Atmospheric general circulation of synchronously rotating terrestrial planets: Dependence on planetary rotation rate

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(3) Center for Planetary Science, Kobe, (4) Kyushu University, Fukuoka,
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(7) RIKEN Advanced Institute for Computational Science, Kobe

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Synchronously rotating planets

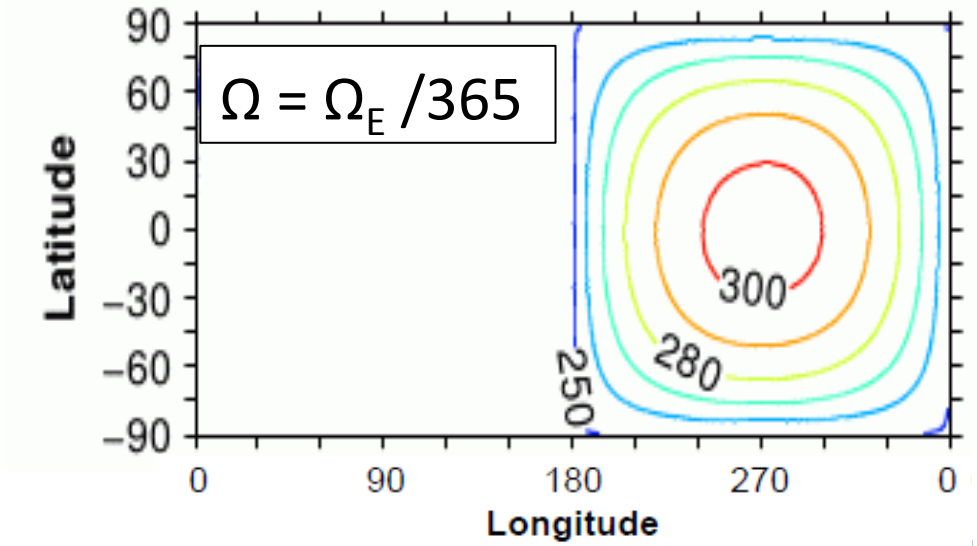
- Some terrestrial exoplanets are expected to be tidally locked.
- Climates of such planets?
  - Numerical experiment of aqua-planet with fixed dayside and nightside

- Previous studies: Atmospheric general circulation model experiments
  - Joshi et al. (1997)
  - Joshi (2003)
  - Merlis and Schneider (2010)
  - Edson et al. (2011)

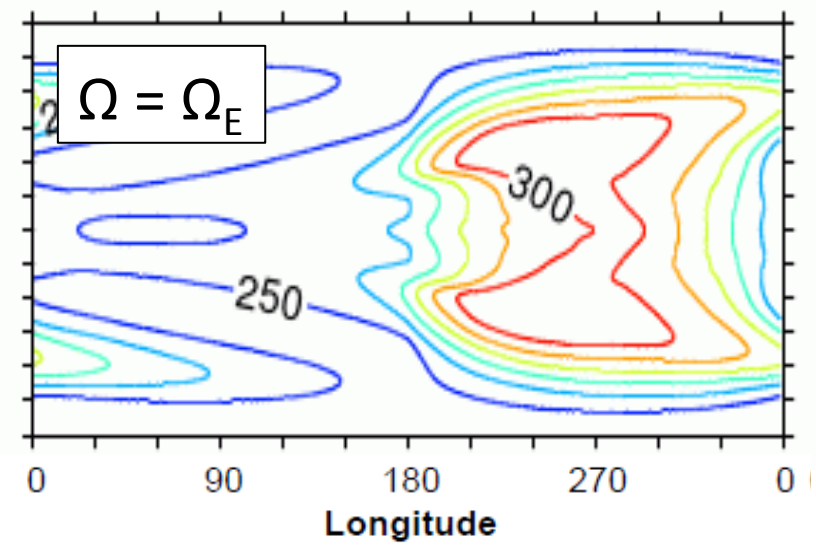
Objectives

- Examination of dependences of circulation and heat/water transports on planetary rotation rate (Ω)
  - Atmospheric structure for intermediate Ω?

Surface temperature(Merlis and Schneider, 2010)



Slowly rotating regime



Rapidly rotating regime

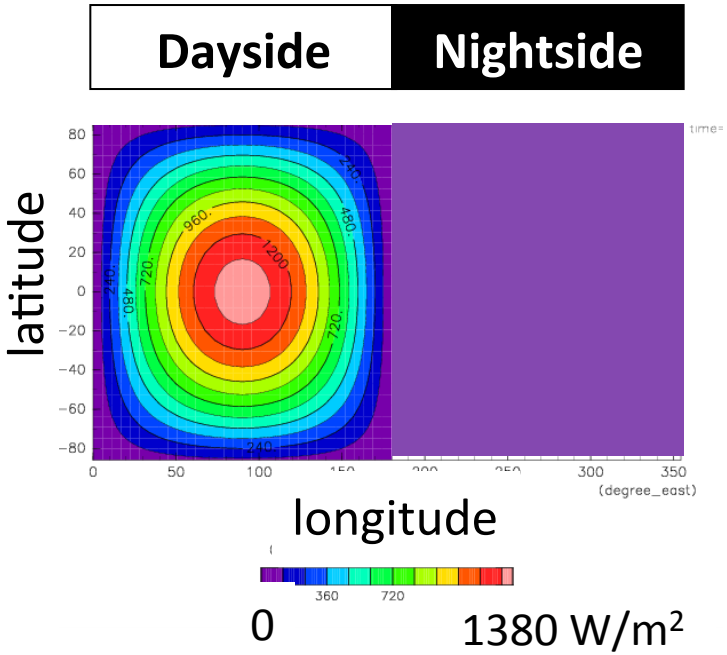
General circulation model

dcpam5 (http://www.gfd-dennou.org/library/dcpam/index.htm.en)

