

金星のような惑星大気超回転の ロスビー数依存性

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Tsunoda Y. et al., “Rossby number dependence of Venus/Titan-type superrotation and its related intermittency,” J. Geophys. Res.: Planets, 126 (2021), e2020JE006637

金星のような惑星大気超回転の ロスビー数依存性

＜今日の話の内容＞

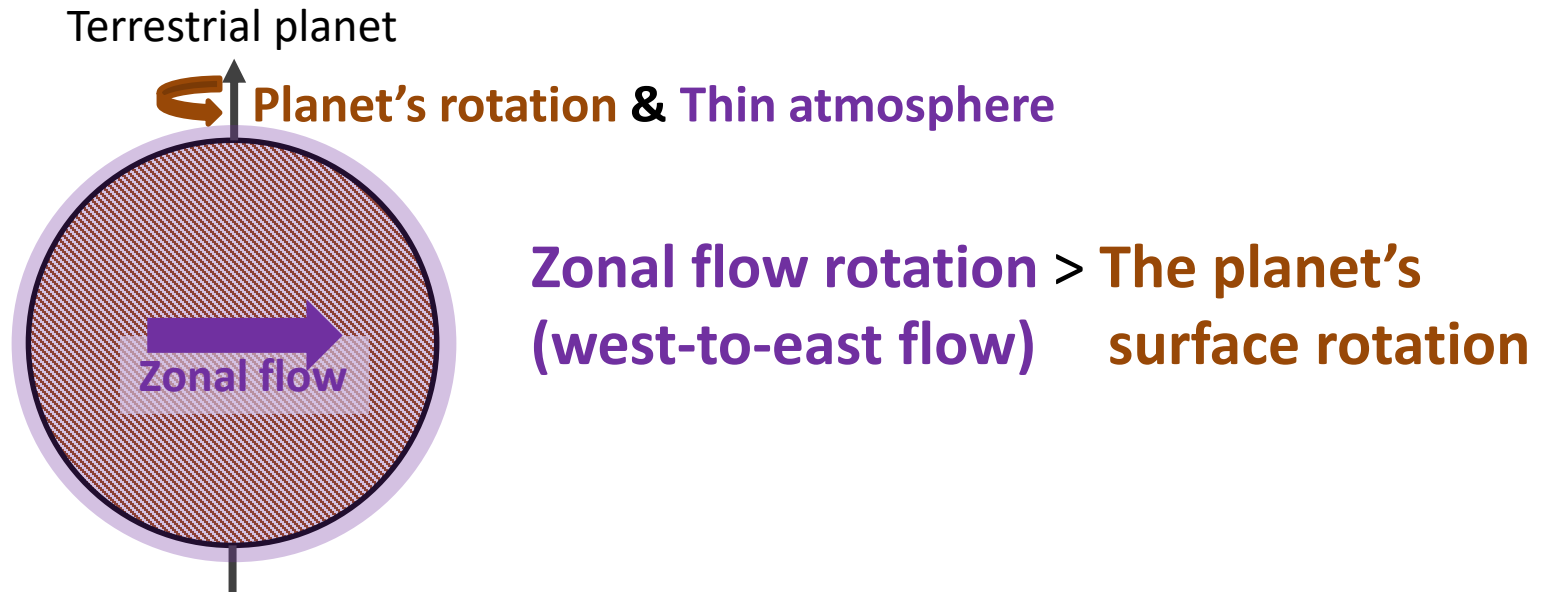
超回転について

雲で覆われた惑星について



高Rossby数(>1)の雲に覆われた惑星の
超回転のメカニズム (Tsunoda et al. 2021)

超回転について(地球型惑星)

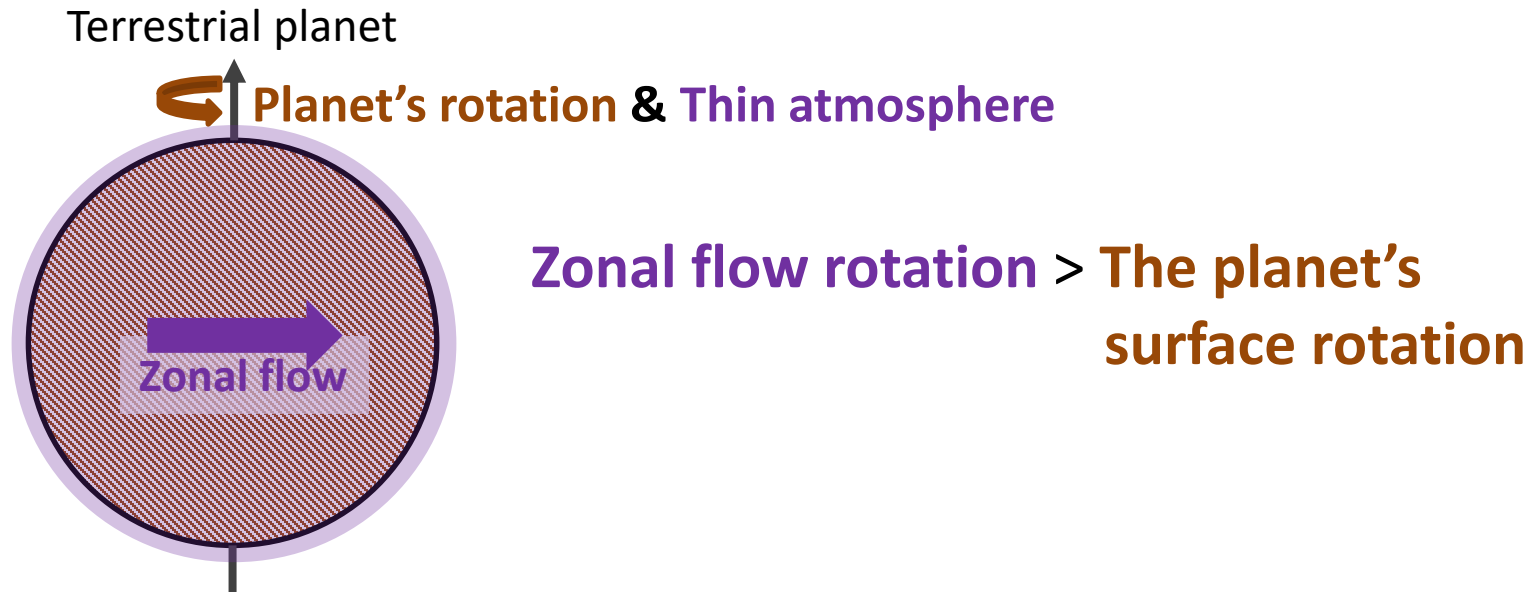


带状流が、全球にわたって惑星個体部の回転(自転)よりも早く回転する現象。例)金星大気は、雲頂で自転(243日)の60倍の高速回転(4日循環)している。



超回転は様々な天体で観測されている。
これらの惑星の間の超回転の相似性や違いは、
十分に理解されていない

超回転について(地球型惑星)



帯状流が、全球にわたって惑星個体部の回転(自転)よりも早く回転する現象。例)金星大気は、雲頂で自転(243日)の60倍の高速回転(4日循環)している。

地球型惑星の場合

惑星個体部の回転が、大気超回転の角運動量のソース、どのように角運動量が大気超回転に供給されるのか？

どのように角運動量が大气超回転に供給されるのか？

Motionless atmosphere

adhered to the surface by the frictional drag

Specific angular momentum

$$m = r \cos \varphi (\Omega r \cos \varphi) = m_0$$

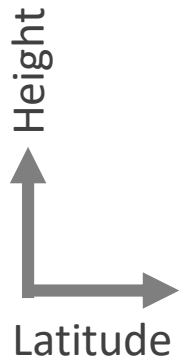
where Ω : Planetary rotation rate

r : Planetary radius, φ : latitude

m_0 : Specific angular momentum at the planet's surface

surface

= angular momentum source



どのように角運動量が大气超回転に供給されるのか？

Super- vs Sub-rotation

Specific angular momentum

$$m = m_0 + ur \cos \varphi$$

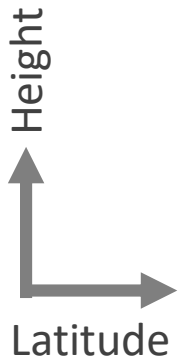
where Ω : Planetary rotation rate

r : Planetary radius, φ : latitude,

u : zonal-mean zonal flow

$m > m_0$: super-rotation

$m < m_0$: sub-rotation



surface

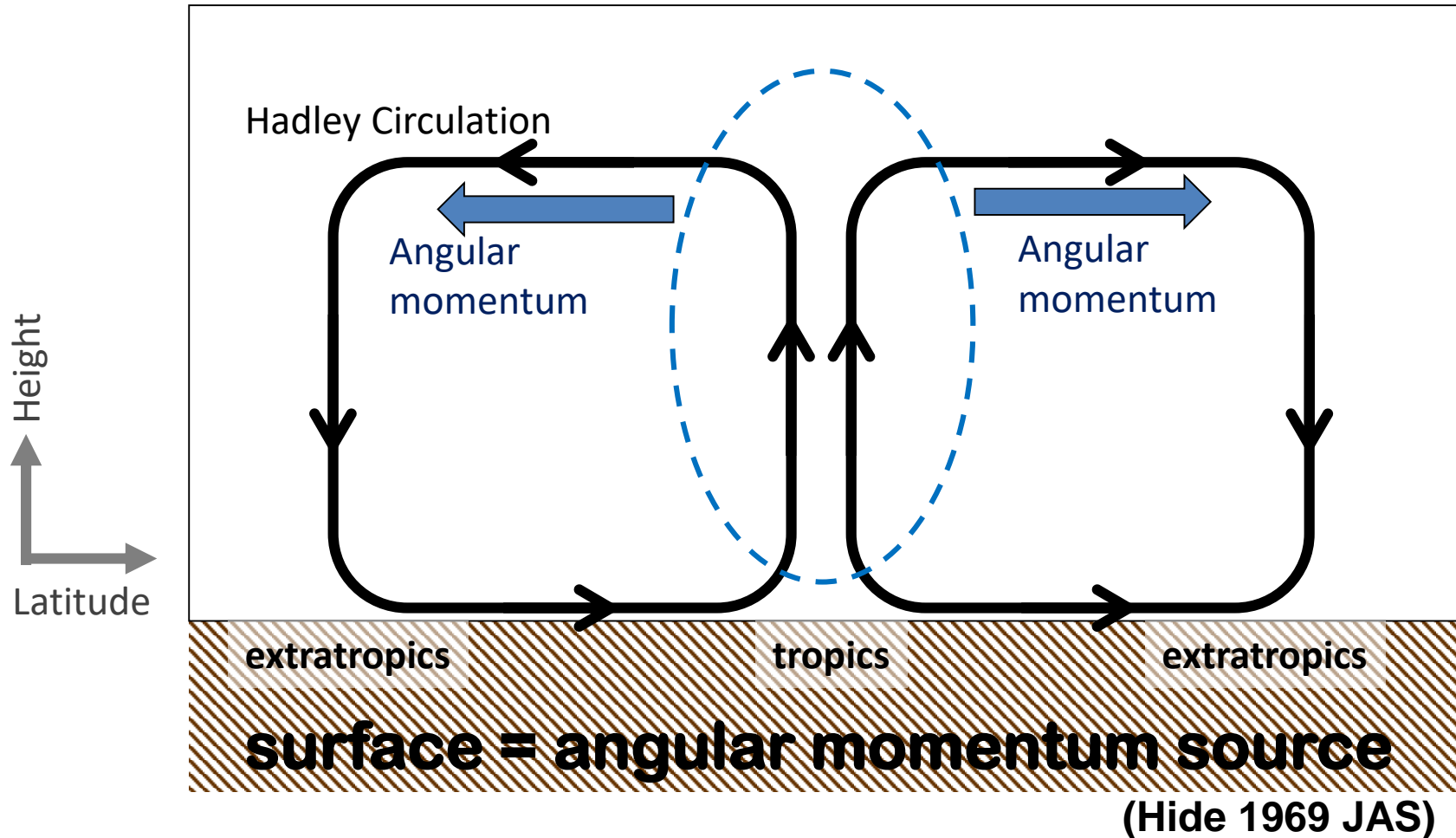
= angular momentum source

On the sub-rotating surface ($u < 0$), the angular momentum is supplied by the frictional drag from the surface.

