Major questions in planetary meteorology

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The major goals of planetary meteorology will be to explain a diversity of the atmospheric general circulation of planets based on common principles of atmospheric physics and to understand how an atmosphere responds to the changes of planetary parameters and the solar flux. Such an understanding would also enable reproduction of the evolutionary path of the Earth and the understanding of the climates of extrasolar planets.

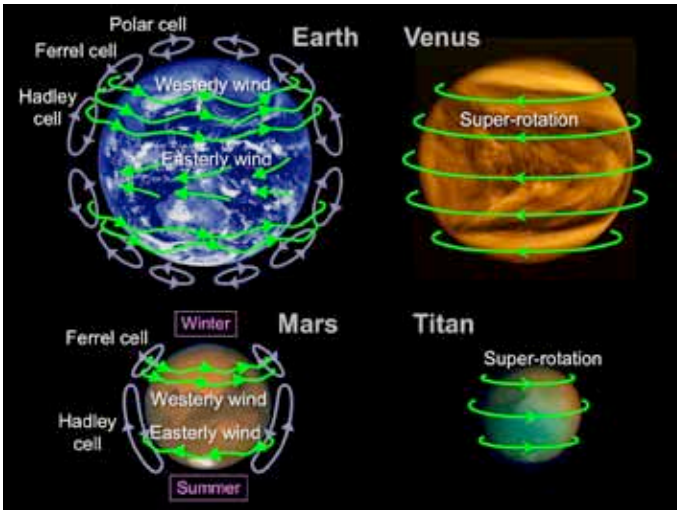
For the last several decades, problems of planetary-scale dynamics have been extensively studied. The major problems include the super-rotation of Venus, dust storms of Mars, multiple jets of Jupiter, etc. Now they are understood to some extent with the aid of general circulation models of these planets; however, meso- and micro-scale (subgrid) processes are empirically parameterized in those models. Because of this limitation, cross-scale interaction, which is thought to be fundamental to the achievement of an equilibrium state of the atmospheric structure, is not well understood. Small-scale processes, such as convection in the planetary boundary layer, katabatic winds, mountain waves, and internal gravity waves, are though to play key roles in atmospheric dynamics and material transport. Moreover, the nature of such small-scale processes and their interaction with planetary-scale dynamics needs to be understood for the classical problems above.

The small-scale processes that needs extensive observations and modeling in the coming decade will be: dust and water transport in the boundary layer of Mars, control of the static stability of subsurface ice of Mars by boundary-layer processes, static stability and the nature of convection near the Venus' surface, angular momentum exchange between the atmosphere and the solid planet of Venus, surface-atmosphere chemical interaction on Venus, and energy and momentum transport by gravity waves in the atmospheres of Venus, Mars and gas giants. Convection and convectively generated waves in extreme environments, such as those in a runaway greenhouse atmosphere, might also be an important topic. Comparative studies of those meso-scale processes including the solar atmosphere will be valuable.

General circulations of planetary atmospheres

Key questions to answer:

- How the thermal structure and dynamics of an atmosphere respond to changes of the solar flux
- How the variation of meteorology changes the composition and structure of the thermosphere where atmospheric escape occurs

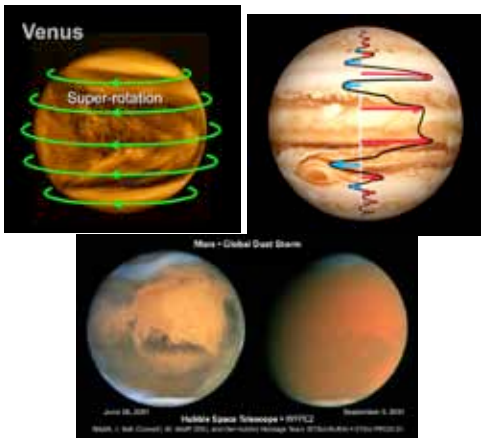


Classical problems related to planetary-scale dynamics

(1) Super-rotation of Venus

(2) Global dust storm of Mars

(3) Multiple jets of gas giants

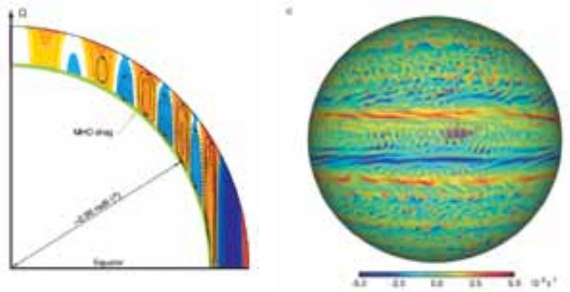


Problems (1) and (2) will probably be roughly understood within 10 years thanks to new observations and development of numerical models. Problem (3) is much more difficult because of the inability to see the interior.

