The habitability of Gl 581c and Gl 581d, and equatorial super-rotation over tidal-locking terrestrial exoplanets

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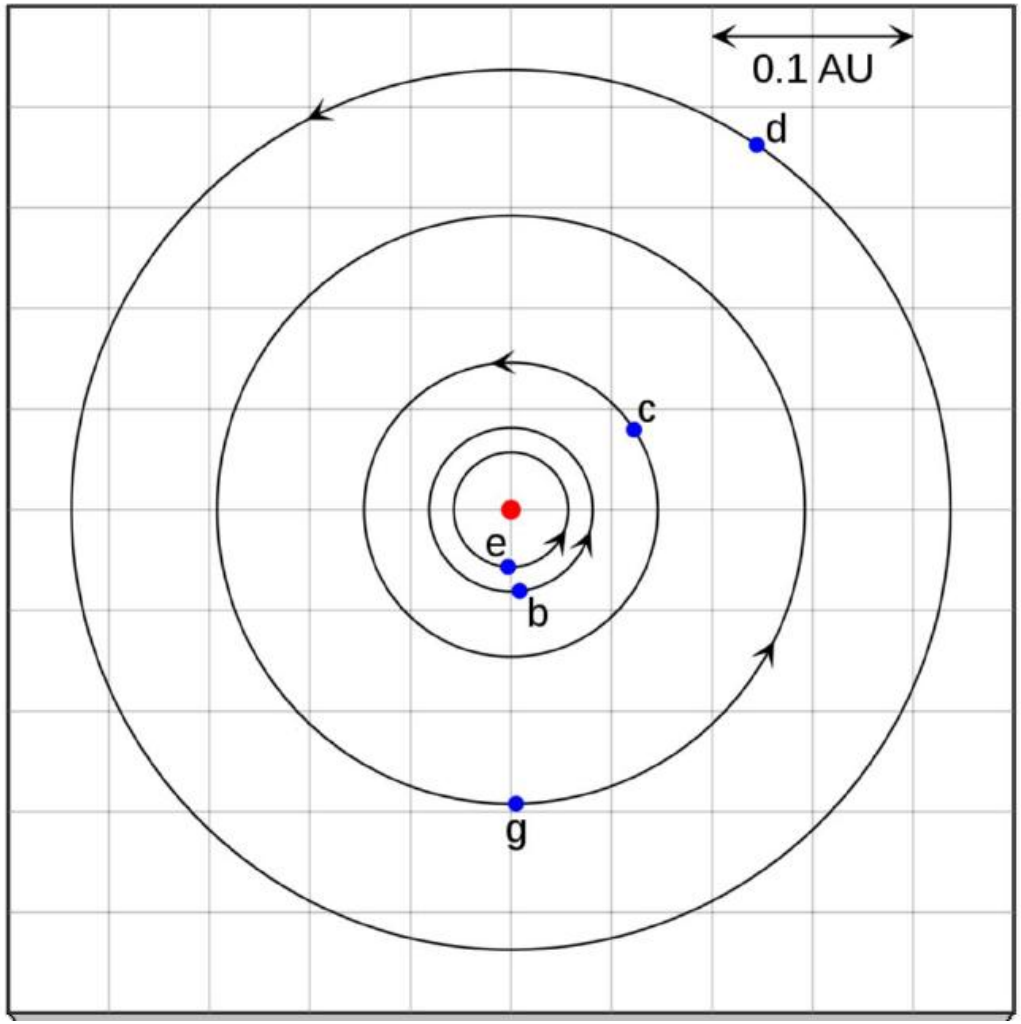
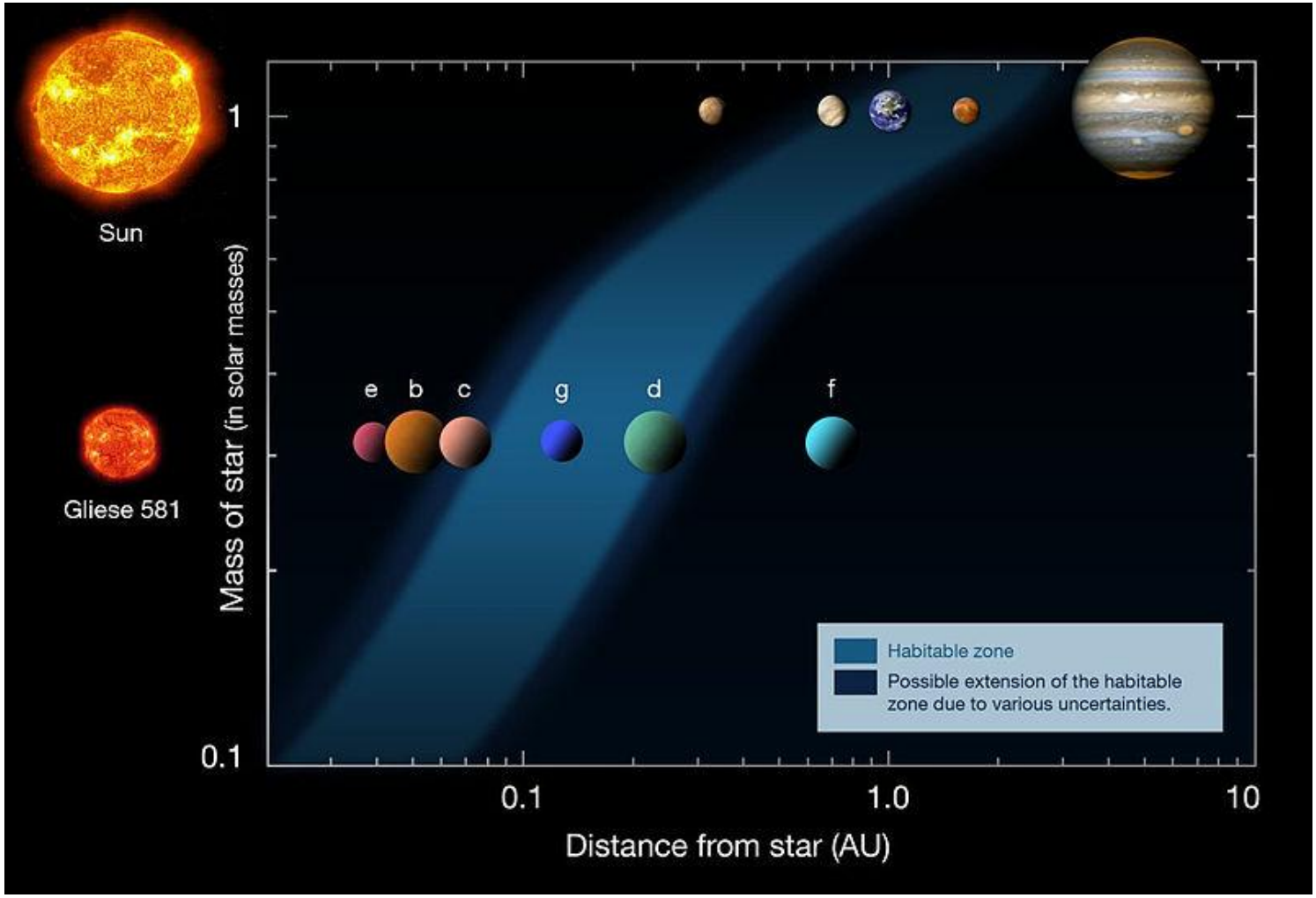
Two super-Earth exoplanets were discovered in April, 2007, i.e., Gl 581c and Gl 581d （Udry，et al. 2007）



Surveys on the habitability of Gl 581 c and d can be found in Selsis et al. (2007) and von Bloh et al. (2007).

The habitable zone



Necessary conditions of habitability

1. **Existence of permanent liquid water, which requires surface temperature above 273 K.**

2. **However, surface temperature cannot be too high. Otherwise, runaway greenhouse would happen.**

$$273\ \mathrm{K} < T_s < 340\ \mathrm{K}$$

Questions:

1. How high level of CO2 is required to keep the surface temperature of Gl 581d above 273 K?

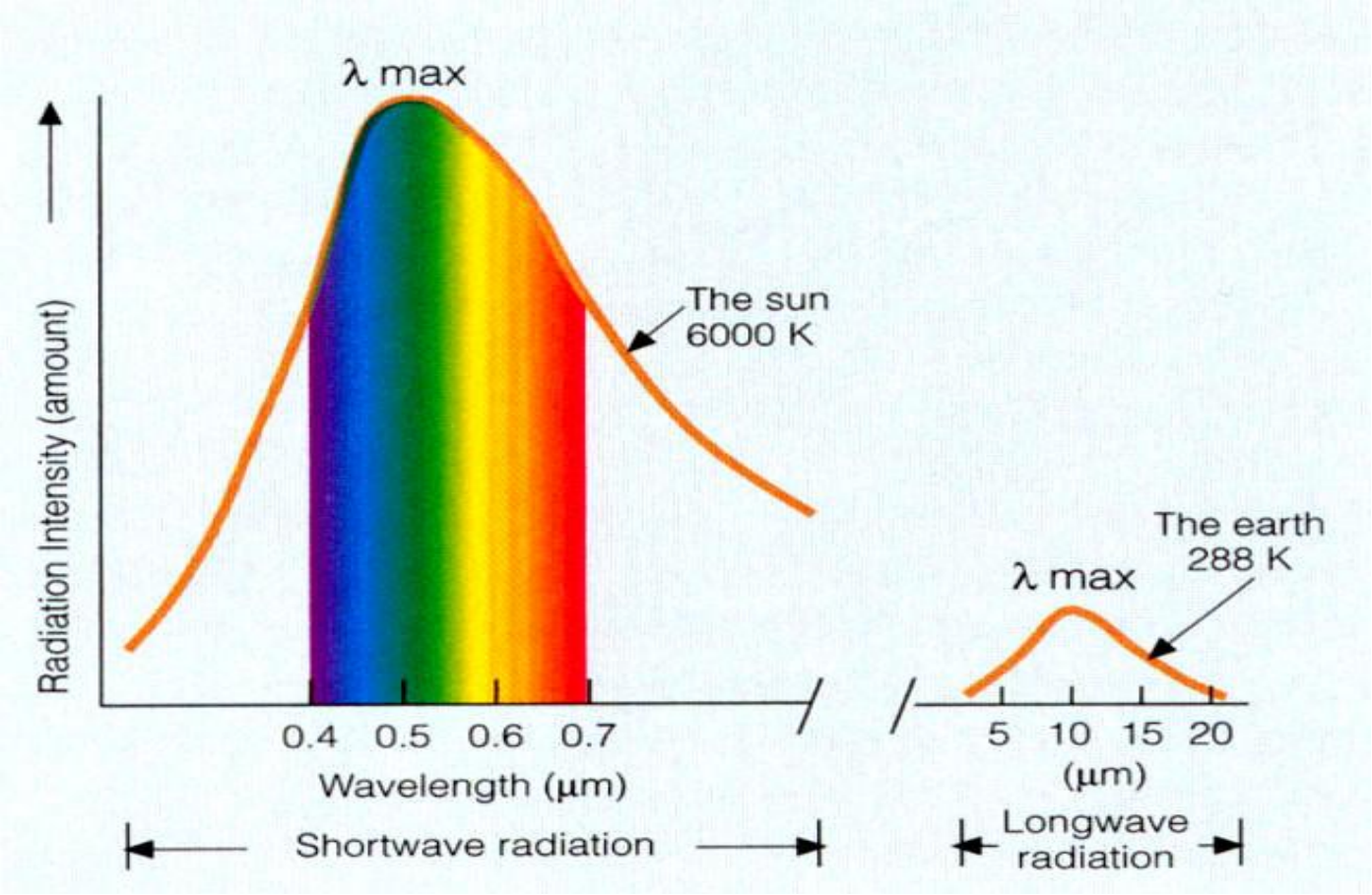
2. Can the surface temperature of Gl 581c be below the threshold of runaway greenhouse?

