Modeling Terrestrial planetary atmospheres with ROCKE-3D

Michael Way, Tony Del Genio, Linda Sohl, Sonny Harman, Nancy Kiang, Igor Aleinov, Chris Colose, Tom Clune, Maxwell Kelley, and many others at GISS, GSFC, and elsewhere

Tokyo Area Planetary Meeting: September 7, 2018

The NExSS Teams

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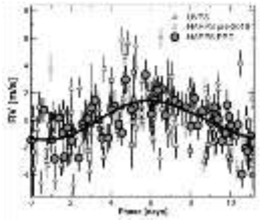

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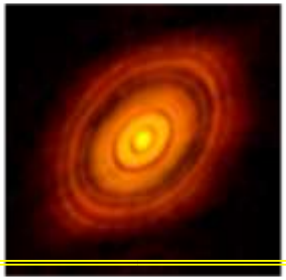

Laboratory Astrophysics *Planetary*
Structure and Evolution *Space*
Weather and Escape

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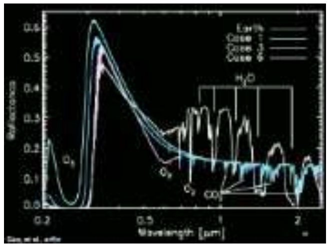
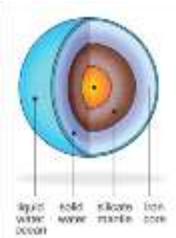
Management

Exoplanet Detection



H. Imanaka

Exoplanet Characterization



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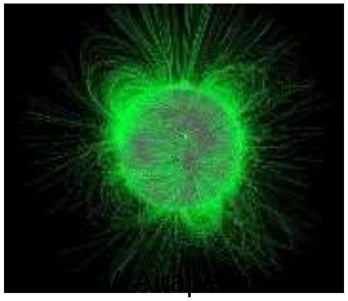
Disks & Planet Formation



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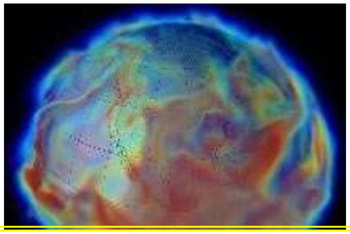
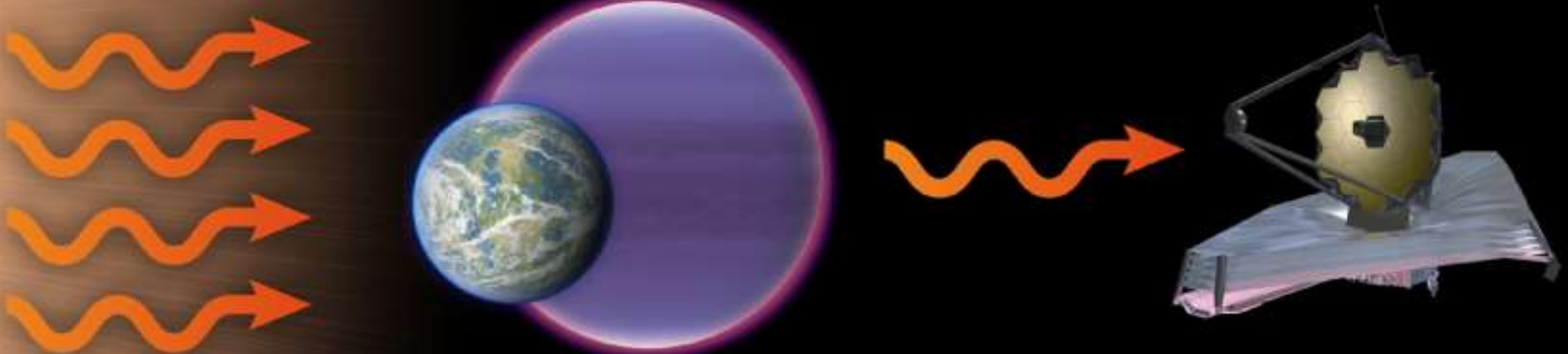


Planetary Habitability and Detectability

Sellers
Exoplanet
Environments
Collaboration

Developing multiscale data-driven integrated science+instrumentation modeling for the study of exoplanet environments



Heliophysics

- Stellar Spectra Models
- CME Models
- Star-Planet Interactions
- Stellar Evolution Models

Earth/Planetary

- 1D Atmosphere Models
- 3D Global Circ. Models
- Planet Evolution Models
- Atm. Radiative Transfer

Astrophysics

- Science Mission Planning
- Observatory/Instrument Models
- Model Fitting & Parameter Retrieval
- Data Interpretation and Discovery

Parent Earth 3-D GCM Model: Model_E2 (IPCC/CMIP)

- 2x2.5 deg Latitude x Longitude grid (1 degree cubed sphere)
- 40 Layer atmosphere (109 layer)
- 13 Layer fully coupled ocean (1x1.25)
- Radiation: In-house developed (fast) present day Earth-specific scheme

ROCKE -3D

- 4x5 deg Latitude Longitude grid (2x2.5)
- 40 Layer atmosphere
- 13 Layer fully coupled ocean
- SOCRATES (Met Office) flexible radiation scheme
  - Thin Atmospheres: Present & Ancient Mars, Ancient Moon (3mb and up)
  - Thicker Atmospheres: Ancient Earth (CO2/N2 dominated up to 10bars with N2O, CH4)
    - Reducing Atmospheres: Titan
- Interactive Chemistry: Modern Earth specific & Reducing chemistry (Fall 2019)
- Details in Way et al. 2017 ApJS, 231, 12

  Resolving Orbital and Climate Keys of Earth and Extraterrestrial Environments with Dynamics (ROCKE-3D) 1.0: A General Circulation Model for Simulating the Climates of Rocky Planets

Chemistry

Sonny Harman & Kostas Tsigaridis

ROCKE-3D inherited an oxygen-dominated atmospheric chemical regime from ModelE2, but it’s not particularly flexible.

The Kinetic PreProcessor (KPP) acts as a box model that builds sparse matrices from the mass balance ODEs; these can be time-marched forward (given a set of reactions and their rates).

KPP is currently working as part of:

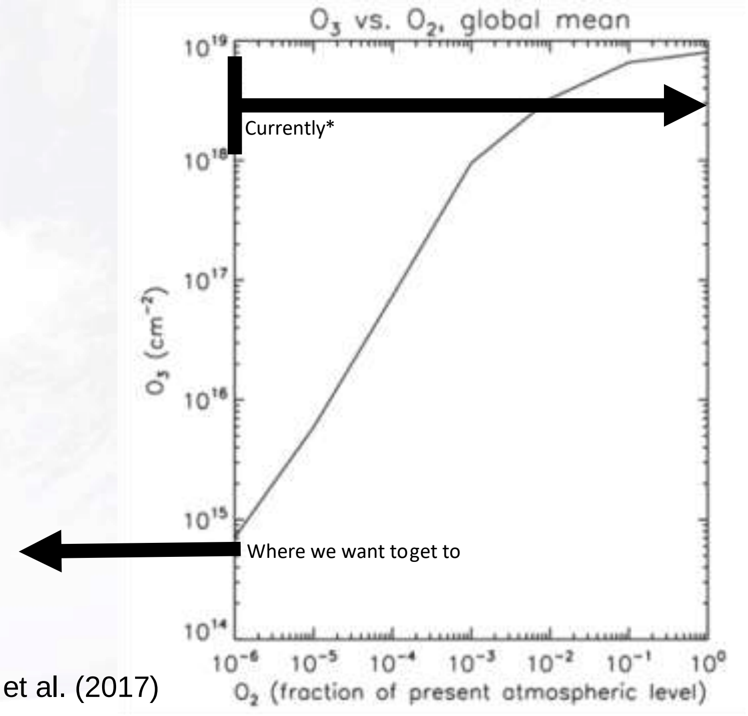
- NCAR’s WRF and BOXMOX : GEOS-Chem : RACM

Why is ROCKE-3D getting KPP?

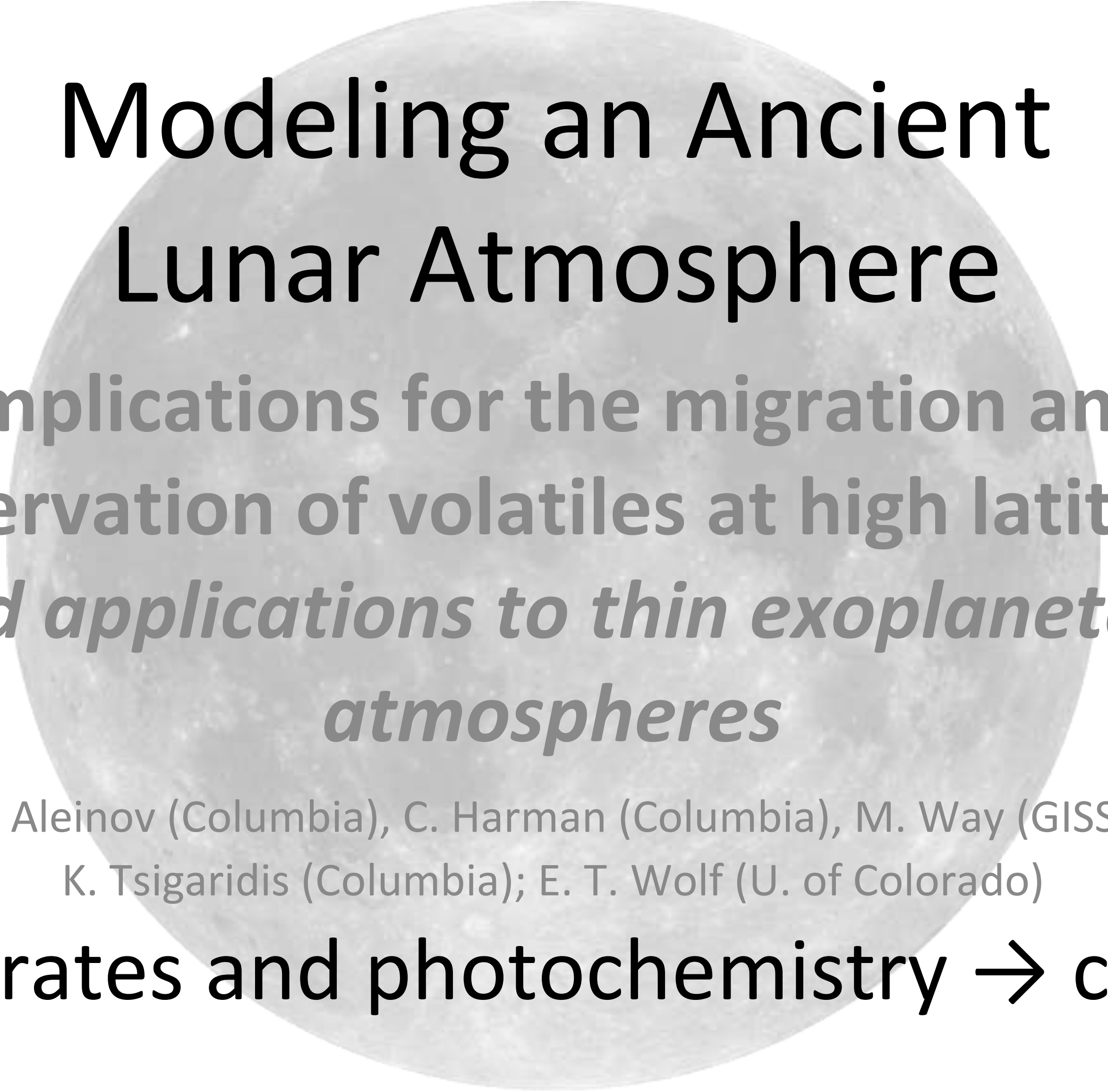
ROCKE-3D needs to be able to handle low -O_2 atmospheres if we want to model the Earth through most of its history, or exoplanets that don’t have life.

We could even model Titan, Venus, and exoplanets like them.

This type of flexibility will profoundly expand ROCKE-3D’s capabilities.



