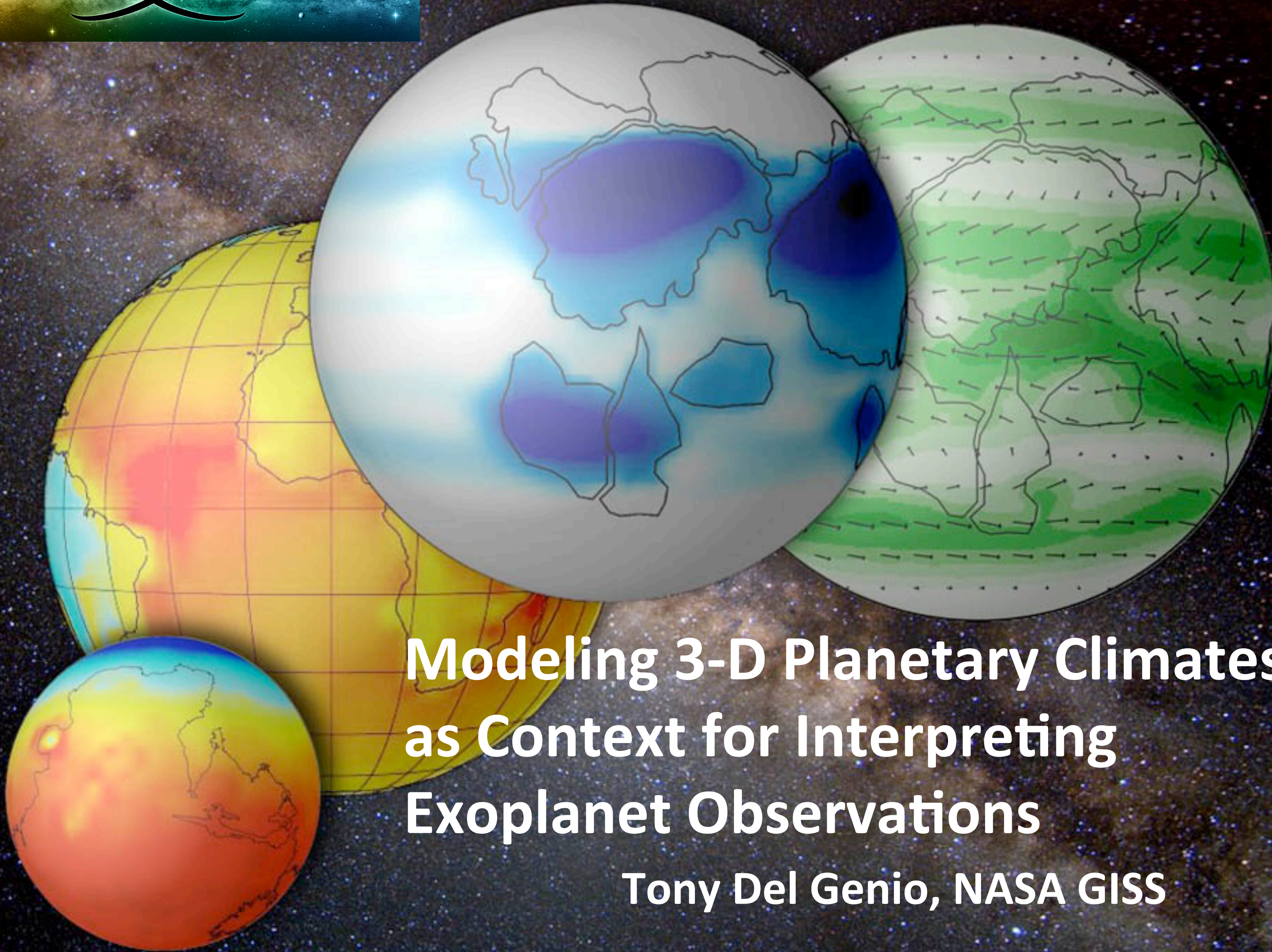


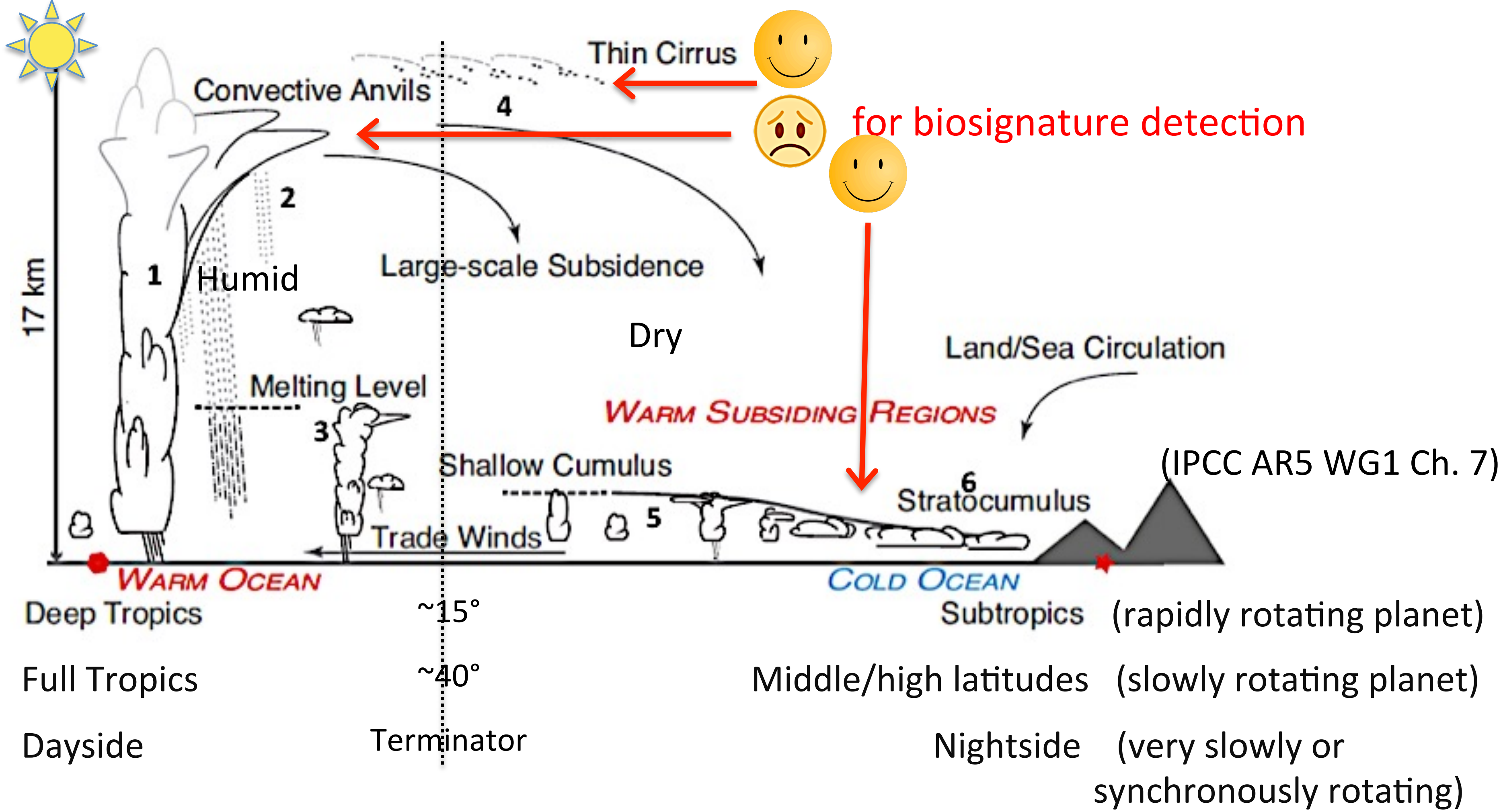
Modeling 3-D Planetary Climates as Context for Interpreting Exoplanet Observations