Basic equations of dynamical part	Primitive equation (hydrostatic, ideal gas), vertical coordinate : $\sigma = p / p_s$
Atmospheric composition	“Water vapor” and “dry gas”
Radiation process	Water vapor : gray to IR radiation Dry gas: transparent
Cumulus process	Convective adjustment (Manabe et al., 1965) condensed water is removed from system immediately (no cloud)
Turbulent vertical mixing	Mellor and Yamada (1972) Level 2
Surface condition	Aqua-planet, flat surface Zero heat capacity

Experimental configuration

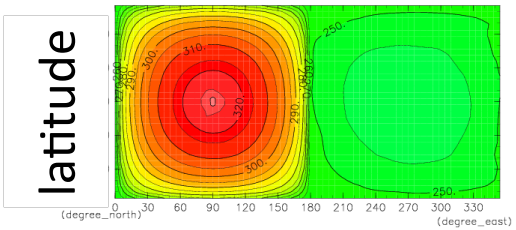
- Solar radiation flux is given only to dayside
- Planetary rotation rate: 0 - Ω_E (Earth)
  - 18 cases
- Planetary radius: 6.371 x 10^6 m
- Solar constant: 1380 W m^{-2}
- gravitational acceleration: 9.8 m s^{-2}
- Averaged surface pressure: 10^5 Pa
- surface albedo: 0



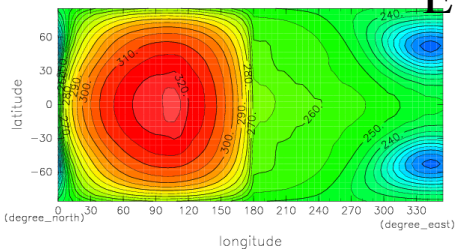
- Resolution
  - Horizontal truncation wave number: T21
  - Vertical levels: L16
- Initial condition: isothermal (280K) rest state
- Integration time: 2000 days (last 1000 days is used for analysis)

