Climate of synchronously rotating planet

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Aquaplanet Workshop
Feb. 21, 2017

Center for Planetary Science

GFD 電脳倶楽部

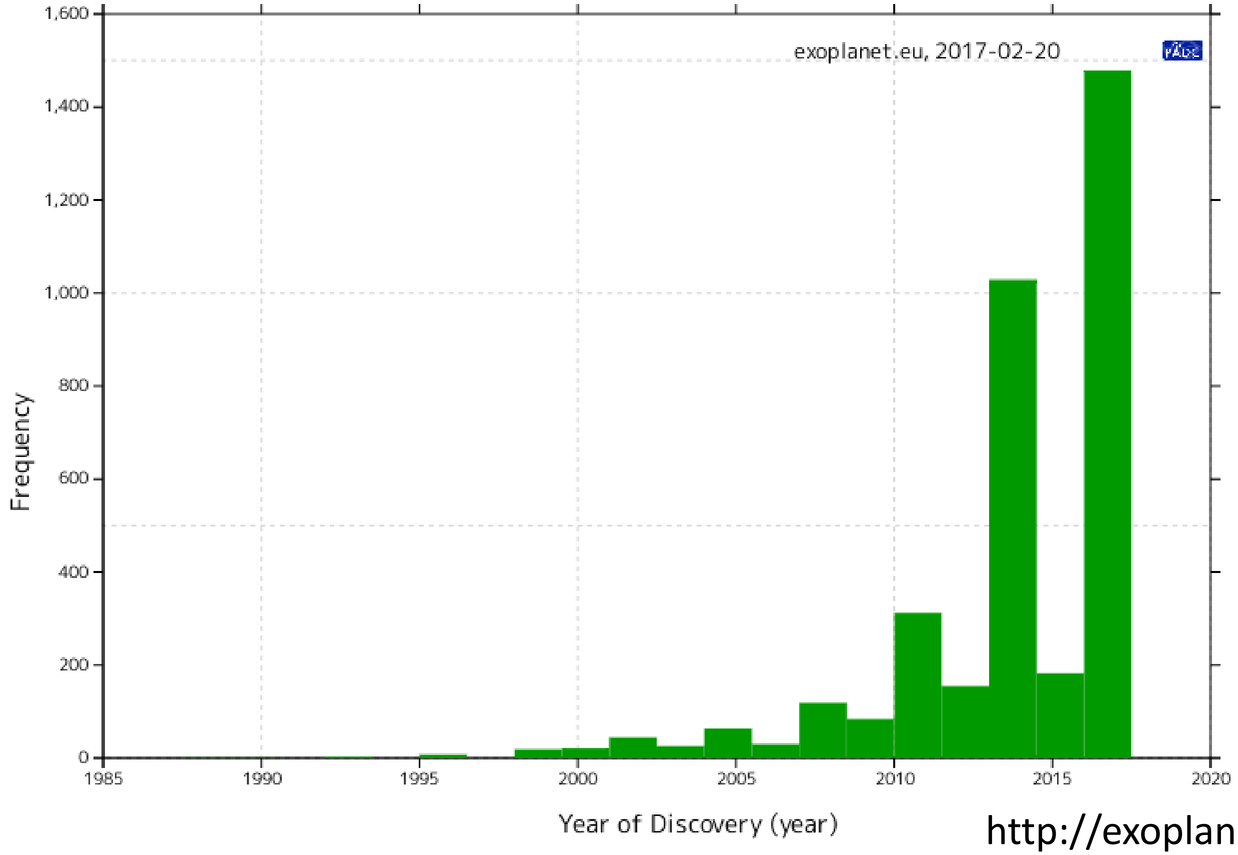
Outline of this presentation

- Introduction
  - What's synchronously rotating planet?
- Planetary rotation rate dependence of climate
  - Circulation pattern
  - Day-night energy transport
- Solar constant dependence
  - Occurrence condition of the runaway greenhouse state
- Concluding remarks

Introduction

Exoplanets

- **The number of discovered exoplanets is increasing**

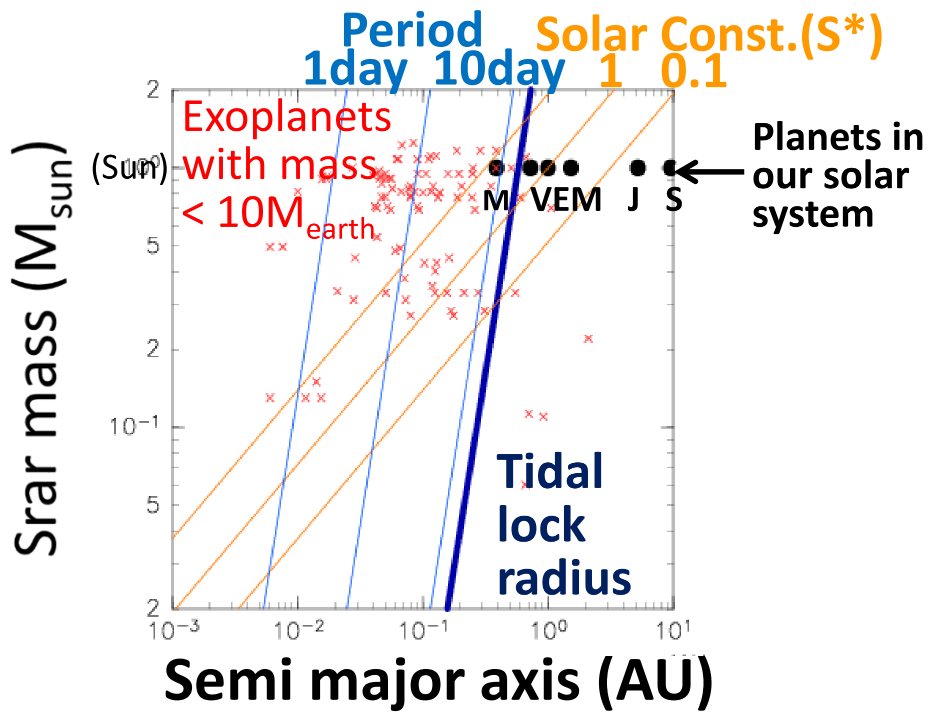


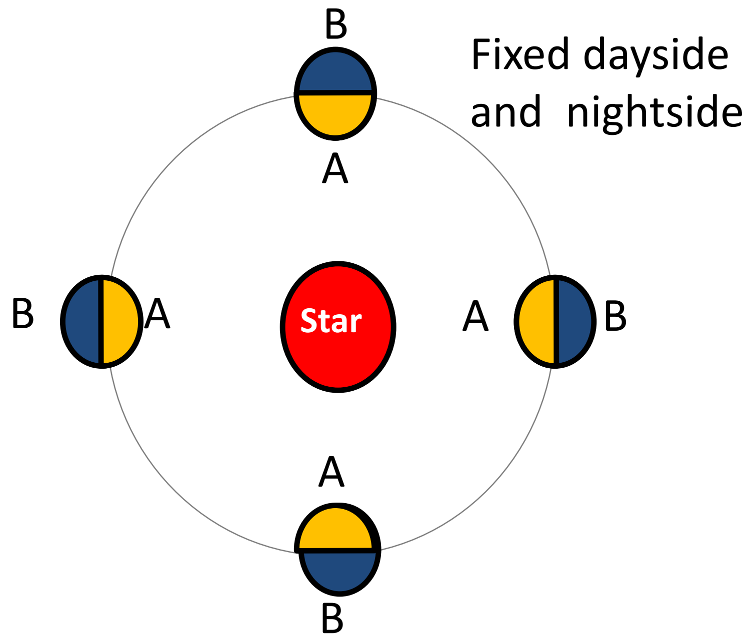
http://exoplanet.eu/diagrams/?t=h

- **Exoplanets have characteristics different from those of solar system planets**

Synchronously rotating planet

- **Many low-mass exoplanets are tidally locked.**
  - **They have fixed dayside and nightside**
- **Some of them may be terrestrial planet**
  - **They are new objects for climate research**