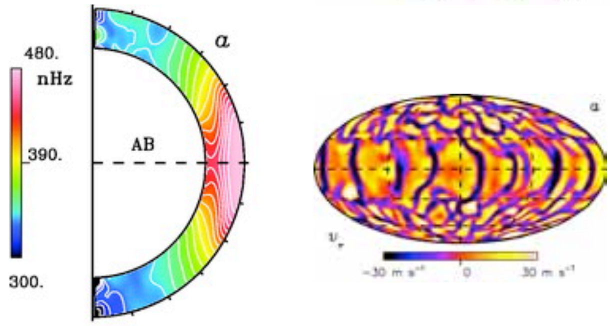
Zonal jets of gas giants

Probably comparative studies of the planets and the Sun will help ..

Jupiter
(Schneider & Liu, 2009)



Sun
(Miesch, 2000)

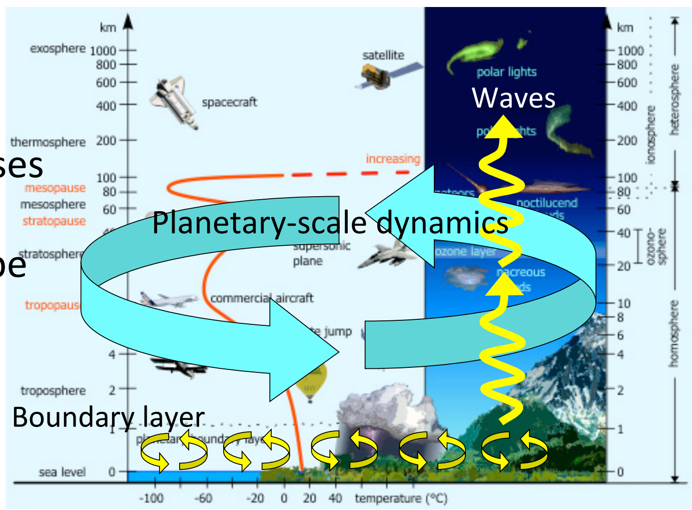


Major issues after 2020s

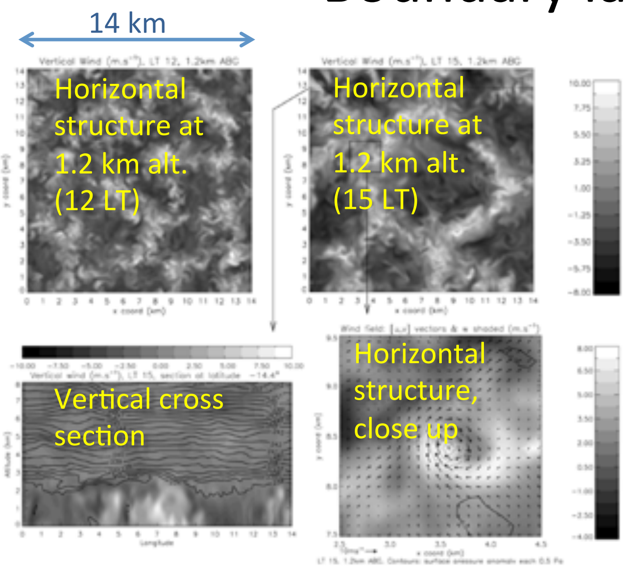
- **Surface-atmosphere interaction**
- **Vertical coupling via small-scale waves**
- **Exoplanets**
- **Climate evolution**

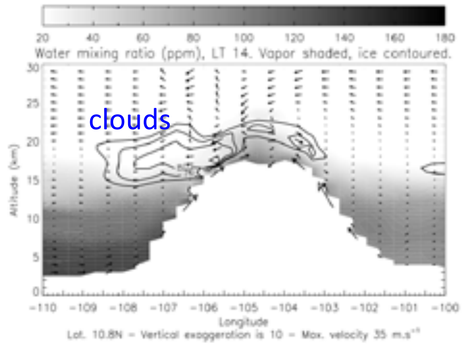
Subgrid scale

Nature of subgrid scale processes and their interaction with planetary-scale fields need to be understood even for 'classical' problems.



