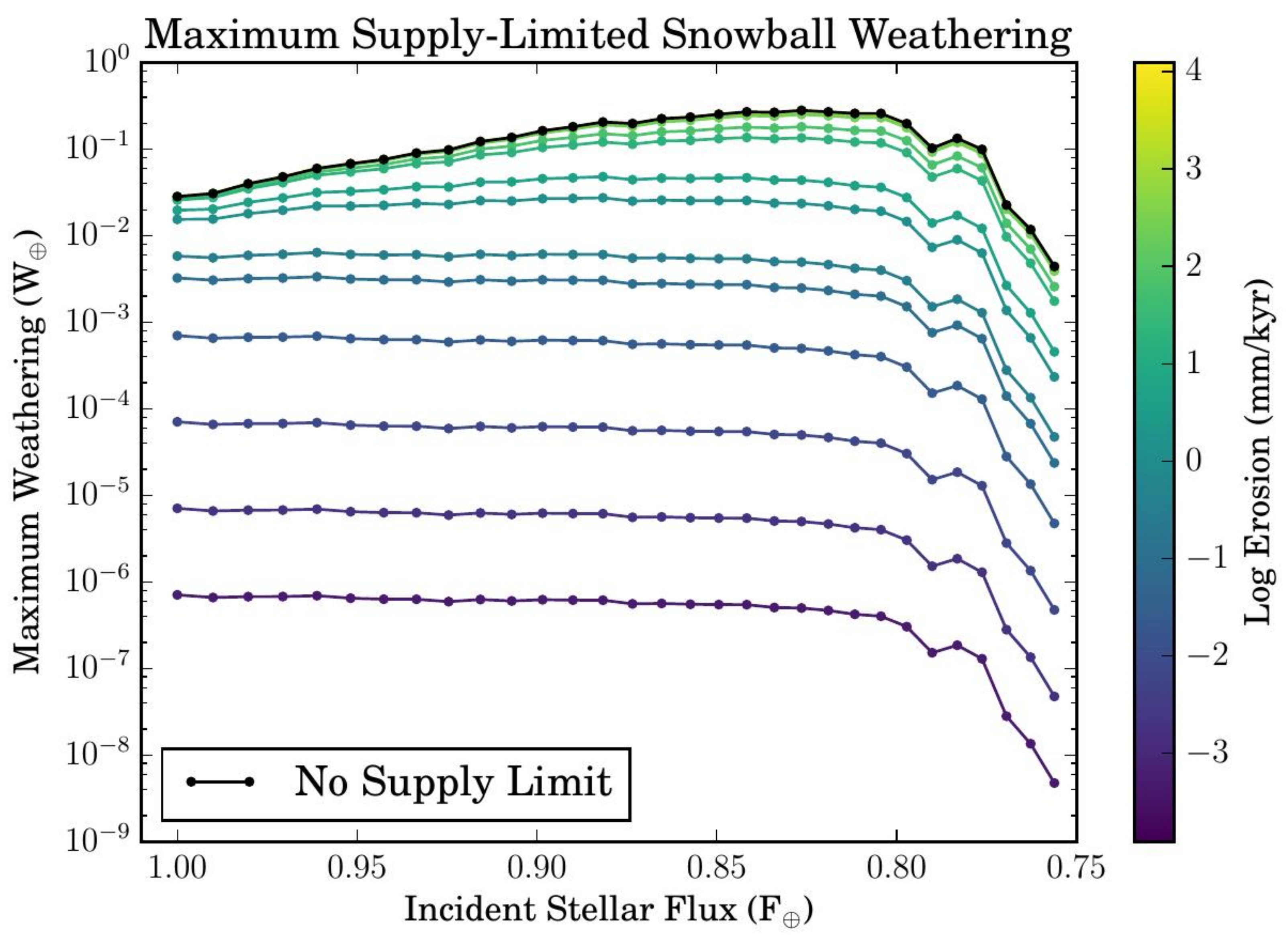

July Average Weathering Rate
0
20
40
60
80
100
120
140
160
180
200
Weathering ($W_\oplus$)

Does this make sense?

What about weatherable supply?