Surface temperature for various Ω

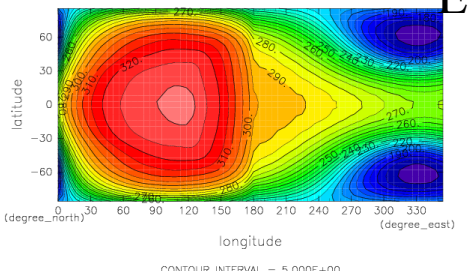
$\Omega = 0$



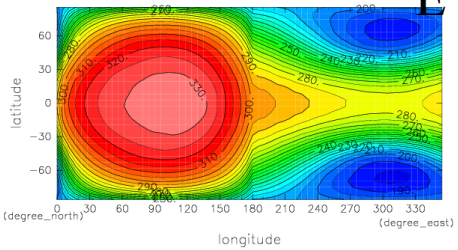
$\Omega = 0.05\ \Omega_E$



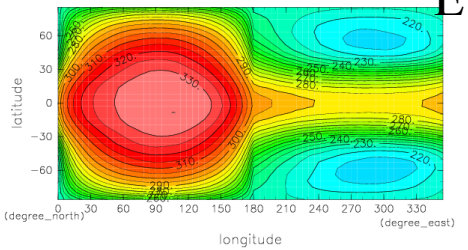
$\Omega = 0.15\ \Omega_E$



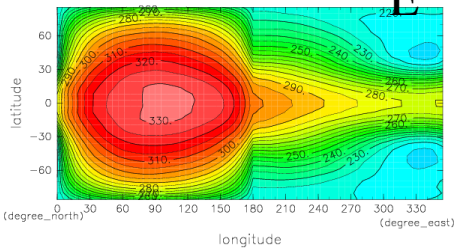
$\Omega = 0.25\ \Omega_E$



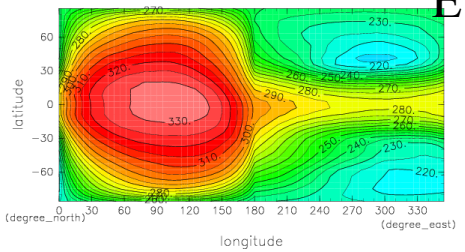
$\Omega = 0.33\ \Omega_E$



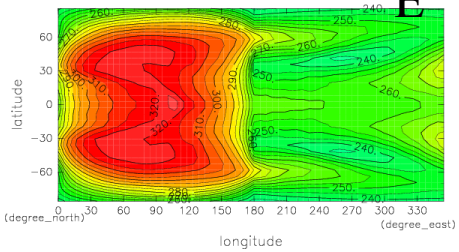
$\Omega = 0.5\ \Omega_E$



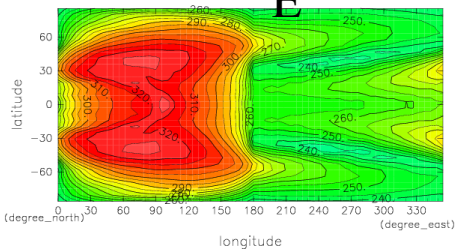
$\Omega = 0.67\ \Omega_E$

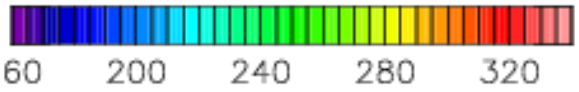


$\Omega = 0.8\ \Omega_E$



$\Omega = \Omega_E$

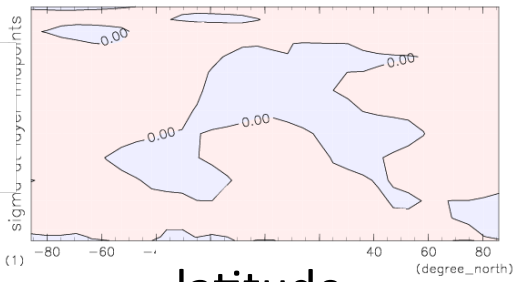




Time mean over 1000-2000day

Zonal mean zonal wind for various Ω

$\Omega = 0$



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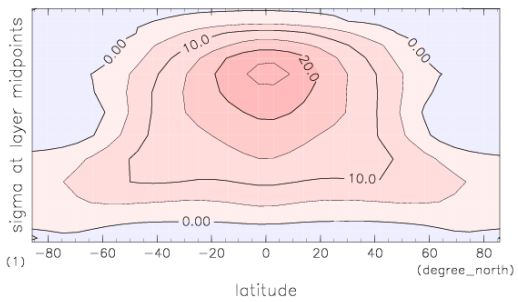
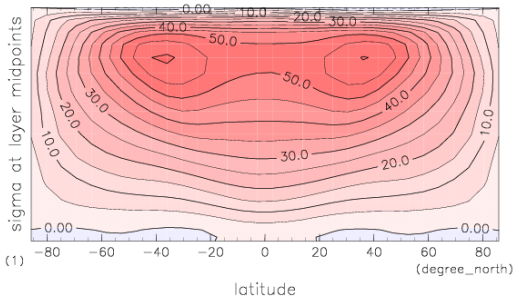


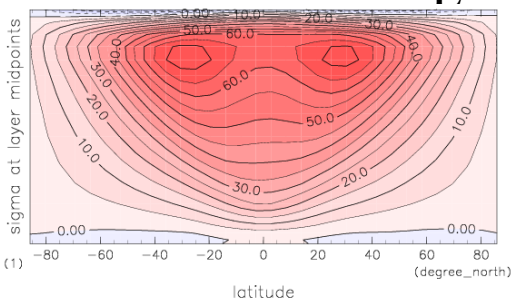
$\Omega = 0.15\ \Omega_E$



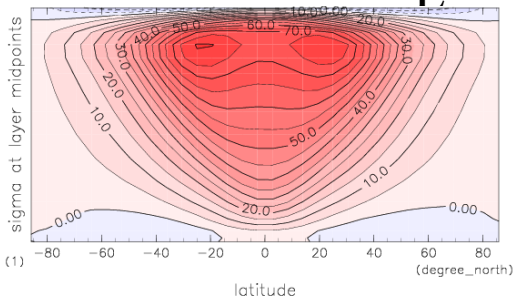
sigma

latitude

$\Omega = 0.25\ \Omega_E$



$\Omega = 0.33\ \Omega_E$



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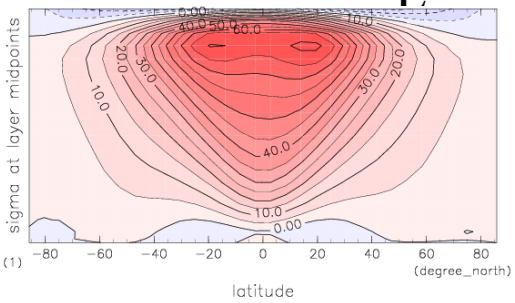
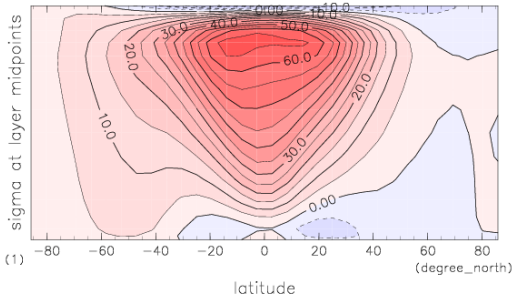
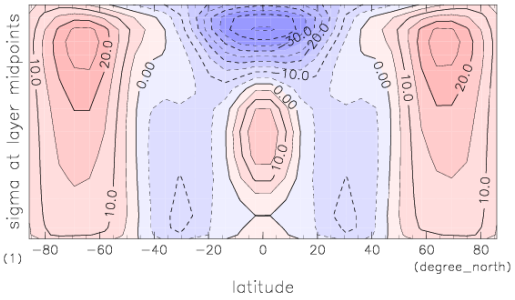