Atmospheric greenhouse effect

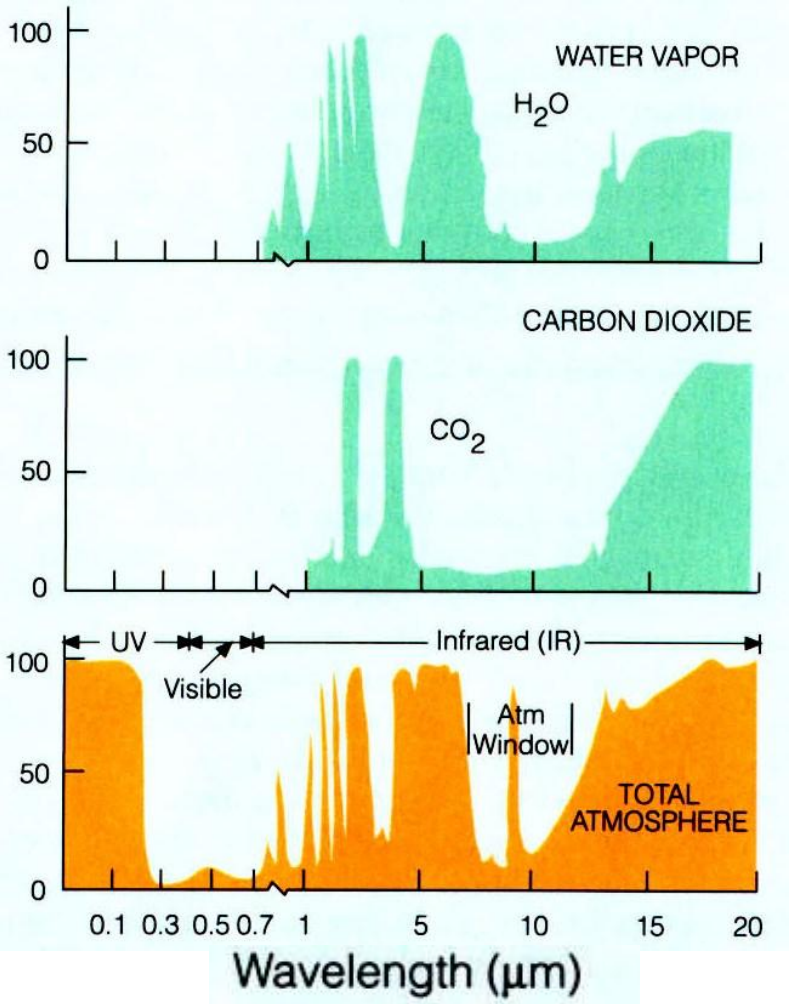
1. **Surface temperature of a planet is also determined by the greenhouse effect of the atmosphere, in addition to by its distance from its parent star and stellar radiation.**

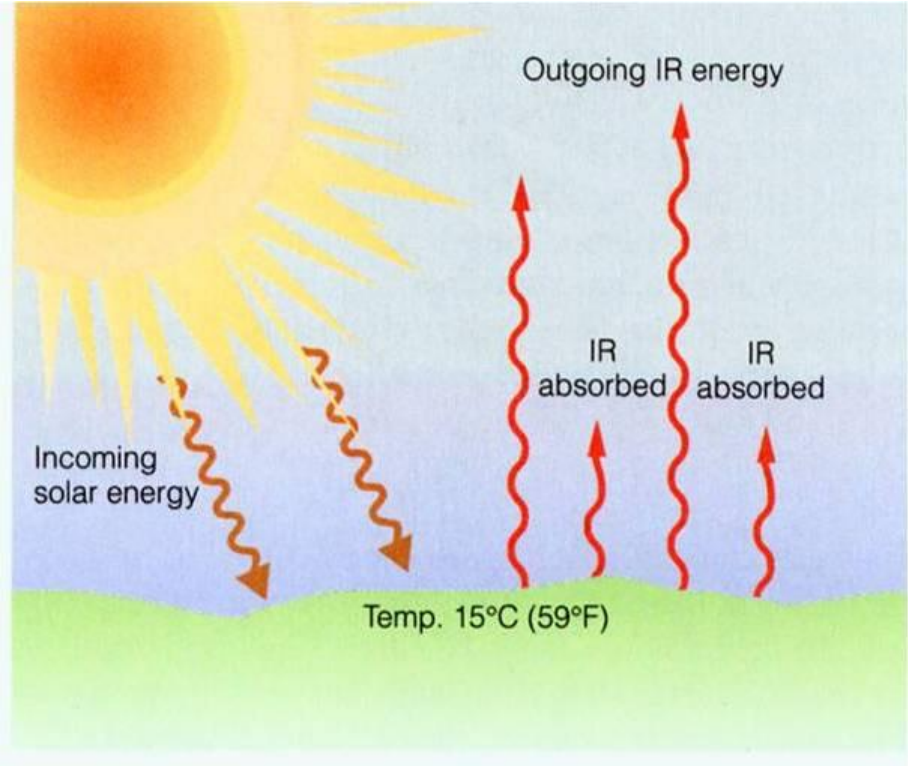
2. **Greenhouse effect raises surface temperature by about 530 and 30 K for Venus and Earth, respectively.**

Radiation spectra of Sun and Earth

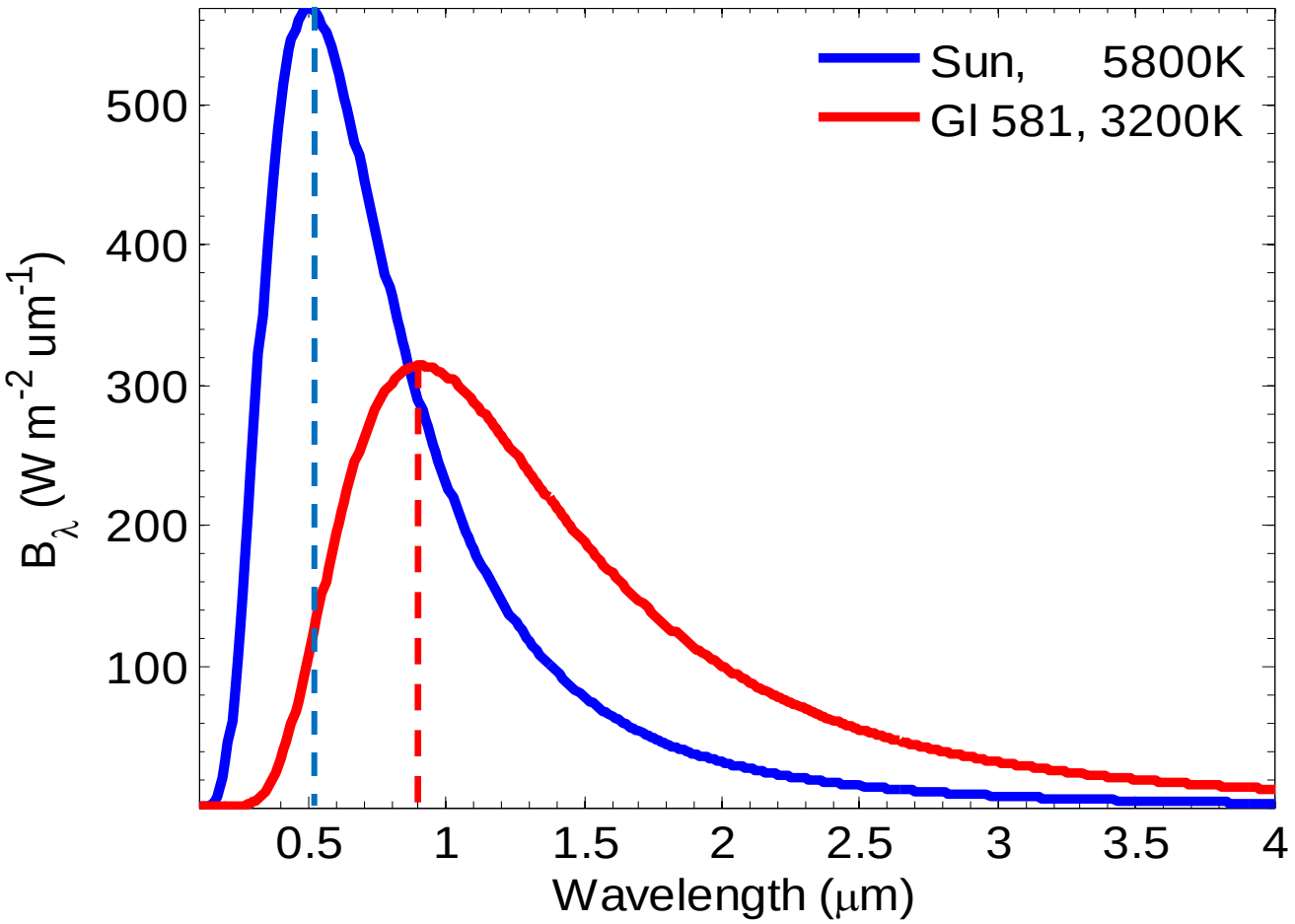


Absorption spectra of CO_2 and H_2O





Comparison of radiation spectra between Sun and Gliese 581



Radiative-convective model

1. The radiation transfer model was developed by Kasting and his colleagues at PSU (Kasting et al, 1984a and b)

2. Convective adjustment： dry-adiabatic

3. Assuming CO2 concentration: 96%, and surface albedo As = 0.15。

4. The model includes pressure-broadening, collision-induced absorption by CO2, and Rayleigh scattering of CO2。

Parameters are from Udry et al. (2007)

Table 1. Properties of the star Gl 581 and its 3 detected planets, from Udry et al. (2007).

Star	T_{eff} (K)	$M/M_\odot$	$R/R_\odot$	$L/L_\odot$
Gl 581	3200	0.31	0.38	0.0135
Planets	a (AU)	$M_{min}/M_\oplus$ *	$R_{min}/R_\oplus$ **	Stellar flux S/S_0***
b	0.041	15.6	2.2–2.6	8.1
c	0.073	5.06	1.6–2.0	2.55
d	0.253	8.3	1.8–2.2	0.21

The potential habitability of planets "c" and "d", highlighted in grey, is discussed in this paper.

