Day–night cloud asymmetry prevents early oceans on Venus but not on Earth

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Jérémy Leconte & Emmanuel Marcq, 2021, Nature

Presented by Yu Wang, student's seminar, 2021/11.15,
Tsinghua University

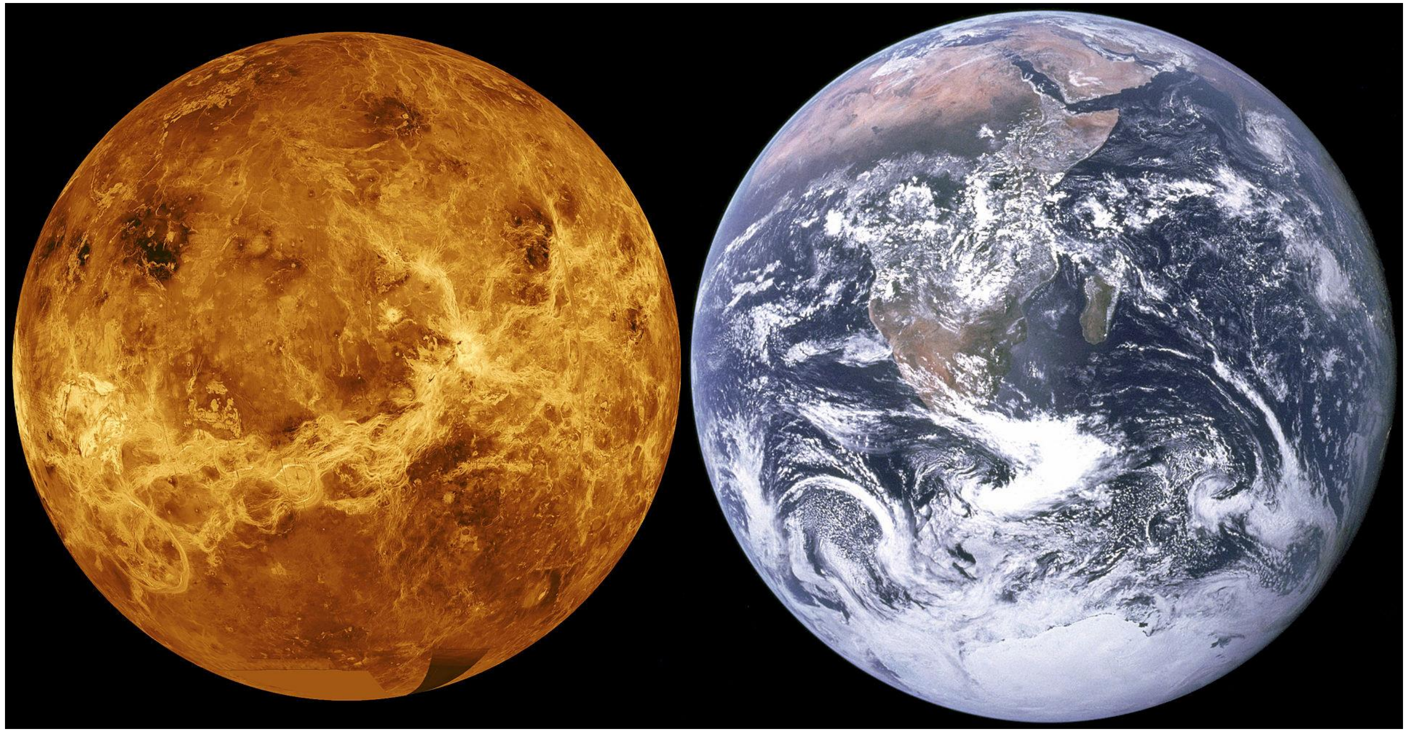
Venus

- our sister planet

- similar size, mass and bulk density to earth

- hell to life

- Global high temperature (~900K)
- 97% CO_2 + 3% N_2 +~0% water
- sulfuric acid (硫酸) clouds



Left (pseudocolor): NASA/Megellan mission
Right: NASA/Apollo 17 crew

Faint young sun problem

Our hydrogen burning sun

$$4\,{}^{1}\mathrm{H} \longrightarrow {}^{4}\mathrm{He} + 2\,\mathrm{e}^{+} + 2\,\nu$$
$$4\,{}^{1}\mathrm{H} + \mathrm{e}^{-} \longrightarrow {}^{4}\mathrm{He} + \mathrm{e}^{+} + 2\,\nu$$

Higher temperature, higher reaction rate.

positive feedback

Sun is currently **1.4 times brighter** today than it was 4.6 billion years ago

Go back to Archaean age (~ 4Gyrs ago), earth's equilibrium temperature would be **too low** to sustain liquid ocean, which is contradictory to geological and paleontological evidence.

ancient riverway, Lichuan, Hubei

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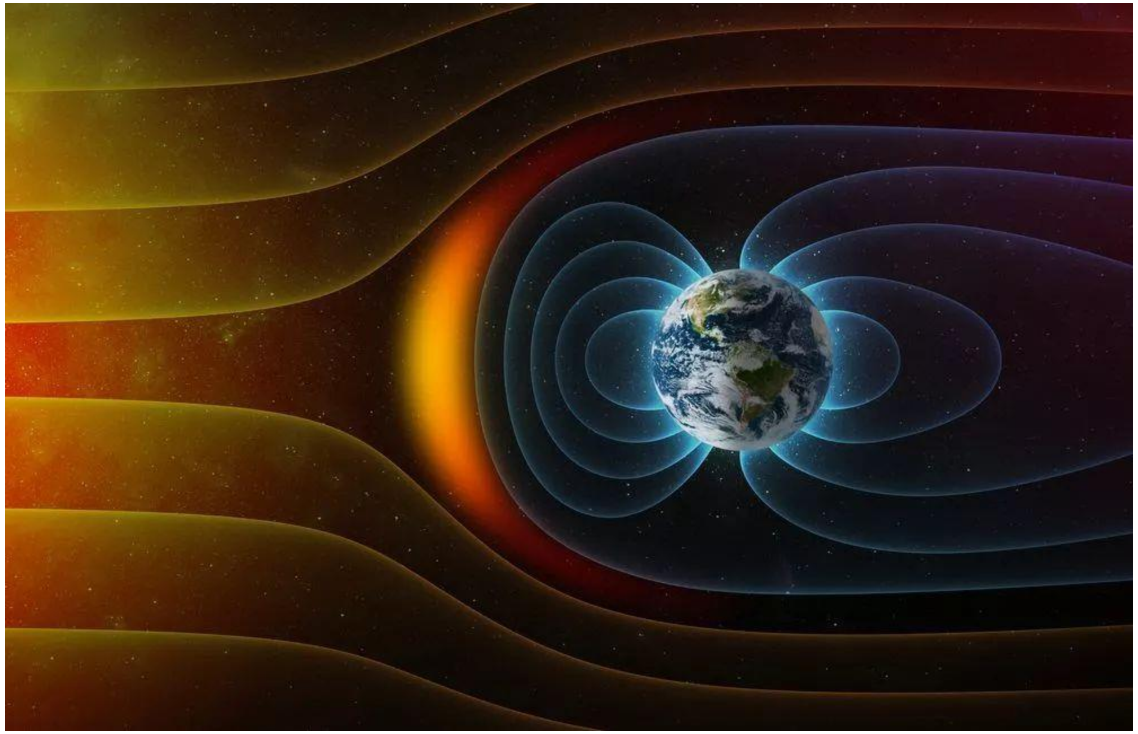
Why venus is lack of water?

- Consequences of runaway greenhouse effect.
water all vaporized to the atmosphere.

- lack of protection from week magnetosphere.
UV photodissociate water as H and O and H is blowed away to space by solar wind.