⇒ The sub-rotating surface is needed to drive the SR during the spin-up.

地球型惑星大気の超回転メカニズム

Hide's theorem

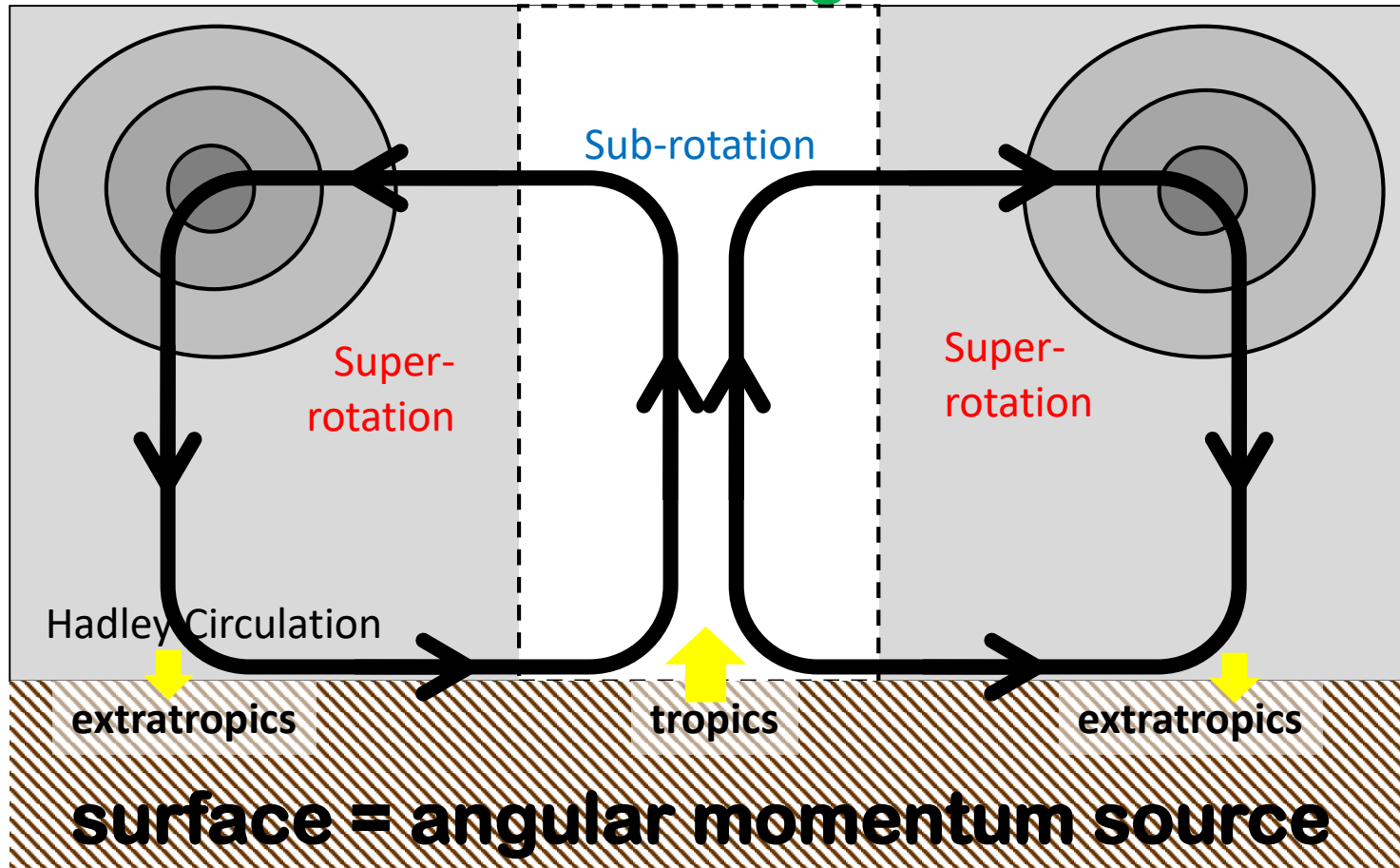


Hadley Circulation removes angular momentum in the tropics.

⇒ **Equatorial zonal flow is decelerated**

地球型惑星大気の超回転メカニズム

Classical regime



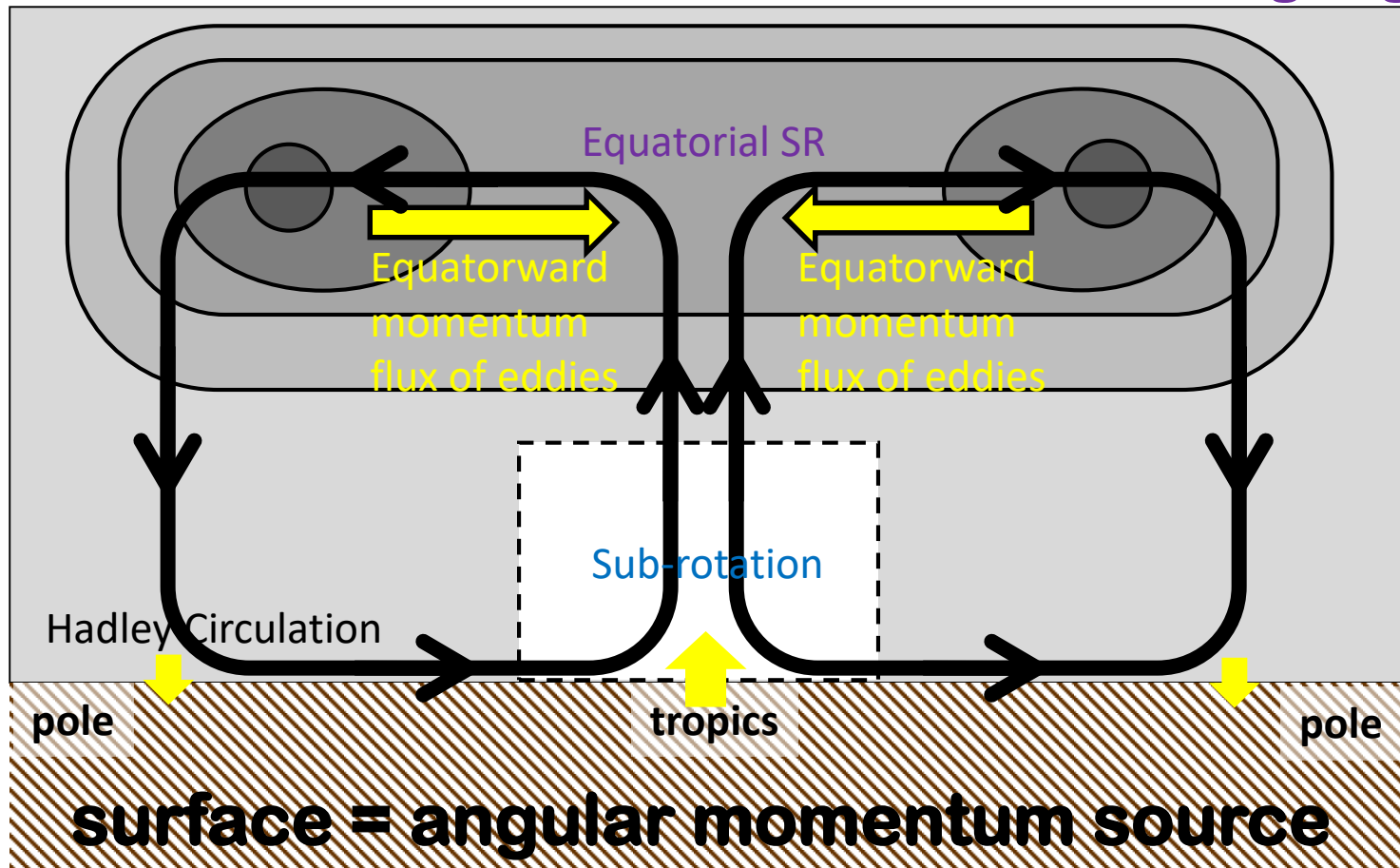
Sub-rotation in the tropic because of equatorial zonal-flow deceleration

Super-rotation in the extratropics because of poleward ang. mom. flux of Hadley cell

Some zonal-flow acceleration is required to produce "equatorial SR"