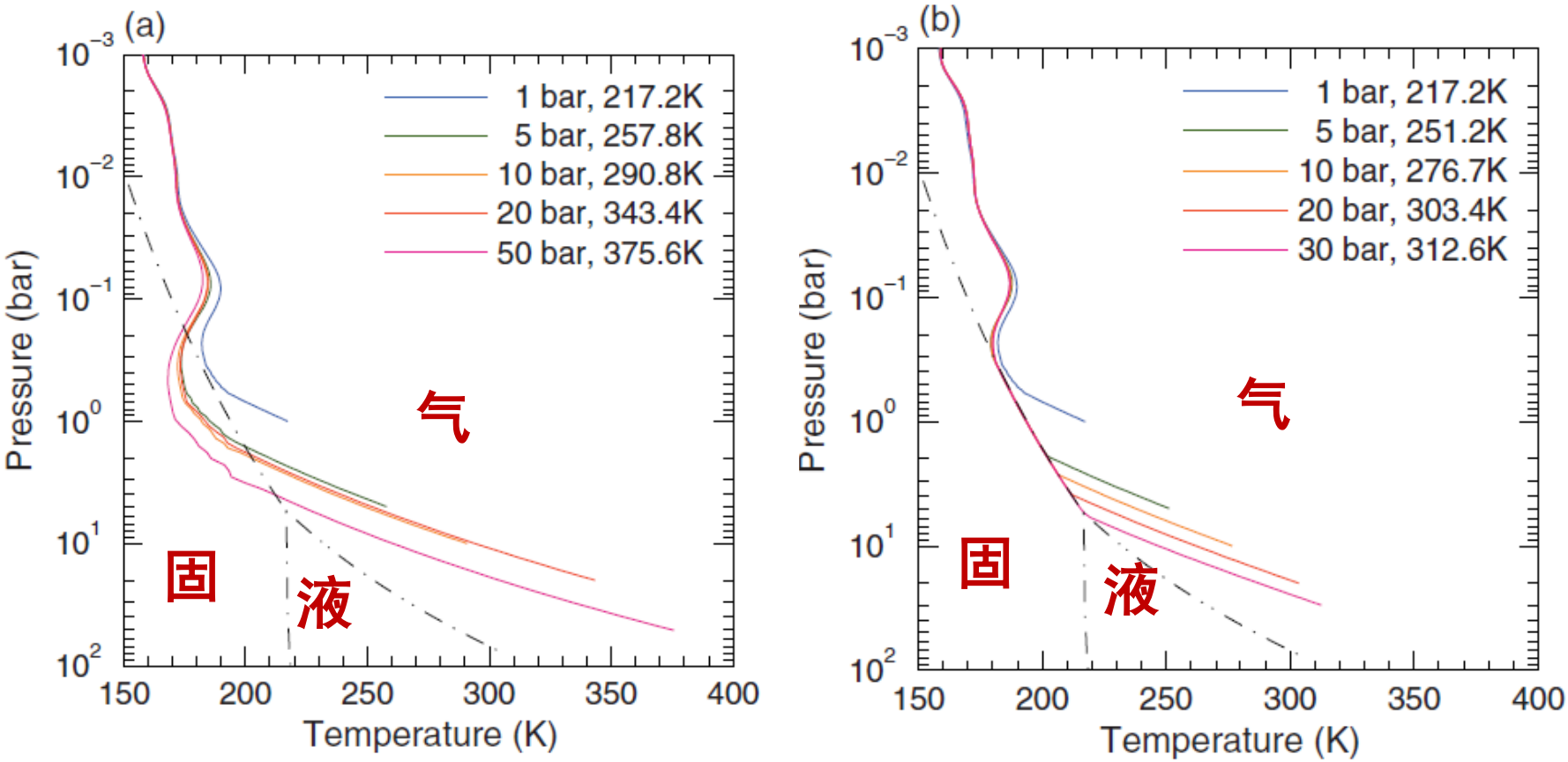
* $M_{min} = M \sin i$, where i is the orbital inclination.

** Radius for a rocky and ocean planet, respectively (Sotin et al. 2007; Valencia et al. 2007b).

*** S_0 is the solar flux at 1 AU: 1360 W m^{-2}.

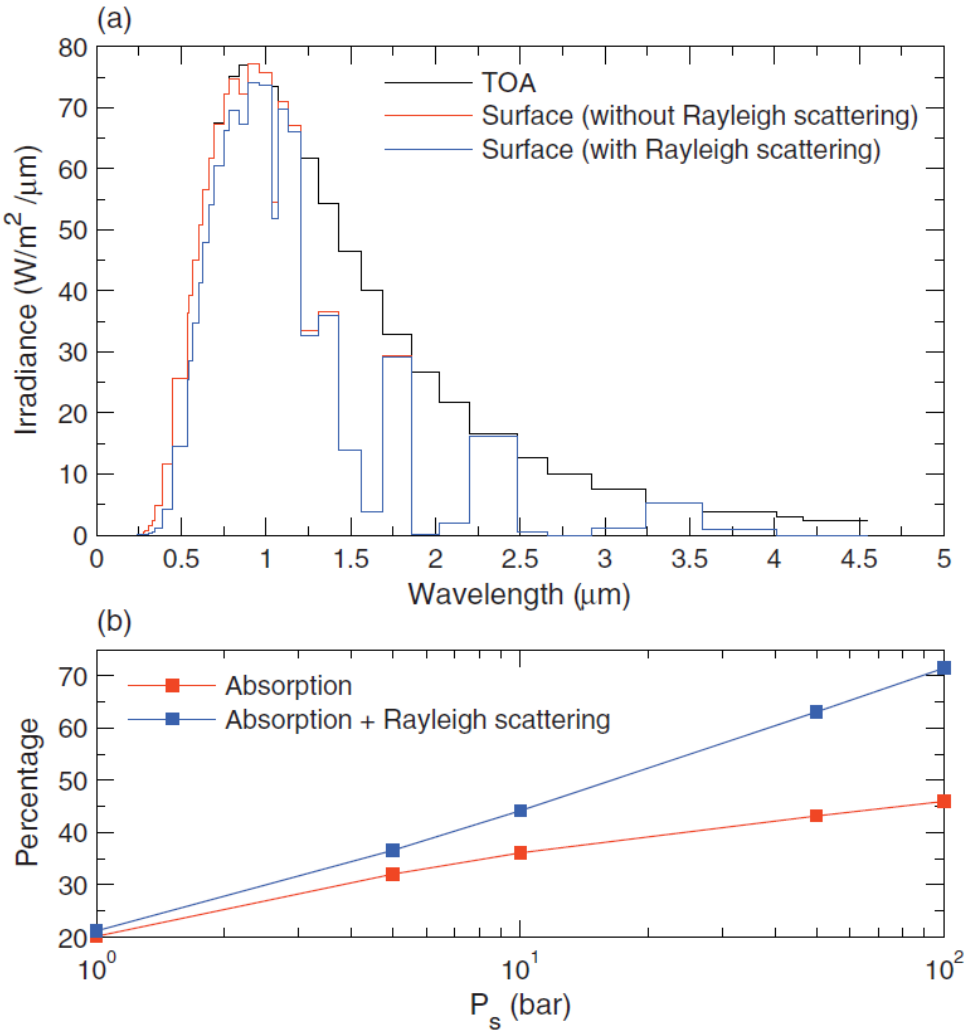
Planets	$M_{min}/M_\oplus$	$r/r_\oplus$	g (ms^{-2})	Γ_d (K km^{-1})	d (AU)
Gl 581c	5.06	1.8	15.3	15.3	0.073
Gl 581d	8.30	2.0	20.3	24.8	0.20

Simulations for Gl 581d, with a dry atmosphere (no water vapor)

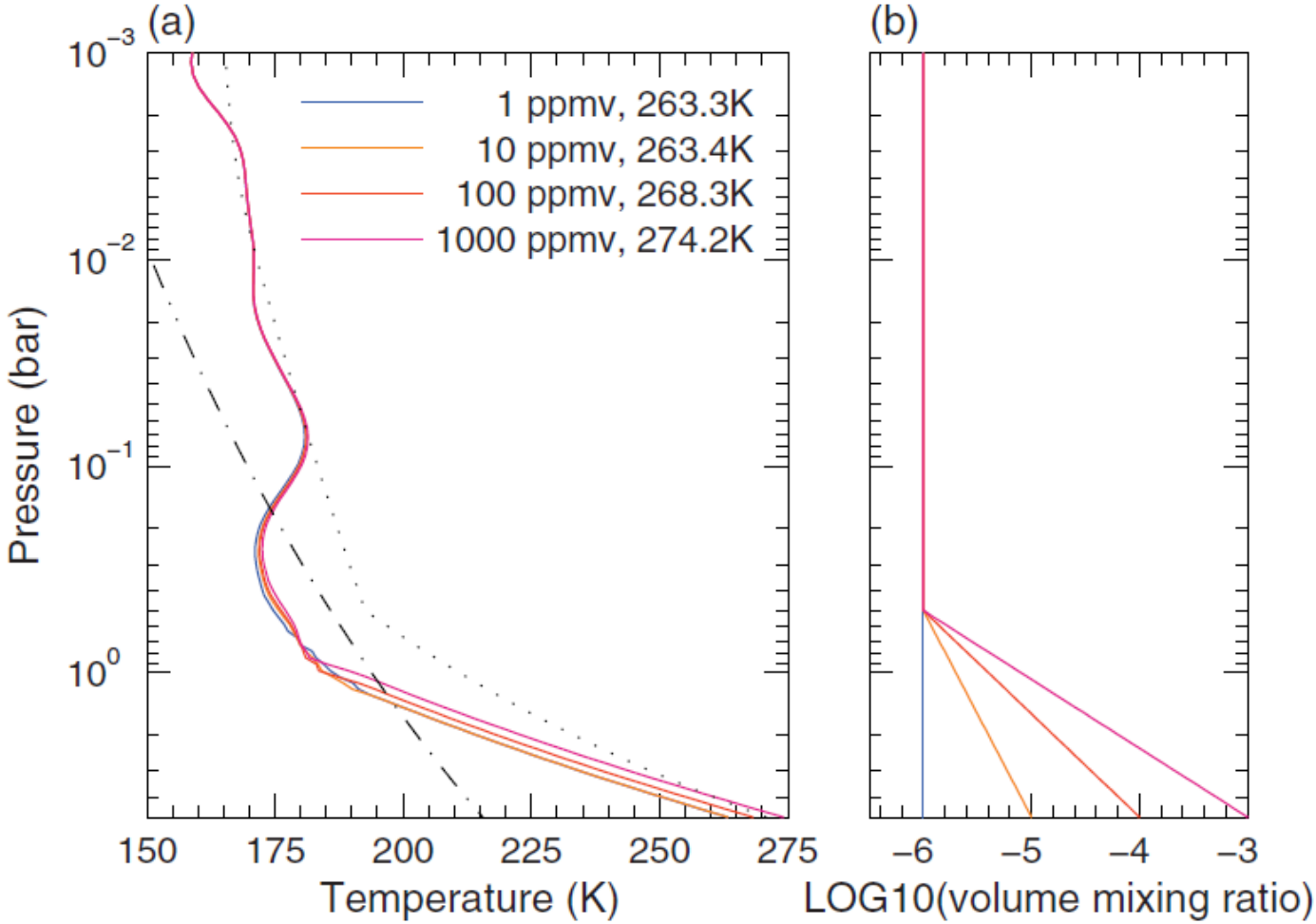


CO_2：96%；反照率A=15%

Gliese 581 stellar radiation absorbed and scattered by CO_2



Simulations for a moist atmosphere (with water vapor, P_{co2} = 5 bar)

