An experiment on the appearance of the complete evaporation of a land planet with a general circulation model

陸惑星における完全蒸発状態の発生に関する大気大循環モデル実験

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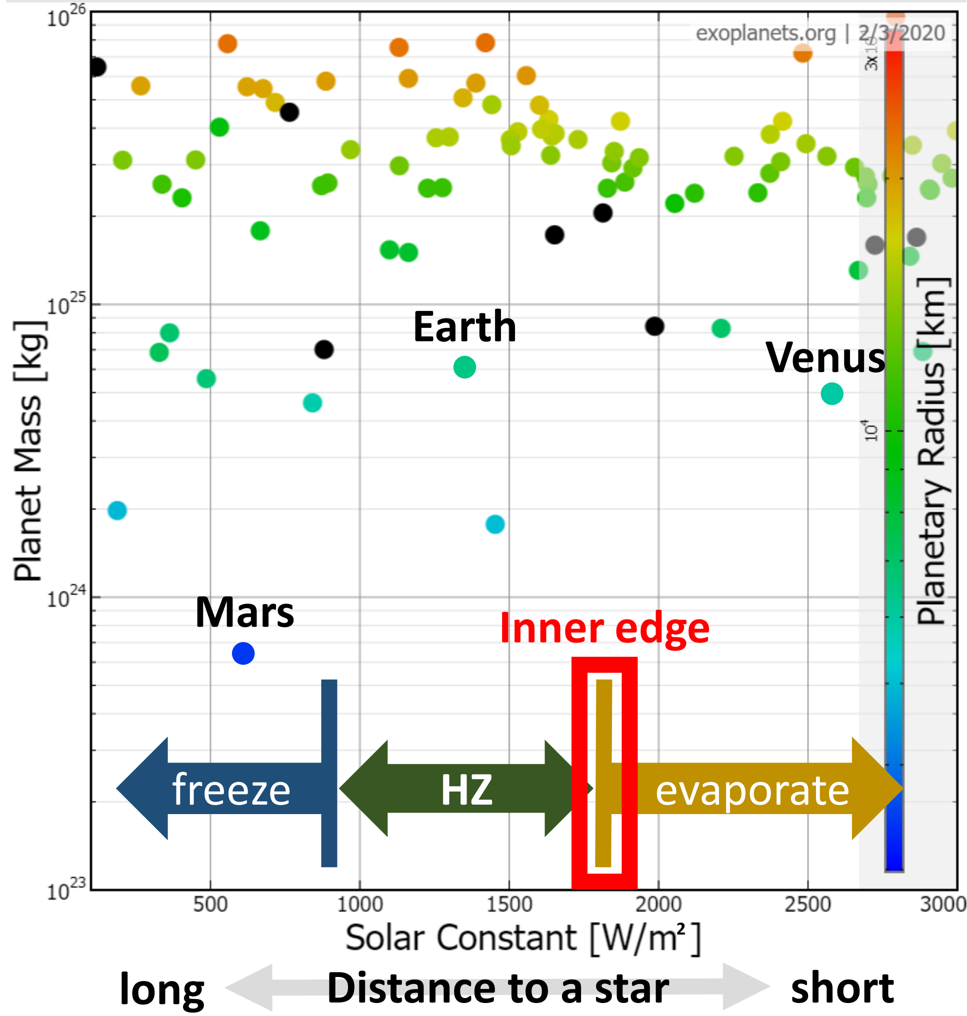
Introduction

Exoplanets in habitable zone

- Exoplanet is a planet out of the solar system
  - Rocky planet may exist
    (http://exoplanets.org/)
- In Habitable zone (HZ), liquid water exist on the planetary surface
  (Kasting et al. 1993)
  - Liquid water is necessary for life like that of the Earth
  - **Inner edge** is focused

