Present status of numerical experiments on climates of terrestrial exoplanets by GFD-Dennou Club dcmodel project

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Japanese-French model studies of planetary atmospheres, May 15, 2015

Outline of this presentation

- **Introduction**
  - **Key words: Earth-like exoplanets, AGCM,**
    Climate regime diagram
- **Present status of our research**
  - **Target of experiment: Synchronously rotating planet**
  - **Planetary rotation rate dependence experiment (gray radiation, no cloud)**
  - **Planetary rotation rate dependence experiment (non-gray radiation, simple cloud model)**
  - **Solar constant dependence experiment (non-gray radiation, simple cloud model)**
- **Concluding remarks**

Introduction

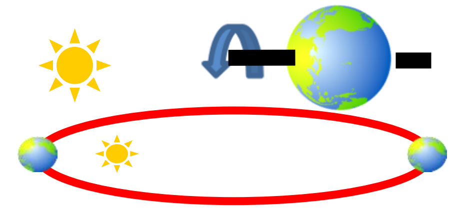
Earth-like exoplanets

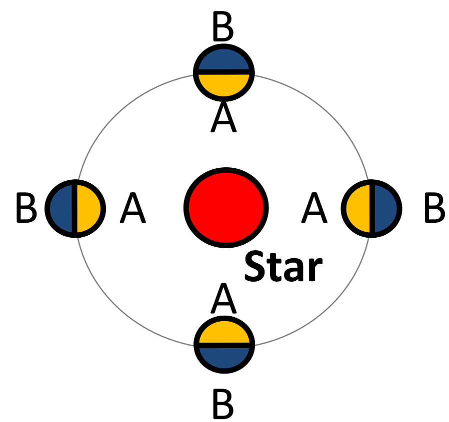
- **Many Earth-size planets have been discovered.**
- **They may have various climates, since exoplanets are under conditions which are different from solar system.**
  - **They provide new problems on existence condition of Earth-like climate.**
- **Atmospheric component has been observable**
  - **Information on the climate can be obtained directly.**

http://www.space.com/21708-images-habitable-alien-planets-gliese-667c.html

Previous GCM experiments

- **Some of previous studies with GCM**
  - **Oblique planet: Williams and Pollard (2003)**
  - **Eccentric planet: Williams and Pollard (2002)**
  - **Land planet: Abe et al. (2005) , Abe et al. (2011)**
  - **Synchronously rotating planet:**
    Joshi et al. (1997), Merlis and Schneider (2011), Edson et al. (2013), Yang et al. (2014)



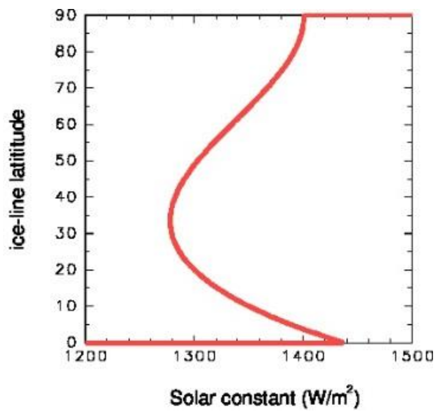


- **Most of previous studies discuss whether exoplanets have habitable environments.**
- **However, neither existence condition of equilibrium state nor parameter range of appearance of each climate state are not investigated well.**

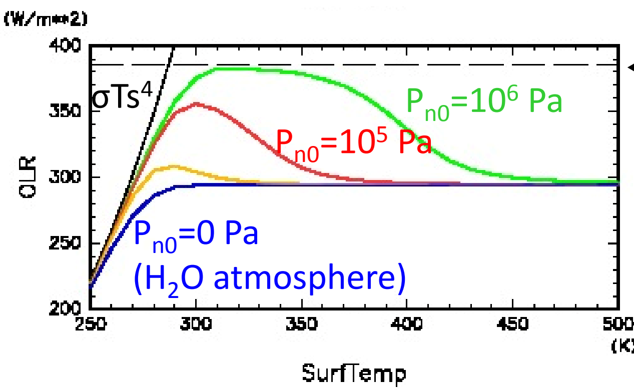
Purpose of this study

- **Making climate regime diagrams**
  - **Determine existence ranges of equilibrium states, the runaway greenhouse state, snowball state**

Snowball state
Budyko (1969), EBM



Runaway greenhouse state
Nakajima et al (1992), 1d model



Komabayashi
-Ingersoll
limit

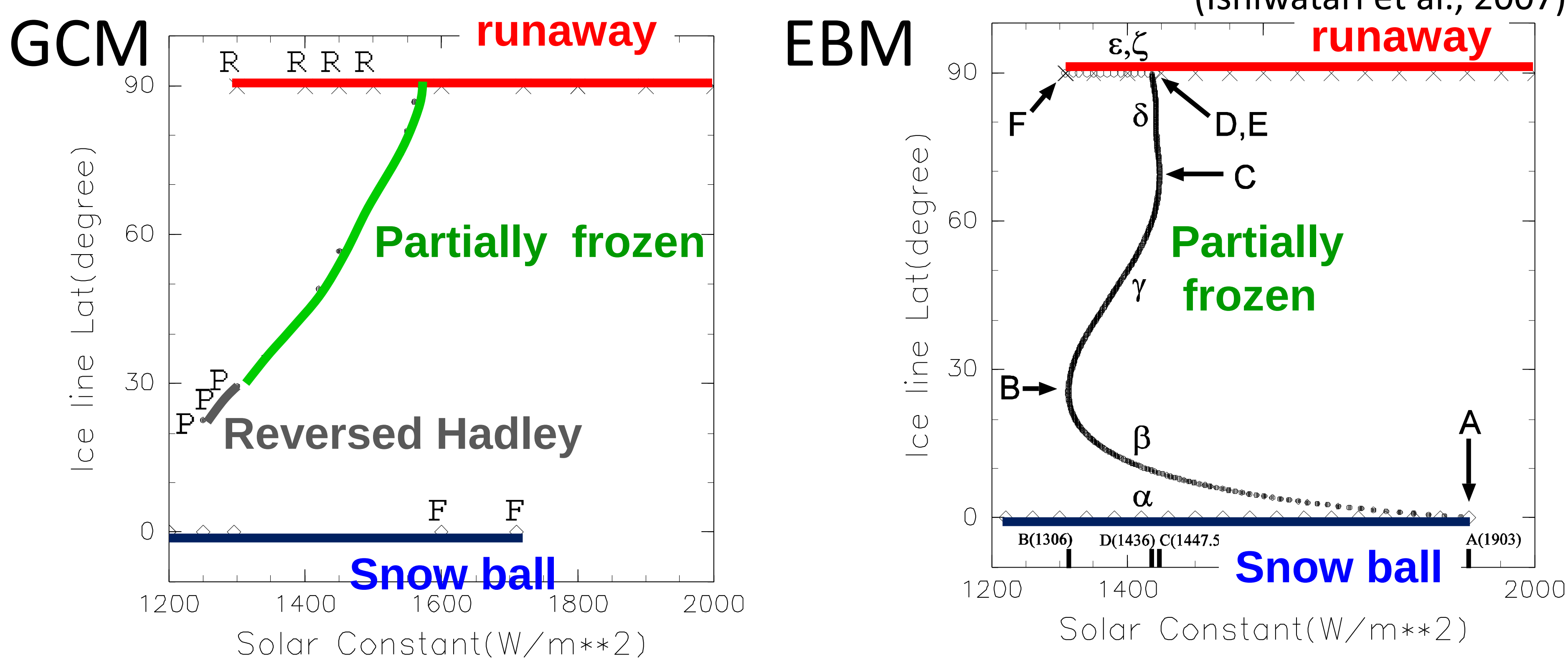
  - **Systematic experiments (parameter sweep with a same model and various initial conditions) are necessary.**