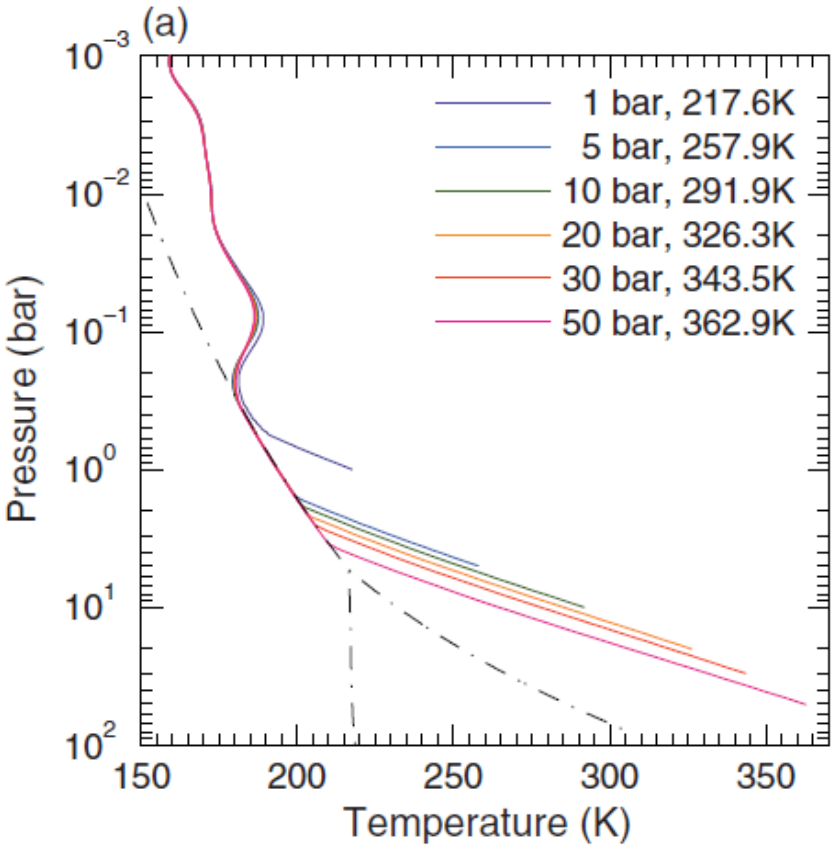


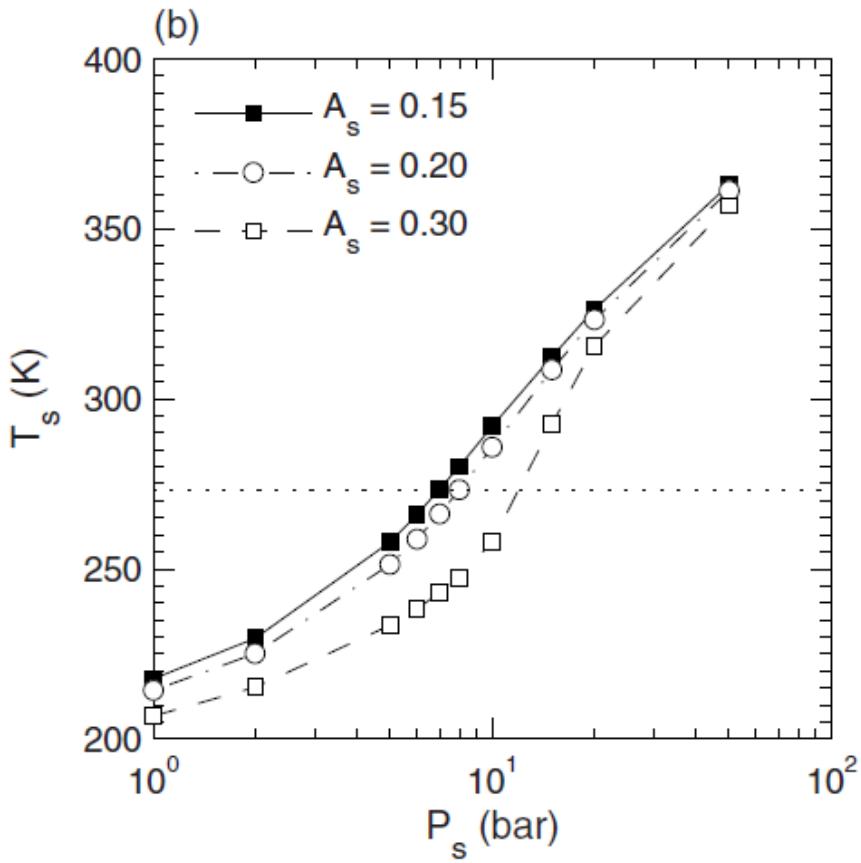
Simulations for fixed relative humidity (surface RH = 80%)

1. Water vapor concentration is determined by air temperature. Water vapor must be condensed out as it is saturated.

2. Usually, fixed relative humidity is used, with which water vapor varies with air temperature.

Simulation results for fixed relative humidity





How to maintain such high levels of CO2 (7 bars)?

If Gl 581d is an aqua-planet, weathering reactions are cut off, so that CO2 can be accumulated in the atmosphere.

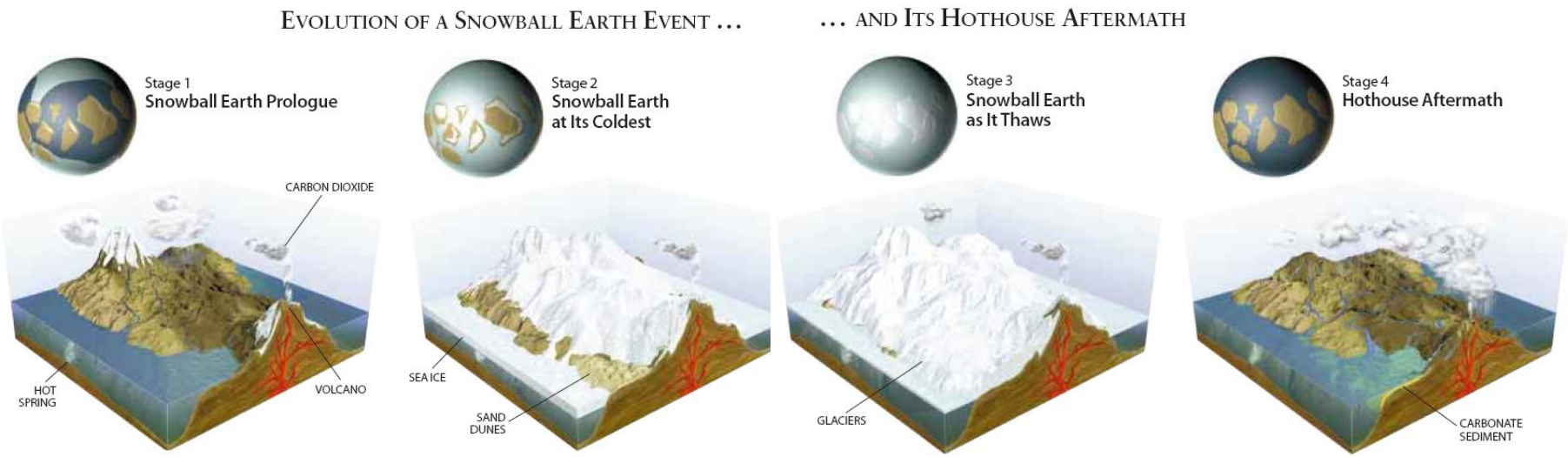
Weathering reactions:

$$CaSiO_3 + 2CO_2 + H_2O \rightarrow Ca^{++} + HCO_3^- + SiO_2$$

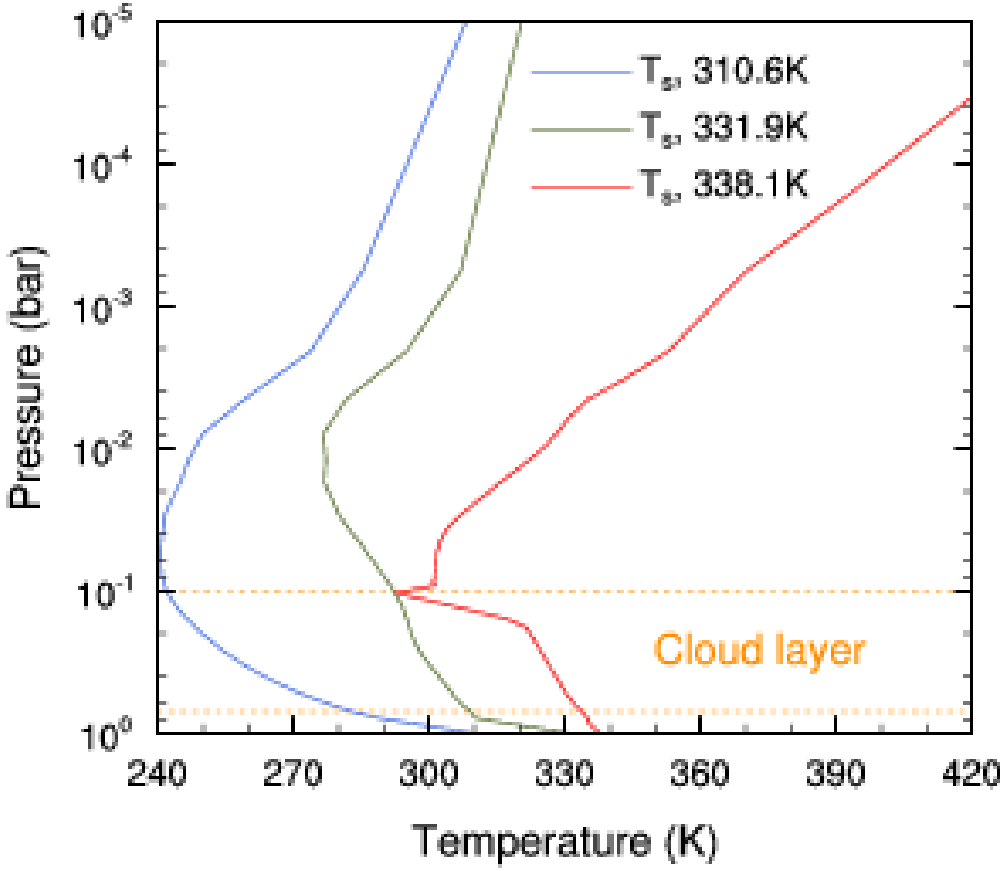
$$Ca^{++} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$$