Distribution of exoplanets

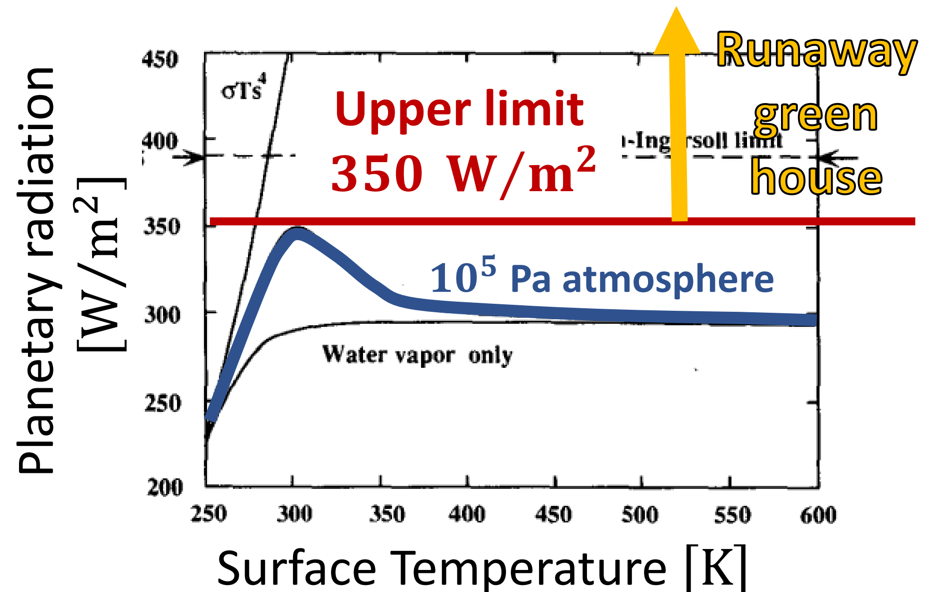


http://exoplanets.org/plots

Previous study

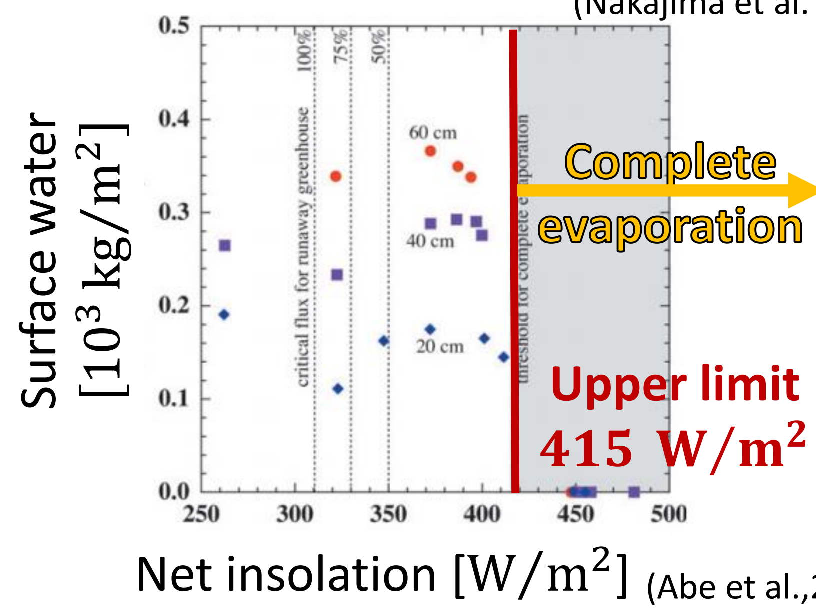
Inner edge of HZ

- An aqua planet
  (Nakajima et al., 1992; Ishiwatari et al., 2002)
  - Covered with ocean
  - Appearance of runaway green house state
    - Runaway green house state: Planetary radiation < Insolation



(Nakajima et al. 1992)

- A land planet
  (Abe et al., 2011)
  - Covered with soil and has small amount of water
  - Appearance of complete evaporation state
    - Complete evaporation state: All surface water evaporate