- lack of plate tectonics.
cause the lack of dynamo effect to produce strong magnetosphere



solar wind and earth’s magnetosphere

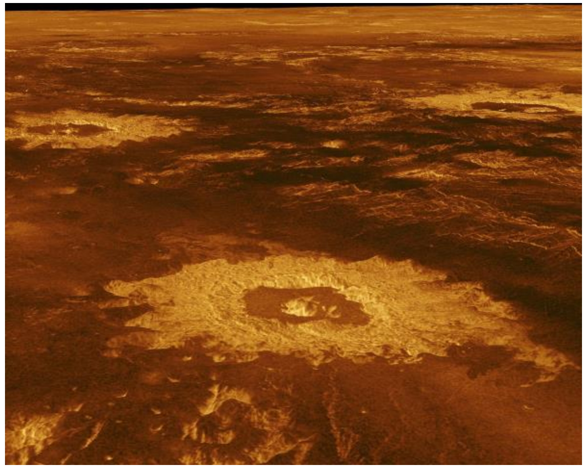
https://www.sohu.com

Any evidence that Venus has an early ocean?

Unluckily, global **resurfacing** events (300-600 Myrs ago) on Venus may obscure most geological record.

volcanoes, impact craters, heating crust?

In the contray, Mars has rivers ~ 3.5-3.8 billion years ago. Earth has had oceans for ~4 billion years.



impact craters on Venus

NASA.org

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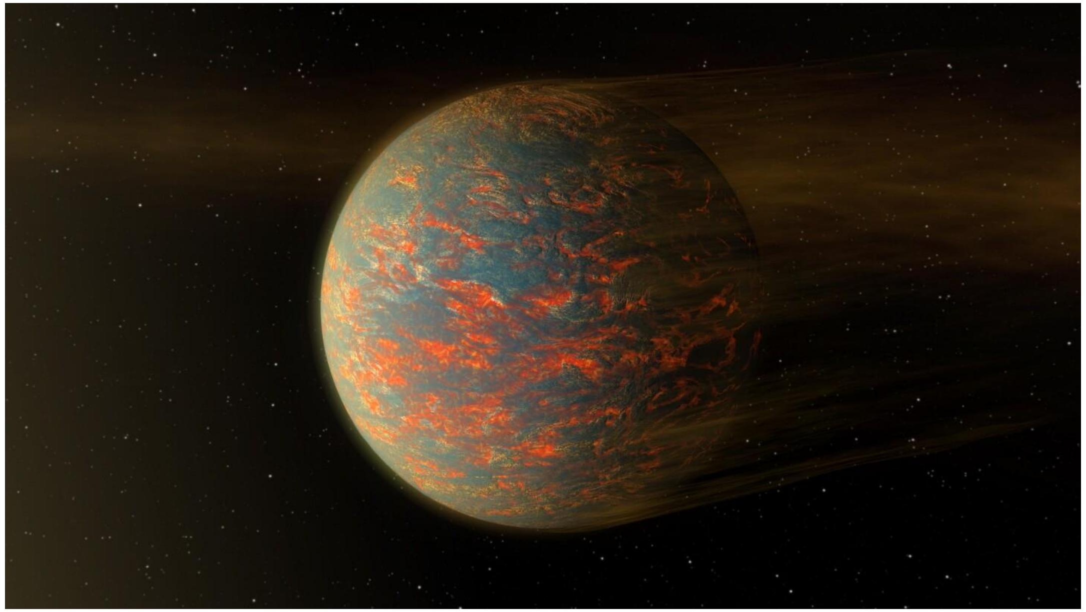
Previously many studies initially assume surface liquid water present. It is surly right for Mars and Earth, but not really sure for Venus.

Think back before we have water

During early stage of planet formation, the **magma ocean** era, we expect all superficial water in vapor phase.

Vapor needs to **condense** to form oceans.
- for now only studied by 1D climate model.
- neglect atmospheric dynamics and effect of clouds.



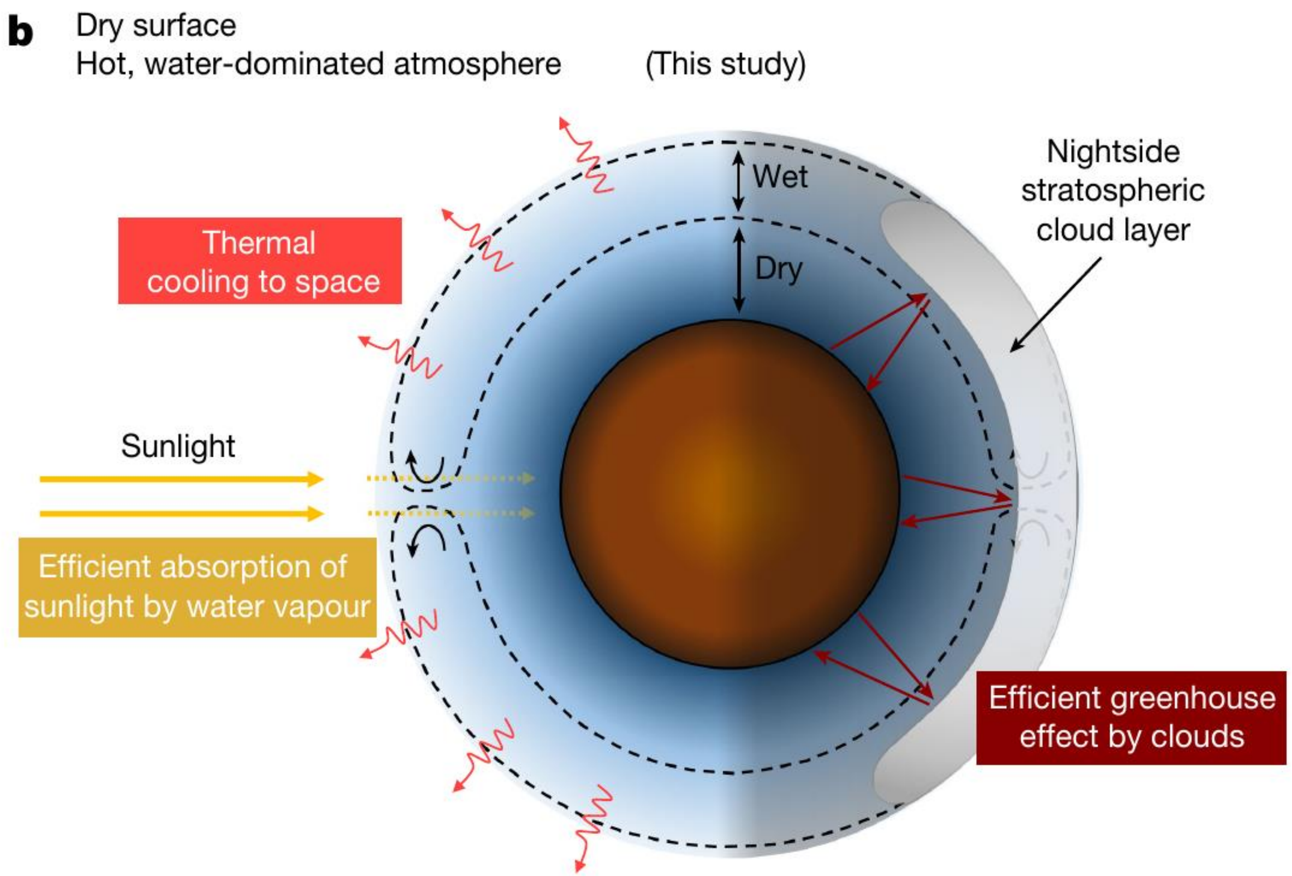
exoplanets.nasa.gov

They do comprehensive 3D Global Climate Model(GCM) simulations with radiative transfer and all kinds of phase transfer of water to explore **whether the vapor can condense on early Venus.**

Take-home message

- Early earth and Venus clouds preferentially form on the nightside and have a strong net warming effect.
- They suggest ocean has never been formed on the surface of Venus.
- The formation of Earth’s oceans required much lower insolation than today, which is made possible by the faint young sun “problem”.