地球型惑星大気の超回転メカニズム

Gierasch–Rossow–Williams mechanism → SRing regime



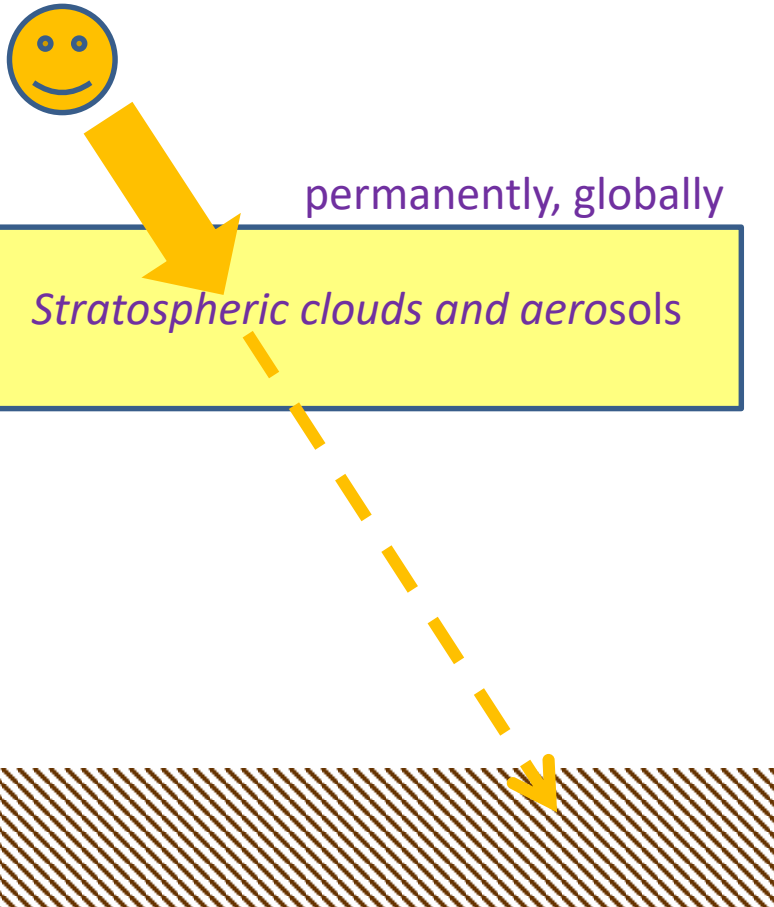
(Gierasch 1975 JAS; Rossow&Williams 1979 JAS)

Equatorward momentum flux of eddies
accelerates the equatorial SR

雲で覆われた惑星について

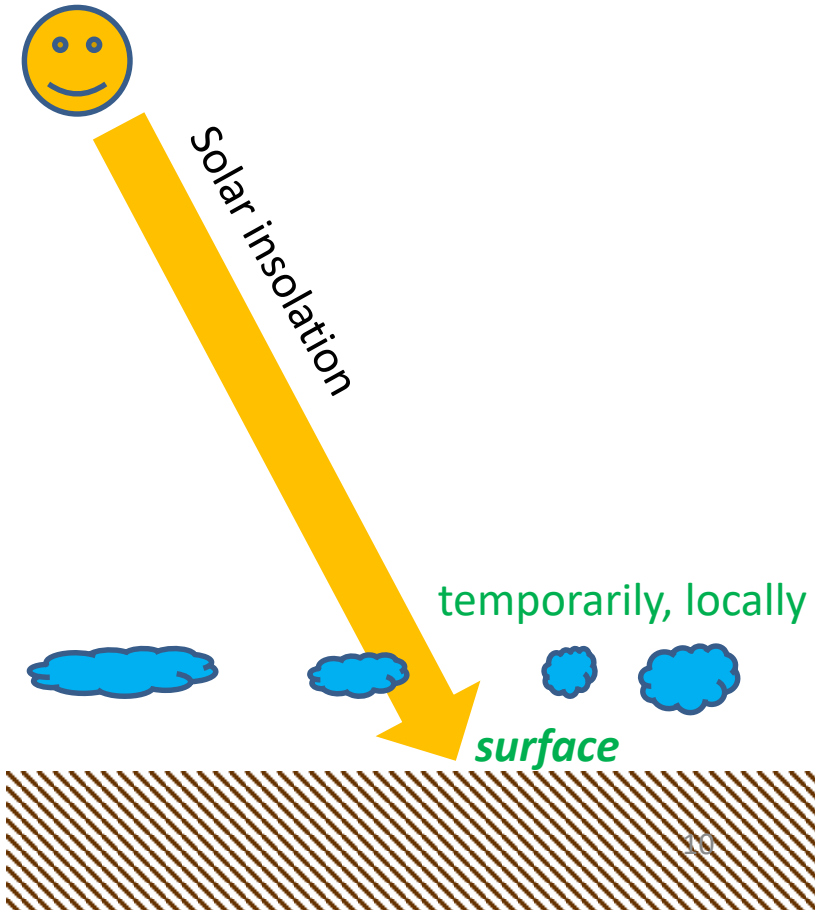
<Venus-type>

太陽放射の大部分が上層の雲で吸収され、その雲による加熱が大循環を駆動する。



<Earth-type>

太陽放射の大部分が地表面で吸収され、その地表面加熱が大循環を駆動する。



雲で覆われた惑星について

<Venus-type>

太陽放射の大部分が上層の雲で吸収され、その雲による加熱が大循環を駆動する。

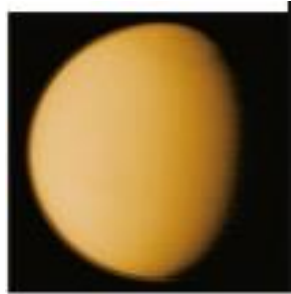
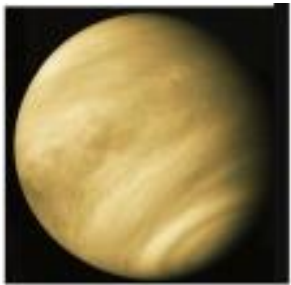
<Earth-type>

太陽放射の大部分が地表面で吸収され、その地表面加熱が大循環を駆動する。

Slow planet. rot



Fast planet. rot.



<Venus>

Rotation: 243d

Radius: 6,052 km

Sur Press: 90 atm

Sur Temp : 735 K

*Sulfuric-acid
cloud layer*

<Titan/moon>

Rotation: 16d

Radius: 2,575 km

Sur Press: 1.45 atm

Sur Temp : 94 K

*Organic haze
layer*

<Mars>

Rotation: 1d

Radius: 3,397 km

Sur Press: 0.006 atm

Sur Temp : 210 K

Photo : NASA/JPL

<Earth>

Rotation: 1d

Radius: 6,378 km

Sur Press: 1 atm

Sur Temp : 288K

雲で覆われた惑星の大気大循環構造

<Venus-type>

<Earth-type>

Rossby number (Ro)

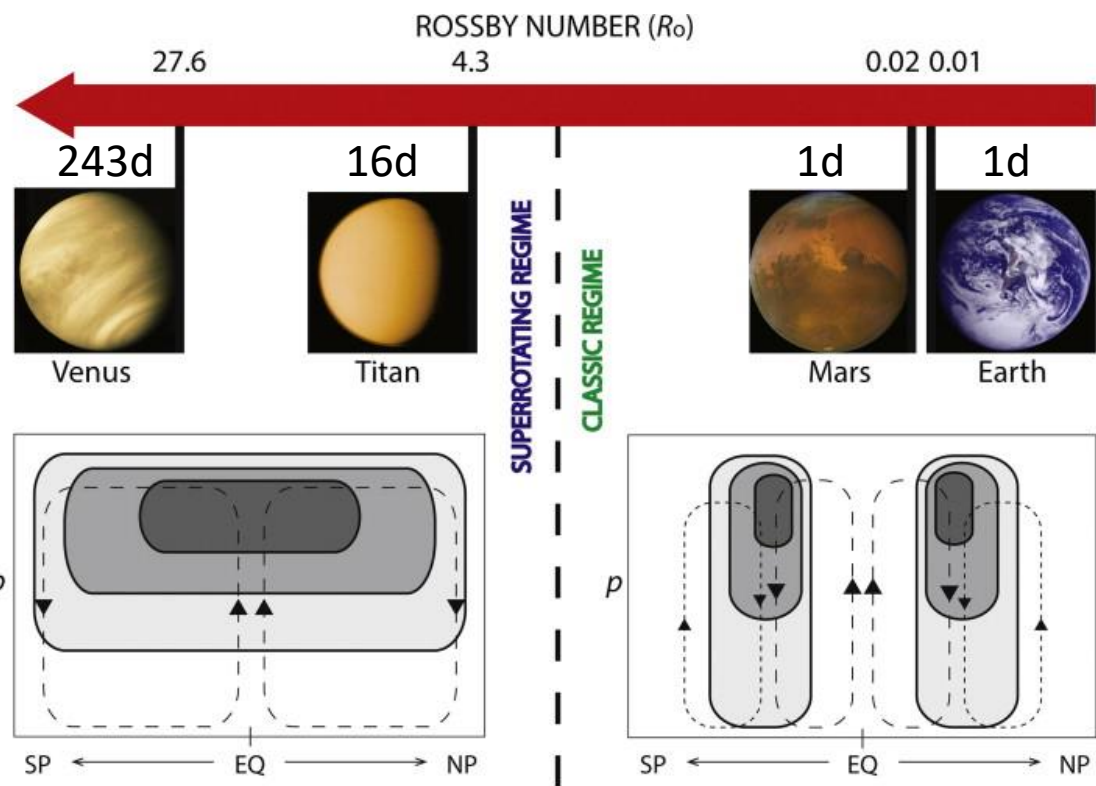
$$\sim \frac{\text{Inertial force}}{\text{Coriolis force}}$$

$$R_o \equiv \frac{U}{2\Omega L}$$

U : Wind Speed Scale
 Ω : Planet. Rot. Rate
 L : Horizontal Scale

Rotation : Slow
 Size : Small

Rotation : Fast
 Size : Large



(Dias Pinto & Mitchell, 2014) Photo : NASA/JPL

Gray shade : SR zonal flow (the darker shade presents the faster zonal flow)

雲で覆われた惑星の大気大循環構造

<Venus-type>

<Earth-type>

<研究動機>

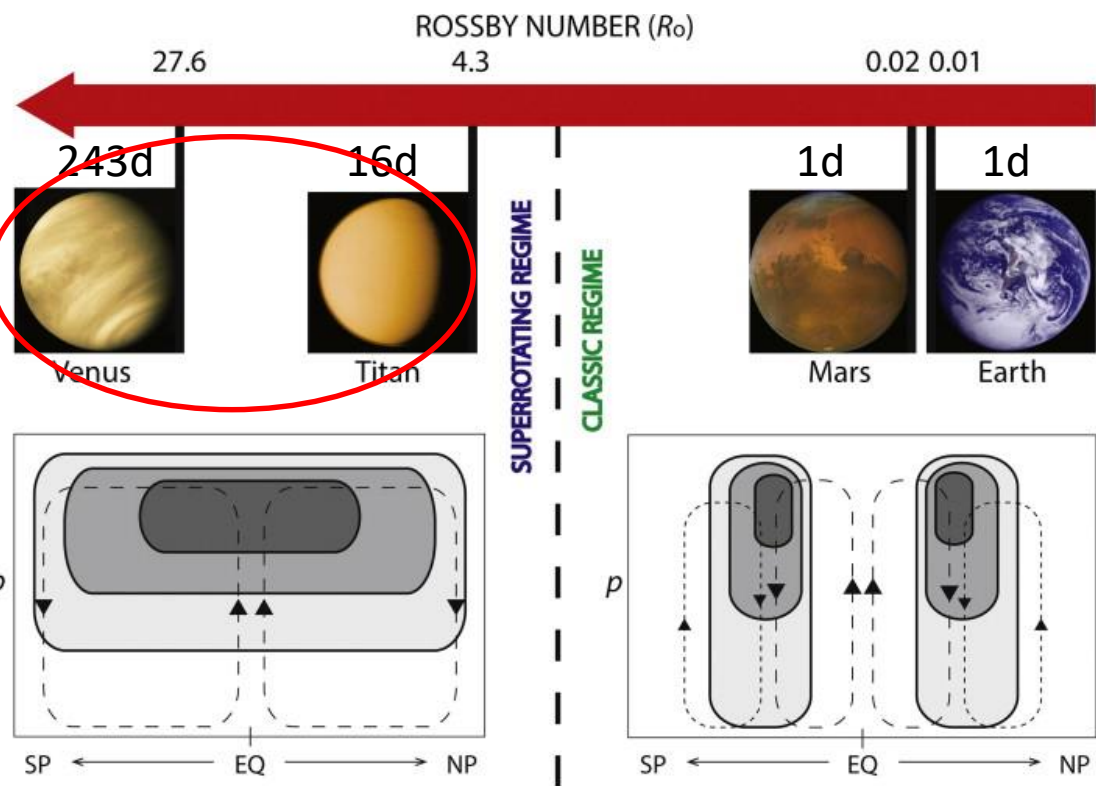
流体力学として惑星大気大循環構造(特に超回転)を理解したい



○対流圏内の放射強制で駆動するEarth-type大気大循環(Williams 1980以降多数)