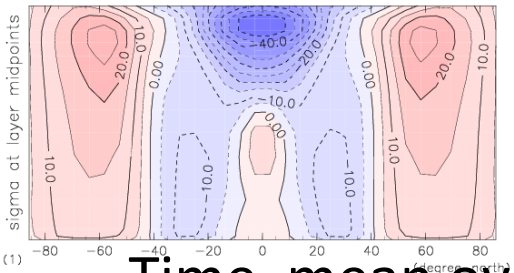
$\Omega = 0.67\ \Omega_E$



$\Omega = 0.8\ \Omega_E$



$\Omega = \Omega_E$



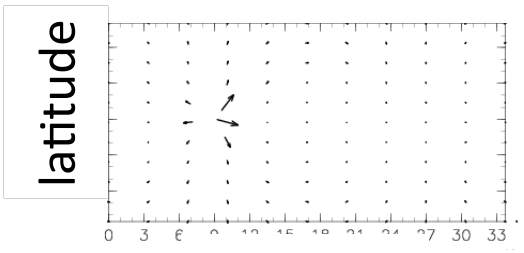
CONTOUR INTERVAL = 5.000E+00

-100 m/s  100 m/s

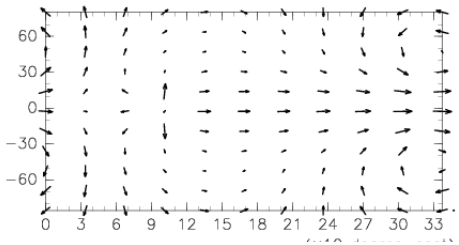
Time mean over 1000-2000day

Wind (σ=0.2) for various Ω

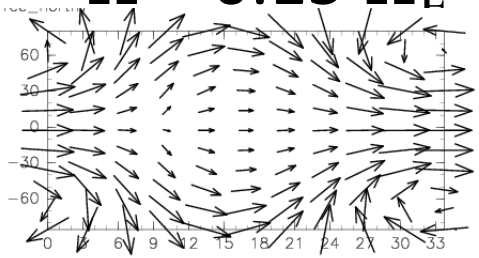
$\Omega = 0$



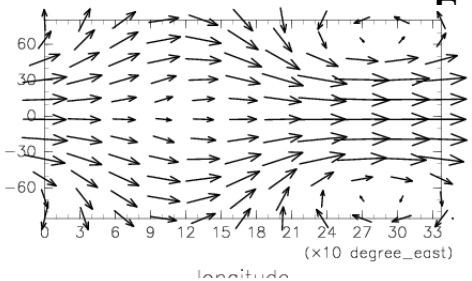
$\Omega = 0.05\ \Omega_E$



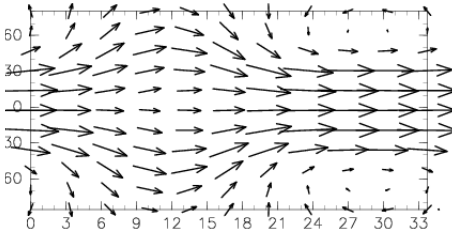
$\Omega = 0.15\ \Omega_E$



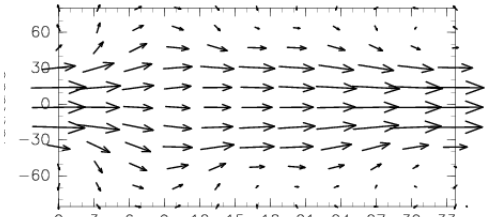
$\Omega = 0.25\ \Omega_E$



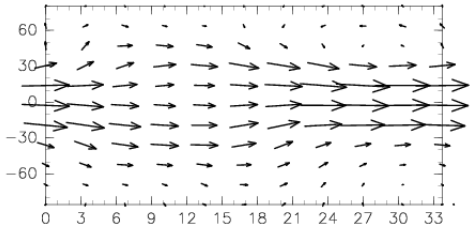
$\Omega = 0.33\ \Omega_E$



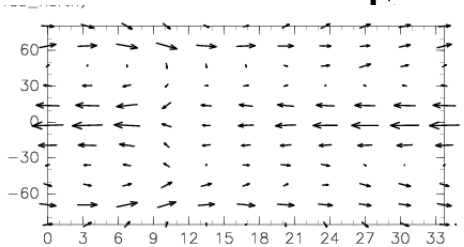
$\Omega = 0.5\ \Omega_E$



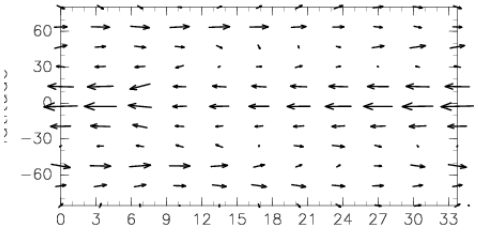
$\Omega = 0.67\ \Omega_E$



$\Omega = 0.8\ \Omega_E$



$\Omega = \Omega_E$



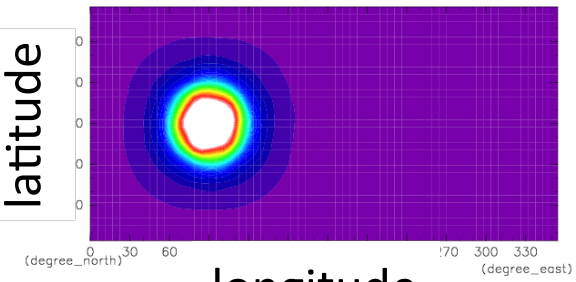