- **Numerical simulation with more realistic configuration (in the next step)**

An example of climate regime diagram

Results of gray radiation model, Earth-like condition

(Ishiwatari et al., 2007)



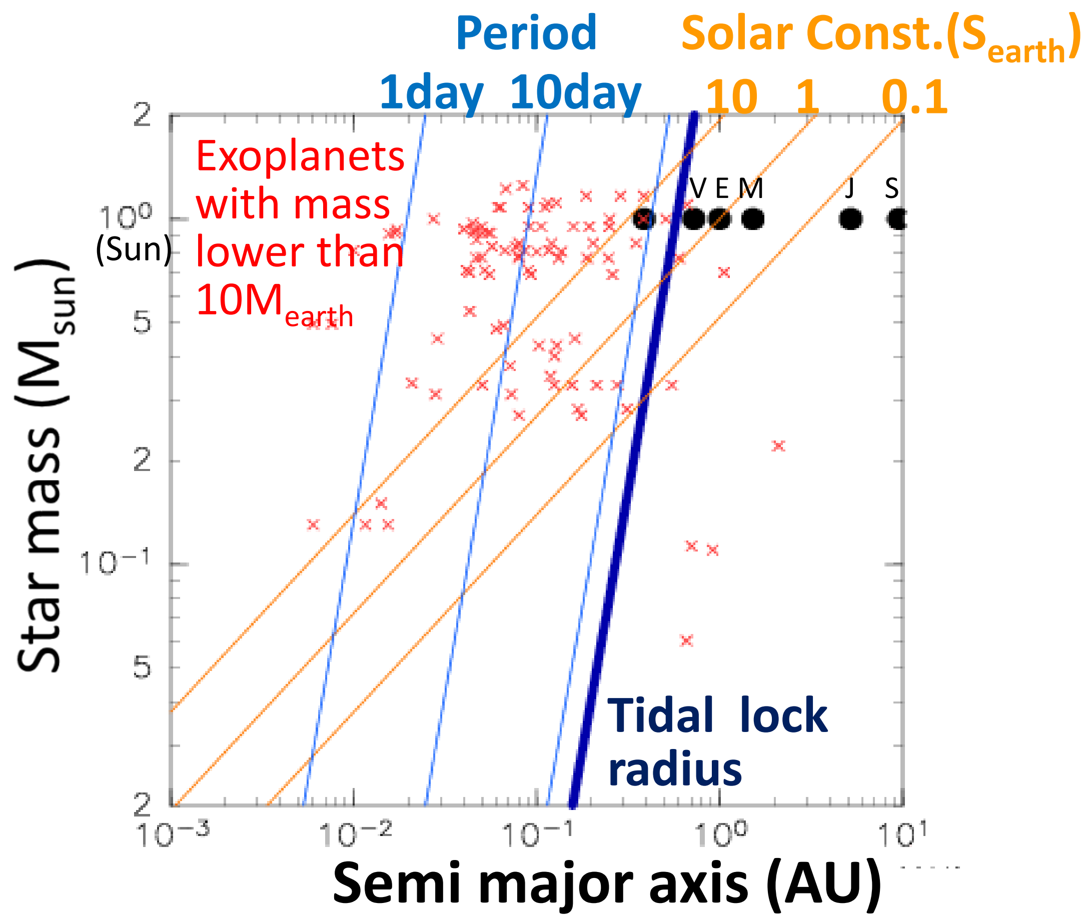
- **Regime diagram makes existence ranges of regimes makes clear.**
- **Important points are (1) using multiple initial condition, (2) comparison with low order model**

Present status of our research

(in a way to goal)

Target of experiment

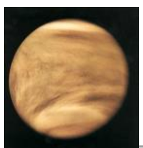
- **Synchronously rotating planets**
  - Many have been detected by exoplanet surveys
  - Planets near M-type stars may be habitable



http://exoplanet.eu/catalog

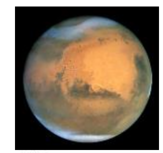
Model

- **General circulation model: dcpam5**
  - **http:www.gfd-dennou.org/library/dcpam/**
  - **Takahashi et al. (talk on Monday)**
- **For various experiments with a same framework**



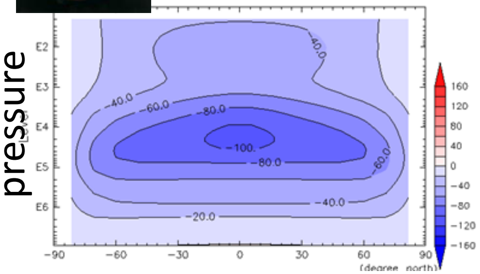
Venus (simple radiative forcing)

Earth



Mars

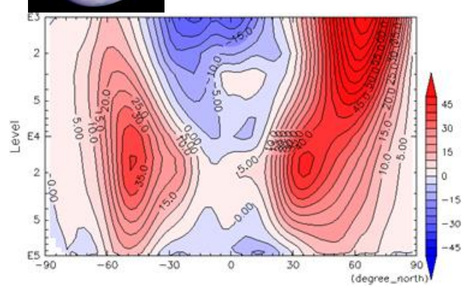
Zonal mean zonal wind



pressure

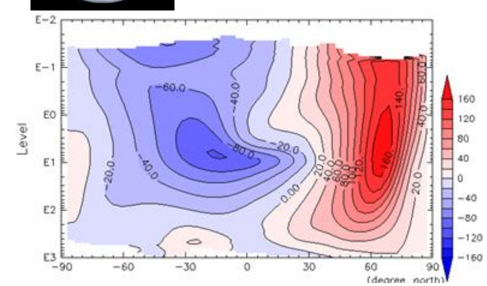
90°S Eq. 90°N

latitude



90°S Eq. 90°N

latitude



90°S Eq. 90°N

latitude

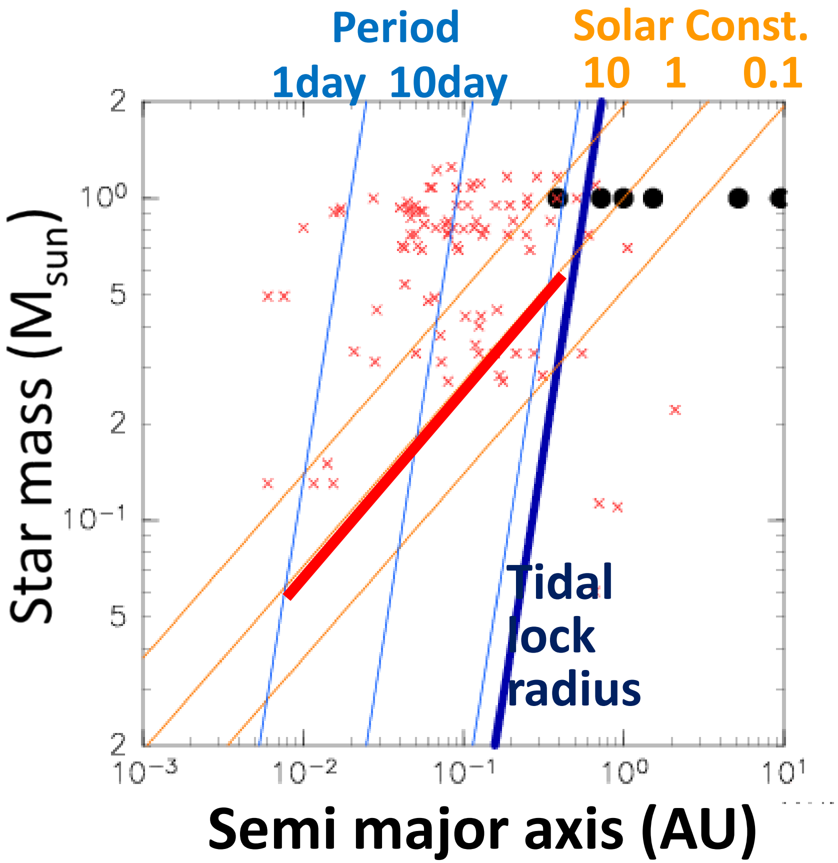
Tone pattern differs among figures.