Surface-atmosphere interaction = Boundary layer physics



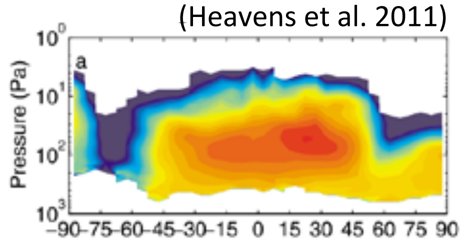


Meso-micro scale modeling of Martian boundary layer (Spiga & Forget, 2009)

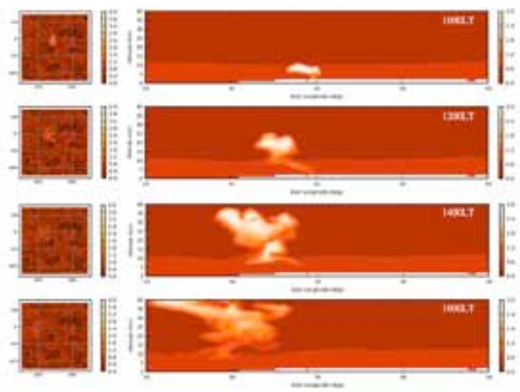
- Plumes, tornados, and updrafts governing transport of energy, momentum and atmospheric composition
- Highly variable in space and time
- Highly nonlinear

Dust processes on Martian surface

Meridional distribution of dust (Heavens et al. 2011)



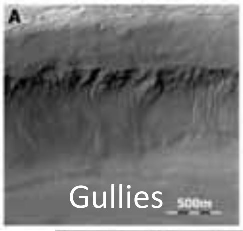
'Rocket dust storm' to explain the detached dust layer (Spiga et al. 2013)

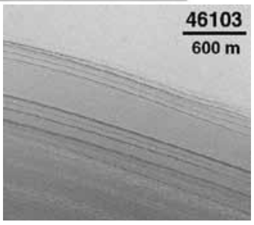


What determines the background dust opacity of the frozen planet ?
-- Dust lifting by meso/micro-scale processes should play key roles

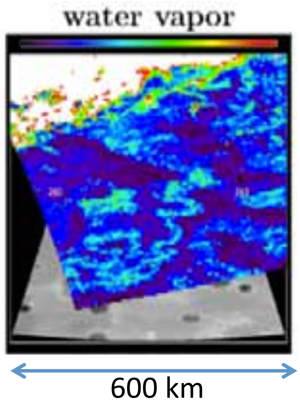
Dust devils

Water cycle of Mars

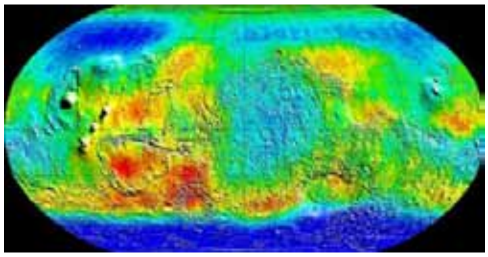


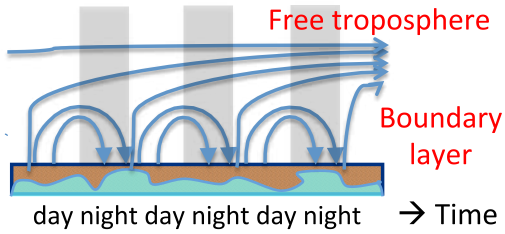


Polar deposits



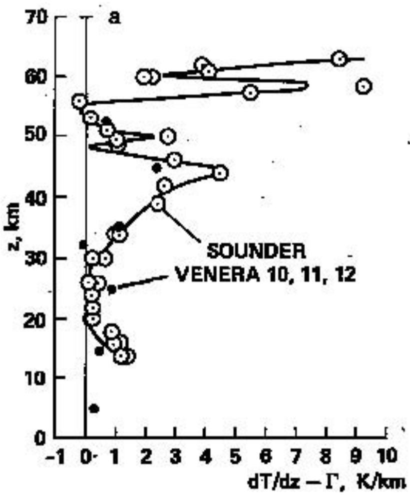
Subsurface water



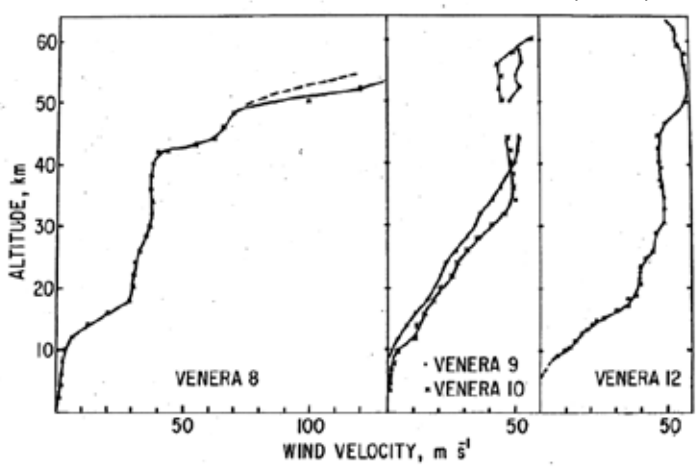


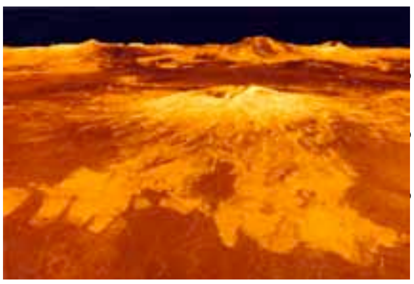
What determines the distribution of (strange) water reservoirs ?
What determines the atmospheric humidity and ultimately limits the water loss to space ?
-- (Unknown) local meteorology should control the water transport across the surface