100 m/s

100 m/s

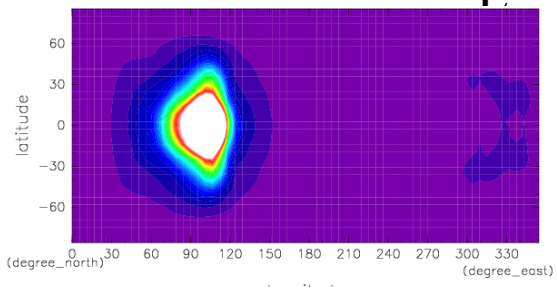
Time mean over 1000-2000day

Condensation heating rate for various Ω

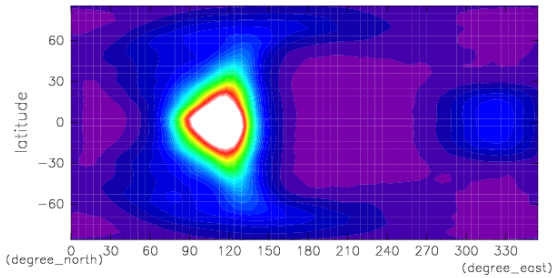
$\Omega = 0$



$\Omega = 0.05\ \Omega_E$

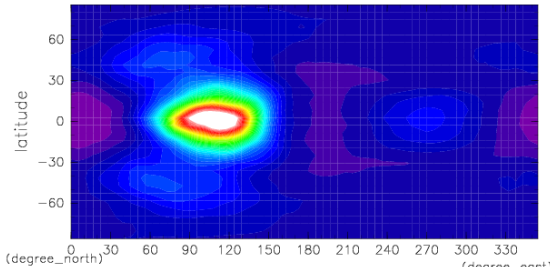


$\Omega = 0.15\ \Omega_E$

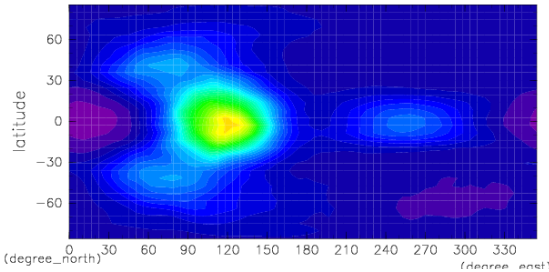


longitude

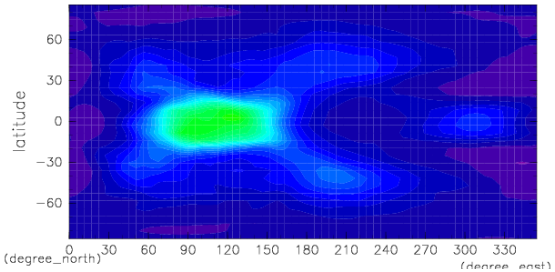
$\Omega = 0.25\ \Omega_E$



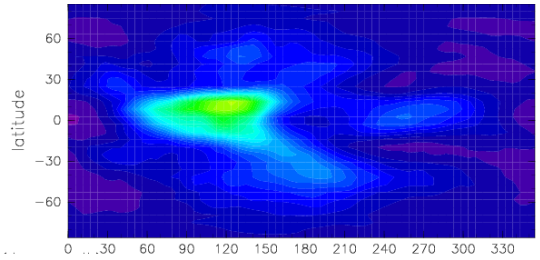
$\Omega = 0.33\ \Omega_E$



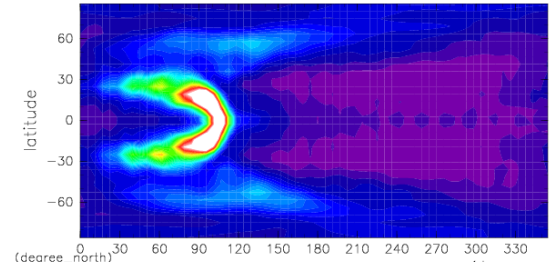
$\Omega = 0.5\ \Omega_E$



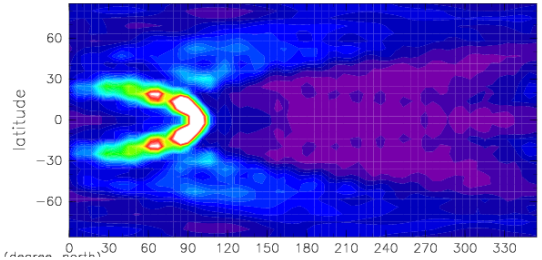
$\Omega = 0.67\ \Omega_E$

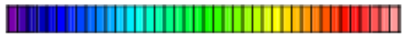


$\Omega = 0.8\ \Omega_E$



$\Omega = \Omega_E$

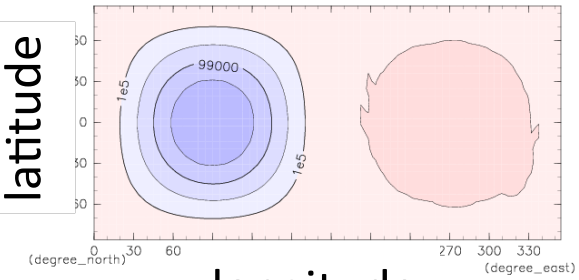


0 W/m^2  2000 W/m^2

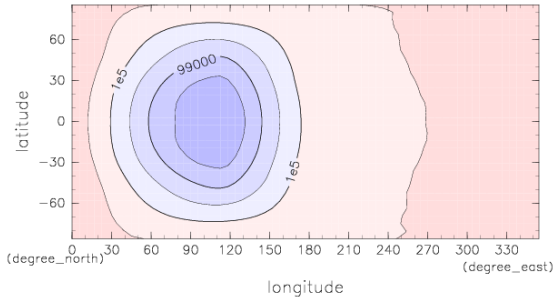
Time mean over 1000-2000day