Models & Methods



Radiation transfer:

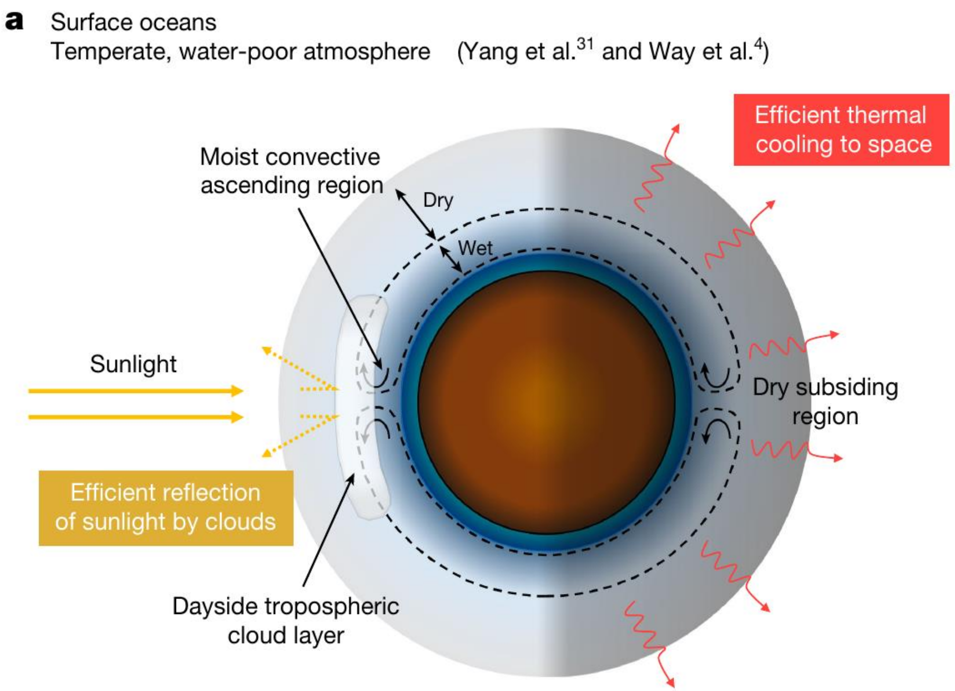
- absorption and scattering by
  - the atmosphere, H_2O & N_2
  - the clouds, H_2O (icy or liquid)
  - and the surface. (Flat surface)

-- Consider 55 spectral bands in the thermal infrared (from 0.65 µm to 100 µm) and 45 in the visible domain (from 0.3 µm to 6.5 µm)

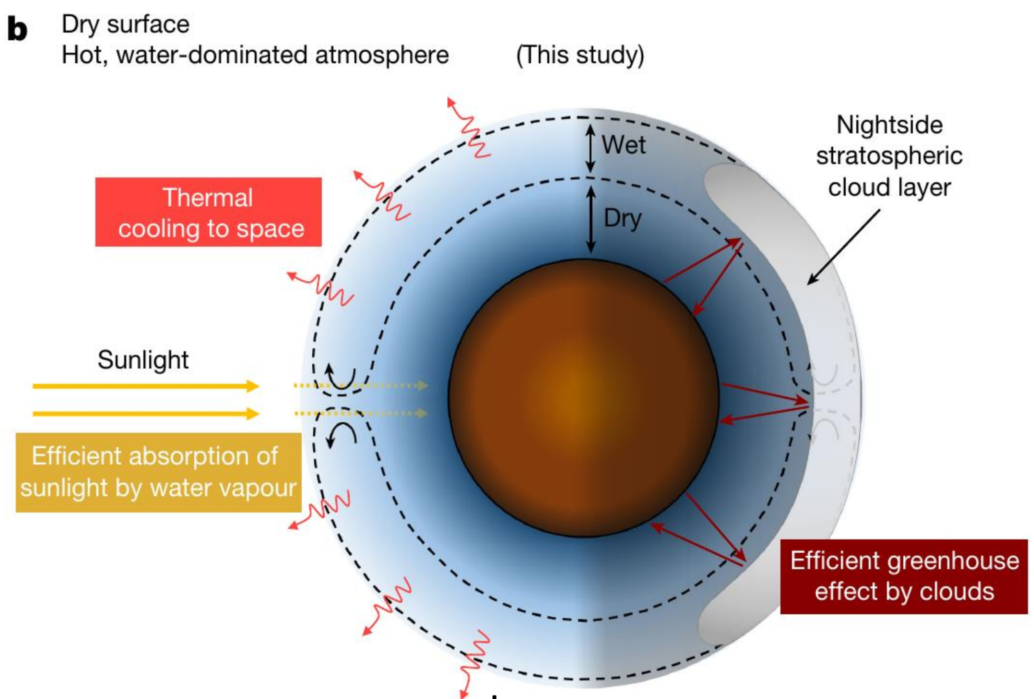
Phase transfer of H_2O :

- condensation, evaporation, sublimation and precipitation (both rainfall and snowfall).

Initial Condition:cold start and hot start



cold start



hot start

All water initially condensed on surface.

- solar insolation:

  - case1: present day's earth ($340.5\ \mathrm{Wm}^{-2}$).

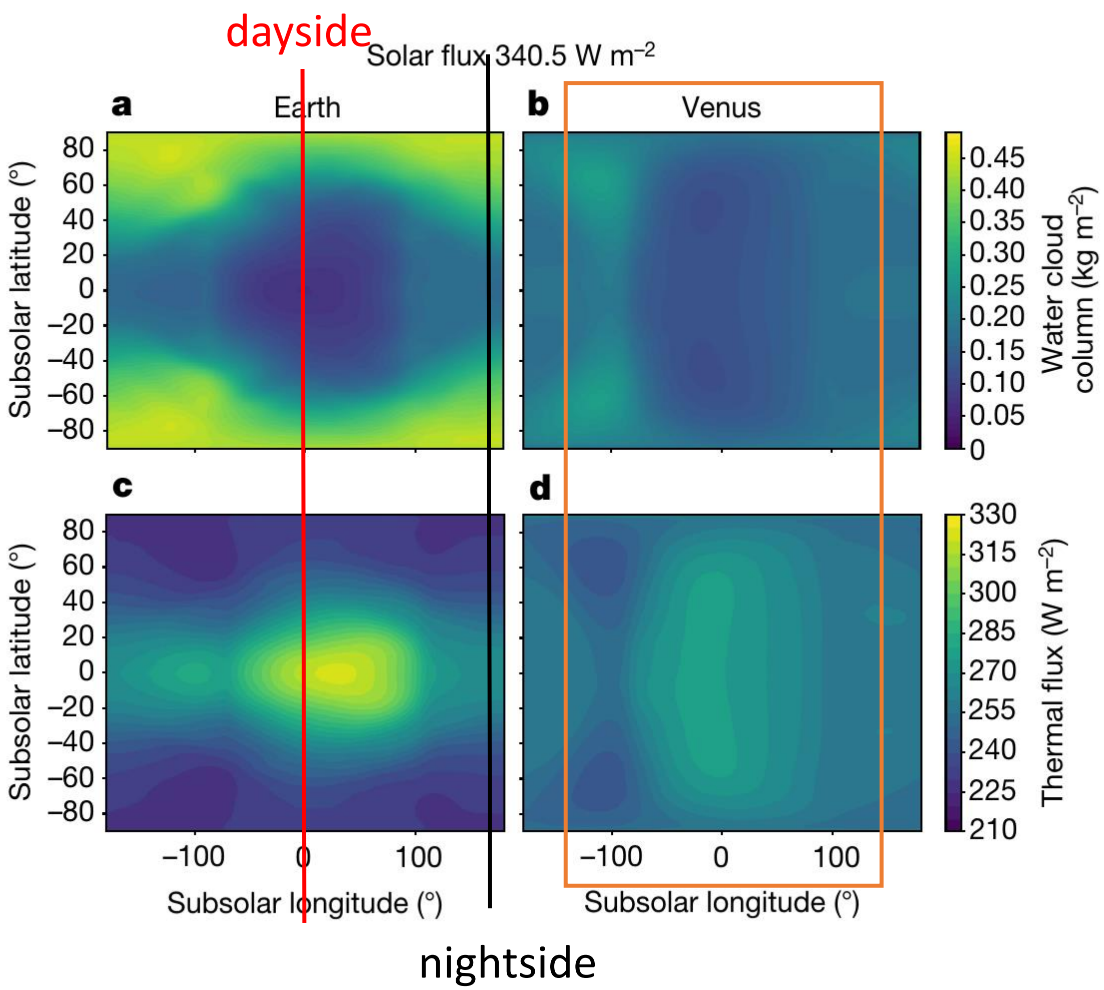
All water in steam.