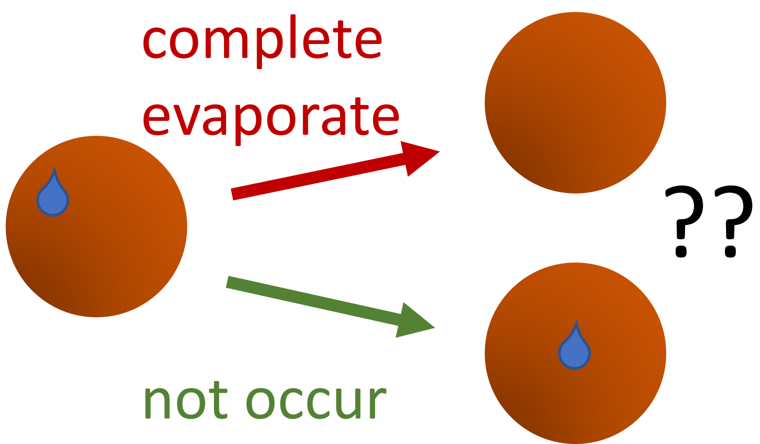


(Abe et al.,2011)

Purpose

- The first purpose was the investigation of dependence on obliquity and planetary rotation rate for the appearance of complete evaporation in a land planet
  - In a preliminary experiment, the complete evaporation did not occur

- The purpose of this study
  - The examination of appearance of complete evaporation in a land planet
  - re-experiment of Abe et al. (2011)



Methods

Model and Equations

Atmospheric general circulation model

DCPAM (Dennou-Club Planetary Atmospheric Model)

Zonal wind $$\frac{du}{dt} = \frac{uv\tan\varphi}{a} + fv - \frac{1}{\rho a\cos\varphi}\frac{\partial p}{\partial\lambda} + F_\lambda$$

Meridional wind $$\frac{dv}{dt} = \frac{u^2\tan\varphi}{a} - fu - \frac{1}{\rho a}\frac{\partial p}{\partial\varphi} + F_\varphi$$

Hydrostatic equilibrium $$0 = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$$

Mass $$\frac{d\rho}{dt} = -\rho\left\{\frac{1}{a\cos\varphi}\frac{\partial u}{\partial\lambda} + \frac{1}{a\cos\varphi}\frac{\partial}{\partial\varphi}(v\cos\phi) + \frac{\partial w}{\partial z}\right\}$$

Energy $$\frac{dT}{dt} = \frac{1}{C_p^d\rho}\frac{dp}{dt} + \frac{Q^*}{C_p^d}$$

Water mass $$\frac{dq}{dt} = S_q$$

Equation of state $$p = \rho R^d T_v$$

- Primitive equations
  - Hydrostatic equilibrium
- Thin spherical shell approximation
- The horizontal coordinate system is latitude and longitude
- Vertical coordinate $\sigma = p/p_s$

u:Zonal wind, v: Meridional wind, ρ: Density,
T: Temperature, q: Specific humidity,
a: Planetary radius, F: Forcing terms of motion,
f: Coriolis parameter, p: Pressure,
C_p^d: Constant pressure specific heat of dry air,
Q^*: Source term of energy,
S_q: Source term of vapor,
R^d: Gas constant of dry air,
T_v: Virtual temperature

Methods

Numerical schemes for physical processes

- Dynamical process
  - Pseudo-spectral method is used
  - Semi-Lagrange method is used for advection of vapor
- Radiation process
  - Radiation scheme for the Earth is used (Chou and Lee, 1996; Chou et al., 1998; Chou et al., 2001)
- Vertical eddy mixing process
  - Mellor and Yamada level 2.5 scheme (Mellor and Yamada, 1982)
  - Vertical mixing of momentum, energy and water is considered
- Cumulus Convection process
  - Relaxed Arakawa-Schubert with ice is used (Arakawa and Schubert, 1974; Moorthi and Suarez, 1992)
  - Cumulus convectional advection of energy and water is considered
- Large scale condensation process
  - Non-convective condensation with ice (Li Treut and Li, 1991)
  - Condensation of vapor in supersaturated air is considered
- Planetary surface setting
  - Thermal diffusion equation is solved
  - Bucket model is used (Manabe, 1969)