Way et al. (2017)

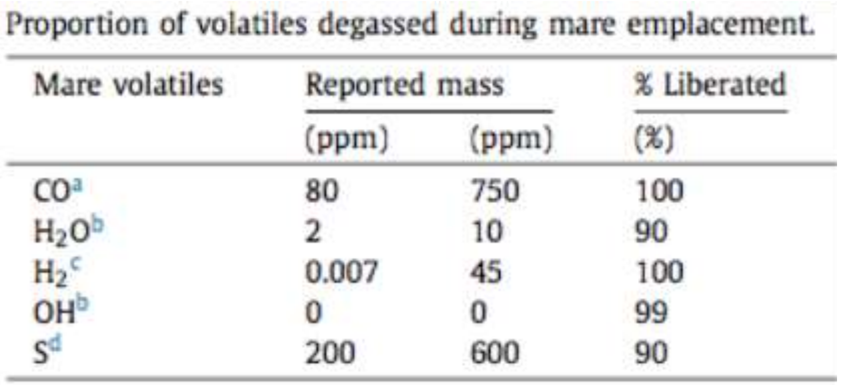


Modeling an Ancient Lunar Atmosphere

Implications for the migration and preservation of volatiles at high latitudes ***and applications to thin exoplanetary atmospheres***

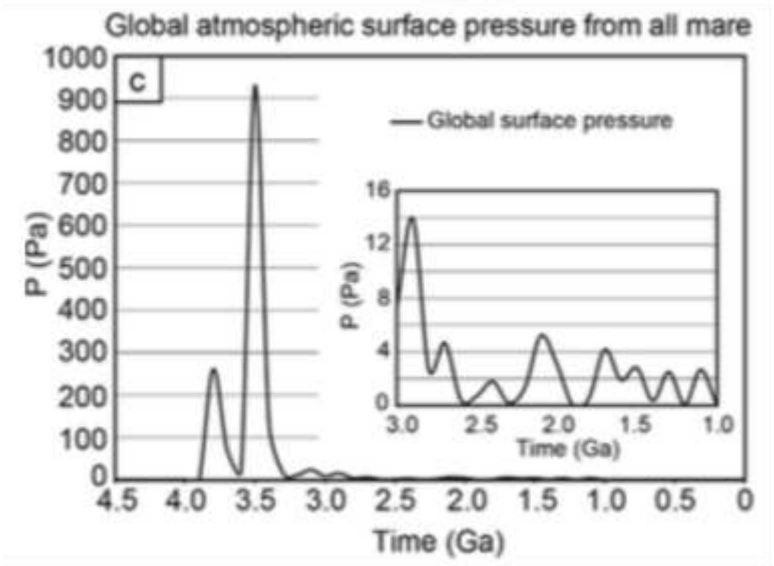
I. Aleinov (Columbia), C. Harman (Columbia), M. Way (GISS)
K. Tsigaridis (Columbia); E. T. Wolf (U. of Colorado)

Escape rates and photochemistry → climate!



Proportion of volatiles degassed during mare emplacement.

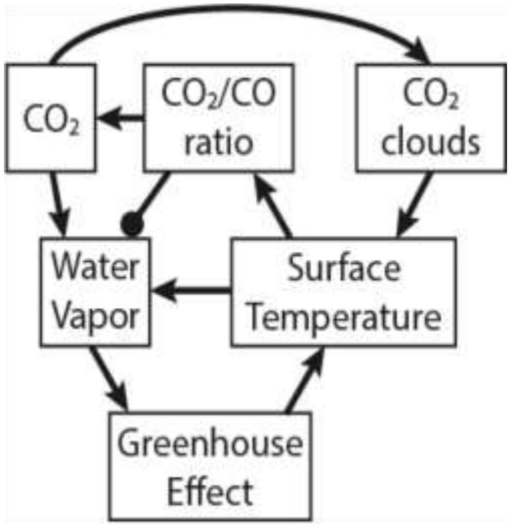
Mare volatiles	Reported mass		% Liberated
	(ppm)	(ppm)	(%)
CO^a	80	750	100
H_2O^b	2	10	90
H_2^c	0.007	45	100
OH^b	0	0	99
S^d	200	600	90



Needham & Kring, 2017

- Needham & Kring assume only escape due to solar wind (~<10 kg/s)
- Nature of escape sets composition? Other mechanisms at work?
- Main outgassed species: CO → CO_2? Photochemical conversion?

  (T-dependent)
- Potential for CO_2 clouds, condensation, dust storms.
- Other feedbacks?



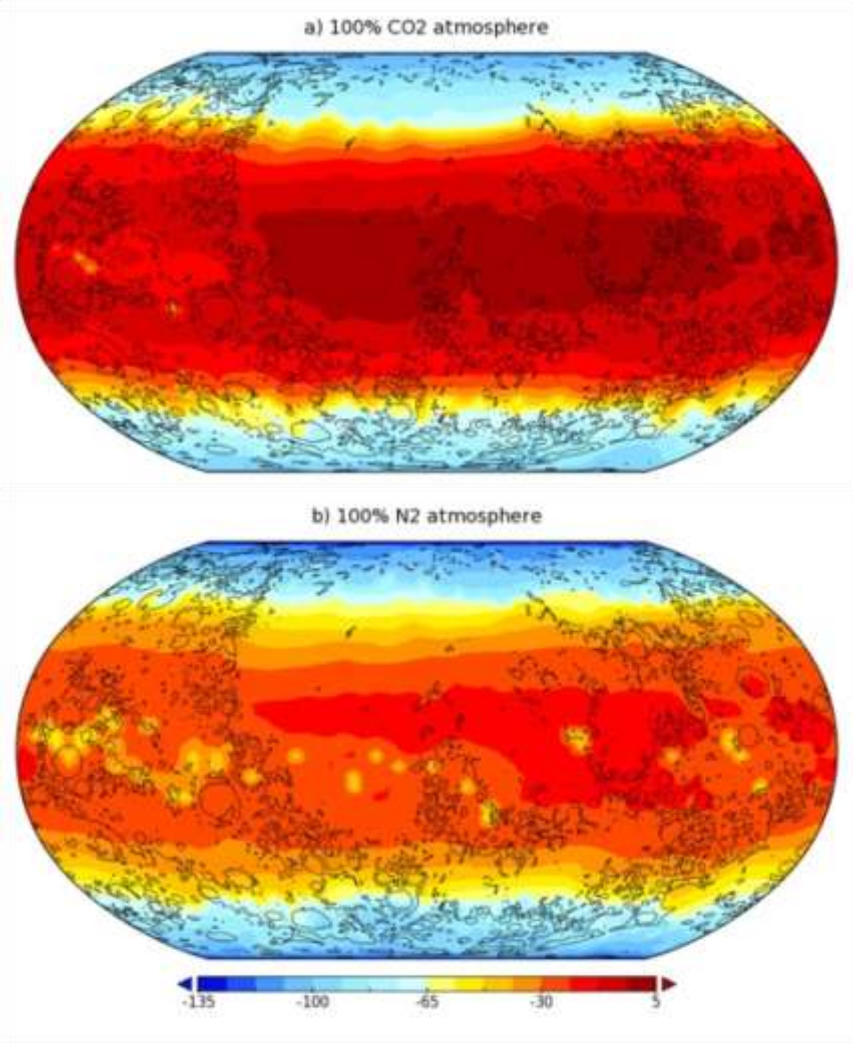
Initial estimates (limiting cases)

Radiatively active (CO_2) and inactive (N_2, ~CO), 3.5 Gya insolation and orbital parameters.

CO_2 atm ~14 K warmer globally than N_2/CO.
Min at poles: CO_2: -118 C, N_2: -134 C
Note: CO_2 condensation @ 10 mb ~ -122 C

Permanently shadowed areas (PSR) are likely to be much colder and may trap H_2O, CO_2 and other volatiles

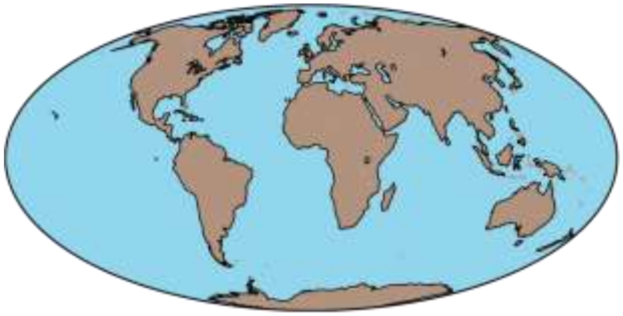
Direct application to thin atm. exoplanets and exomoons. We can provide observables via reflection and transmission spectra
(GISS & PSG)



Surface Air Temperature

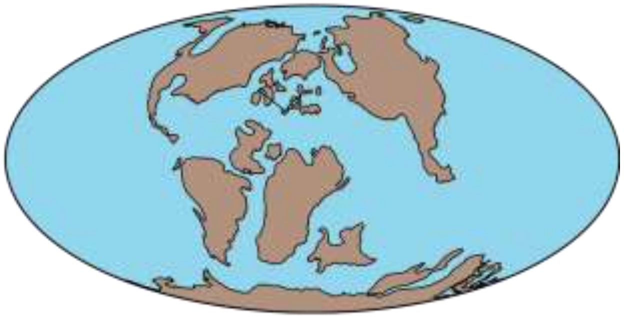
Paleo Earth Studies

Linda Sohl
Mark Chandler
Michael Way
Tony Del Genio



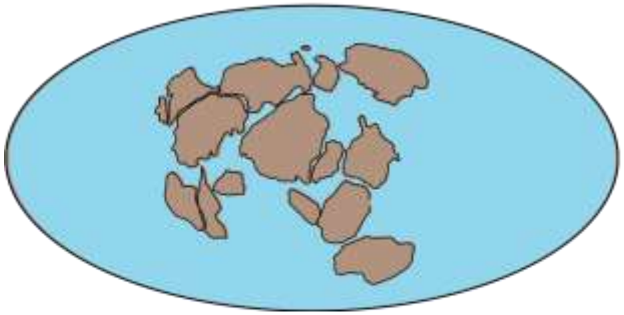
Modern

- Land area: 29.21%
- Land albedo: 20.2%
- Planetary albedo: 29.7%



Mid-Cretaceous (100Mya)

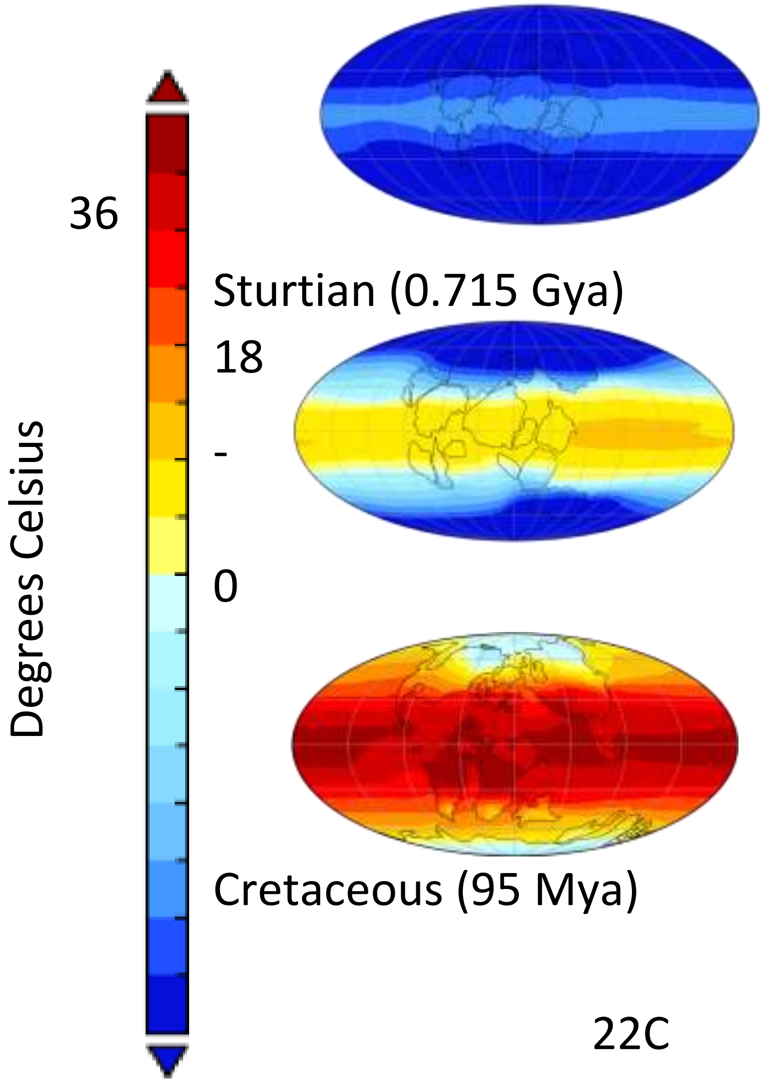
- Land area: 25.4%
- Land albedo: 11.2%
- Planetary albedo: 28.3%



	Sturtian	**Huronian**
• Land area:	19.1%	19.1%
• Land albedo:	39.6%	48.5%
• Planetary albedo:	37.2%	49.5%

SURFACE TEMPERATURE

Huronian (2.1 Gya)



-43C

Sturtian (0.715 Gya)