Tony Del Genio, NASA GISS

Exoplanet Biosignatures Workshop, 7/29/16

Why 3-D models?

- Strengths of 3-D global climate models (GCMs):
  - self-consistent, spatially/temporally varying convection, clouds, atmospheric and oceanic transports, ice
  - effects of obliquity, eccentricity, tidal locking
- Possible uses for GCMs in biosignature research:
  - distinguish clouds from hazes?
  - prospects for detecting or inferring surface liquid water?
  - detectability and uniqueness of spectral signatures of life
  - broaden thinking: sub- vs. superhabitable planets, habitable but not Earthlike planets
- Synergies between 3-D and 1-D models
- "Wrong but useful"

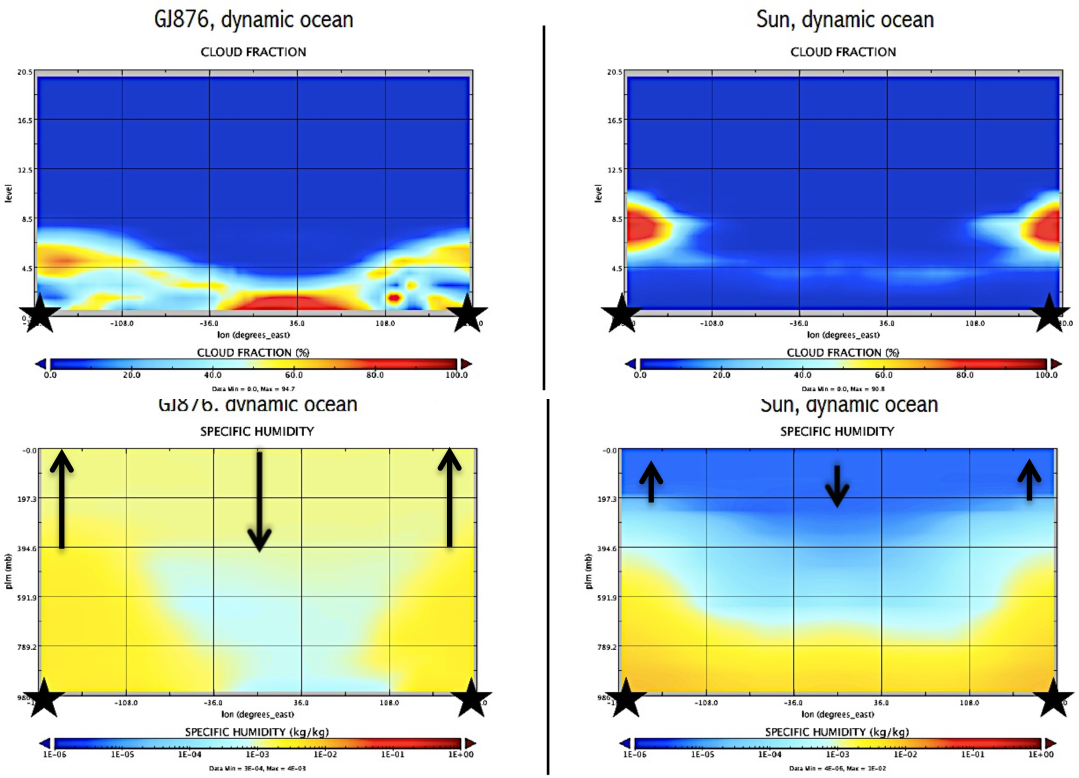


Differential insolation on rocky planets drives up-down circulations that cause large spatial differences in cloudiness and cloud altitude

Hazy rocky planets in our solar system are more homogenous – is this universal? Does a flat spectrum imply haze and not cloud?

