Exotic Climates on Exoplanets

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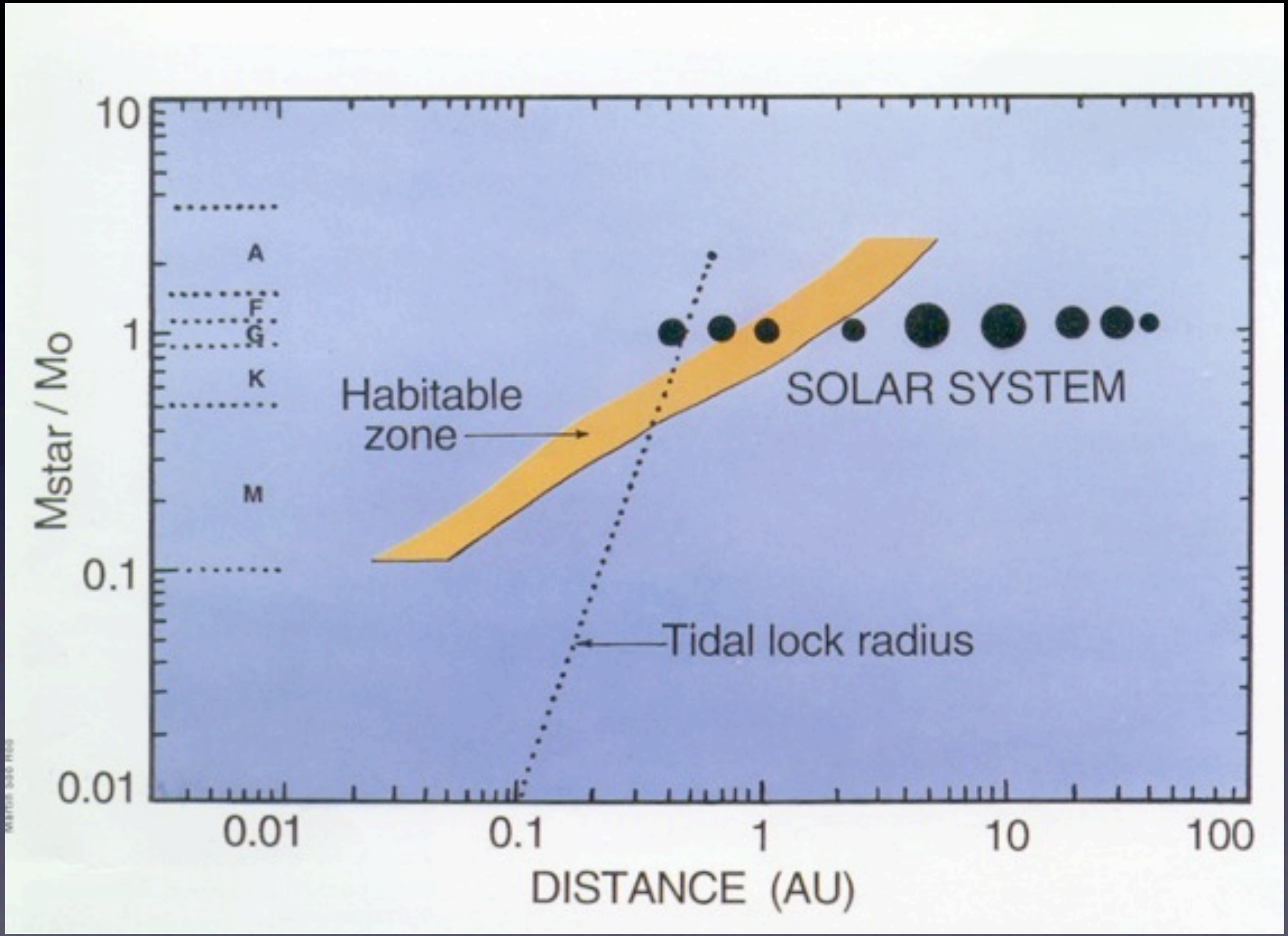
Planetary Habitability



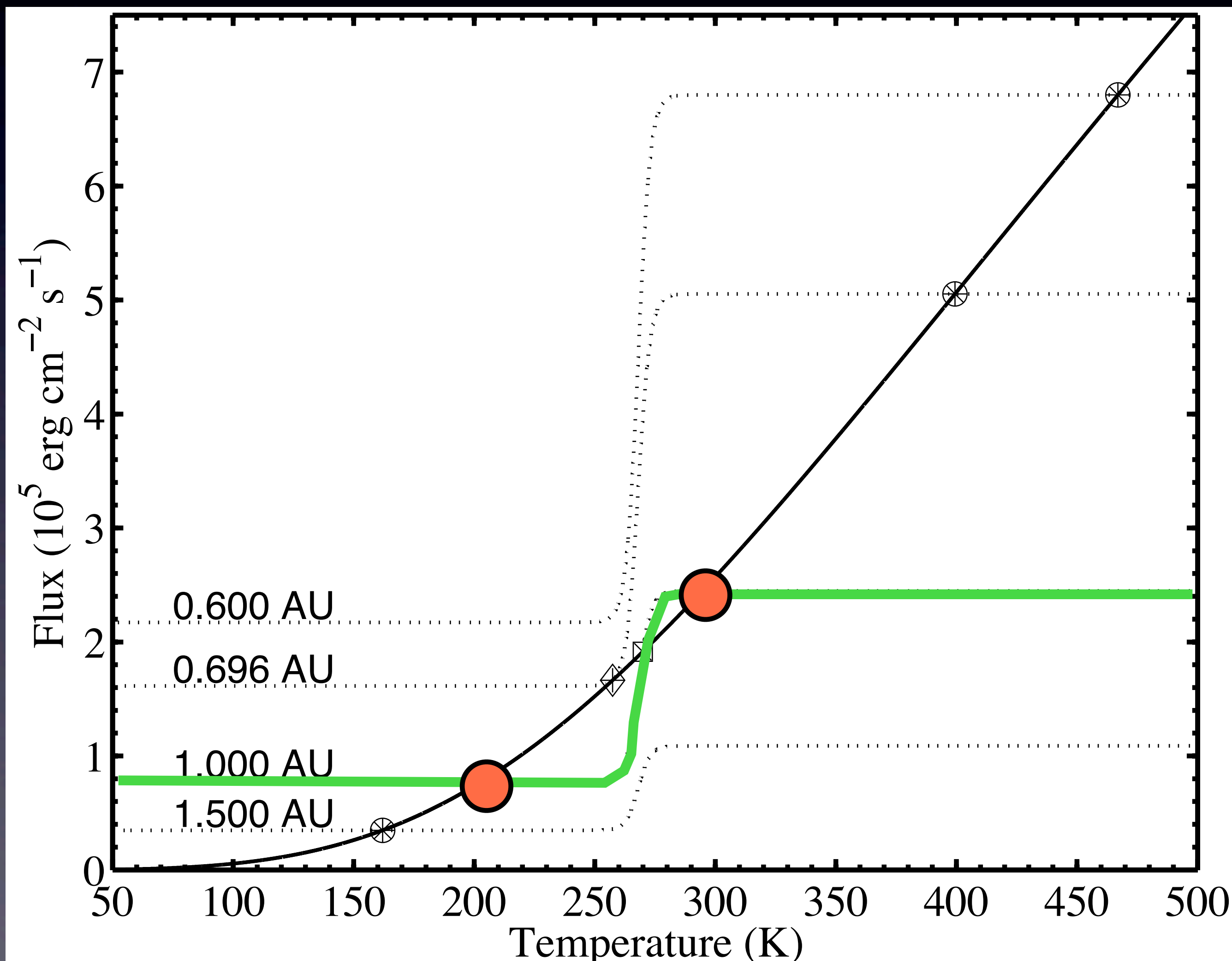
Kasting et al. (1993) - Radiative Balance Model

Exoplanetary Climate Parameter Space

- Obliquity* & Eccentricity*
- Rotation rate (including tidally-locked)*
- Planetary radius and surface gravity
- Ocean-land distribution
- Atmospheric mass & composition
- History of the climate...

Two Climate States

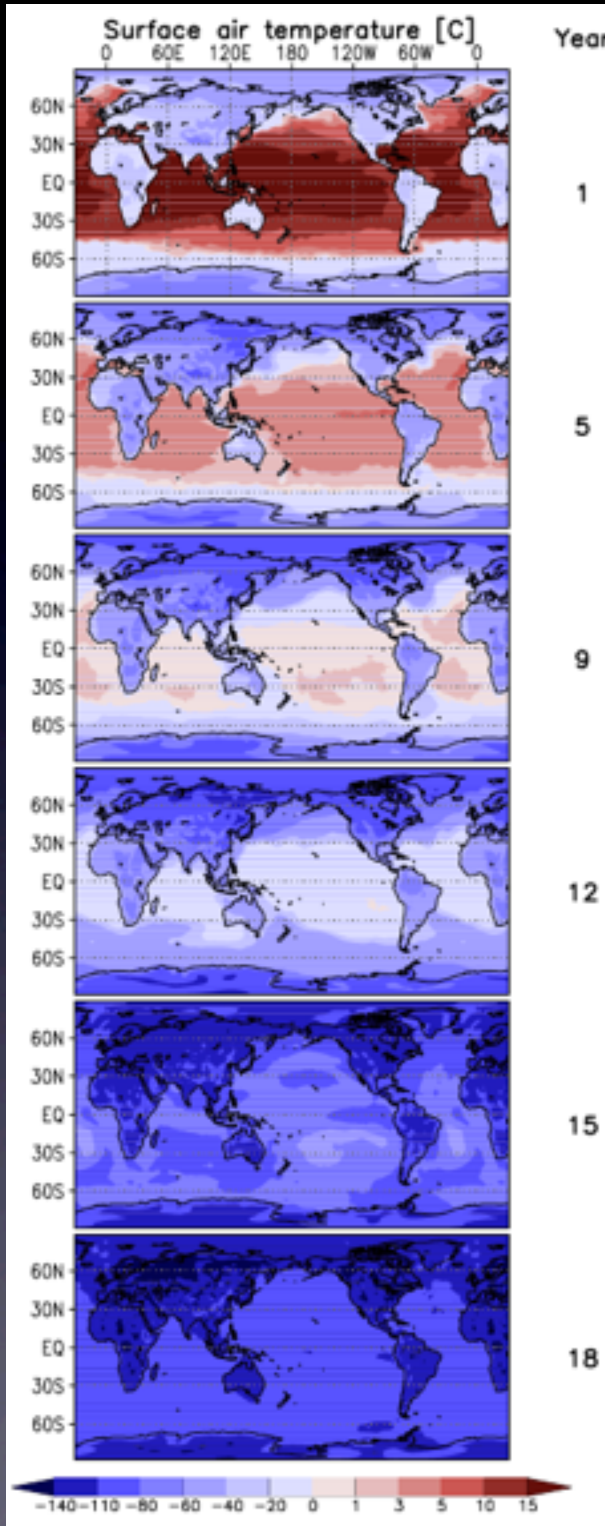
Spiegel et al. (2008): $I[T] = S(1 - A[T]),$ = Radiative Balance



Q-=I[T]

Q+=S(1-A[T])

Forced system can transition in a dynamical theory.