13C

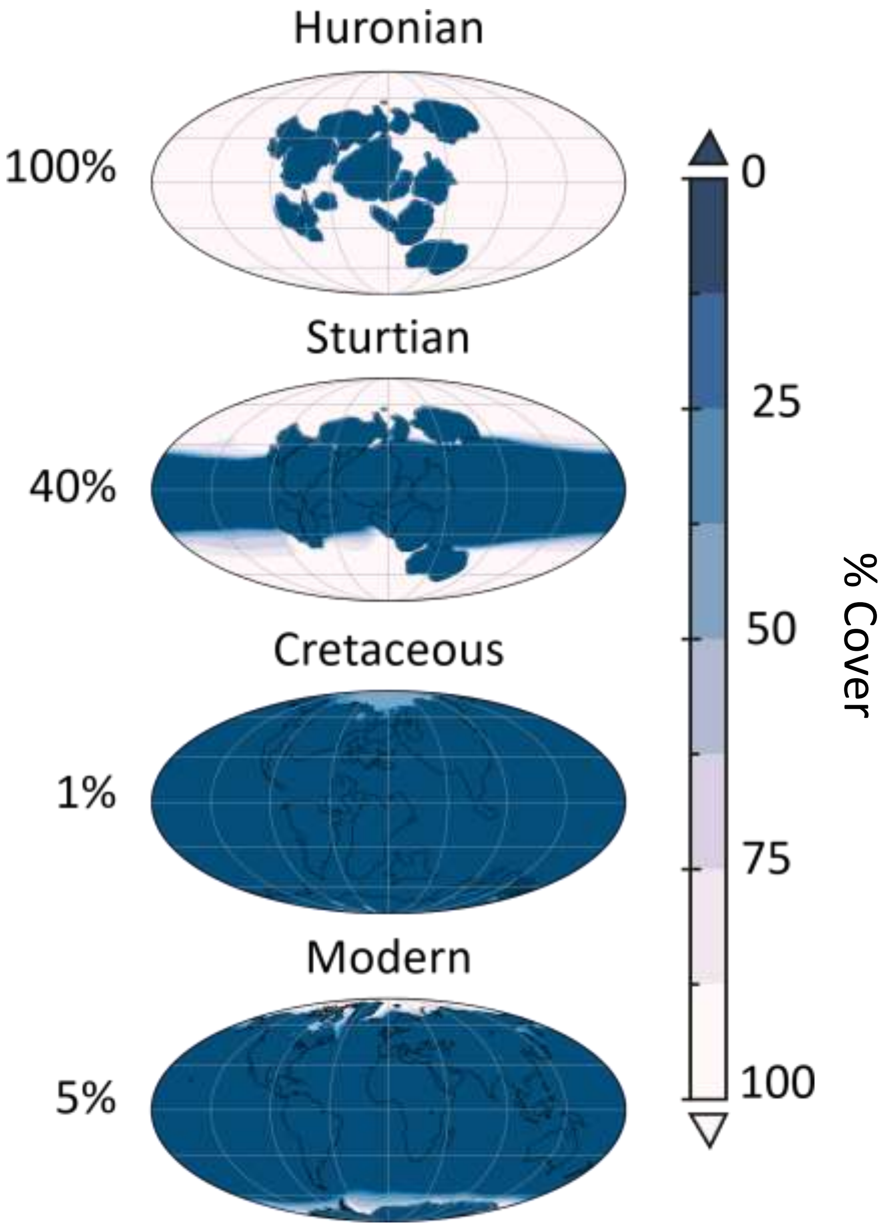
Cretaceous (95 Mya)

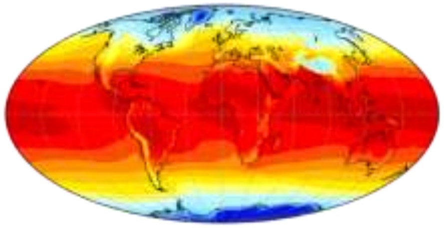
22C

- 18

Modern

OCEAN ICE COVER





-36

14C

(Sohl, Chandler, Jonas)

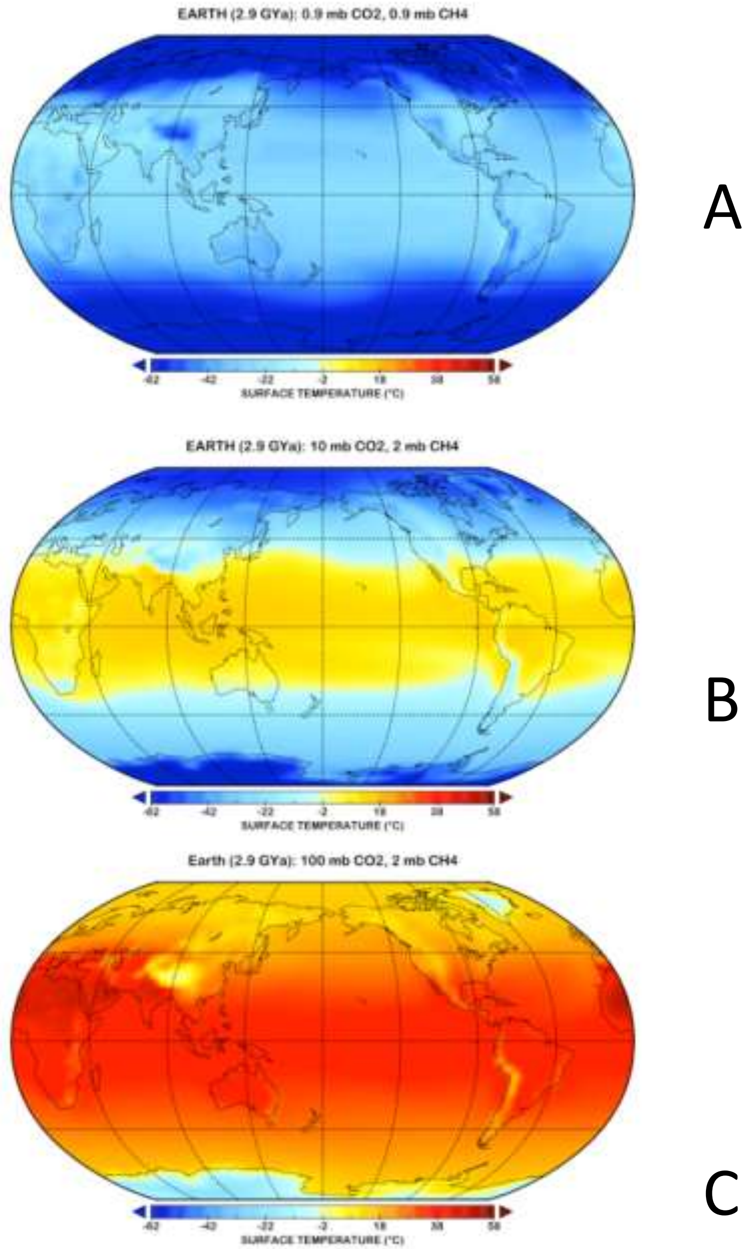
ARCHEAN EARTH SIMULATIONS 2.9 Gya

Del Genio, Brain, Noack, Schaefer 2018,

Planet. Astrobio. Book)

Compositions taken from Charnay et al. (2013) cases A, B, C

Hot Archean Earth scenario(Case C) consistent with results of coupled carbon-climate models (Charnay et al., 2017; Krissansen-Totten et al., 2018) but difficult to reconcile with



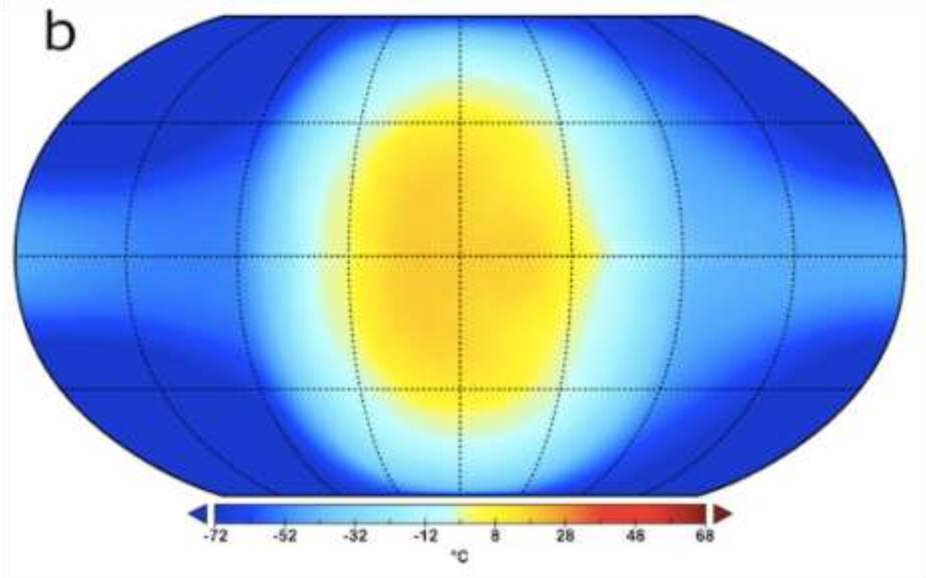
CH_4 destruction in GOE as
initiator of
Huronian snowball

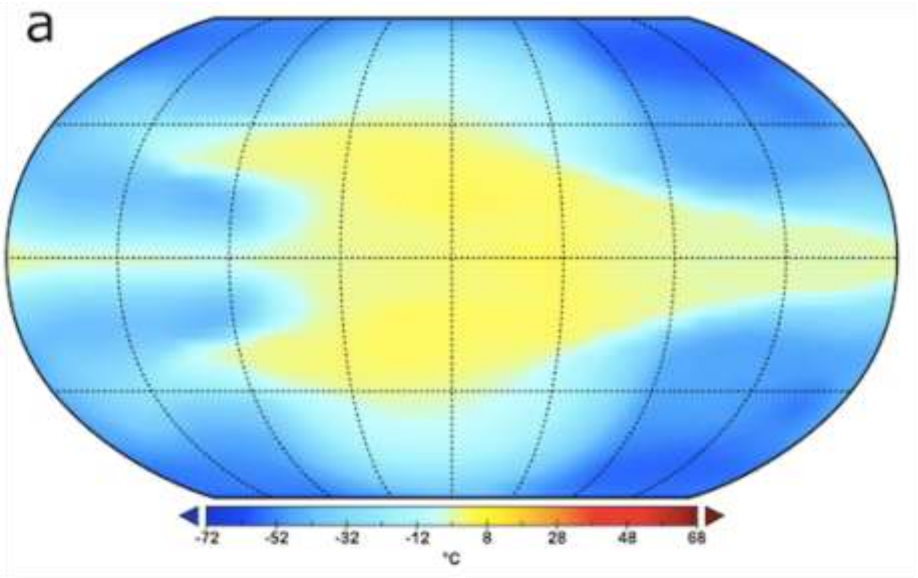
POSSIBLE PROXIMA CENTAURI B CLIMATES

(Del Genio, Way, Amundsen, Aleinov, Kiang... 2018, *Astrobio.*, in press)