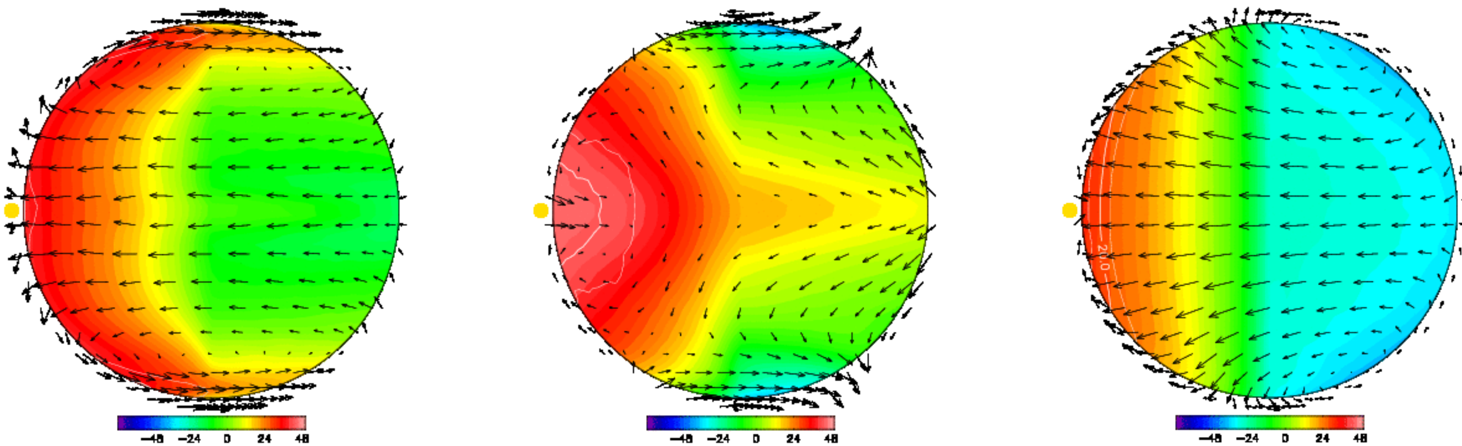


- **Climate of synchronously rotating planets?**

Examples of atmospheric state

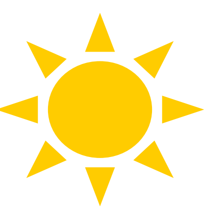
Time mean field (365 day) with changing viewpoint

$\Omega^*=1.0$, $S=2000W/m^2$ | $\Omega^*=0.5$, $S=1600W/m^2$ | $\Omega^*=0.1$, $S=1366W/m^2$



Yellow dot:
subsolar point

Colors: surface temperature
Vectors: surface wind
Contours: precipitation



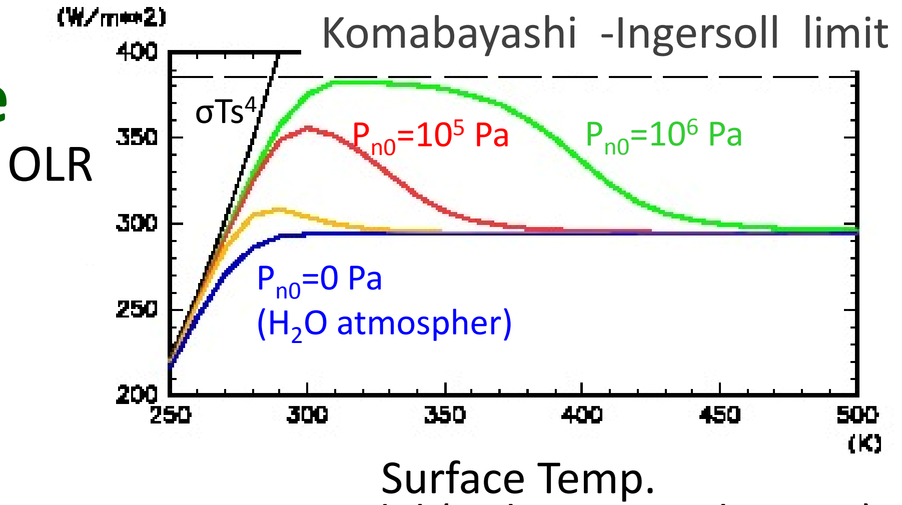
large **Solar constant: S*** small

large **Planetary rotation rate: Ω*** small

Two key parameters

- **Climate state depends on**
  (1) planetary rotation rate
  (2) solar constant
- **Planetary rotation rate changes atmospheric circulation pattern**
  - **Ω-dependence experiment for a gray atmosphere**
- **Solar constant determines whether equilibrium state can be obtained**
  - **S-dependence experiment with non-gray atmosphere including simple cloud model**

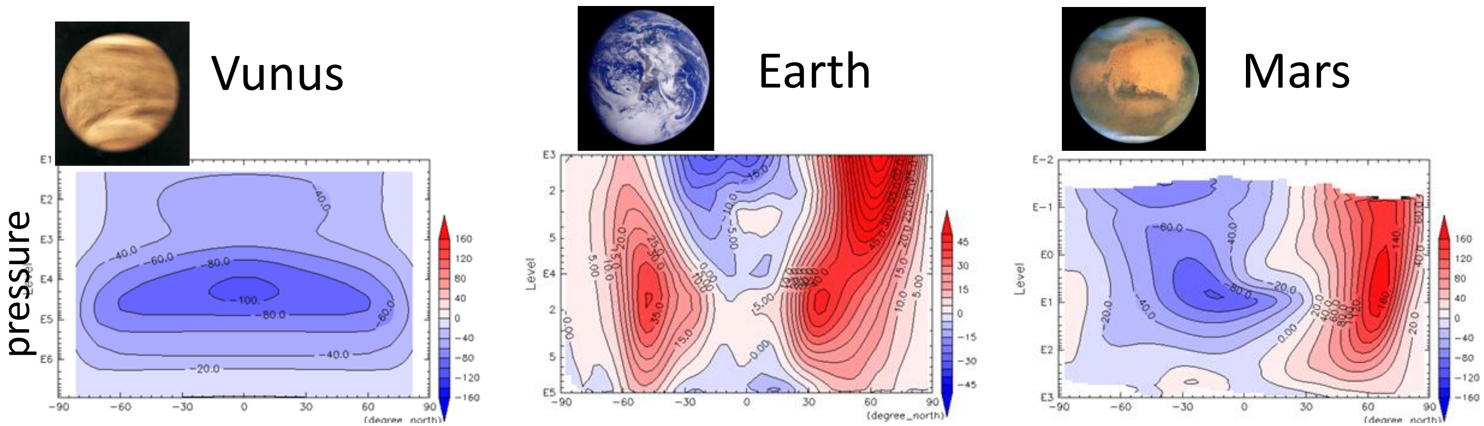
The runaway greenhouse state



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

Model

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



Tone pattern differs among figures.

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

Ω-dependence experiment with gray AGCM

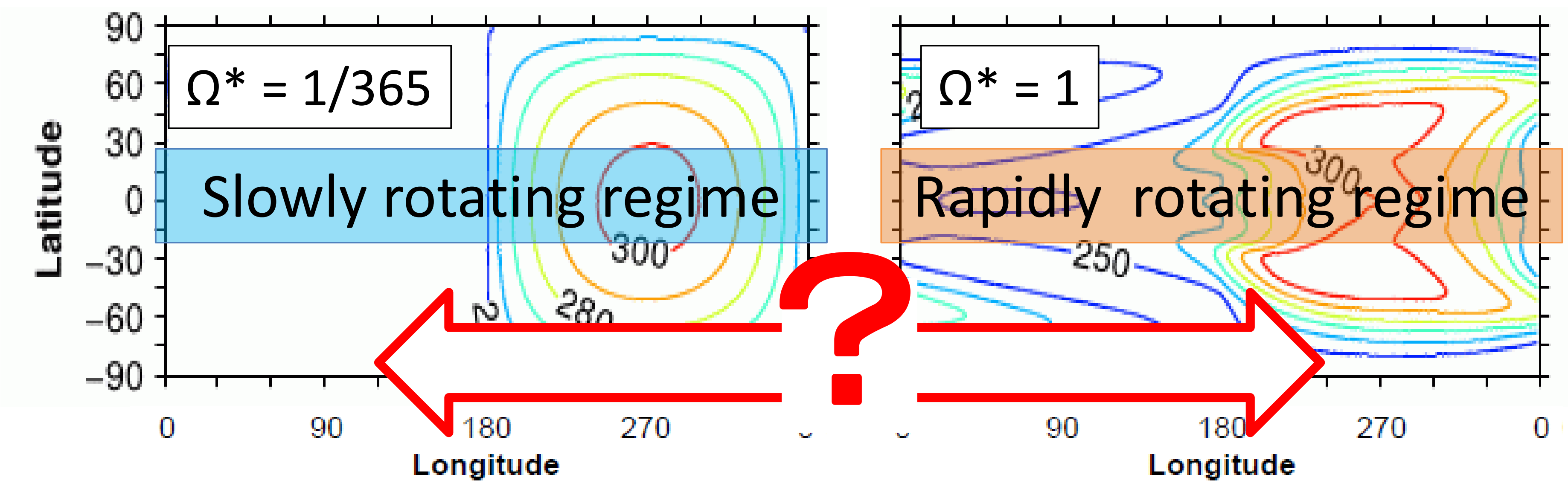
Noda et al. (2017), Icarus

What’s problem?