Full Climate Model Confirmation

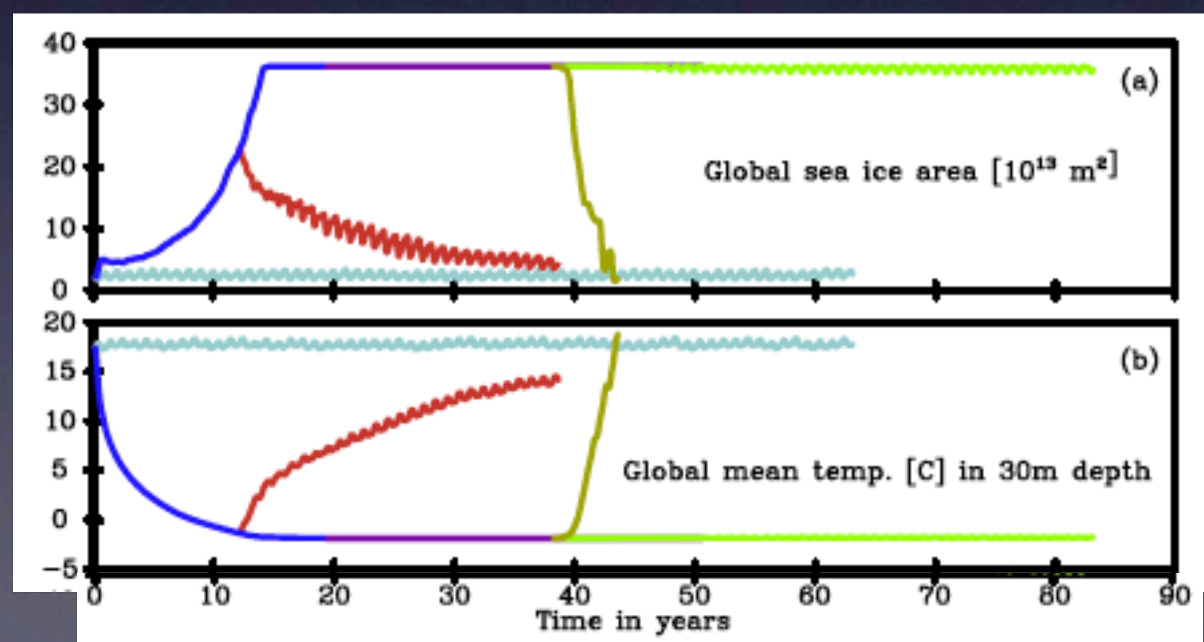
Present-day and ice-covered equilibrium states in a comprehensive climate model

Jochem Marotzke[1] and Michael Botzet[1]

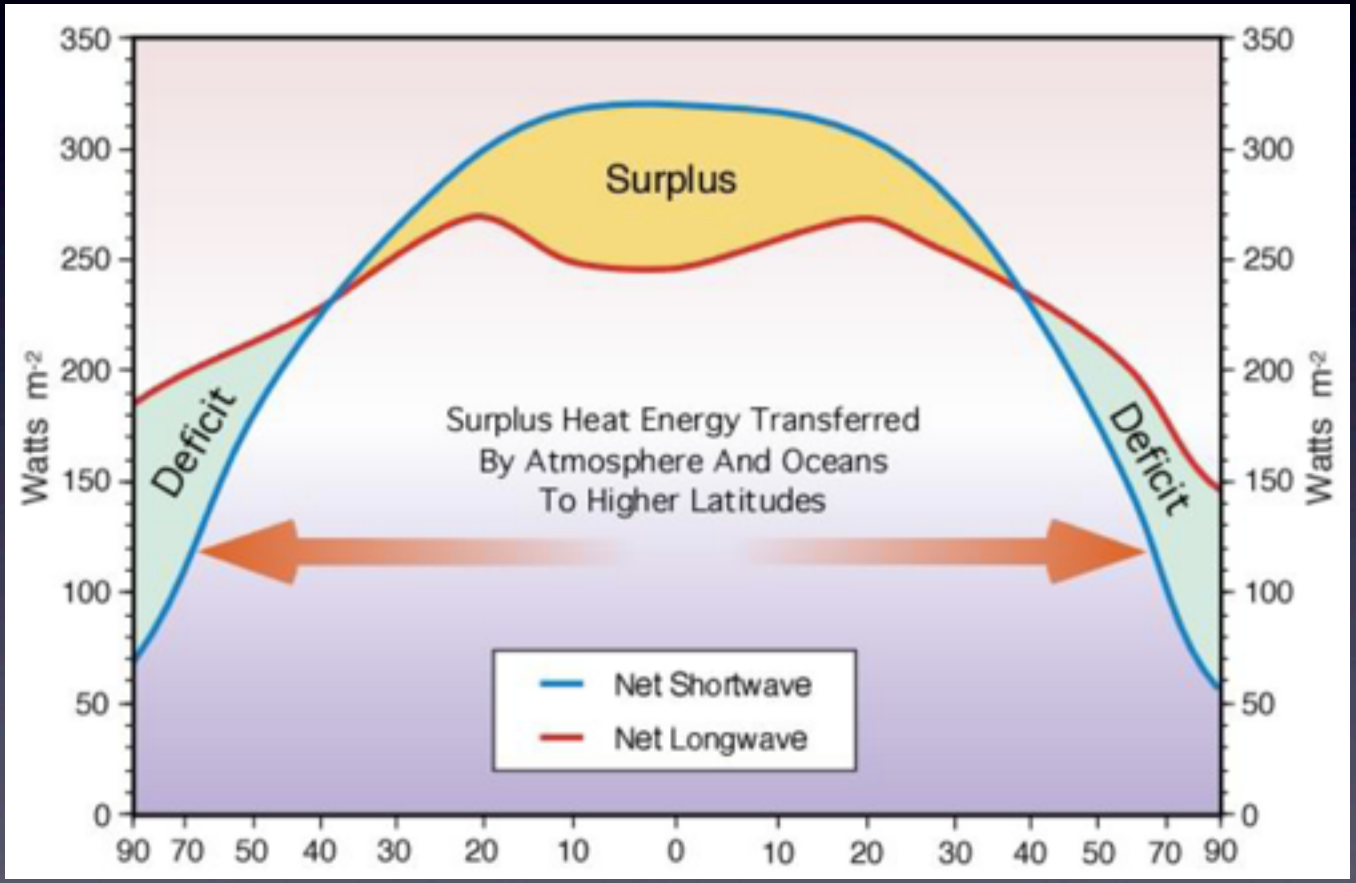
Received 24 November 2006; revised 29 June 2007; accepted 19 July 2007; published 17 August 2007.

[1] We show that in a comprehensive climate model both the current climate and a completely ice-covered Earth are stable states under today's total solar irradiance (TSI) and CO_2 level. We employ the Max Planck Institute for Meteorology coupled atmosphere-ocean general circulation model ECHAM5/MPI-OM, at relatively high resolution (horizontally T63 in the atmosphere and 1.5 degrees in the ocean). Setting TSI to near-zero causes

solution in a low-resolution coupled G
al., 2001; *Poulsen and Jacob*, 2004].
previous work, we apply here a state-o
climate model, the Max Planck Institute
atmosphere-ocean general circulation m
ECHAM5/MPI-OM [*Marsland et al.*, 20
al., 2003], which has been extensively
evaluated against observations [*Hagema*



Latitudinal Heat Transport Matters

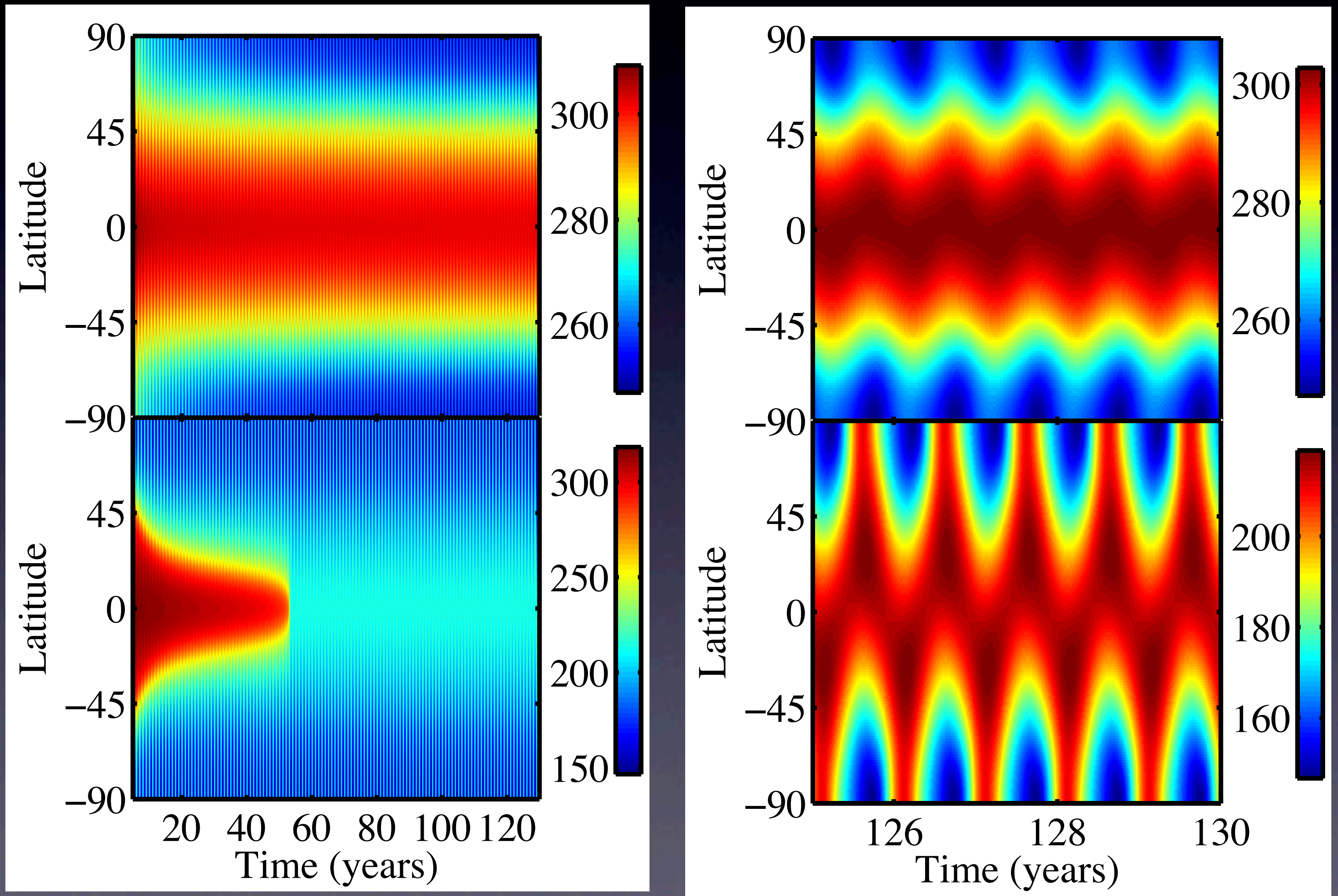


Showman et al. (2010)