Earthlike atmosphere, static ocean

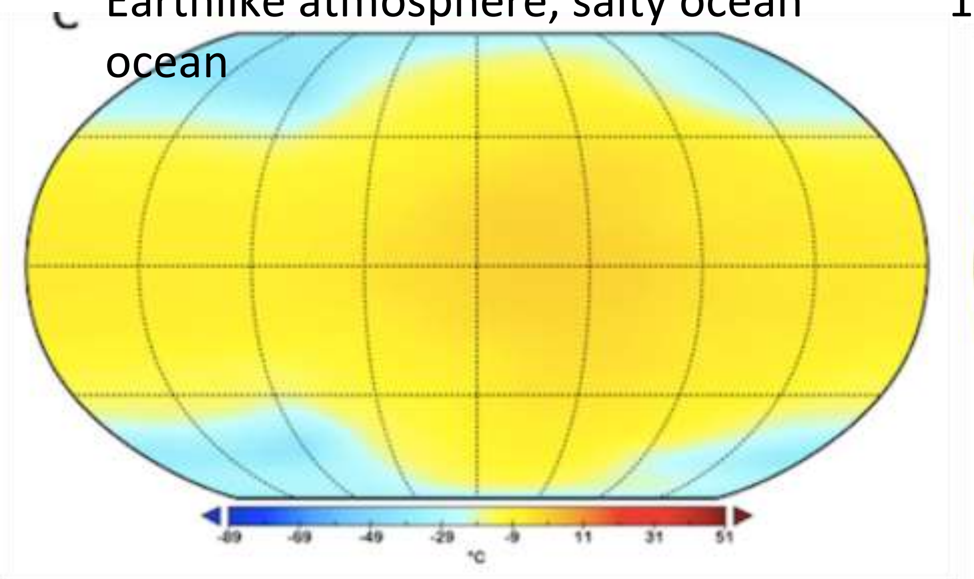
Earthlike atmosphere, dynamic ocean

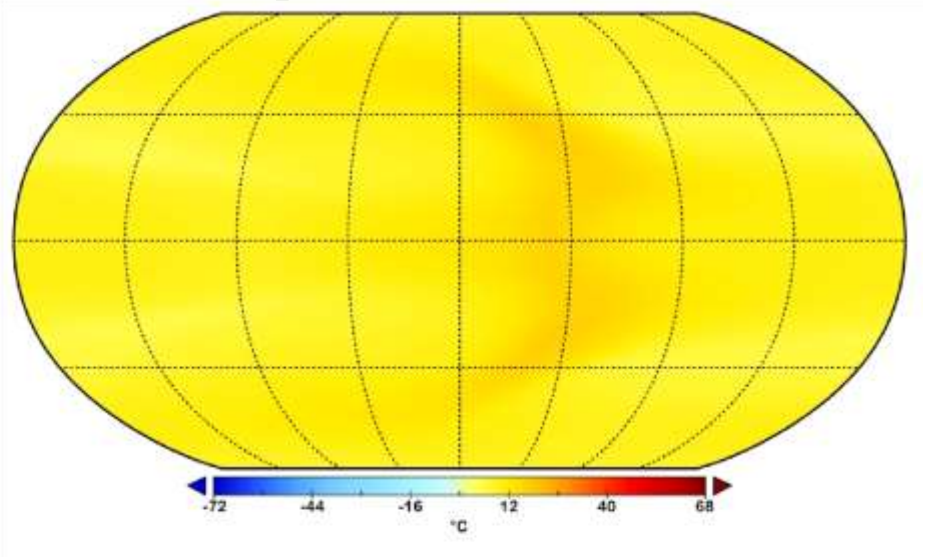




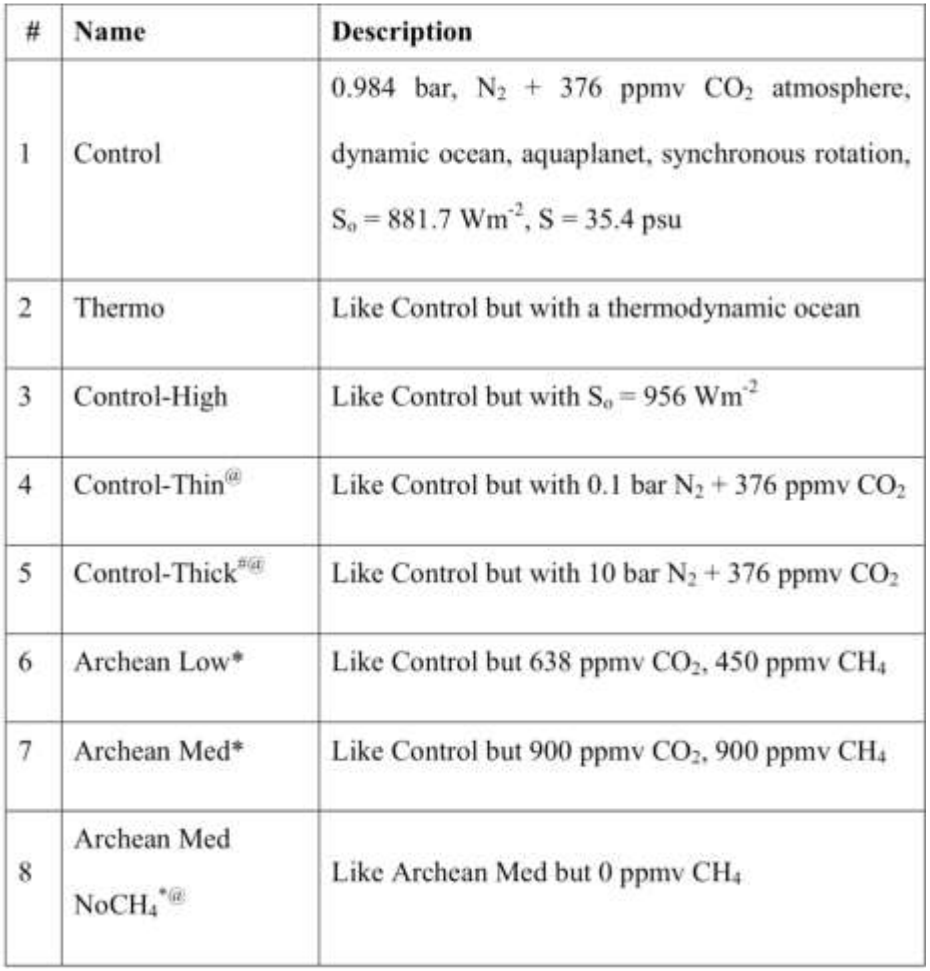
Earthlike atmosphere, salty ocean ocean

1 bar pure CO_2 atmosphere, dynamic





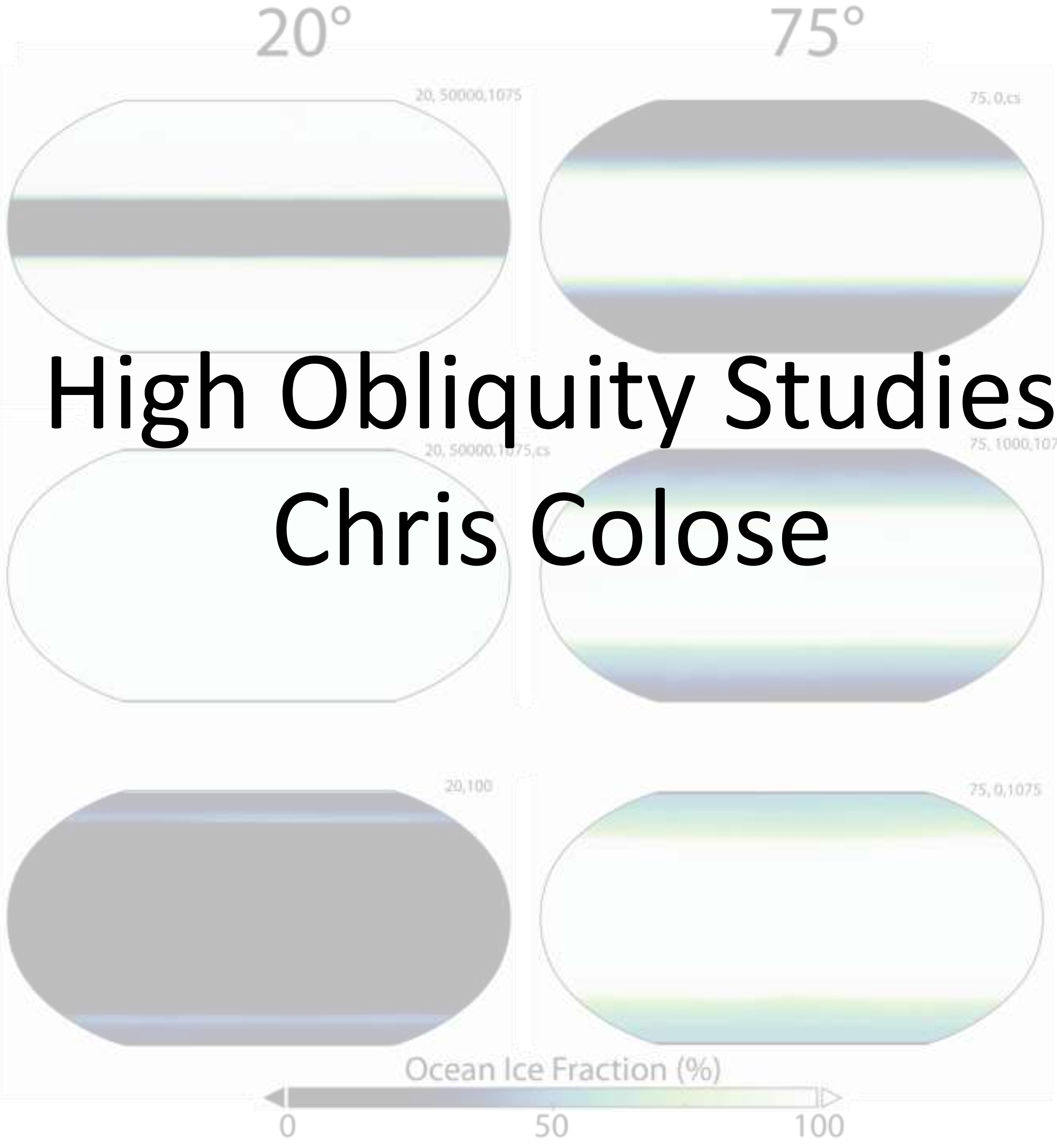
Proxima Centauri b – List of Simulations

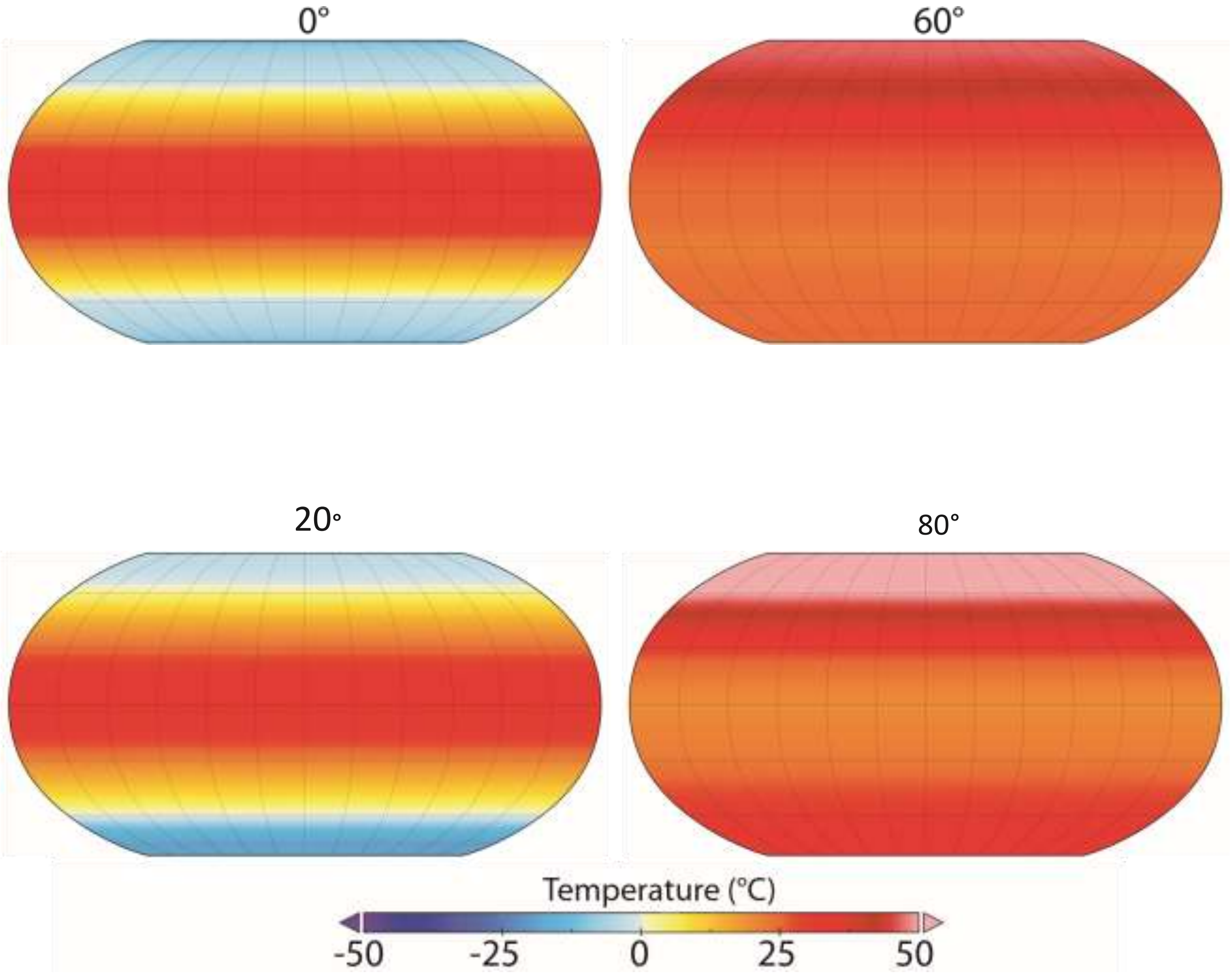


#	Name	Description
1	Control	0.984 bar, N_2 + 376 ppmv CO_2 atmosphere, dynamic ocean, aquaplanet, synchronous rotation, $S_o = 881.7\ Wm^{-2}$, $S = 35.4$ psu
2	Thermo	Like Control but with a thermodynamic ocean
3	Control-High	Like Control but with $S_o = 956\ Wm^{-2}$
4	Control-Thin$^{@}$	Like Control but with 0.1 bar N_2 + 376 ppmv CO_2
5	Control-Thick$^{\#@}$	Like Control but with 10 bar N_2 + 376 ppmv CO_2
6	Archean Low*	Like Control but 638 ppmv CO_2, 450 ppmv CH_4
7	Archean Med*	Like Control but 900 ppmv CO_2, 900 ppmv CH_4
8	Archean Med NoCH$_4^{*@}$	Like Archean Med but 0 ppmv CH_4
9	Archean High*	Like Control but 10000 ppmv CO_2, 2000 ppmv CH_4
10	Pure $CO_2^{+@}$	Like Control but 0.984 bar pure CO_2 atmosphere
11	Control-Shallow$^{@}$	Like Control but with a 158 m depth ocean
12	Control-Deep$^{@}$	Like Control but with a 2052 m depth ocean
13	Zero Salinity	Like Control but S = 0 psu
14	High Salinity	Like Control but S = 230 psu
15	3:2e0	Like Control but in 3:2 resonance with e=0
16	3:2e30	Like Control but in 3:2 resonance with e=0.30
17	Day-Ocean	Like Control but with Earth land-ocean distribution and substellar point over Pacific
18	Day-Land	Like Day-Ocean but substellar point over Africa