- **In previous GCM experiments, two kinds of equilibrium states are obtained.**
  - **Joshi (2003): Ω*=1**
  - **Merlis and Schneider (2010): Ω*=1/365～1**
  - **Edson et al. (2011): Ω*=1/100～1**

(Ω*: planetary rotation rate normalized by the Earth’s value)

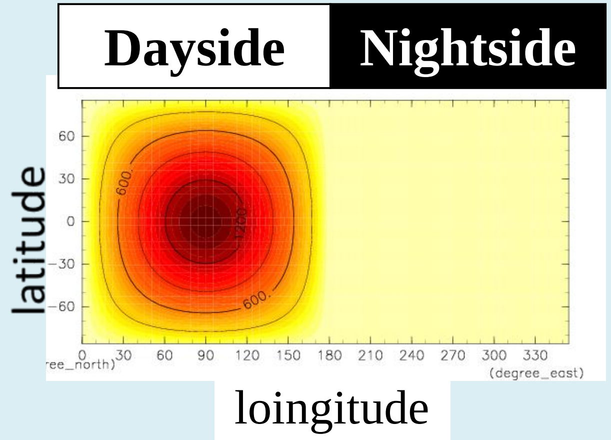
Surface temperature (Merlis and Schneider, 2010)



Physical processes

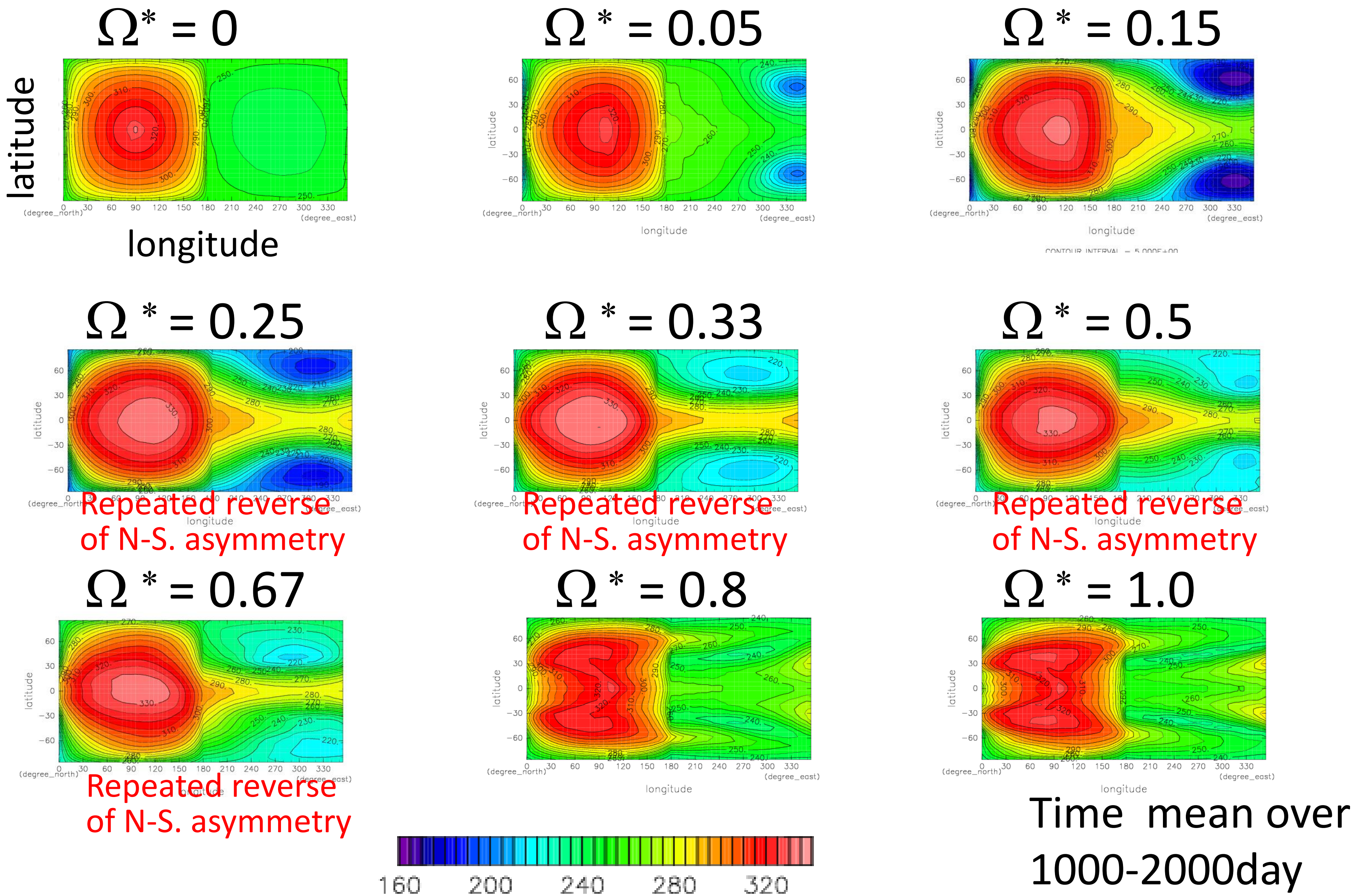
- **Radiation**
  - Water vapor : gray to IR radiation
  - Dry gas: transparent
- **Cumulus convection**
  - Convective adjustment (Manabe et al., 1965)
- **Surface flux: Beljaars and Holtslag (1991)**
- **Vertical turbulent mixing:**
  Mellor and Yamada (1974) level2.5
- **Planetary surface：**
  ocean with zero heat capacity,
  no horizontal heat transport
- **No cloud**

Experimental setup

Solar flux distribution	**Synchronously rotating planet configuration** 
Solar Constant	S=1380 [W/m^2] (Earth's value)
Rotation rate	Ω*= 0, …… ,1.0 (18 cases)

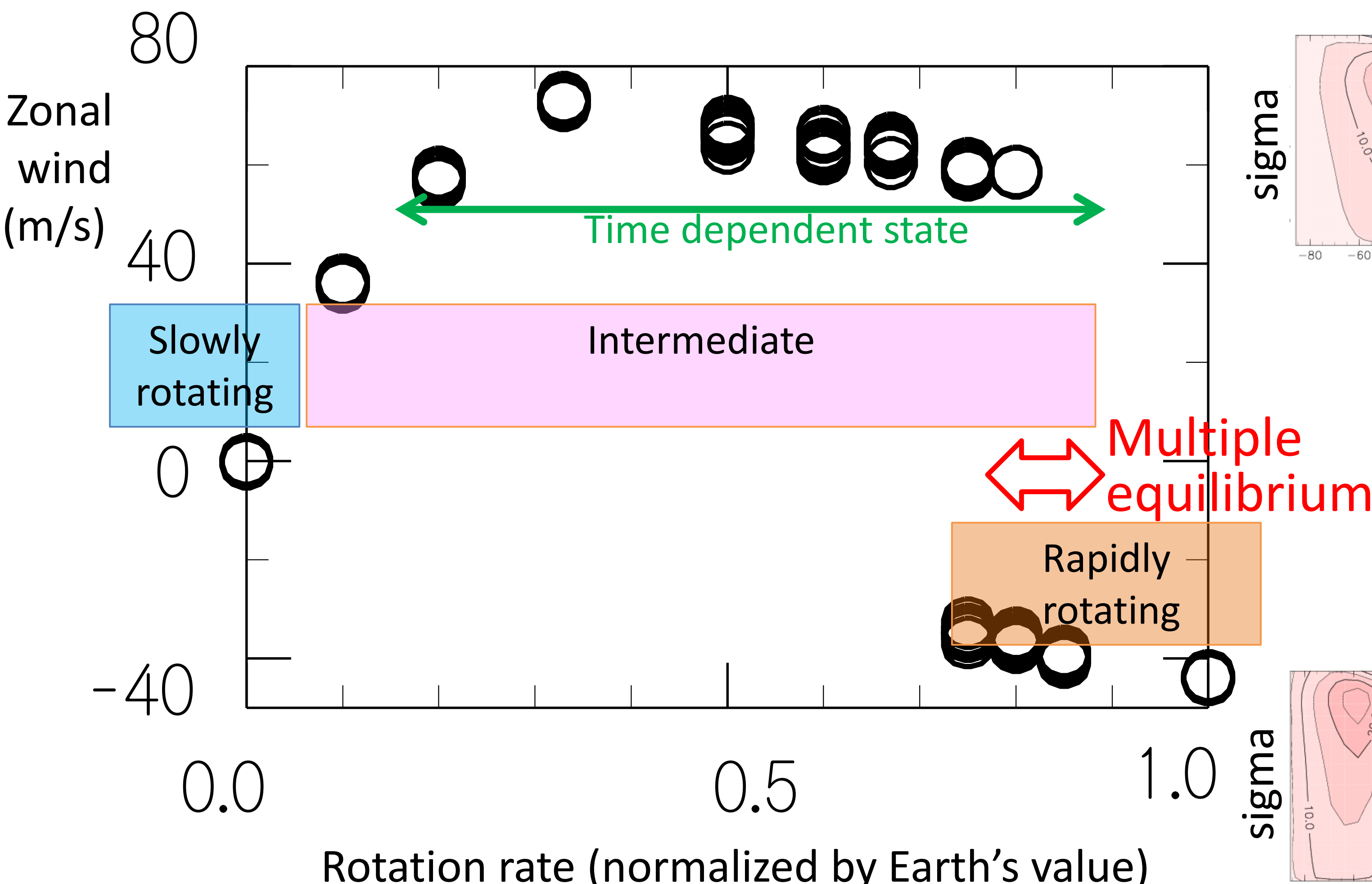
- **Dry air amount at surface: 10^5Pa, Surface albedo : 0.0**
- **Other parameters have same values to Earth's**
- **Resolution: T21L16, Integration Period: 2000 days**
- **Initial condition : isothermal (280K) rest state with different random seed (10 member)**