Boundary layer of Venus



Kerzhanovich and Marov (1983)





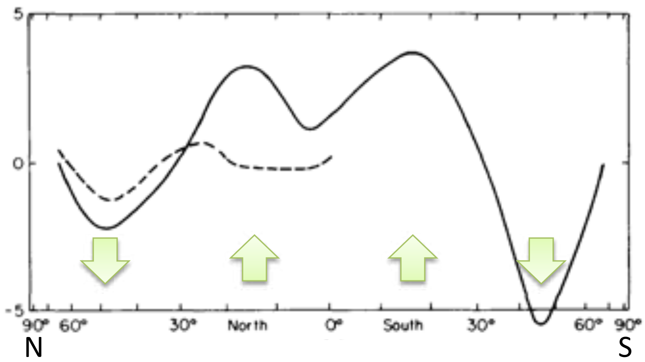
- Static stability is unknown
- Very slow motions (below detection limit)

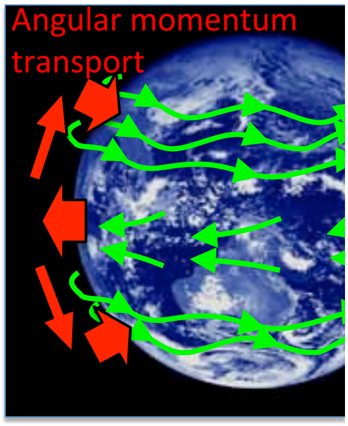
Even the occurrence of convection is unclear.

Angular momentum balance

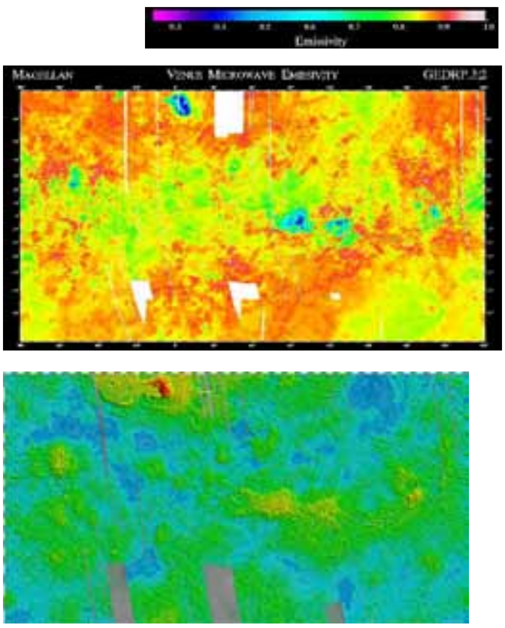
- There must be anti-superrotational flow somewhere near the surface.
- How does the surface exert torque on the free atmosphere through the boundary layer ?

Surface torque on the Earth
(angular momentum flux across the surface)

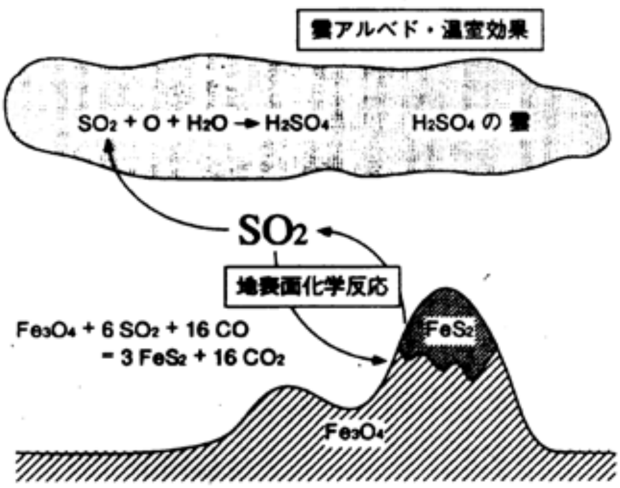




Surface-atmosphere chemical interaction on Venus



Radio emissivity distribution correlated with topography

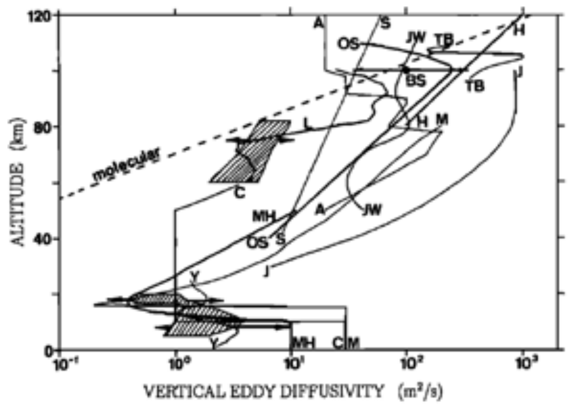


(Hashimoto & Abe, 2005)