High Obliquity Studies

Chris Colose





JJA Aquaplanet Temperature

- ➢High obliquity increases global temperature despite a globally conservative redistribution of sunlight . This is related to low cloud reduction at high latitudes & reduced planetary albedo

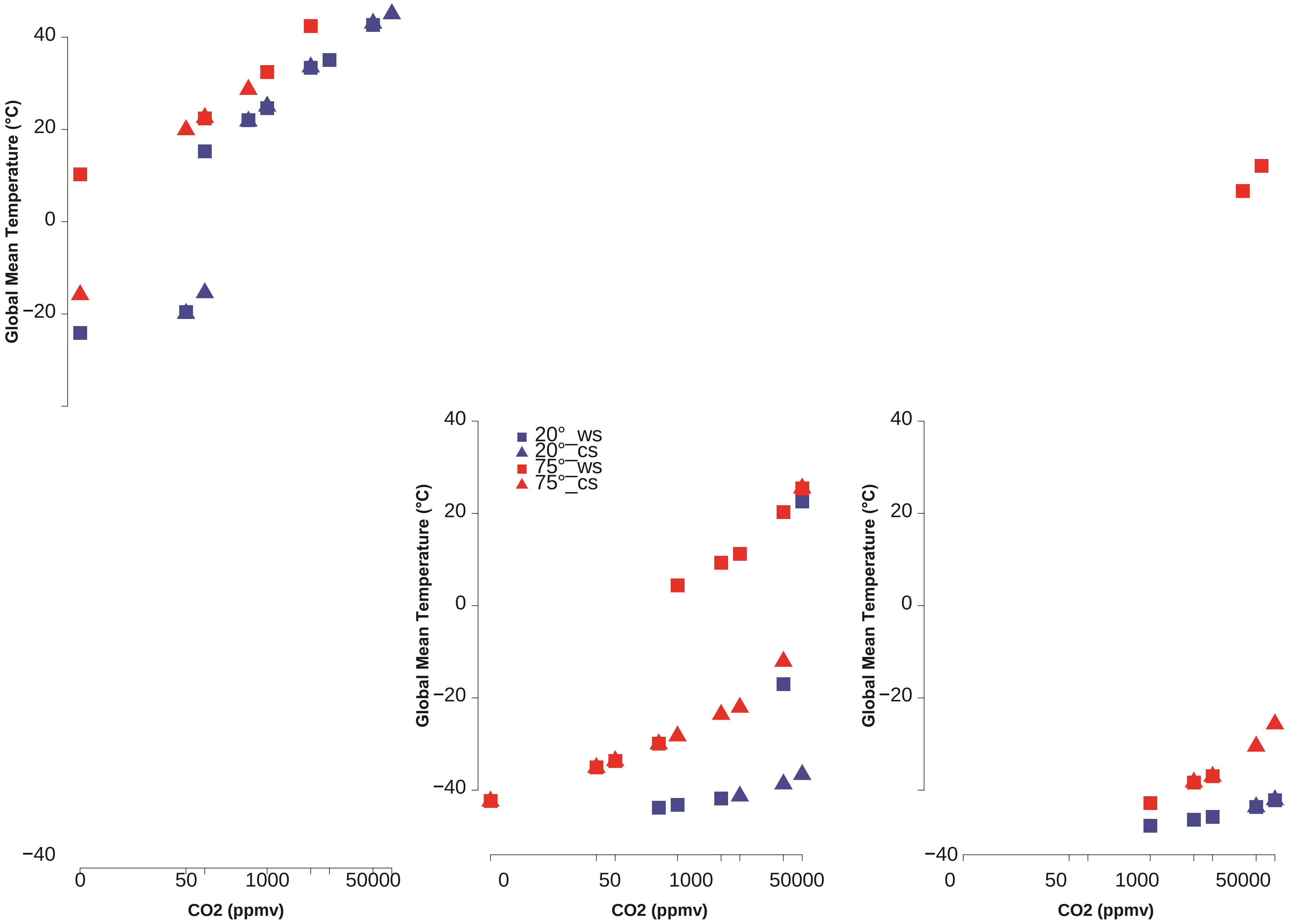
- ➢High latitude winters remain very warm at high obliquity due to ocean heat storage (see also Ferreria et al., 2014)

Hysteresis at Low & High Obliquity

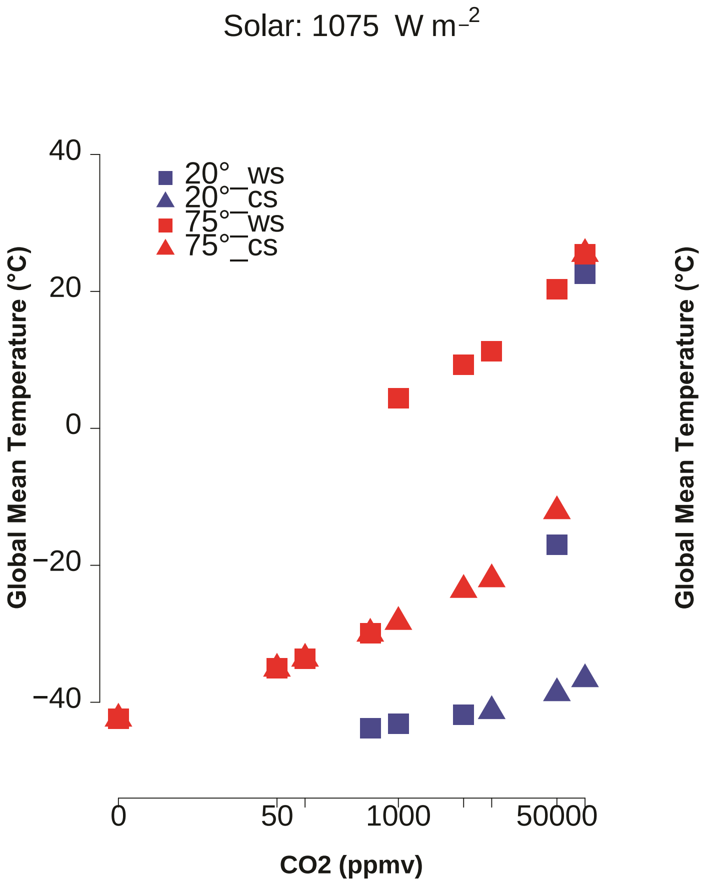
Solar: 1360 W m^{-2}

Solar: 1075 W m^{-2}

Solar: 950 W m^{-2}


Global Mean Temperature (°C)
40
20
0
−20
−40
0
50
1000
50000
CO2 (ppmv)
■ 20°_ws
▲ 20°_cs
■ 75°_ws
▲ 75°_cs
Global Mean Temperature (°C)
40
20
0
−20
−40
0
50
1000
50000
CO2 (ppmv)
Global Mean Temperature (°C)
40
20
0
−20
−40
0
50
1000
50000
CO2 (ppmv)

Hysteresis at Low & High Obliquity



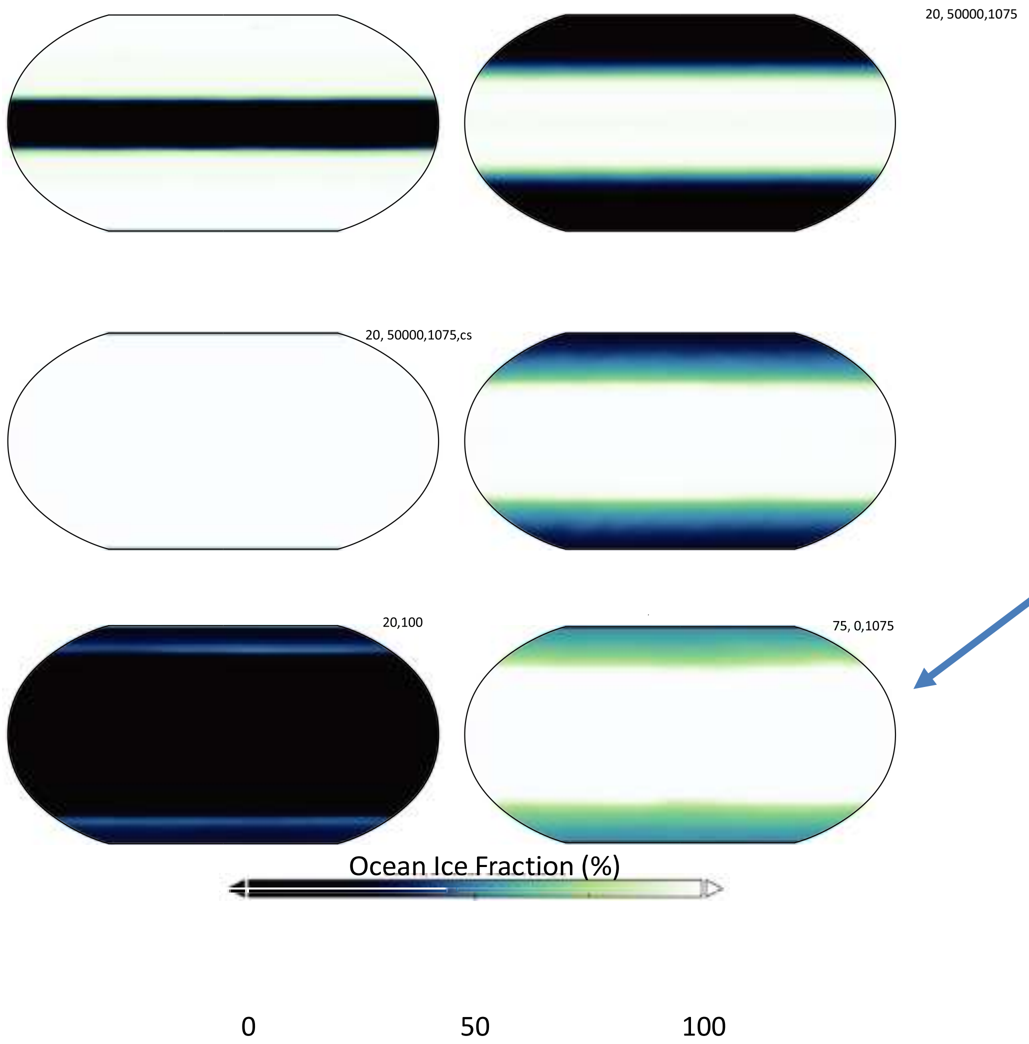
- High obliquity planets are systematically warmer than their low obliquity counterparts.

- High obliquity bistability between 1000 to 50,000 ppm CO2

- “Warm” global temperatures and local or global ice-free conditions are achieved at much lower CO2 concentrations at high obliquity.

Example Cryospheres

20° 75°



- Possible states include equatorial waterbelts (low obliquity) and equatorial icebelts (high obliquity) with varying degrees of polar or equatorial ice.

- Global temperatures below -40 C still have some liquid water.