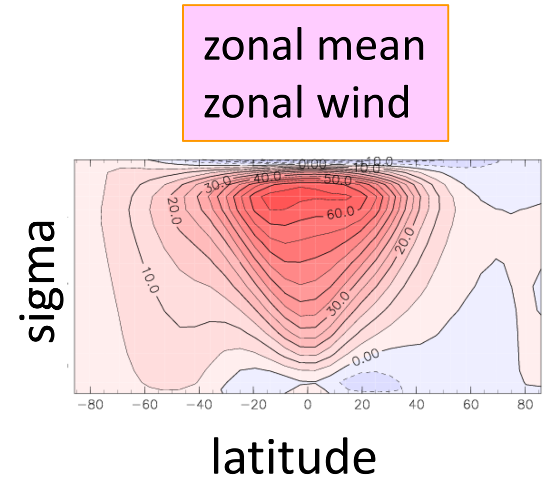
Surface temperature for various Ω*

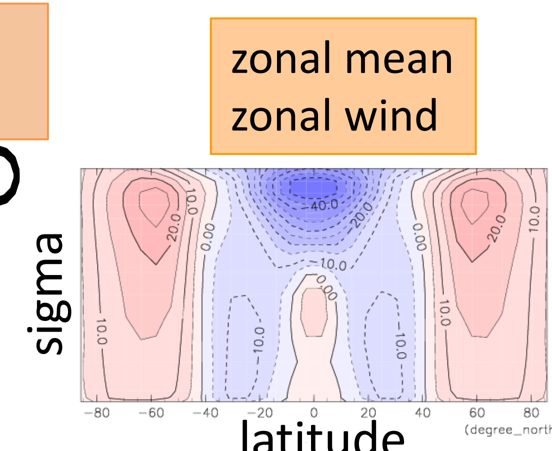


Regimes of atmospheric structures

- **Zonal wind at σ=0.17 level at equator (zonal mean, time mean)**





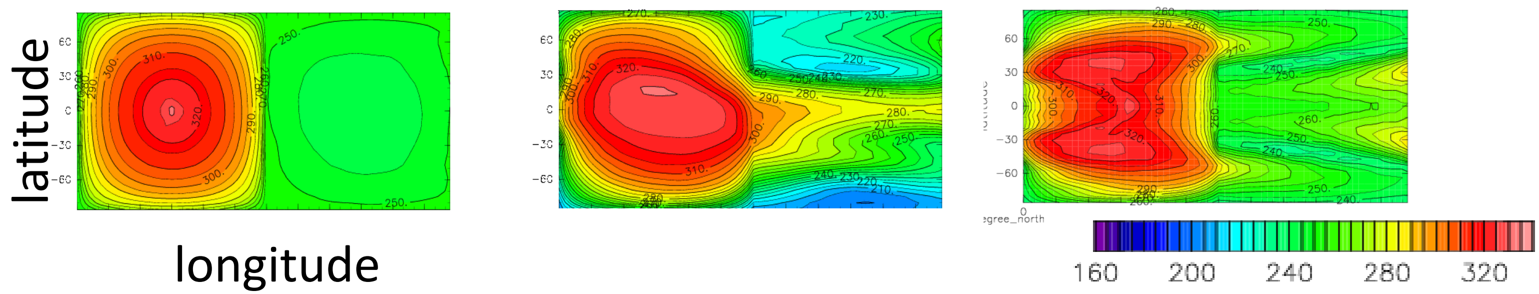


Atmospheric structures for various Ω*

Time mean over 1000-2000day

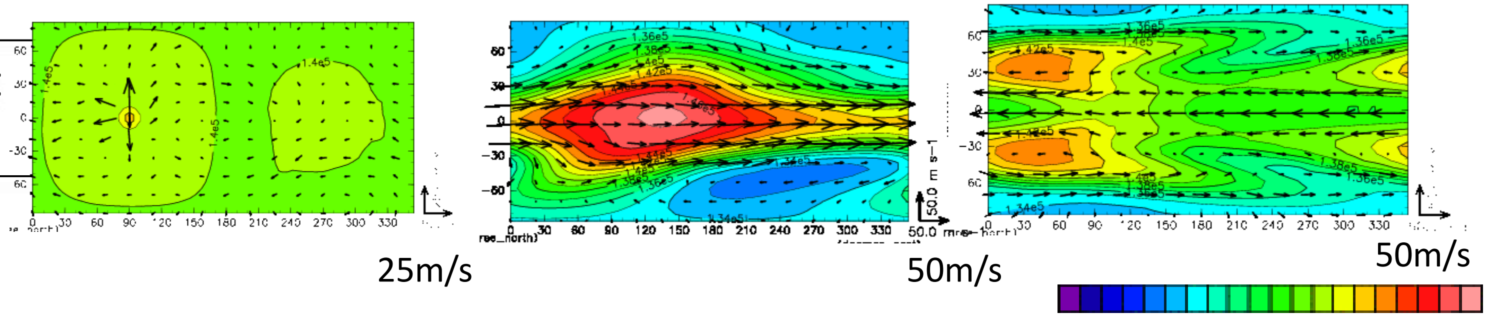
	Slowly rotating	intermediate	Rapidly rotating
	$\Omega^* = 0.0$	$\Omega^* = 0.75$	$\Omega^* = 1.0$

Surface Temperature



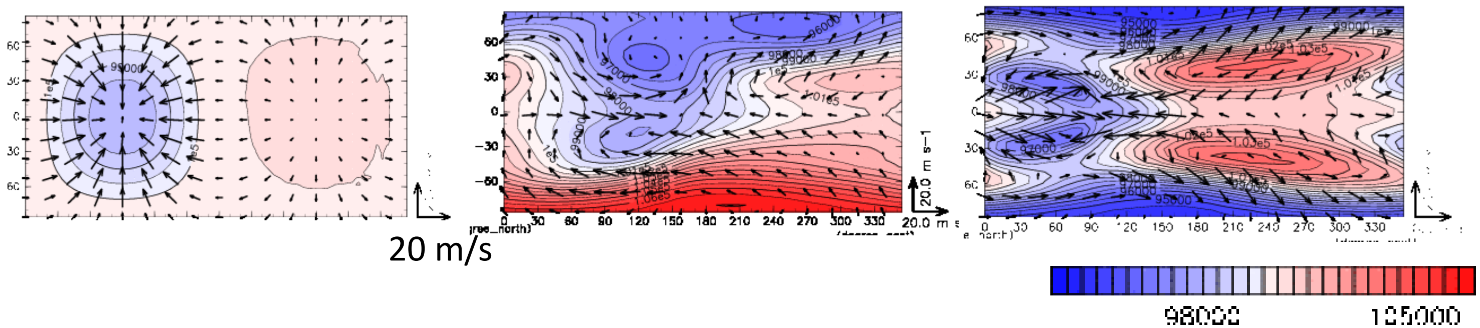
Day-night circulation | **Super rotation** | **Multiple jets**