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

Planetary rotation rate dependence experiment (gray radiation, no cloud)

Planetary rotation rate dependence experiment

- **Purpose**
  - **Examination on Ω* (planetary rotation rate normalized by Earth's value) dependence of day-night energy transport**
    - Circulation changes according to Ω^*. Then, does day-night energy transport also change according to Ω^*?
  - **Investigating the change of atmospheric circulation fields according to Ω^***

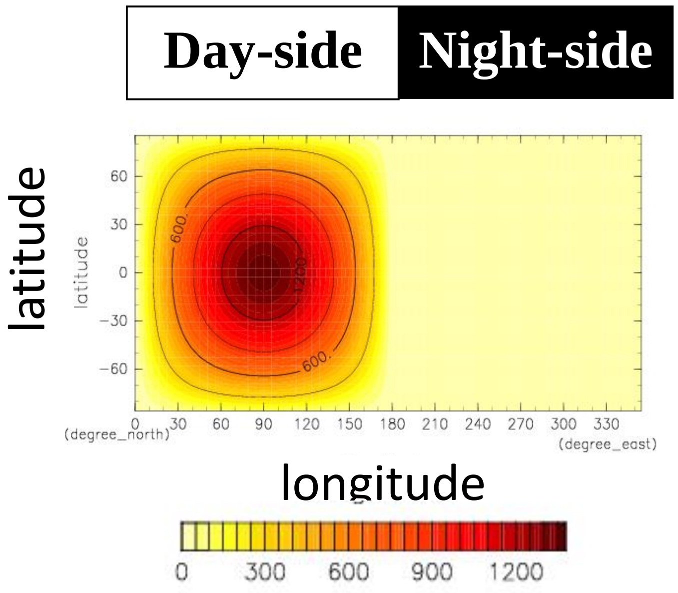


Physical parameterizations

- **Radiation**
  - **Water vapor is gray to IR radiation**
  - **Dry gas is transpare**nt
- **Cumulus convection**
  - **Convective adjustment (Manabe et al., 1965)**
- **Surface flux: Louis et al. (1982)**
- **Vertical turbulent mixing:**
  Mellor and Yamada (1974) level2.5
- **Planetary surface ：**
  flat surface,
  ocean with zero heat capacity (swamp condition),
  no horizontal heat transport
- **No cloud**

Experimental configuration

- Solar radiation flux is given only to dayside
- Planetary rotation rate Ω*:
  0 – 1.0 (18 cases)
- Planetary radius: 6.371 x 10^6 m
- Solar constant: 1380 W m^{-2}
- gravitational acceleration: 9.8 m s^{-2}
- Averaged surface pressure: 10^5 Pa
- surface albedo: 0

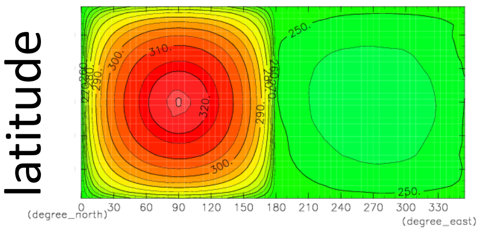


- Resolution: T21L16
- Initial condition: isothermal (280K) rest state(10 runs with different noise)
- Integration time: 2000 days
  (last 1000 days is used for analysis)