Net： $CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$

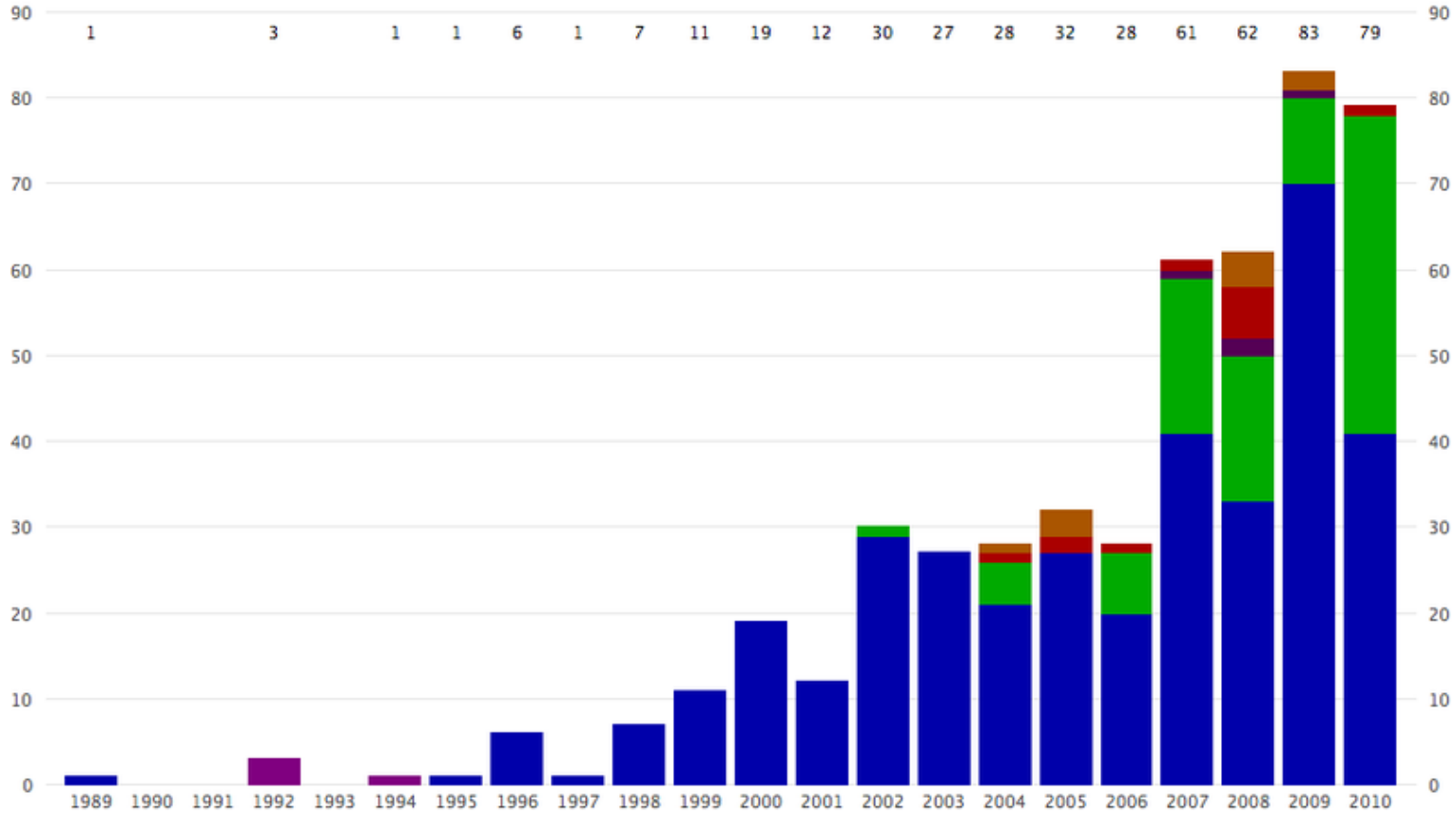
Carbonate-silicate cycle during the Snowball Earth in the Neoproterozoic era (700 Ma ago)



Simulations for Gl 581c



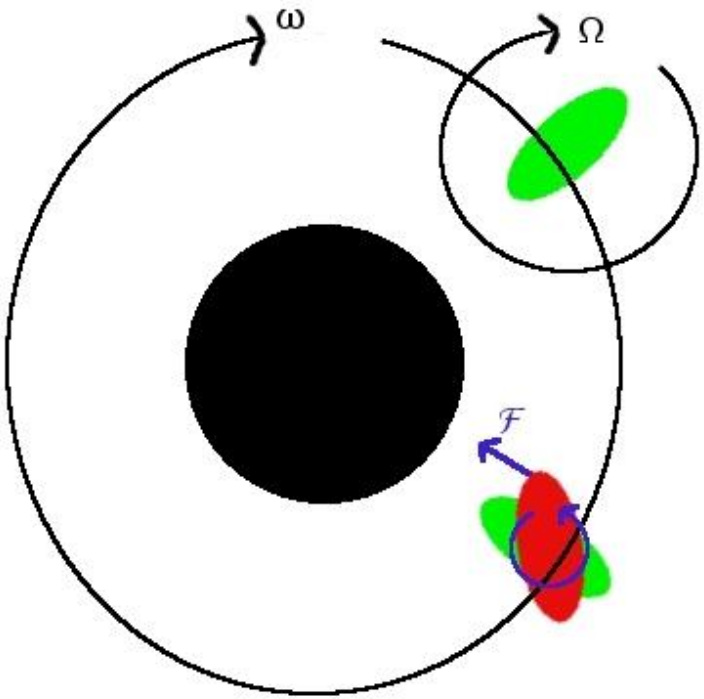
Atmospheric circulations for tidal-locking terrestrial exoplanets

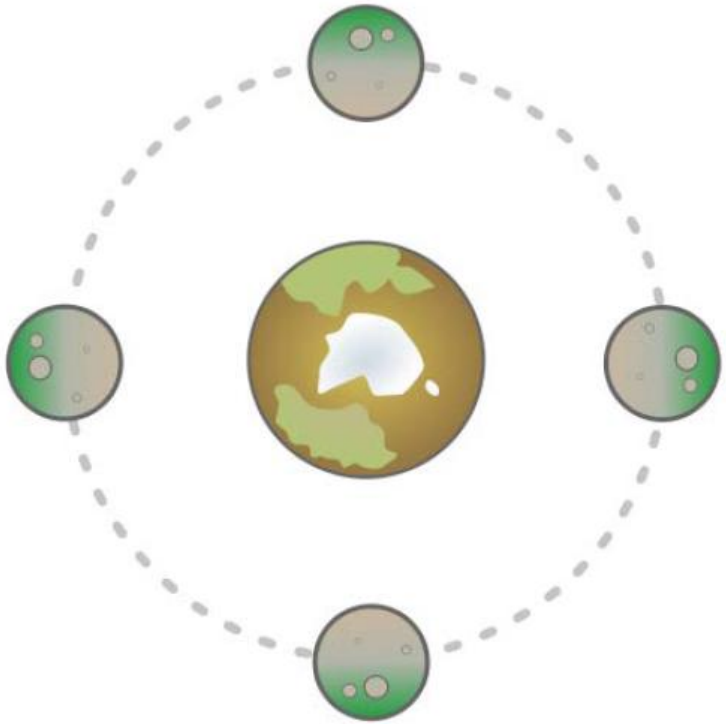


By Dec. 31, 2010, there have been 516 exoplanets discovered. Most are tidal-locking planets.

Tidal locking

As a planet is sufficiently close to its parent star, strong gravitational gradient forces one side of the planet constantly facing the star, resulting in synchronous rotation.