White is ice, blue open water

How Studies of Ancient Earth may inform Studies of Ancient Venus:

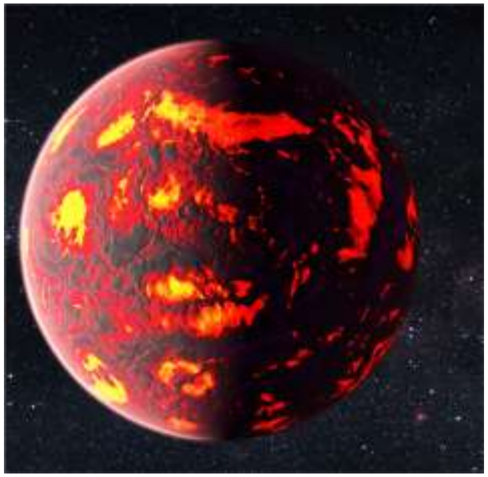
Venus’ evolutionary history & how it might inform Venus-like worlds & vice versa

From Magma Ocean -> first stable climate -> Today

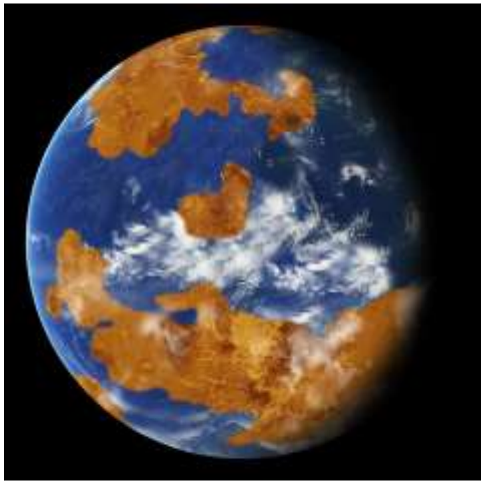
3-4 Gya ~1 bar ~**15 C**

N_2/CO_2 (CH_4)

Earth & Venus



4.5Gya



3-4 Gya ~1 bar? ~**15 C**
N_2/CO_2

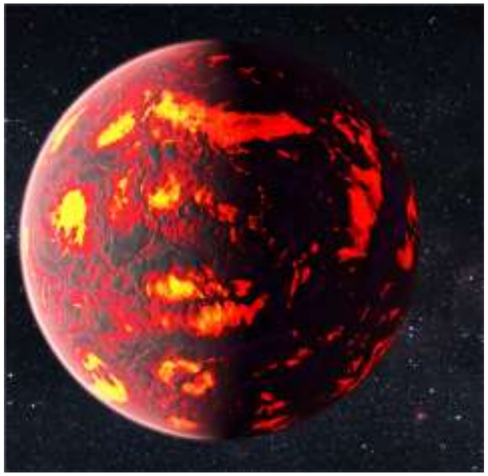
Today 92 bar **450 C**
CO_2/N_2

3-4 Gya ~1 bar ~**15 C**
N_2/CO_2 (CH_4)

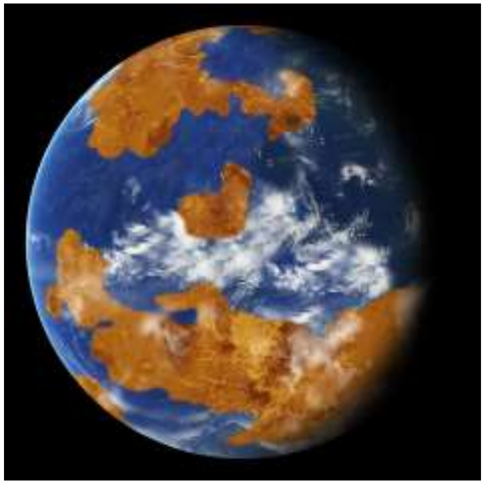
Today 1 bar ~**15 C**
$N_2/O_2/CO_2/CH_4$

From Magma Ocean World -> the first stable climate?

Earth & Venus



4.5Gya



3-4 Gya ~1 bar? ~**15 C**
N_2/CO_2

Lack of Primordial water?
~100Mya Magma Ocean
Hamano et al.
Chassiefiere, Gillman. Kislyakova

Replenished via LHB/Late Veneer?
Greenwood et al. 2018

3-4 Gya ~1 bar ~**15 C**
N_2/CO_2 (CH_4)

Primordial water remains
1My Magma Ocean

LHB/Late Veneer
contributed 5-30%
Greenwood et al. 2018

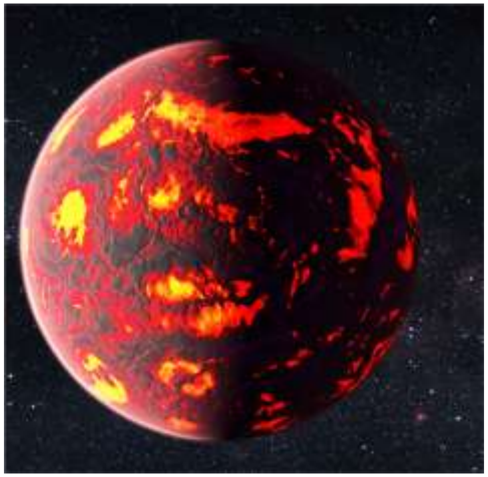
FYSP?

From Magma Ocean -> first stable climate -> Today

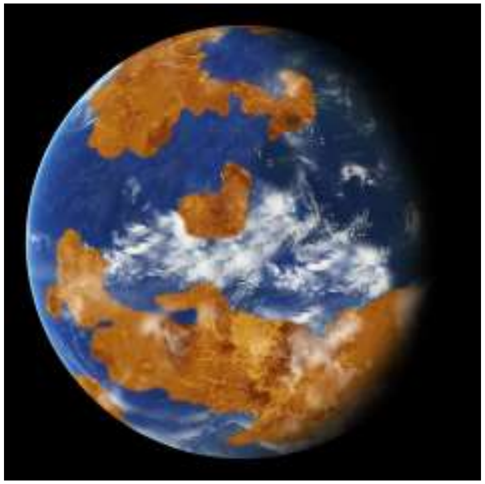
3-4 Gya ~1 bar ~**15 C**

N_2/CO_2 (CH_4)

Earth & Venus



4.5Gya



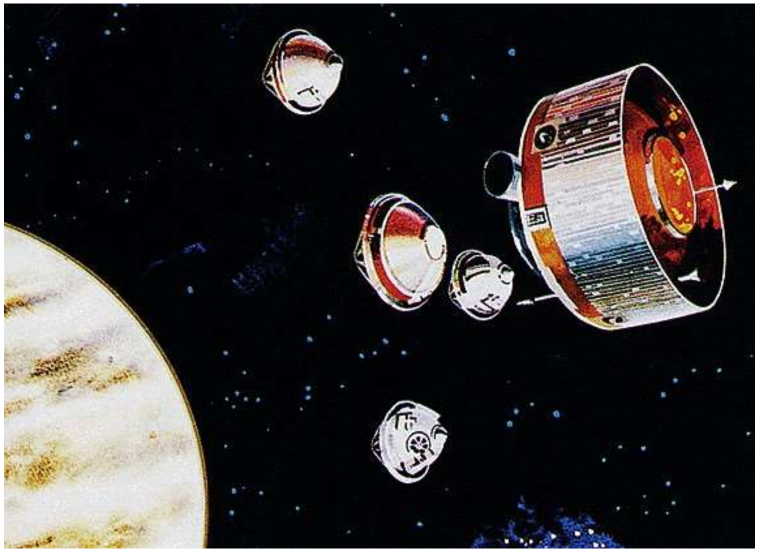
3-4 Gya ~1 bar? ~**15 C**
N_2/CO_2

Today 92 bar **450 C**
CO_2/N_2

3-4 Gya ~1 bar ~**15 C**
N_2/CO_2 (CH_4)

Today 1 bar ~**15 C**
$N_2/O_2/CO_2/CH_4$

Pioneer Venus, ALMA, SOFIA



- Water abundance:
  - High D/H ~150 x terrestrial
  - Received similar H_2O as Earth
  - Primordial abundance?
  - And/or LHB/Late Veneer
    - Greenwood et al. 2018: Earth received 5-30% of its water in late Veneer

○Timescale of H_2O loss unknown ○ Cannot constrain **Early** Dry or Wet: Need DATA! ○Will ALMA, SOFIA or future Earth-based obs ever help us?

ROCKE-3D: 3-D General Circulation Model

- Resolution 4x5˚ lat x lon, 40L atmos, 13L ocean
- Radius/Mass: Modern Venus • **Spin & Obliquity: Modern**
- Atmospheres **1bar**:
  - CO_2 (100%) @ 2.9Gya

- $N_2 + CO_2$ (400ppmv) + CH4 (1ppmv) @ Today

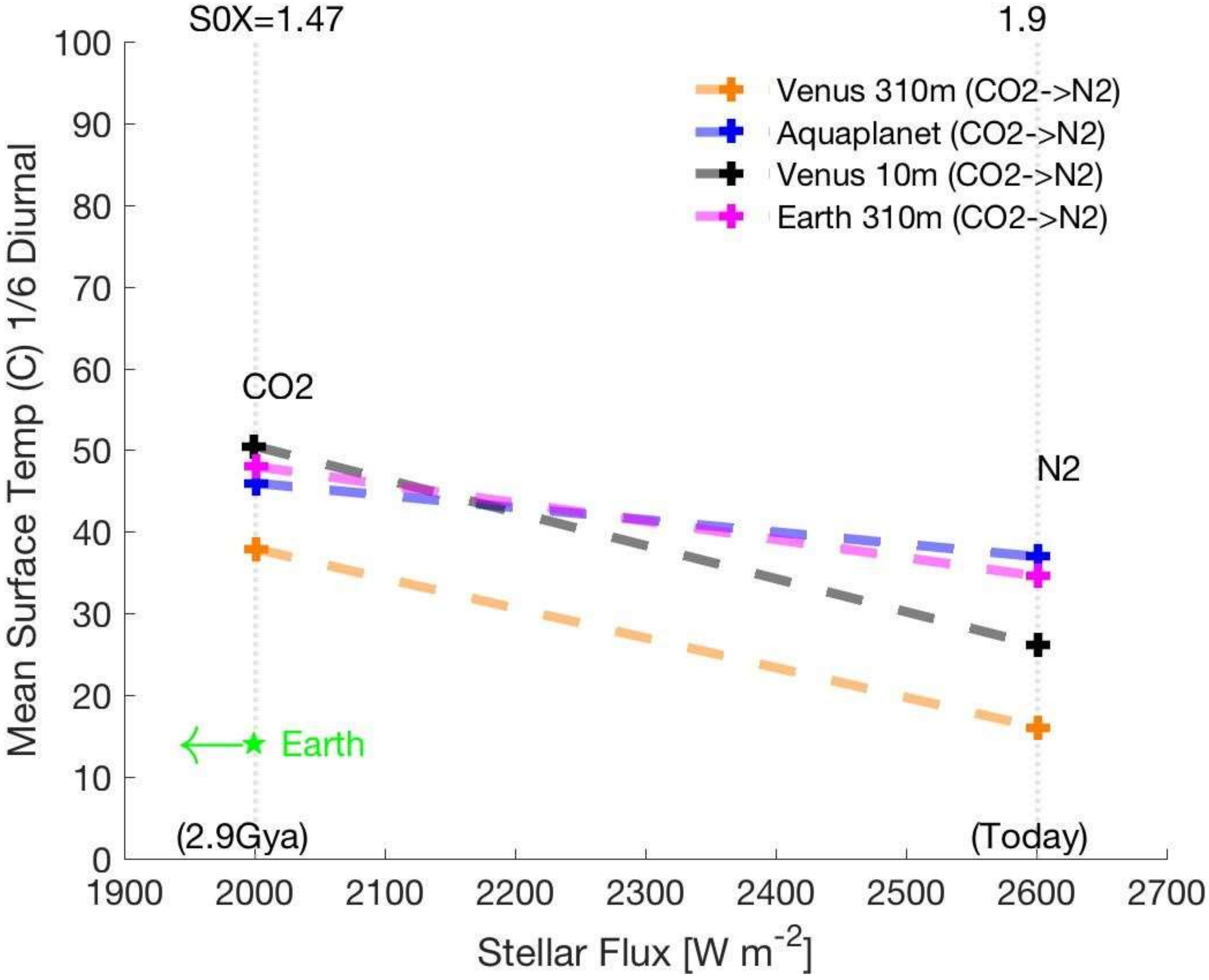
- Incident Flux: 2.9Gya → Present-Day:

  1.46 → 1.9 Earth today

- Topography/Ocean
  1. Mean Radius: above land, below ocean (310m)
  2. 10m equivalent (Dune like land planet)
  3. Earth: Modern Topography
  4. Aquaplanet