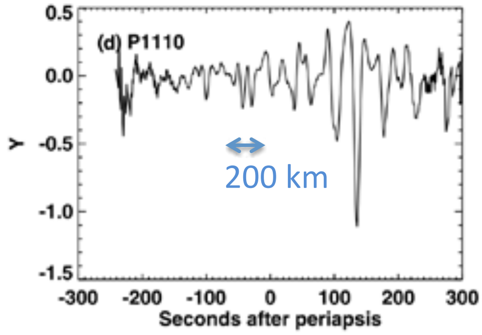
Gravity waves

- Gravity waves provide momentum, energy and turbulence in the Earth's upper atmosphere. Their roles in other planetary atmospheres are unclear.
- Only waves with long horizontal wavelengths are observable via radio/infrared limb observations. Aerobraking experiments at Mars suggest importance of short-wavelength waves.

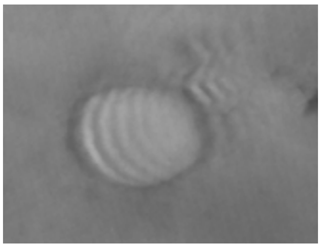
Eddy diffusivity (Fukao et al. 1994)



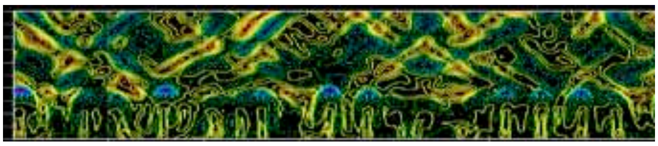
Fractional density fluctuation at ~110 km altitude measured by Mars Global Surveyor (Withers, 2006)