Geopotential height & (u,v) at σ=0.2



Asymmetric Oscillation

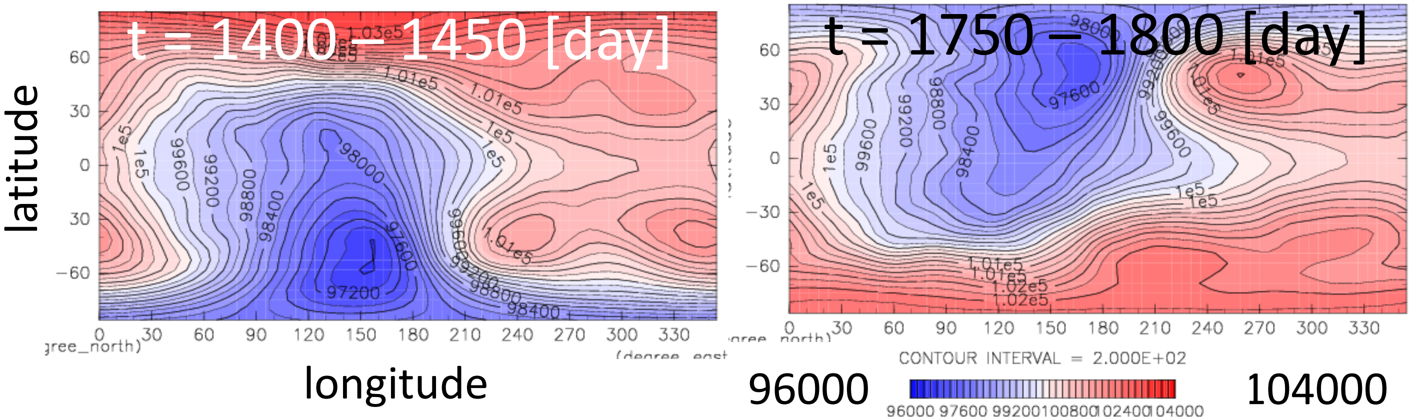
Surface pressure & (u,v) at σ=0.99



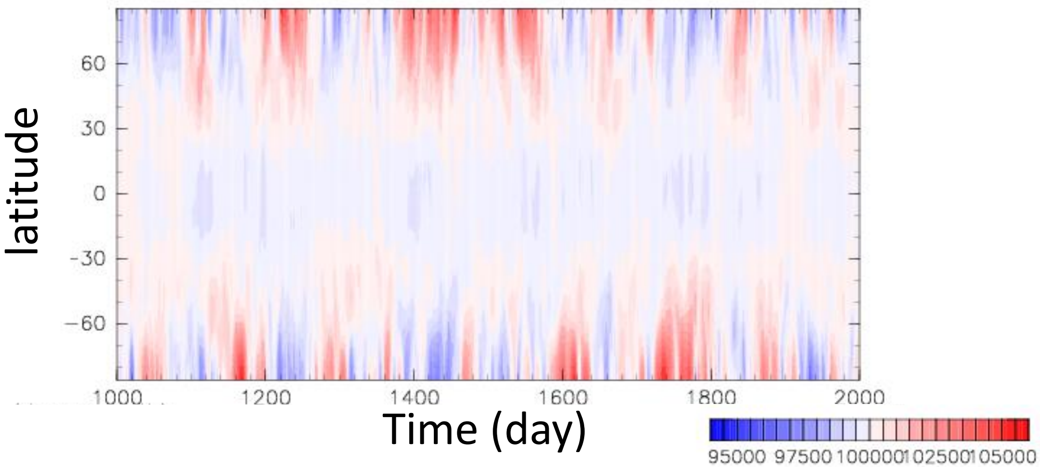
North-south asymmetric state

$\Omega^{*} = 0.5$

Surface pressure

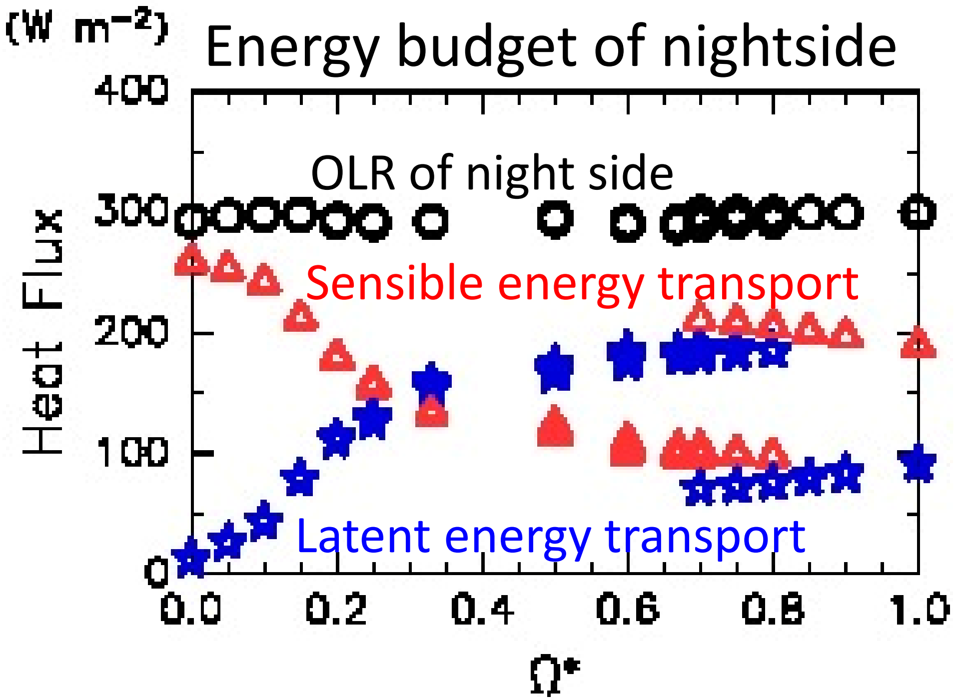


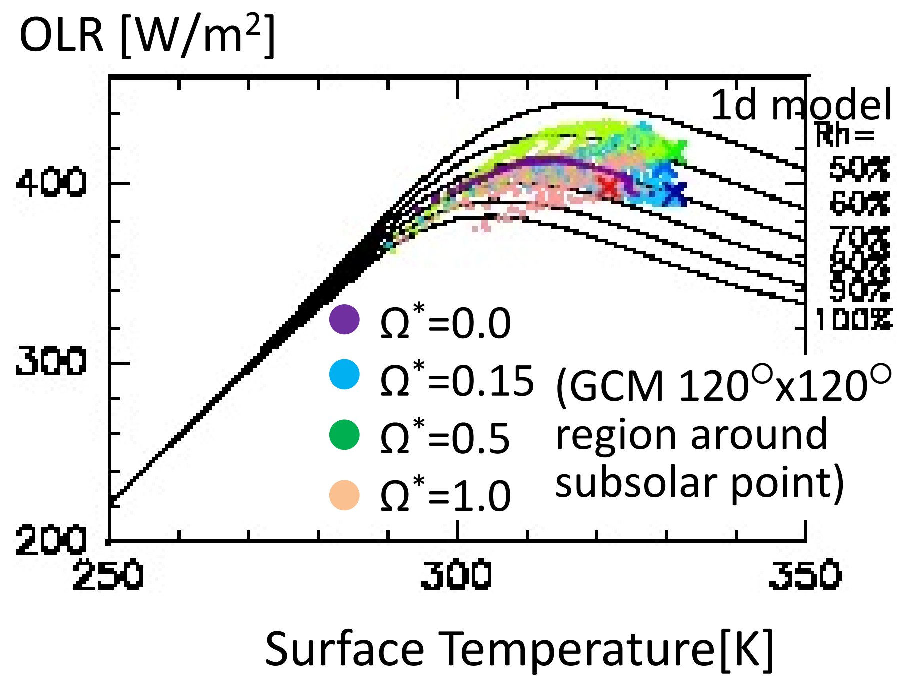
zonal mean surface pressure



- **Significant asymmetric states appear in $0.2 \leq \Omega^{*} \leq 0.8$**
- **The pattern reverses repeatedly.**
- **"period" : 10 day-1000day, Non-periodic for large Ω**
- **Also appear in high resolution experiment**

Ω^* Dependence of energy transport





- **Total energy transport is almost independent of Ω^***
- **Day-side OLR is bounded by radiation limit of 1D model**
  - **Radiation limit: Nakajima et al. (1992), Ishiwatari et al. (2002)**
- **(Energy transport) = (Incident flux) – (radiation limit): independent of Ω^***