Surface temperature for various Ω^*

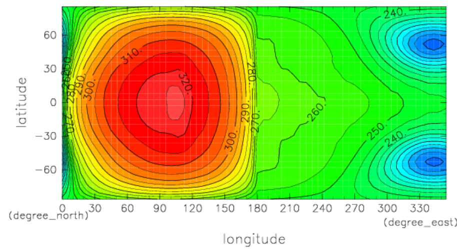
$\Omega^* = 0$

latitude

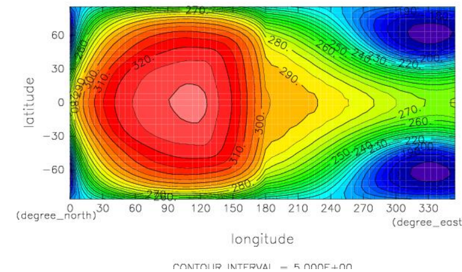


longitude

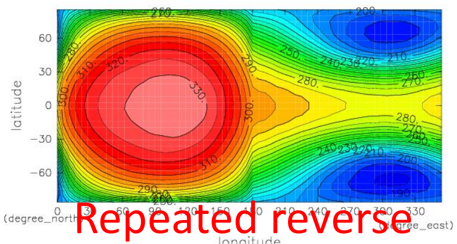
$\Omega^* = 0.05$



$\Omega^* = 0.15$

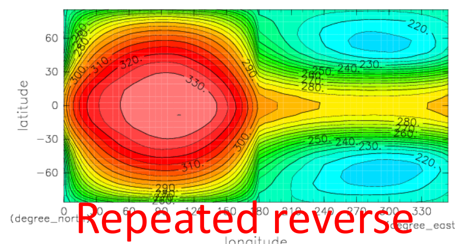


$\Omega^* = 0.25$



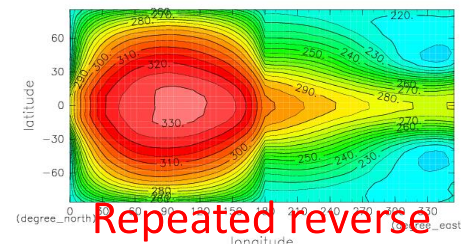
Repeated reverse of N-S. asymmetry

$\Omega^* = 0.33$



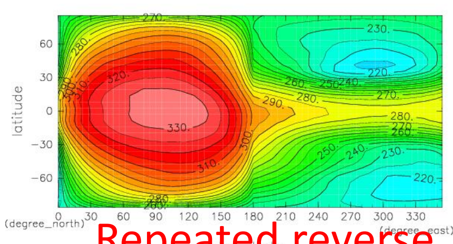
Repeated reverse of N-S. asymmetry

$\Omega^* = 0.5$



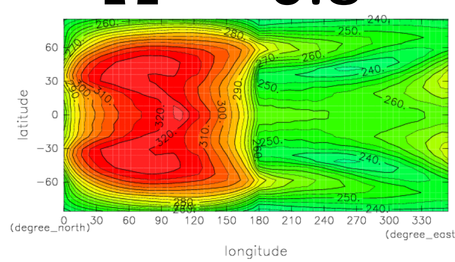
Repeated reverse of N-S. asymmetry

$\Omega^* = 0.67$

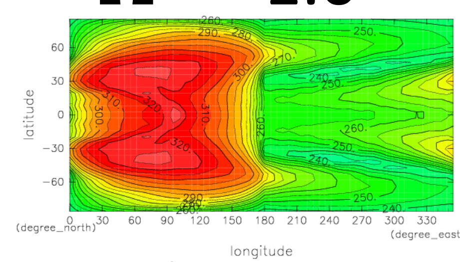


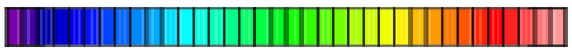
Repeated reverse of N-S. asymmetry

$\Omega^* = 0.8$



$\Omega^* = 1.0$



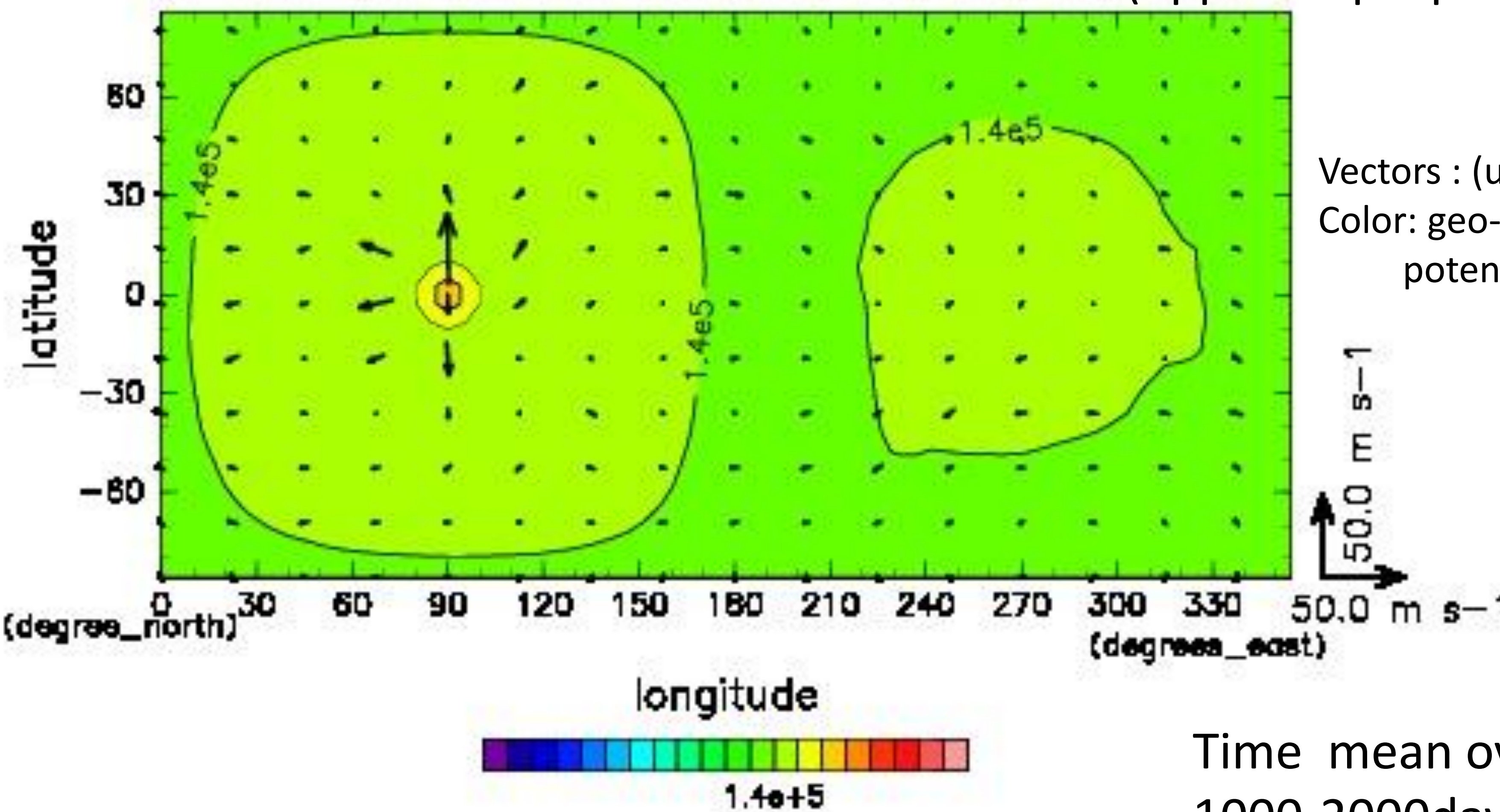


Time mean over 1000-2000day

Horizontal wind and geopotential

$\Omega^* = 0.0$

σ=0.17 (upper troposphere)



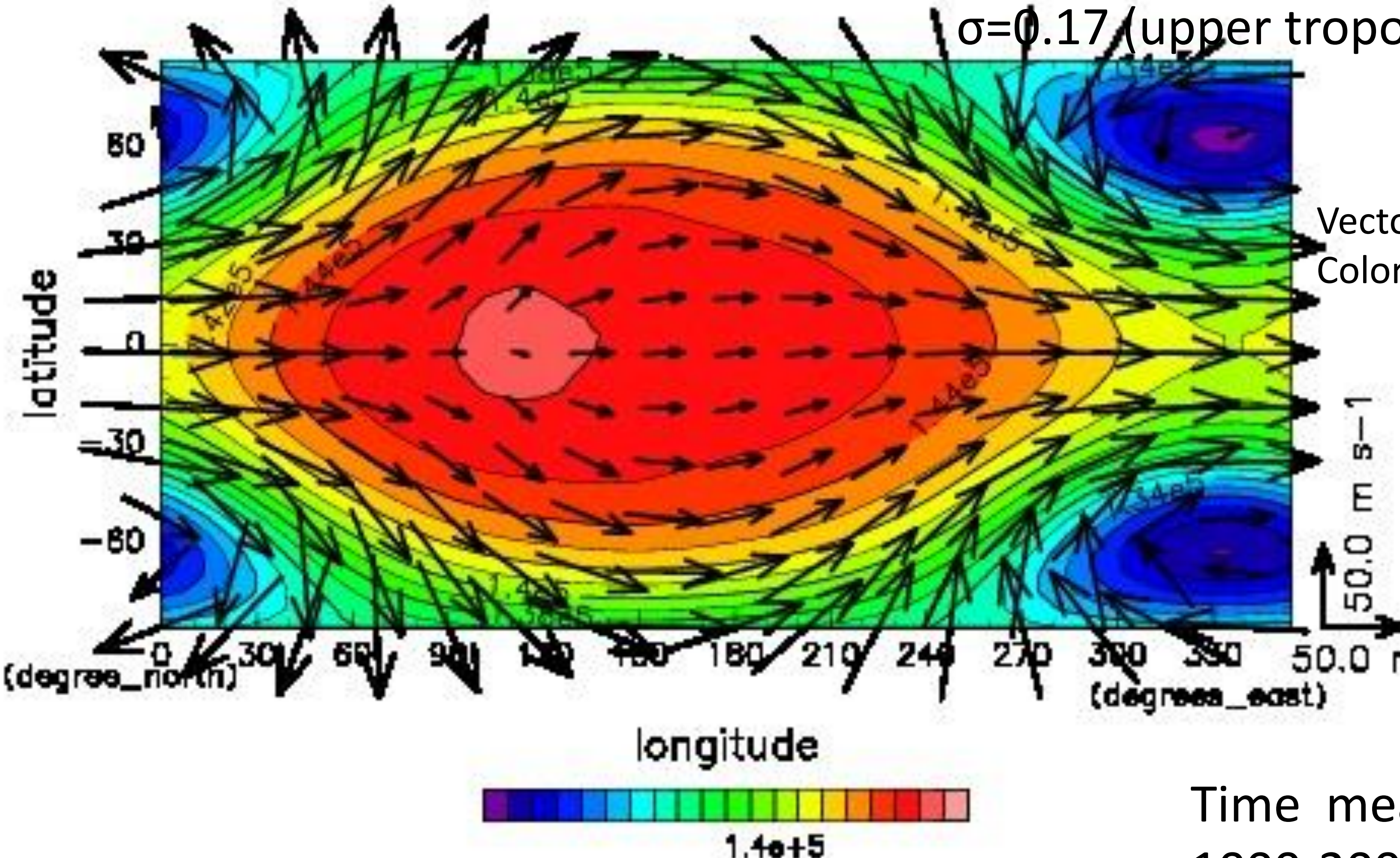
Vectors : (u,v)
Color: geo-
potential

Time mean over
1000-2000day

Horizontal wind and geopotential

$\Omega^{*} = 0.15$

σ=0.17 (upper troposphere)



Vectors : (u,v)