Another pathway to snowball

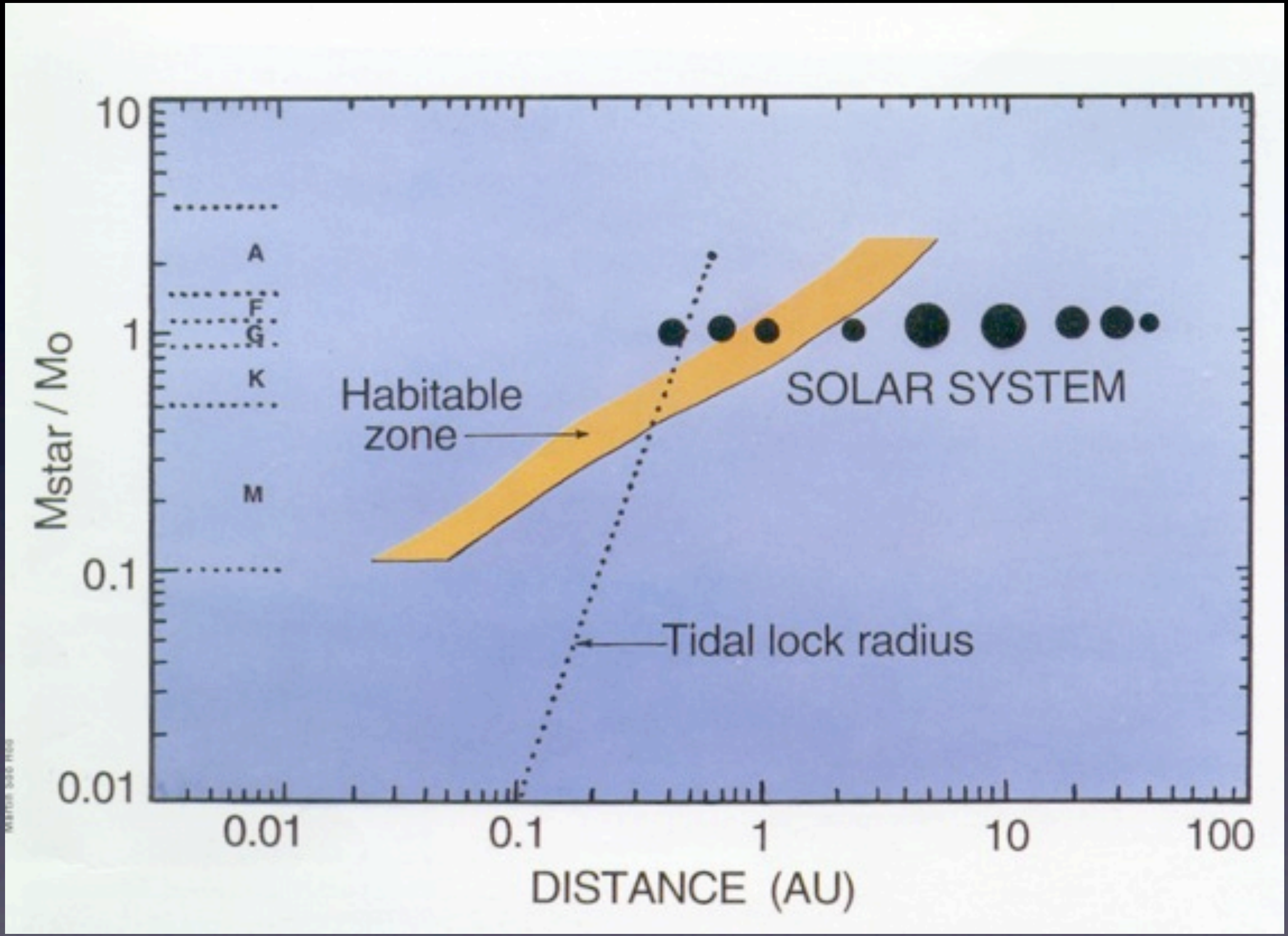
Earth

"Fast-Spinning" Earth



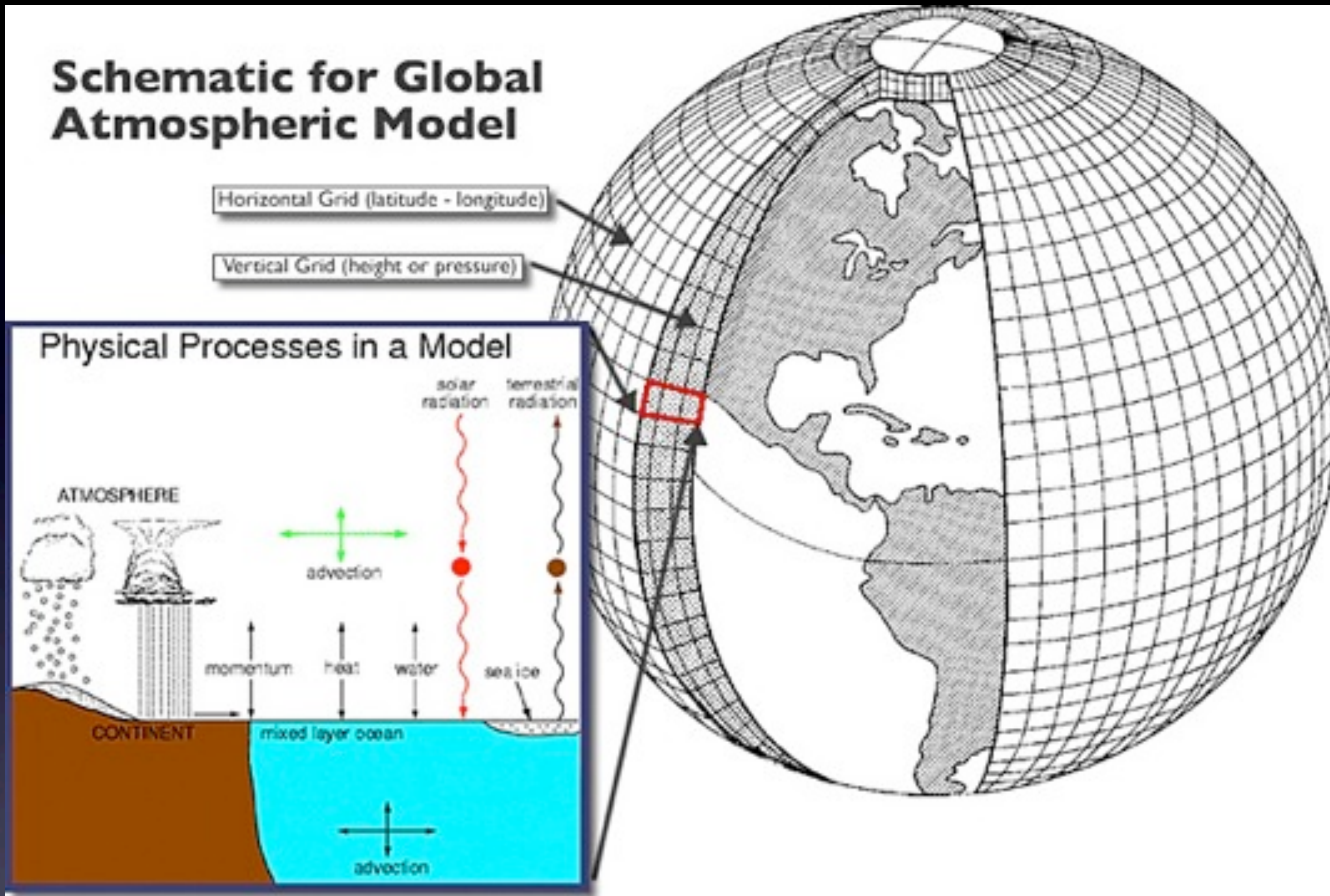
Spiegel et al. (2008) 1D EBM

Planetary Habitability



Feedback from Carbon-Silicate cycle is crucial

Modeling Hierarchy Primer



Full Physics GCM:

3D
advection
radiation
surface exchange
hydrology

$$C\frac{\partial T[x,t]}{\partial t} - \frac{\partial}{\partial x}\left(D(1-x^2)\frac{\partial T[x,t]}{\partial x}\right) + I[T] = S(1-A[T]),$$

1D EBM (latitude)

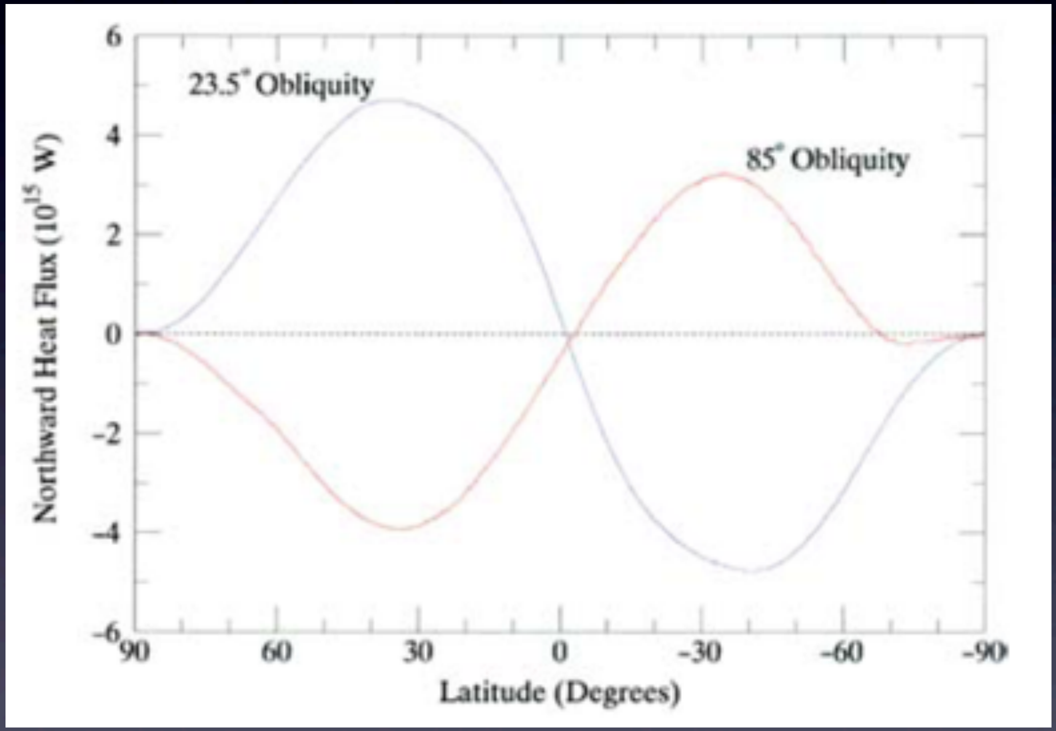
$$I[T] = S(1-A[T]),$$

1D Radiative Model (vertical)