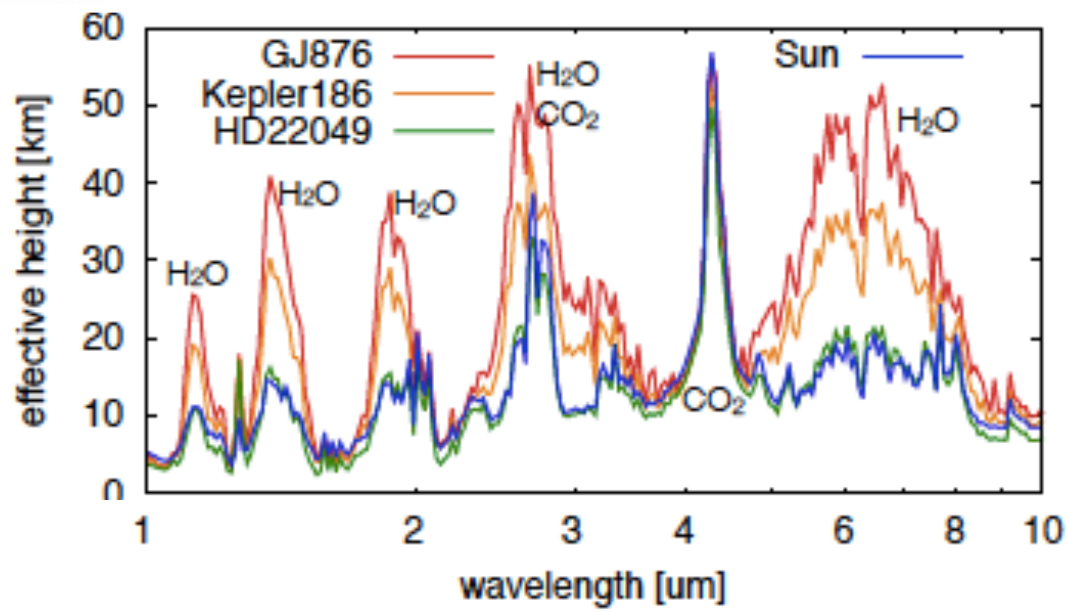
GCM simulations of tidally locked planets:

- Near-IR H_2O absorption warms stratosphere and tropopause
- Suppresses convection on planet orbiting M-star vs. Sun
- Radiatively driven circulation pumps H_2O to high altitude -> 3D models can provide effective diffusivities for 1D models



(★ = substellar point)

Increased separation of H_2O from cloud tops enhances detectability of H_2O for M-star planets



(Courtesy Yuka Fujii-Ebihara)

Could we infer surface liquid water on a planet with an upper level H_2O detection?

With direct imaging, chances are good (Ford, Cowan, Fujii papers)

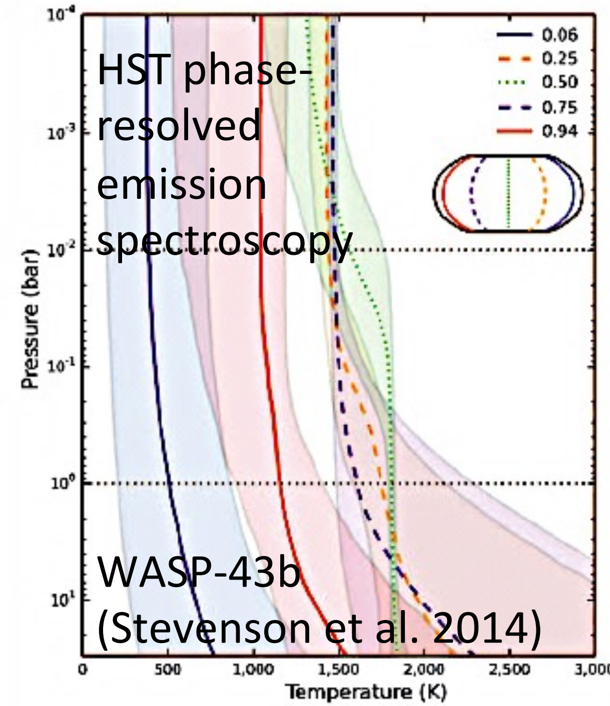
With transit/eclipse obs, a challenge?

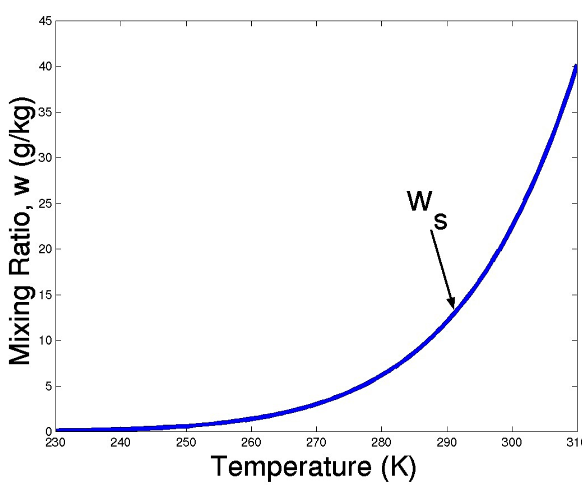
dT/dp for dry planet vs. wet planet: Tropopause-surface ΔT differs by 10s of K, increasing with surface T:

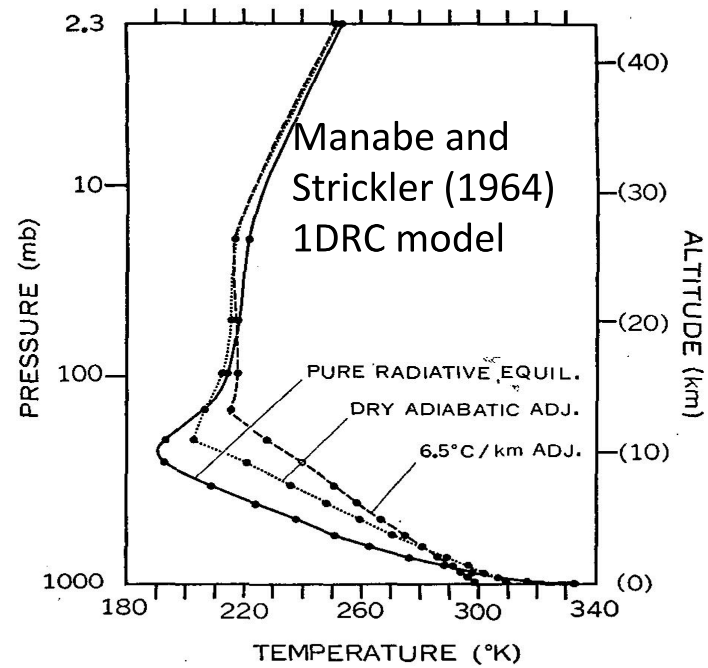
$\Delta T \sim L\, q_{sat}(T_{surf})/c_p$