- Snowballs might have low erosion—does that limit weathering?
- $W = W_{max} \times [1 - \exp(-W_k / W_{max})]$ (West 2012; Foley 2015)
  - W_k is the kinetic weathering – weathering not limited by supply
  - W_{max} is the maximum weathering possible given an erosion rate:
    $W_{max} \propto$ Erosion rate

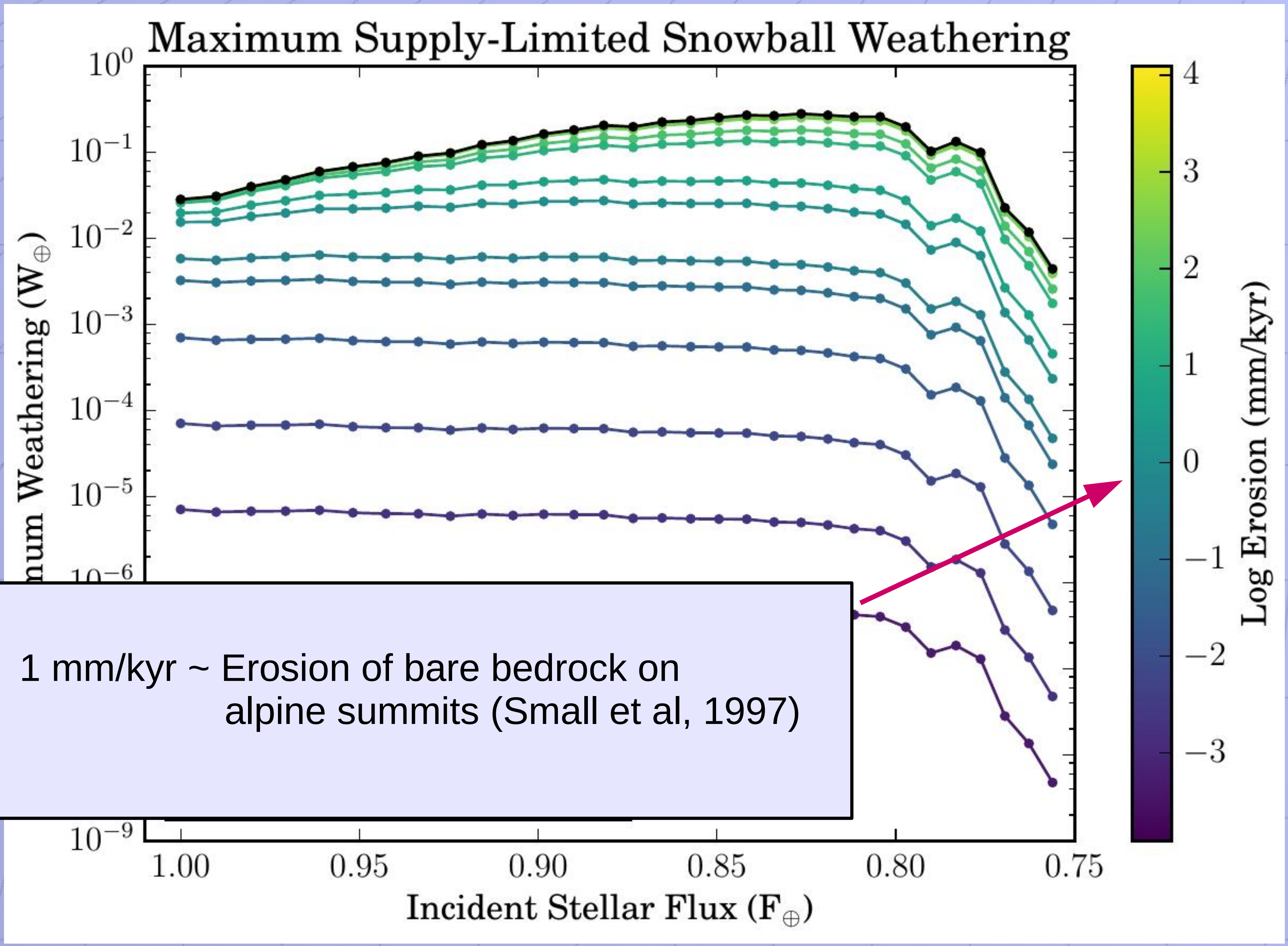
If we do consider various erosion rates:



Astronomy & Astrophysics
UNIVERSITY OF TORONTO

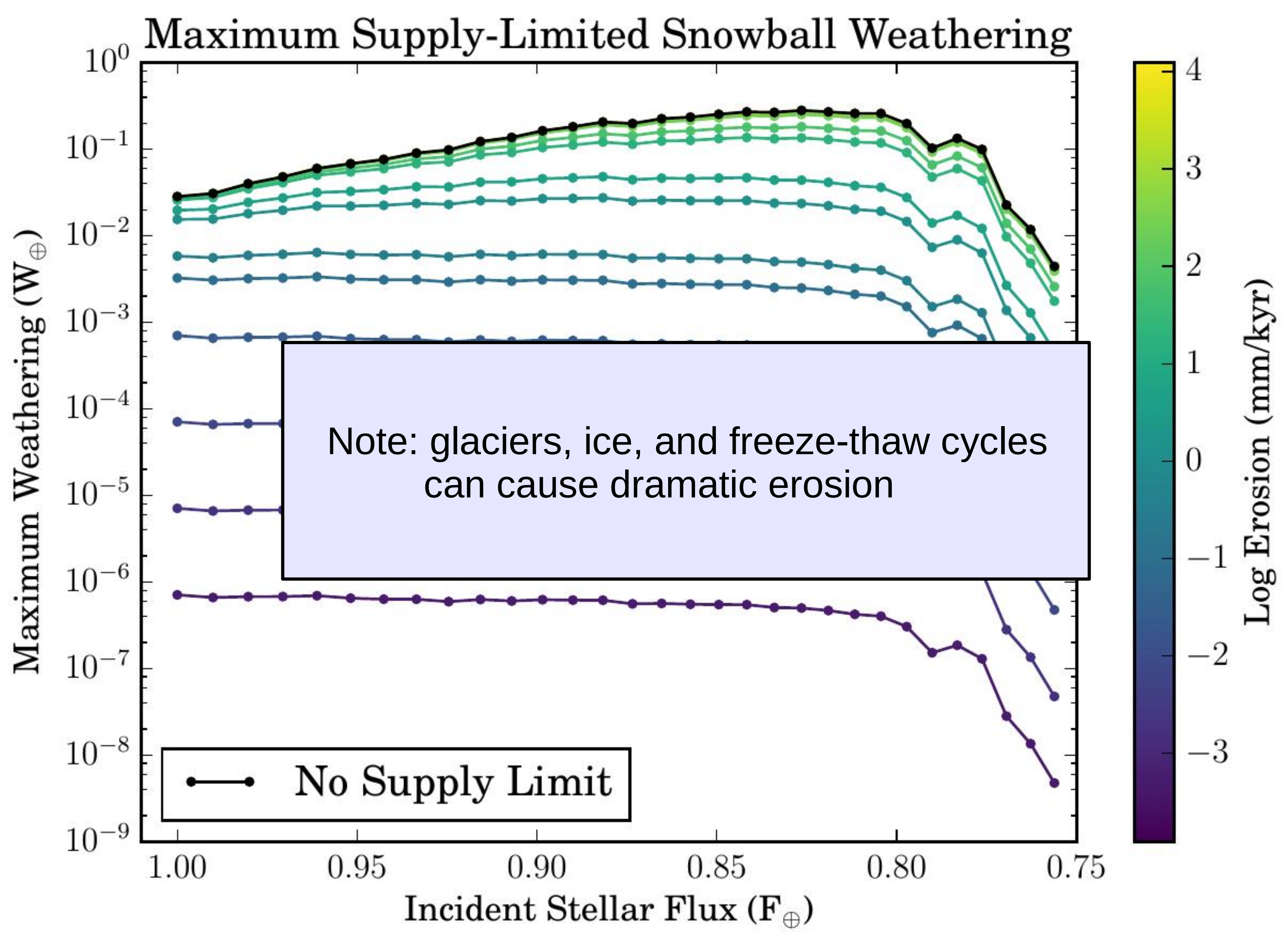
CPS

If we do consider various erosion rates:

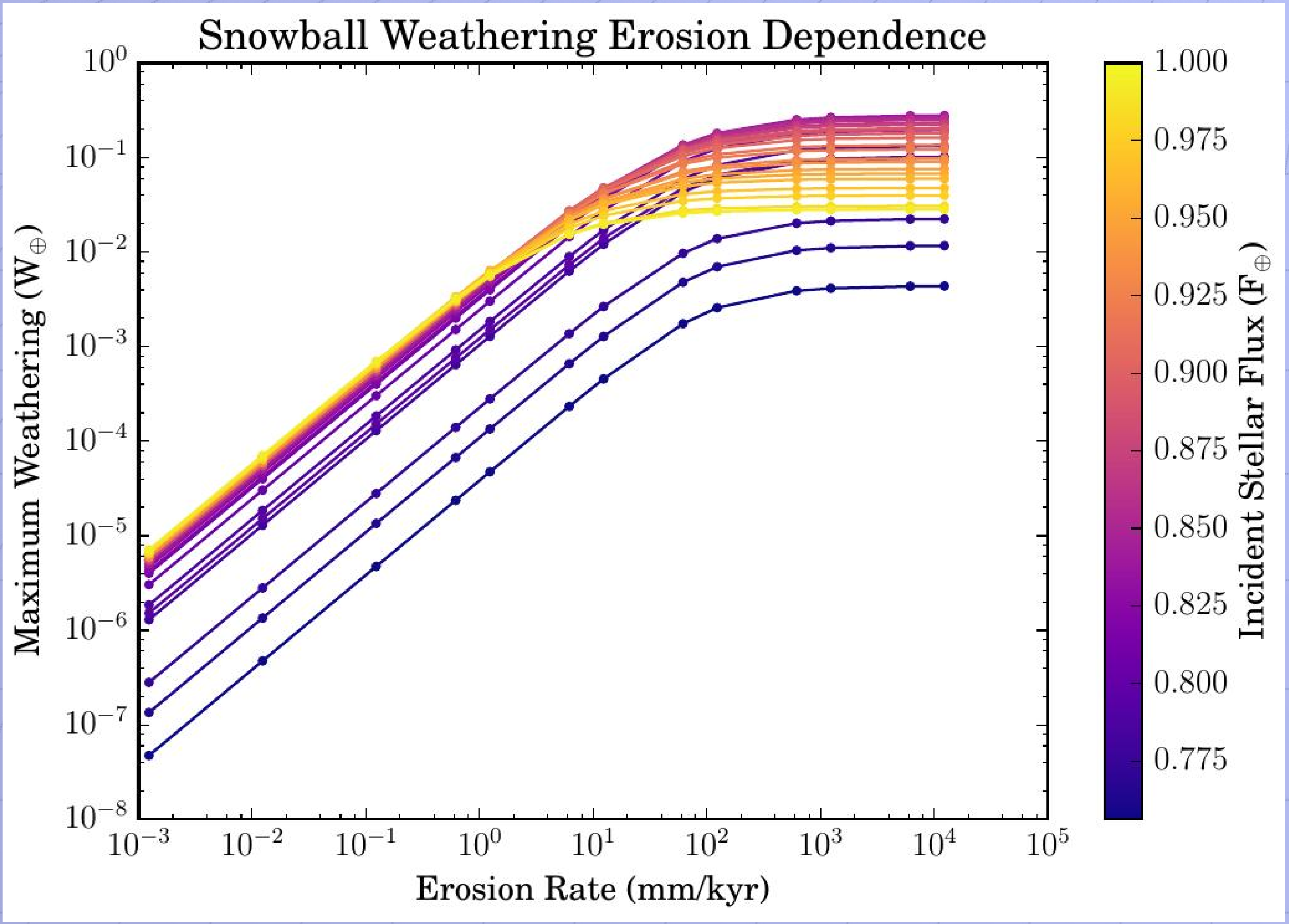


1 mm/kyr ~ Erosion of bare bedrock on
alpine summits (Small et al, 1997)

If we do consider various erosion rates:



Note: glaciers, ice, and freeze-thaw cycles can cause dramatic erosion


Snowball Weathering Erosion Dependence
Maximum Weathering ($W_\oplus$)
Erosion Rate (mm/kyr)
Incident Stellar Flux ($F_\oplus$)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5
1.000
0.975
0.950
0.925
0.900
0.875
0.850
0.825
0.800
0.775