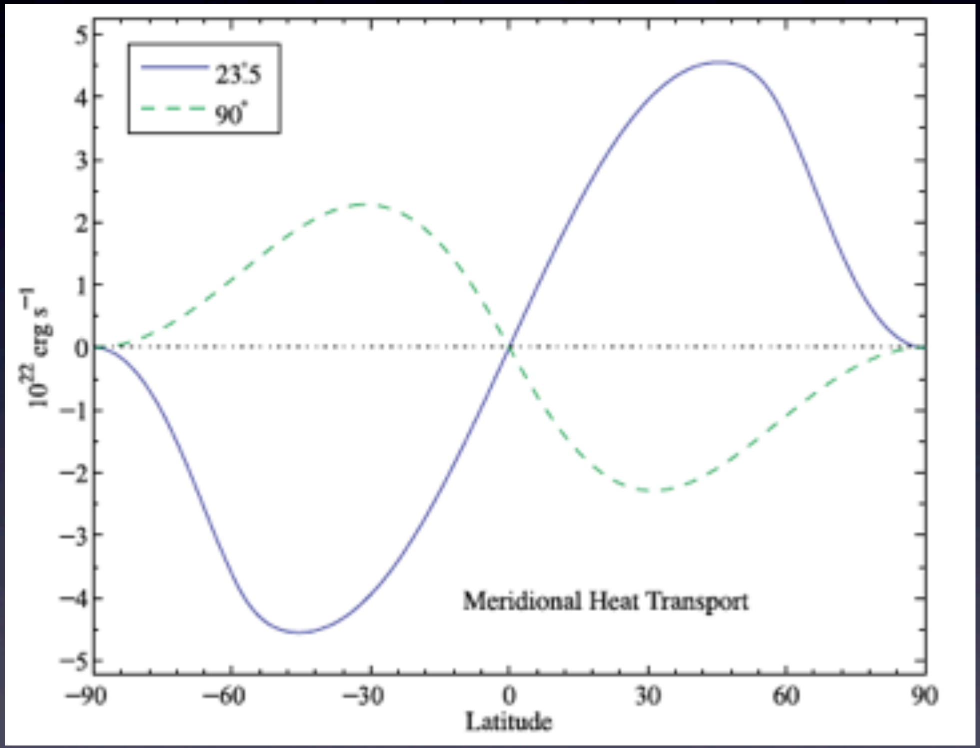
Climate on “Oblique Earths”

Key Features: strong seasonality +
mean latitudinal transport is reverted for i> 54 deg

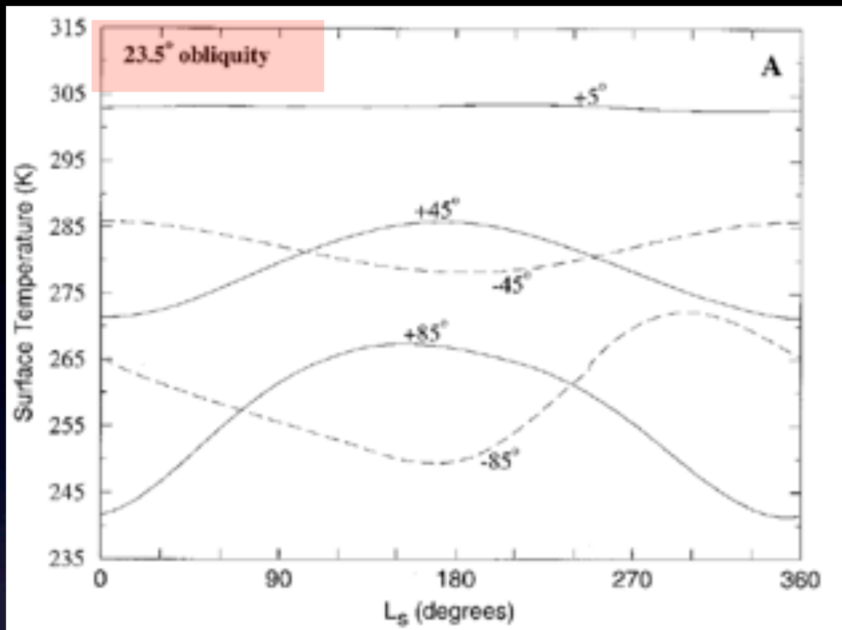
Reverted Mean Transport

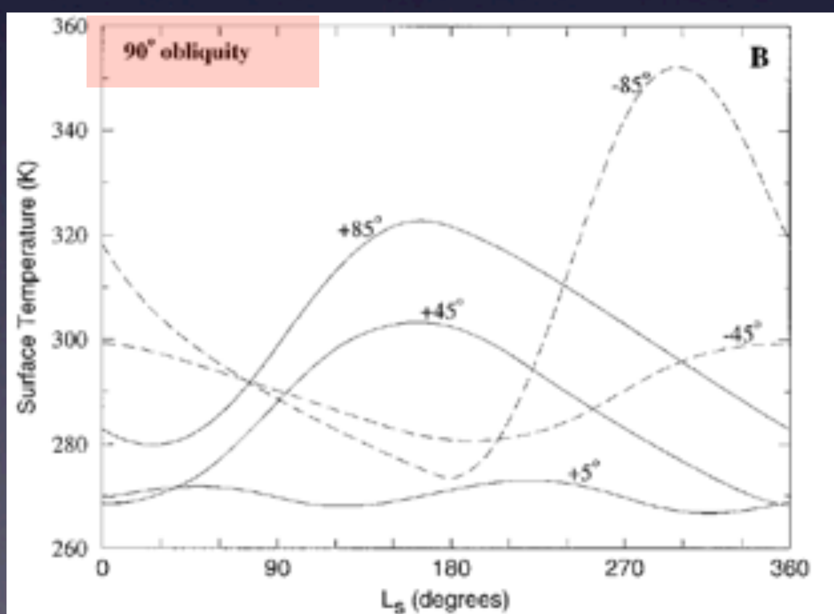


Williams & Pollard (2003)
Full Physics GCM



Spiegel et al. (2009)
1D EBM



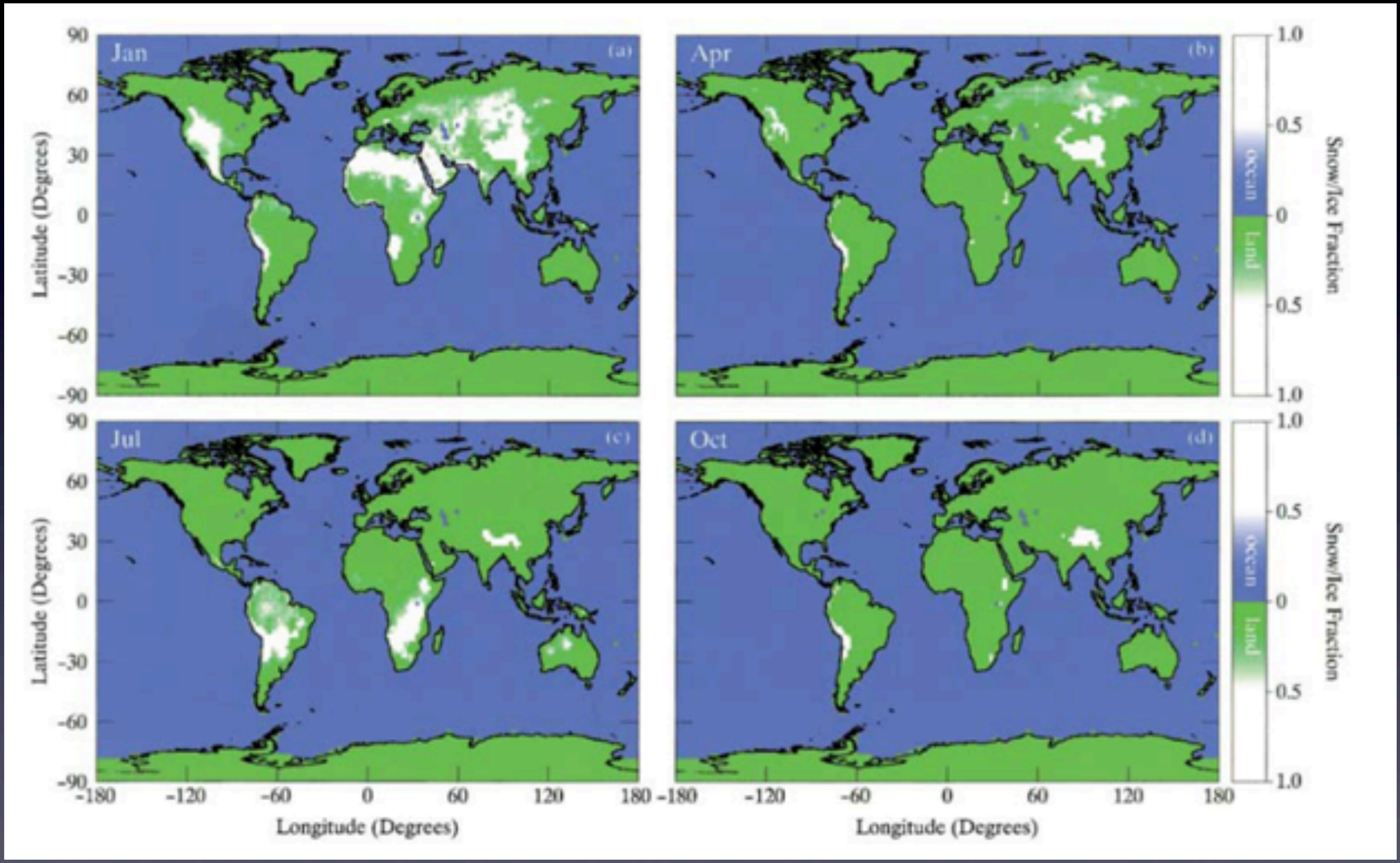


Williams & Kasting (1997)
1D EBM

High Obliquity:

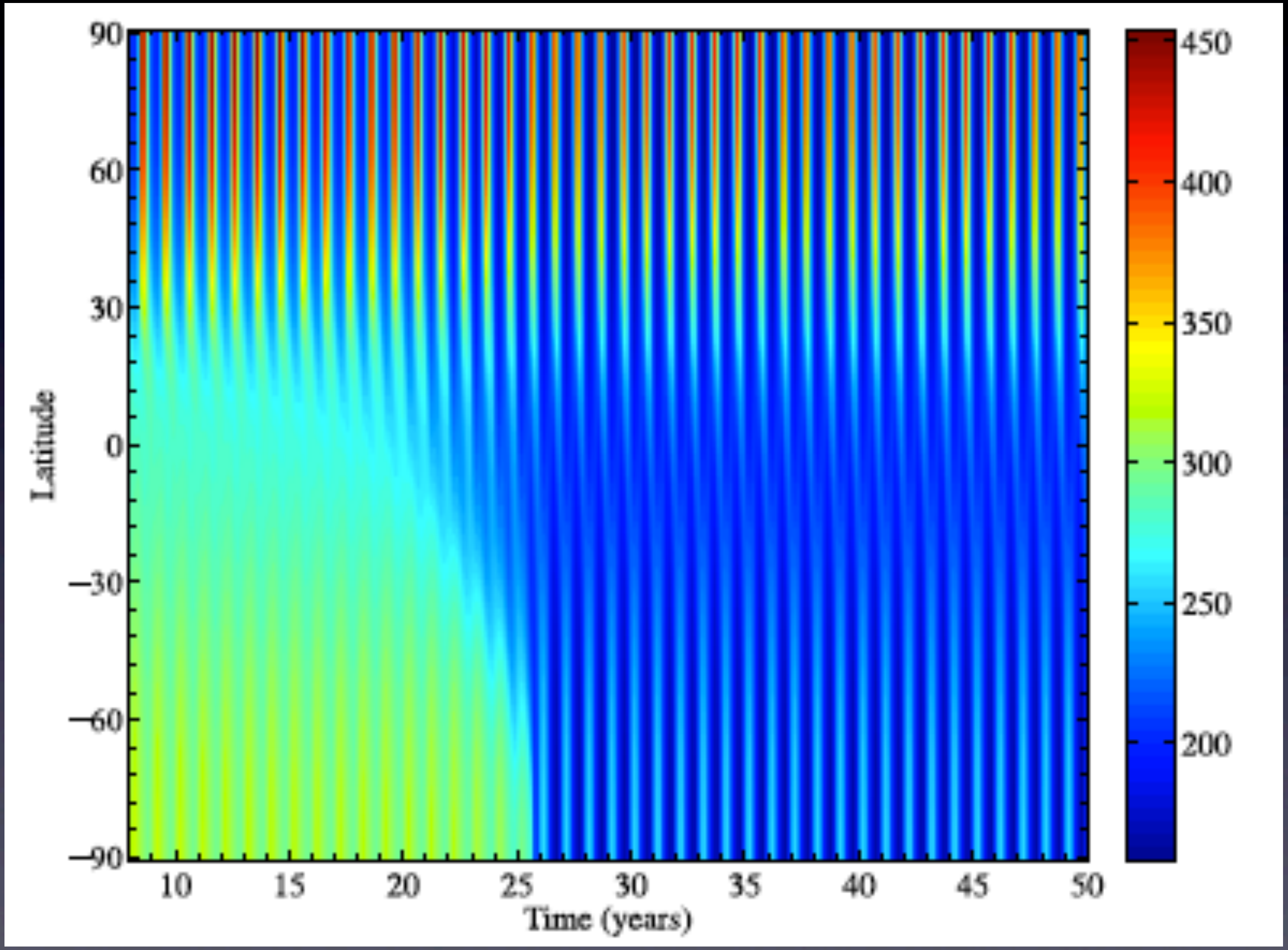
Reverted mean transport
Cool equator
Hot poles
Extreme seasonality

Williams & Pollard (2003)
Full Physics GCM at 85 deg obliquity



Ice-free Poles, Icy Equator!

Partial Snowballs?



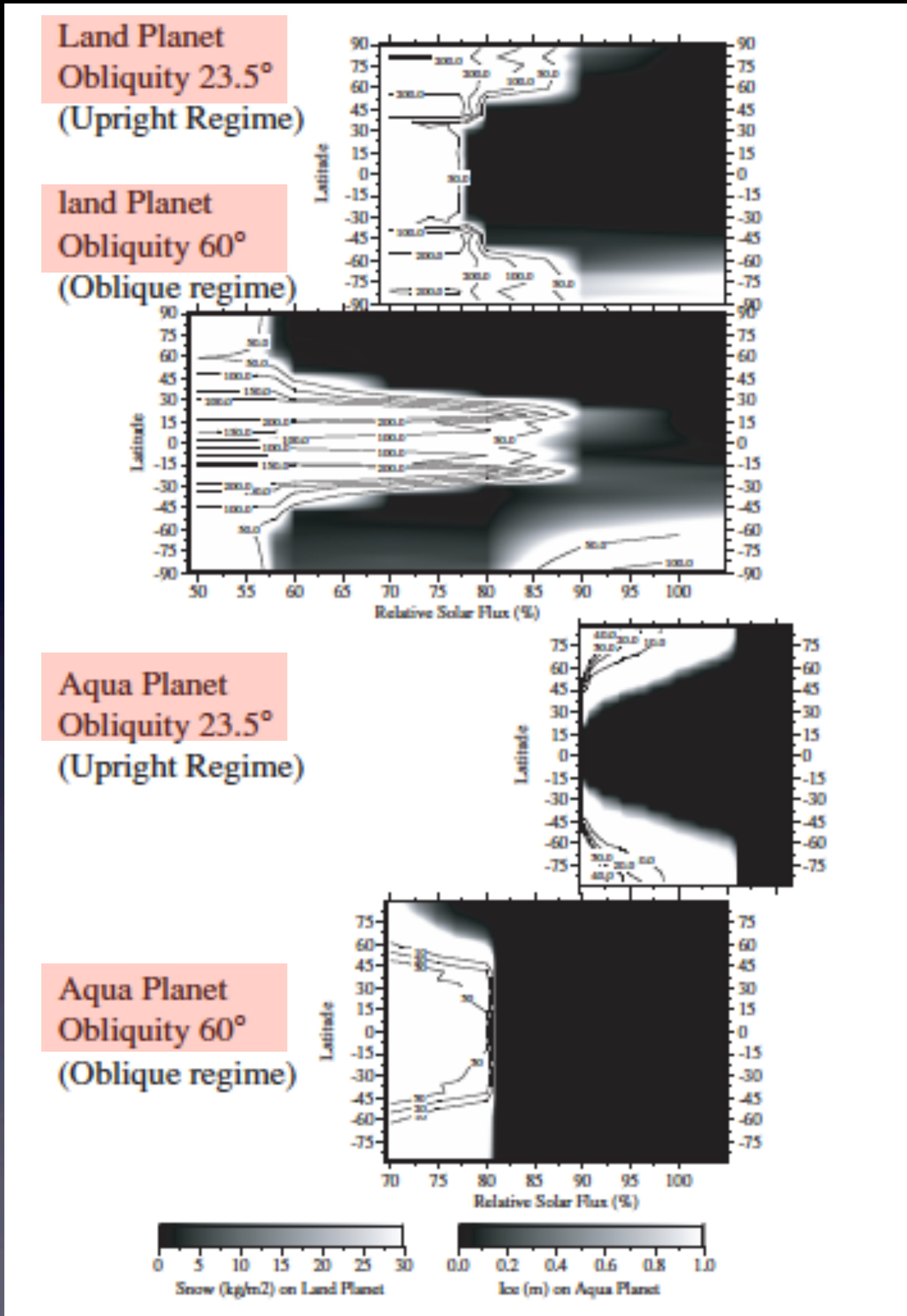
Spiegel et al. (2009)
1D EBM

90 deg obliquity

North polar continent (30%)

Southern ocean (70%) freezes!

Abe & Abe-Ouchi (2003)
Full Physics GCM



"Global freezing edge"
is not well determined

land & ocean
distribution matters
(as known from
paleoclimate studies)

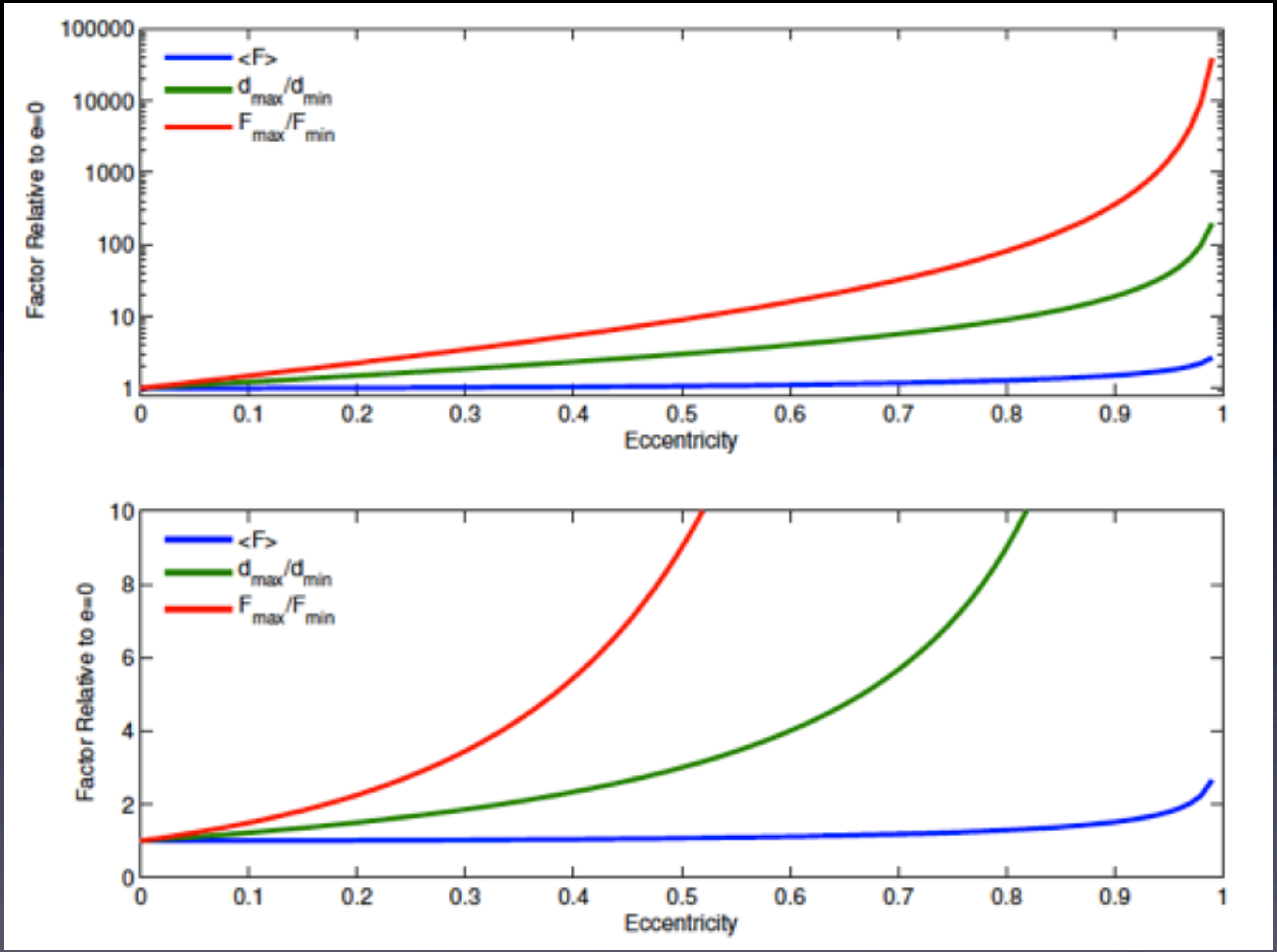
“Oblique Earths”: open questions

- Earth rotation rate
- Earth-like atmospheric mass & composition
- Inner HZ edge: runaway greenhouse limit?
- ....