Rotation : Slow
Size : Small

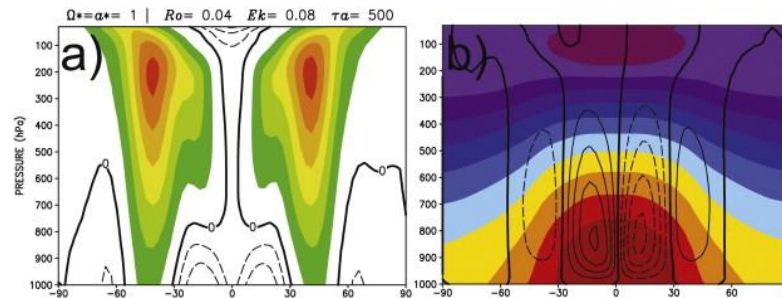
Rotation : Fast
Size : Large



(Dias Pinto & Mitchell, 2014) Photo : NASA/JPL

Gray shade : SR zonal flow (the darker shade presents the faster zonal flow)

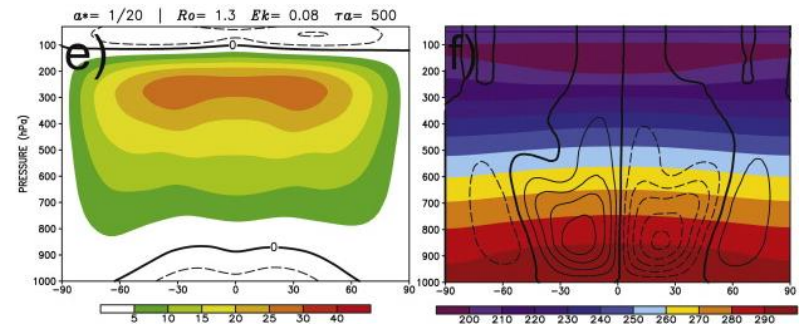
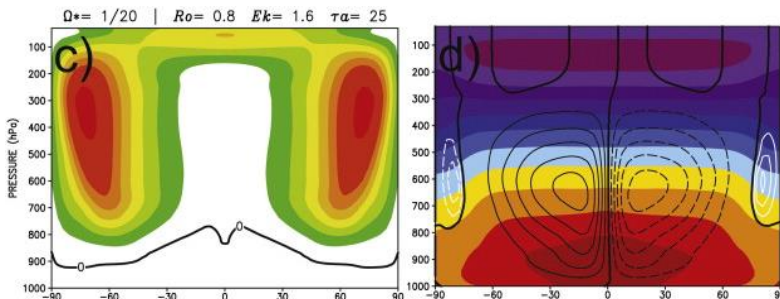
Held & Suarez (1994)の計算設定で、 Ro を変える実験



地球条件

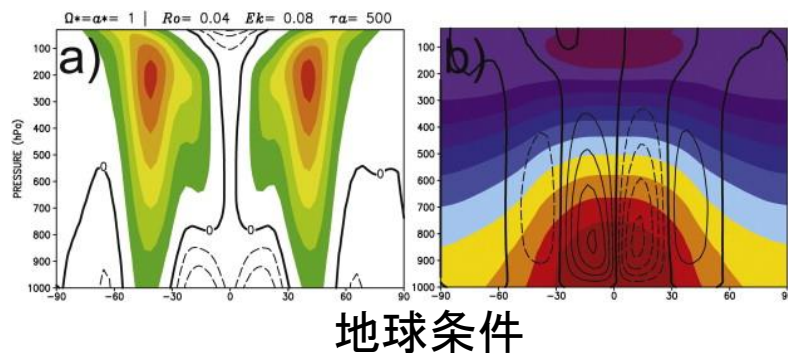
自転速度だけ
を20分の1

惑星半径だけ
を20分の1



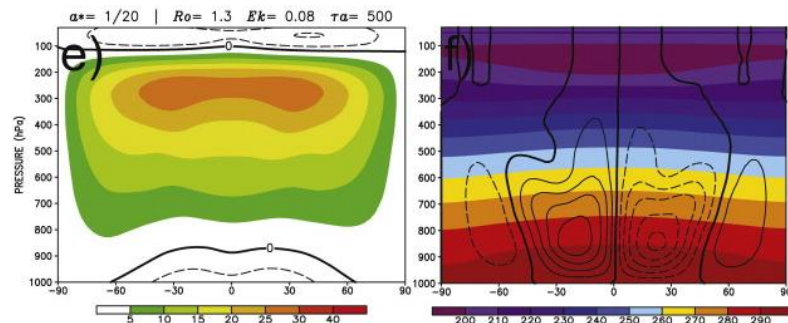
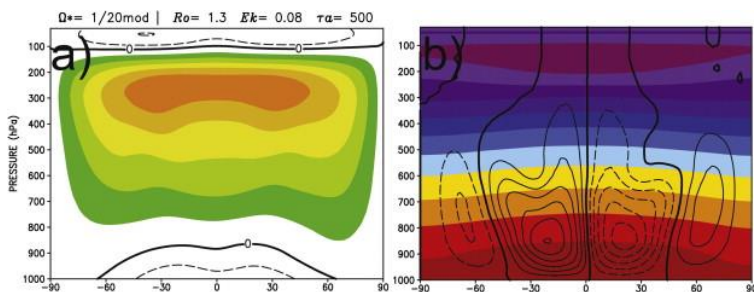
同じ比率で、惑星自転速度と惑星半径を変えて Ro を変えると、
無次元摩擦抵抗 Ek および無次元熱緩和時定数 τ_a が違うので相似にならない。

Held & Suarez (1994)の計算設定で、 Ro を変える実験



無次元摩擦抵抗 Ek
および無次元熱緩和
時定数 $\tau\alpha$ を変えず
に、自転速度
を20分の1

惑星半径だけ
を20分の1

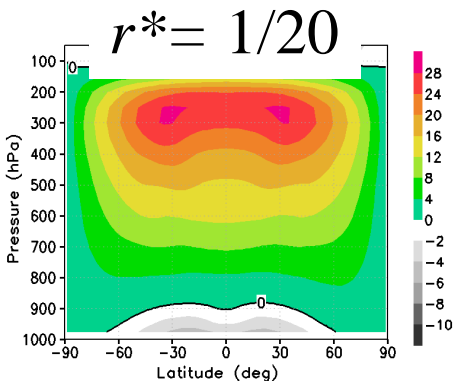
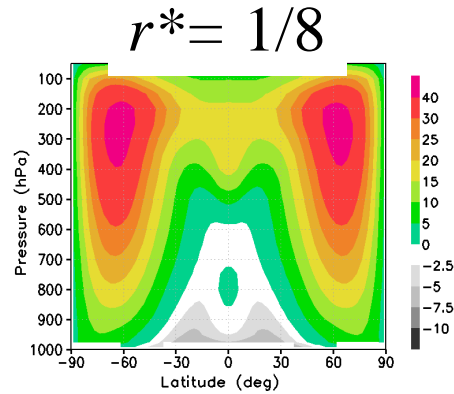
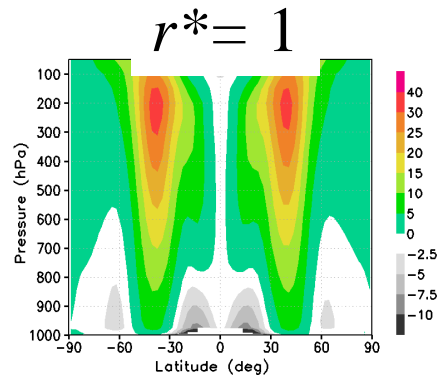
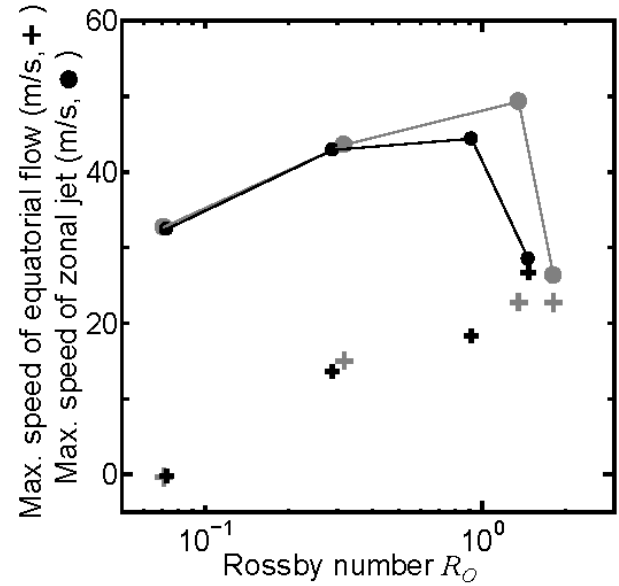


Ro だけを変える実験をするためには、無次元摩擦抵抗 Ek および無次元熱緩和時定数 $\tau\alpha$ を変えずに、同じ比率で、惑星自転や惑星半径を変えればよい。