Strong wave generation in tenuous atmospheres

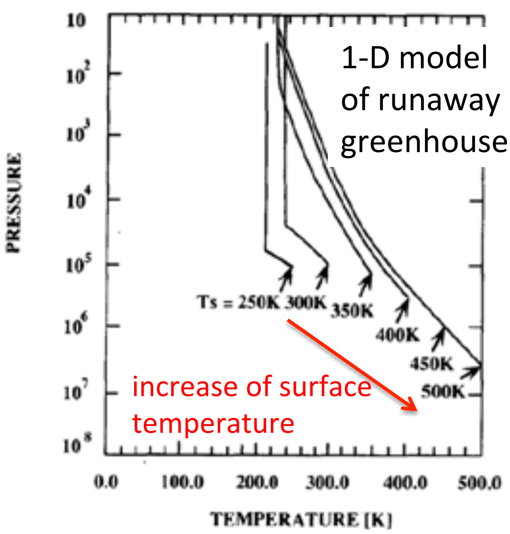


Mountain waves on Mars



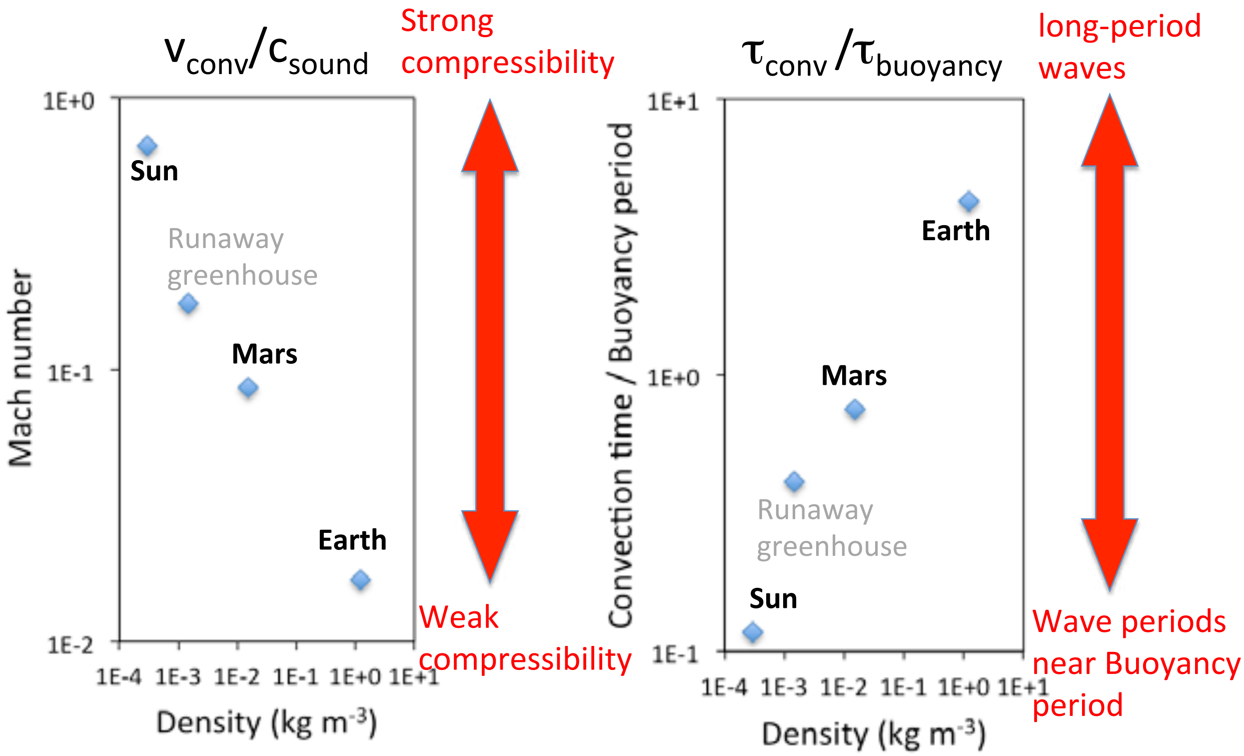
Convective generation of gravity waves on Mars (Watanabe et al., talk on Friday)

- A tenuous atmosphere like the one on Mars favors strong winds, which lead to generation of strong, short-period, small-scale, fast waves.
- An extreme example will be the upper troposphere of a runaway greenhouse atmosphere (early Venus ?), where the troposphere extends to 10^{-4} bar level.



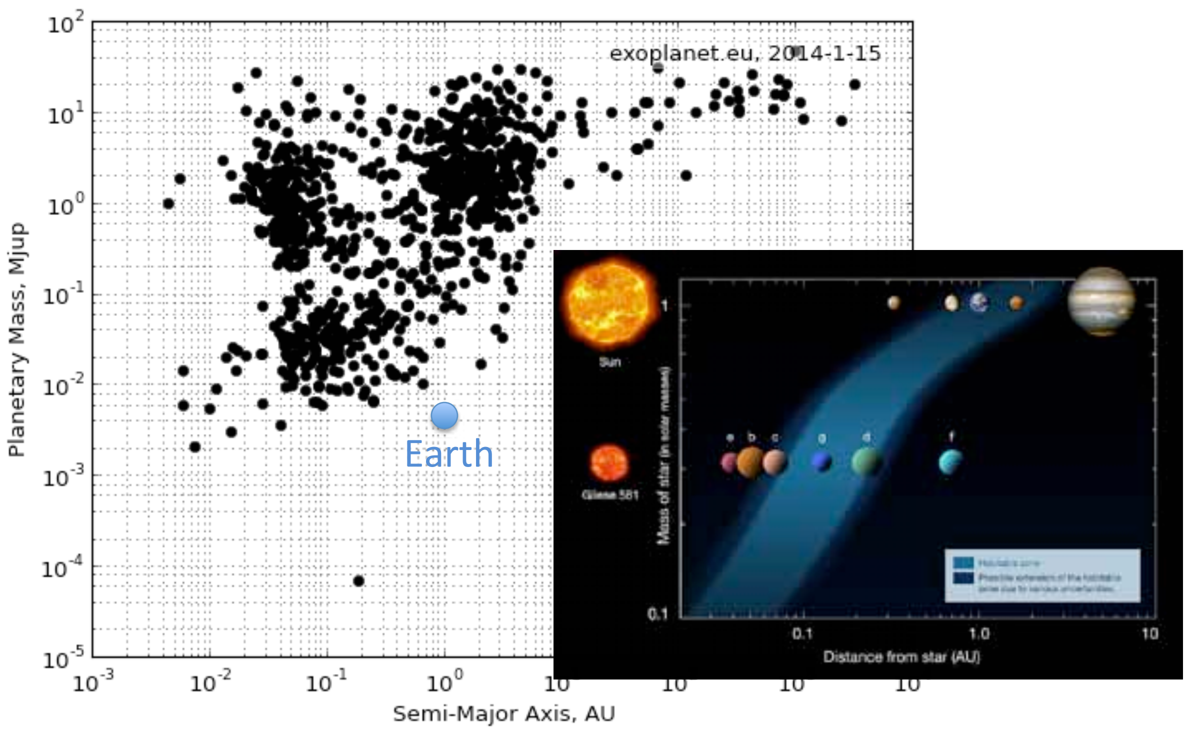
(Nakajima et al. 1992)

Even more extreme example is the Sun’s convective layer ..