- solar insolation:

  - case2: present day's earth ($340.5\ \mathrm{Wm}^{-2}$)
  - case3: minimal solar insolation received on Venus 4 billion years ago. ($500\ \mathrm{Wm}^{-2}$)

Results

1. Preferential cloud formation on the nightside



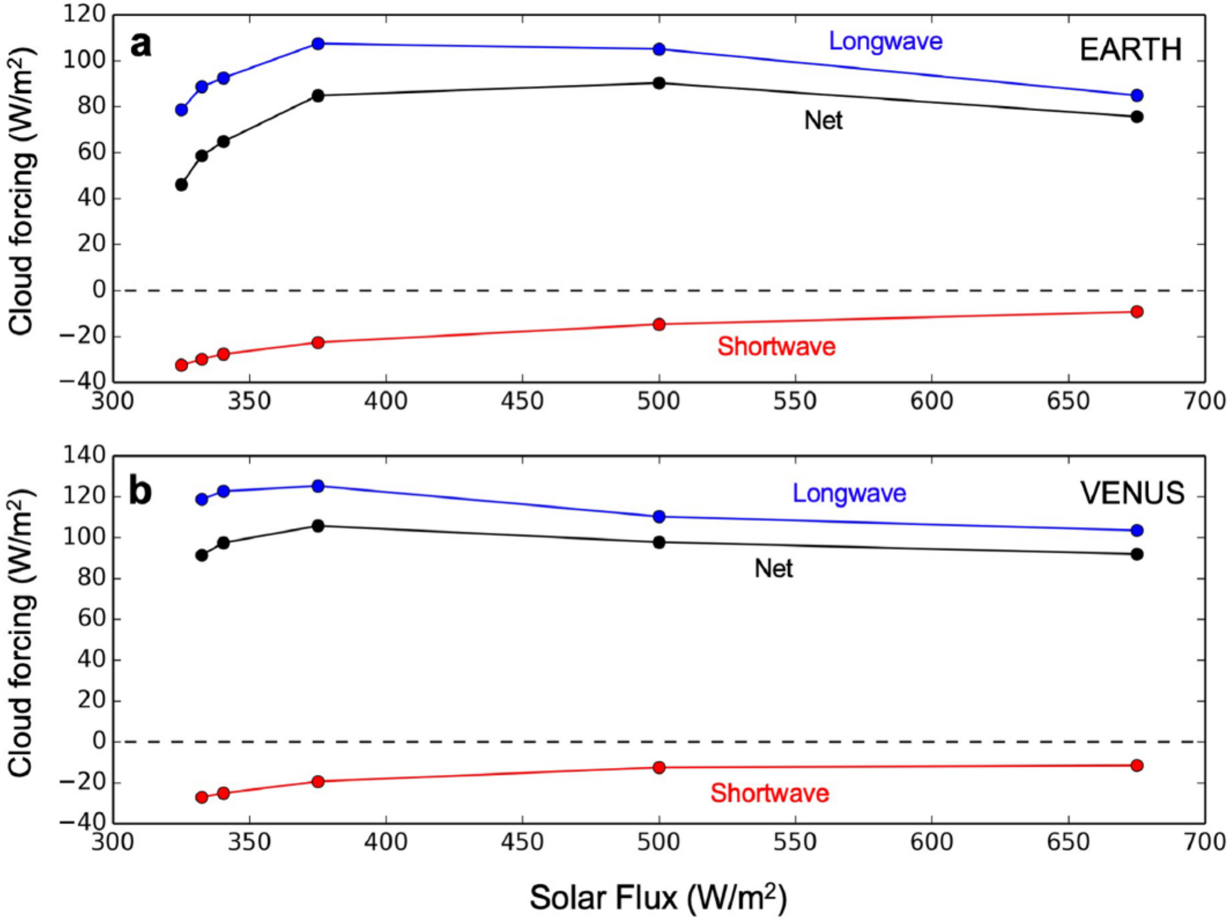
Coordinate in the heliocentric frame.
(0 deg, 0deg): subsolar point, where the sun directly shines.

Robust for a wide range of solar insolations. (From $312.5\ \mathrm{Wm}^{-2}$ to $675\ \mathrm{Wm}^{-2}$)

Thermal emission to space is **anticorrelated** with the position of water clouds, which means clouds produce a strong greenhouse effect.

Results

2. Net warming effect (quantitively)



Longwave: absorption, reemission and reflection of longwave thermal emission. (**Clouds' greenhouse effect**)

Shortwave: imcoming solar radiation reflected back by clouds.

Net: always positive -> Net warming effect in the hot start scenario.

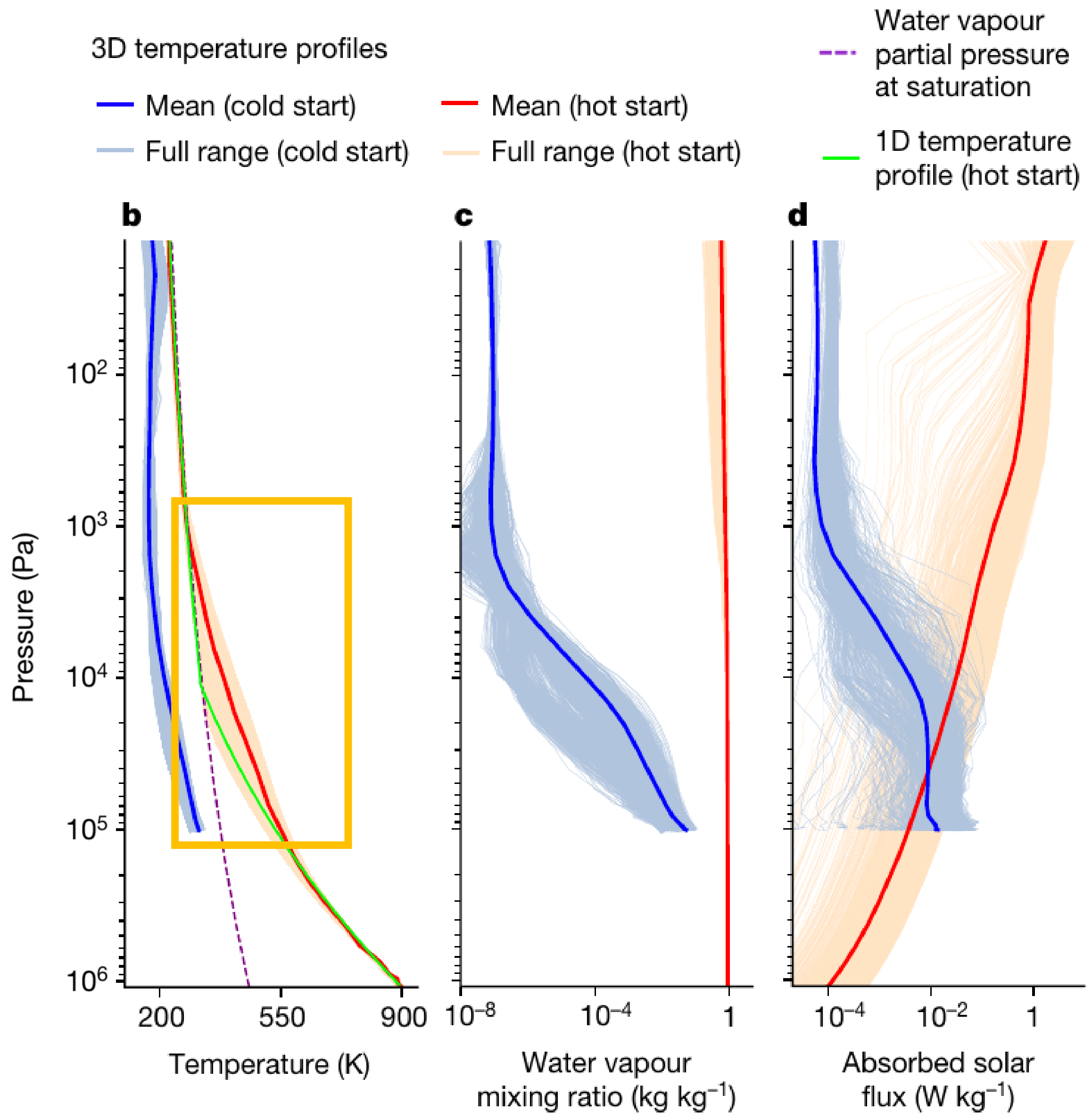
Results

3. Profiles
cold start: aquaplanet
hot start: steamy planet

3D feature of clouds do induce bigger greenhouse effect than 1D cloud-free model.
-> **lower solar insolation needed** for water to condense

The simulations carried out at multiple insolations reveal that:
(1) the insolation required to condense water on early Venus is about $\mathbf{325\ Wm^{-2}}$ (~0.95 times the Earth solar constant)

(2) on Earth is about $\mathbf{312.5\ Wm^{-2}}$ (~0.92 times the Earth solar constant).



