Existence conditions of surface water on aquaplanet and land planet

Masaki Ishiwatari[(1)]

Collaborators

Tetsuji Yoshida[(1)], Kensuke Nakajima[(2)], Yoshiyuki O. Takahashi[(3)], Shin-ichi Takehiro[(4)], Yoshi-yuki Hayashi[(3)]

(1) Hokkaido Univ. (2) Kyushu Univ. (3) Kobe Univ. (4) Kyoto Univ.

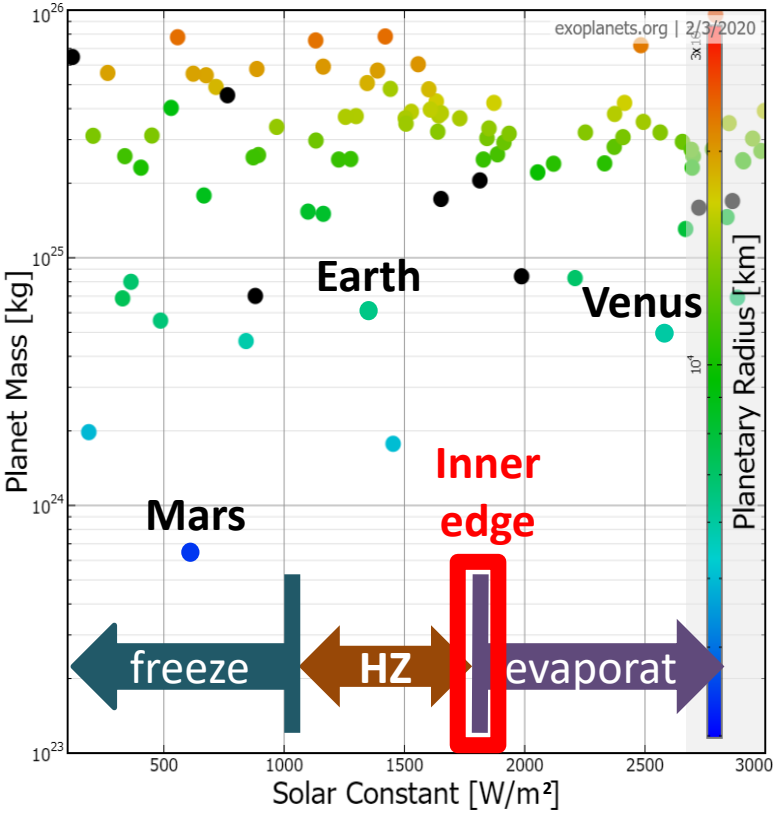
ABC Project/CPS Workshop on Climates of Terrestrial Planets in Various Solar System
Feb. 12, 2020

CPS Center for Planetary Science

GFD 電脳倶楽部

Motivation of our study

- **Conditions determining inner edge ofhabitable zone**
  - **Aquaplanets and land planets**
    - “end members” of various land-sea patterns



Aquaplanet

Planet whose surface is covered with ocean

Land planet

Planet with small amount (10m order) of water

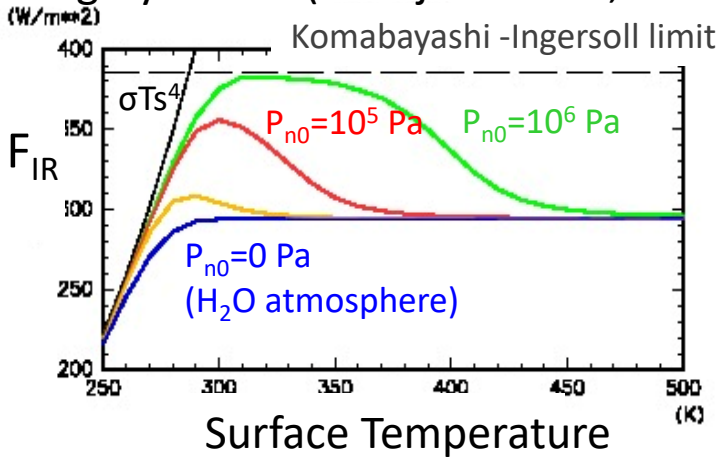
- **Parameter experiments using an atmospheric general circulation model(AGCM)**

Aquaplanet Experiment

HZ inner edge of aquaplanet

- **Appearance of runaway greenhouse**
  - **One of the conditions determining HZ inner edge**
- **Runaway condition was considered for various cases:**
  - **Leconte et al. (2013): Earth-like planet, Importance of drying in subtropics**
  - **Yang et al. (2013): Synchronously rotating planet, Importance of albedo of dense clouds**

1D gray model (Nakajima et al., 1992)

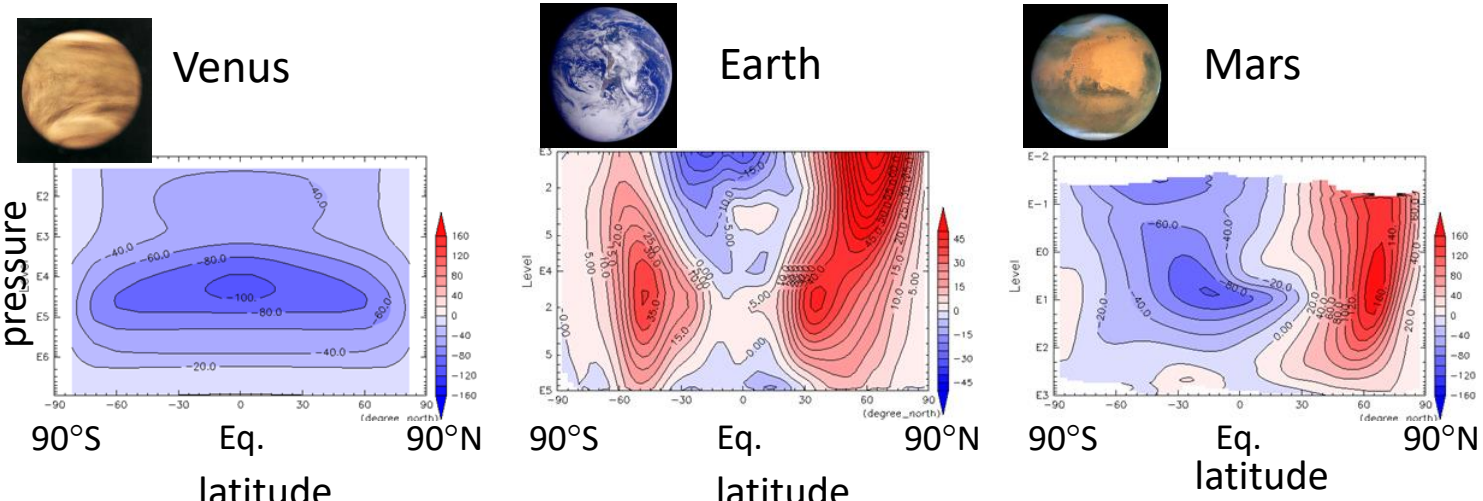


- **Our previous result: Runaway condition is that global mean stellar flux exceeds F_{IR} upper limit**
  - **Ishiwatari et al. (2002): gray atmosphere AGCM w/o cloud**
- **In this study, appearance condition of runaway state is re-examined**
  - **Existence of the upper limit of F_{IR} in 3D system?**
  - **for synchronously/non-synchronously rotating planets , w/ cloud and w/o cloud**

Model

- **General circulation model: DCPAM5**
  - **http://www.gfd-dennou.org/library/dcpam/**
- **Various experiments with a same framework**

Zonal mean zonal wind



Tone pattern differs among figures.