Model and Experiments

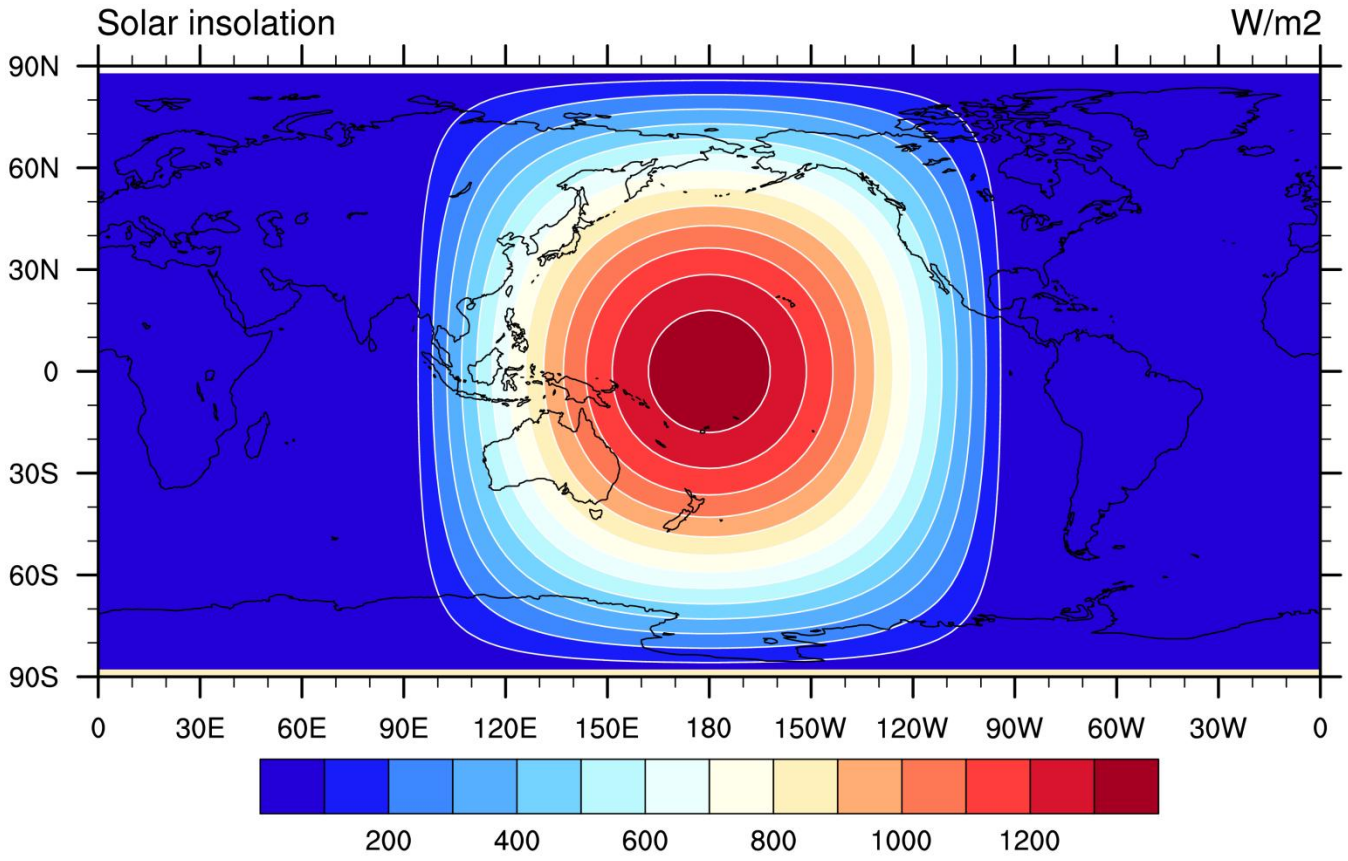
1. **Modified Earth GCM (NCAR-CAM3),**

2. **Earth atmospheric conditions,**

3. **Various rotating rates and stellar insolation,**

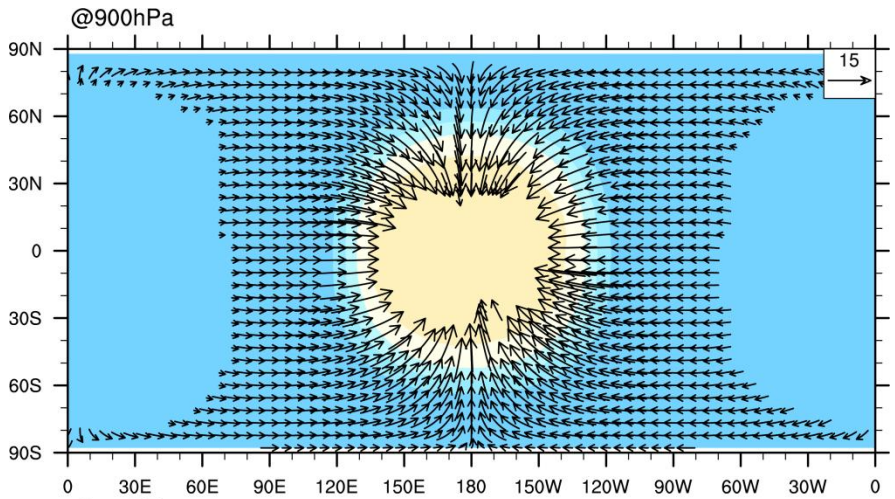
4. **50-meter slab ocean,**

Stellar insolation

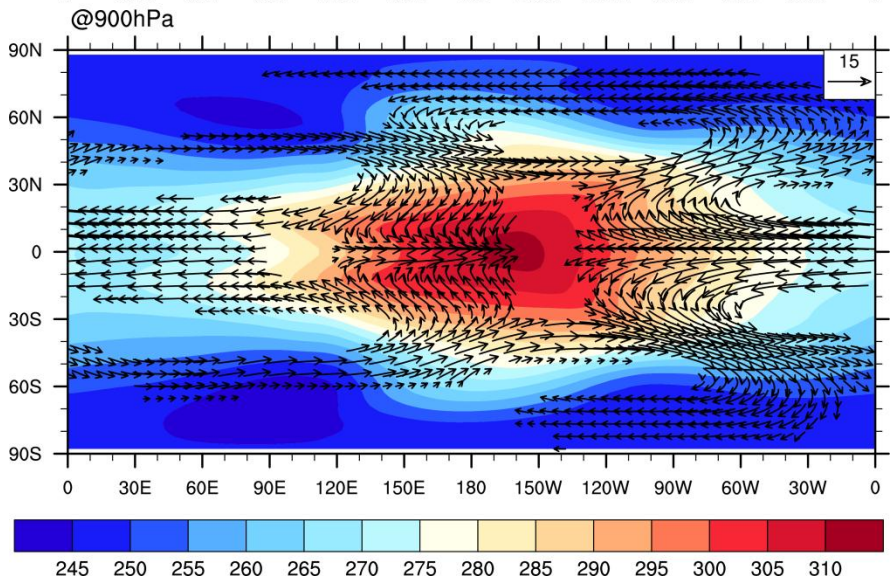


Near-surface winds and temperatures

None-rotating



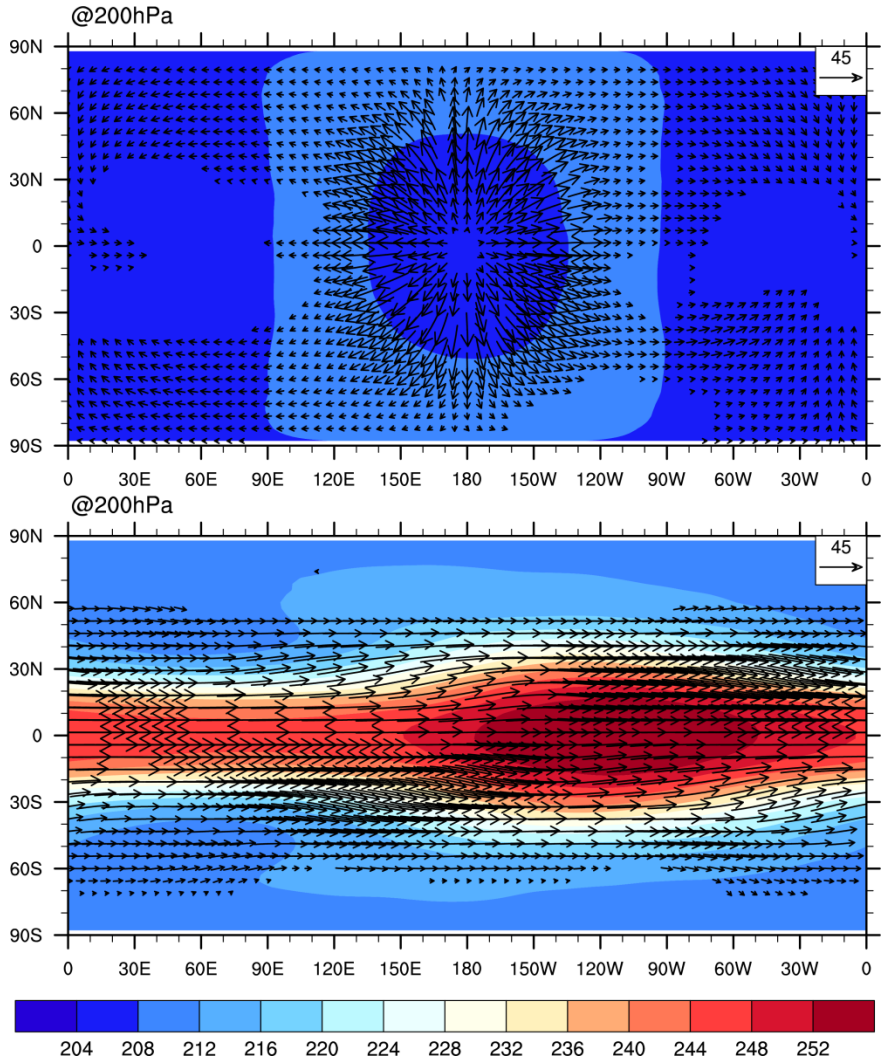
Rotating



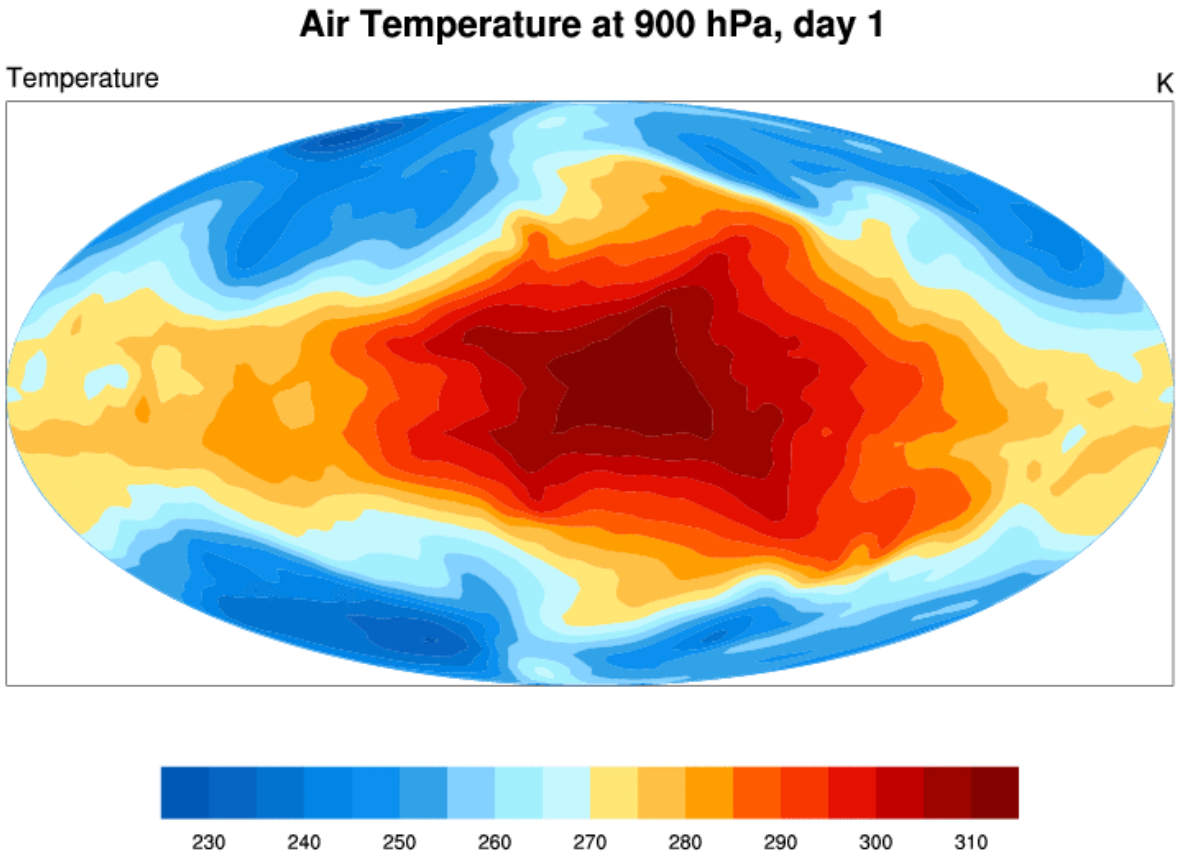
Upper-tropospheric winds and temperatures