~2x per 10 °C change

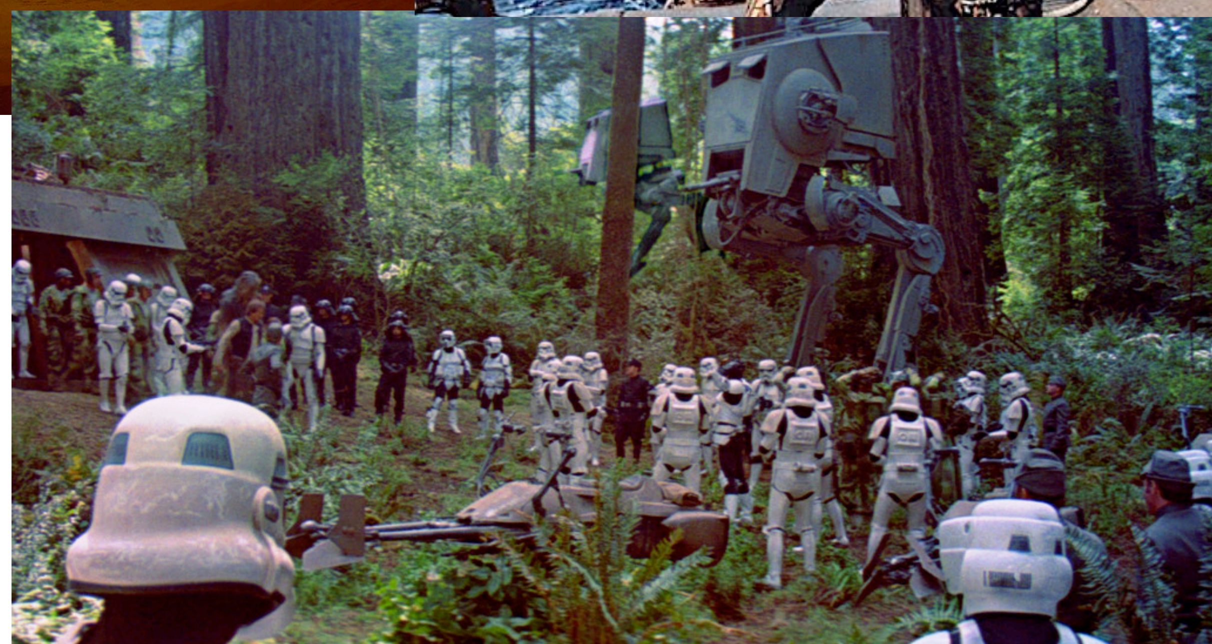
(~55 K @ 30°C, 80%RH for a 1 b N_2 atmos.)







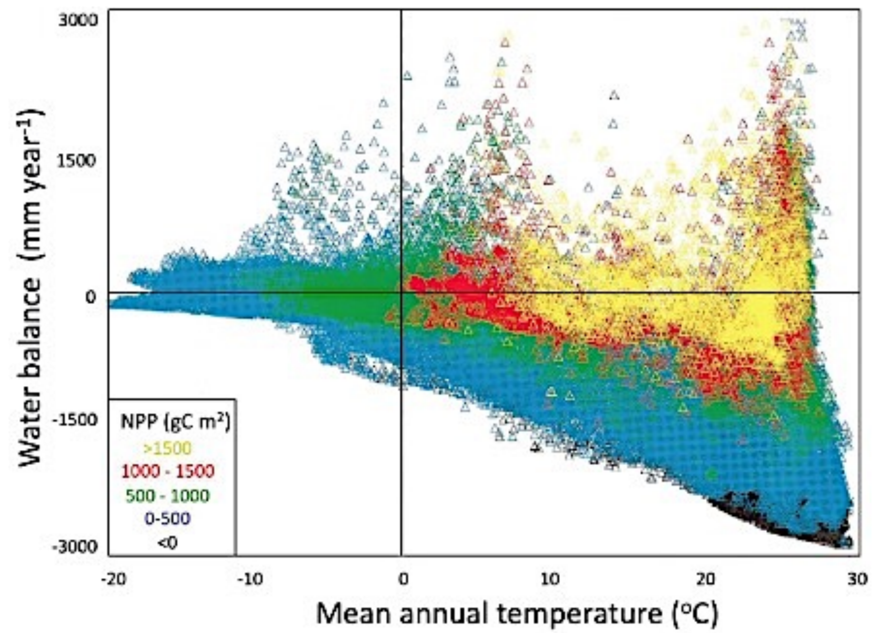
Three habitable planets: How distinctive are their biosignatures? Partly a climate question

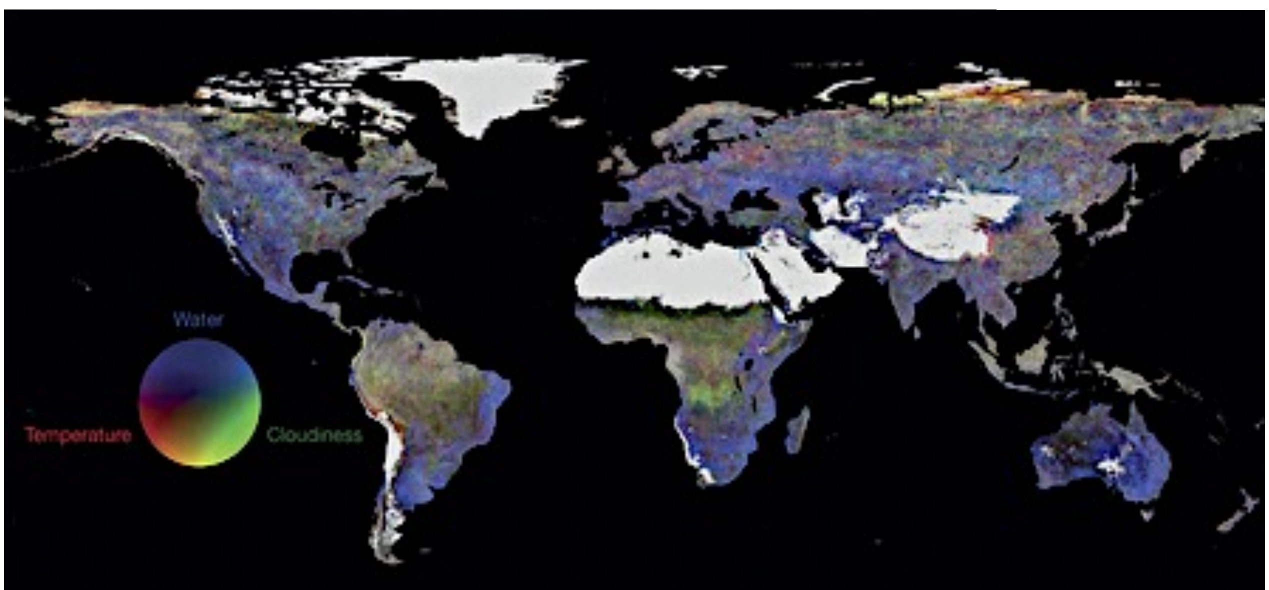


So as you decide what biosignatures to look for, the next question is: What kind of planet(s) will provide them in abundance?