- **Basic equations:3D primitive equation on a sphere**
- **Discretization: spectrum method(horizontal), finite difference method(vertical)**

Physical processes (using schemes for Earth's atmosphere)

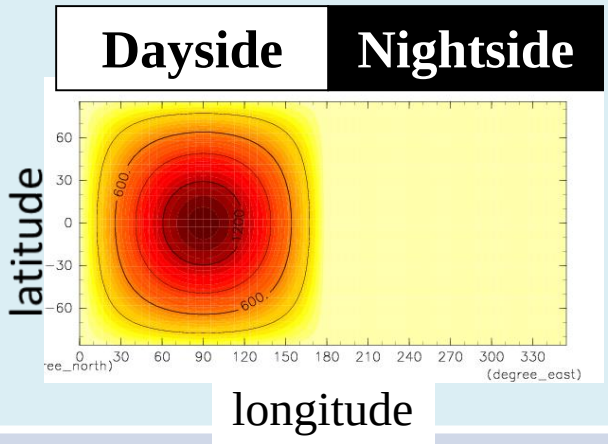
- **Radiation**
  - **Absorption and emission by water vapor, CO_2, cloud water: Chou and Lee (1996), Chou et al (2001)**
    - **δ-Eddington approximation: Toon et al. (1989)**
    - **Insolation spectrum is assumed to be same as that of Sun**
- **Cumulus convection**
  - **Relaxed Arakawa-Schubert: Moorthi and Suarez (1992)**
- **Surface flux: Beljaars and Holtslag (1991)**
- **Vertical turbulent mixing: Mellor and Yamada (1982) level2.5**
- **Cloud model**
  - **Simple model: considering its generation, advection, turbulent mixing and extinction**

$$\frac{\partial q_c}{\partial t} = -v \cdot \nabla v - \dot{\sigma}\frac{\partial q_c}{\partial \sigma} + F_{turb} + S_c + \frac{q_c}{\tau_{LT}}$$

S_c : Source of cloud water
–Condensation in large scale condensation scheme
–Detrainment from could top in RAS scheme

$\frac{q_c}{\tau_{LT}}$: extinction of cloud water
tuned as $\tau_{LT} = 1500$sec
under Earth condition(T42L26)

Setup of aquaplanet experiment

Solar flux distribution	**Synchronously rotating planet configuration** 	**non-Synchronous configuration (Earth-like)** with diurnal and seasonal changes
Solar Constant	S=1366 , 1600, 1800, 2000, 2200 [W/m^2]	
Rotation rate	Ω*= 0, 0.1, 0.5, 1.0	
Cloud extinction time	τ_{LT}=0 (no cloud), 1500 [sec]	

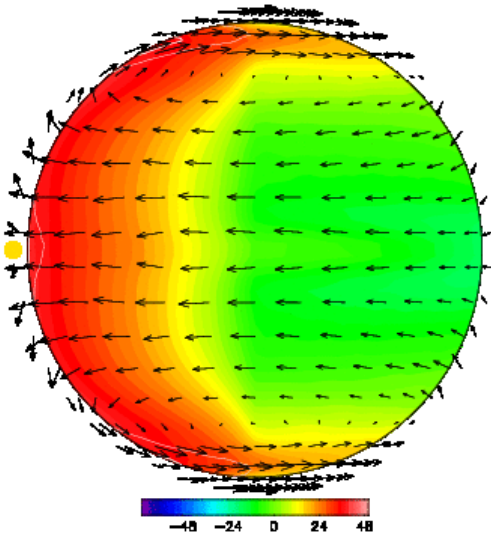
- **Planetary surface: ocean with zero heat capacity, no horizontal heat transport**
- **Dry air amount at surface: 10^5Pa, Surface albedo : 0.15**
- **Resolution: T42L26, Integration Period: 3 years**

Examples of atmospheric state

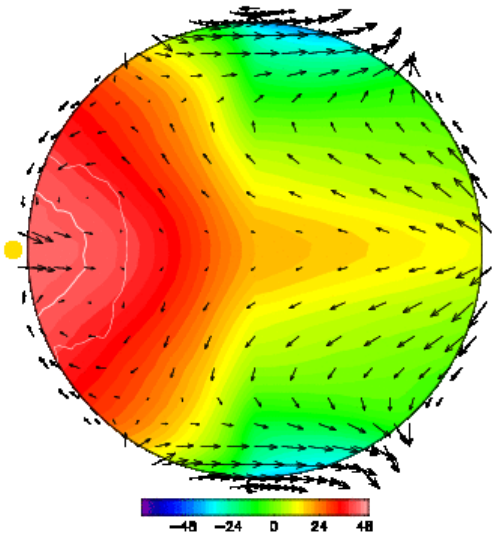
Time mean field (365 day) with various distance from star

With changing viewpoint

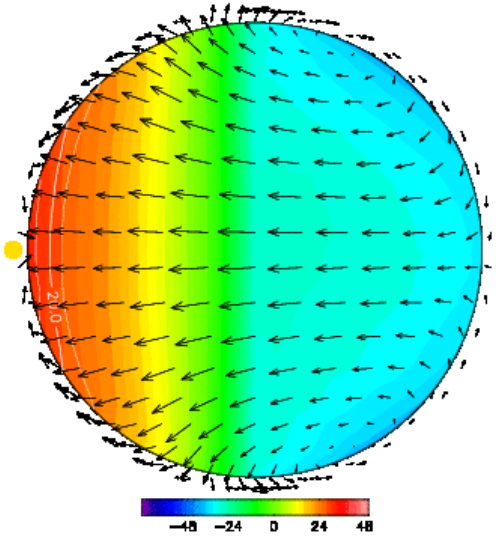
Ω*=1.0, S*=1.46



Ω*=0.5, S*=1.17



Ω*=0.1, S*=1.0



Yellow dot:
sub-stellar point

color: surface temperature
arrow: horizontal wind at lowest level
Contour: precipitation

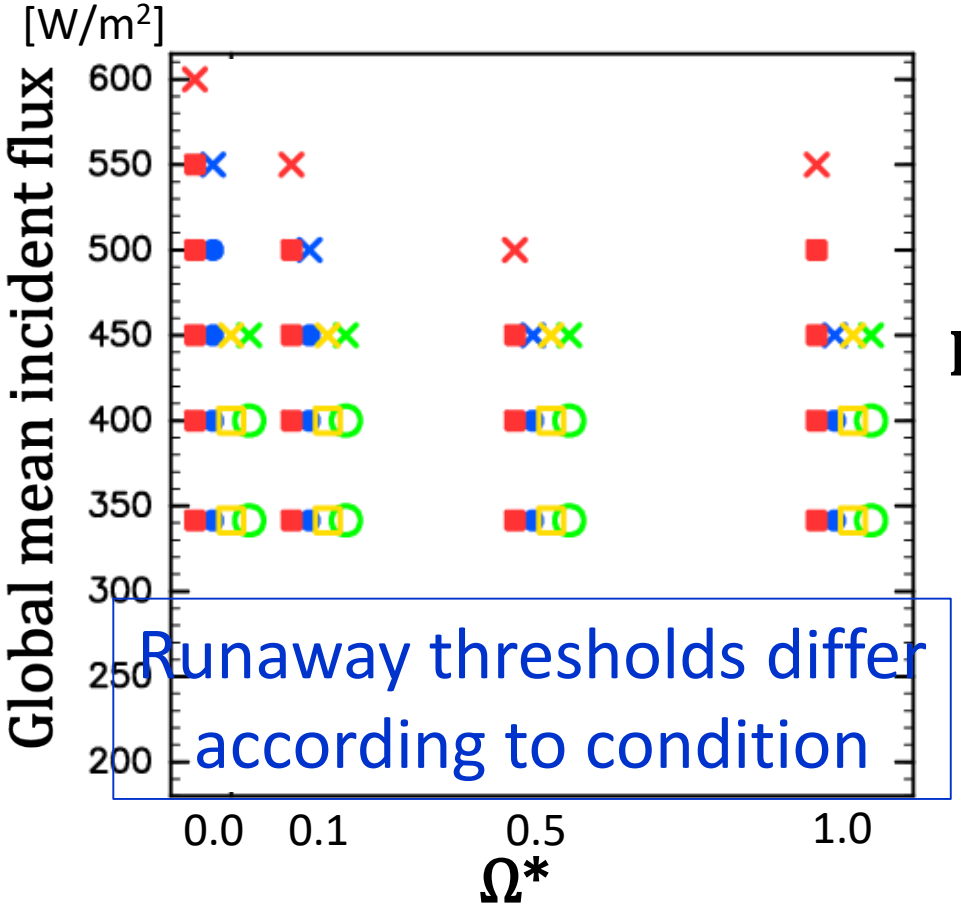
large **Solar Constant: S (influences temperature)** small