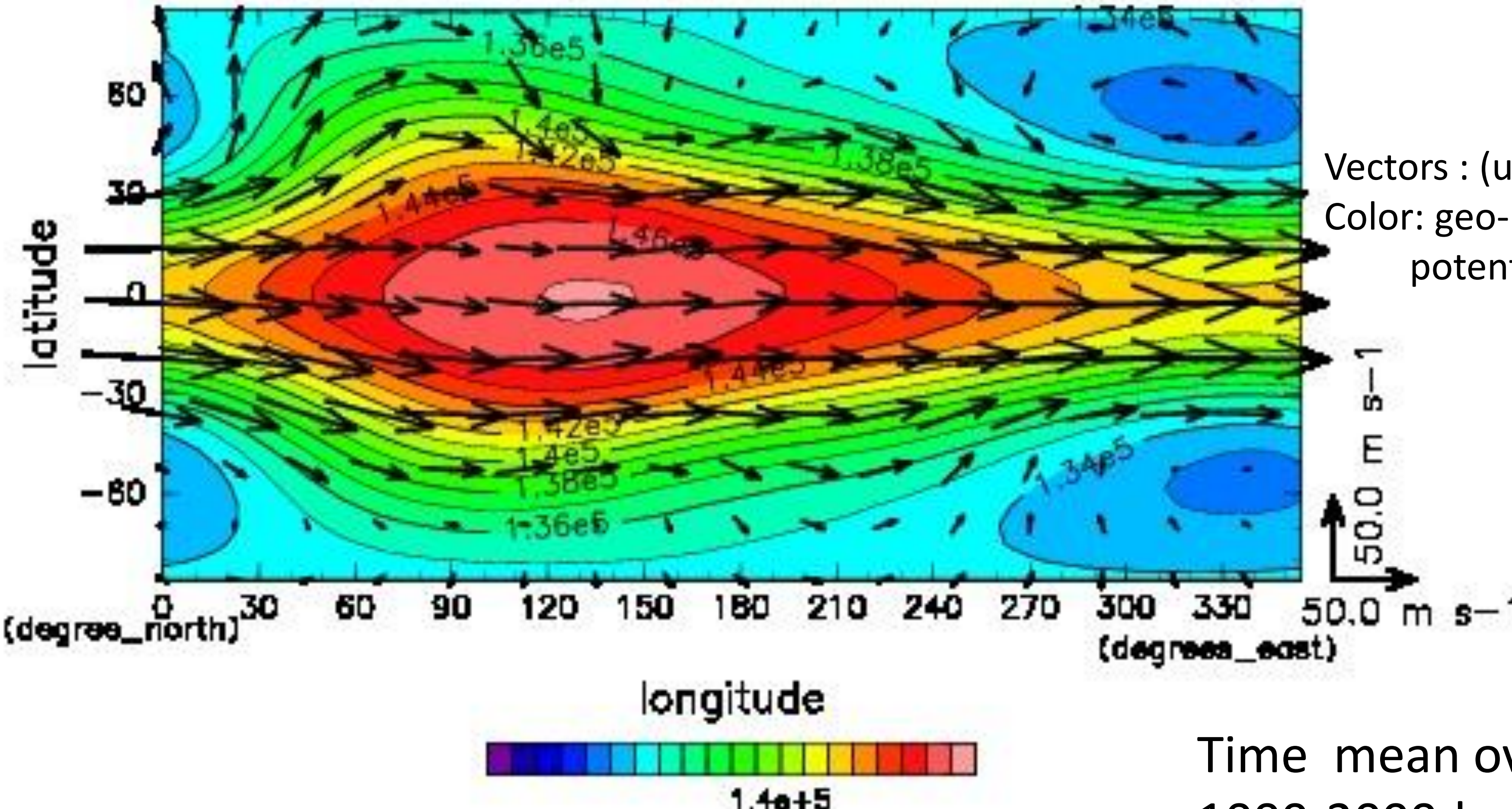
Color: geo-potential

Time mean over 1000-2000day

Horizontal wind and geopotential

$$\Omega^{*} = 0.5$$

σ=0.17 (upper troposphere)



Vectors : (u,v)
Color: geo-
potential

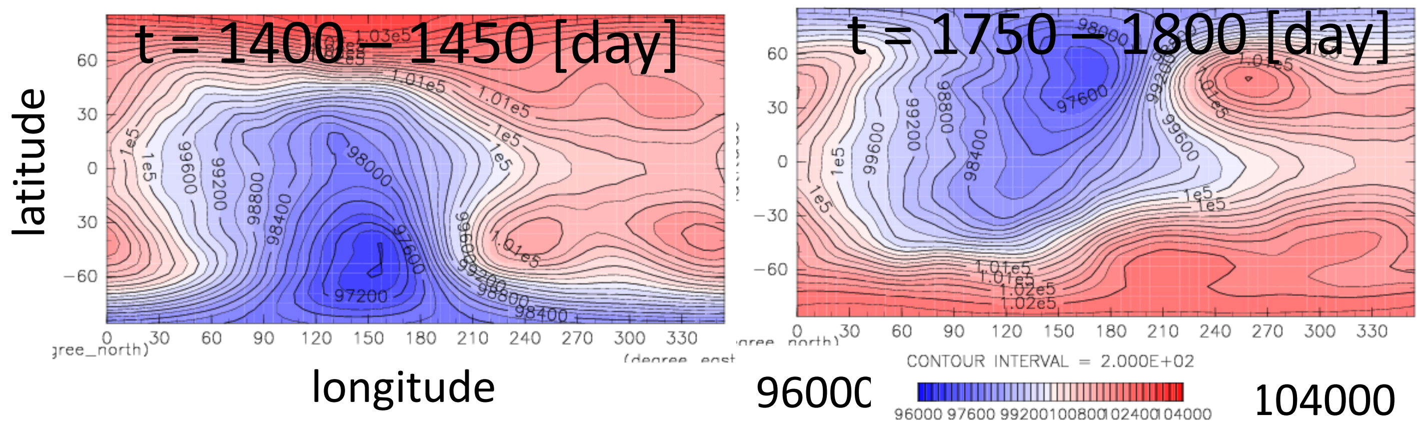
Time mean over
1000-2000day

North-south asymmetric state

- **Significant north-south asymmetric states appear in $0.2 \leq \Omega^* \leq 0.8$**
- **The pattern reverses repeatedly.**