Water availability the #1 limiting climate factor for land biomass

Churkina and Running (1998): Biogeochemical model

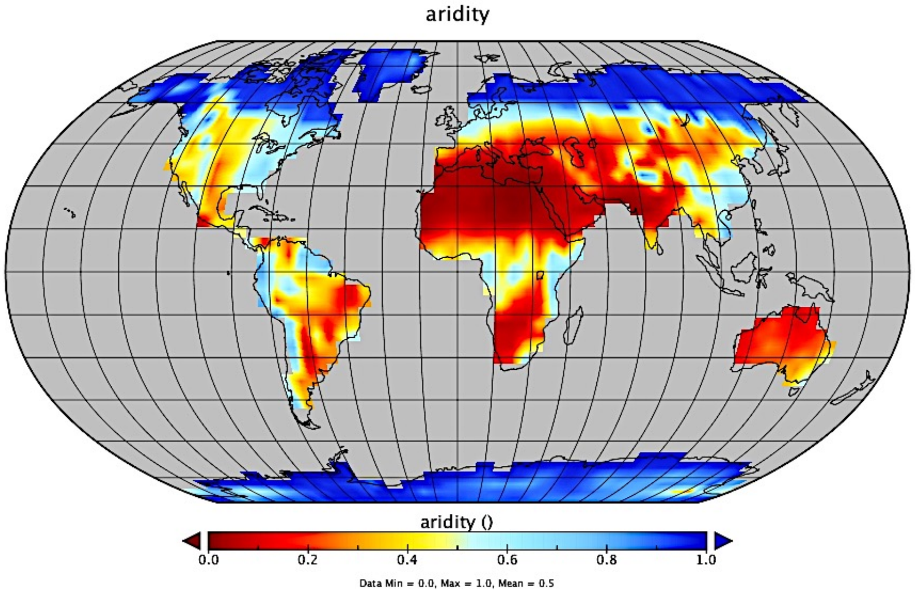




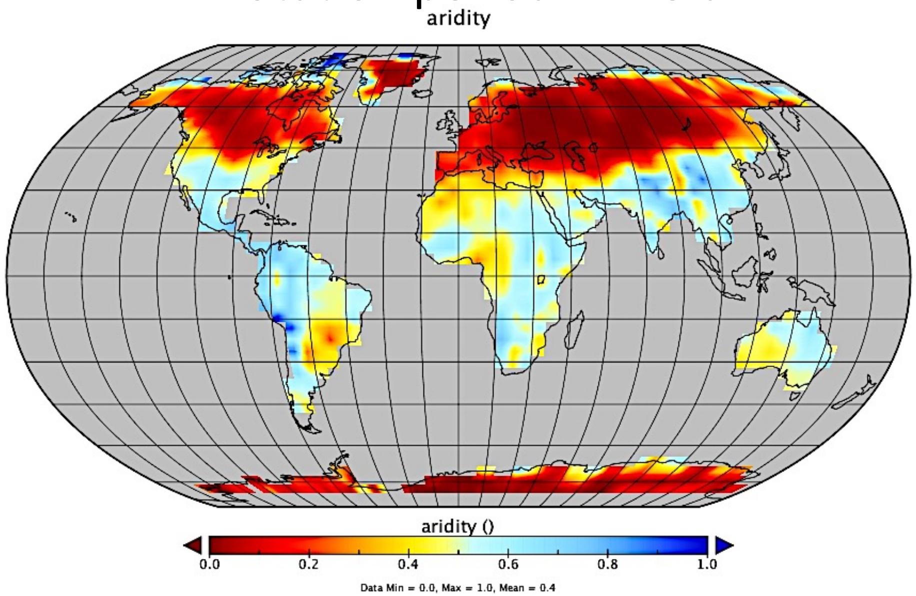
Seddon et al. (2016): Vegetation sensitivity index (MODIS near-IR vs. vis and retrieved climate variables)

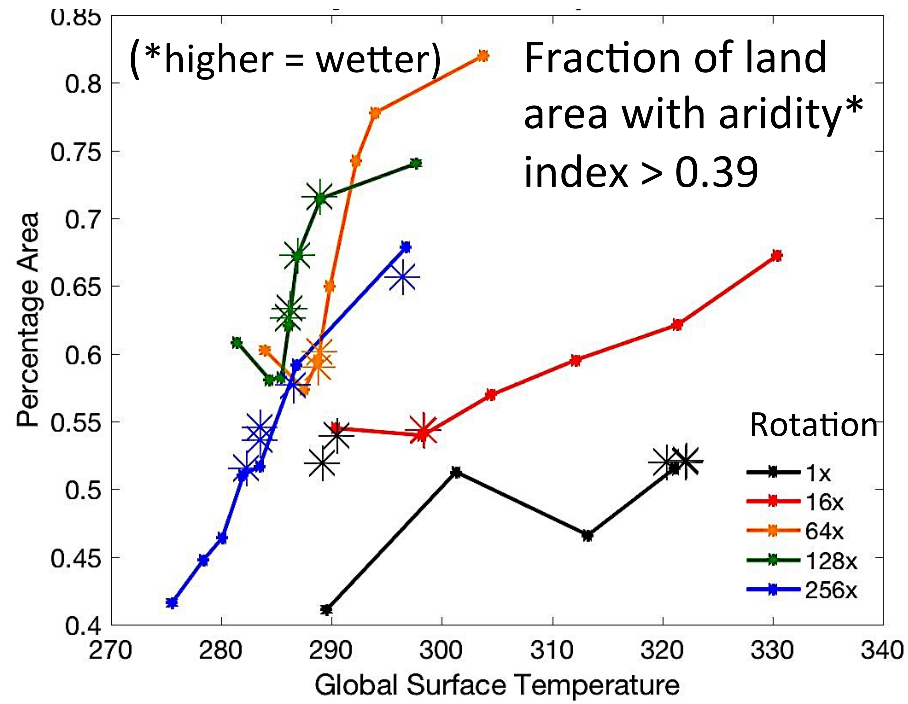
What kind of planet maximizes available water?