<u>Methods</u>

Experimental settings

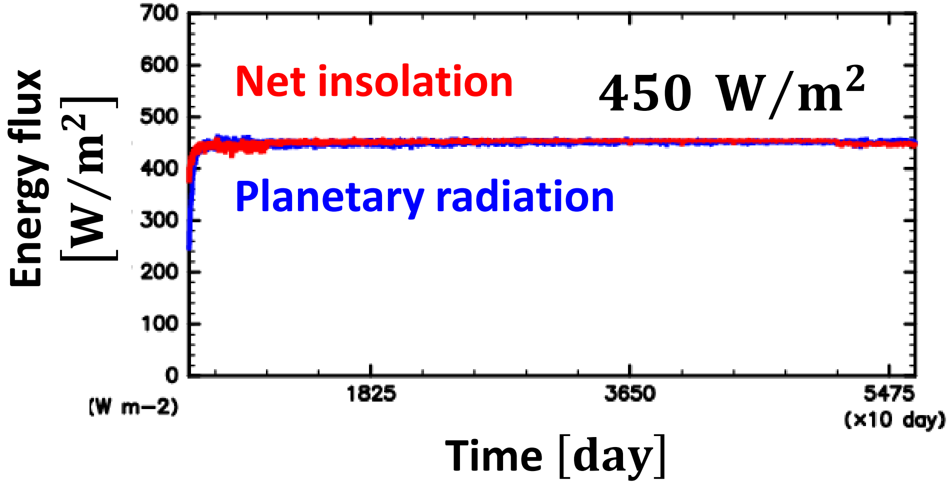
Experiment Name	Surface condition	Solar const. $\left[\mathrm{W/m^2}\right]$	Initial state
L_S1365_IniWet	bucket	1365	Isothermal, Wind static
L_S2400_IniWet	**bucket**	**2400**	**A_S1365_IniWet**
L_S2400_IniRun	bucket	2400	A_S2000_IniWet
L_S3600_IniWet	bucket	3600	L_S2400_IniWet
A_S1365_IniWet	swamp	1365	Isothermal, Wind static
A_S2000_IniWet	swamp	2000	Isothermal, Wind static

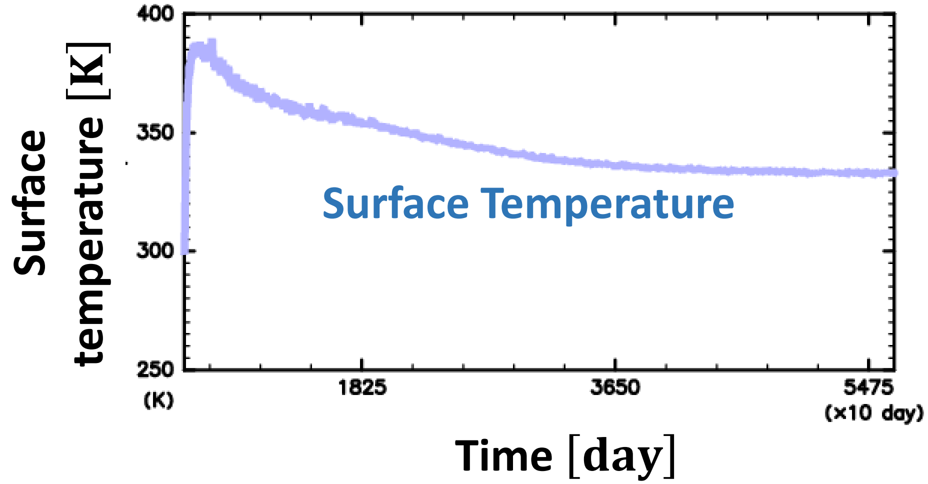
bucket : A land planet assumed ; total water is unchanged
swamp : An aqua planet assumed ; water is supplied continuously

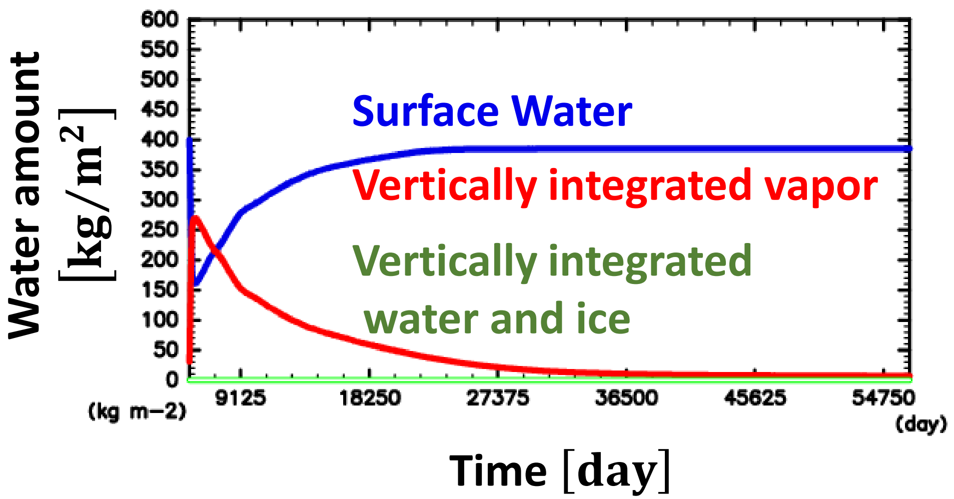
- Resolution
  - T21L26
- Other parameter
  - Eccentricity, obliquity are 0
  - Atmospheric components are same the Earth not including O_3