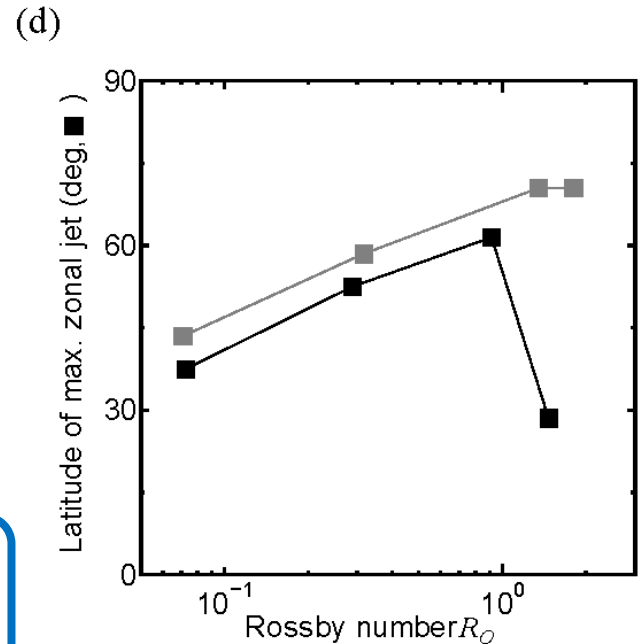
○ Ro が大きくなると赤道風が強まる

○ $Ro < 1$ では、 Ro が大きくなると、西風ジェットは強まり、より高緯度に位置する

○ $Ro > 1$ で、西風ジェットは弱くなる



灰色 : Smagorinsky 無
 黒色 : Smagorinsky 有



雲で覆われた惑星の大気大循環構造

<Venus-type>

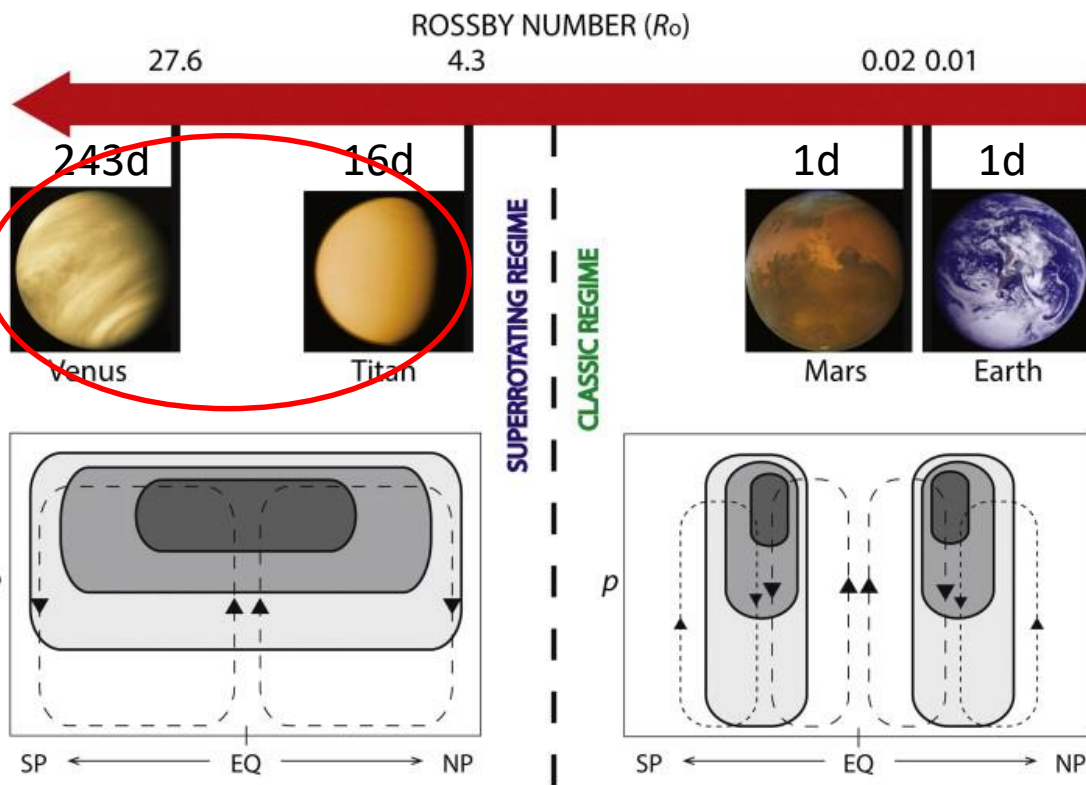
<Earth-type>

<研究動機>

Rotation : Slow
Size : Small

Rotation : Fast
Size : Large

流体力学として惑星大気大循環(特に超回転)を理解したい



○対流圏内の放射強制で駆動するEarth-type大気大循環 (Williams 1980 以降多数)

○高ロスビー数で中層大気の放射強制で駆動する、Venus-type大気大循環 (Yamamoto & Takahashi 2016, 本研究)

(Dias Pinto & Mitchell, 2014) Photo : NASA/JPL

Gray shade : SR zonal flow (the darker shade presents the faster zonal flow)

<Venus-type>

Yamamoto & Takahashi (2016 JGR)

T106 GCM

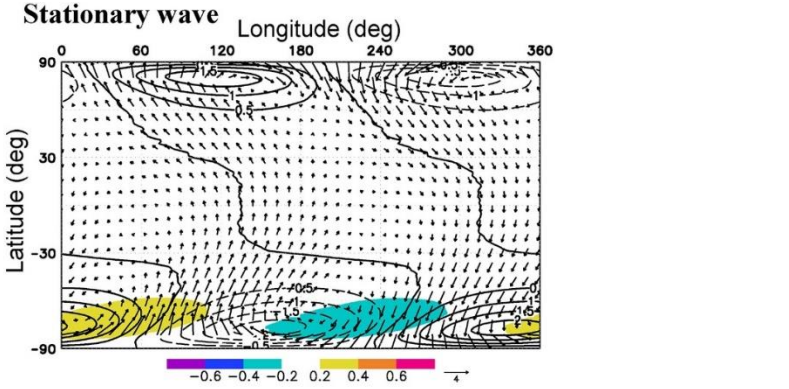
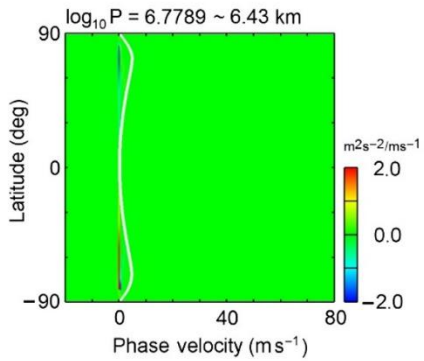
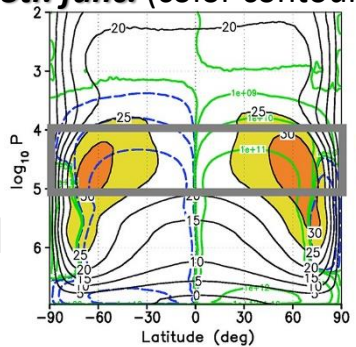
Zonal flow (black contour)
Str. func. (color contours)

$u'v'$ (shade)

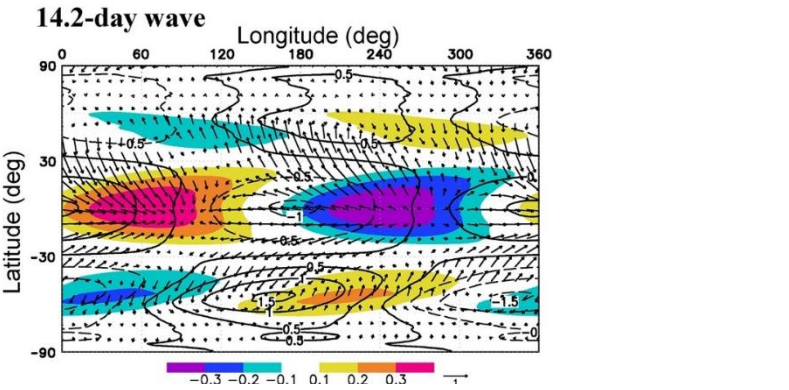
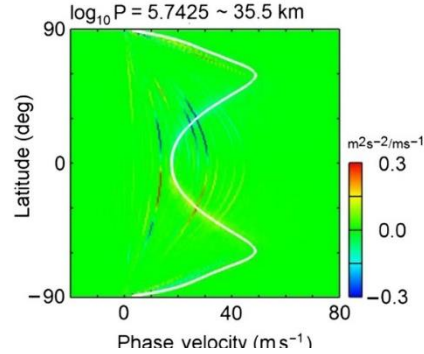
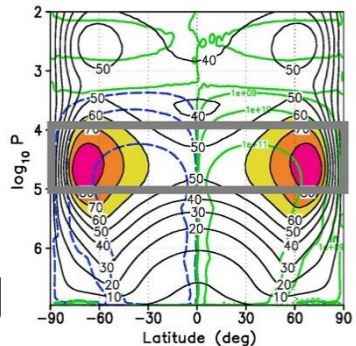
Z' (contour), u' & v' (vector), T' (shade)

ISSI Venus
GCM inter-
comparison
(2013)

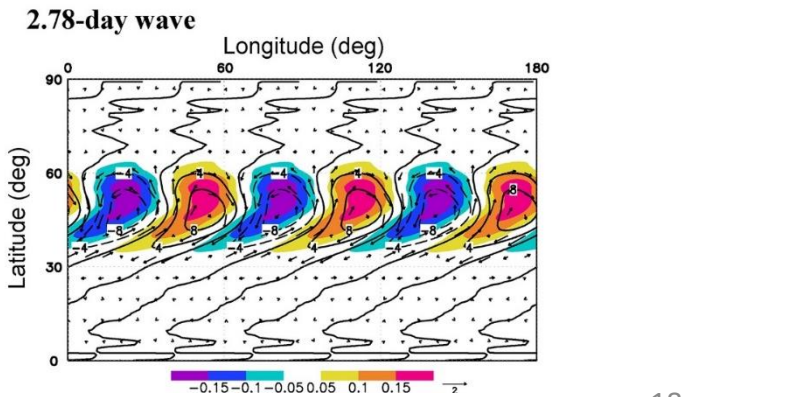
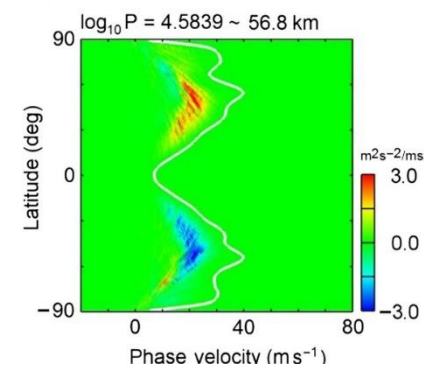
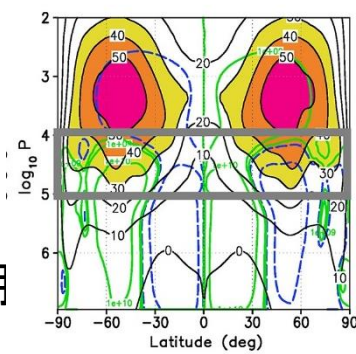
243日
周期