Surface pressure for various Ω

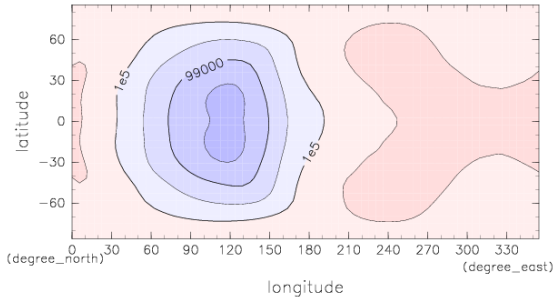
$\Omega = 0$



$\Omega = 0.05\ \Omega_E$

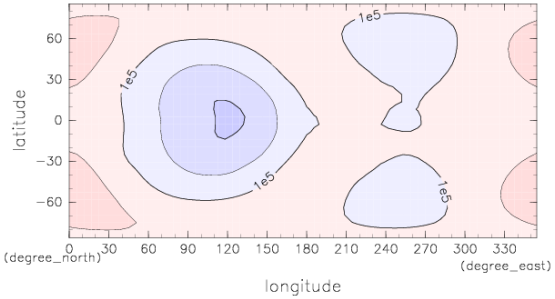


$\Omega = 0.15\ \Omega_E$

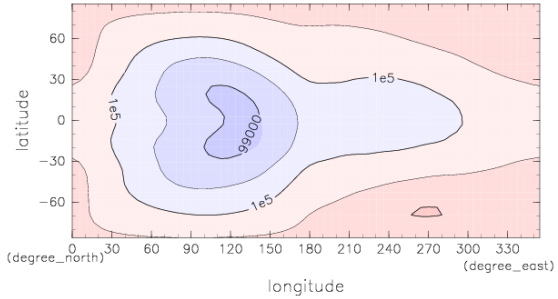


longitude

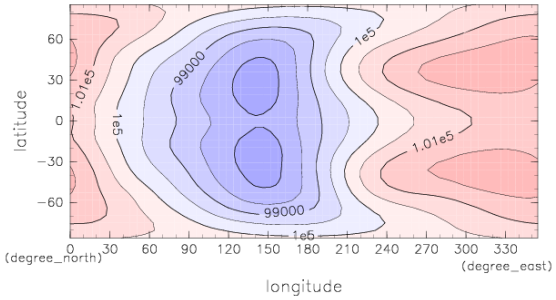
$\Omega = 0.25\ \Omega_E$



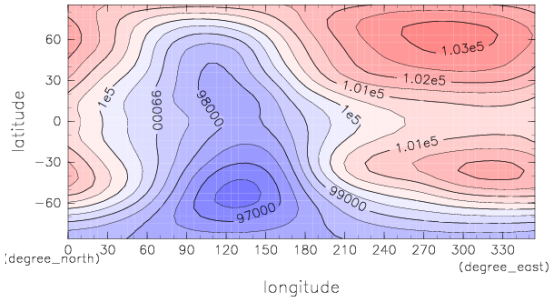
$\Omega = 0.33\ \Omega_E$



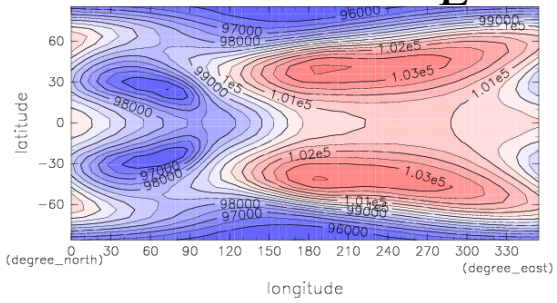
$\Omega = 0.5\ \Omega_E$



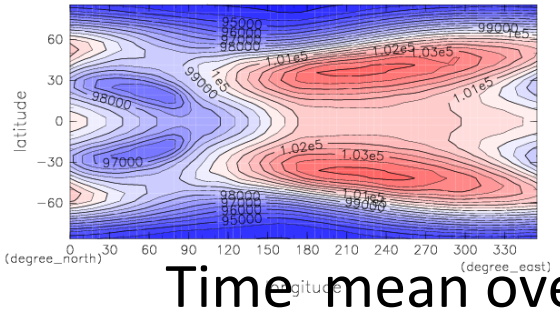
$\Omega = 0.67\ \Omega_E$



$\Omega = 0.8\ \Omega_E$



$\Omega = \Omega_E$



CONTOUR INTERVAL = 5.000E+00

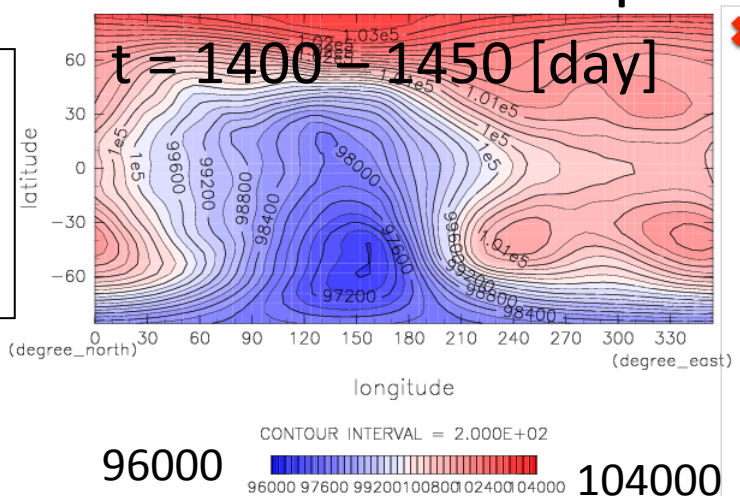
93000 Pa — 107000 Pa

Time mean over 1000-2000day

Asymmetric state: $0.2\Omega_E$ –$0.67\Omega_E$

North-south Asymmetric State

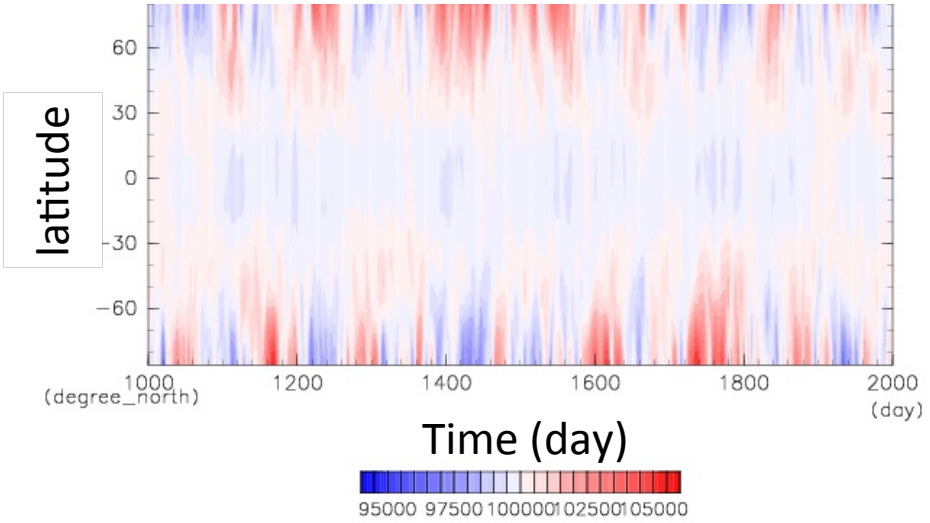
Surface pressure for $0.5\Omega_E$



t = 1750 – 1800 [day]