A statistical equilibrium state is obtained

Exp. L_S2400_IniWet







- Net insolation exceeds that of Abe et al. (2011)
- Complete evaporation does not occur

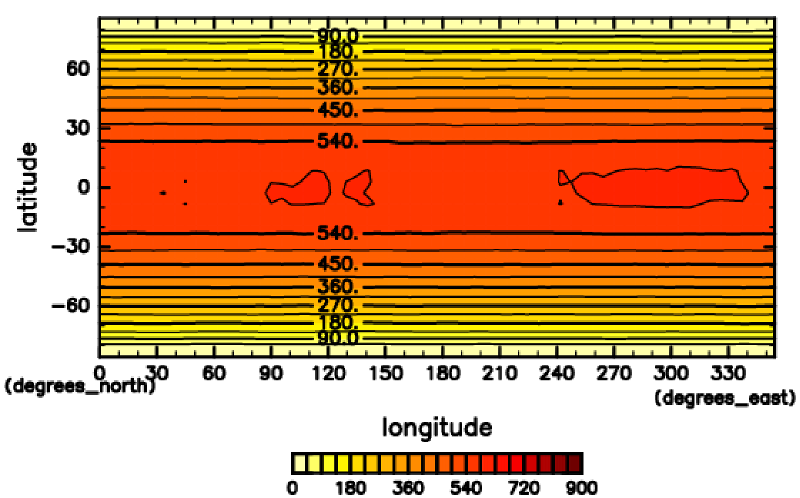
Results

The structure of statistical equilibrium state

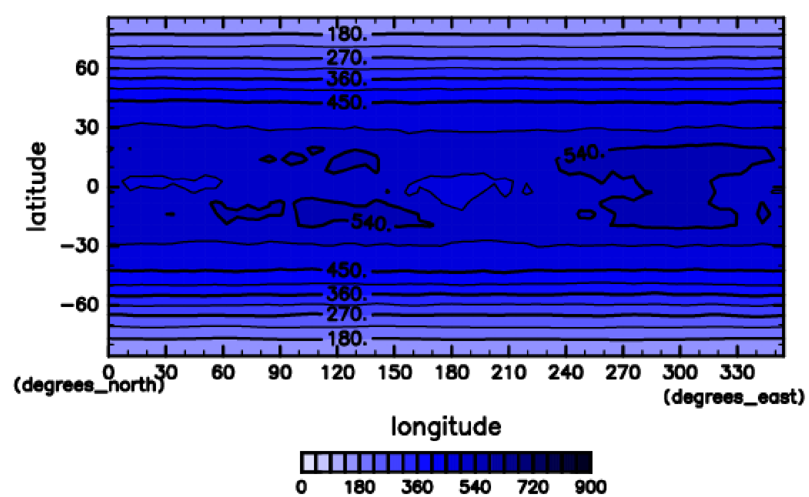
Exp. L_S2400_IniWet

- A statistical equilibrium state is maintained
  - Equatorial Planetary radiation is $520\,\mathrm{W/m^2}$
    - Much larger than $350\,\mathrm{W/m^2}$ (upper limit for aqua planet)
    - Because of dry atmosphere in the equatorial region
  - Can be balanced with large solar constant (Abe et al., 2011)

Net insolation (annual mean)



Planetary radiation (annual mean)