large **Planetary rotation rate: Ω*(influences circulation)** small

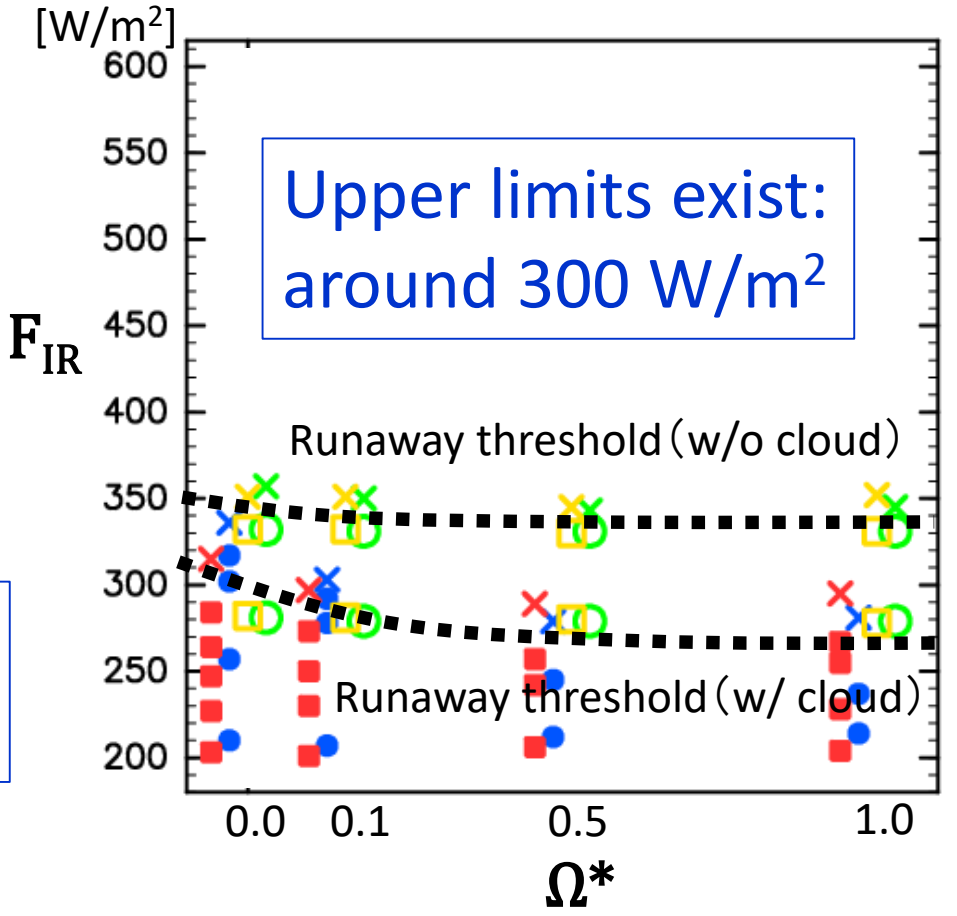
ex. Noda et al. (2016)

Outgoing planetary radiation

Threshold values of solar constant and F_{IR}



Runaway thresholds differ according to condition



Square, Circles: Equilibrium states

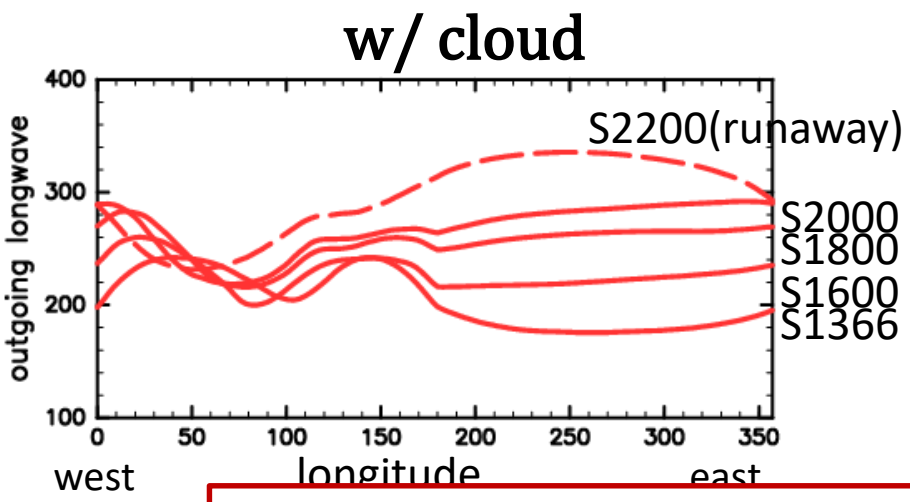
- ■ : Synchronous (w /cloud)
- ● : Non-Synchronous (w /cloud)
- □ : Synchronous (w/o cloud)
- ○ : Non-Synchronous (w/o cloud)

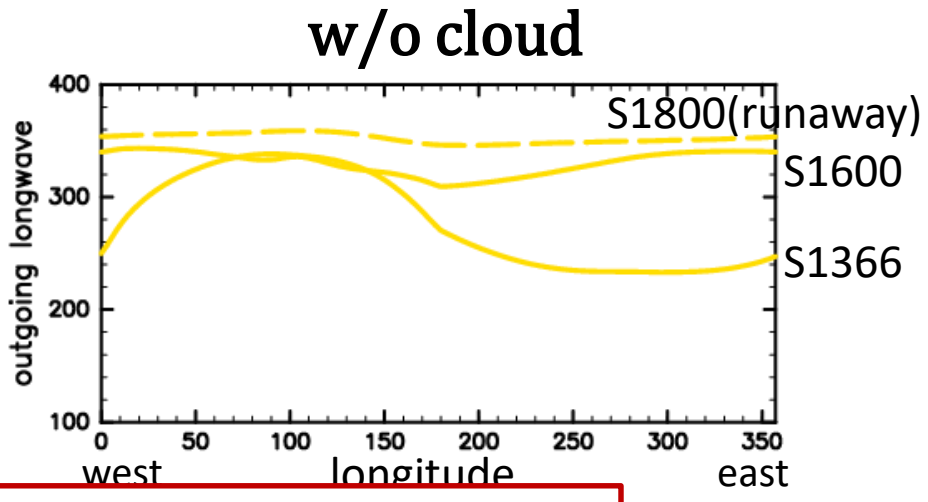
Crosses: The runaway greenhouse state

- × : Synchronous (w / cloud)
- × : Non-Synchronous (w / cloud)
- × : Synchronous (w/o cloud)
- × : Non-Synchronous (w/o cloud)

Horizontal distributions of F_{IR}

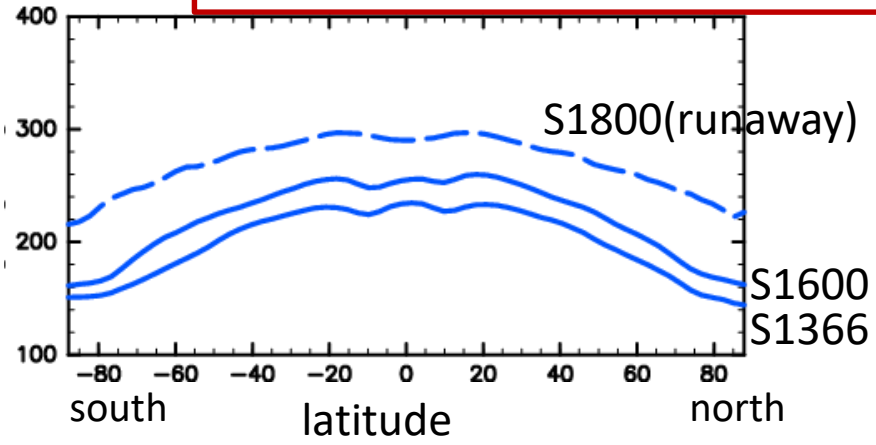
- **Synchronous cases: Zonal (meridional mean)** $\Omega^*=1.0$

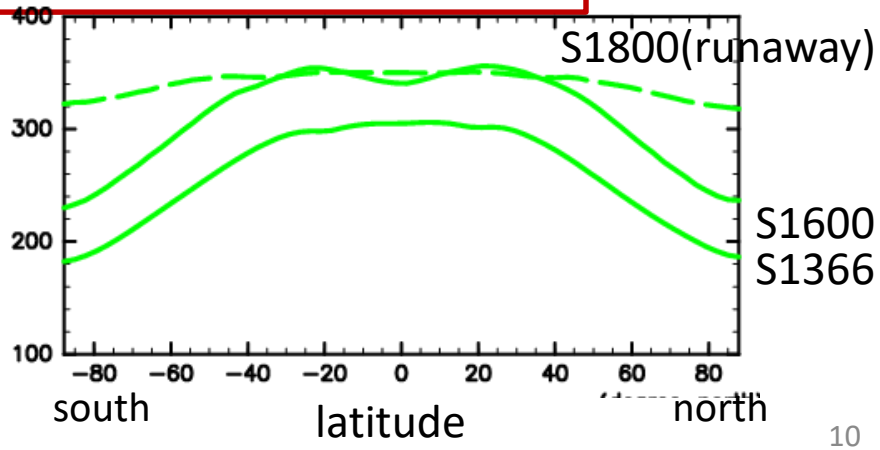




- **Non-(** **mean)**

F_{IR} are bounded by upper limit values.
Upper limit value of cloud case is smaller.