Summary of Ω-dependence experiment

- **Dependence of atmospheric states of synchronously rotating aqua-planet on Ω is studied by a gray GCM**
- **There exists a definite regime boundary between ``slowly rotating regime’’ and ``rapidly rotating regime’’**
  - **Existence of multiple equilibrium solutions**
- **There exist a range where asymmetric states appear**
- **Summation of sensible/latent heat transport is almost independent of rotation rate**
  - **Amount of heat transport is constrained by radiation limit**

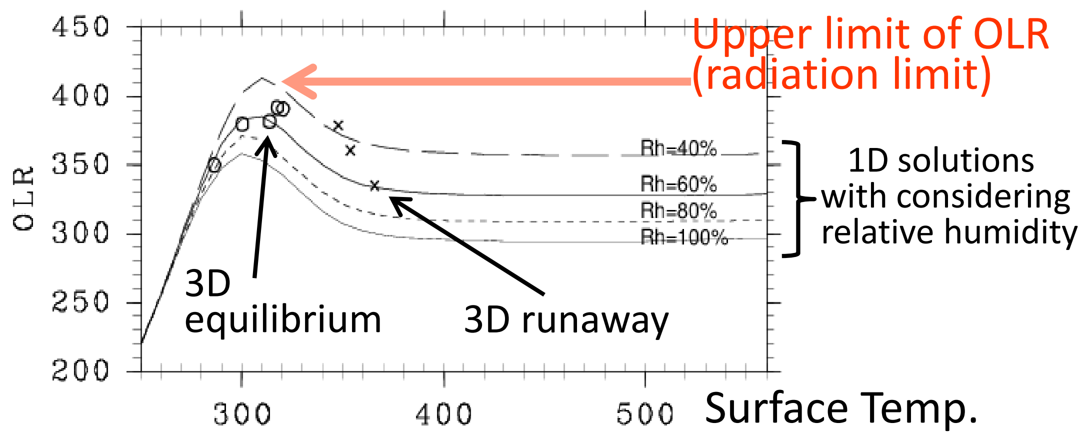
S-dependence experiment with nongray AGCM

What's problem?

- **GCM experiments for runaway state in recent years**
  - **seem to imply that runaway condition is influenced by multiple processes**

Configuration	Synchronous	Non-synchronous
Runaway threshold	S=2200W/m^2	S∼1500W/m^2
Important factor	Albedo of dense clouds (Yang et al., 2013)	Drying in subtropics (Leconte et al., 2013)

- **Our old result: Runaway condition is that global mean stellar flux exceeds OLR upper limit**
  - **Ishiwatari et al. (2002)**
    gray atmosphere
    AGCM w/o cloud



- **In this study, runaway condition is re-examined**
  - **We expect that results obtained by previous studies can be described by a common condition**

Physical processes

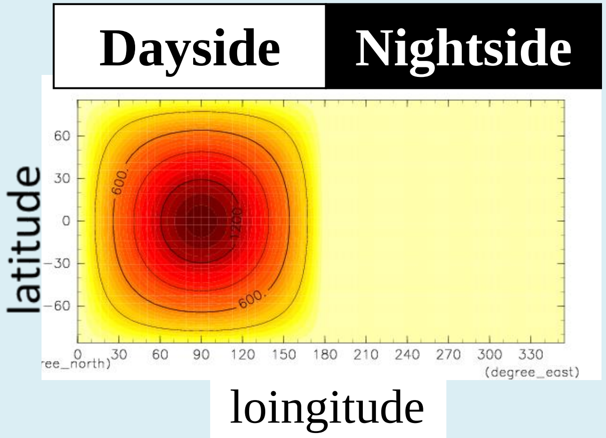
- **Parameterized with methods of terrestrial Meteorology**
- **Radiation**
  - **δ-Eddington approximation: Toon et al. (1989)**
  - **Absorption and emission by water vapor, CO_2, cloud water: Chou and Lee (1996), Chou et al (2001)**
  - **Solar radiation is assumed to be same as that of Sun**
- **Cumulus convection**
  - **Relaxed Arakawa-Schubert: Moorthi and Suarez (1992)**
- **Surface flux: Beljaars and Holtslag (1991)**
- **Vertical turbulent mixing: Mellor and Yamada (1974) level2.5**
- **Planetary surface : ocean with zero heat capacity, no horizontal heat transport**
- **Simple cloud model**
  - **Integrating time dependent equation including 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
–Detrain from could top in RAS scheme

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

Experimental setup

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]	

- **Dry air amount at surface: 10^{5}Pa, Surface albedo : 0.15**
- **Resolution: T42L26, Integration Period: 3 years**

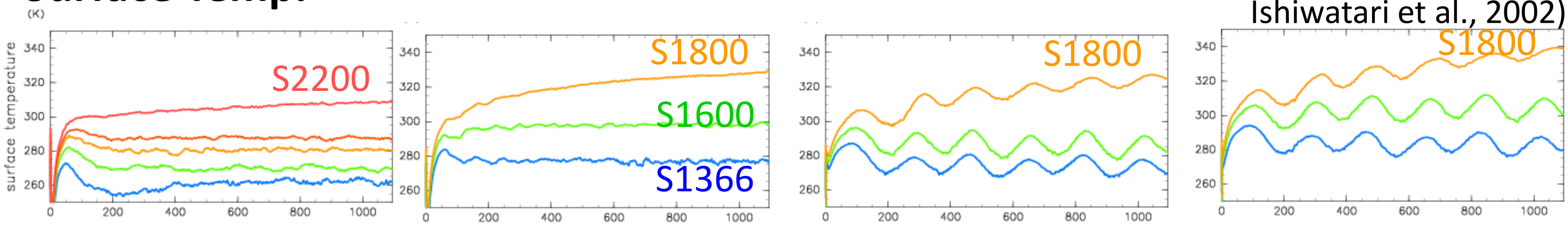
Time evolutions of Ts and OLR

Global mean values for Ω* =1.0

Synchronous | **Non-synchronous**

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

Surface Temp.