Rotation period = 1 d



Rotation period = 128 d

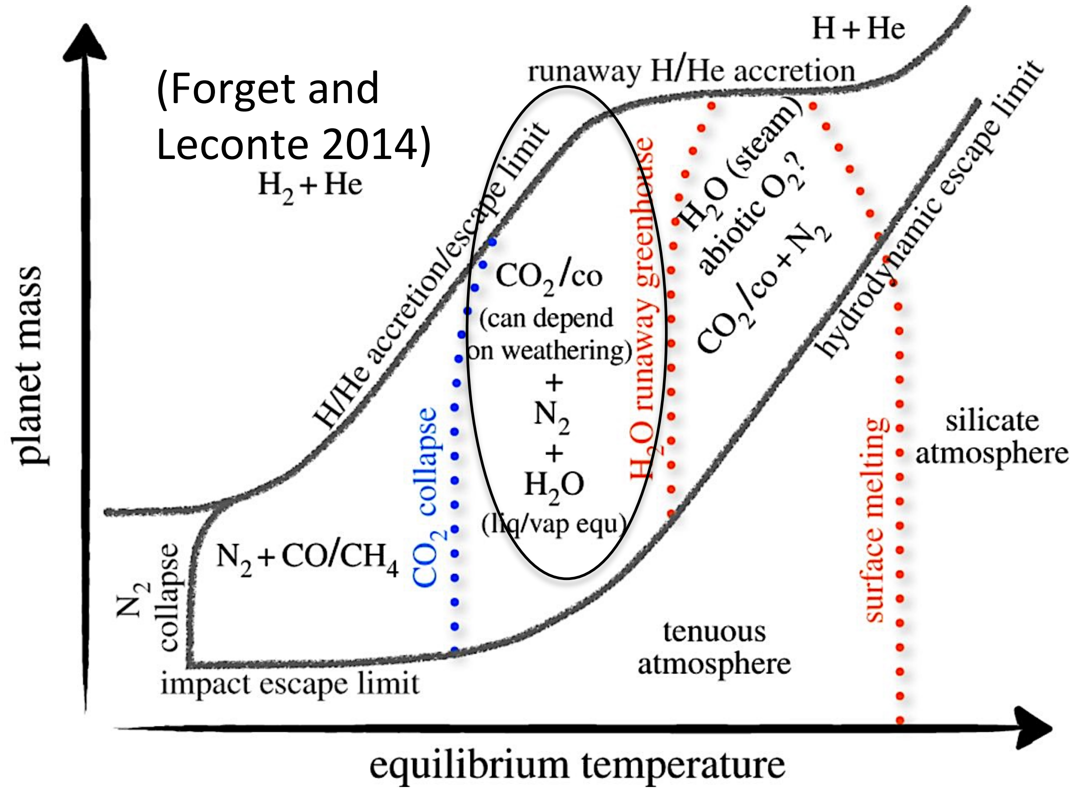




0° obliquity worlds:

More land area with "humid" climate for slow rotators and higher instellation – stronger biosignature?

(Way et al,. in preparation)

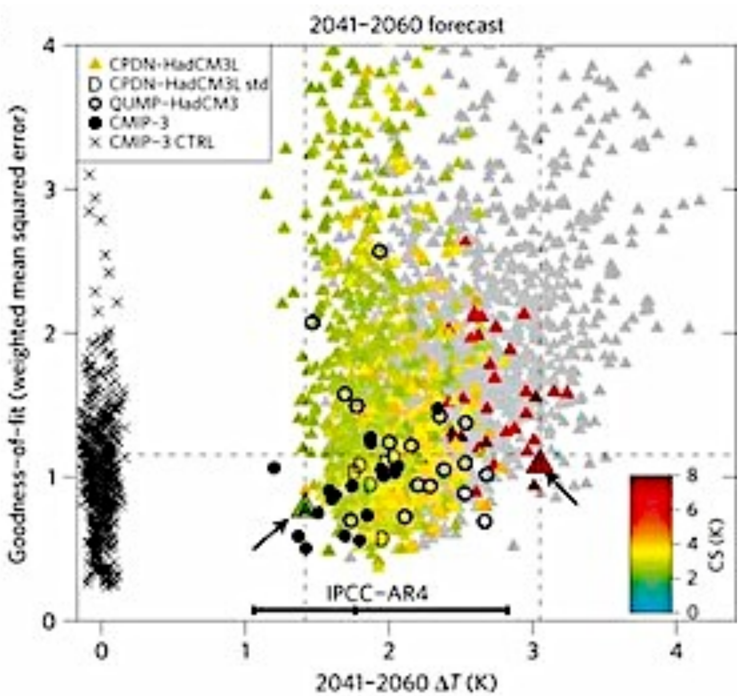


So rather than look for exo-Earths, run many simulations and look for something better (and with stronger biosignatures)

Benchmark atmospheres (loosely after Hu et al. 2012):