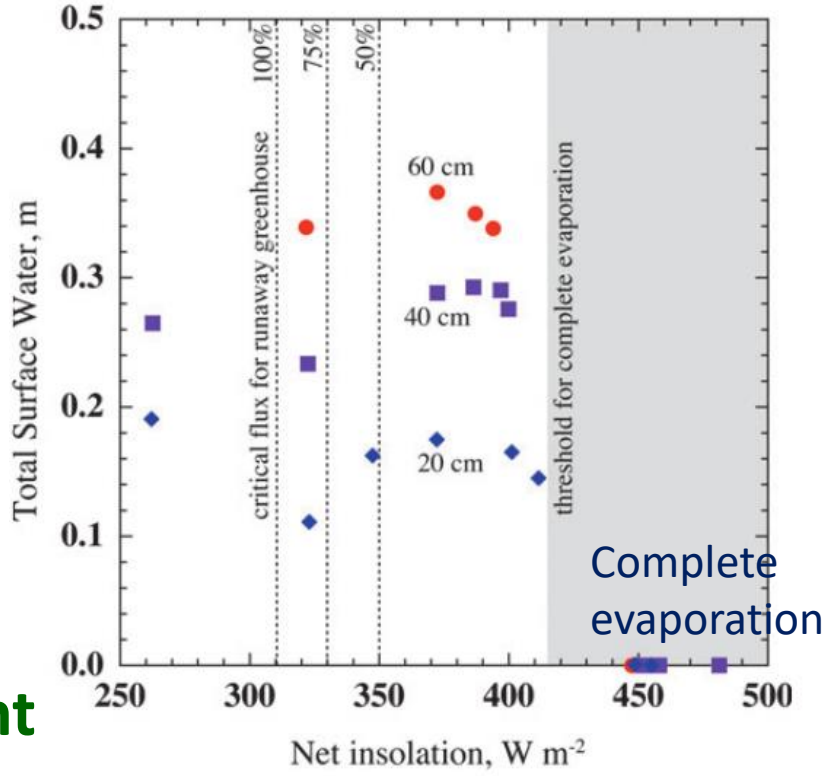




Land planet experiment

HZ inner edge of land planet

- **Appearance of complete evaporation**
- **Previous studies perform GCM experiments with increased solar constant**
  - **Abe et al. (2011): Complete evaporation of surface water for net insolation over 415 W/m²**
- **In this study:**
  - **We aimed the examination of planetary rotation rate dependence**
  - **However, we obtained different results from Abe et al. (2011)**
  - **We perform GCM experiment for confirming whether complete evaporation really occurs**



Abe et al. (2011)

Setup of land planet experiment

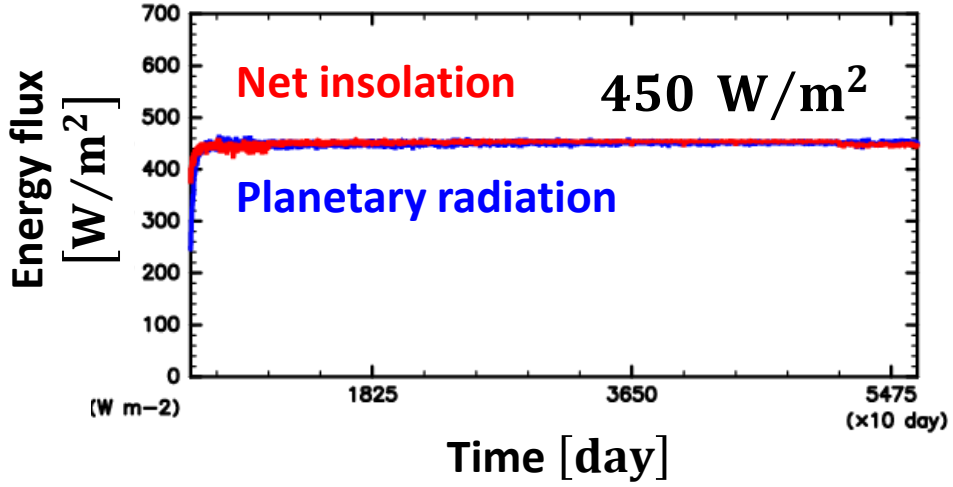
Experiment Name	Surface condition	Solar const. $[W/m^2]$	Initial state
L_S1365_IniWet	bucket	1365	Isothermal, Wind static
L_S2400_IniWet	**bucket**	**2400**	**A_S1365_IniWet**
L_S2400_IniRun	bucket	2400	A_S2000_IniWet
L_S3600_IniWet	bucket	3600	L_S2400_IniWet
A_S1365_IniWet	swamp	1365	Isothermal, Wind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

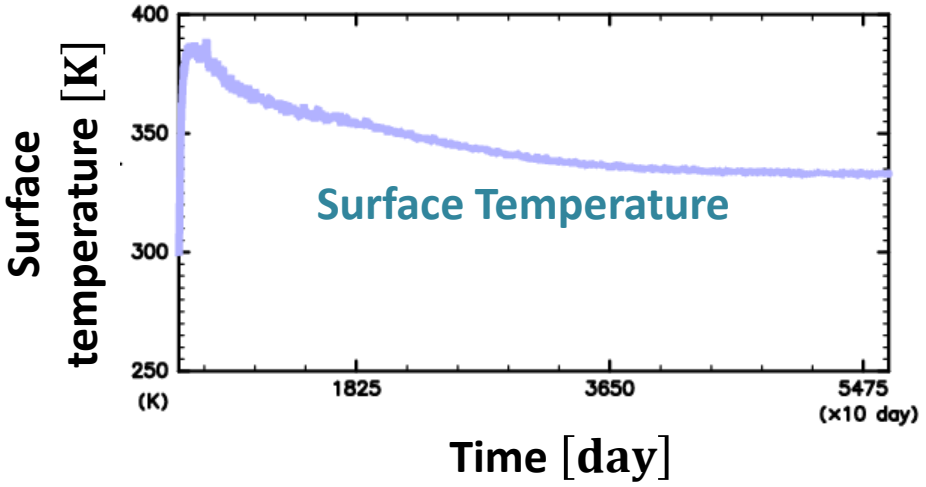
bucket : Land planet
swamp : Aqua planet

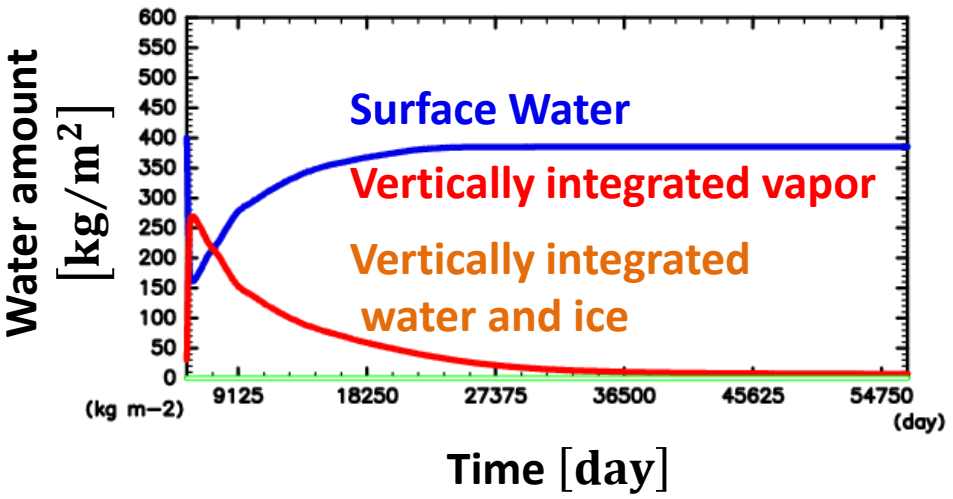
- **Rotation rate : Earth's value**
- **Obliquity: 0**
- **Initial water depth :40cm**
- **Resolution: T21L26**