→ Comparative studies will be valuable

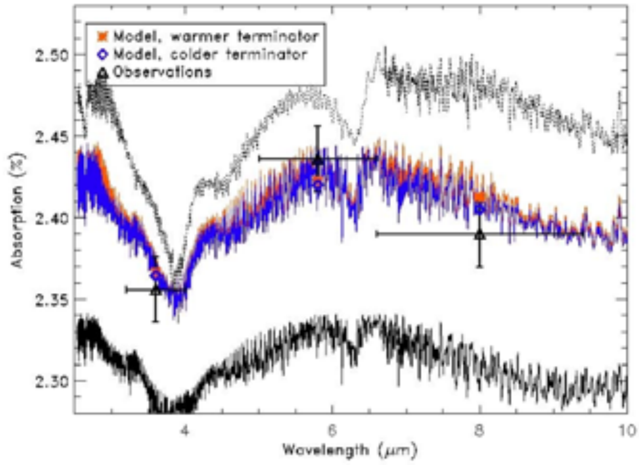
Exoplanets



Atmospheres of exoplanets

- Spectral data in visible (→albedo) and infrared (→temperature) are going to be obtained in the near future. Atmospheric compositions also begin to be observed.

hot-Jupiter HD189733b6

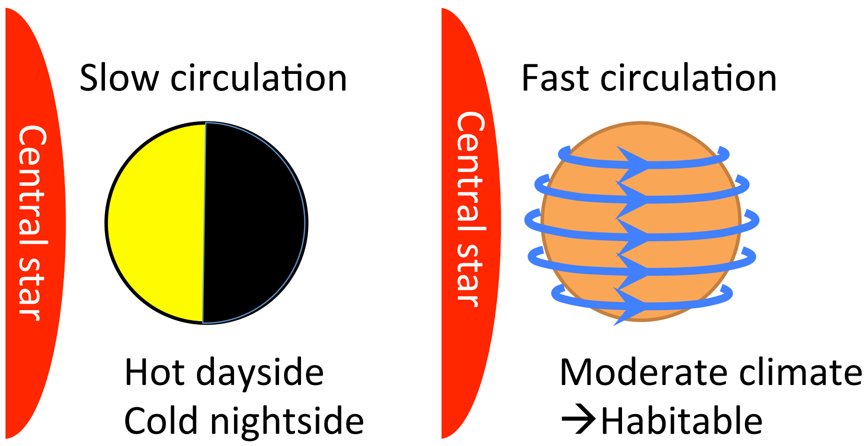


→Water vapor mixing ratio ~ 5 x 10^{-4}

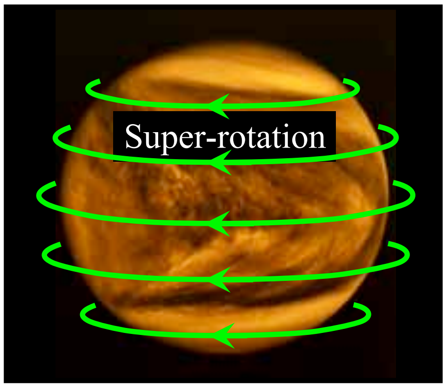
(Tinetti et al., 2007)

Atmospheric circulation of exoplanets

- Reproduction of the spectral data based on GCMs is needed to draw a physically consistent picture. Through this investigation we can develop a robust atmospheric modeling scheme which is applicable to a wide range of planetary environments.
- Tidally-locked planets seem to be ubiquitous. Those planets are slow rotator like Venus. It is possible that super-rotation redistributes energy on such planets.



Understanding of Venus atmosphere is a key to assess the 'habitability' of tidally-locked exoplanets.



Antisolar

Subsolar

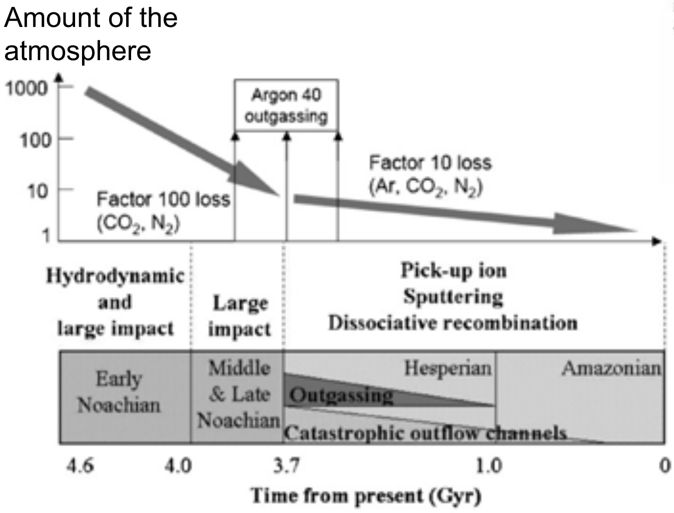
Polar view of the atmospheric circulation and temperature distribution at 20 km altitude on a synchronously rotating terrestrial planet (Joshi et al., 1997)