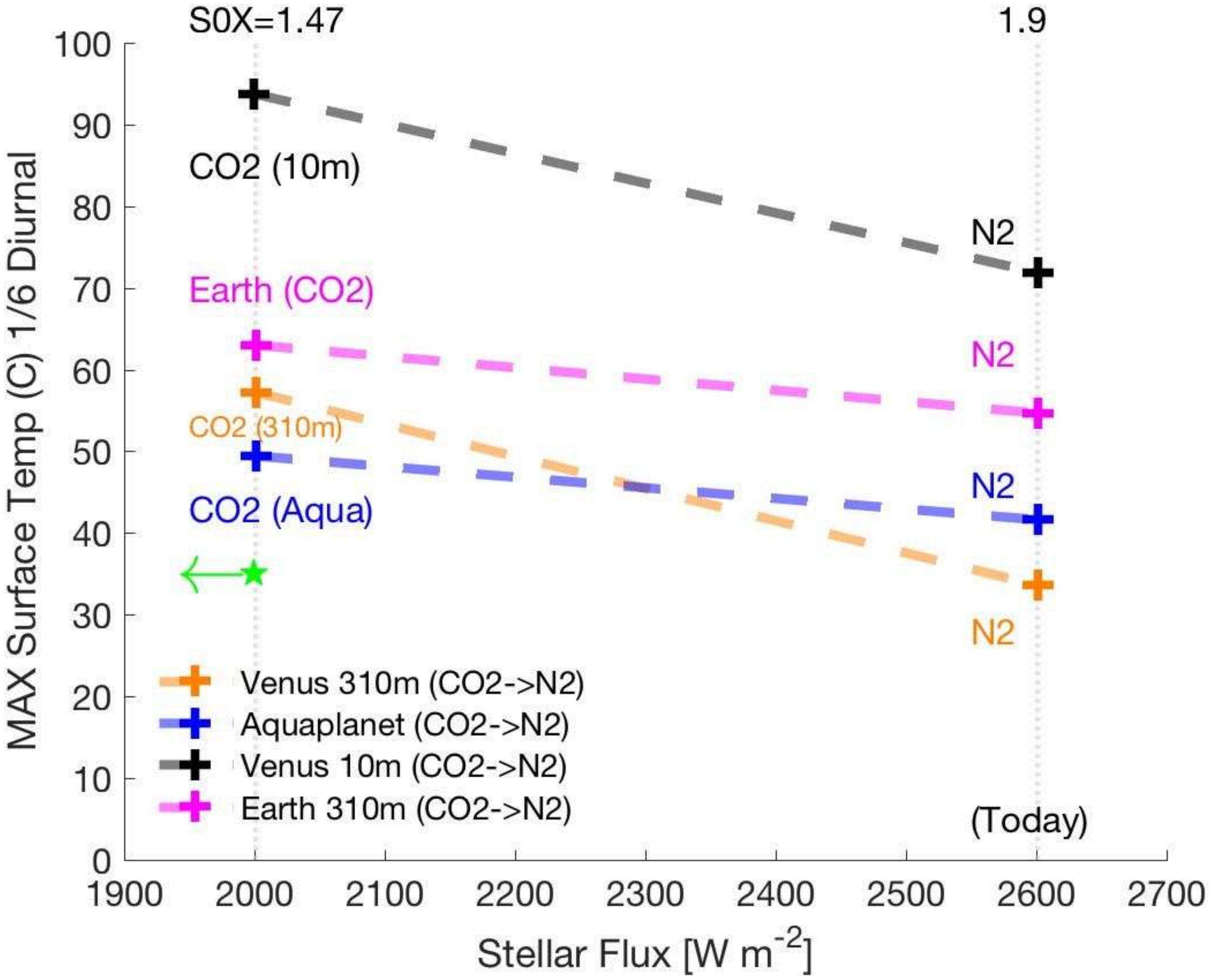
Mean Global Surface Temperature

CO_2 dominated to N_2 dominated



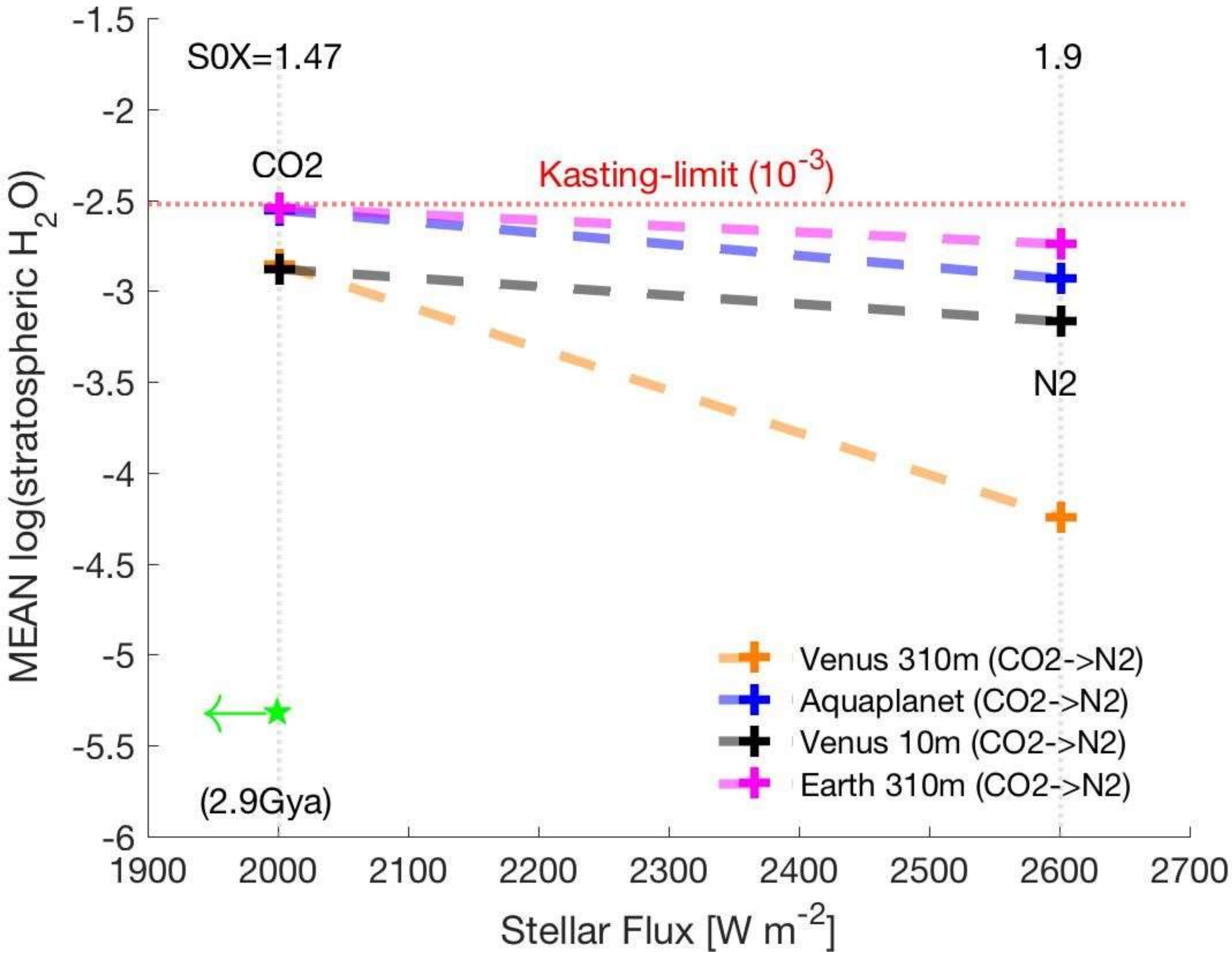
S0X=1.47
1.9
Venus 310m (CO2->N2)
Aquaplanet (CO2->N2)
Venus 10m (CO2->N2)
Earth 310m (CO2->N2)
CO2
N2
Earth
(2.9Gya)
(Today)
Mean Surface Temp (C) 1/6 Diurnal
100
90
80
70
60
50
40
30
20
10
0
1900
2000
2100
2200
2300
2400
2500
2600
2700
Stellar Flux [W m^-2]