Results : Time evolution

Exp. L_S2400_IniWet







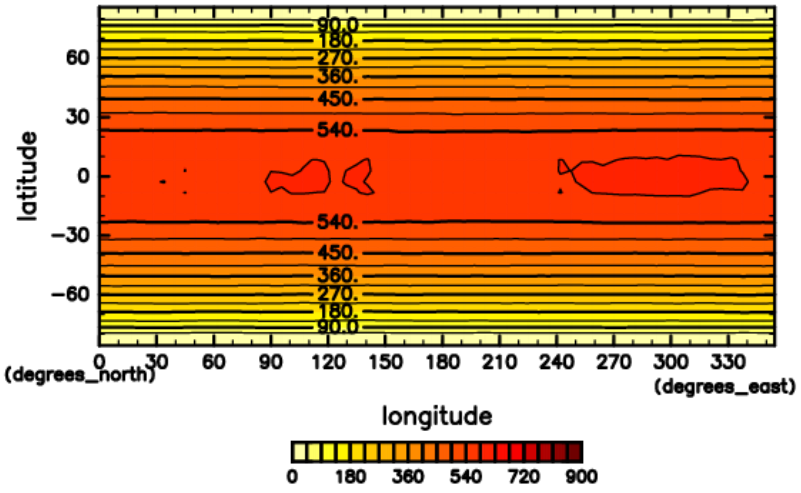
- Net insolation exceeds that of Abe et al. (2011)
- Complete evaporation does not occur

Radiation fields

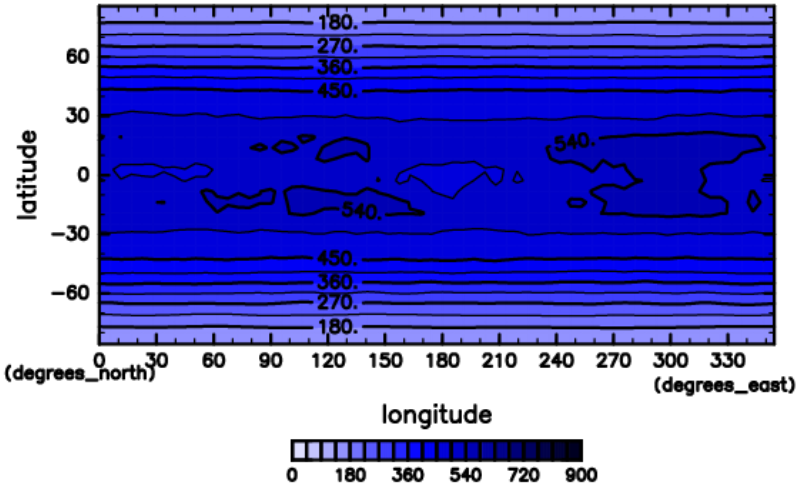
Exp. L_S2400_IniWet

- **Equatorial Planetary radiation is $520\,\mathrm{W/m^2}$**
  - **Much larger than $350\,\mathrm{W/m^2}$ (upper limit for aquaplanet)**
  - **Because of dry atmosphere in the equatorial region**

Net insolation



Planetary radiation

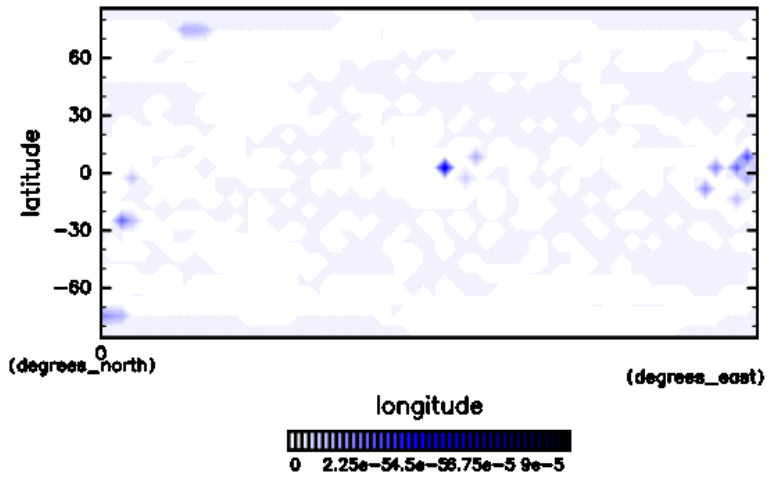


Rain & Evaporation

Exp. L_S2400_IniWet

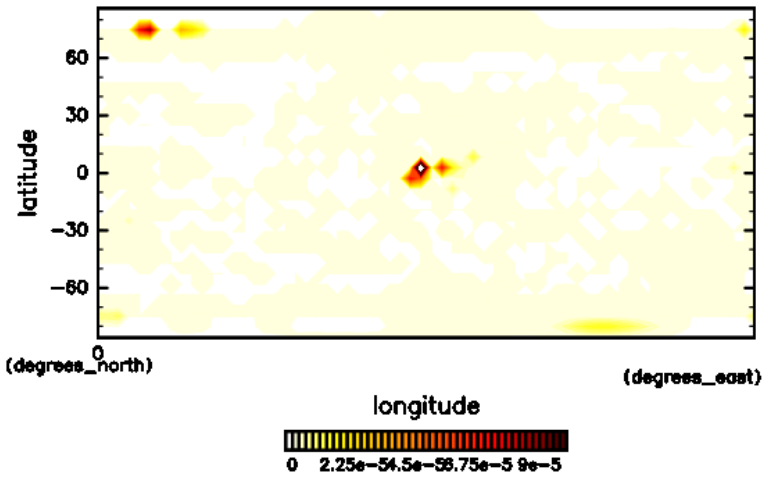
Precipitation flux

10 days, animation (interval:0.1 day)



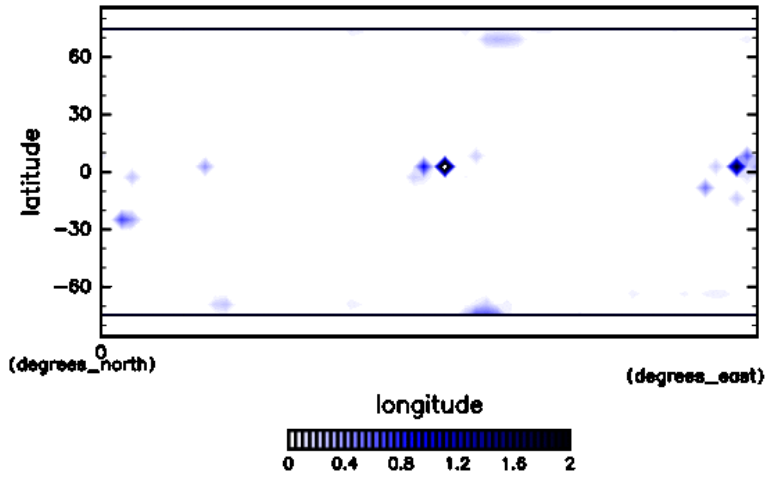
Evaporation flux

10 days, animation (interval:0.1 day)



Surface water

10 days, animation (interval:0.1 day)