16日
周期



1日
周期



※自転のみ変えた実験で、Roだけでなく、EkやNTも変わる。

雲で覆われた惑星の大気大循環構造

(Tsunoda et al. 2021 JGR)

<Venus-type>

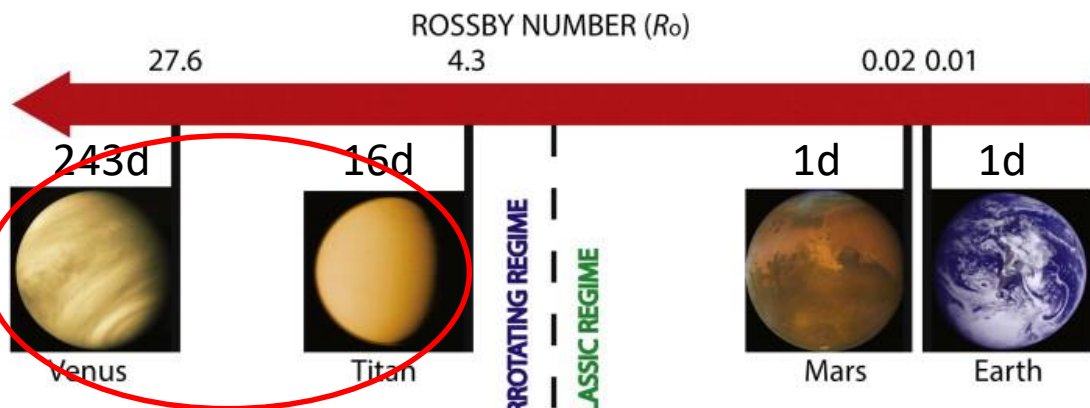
<Earth-type>

研究目的

金星型大気の超回転のRo依存性を明らかにする

Rotation : Slow
Size : Small

Rotation : Fast
Size : Large



$$R_o \equiv \frac{U}{2\Omega L} \quad (\text{ロスビー数})$$

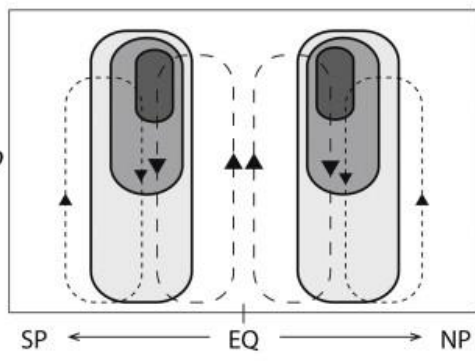
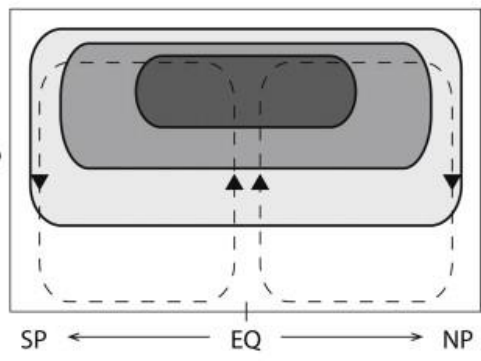
$$E_K \equiv \frac{1}{2\Omega\tau_f} \quad (\text{エクマン数})$$

$$N_T \equiv 2\Omega\tau_r \quad (\text{熱緩和無次元数})$$

L : 水平スケール(惑星半径 r)

τ_f : 摩擦の時定数

τ_r : 放射緩和の時定数



(Dias Pinto & Mitchell, 2014)

Photo : NASA/JPL

ISSI Venus GCM inter-comparison (2013)と同じ条件で、自転および惑星サイズを変えて、 E_K と N_T を不変になるように実験

⇒超回転の R_o 依存性のみを調査

Model

Idealized model setup of ISSI Venus GCM inter-comparison project (2013)

- **Venus-type radiative forcing:**

Equator-pole temperature contrast (color shade) is relaxed by Newtonian cooling.

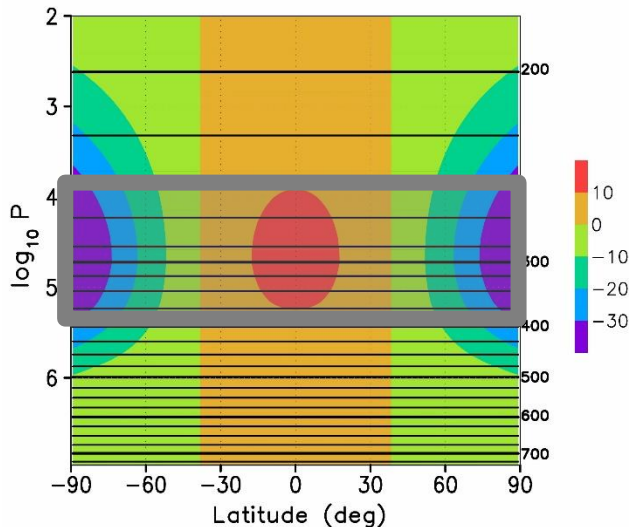
- **Primitive equation system using T42 GCM**

- **Experimental condition**

Exp.	r^* (-)	Ω^* (-)	τ_R (Eday)	τ_N (Eday)	E_K (-)	N_T (-)
V	1	1	2.96	24.6	6.45	1.29
3r	3	1	2.96	24.6	6.45	1.29
3 Ω	1	3	0.987	8.21	6.45	1.29
8r	8	1	2.96	24.6	6.45	1.29
8 Ω	1	8	0.37	3.08	6.45	1.29
15r	15	1	2.96	24.6	6.45	1.29
15 Ω	1	15	0.197	1.64	6.45	1.29

Ω^* : Non-dim. planetary angular velocity normalized by Venus one ($2\pi/240d$)

r^* : Non-dim. planetary radius normalized by Venus one (6050 km)



Model

- Venus-type radiative forcing

- Primitive equation system

- > Global three-dimensional flow under hydrostatic approximation

- > Rossby number is altered with thermal and frictional non-dimensional numbers fixed (i.e., E_K and N_T are unchanged)



Rossby number is a only parameter which determines the dynamical similarity of SR and its related waves

<Dimensional primitive equations>

$$\begin{aligned}\partial \mathbf{u} / \partial t + (\mathbf{V} \cdot \nabla) \mathbf{u} + \mathbf{f} \times \mathbf{u} &= -\nabla \Phi - \mathbf{u} / \tau_R, \\ \partial \theta / \partial t + (\mathbf{V} \cdot \nabla) \theta &= -(\theta - \theta_{eq}) / \tau_N,\end{aligned}$$

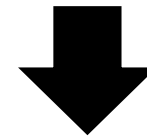
where $\mathbf{u} = u\mathbf{i} + v\mathbf{j}$ and $\mathbf{V} = u\mathbf{i} + v\mathbf{j} + \omega\mathbf{k}$

u : zonal wind velocity, v : meridional wind velocity,

ω : vertical pressure velocity in the pressure coordinate,

Φ : the geopotential, $\mathbf{f} = 2\Omega\sin\phi$, θ : potential temperature,

θ_{eq} : equilibrium potential temperature



<Non-dimensional primitive equations>

$$\begin{aligned}\partial \hat{\mathbf{u}} / \partial t + Ro(\hat{\mathbf{V}} \cdot \nabla) \hat{\mathbf{u}} + \hat{\mathbf{f}} \times \hat{\mathbf{u}} &= -\nabla \hat{\Phi} - E_K \hat{\mathbf{u}}, \\ \partial \hat{\theta} / \partial t + Ro(\hat{\mathbf{V}} \cdot \nabla) \hat{\theta} &= -(\hat{\theta} - \hat{\theta}_{eq}) / N_T,\end{aligned}$$

$$Ro = U / (2\Omega L),$$

$$E_K = 1 / (2\Omega\tau_R),$$

$$N_T = 2\Omega\tau_N.$$

(Dias Pinto & Mitchell, 2014)

Model

<Non-dimensional equations>

$$\partial \hat{\mathbf{u}} / \partial t + Ro(\hat{\mathbf{V}} \cdot \nabla) \hat{\mathbf{u}} + \hat{\mathbf{f}} \times \hat{\mathbf{u}} = -\nabla \hat{\Phi} - E_K \hat{\mathbf{u}},$$

$$\partial \hat{\theta} / \partial t + Ro(\hat{\mathbf{V}} \cdot \nabla) \hat{\theta} = -(\hat{\theta} - \hat{\theta}_{eq}) / N_T,$$

$$Ro = U / (2\Omega L),$$

$$E_K = 1 / (2\Omega \tau_R),$$

$$N_T = 2\Omega \tau_N.$$

Exp.	r^* (-)	Ω^* (-)	τ_R (Eday)	τ_N (Eday)	E_K (-)	N_T (-)	Ro^{JET} (-)
V	1	1	2.96	24.6	6.45	1.29	23.2
3r	3	1	2.96	24.6	6.45	1.29	19.8
3 Ω	1	3	0.987	8.21	6.45	1.29	19.0
8r	8	1	2.96	24.6	6.45	1.29	12.2
8 Ω	1	8	0.37	3.08	6.45	1.29	12.8
15r	15	1	2.96	24.6	6.45	1.29	7.8
15 Ω	1	15	0.197	1.64	6.45	1.29	7.4

E_K & N_T
unchanged



High $Ro (>1)$ is realized

• Venus-type radiative forcing

• Primitive equation system

• Experiments for high Ro

> Venus condition ($\Omega^*=1, r^*=1$)

> Size dependence with $\Omega^*=1$

($r^*=1, r^*=3, r^*=8, r^*=15$)