Climate evolution

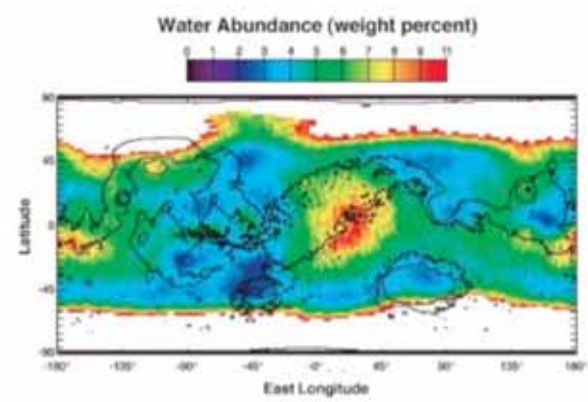
- A robust modeling scheme developed through the studies of various planets is suitable for investigation of various evolutional stages of the terrestrial planets: Earth, Venus, and Mars. How did they followed different evolutional paths ?
- How does 'faint young Sun' influence their evolution ?

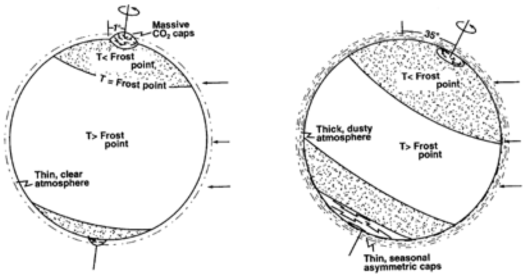
Climate evolution of Mars

How have the Martian climate changed in long-term (~Gyr) and short-tem (~10^5 yr) ?



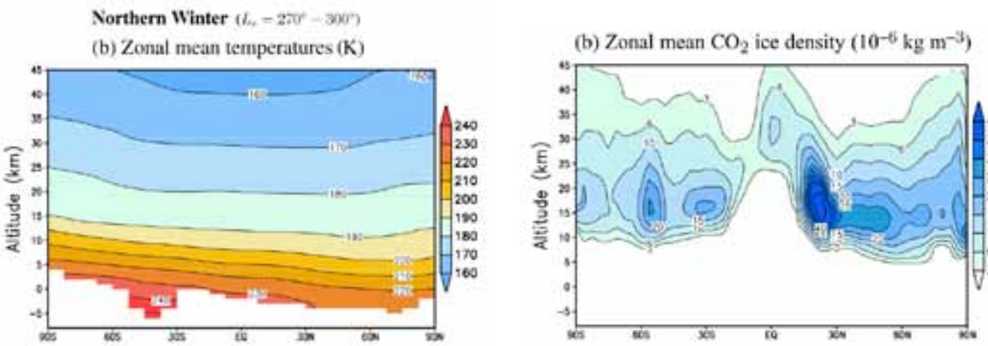
Chassefiere et al. (2007)





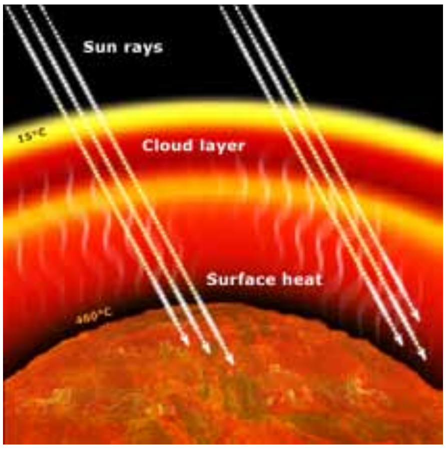
- It was expected that the combination of the greenhouse effects of CO_2 and CO_2 ice clouds can raise the temperature to above the melting point even in the **faint young Sun** condition (Forget & Pierrehumbert, 1997).
- Studies using Mars GCMs suggest this scenario is difficult (Forget et al. 2013).

Mars GCM with 2-bar CO_2 atmosphere



(Forget et al. 2013)

Loss of water from Venus: runaway greenhouse or moist greenhouse



- Have an ocean once existed on early Venus ?
- How was water transported to the thermosphere ?
- Why is the water of the Earth kept on the surface ?

Hierarchy of Earth’s meteorology