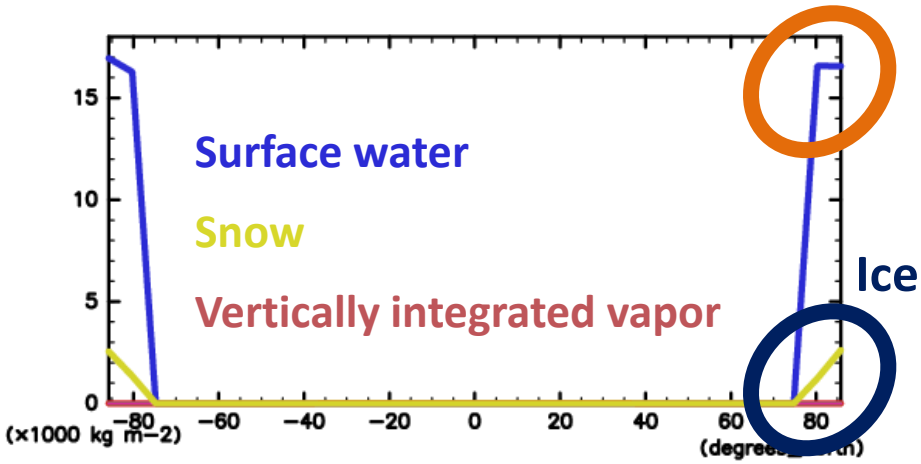
- Precipitation occurs in the region where evaporation occurs
  - Equatorial region
  - Polar region

Rain & Evaporation

Exp. L_S2400_IniWet

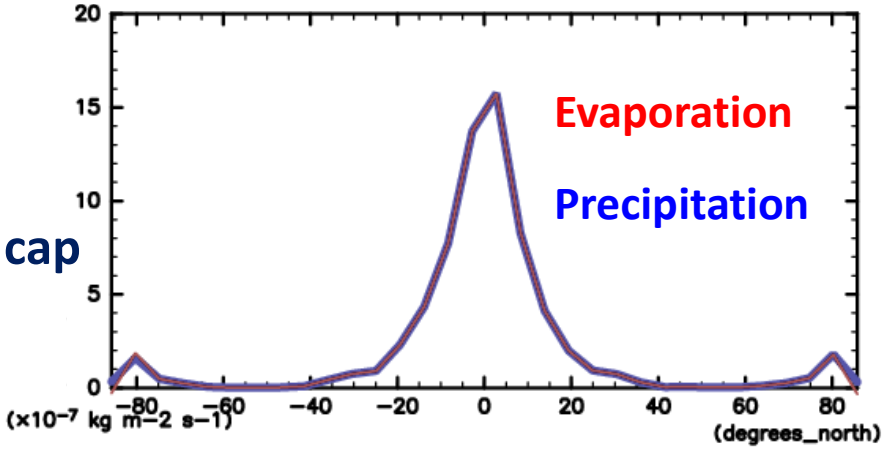
- **Surface water is localized in polar region**
- **Polar ice cap exists**
- **Because temperature of polar region is low, surface water does not evaporate**

Amount of water



Latitude

Water fluxes

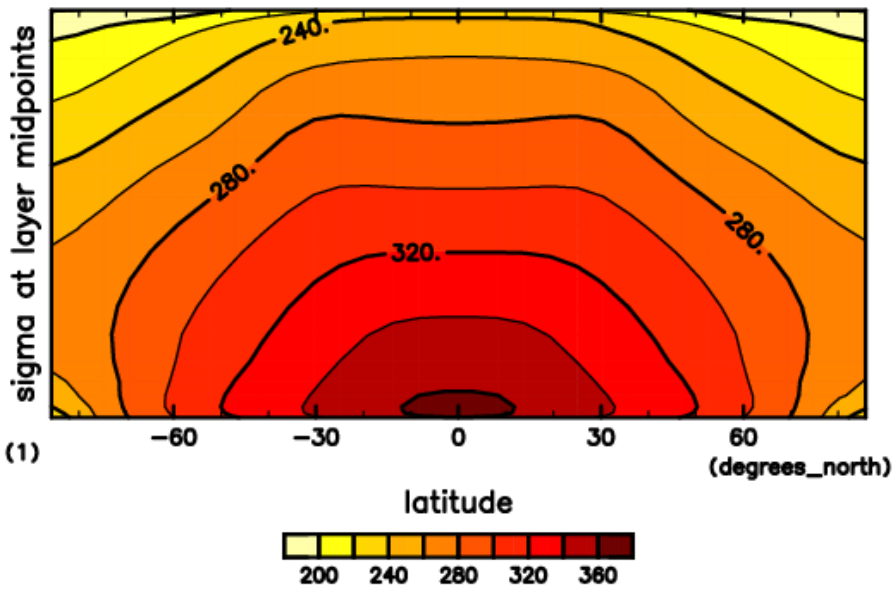


Latitude

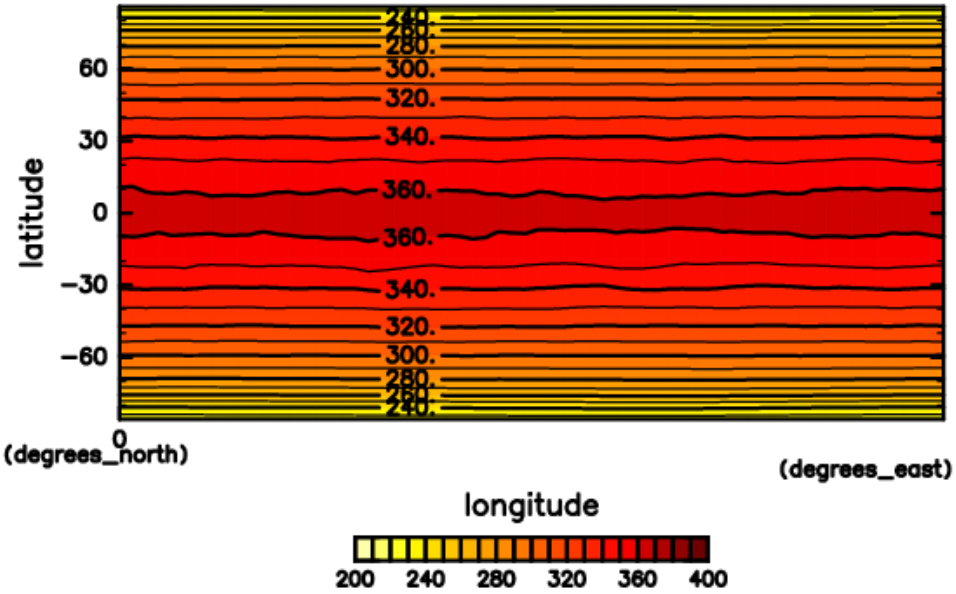
Temperature Fields

Exp. L_S2400_IniWet

Meridional distribution



Horizontal distribution



In polar region, temperature does not rise

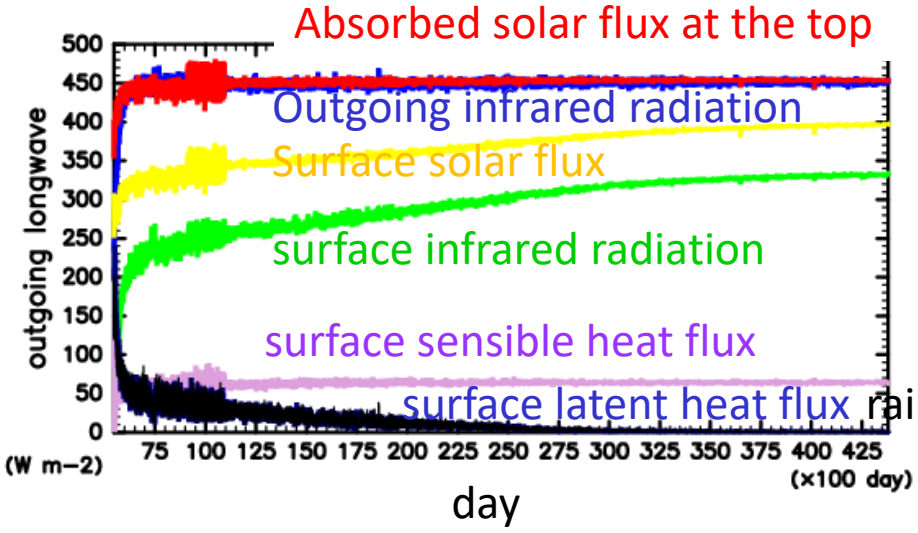
Summary

- **We performed GCM experiments on the inner edge of habitable zone**
- **Aquaplanet experiment**
  - **There exists F_{IR} upper limit regardless of existence of cloud, planetary rotation rate, solar flux distribution**
    - Upper limit value is 350W/m^2 for no cloud case, 300W/m^2 for cases with cloud
    - Remaining problem: What determines upper limit value of F_{IR} for cloud case?
- **Land planet experiment**
  - **Complete evaporation does not occur with net insolation flux obtained by previous study**
    - Liquid water may exist on land planet for net insolation larger than those previously discussed
    - Next problem: confirmation of the occurrence of complete evaporation with increased obliquity