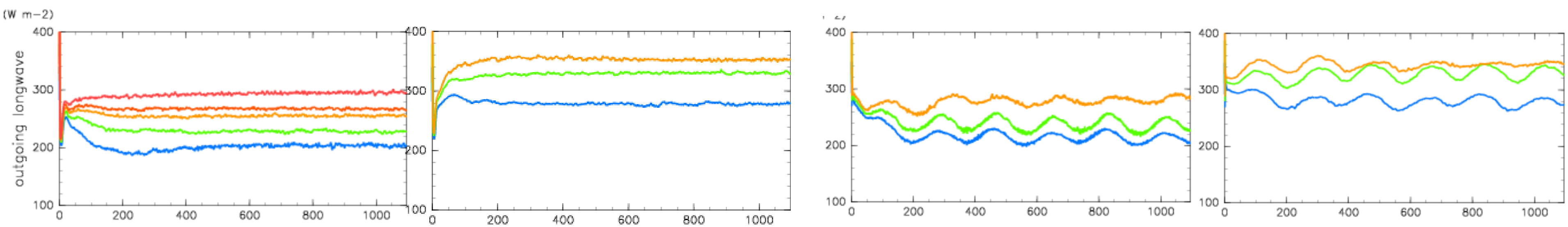


1000day

Time（day）

In runway state: temperature keeps increasing

OLR



1000day

Time（day）

In runway state: OLR is smaller than absorbed stellar flux

Most upper line in each figure shows result of runaway case

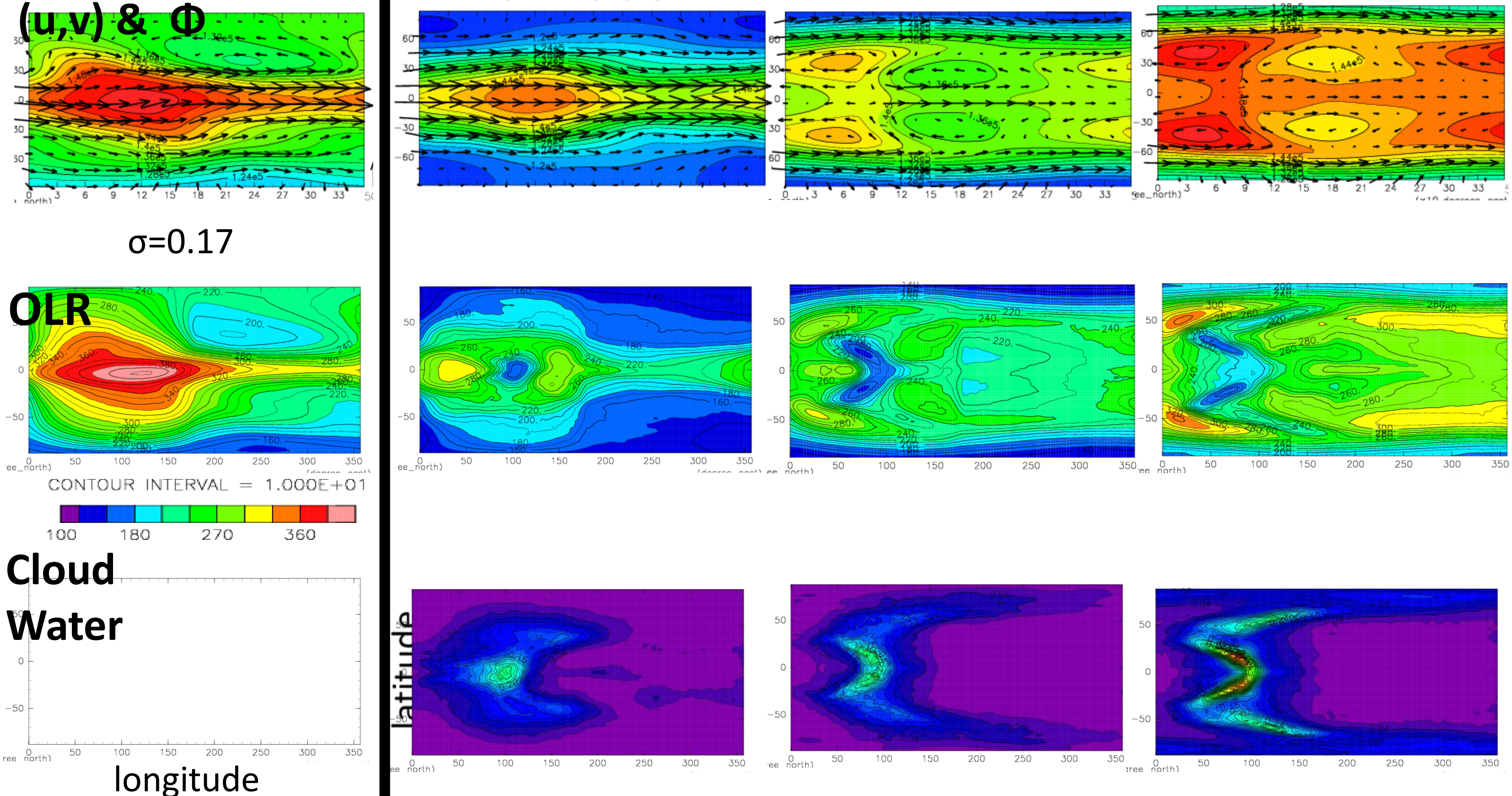
Atmospheric structures for various S

w/o cloud

w cloud $(\tau_{LT} = 1500\text{sec})$

$\Omega^*=1.0$

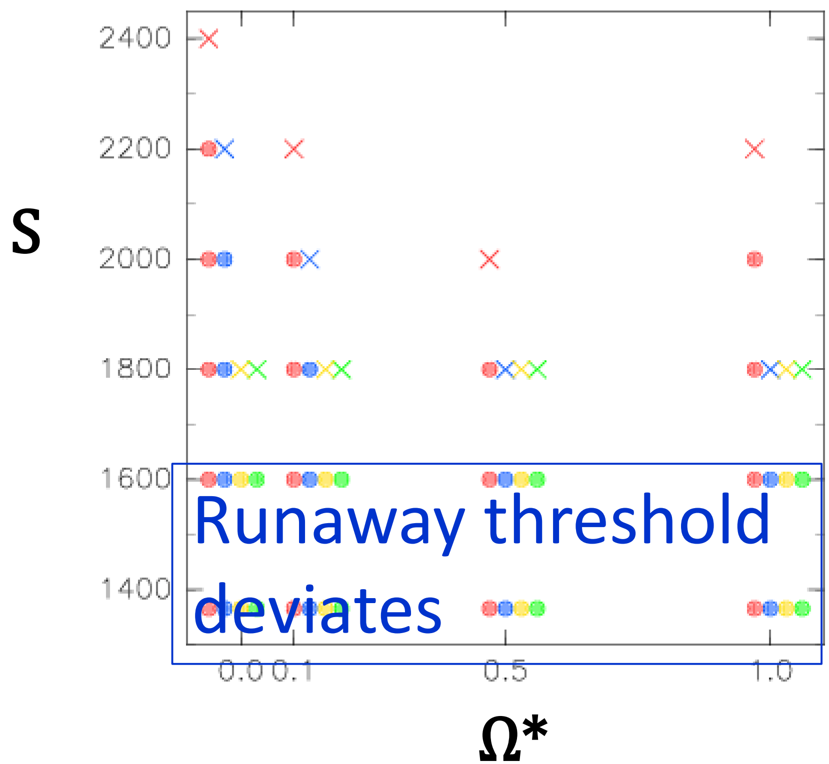
S=1366 | S=1366 | S=1600 | S=2000

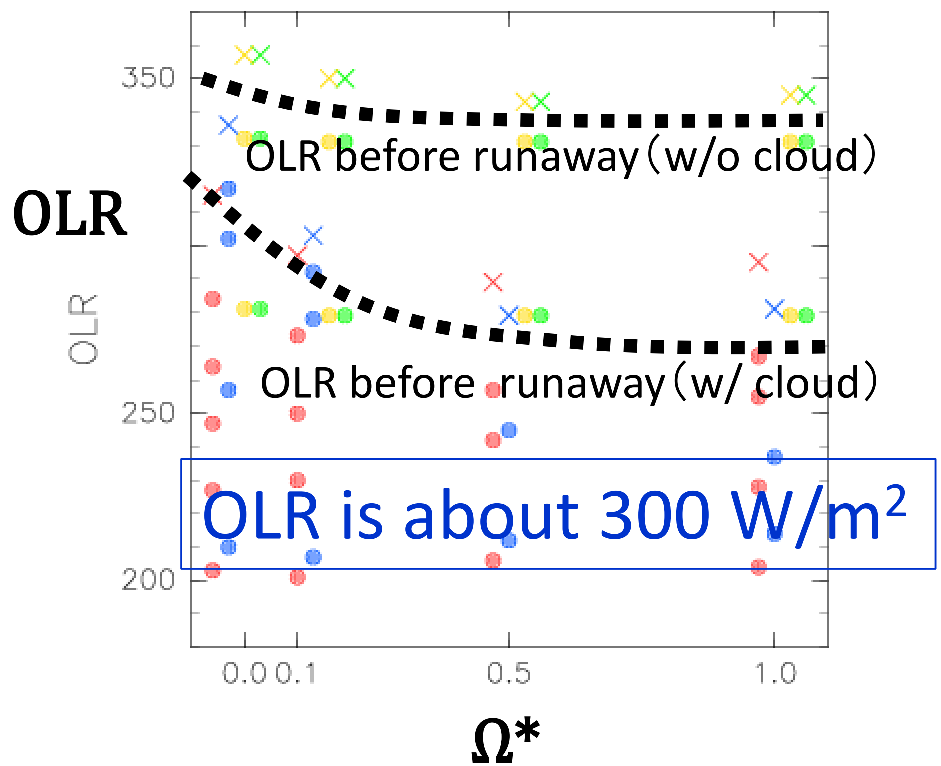


365 day mean of last third year

Runaway thresholds

Ω* dependence of threshold value of S and OLR





Circles: Equilibrium states

- ● : Synchronous (w /cloud)
- ● : Non-Synchro (w /cloud)
- ● : Synchronous (w/o cloud)
- ● : Non-Synchro (w/o cloud)