Maximum Global Surface Temperature



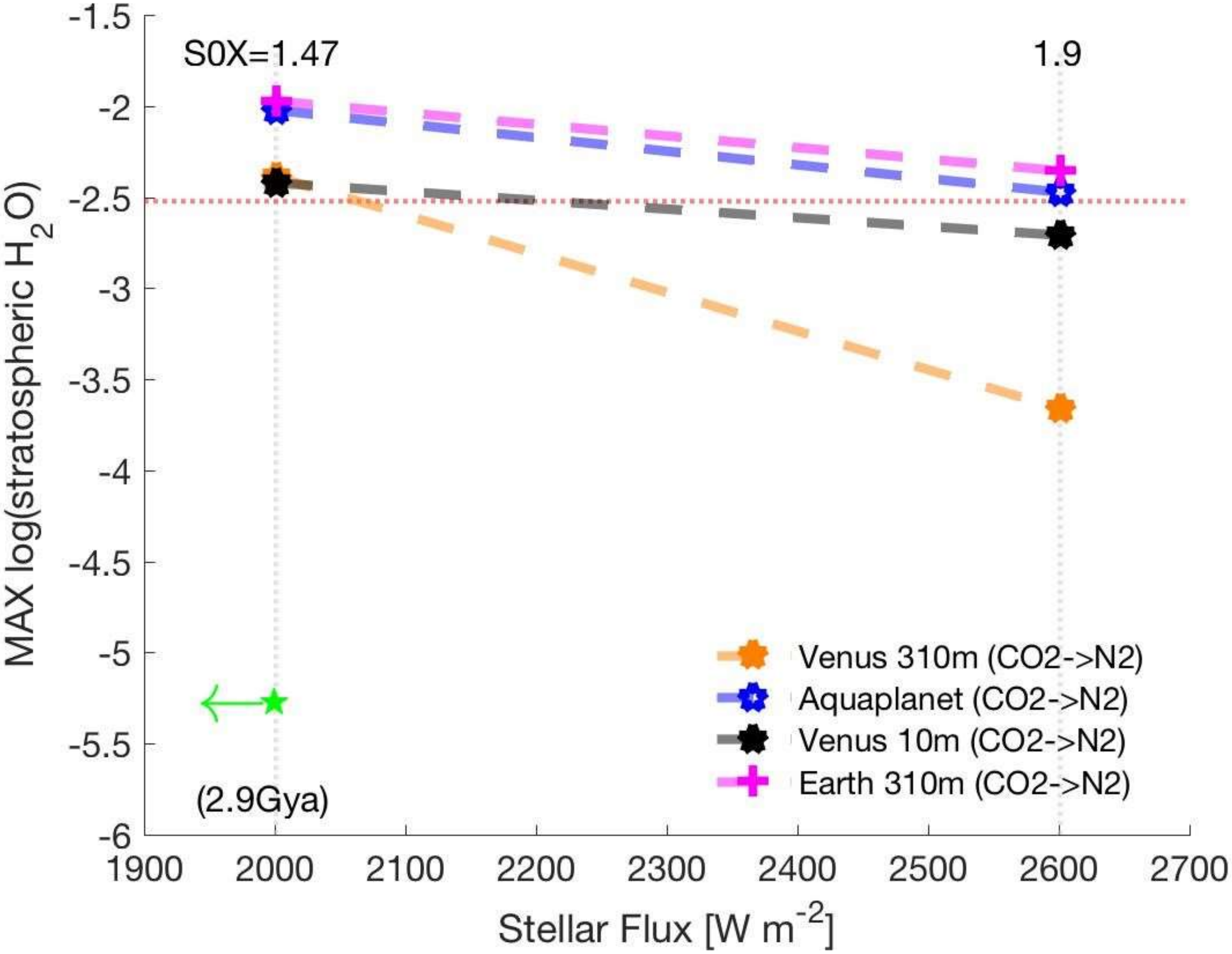
Water Loss: Kasting Limit

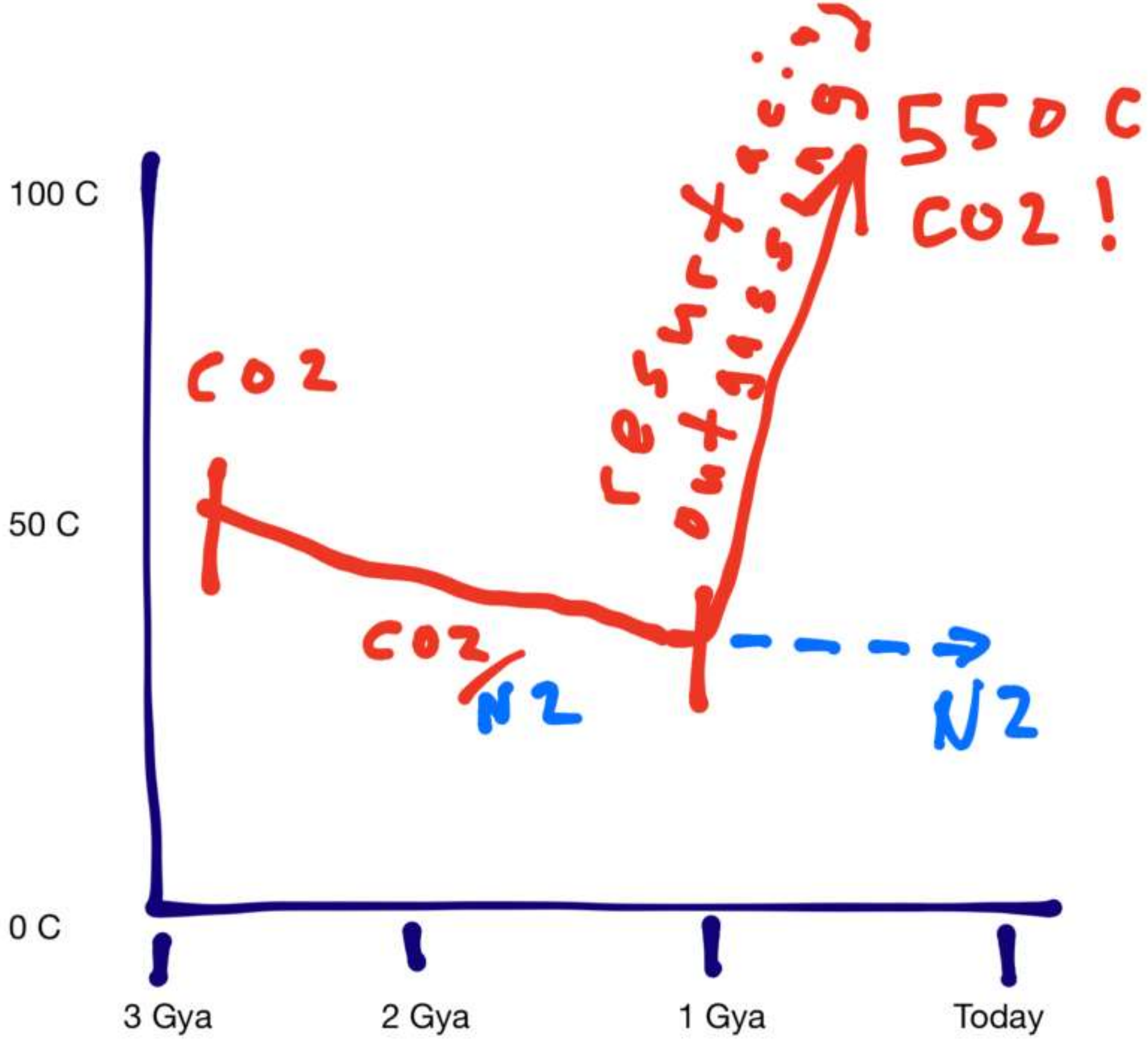
If mixing ratio of H_2O reaches ~0.1%



Maximum Water Loss: Kasting Limit

If mixing ratio of H_2O reaches ~0.1%

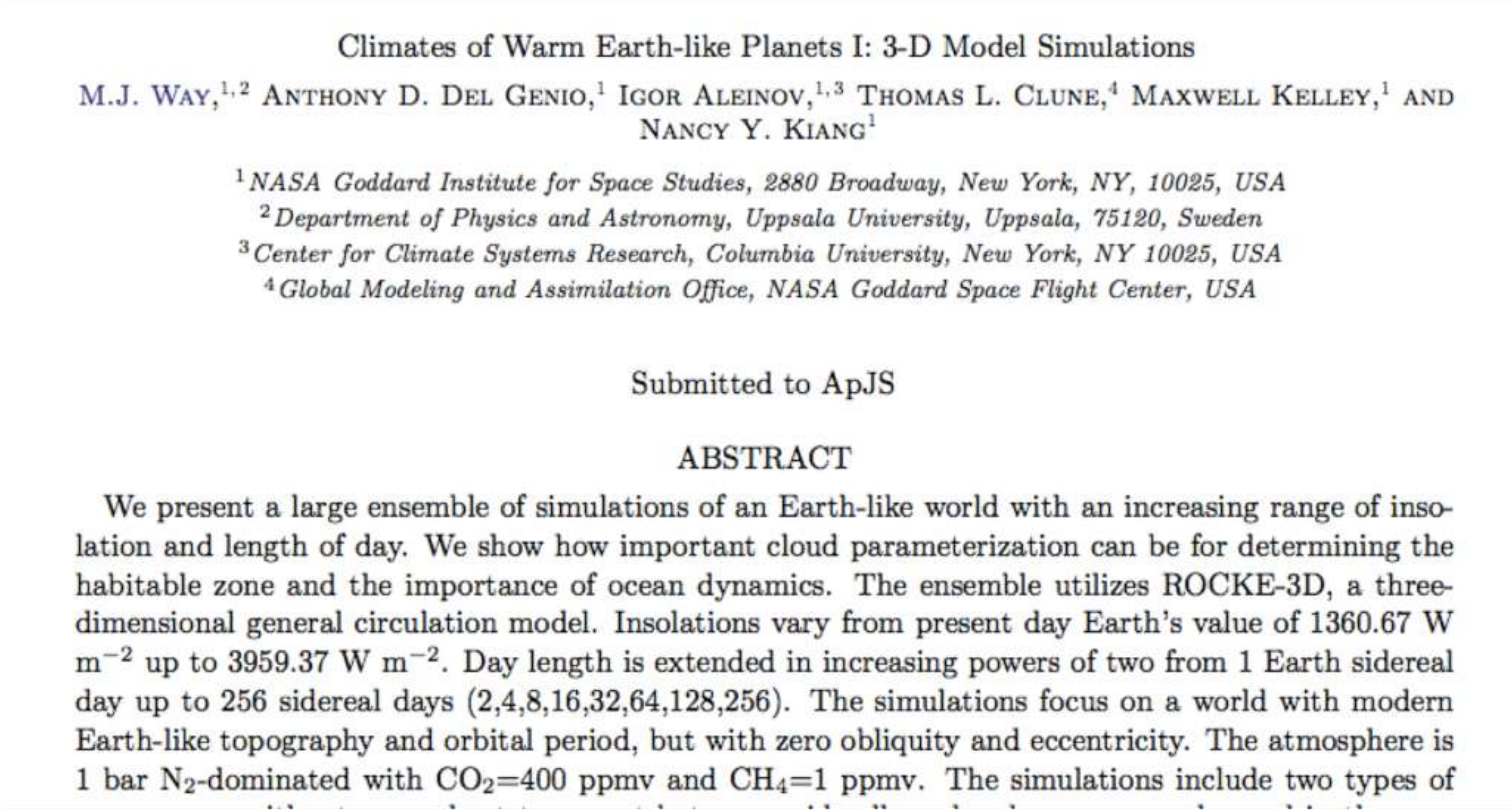



100 C
50 C
0 C
3 Gya
2 Gya
1 Gya
Today
CO2
CO2/N2
resurface
outgassing
550 C
CO2 !
N2

Conclusions

- If Venus had surface liquid water after formation/cool-down **it is not clear that solar luminosity is defining factor in its climate evol.**
- Venus-like exoplanet habitability estimates may require rotation rate knowledge
- More parameter space needs to be mapped
- Need new Venus in-situ observations to confirm its geologic & volatile history
- Exoplanets will inform Venus' climatic history and possibly vice-versa (if we ever get data!)

Further Propaganda found on arXiv.org



Climates of Warm Earth-like Planets I: 3-D Model Simulations

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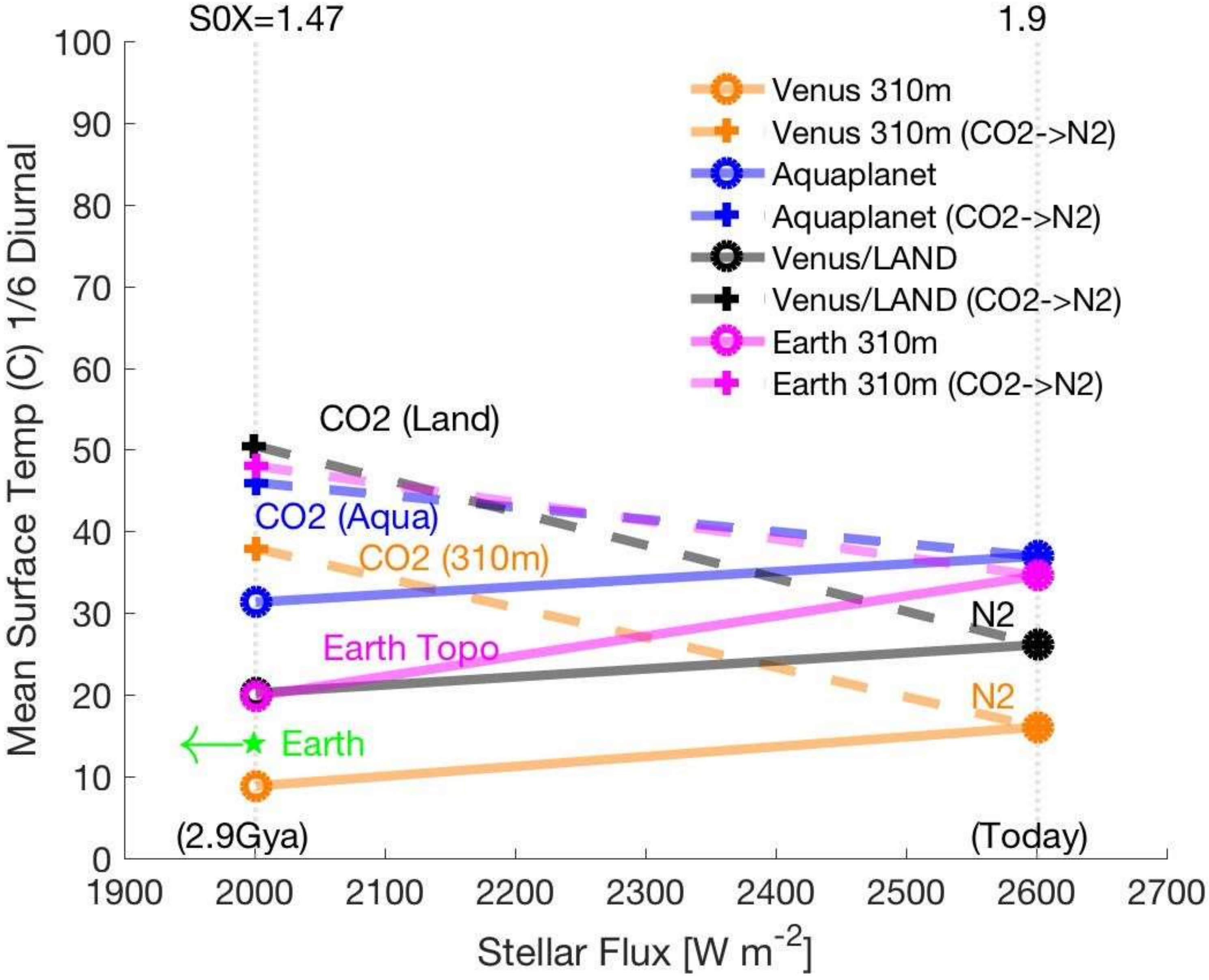
ABSTRACT

We present a large ensemble of simulations of an Earth-like world with an increasing range of insolation and length of day. We show how important cloud parameterization can be for determining the habitable zone and the importance of ocean dynamics. The ensemble utilizes ROCKE-3D, a three-dimensional general circulation model. Insolations vary from present day Earth's value of 1360.67 W m^{-2} up to 3959.37 W m^{-2}. Day length is extended in increasing powers of two from 1 Earth sidereal day up to 256 sidereal days (2,4,8,16,32,64,128,256). The simulations focus on a world with modern Earth-like topography and orbital period, but with zero obliquity and eccentricity. The atmosphere is 1 bar N_2-dominated with CO_2=400 ppmv and CH_4=1 ppmv. The simulations include two types of

Mean Global Surface Temperature


S0X=1.47
1.9
Mean Surface Temp (C) 1/6 Diurnal
100
90
80
70
60
50
40
30
20
10
0
Venus 310m
Venus 310m (CO2->N2)
Aquaplanet
Aquaplanet (CO2->N2)
Venus/LAND
Venus/LAND (CO2->N2)
Earth 310m
Earth 310m (CO2->N2)
CO2 (Land)
CO2 (Aqua)
CO2 (310m)
N2
Earth Topo
N2
Earth
(2.9Gya)
(Today)
1900
2000
2100
2200
2300
2400
2500
2600
2700
Stellar Flux [W m-2]