Results

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3D feature of clouds do induce bigger greenhouse effect than 1D cloud-free model.
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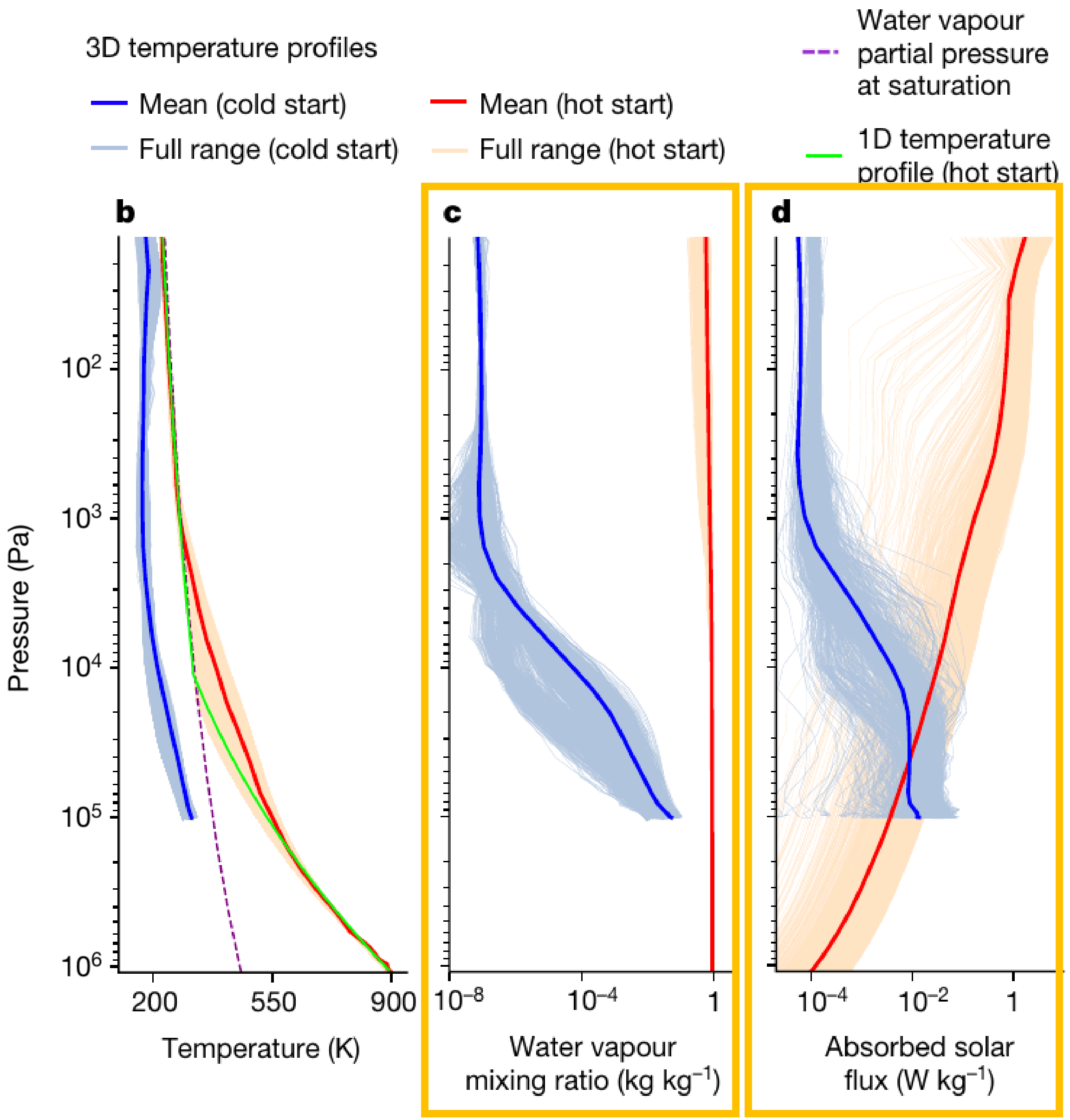
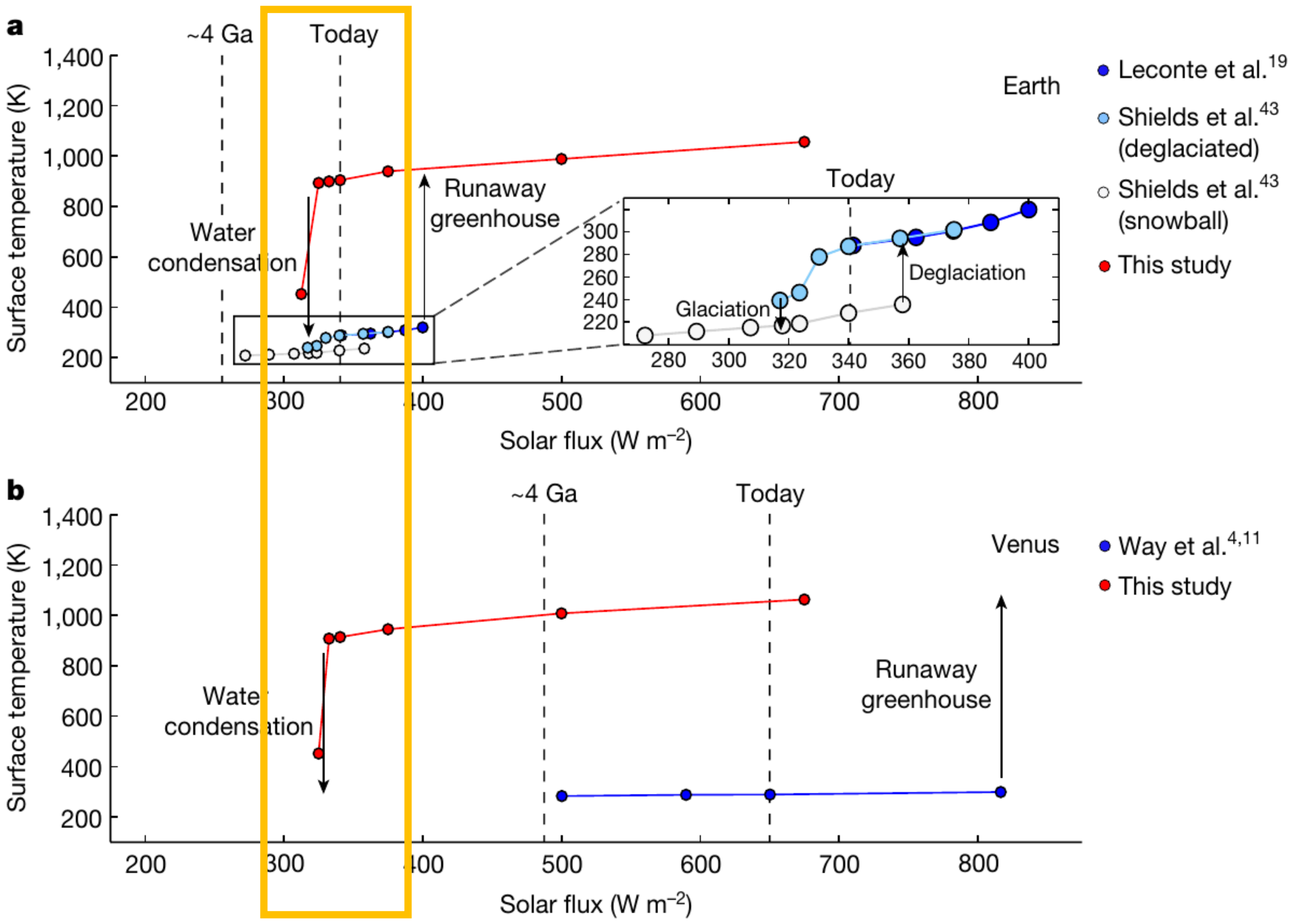
Very different features between cold start and hot start b/o the water vapor maxing ratio varies a lot. -> **different cloud formation mechanism.**