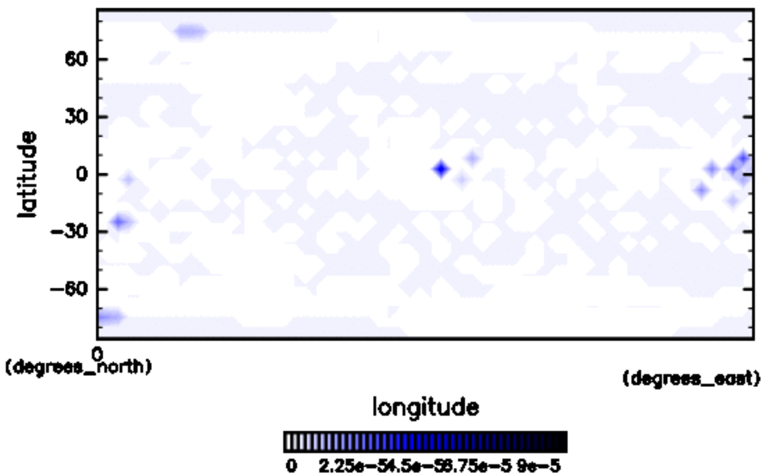
Results

Precipitation and Evaporation

L_S2400_IniWet

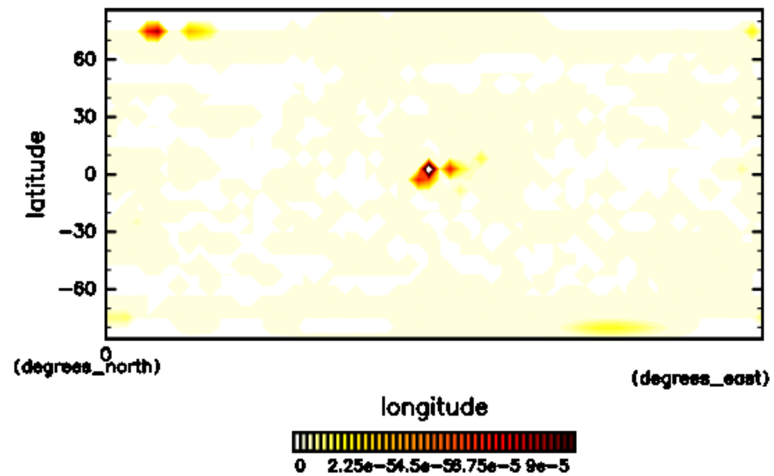
Precipitation flux

10 days, animation (interval:0.1 day)



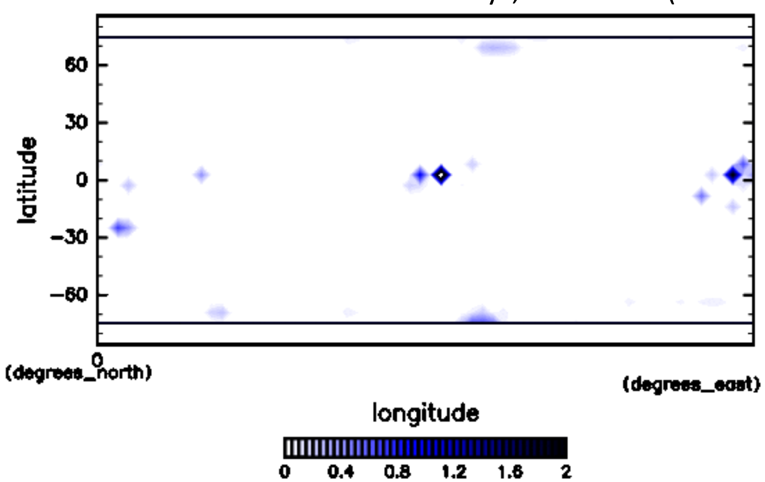
Evaporation flux

10 days, animation (interval:0.1 day)



Surface water

10 days, animation (interval:0.1 day)