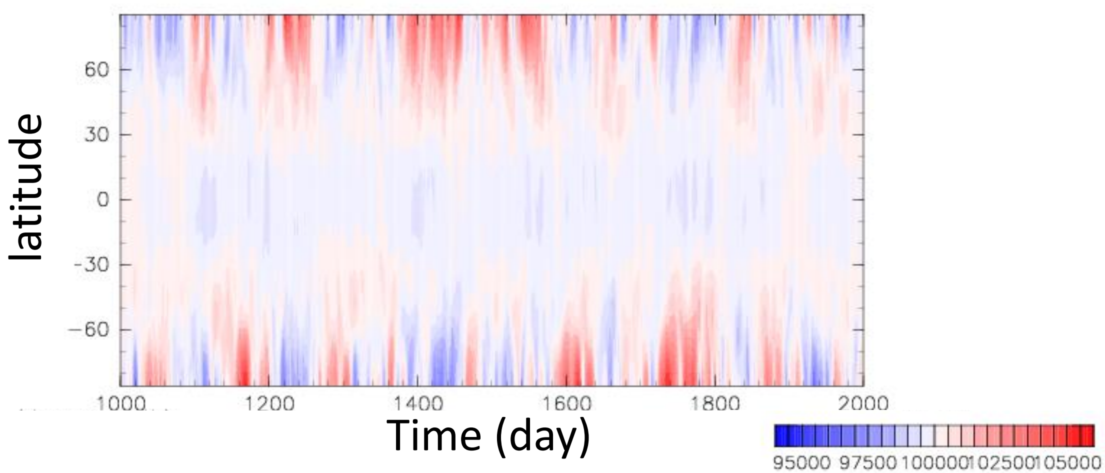
Surface pressure

Ω^* =0.5



zonal mean

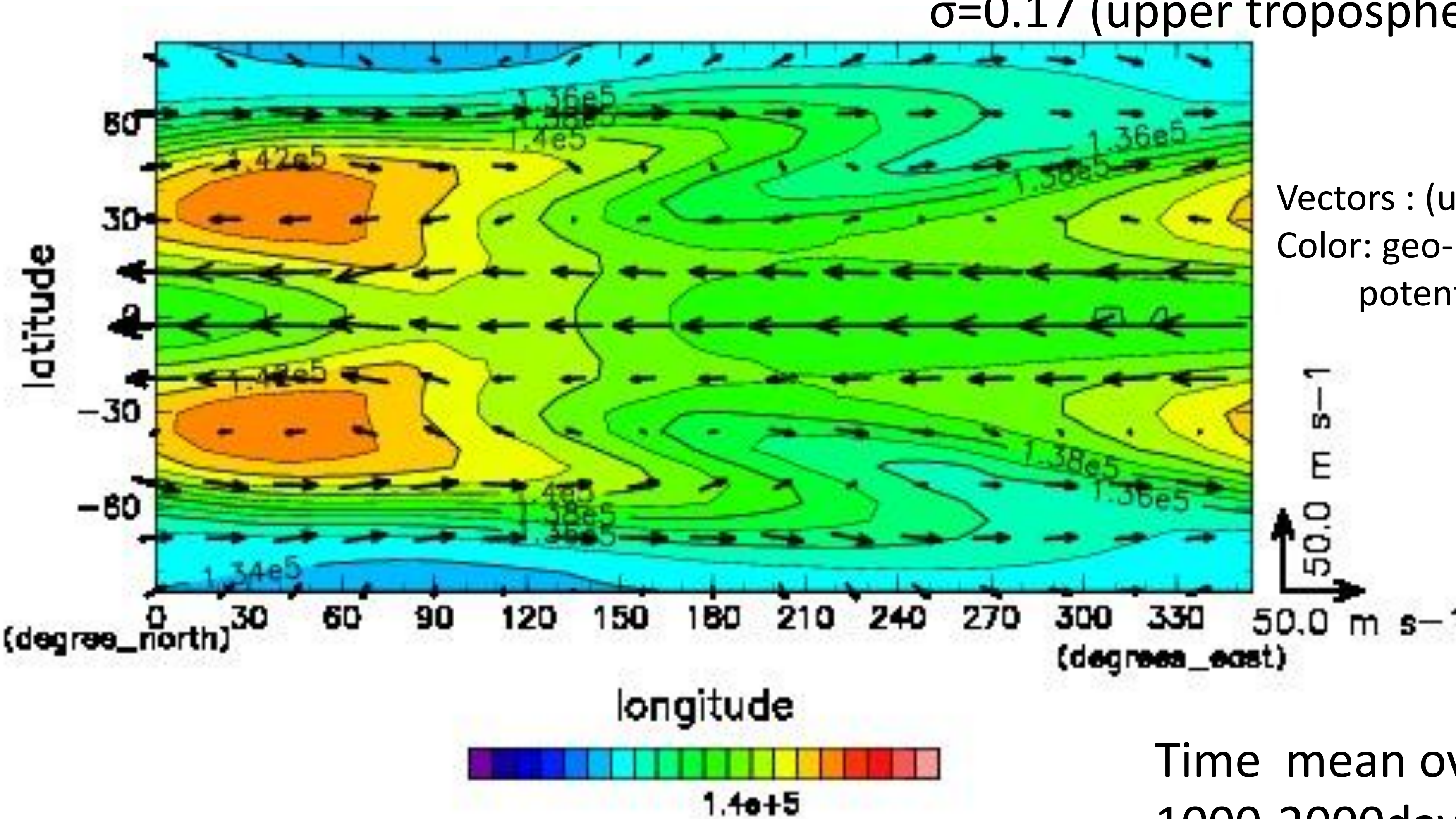
surface pressure



Horizontal wind and geopotential

$$\Omega^* = 1.0$$

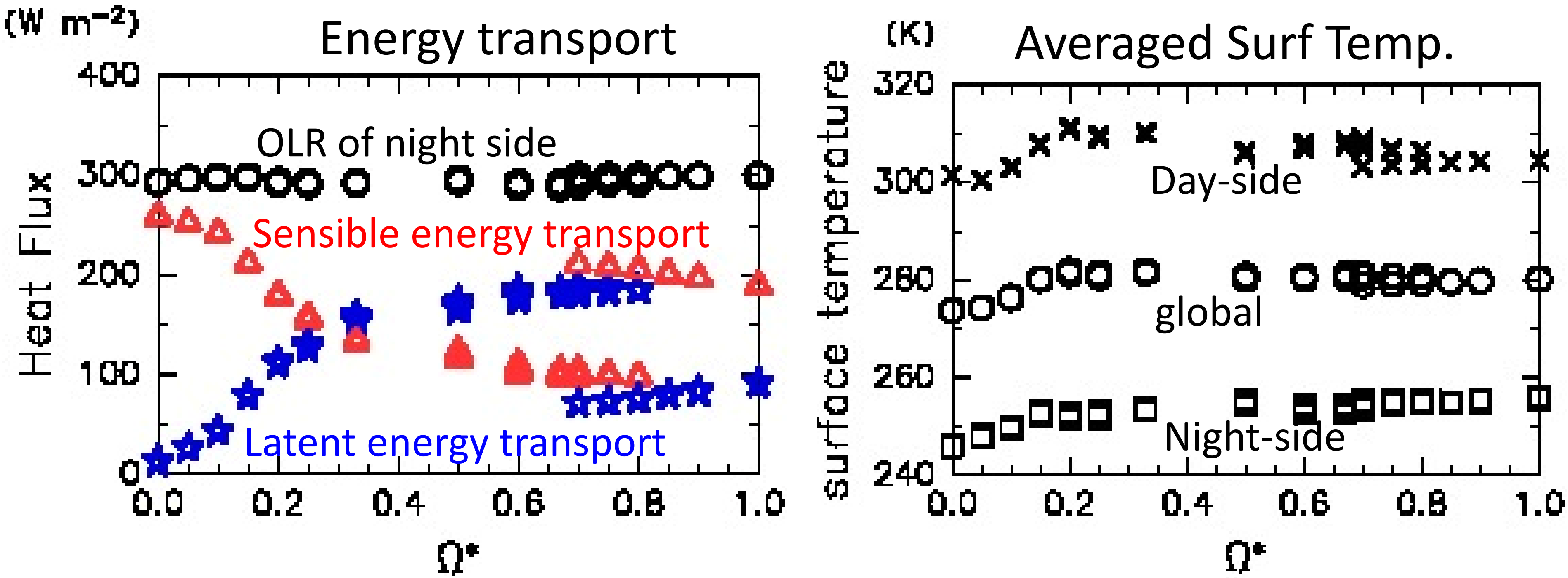
σ=0.17 (upper troposphere)