Crosses: The runaway greenhouse state

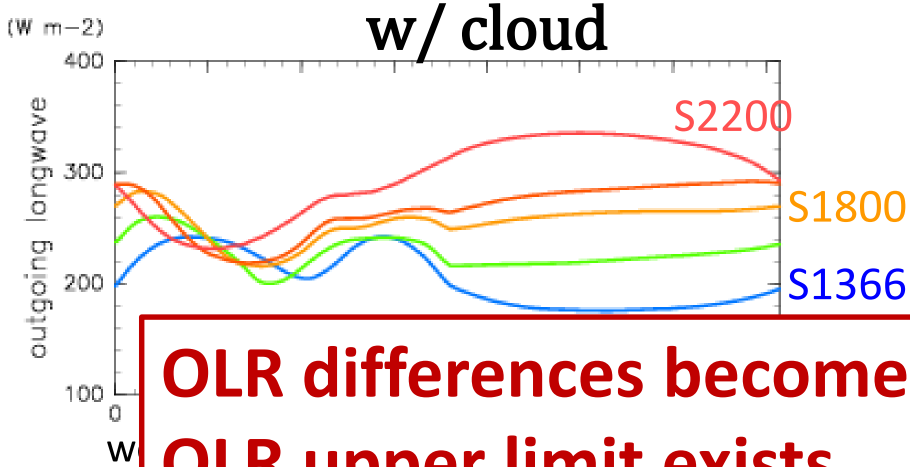
- × : Synchronous (w / cloud)
- × : Non-Synchro (w / cloud)
- × : Synchronous (w/o cloud)
- × : Non-Synchro (w/o cloud)

Horizontal distributions of OLR

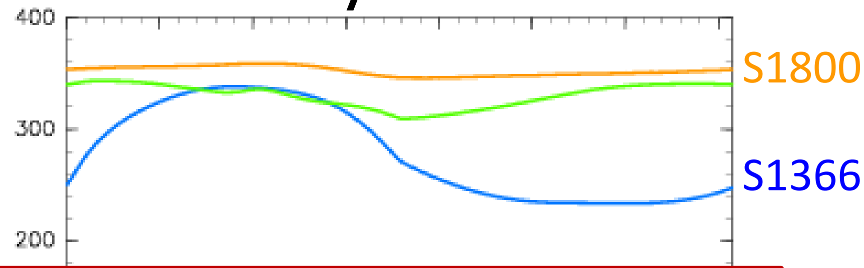
- **Synchronous cases: Zonal (meridional mean)**

Ω*=1.0

w/ cloud

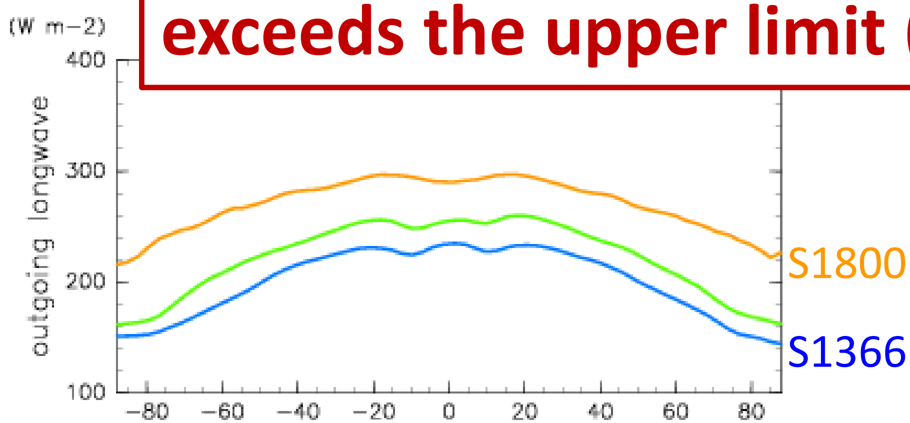


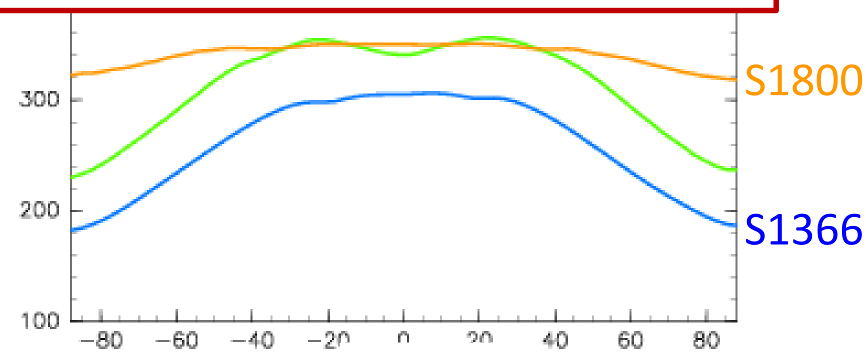
w/o cloud



OLR differences become smaller with increased S.
OLR upper limit exists.
Runaway states occur when absorbed stellar flux exceeds the upper limit (common condition).

- **No)**

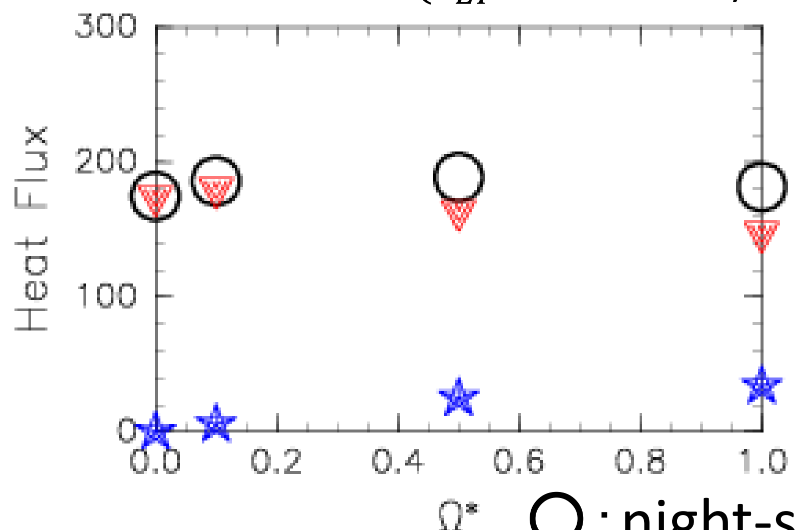




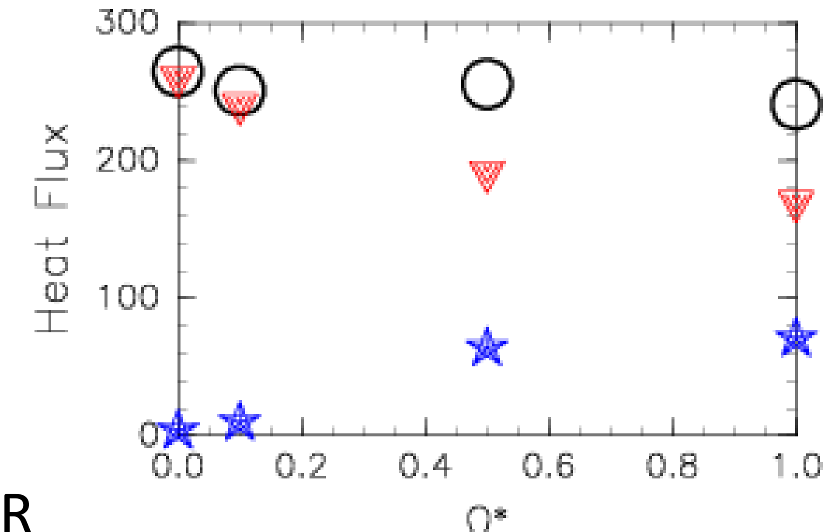
Day-night energy transport

Night side heat budget (S=1366W/m^2 , 365 day mean)

w cloud (τ_{LT} = 1500sec)



w/o cloud (τ_{LT}= 0sec)



○ : night-side OLR
▼ : (sensible heat transport)/$2\pi R^2$
★ : (latent heat transport)/$2\pi R^2$

- **Dependence of day-night heat transport on Ω* is small (similar to gray case: Noda et al., 2017)**
- **(total energy transport)**
  = (absorbed stellar flux) – (dayside OLR)
  = (absorbed stellar flux) – (OLR upper limit)

Summary of S-dependence experiment

- **Re-examination on the occurrence condition for the runaway greenhouse state**
  - **Synchronous configuration vs. Non-synchronous configuration (Earth-like), case w/ cloud vs. case w/o cloud**
- **OLR seems to have upper limit values**
  - **Upper limit of OLR is about 300 W/m^2 regardless model configuration**
  - **The deviation of the upper limit is only 50 W/m^2**
- **Global mean absorbed stellar flux changes according to model configuration**
  - **This causes the difference of Solar constant threshold**
  - **This result is consistent with the results of previous studie**

Concluding remarks

- **In our experiments for synchronously rotating planets, the upper limit of OLR emerge.**
  - **It constrains day-night energy transport**
  - **It determines solar constant at which the runaway greenhouse state emerges**

- **Remaining problems**
  - **Examination with 1D-model**
  - **Refinement of cloud model**
  - **Experiments on other configurations: cases with thick atmosphere , case with reduced S**
  - **Ocean dynamics!**