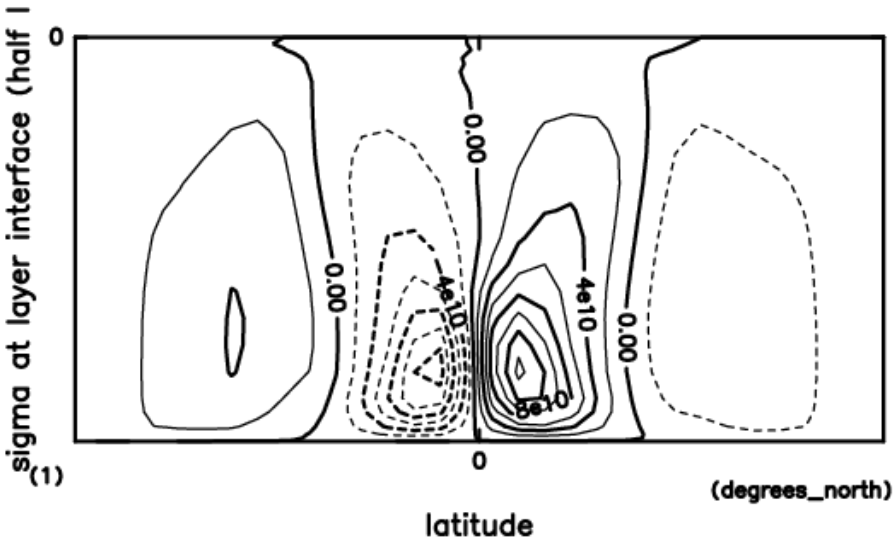
Follow-up exp.: equilibrium state

- **Resolution : T21L26, Surface water amount: 40cm**
  Initial state: Result of aquaplanet experiment (same as Abe et al., 2011)

Heat fluxes



Mass stream function



Heat budget and water budget almost reach equilibrium

Hadley cells and Ferrel cells appear

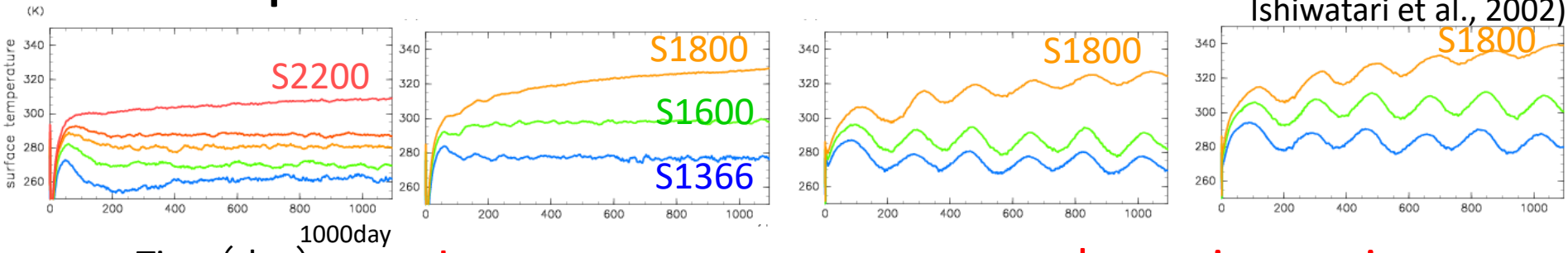
Time evolutions of Ts and OLR

Global mean values for cases with Ω* =1.0

Synchronous | **Non-synchronous**

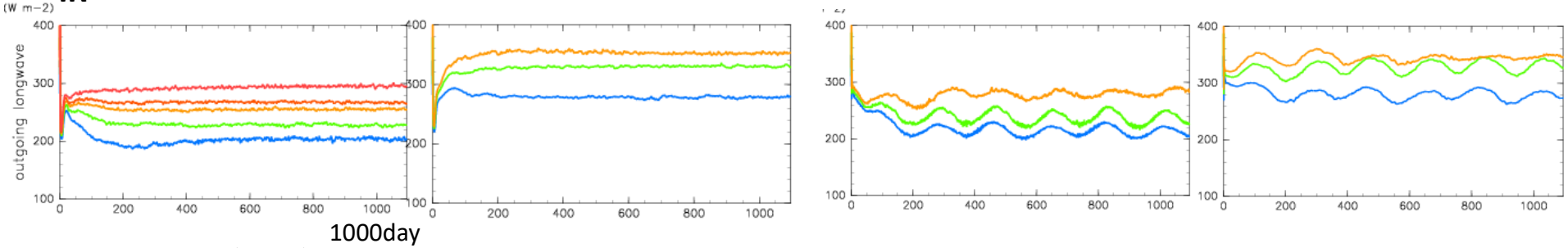
w/ cloud | w/o cloud | w/ cloud | w/o cloud (corresponding to Ishiwatari et al., 2002)

Surface Temp.



In runway state: temperature keeps increasing

F_{IR}



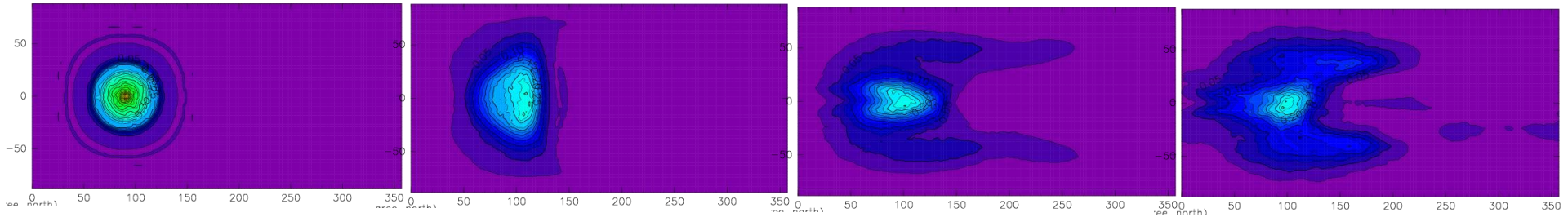
In runway state: F_{IR} is smaller than absorbed stellar flux

Most upper line in each figure shows result of runaway case

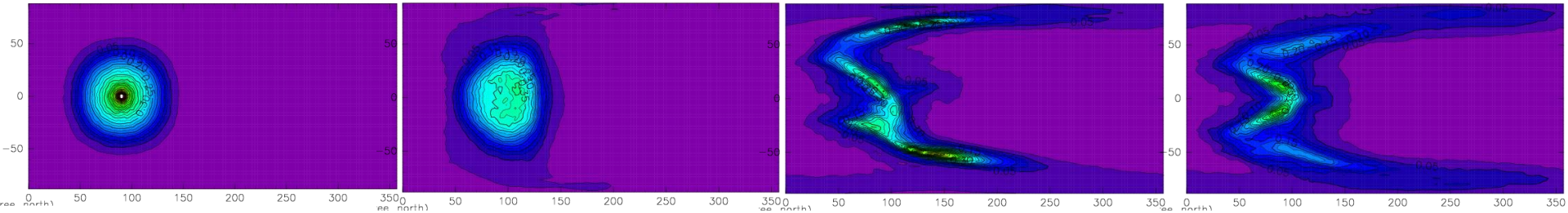
Cloud water (Synchronous case)