Vectors : (u,v)
Color: geo-
potential

Time mean over
1000-2000day

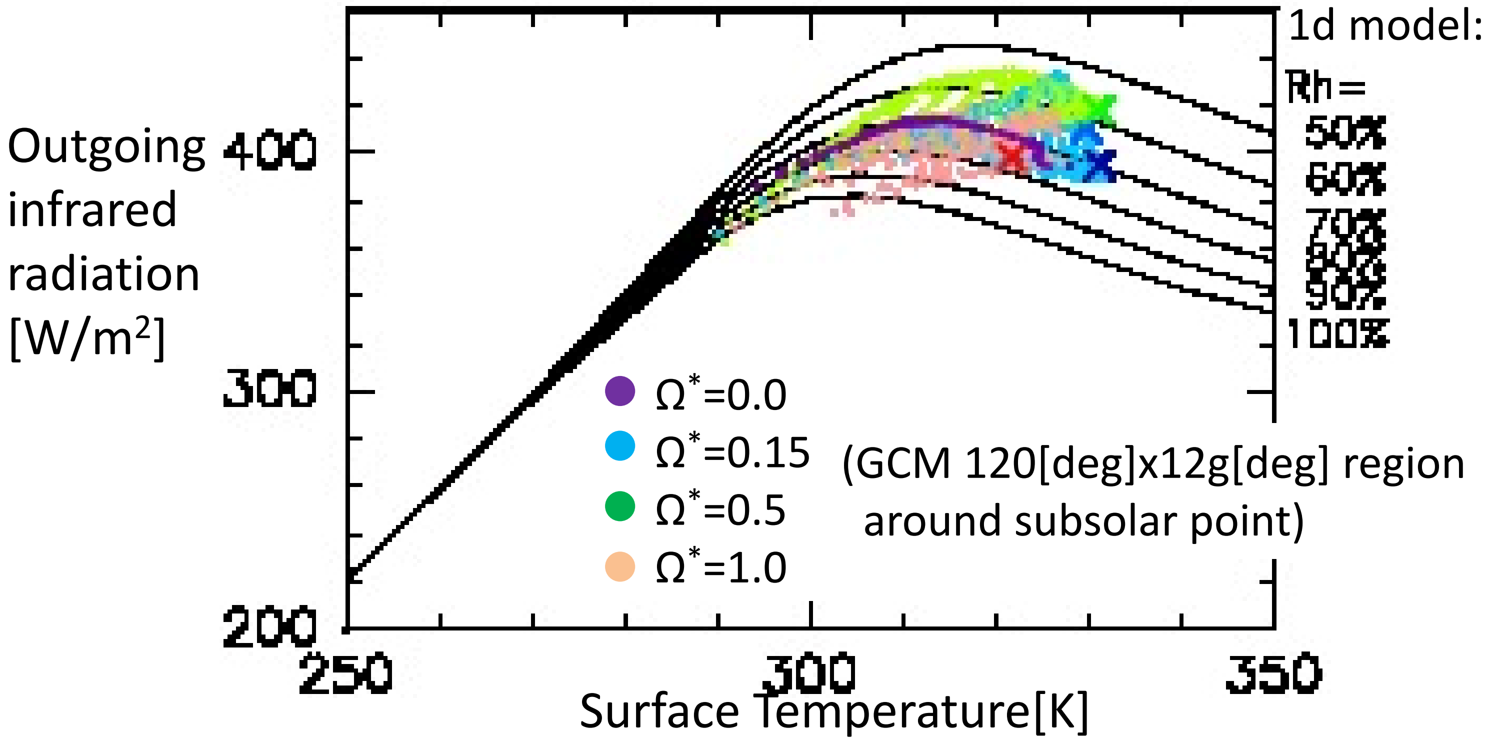
Dependence of energy transport on Ω^*



Rotation rate (normalized by Earth's value)

- Total energy transport (summation of sensible and latent energy transports) is almost independent of Ω^*

The radiation limit constraints energy transport



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

Ω dependence experiment (non-gray radiation, simple cloud model)

Ω^* dependence experiment (non-gray, cloud)

- **Purpose**
  - **Examination of Ω^* dependence of day-night energy transport in more realistic configuration**

Physical parameterizations

- **Radiation**
  - **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**
  - **considering its advection, turbulent mixing, generation 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)

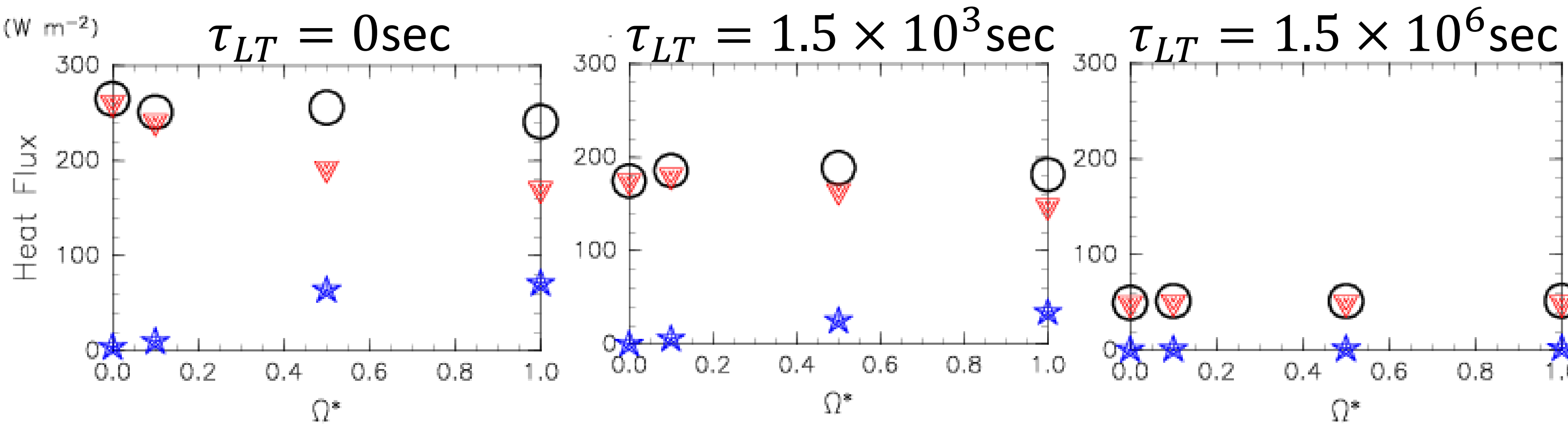
Experimental configuration

- **Rotation rate:**
  Ω^*=0.0, 0.5, 1.0
- **Solar constant is fixed: S=1366 W/m^2**
- **Cloud extinction time:**
  τ_{LT}=0,
  1.5×10^3 sec **(tuned value under Earth condition),**
  1.5×10^6sec
- **Resolution: T42L26**
- **Integration period: 3 Earth year**

Day-night energy transport

Energy transport to the night side（365day mean）

S=1366W/m^2



○ : OLR (= day-night total energy transport)

▼ : (sensible energy transport)/$2\pi R^2$

★ : (latent energy transport)/$2\pi R^2$

- **Again, the amount of day-night total energy transport is almost independent of Ω^***