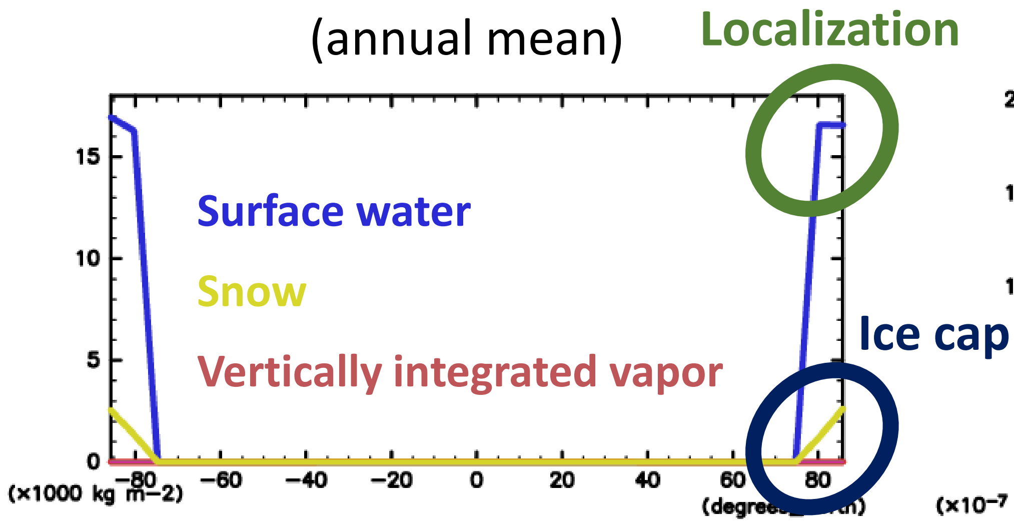
- Precipitation occurs in the region where evaporation occurs
  - Equatorial region
  - Polar region

Water localization

L_S2400_IniWet

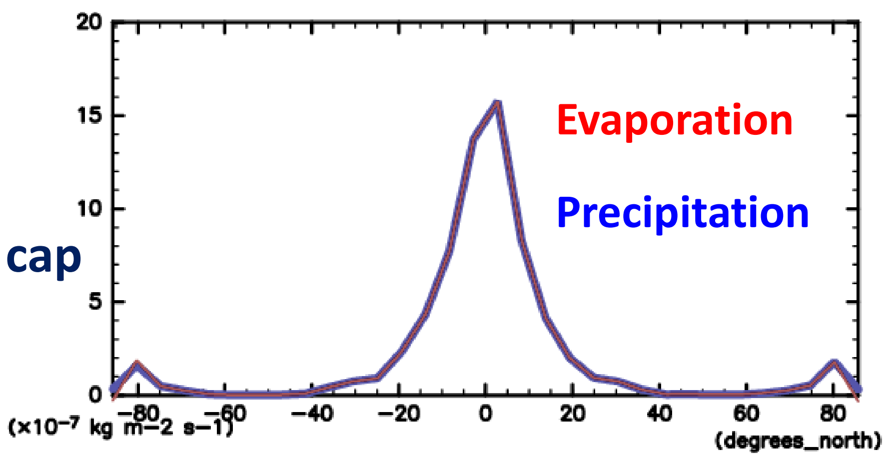
- Surface water is localized in polar region
- Polar ice cap exists
- Because temperature of polar region is low, surface water does not evaporate

Amount of water
(annual mean)



Latitude

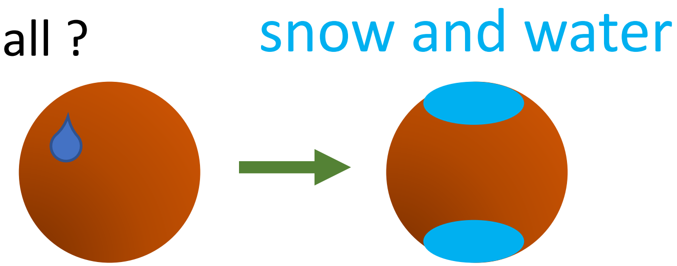
Water flux(annual mean)



Latitude

Conclusions

- Complete evaporation did not occur in the experiment of this study
    - HZ for a land planet can be wider than that for previous study
    - Temperature in polar region did not increase
        - Insolation to the polar region is small
        - Atmospheric meridional heat transport is small ?



- Further experiments
    - Experiments with different settings (increasing polar region temperature)
        - Larger solar constant
        - Various obliquity and planetary rotation rate
    - Comparative experiment using other GCMs