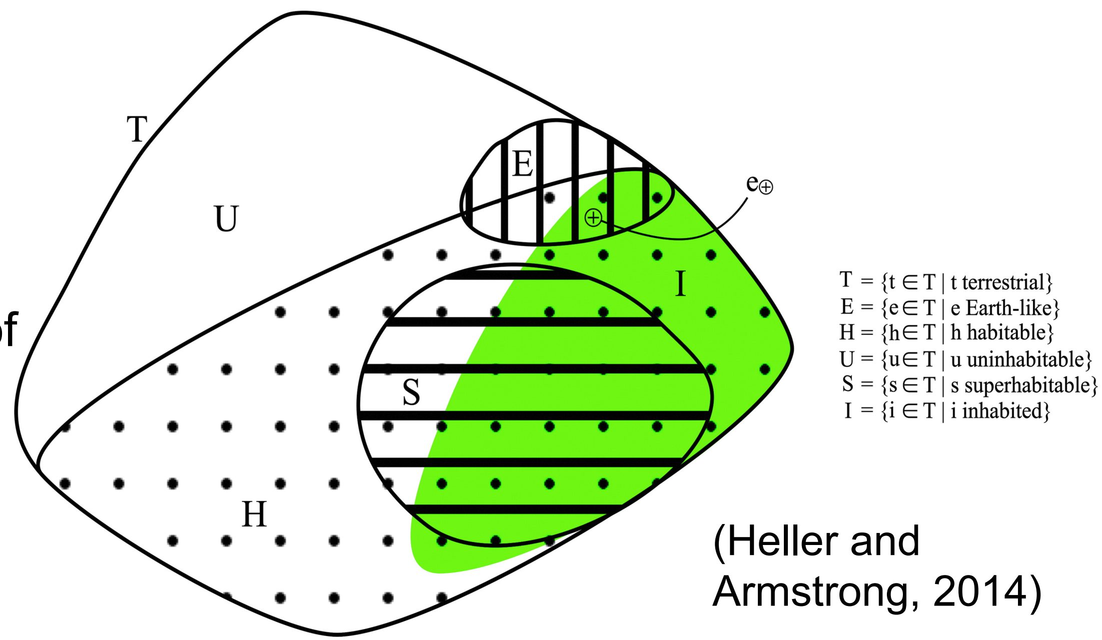
- Earth-like (N_2, O_2 + trace GHGs)
- Archean Earth-like (N_2 + minor GHGs)
- Mars-like (highly oxidizing: CO_2, N_2 + ?)
- Super-Earth (highly reducing: H_2, N_2 + ?)

Perturbed parameter ensemble approach



Earth climate change: Thousands of GCM simulations with varying combinations of free *internal* parameters (e.g., cloud properties) to establish a probable range of global climate sensitivity to increasing CO_2 (Rowlands et al., 2012)

Exoplanets: Vary *external* parameters (size, gravity, rotation, composition, star, etc.); find parts of parameter space most conducive to habitability (or biosignature detectability), assess ability of spectra to differentiate planets



(Heller and Armstrong, 2014)

What parameters affect planetary climate (and maybe our ability to detect a biosignature)?

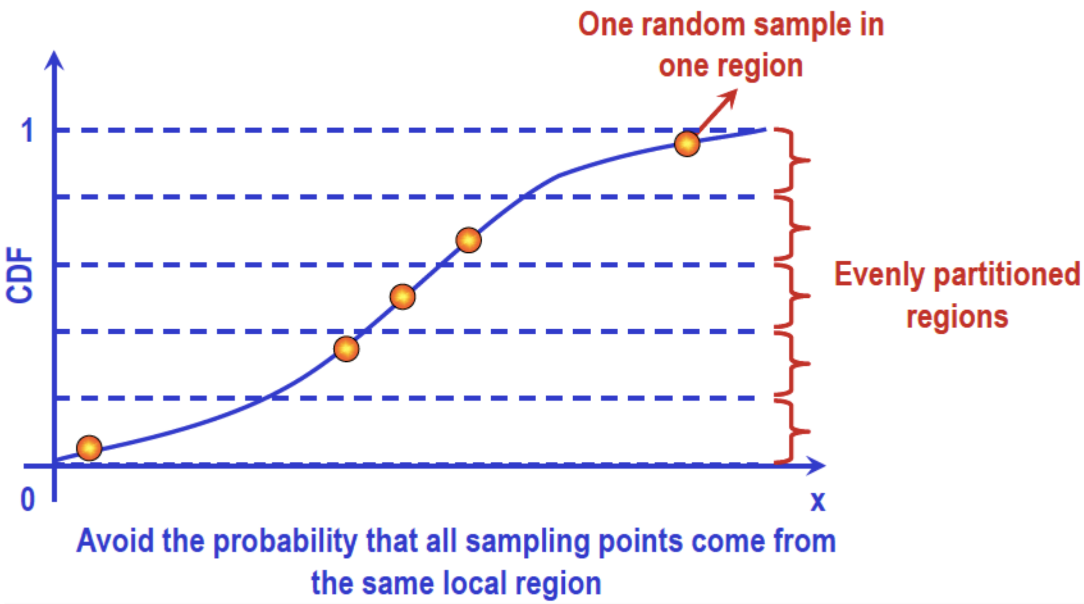
- Stellar temperature ✓✓✓
- Total pressure of "background" gases (N_2, CO_2, H_2) ~✓
- Trace greenhouse gas concentrations (CO_2, CH_4, etc.) ✓
- Rotation period ✓✓
- Orbital period ✓✓✓
- Obliquity ~ ✓
- Eccentricity ~✓
- Planet radius ✓
- Planet mass ✓
- Land-ocean dist. ✓

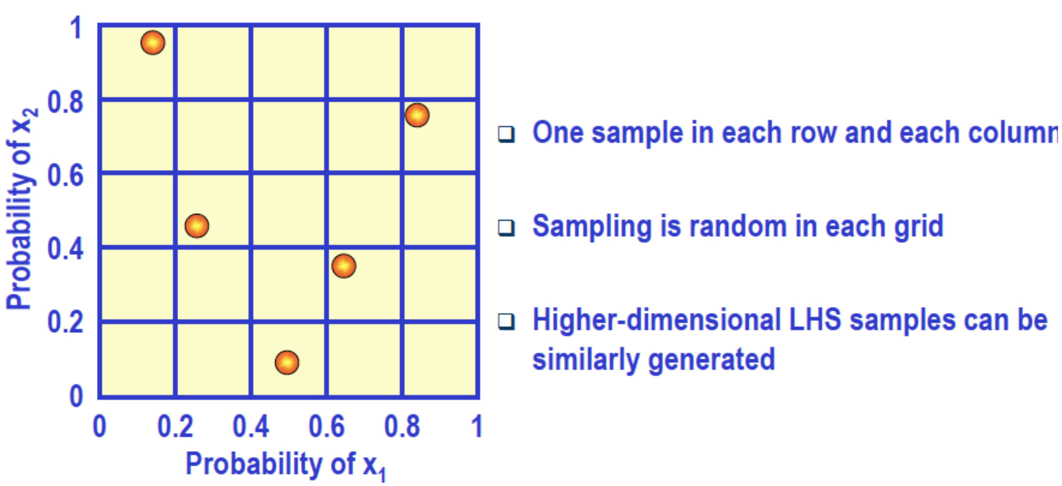
(✓ = transit; ✓ = direct imaging; ✓ = RV)