Pathways to water condensation



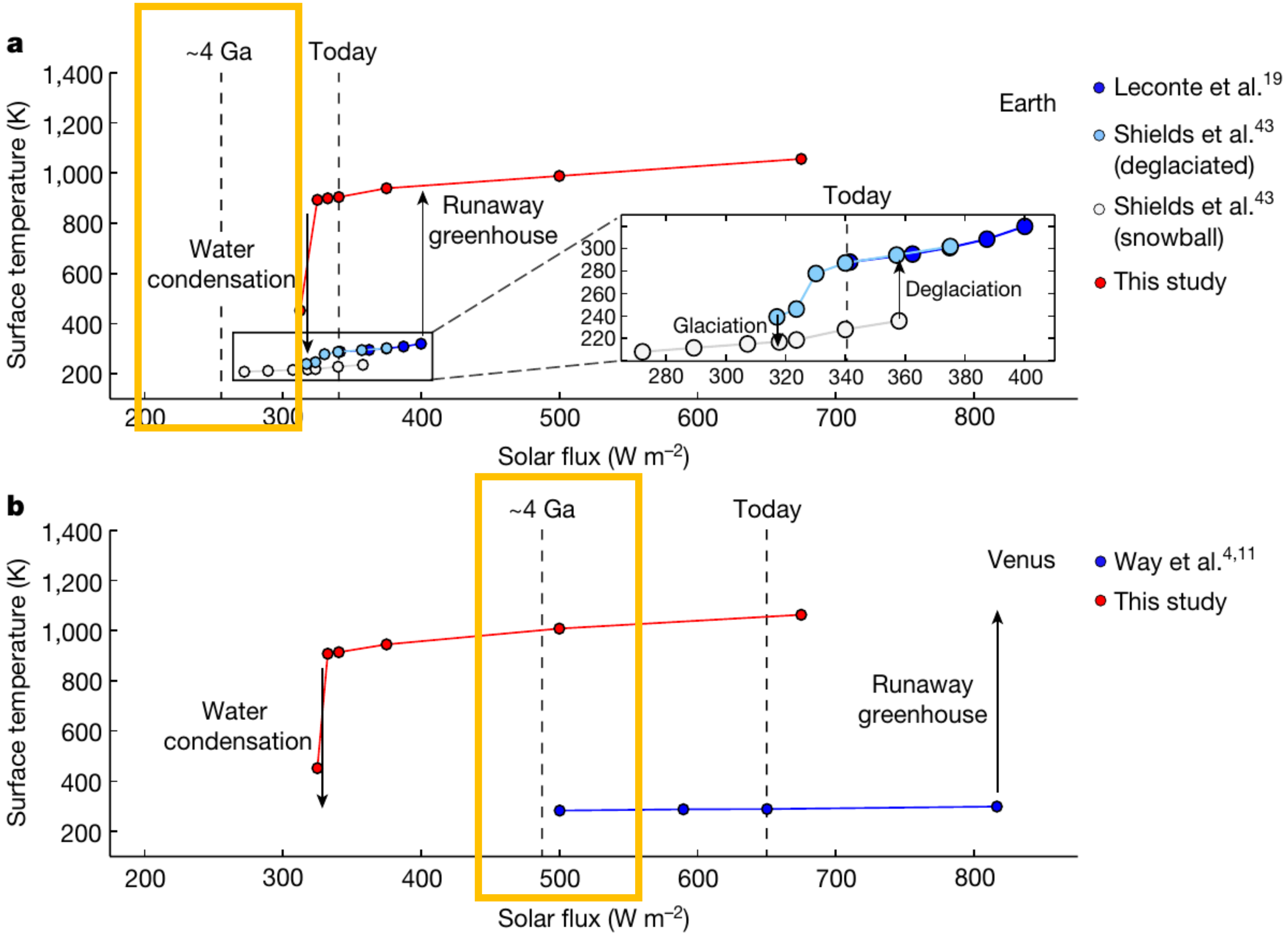
initially hot and steamy (Red Branch) planetary atmospheres reach insolation thresholds.

clouds start to form on the dayside.

The bond albedo suddenly jump, and produce a net cooling effect.

water condense and the evolution switches to Blue Branch (aquaplanet).

Pathways to water condensation



The minimal insolation received on Venus ~4 Gyrs ago is much larger than the condensation requirement.

While for earth the insolation ~4 Gyrs ago is lower than the condensation threshold, which is also lower than present day's insolation.

Faint young sun help earth obtain early oceans but not Venus.

Faint young sun problem

Our hydrogen burning sun

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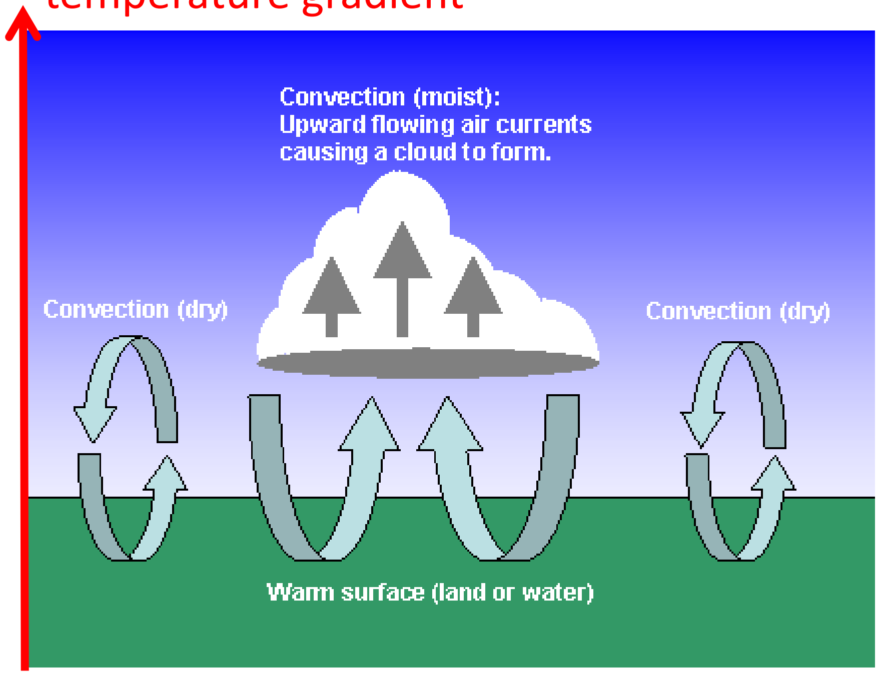
Cloud formation mechanism

dayside cloud:

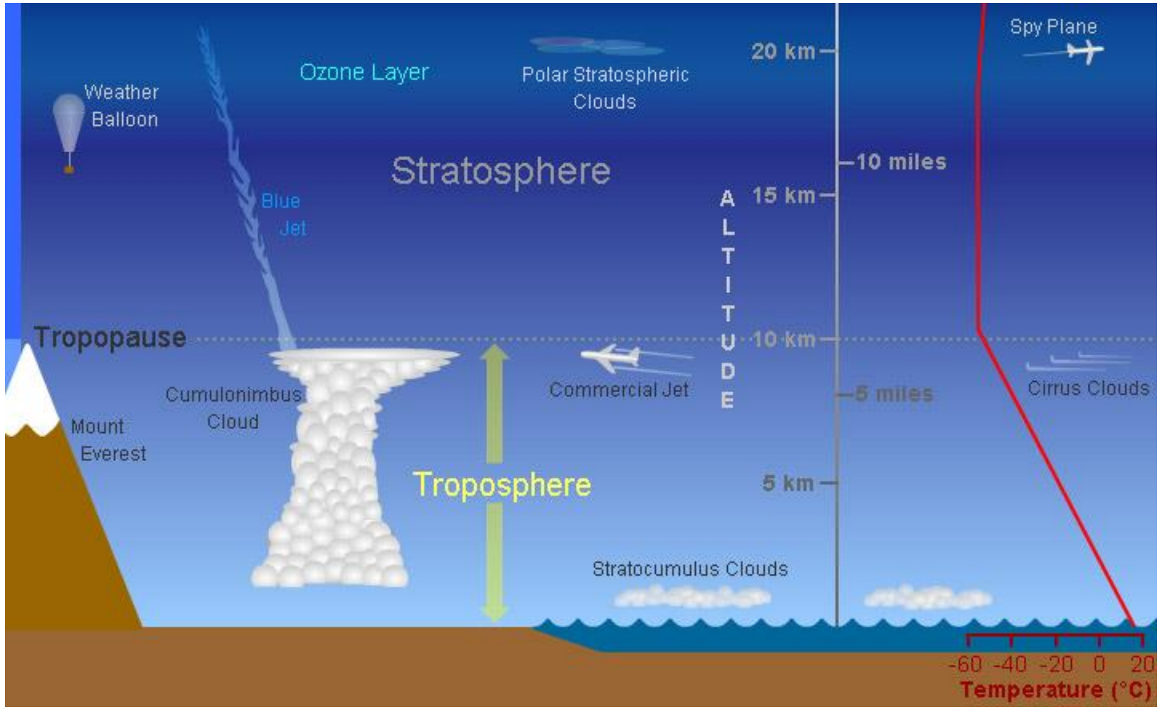
Moist convection, water condenses at high altitude with the decrease of temperature.

Clouds form at **Troposphere**
A region of stable and intense moist convection is needed to produce thick and reflective clouds.

temperature gradient



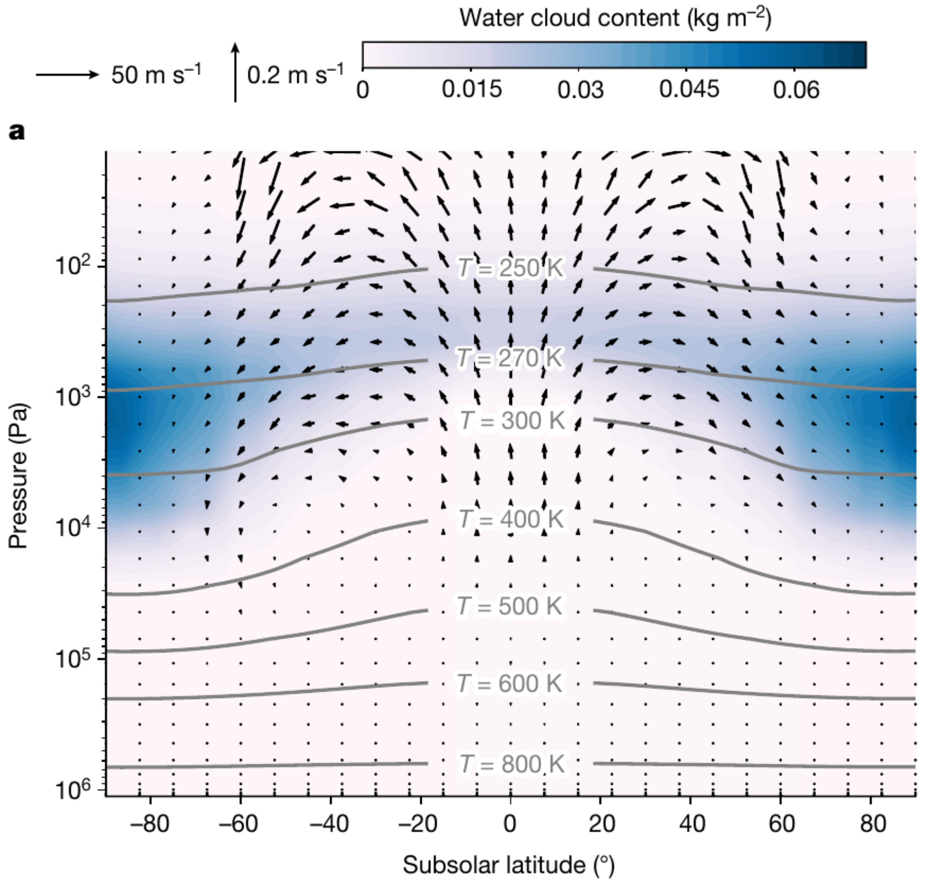
https://weatherstreet.com



https://scied.ucar.edu

Cloud formation mechanism

nightside cloud:



Brewer–Dobson-like circulation, which transports warm stratospheric air parcels from the equator to the poles

water vapor ascends b/o abundant equatorial insolation.

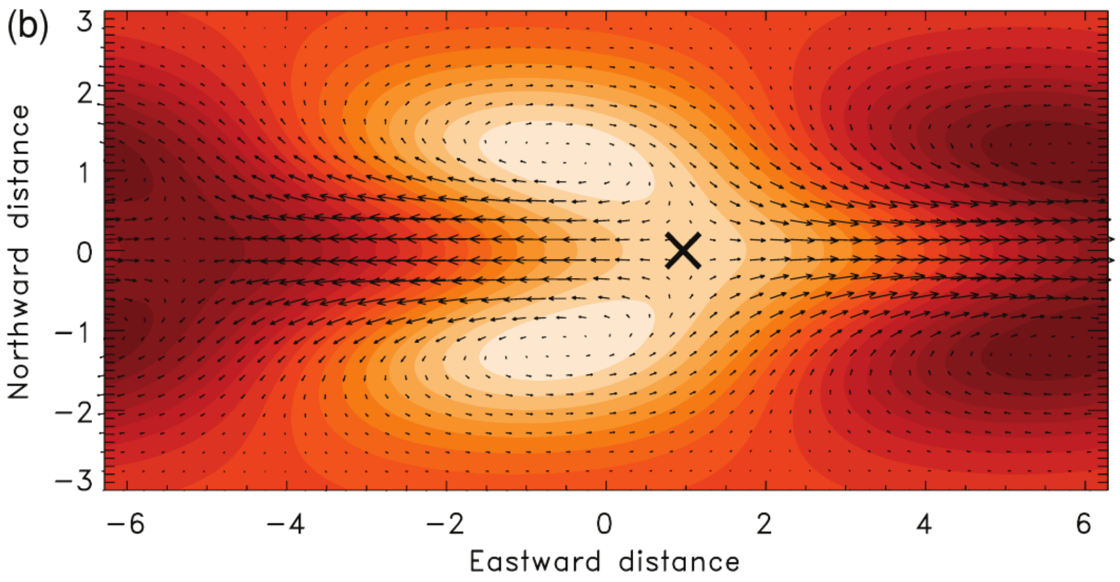
Rossby wave drag the water vapor westward at high altitude. (~ 0.1 bar)

Lost angular momentum, move poleward

radiatively cooling, descend near the pole

Cloud formation mechanism

nightside cloud:



showman & polvani(2011)

please refer to showman & polvani(2011) or Butchart, N. (2014) review if interested.

Also the air parcel move eastward due to strong **eastward jet** at high altitude.(~ 0.1 bar)

wave-mean interaction

Rossby wave and Kelvin wave together pump eastward momentum from high latitude to equator.

eastward jet

water vapor leave the subsolar region and descend at nightside.