Climate on “Eccentric Earths”

Key Features: increased mean insolation + flash-heating at periastron + extended cooling at apoastron

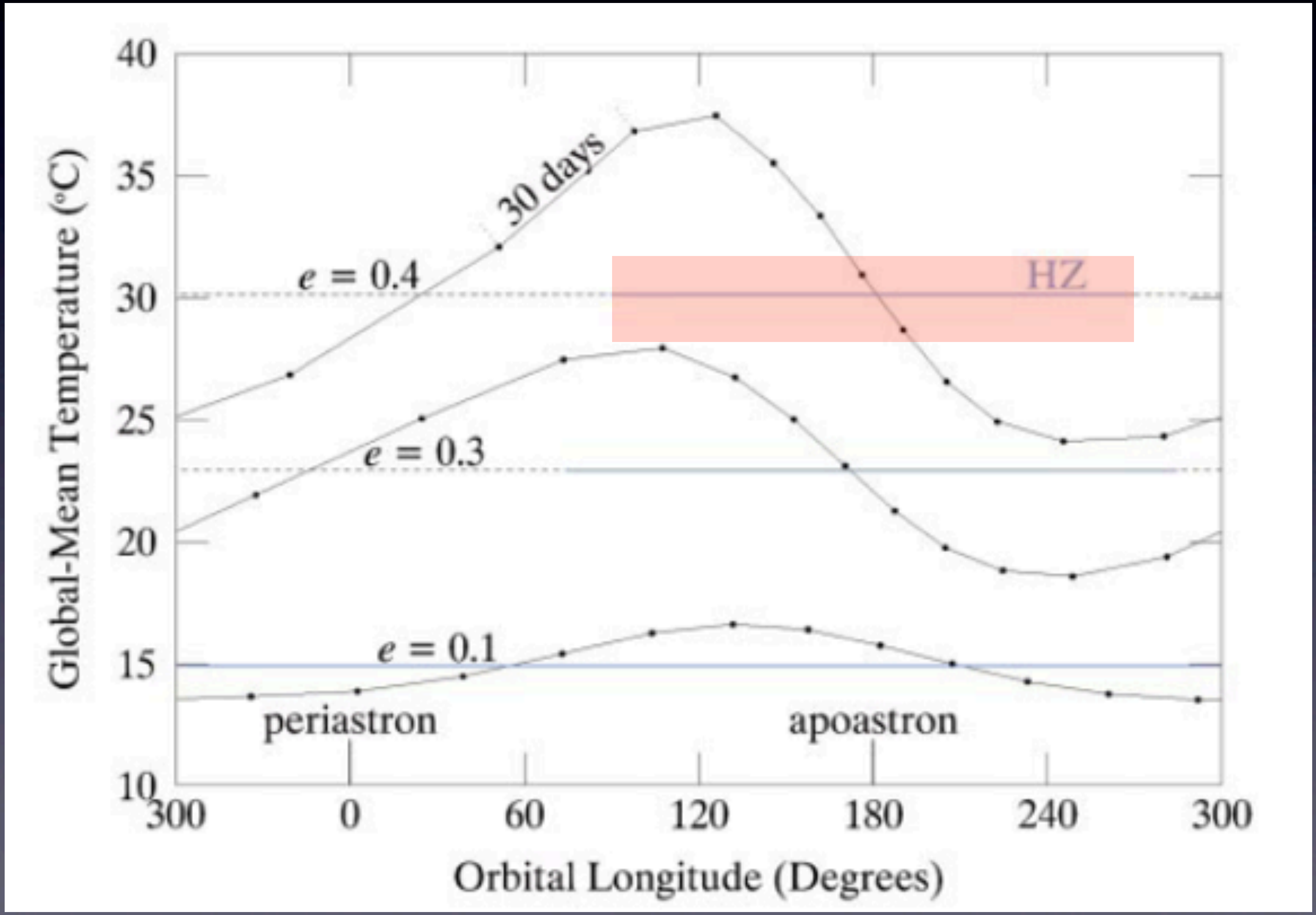
Eccentric Forcing



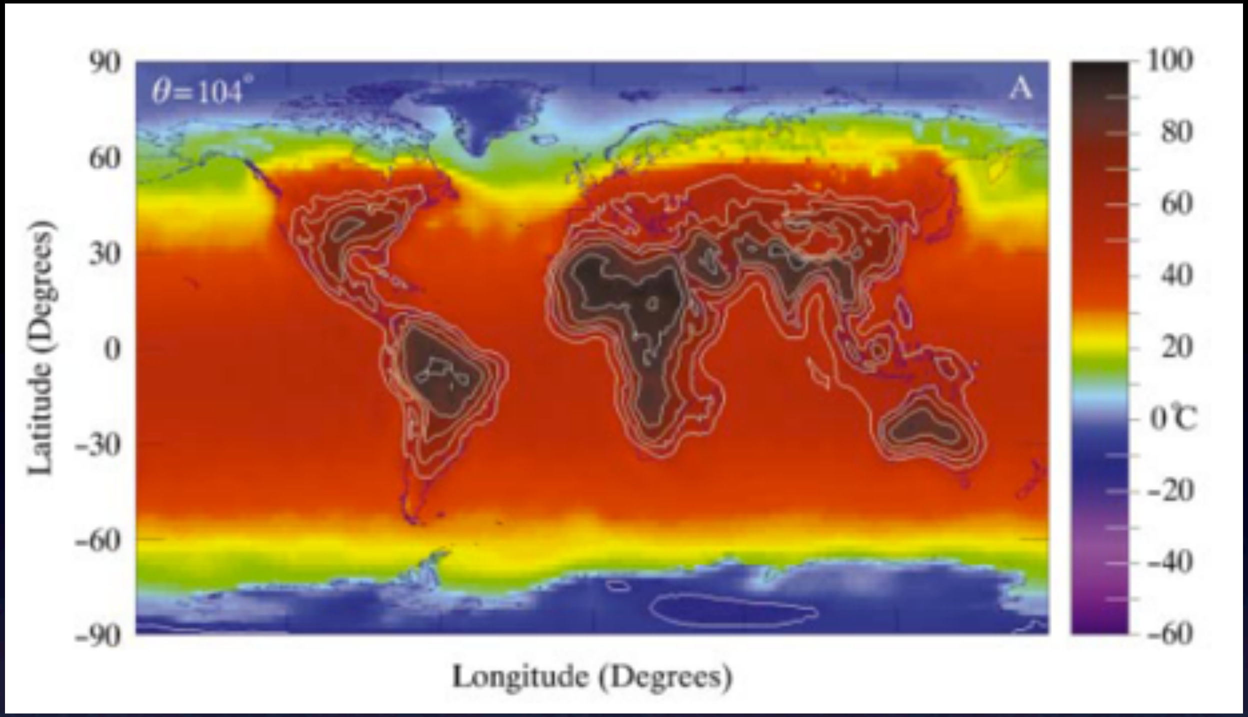
Dressing et al. (2010) - 1D EBMs of "eccentric Earths"

Williams
& Pollard (2003)

Full Physics GCM
with e=0.1-0.3-0.4



Hottest

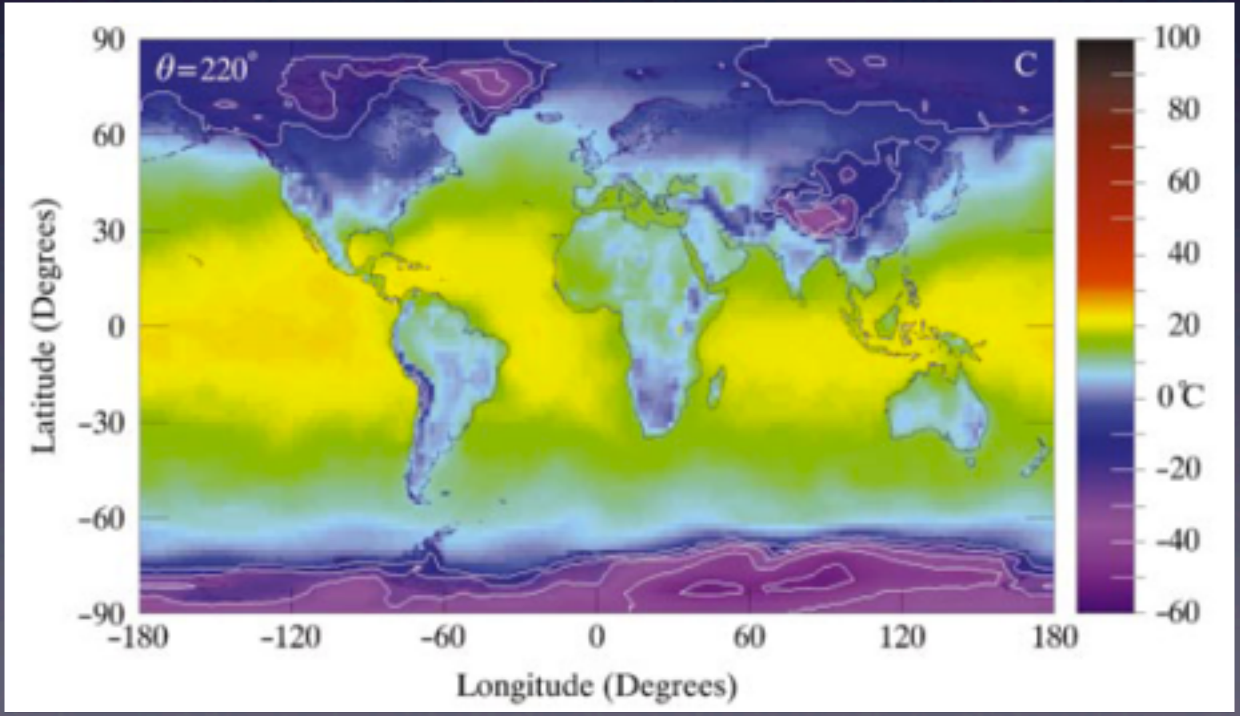


Williams & Pollard (2003)

Coldest

Full Physics GCM with e=0.7:

extreme seasonality!