> Rotation dependence with $r^*=1$

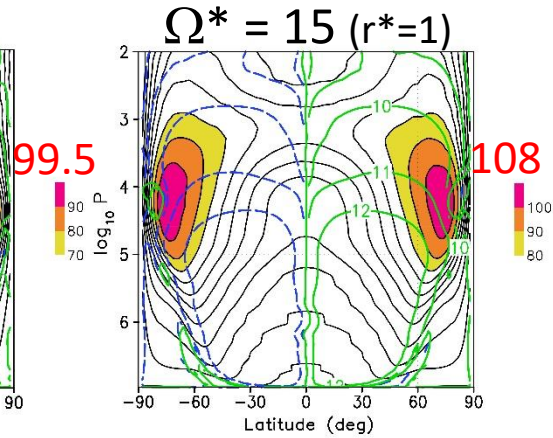
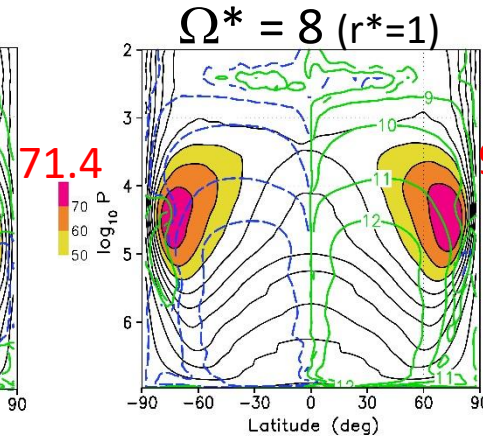
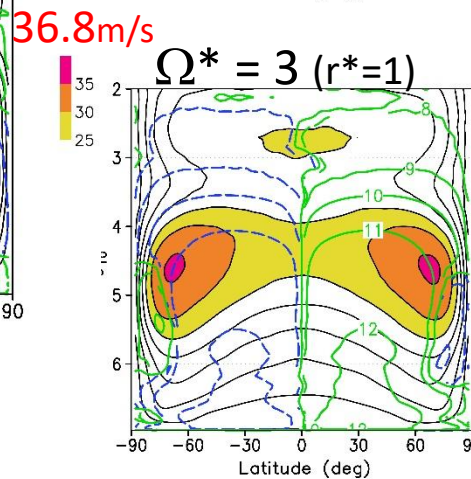
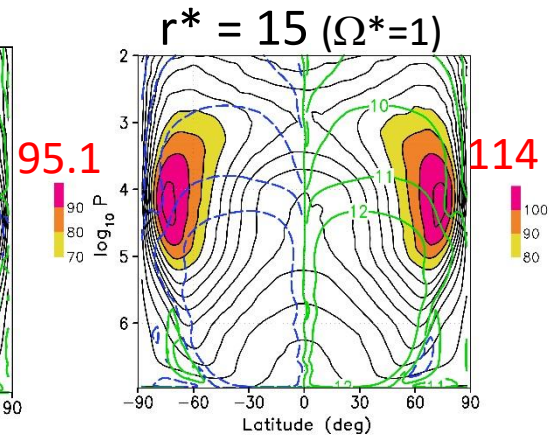
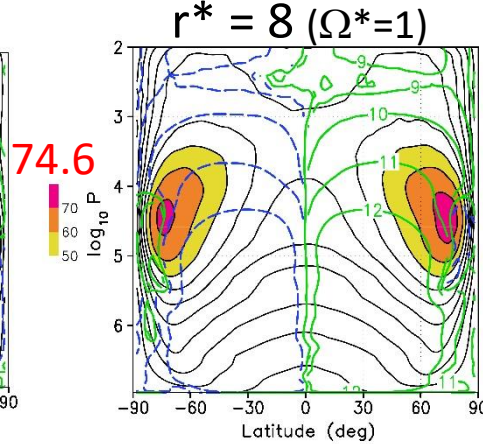
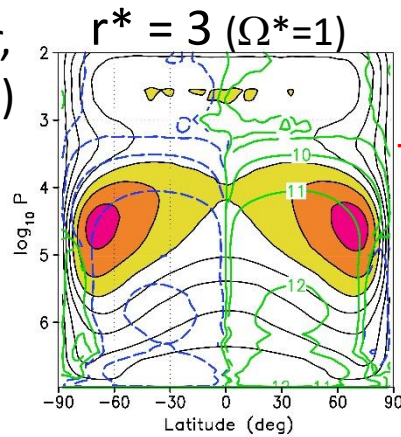
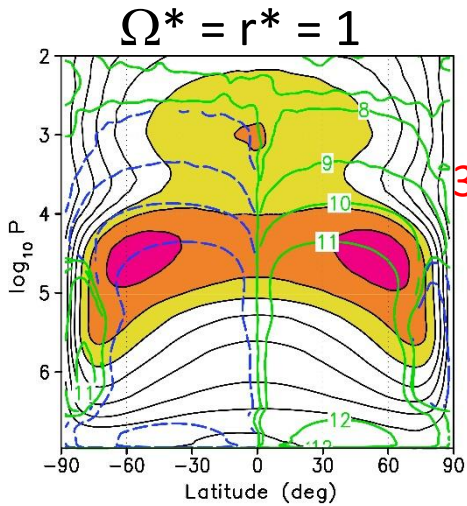
($\Omega^*=1, \Omega^*=3, \Omega^*=8, \Omega^*=15$)

Ω^* : Non-dim. planetary angular velocity
normalized by Venus one ($2\pi/240d$)

r^* : Non-dim. planetary radius
normalized by Venus one (6050 km)

Zonal-mean general circulations for Ro

Zonal flow (black contour, warm color shade for fast)
Clock & anticlock stream func. (color contour)
func. (color contour)



$Ro^{JET} \sim 15$

$Ro^{JET} \sim 12$

$Ro^{JET} \sim 8$

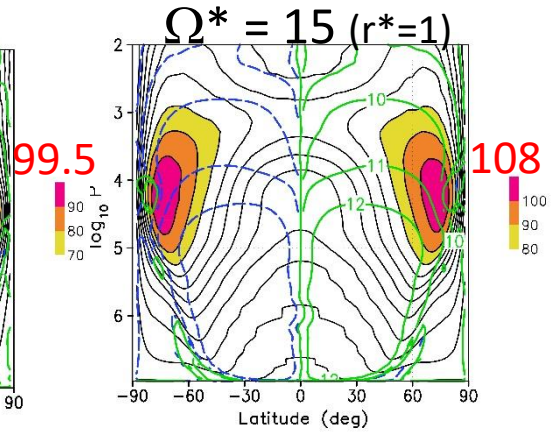
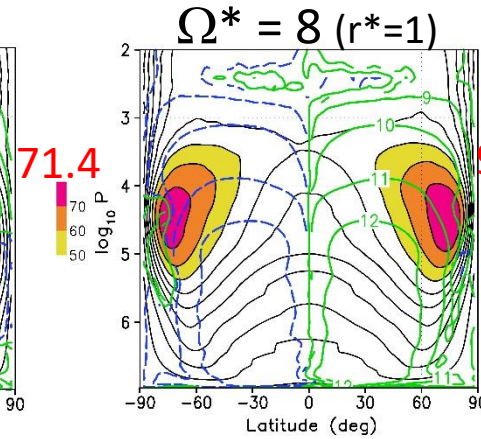
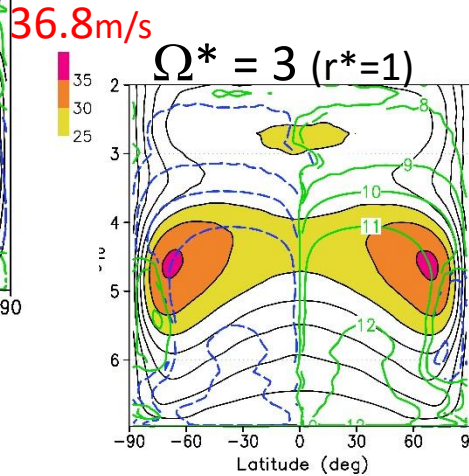
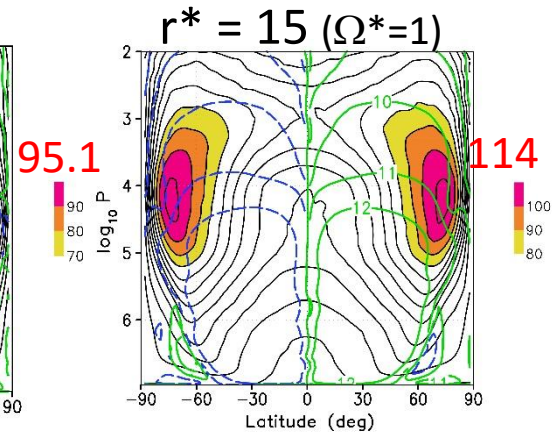
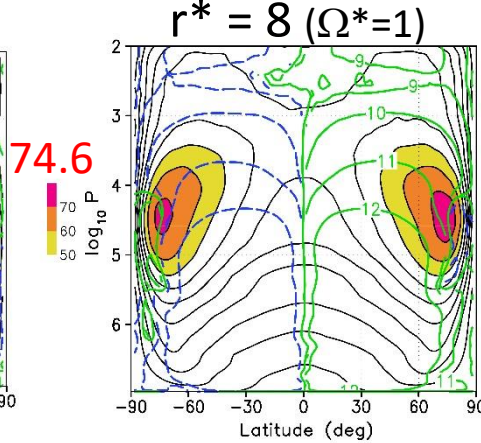
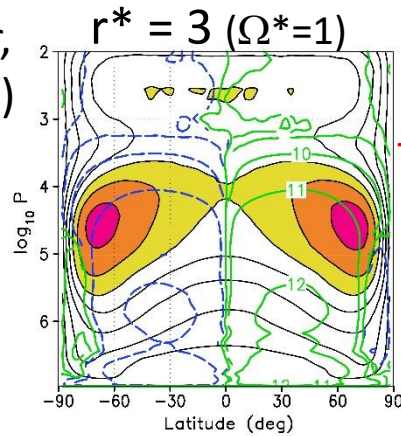
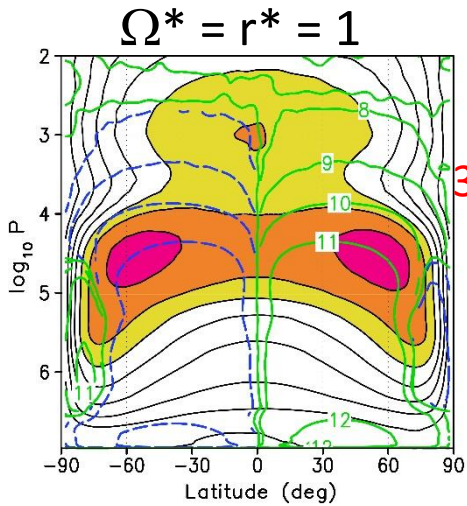
$Ro^{JET} \sim 23$



**Dynamical similarity for same Ro
 between different experiments**

Zonal-mean general circulations for Ro

Zonal flow (black contour, warm color shade for fast)
Clock & anticlock stream func. (color contour)
func. (color contour)



$Ro^{JET} \sim 15$

$Ro^{JET} \sim 12$

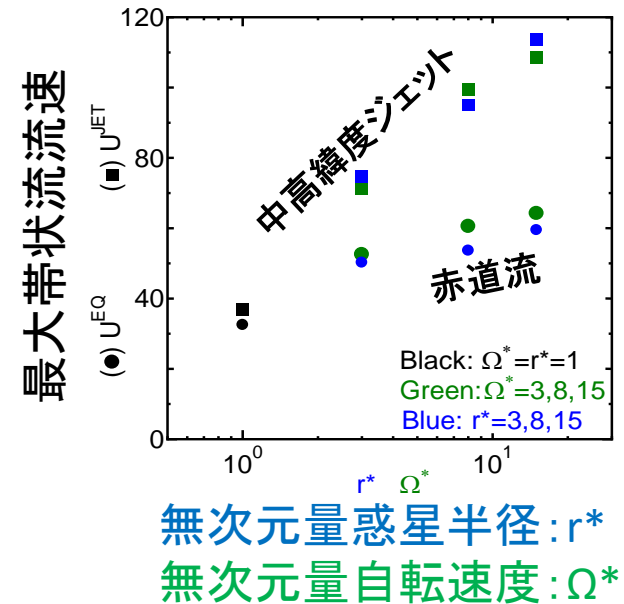
$Ro^{JET} \sim 8$

$Ro^{JET} \sim 23$



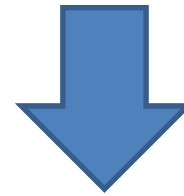
As r^* or Ω^* is increased, **max. zonal-flow speed** becomes greater.