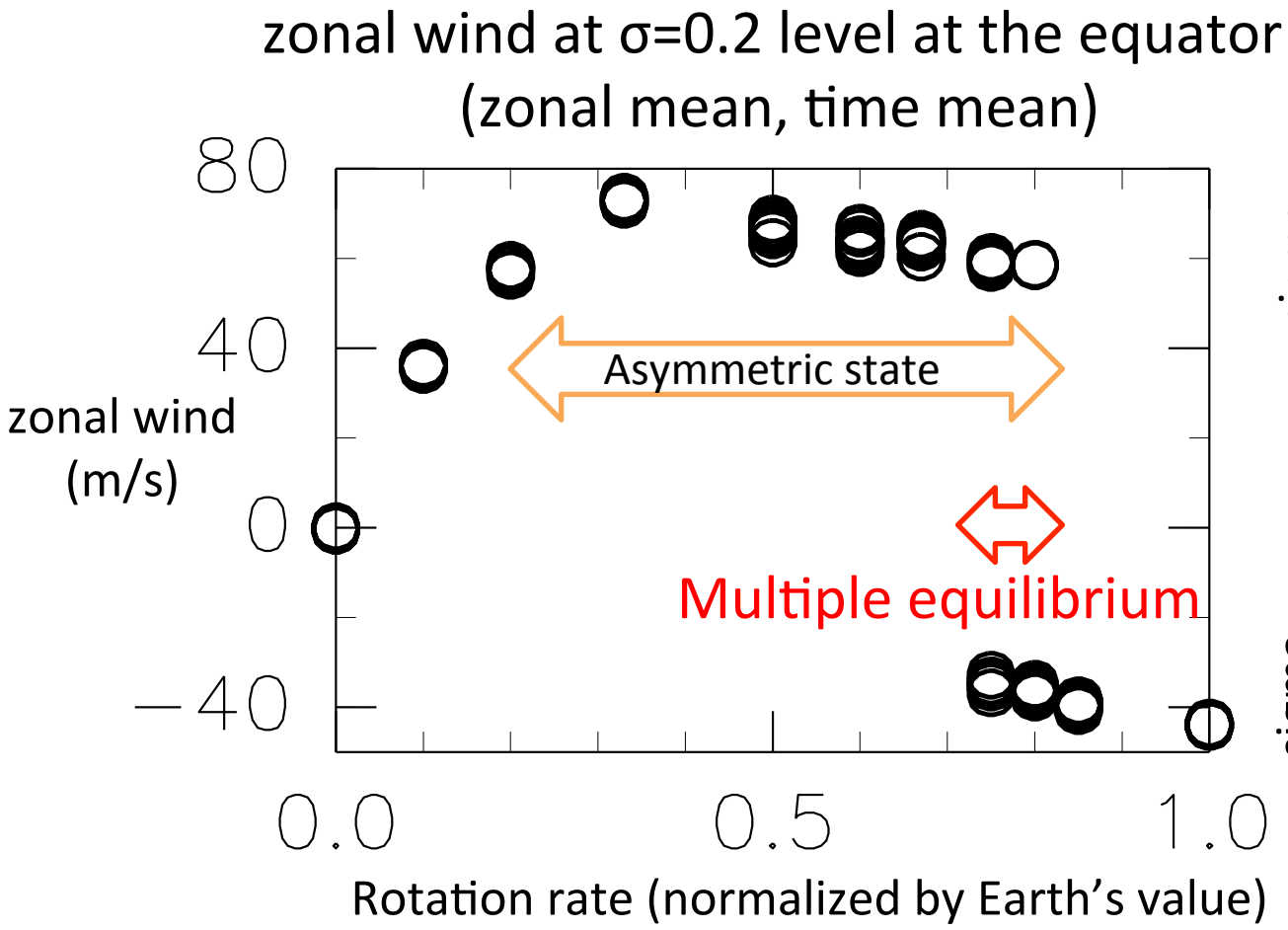
- Oscillation
  - Non-periodic for large Ω
  - “period”: 10day – 1000day
  - also in high reso. experiments

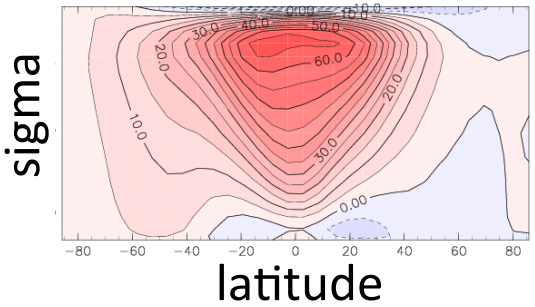
zonal mean surface pressure

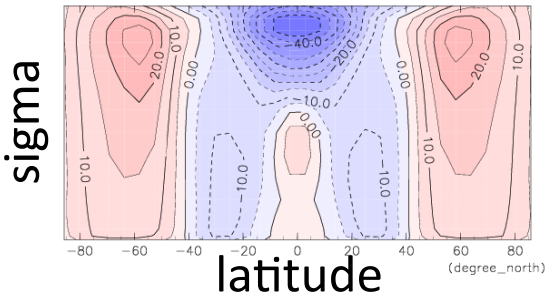


Multiple equilibrium states

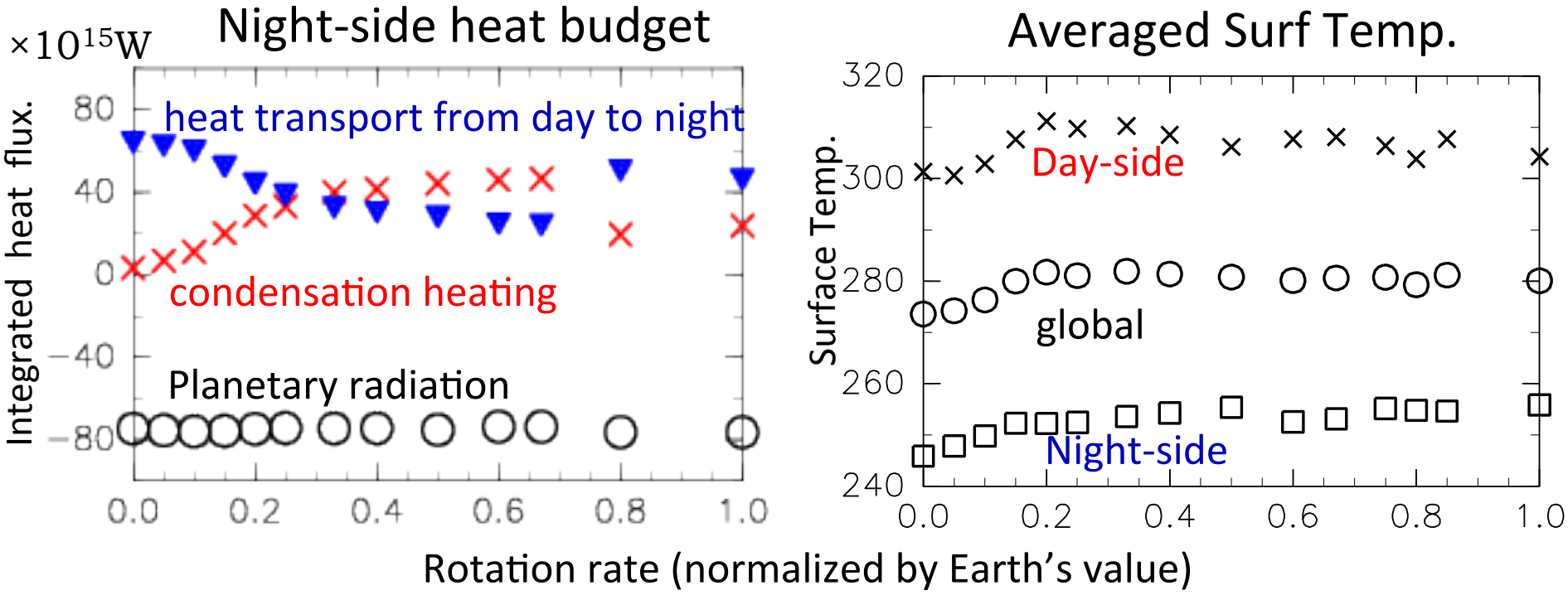
- 10 member Ensemble experiment
  - different random seed for Temperature