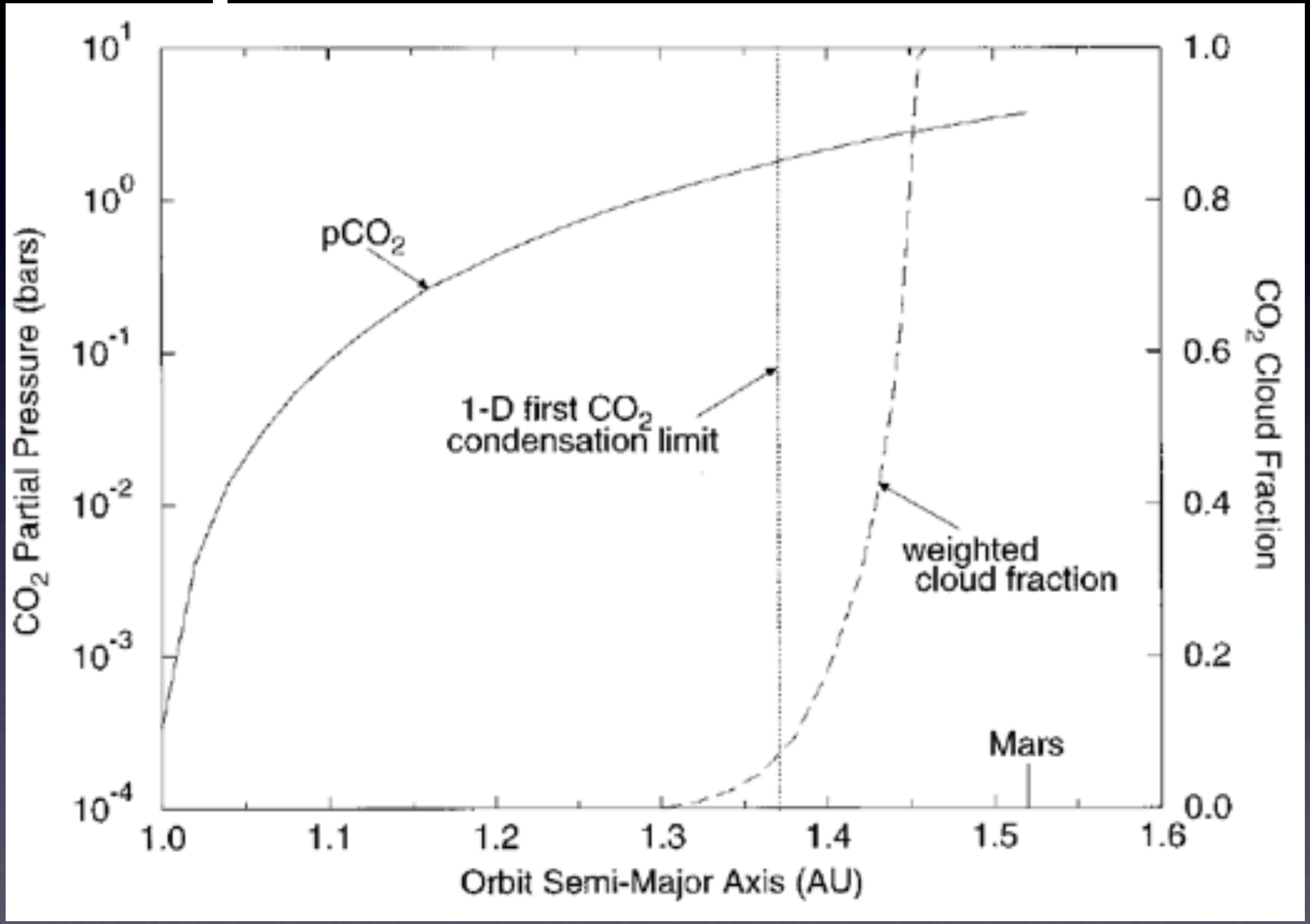


“Eccentric Earths”: open questions

- Earth rotation rate
- Earth-like atmospheric mass & composition
- Outer HZ: global freezing edge?
- Inner HZ edge: runaway greenhouse limit?
- ....

Long-Term Feedback: Carbon-Silicate Cycle

Outer Habitable Zone: Still prone to snowball?



Williams & Kasting (1997)

1D EBM - steady state weathering

Snowball vs. Carbon-Silicate: open questions

- General timescale mismatch (snowball vs. CO_2 buildup): opens a window for an astronomically forced transition?
- Are cyclic snowball and CO_2 buildup states possible? ("Titan-like")
- Snowball transition & seasonal extremes: can CO_2 buildup be prevented by CO_2 condensation conditions being met? (Spiegel et al. 2009)?

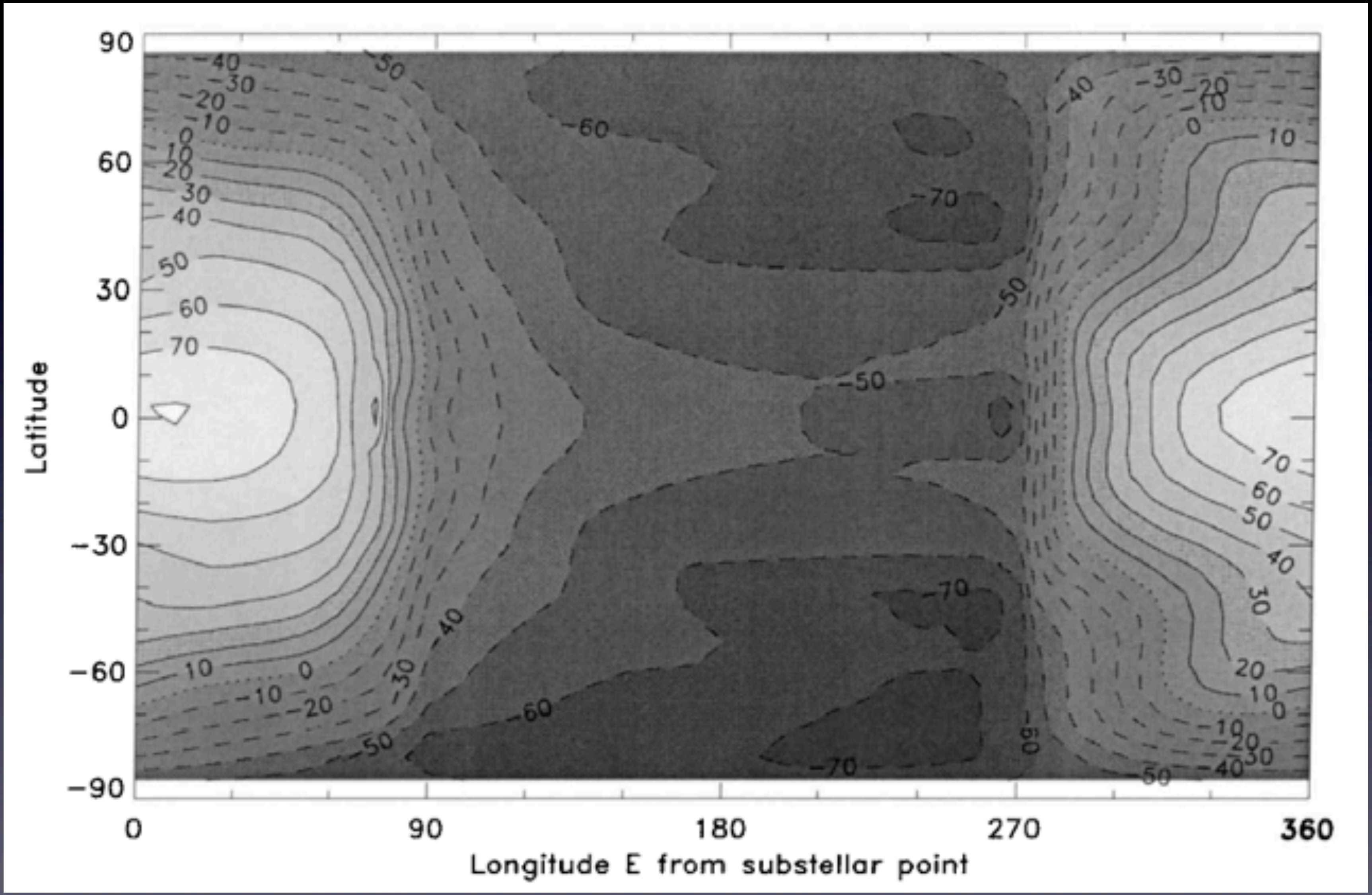
Climate on “Tidally-locked Earths”

<u>Key Features:</u> slow rotation + day-night hemispheric forcing

JWST & Habitable Earths

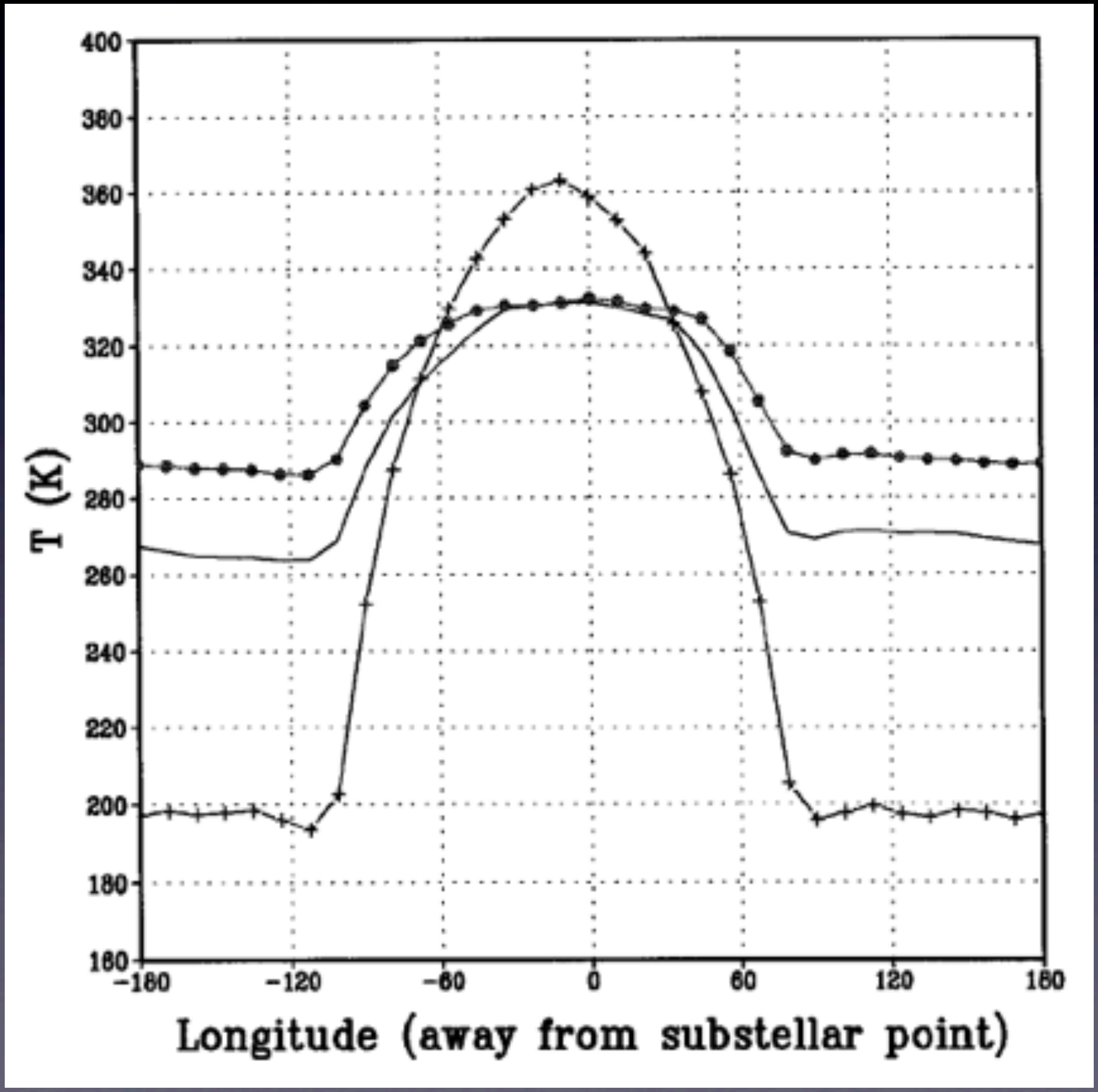
If transiting (super-)Earth can be detected around nearby M dwarfs, JWST eclipses, phase curves, spectra may be obtainable