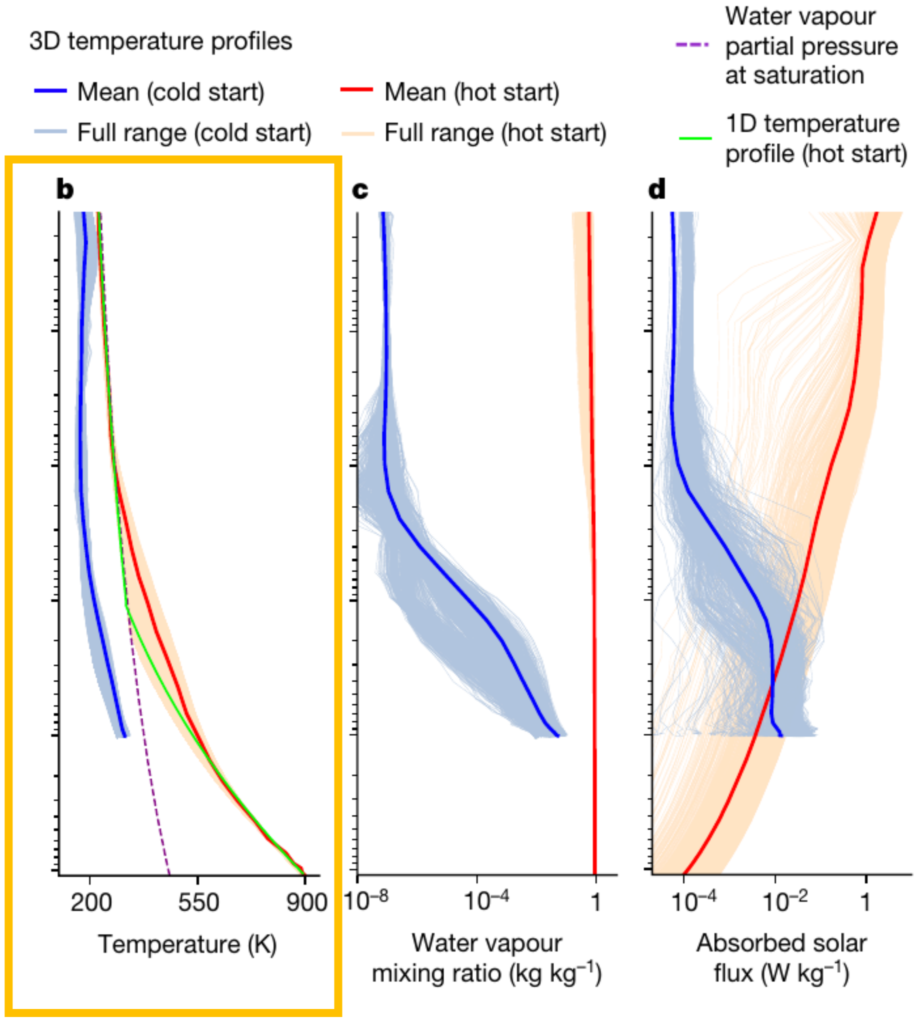
Cloud formation mechanism

- overall view:

Higher solar insolation at dayside increases temperature and lower the tropopause, which make the moist convection weaker and more vapor transported to nightside.

In other words,
effectively **destroy** dayside cloud and **reform** them on nightside.

Only when solar insolation decreases gives the oppotunity to form dayside clouds.



Summary

- Early earth and Venus clouds preferentially form on the nightside and have a strong net warming effect.
- The preferential cloud formation is driven by high insolation at subsolar region as well as planetary scale waves and circulations which transport vapor to nighside.
- Net warming effect of clouds **may** prohibit Venus's water condensation but not earth.
- The formation of Earth's oceans required much lower insolation than today, which is made possible by the faint young sun “problem”.

Questions

1. Any observations to distinguish between the “hot start” and “cold start” scenario?

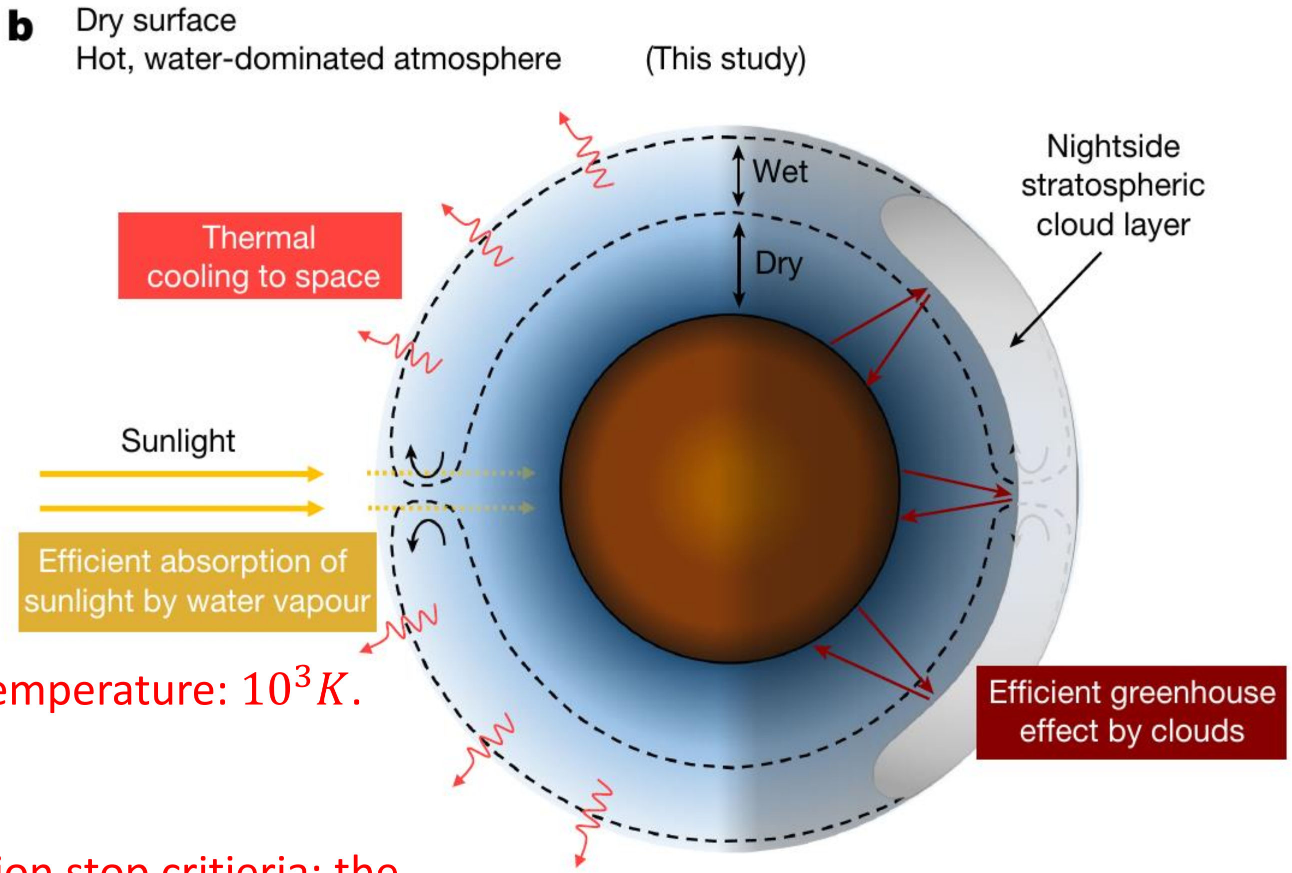
EUV needed to dissociate water efficiently, which means water loss should happen very early.

2. The scheme is robust because it is clean, what about considering more complicated chemical species as well as the interaction with magma ocean?

3. Water content really so high as earth (~100m GEL) initially on Venus?

May be problematic to today’s poor water situation.

Models & Methods (more details)



initial temperature: $10^3 K$.

simulation stop critieria: the top-of-the-atmosphere radiative imbalance is lower than about 1 W m−2.

Cloud formation

- include cloud condensation nucleis (CCNs). Clouds are essentially treated as particles.

$$r_{eff} = \left(\frac{3q_c}{4\pi\rho_c N_c} \right)^{1/3}$$

r_{eff}: effective cloud radius, determined by q_c (mass mixing ratio of cloud particles kg/kg of air), N_c (CCNs / unit mass of air) and ρ_c (density of the cloud particles).

r_{eff} is used to compute (1) clouds' radiative properties calculated by Mie scattering and (2) their sedimentation velocity

Robustness of nighside cloud formation

Nightside cloud formation is more **robust** to parameters like solar insolation, a wide range of cloud properties, total amount of water vapour, planetary rotation period and addition of carbon dioxide (Not included here, please refer to their paper.) since the dynamic is driven by planetary scale waves and do not respond sensitively to local turbulence.