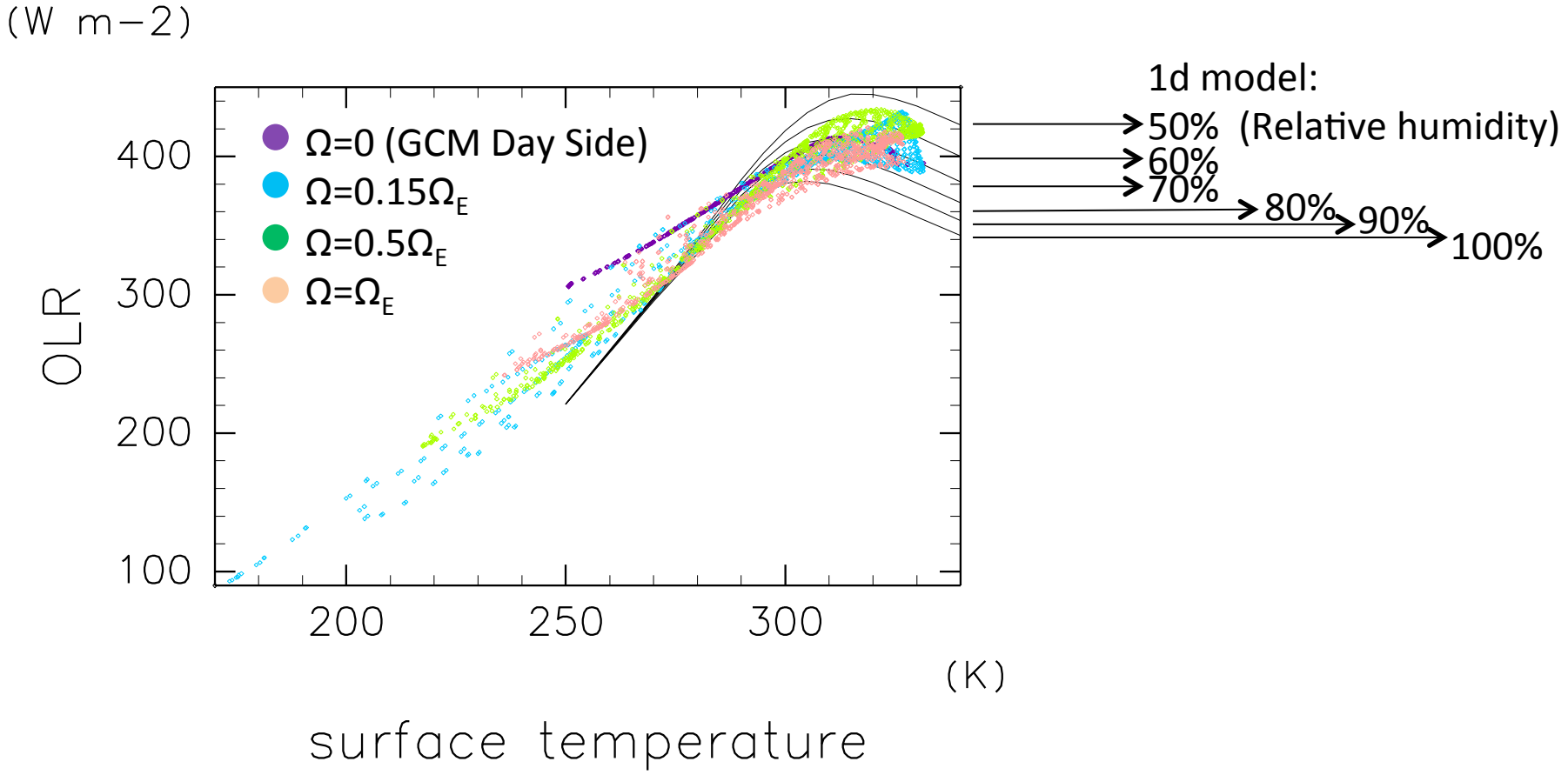


Dependence of heat budget on Ω



- Small dependence of summation of sensible/latent heat transports on Ω
- Total heat transport may be determined by (Incident solar flux) – (radiation limit)
  - Radiation limit: Nakajima et al. (1992), Ishiwatari et al. (2002)

Comparison with 1-d model



- Outgoing Longwave Radiation does not exceed radiation limit obtained by 1-dim radiative convective equilibrium model.

Summary

- Dependence of atmospheric states of synchronously rotating aqua-planet on Ω is studied by a GCM.
- Summation of sensible/latent heat transport is almost independent of rotation rate
- 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.