Ω=0.0 **Ω=0.1** **Ω=0.5** **Ω=1.0**

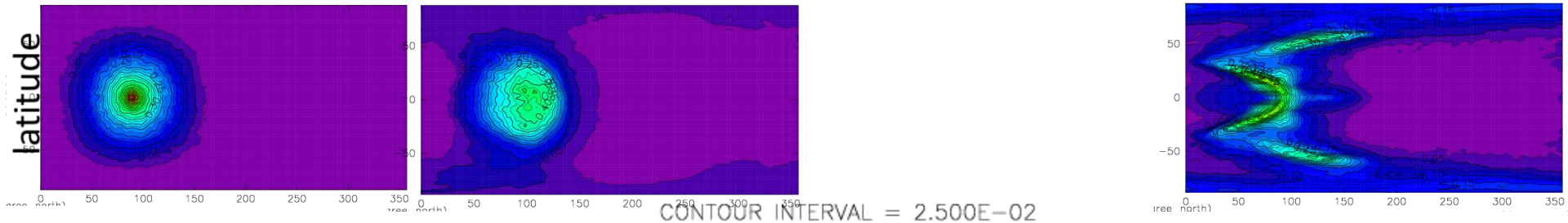
S=1366



S=1800



S=2200

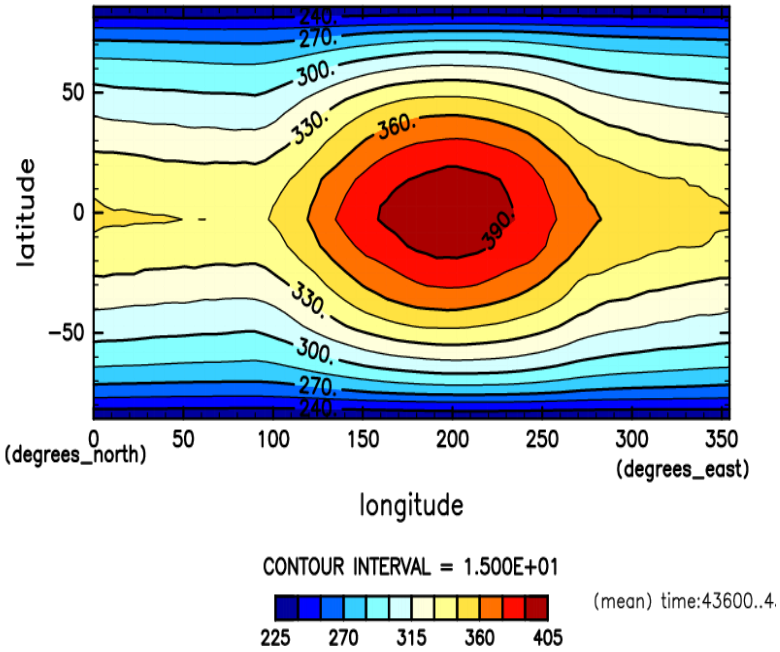


365 day average

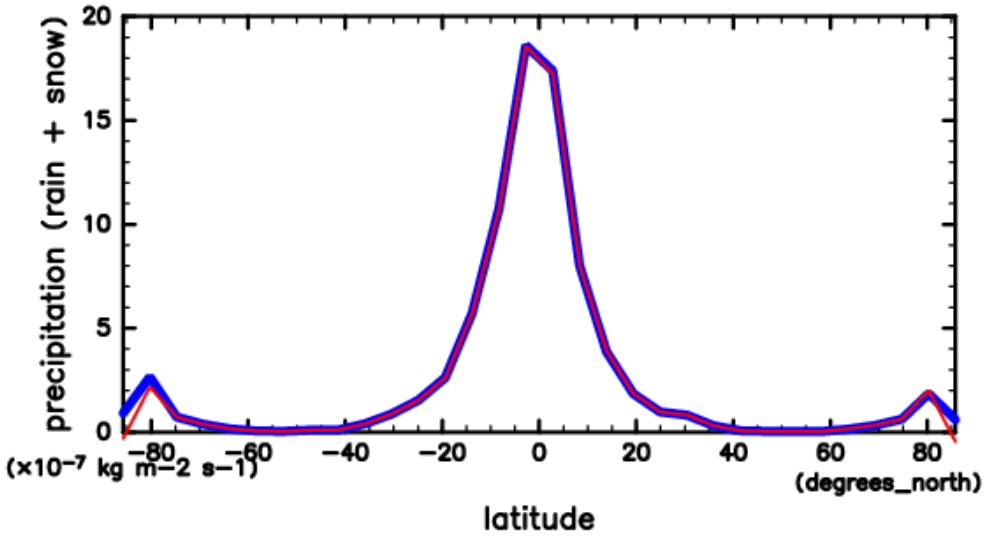
Surf. Temp & Precipitation

- **Resolution : T21L26, Surface water amount: 40cm**
  Initial state: Result of aquaplanet experiment (same as Abe et al., 2011)

Surface Temperature



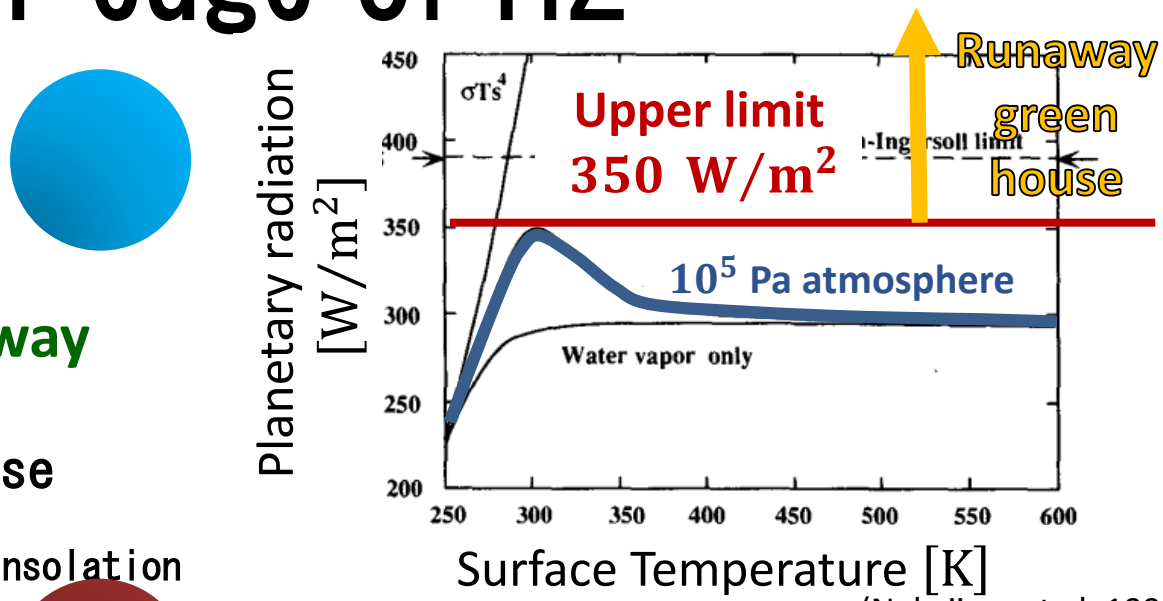
Precipitation, Evaporation



Previous study

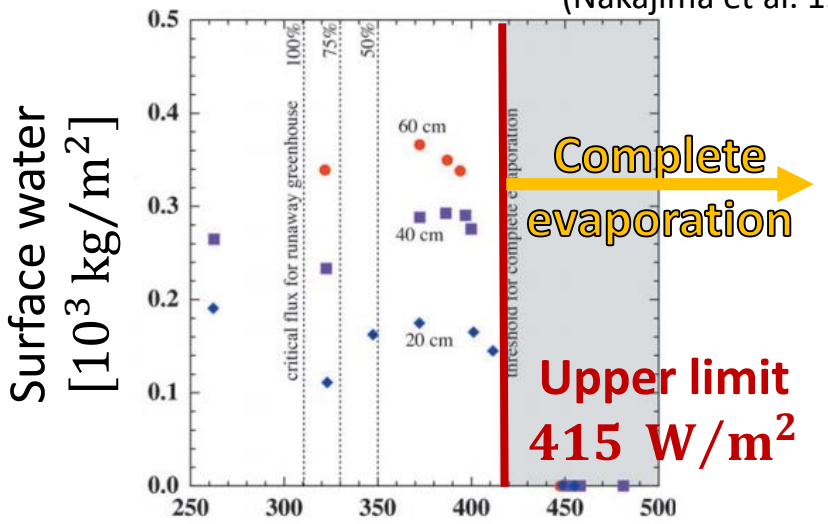
Inner edge of HZ

- **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)