None-rotating

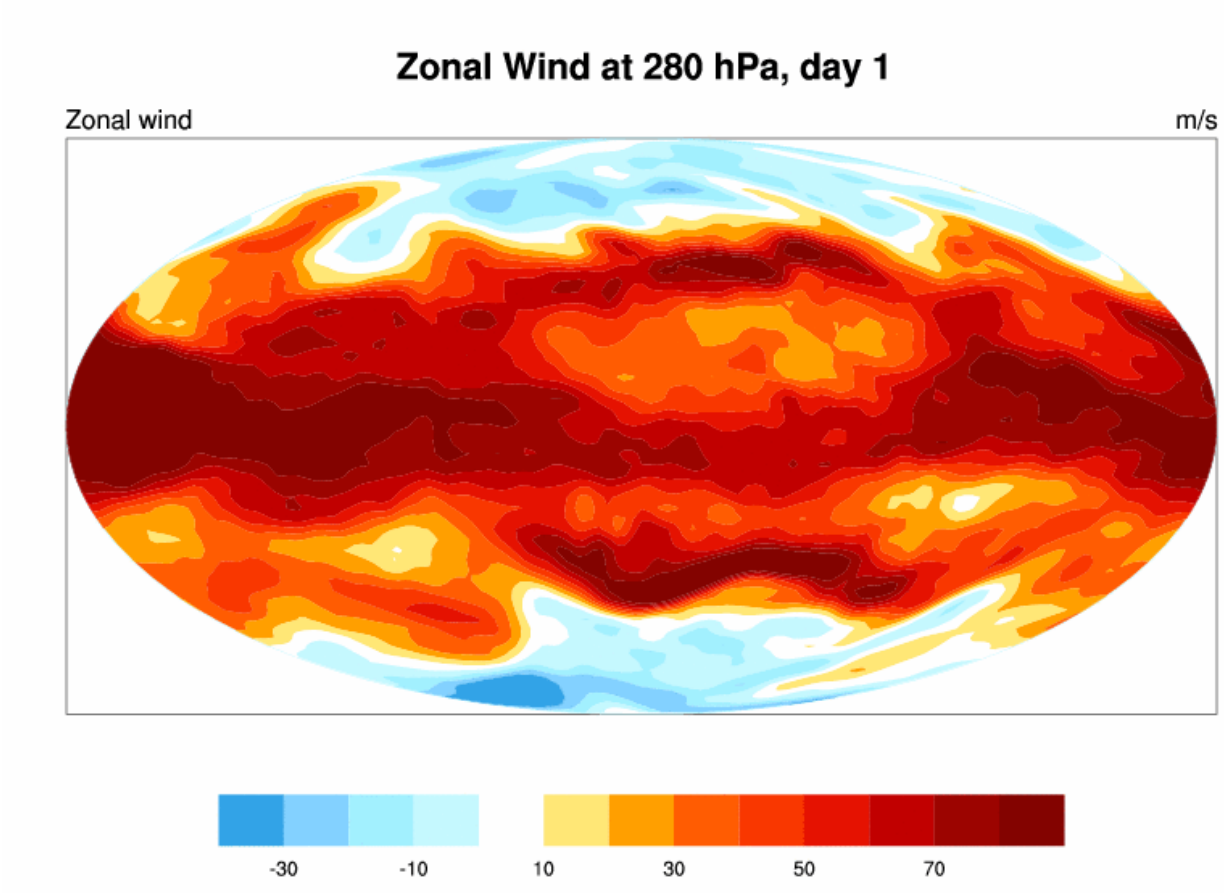
Rotating



Global view of near-surface temperatures

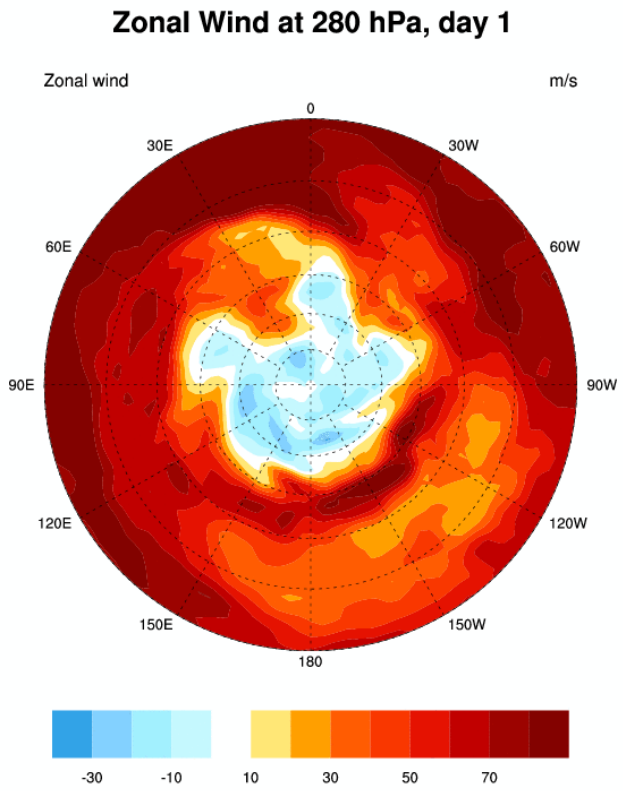


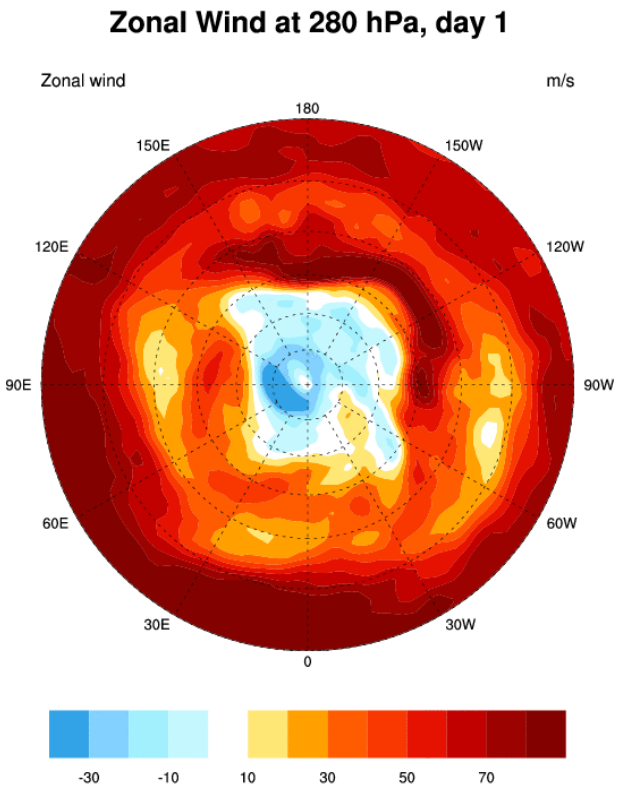
Global view of zonal winds at upper troposphere



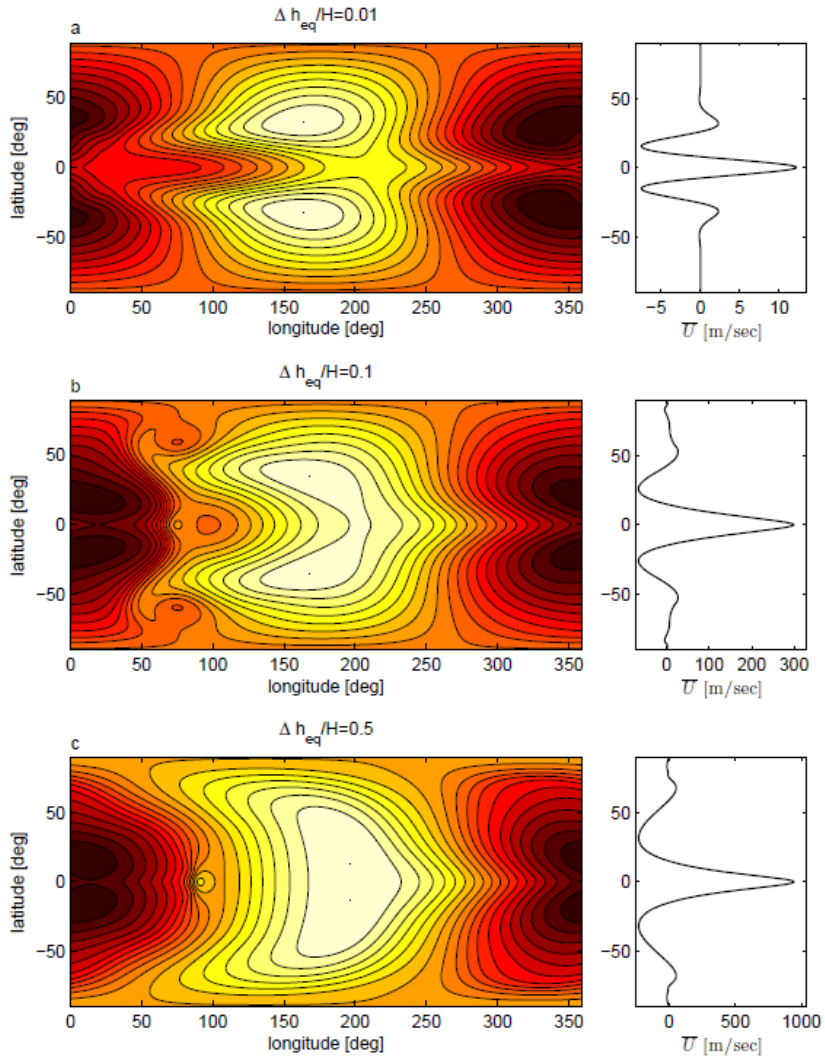
Strong westerly jet over the equator, with maximum winds over the nightside.