For 6 free parameters, 729 simulations to sample high/med/low values of all; for 10, ~59K simulations

One way to deal with this:

Latin hypercube sampling



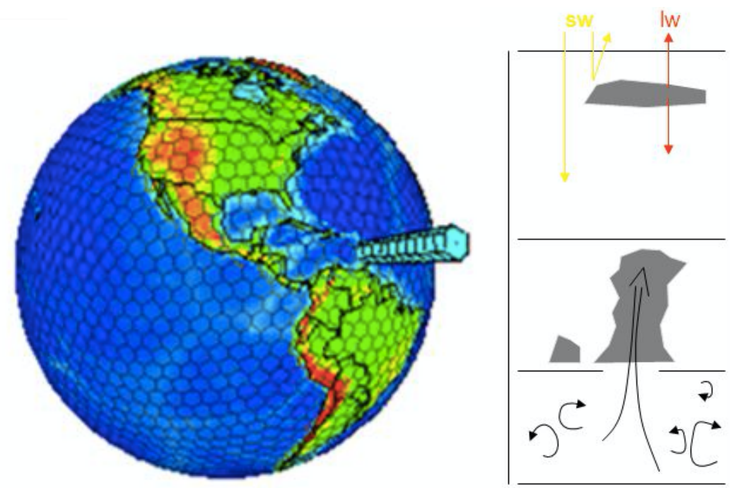


But need to fill gaps:

1.) Statistical or non-statistical emulators:

(e.g., Sanderson et al.2008; Rougier et al. 2012)

2.) Physical: 1D or Single Column Model

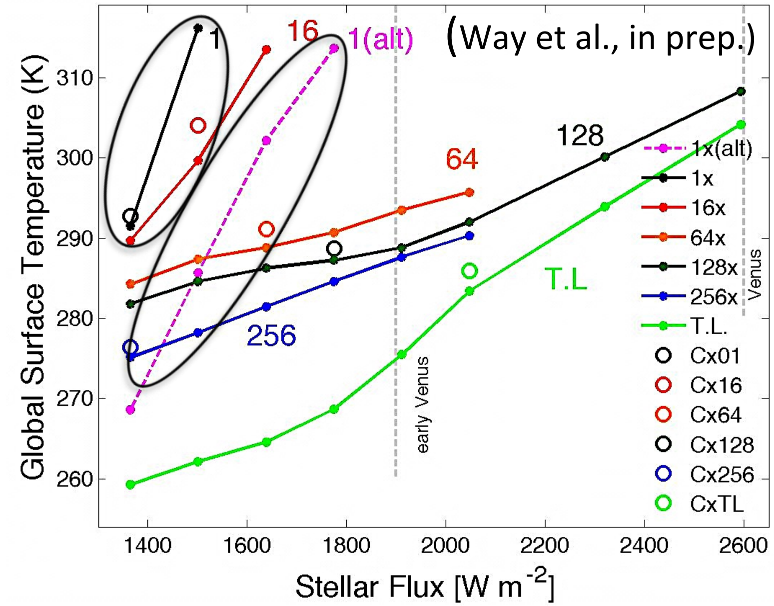


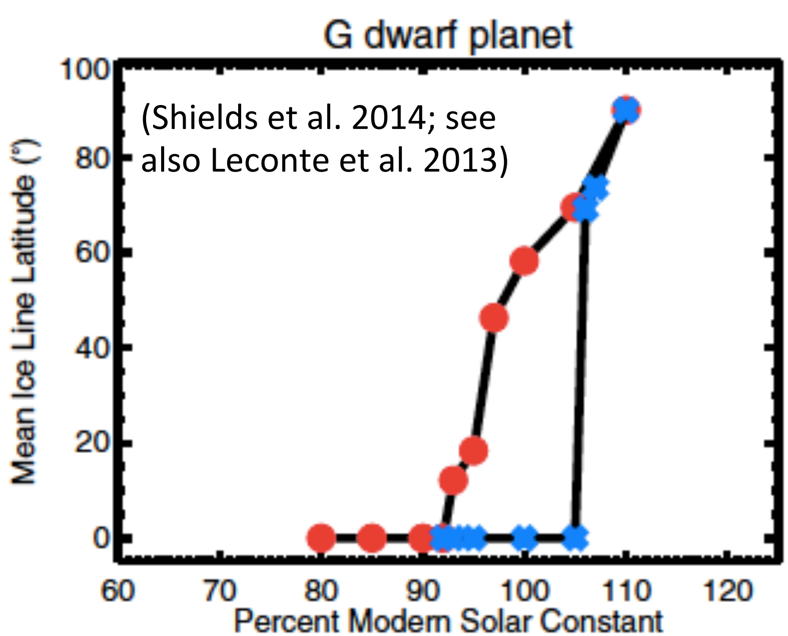
(but see Leconte et al. 2013, Godolt et al. 2016)

Model uncertainty

Free parameters in every model (e.g., cloud formation, properties) preclude definitive statements about HZ limits

Different models + PP ensemble for a given model needed to sort out robust vs. model-dependent behavior





Sensitivity to initial conditions, hysteresis – potentially > 1 equilibrium state for a given forcing

Role of ocean dynamics needs to be further explored

Looking to the future:

- 3-D interactive atmospheric chemistry
- Ocean chemistry
- Tidal effects on habitability
- Embrace model improvements: More realism, not necessarily more Earth-specificity

Bottom line:

- Don’t pop the cork until you understand what kind of planet is producing your biosignature – does your biosignature make sense?