Surface Temperature



Joshi (2003) - Full Physics GCM - Titan rotation rate

Atmospheric mass vs. collapse



Joshi et al. (1997)
Dry Grey GCM

1500 mbar (Tau_IR=1.5)
1000 mbar (Tau_IR=1)

100 mbar (Tau_IR=0.3)

Collapse at 30 mbar

“Tidally-locked Earths”: open questions

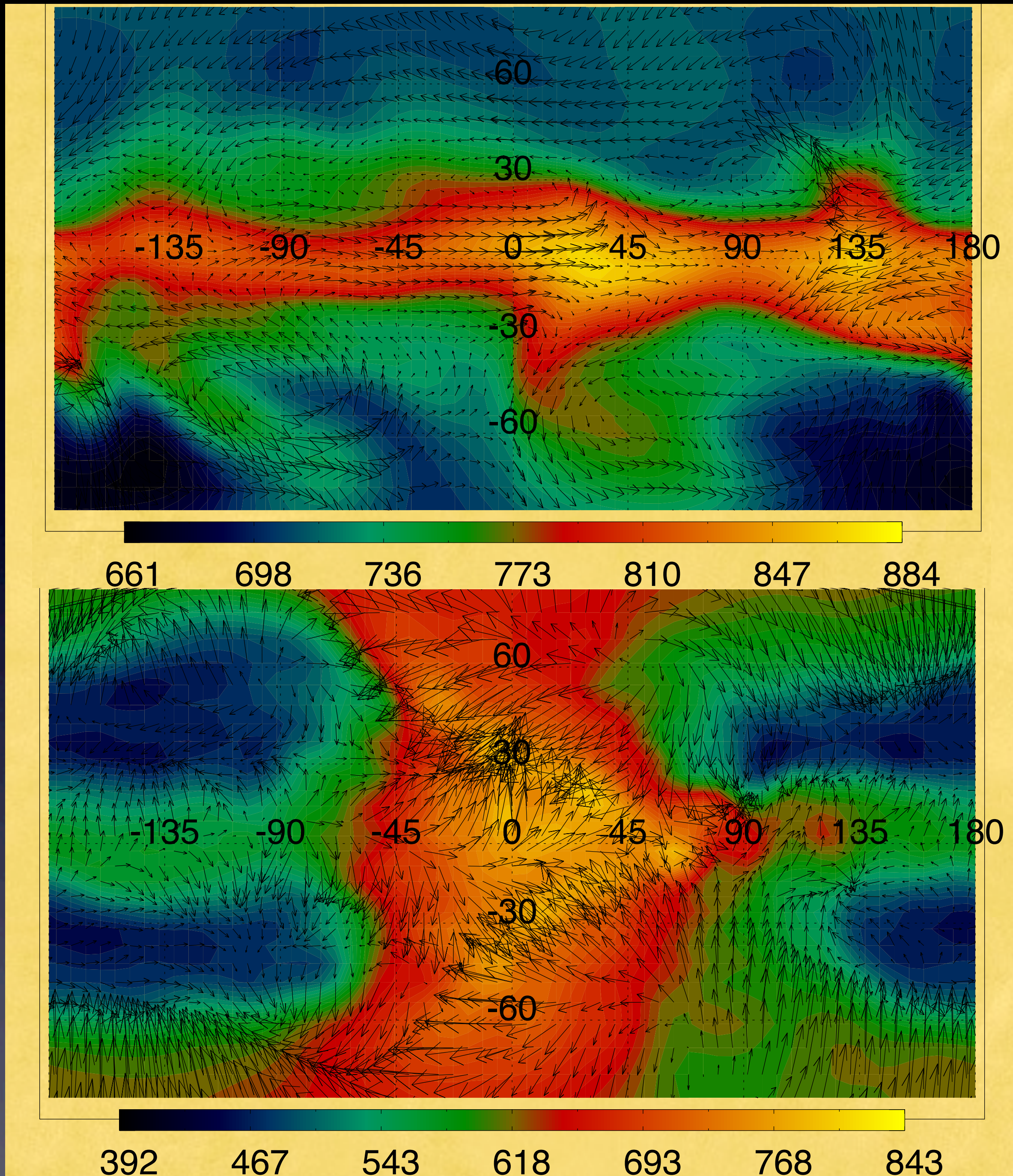
- Planetary rotation rate*
- Atmospheric mass* & composition
- Stellar flares*
- Is global freezing possible?
- ....

Possibilities for the future...

- Flexible idealized models (e.g., dry grey GCMs)
- General exploration studies (e.g., Merlis & Schneider 2010, Mitchell & Vallis 2010, Wang & Read 2010)
- Planet-specific investigations

GJ1214b Models

- 6.6 Earth mass super-Earth, 2.7 Earth radius
- 1.6 Earth-day orbit around low-luminosity M dwarf: Teq=550-660 K (Charbonneau et al. 2009)
- Assume tidally-locked circular orbit
- Assume Earth-like optical/thermal grey absorption coefficients
- *Can nightside/limb have habitable conditions?*
- Dry, grey-radiation GCM (w/ surface scheme)
- Preliminary results!



"Surface" Temperature (K) + wind vectors
Substellar point at (0,0)

Atm = 10 bar

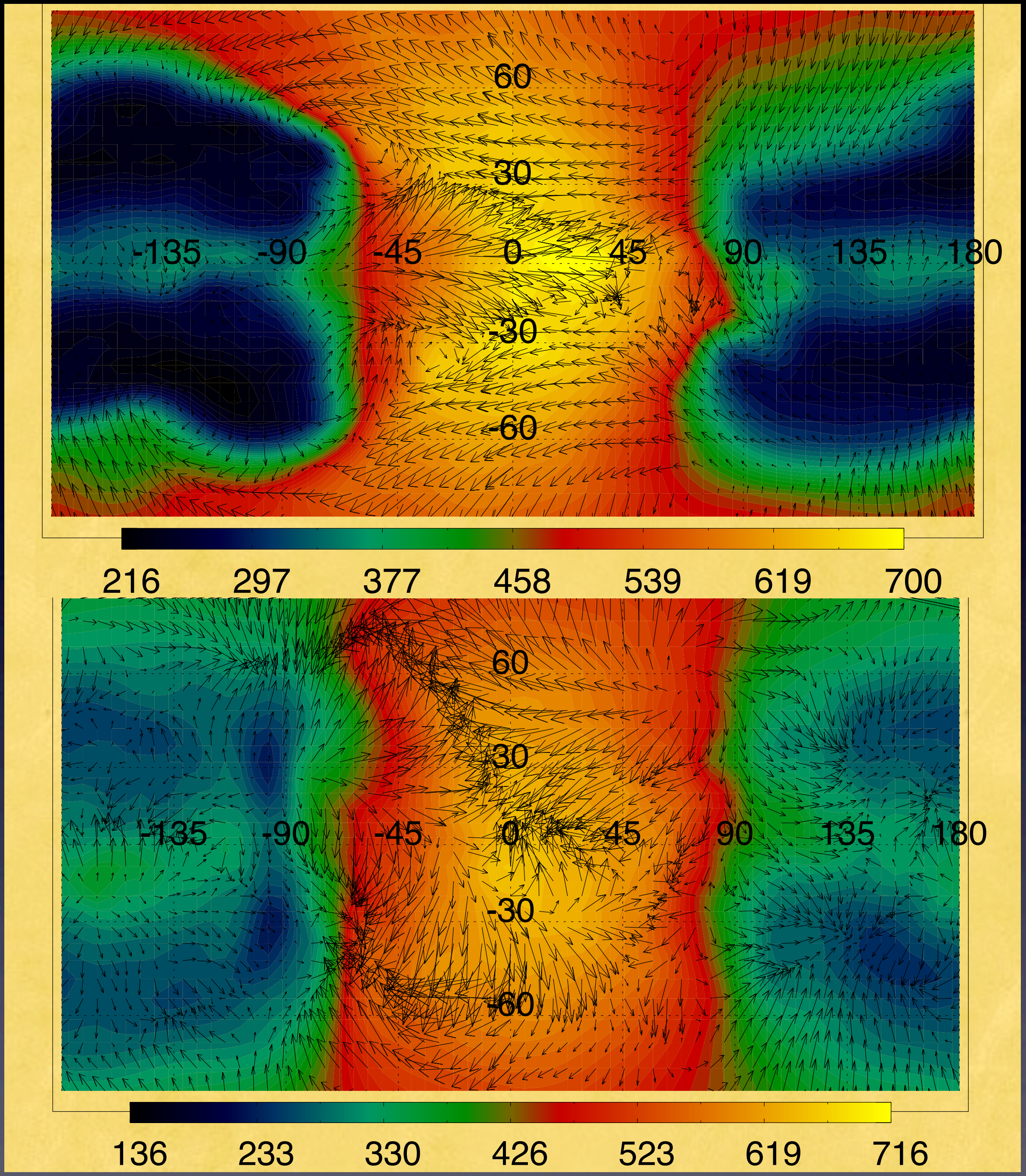
strong advection

strong greenhouse

Atm = 1 bar

some advection

hot nightside



Surface Temperature (K) + wind vectors
Substellar point at (0,0)

Atm = 0.3 bar

weaker advection

interesting night?

Atm = 0.1 bar

weak advection

interesting limb?
collapse?

Concluding Remarks

- Climates on oblique, eccentric and tidally-locked Earths have been somewhat explored
- Exoplanet discoveries have opened a comparatively huge parameter space. How can we address it?
- Snowball transition and carbon-silicate feedback are subjects of particular interest