Zonal winds over poles

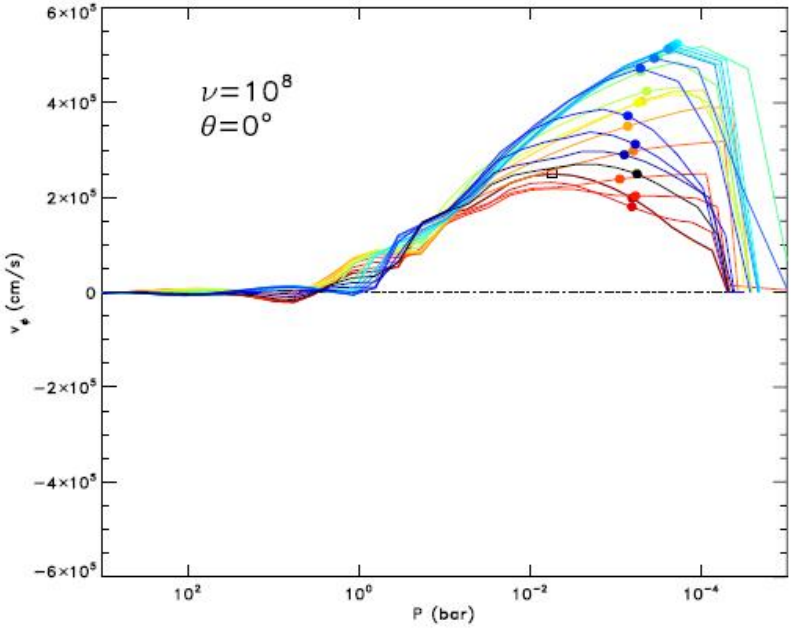


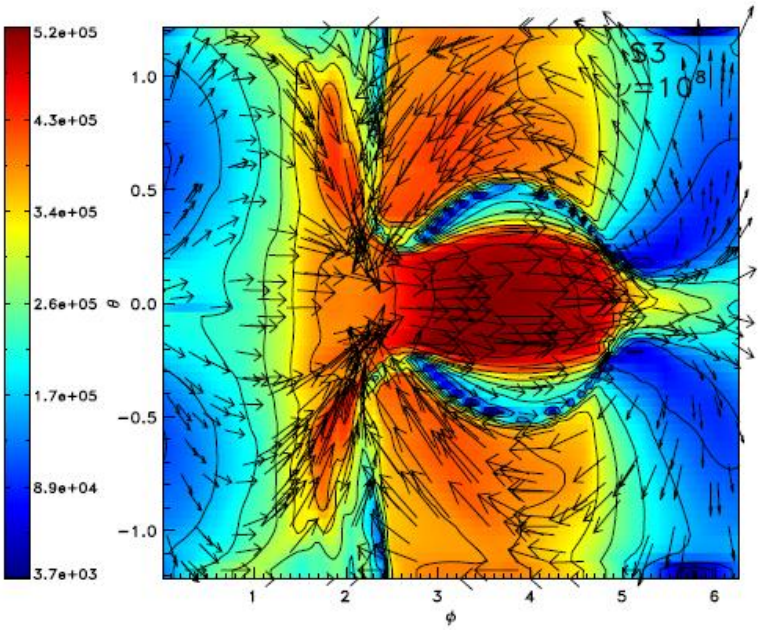


Showman and Polvani's (2011) solution from a shallow-water model

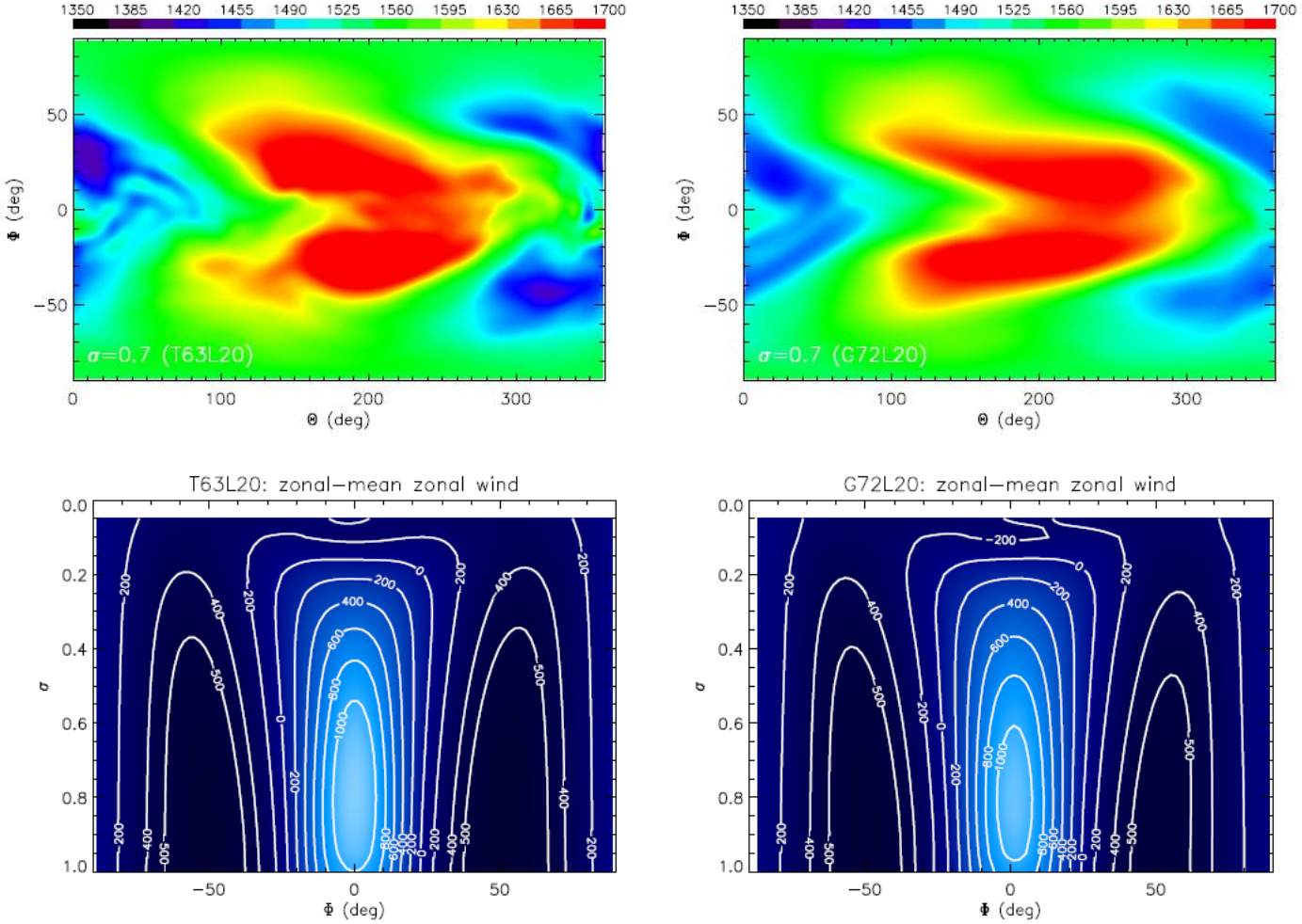


Dobbs-Dixon et al.'s (2010) solution

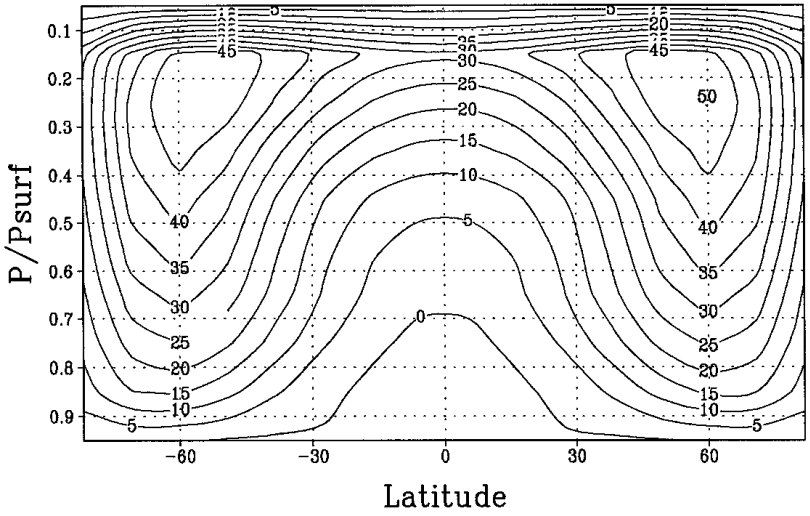


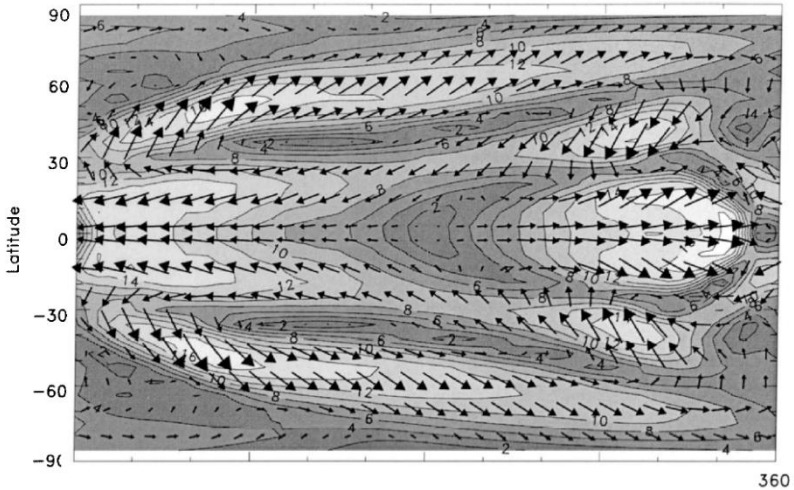


Heng et al.'s (2010) solution

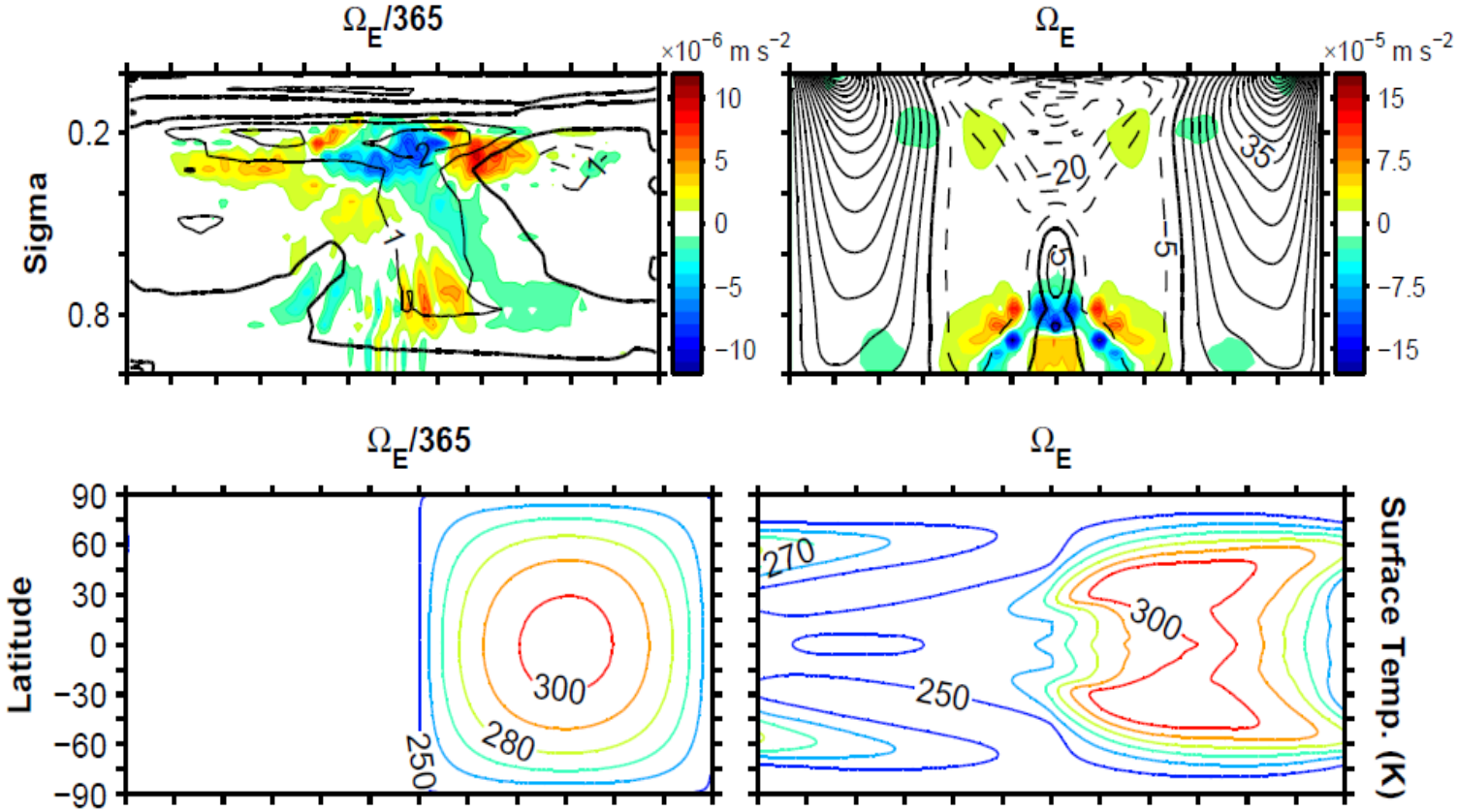


Joshi (1997), Joshi (2003)





Merlis and Schneider's (2010) solution



Conclusions

1. Gl 581c is too hot to be habitable, and it is very likely that the planet experienced runaway greenhouse, like Venus.
2. It requires at least 7 bars of CO2 for Gl 581d to be habitable.
3. Super-rotation is likely a common feature for tidal-locking exoplanetary atmospheres (both super-Earths and hot Jupiters), as shown by different types of models.
4. The super-rotation is generated due to poleward-propagating Rossby waves, which causes wave flux convergence over the equator and forces westerly winds.
5. What do the circulation and wave patterns imply for observations?