Surface temperature & cloud water

S=1366W/m^2

Ω=0.0 **Ω=0.5** **Ω=1**

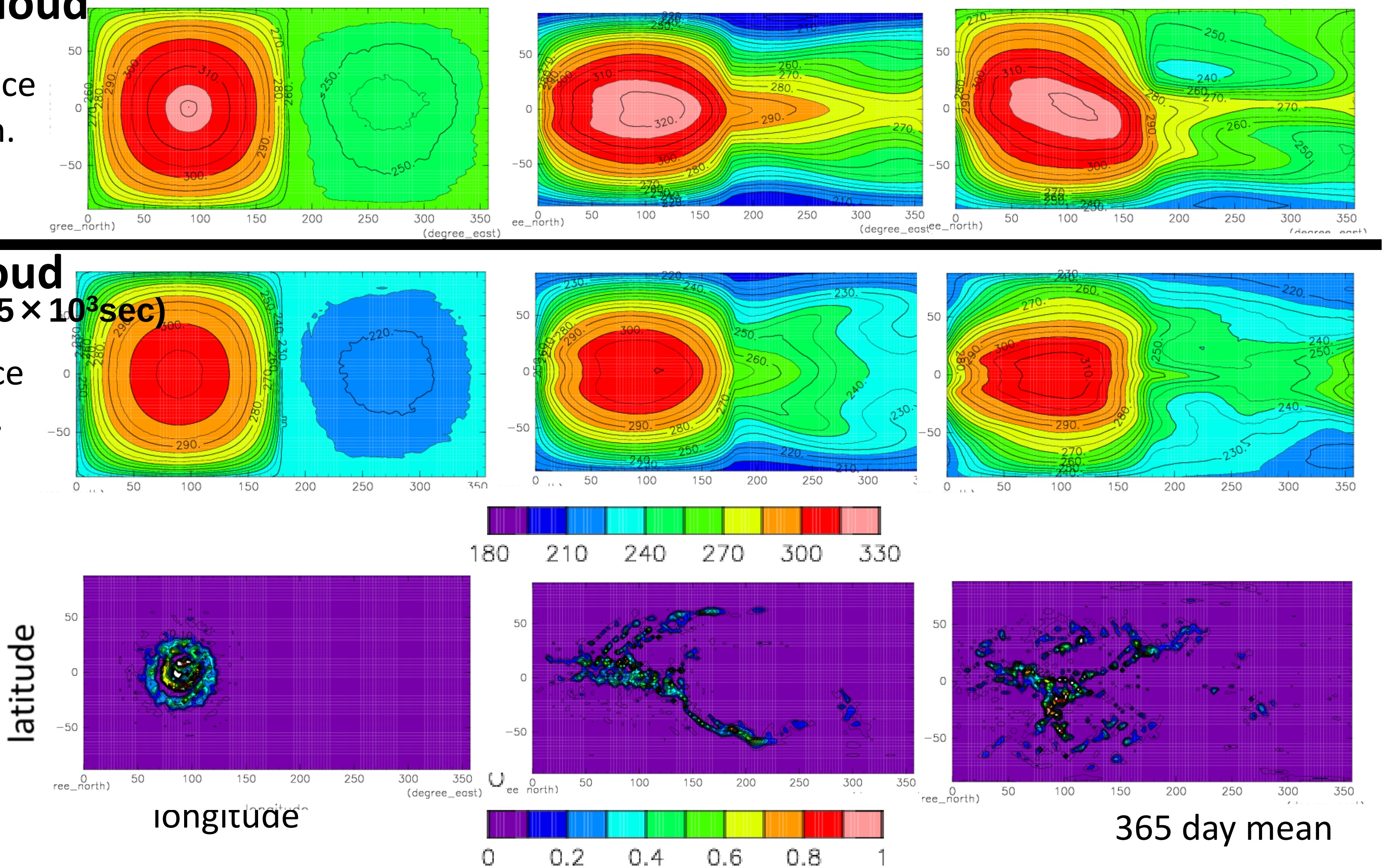
w/o cloud

Surface Tepm.

w/ cloud
(τ_{LT} = 1.5×10^{3}sec)

Surface Tepm.

Total cloud water

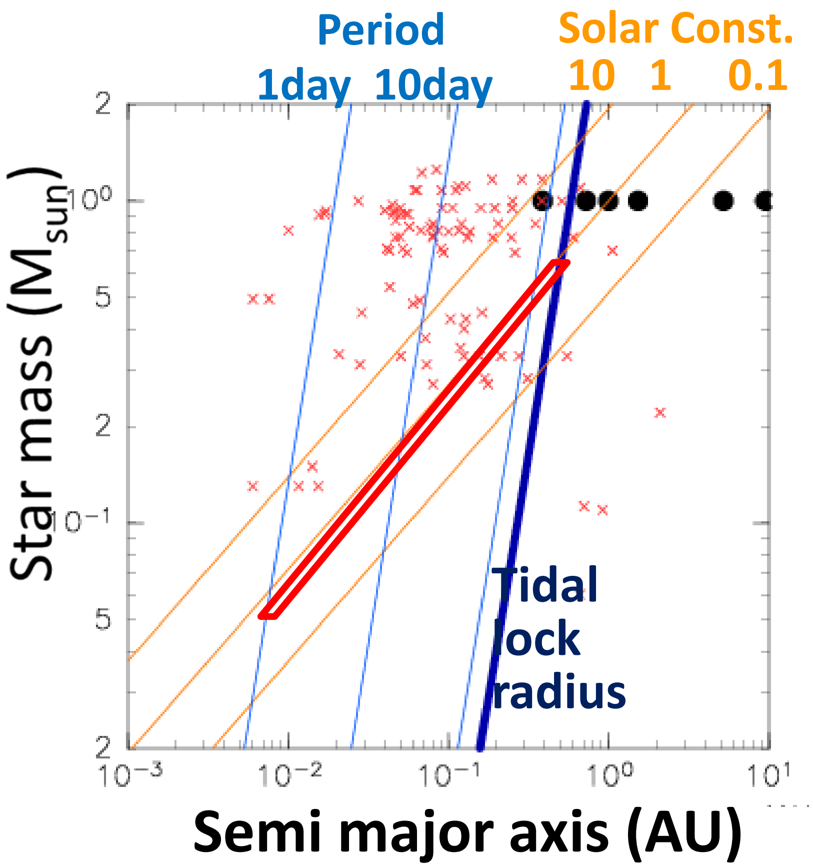


365 day mean

Solar constant dependence experiment (non-gray radiation, simple cloud model)

Solar constant dependence experiment (ongoing)

- **Purpose**
  - Examination on the occurrence condition of the runaway greenhouse state
  - Comparison of cases with clouds and cases without clouds
  - Comparison of synchronously rotating planet configuration and Earth configuration



Experimental configuration

- **Rotation rate: Ω*=1.0**
- **Cloud extinction time:**
  τ_{LT}=0, 1.5 × 10^3 sec
- **Solar constant: S=1366-2200W/m^2**
- **Two kinds of distributions of incident solar flux**
  - **Synchronously rotating planet configuration**
  - **Earth configuration**
- **Resolution: T42L26**
- **Integration period: 3 Earth year**

Runaway threshold

- **Results of runs with increased solar constant**

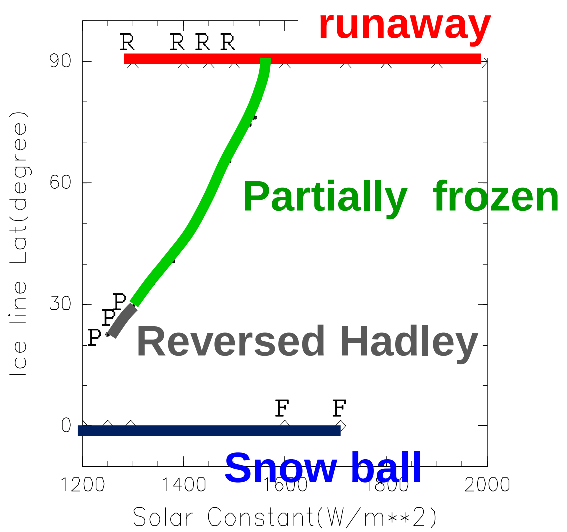
	Without Cloud		With cloud	
	SyncRot	No-SyncRot	SyncRot	No-SyncRot
S=1366	○	○	○	○
S=1600	○	○	○	○
S=1800	×	×	○	
S=2000			○	× ?
S=2200			×	

○ : equilibrium states, × :runaway greenhouse states

Concluding remarks

TODO list (very long...)

- **Experiments with more realistic configuration**
  - Stellar spectrum type, Ocean, Sea ice, ...
  - Model development is also ongoing:
    radiation scheme (Onishi's talk in today's afternoon)
- **Understanding variety of climate with climateregime diagram**
  - Examination of occurrence conditions of runaway greenhouse and snowball state
  - Making climate regime diagrams
    - We have not been able to draw regime diagram even for synchronously rotating planet.
  - Consideration on other configuration:
    land planet,
    very hot planet (runaway planet), etc.



Summary

- **We are performing numerical experiments and model development in order to make climate regime diagrams.**
- **Experiments on synchronously rotating planets**
  - **Day-night energy transport is almost independent of Ω*.**
  - **Examination on the occurrence condition of the runaway greenhouse is ongoing. Is runaway threshold also independent of Ω*?**
- **On going (or near future) subjects**
  - **Model development for more realistic simulation**
  - **Examination of climate regimes in parameter spaces not only for synchronously rotating planet but also for land planet etc.**