Sensitivity of SR to Ro



惑星半径や自転速度に比例し、
中高緯度ジェットが増加する。

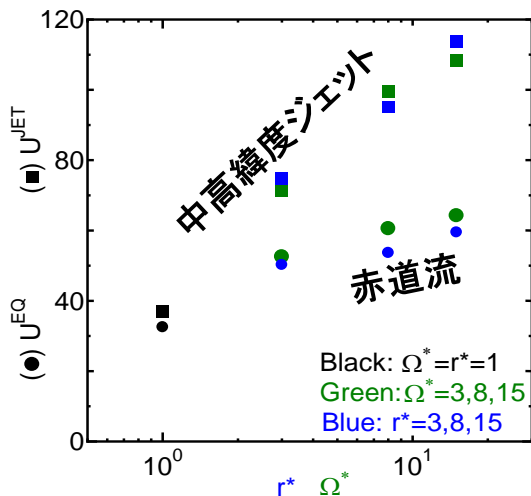
惑星半径や自転速度の増加に伴う
赤道流増加が鈍る。
($r^* = \Omega^* \sim 10$ で傾きが小さくなる)



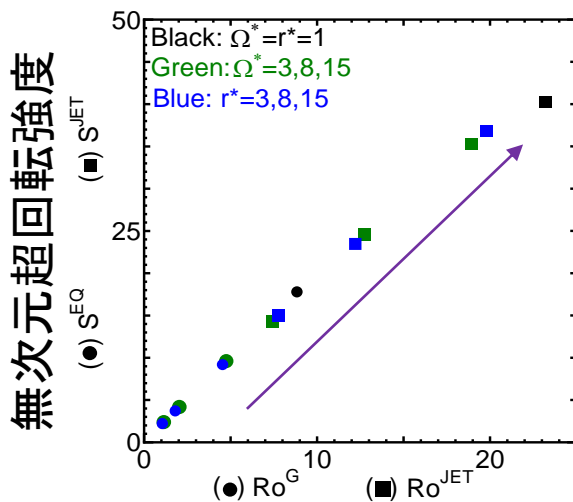
超回転をRoで整理

Sensitivity of SR to Ro

最大東西風速



無次元量惑星半径: r^*
無次元量自転速度: Ω^*



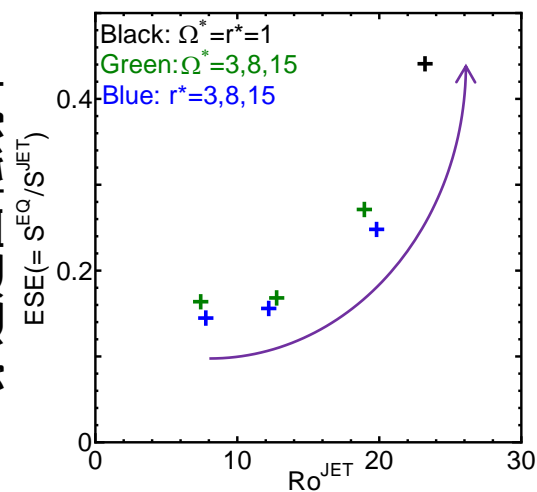
ロスビー数

$$S^{EQ} \equiv \frac{u^{EQ} / r}{\Omega} \quad S^{JET} \equiv \frac{u^{JET} / r \cos \varphi^{JET}}{\Omega}$$

$$Ro^G \equiv \frac{u^{EQ} / r}{2\Omega} \quad Ro^{JET} \equiv \frac{u^{JET} / (r \cos \varphi^{JET})}{2\Omega \sin \varphi^{JET}}$$

Roが大きくなるにつれて、
線形的に超回転が強まる
⇒赤道流も中高緯度ジェットも
一つの線にのる

赤道超回転効率



ロスビー数

$$ESE \equiv S^{EQ} / S^{JET}$$

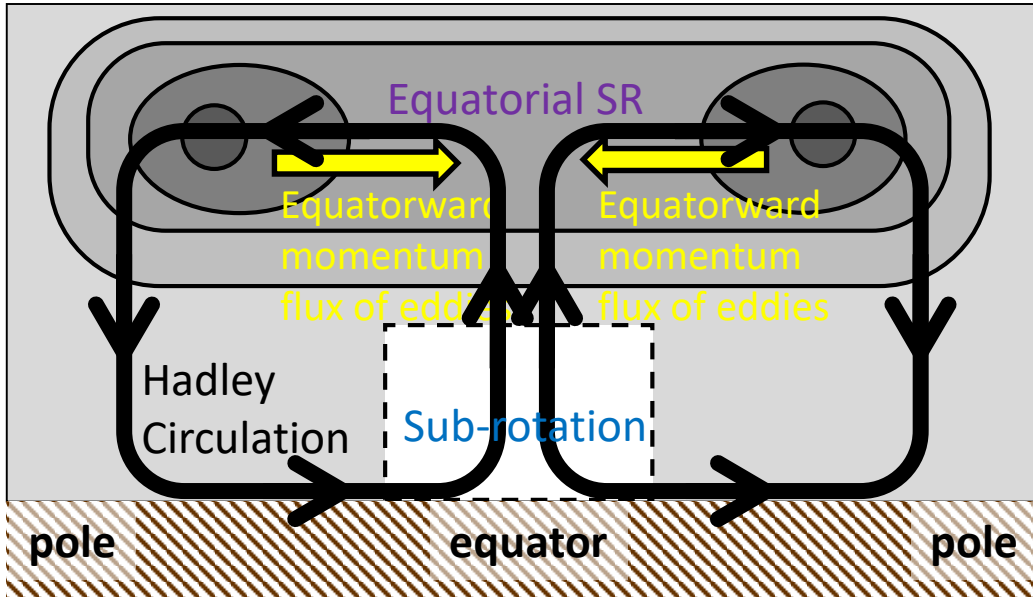
$ESE \rightarrow 1$ 剛体回転型
赤道超回転 大

$ESE \rightarrow 0$ 中高緯度ジェット型
赤道超回転 小

Roが大きいと、
効率よく赤道超回転
が発達する

SR dynamical process (Exp. V)

Gierasch–Rossow–Williams mechanism

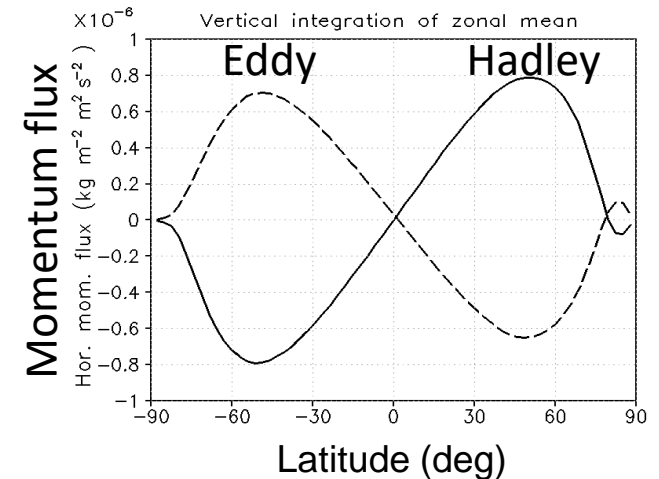
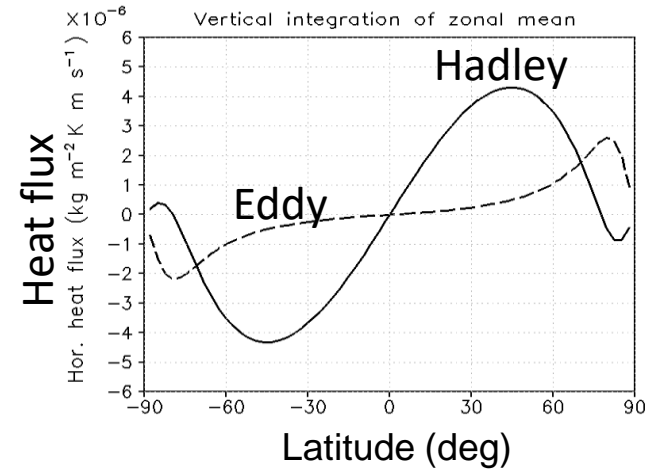


Hadley circulation globally transport both heat and momentum poleward.

Hadley circulation heat flux dominates over eddies, except for the polar region.

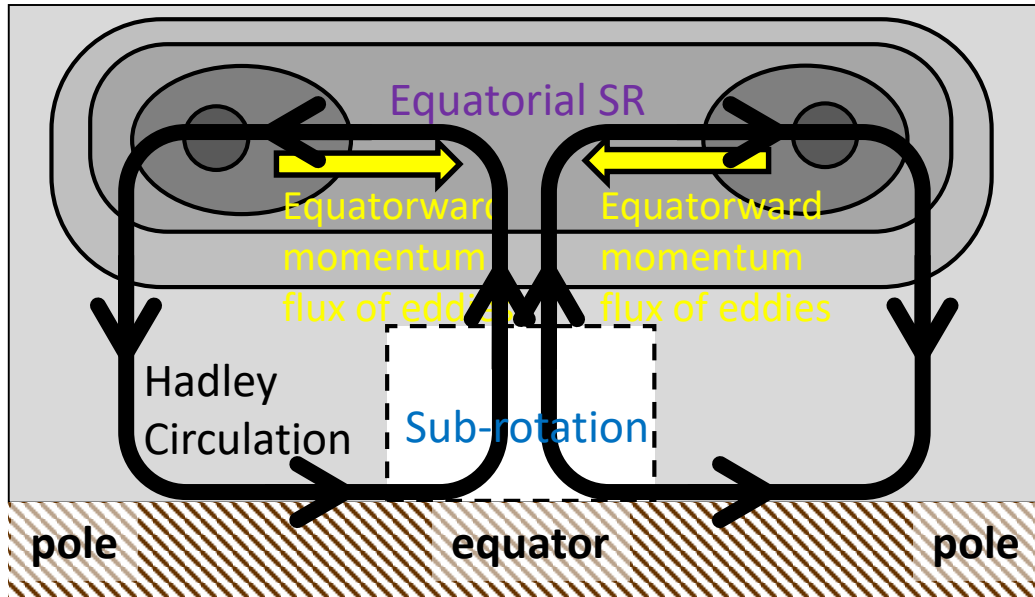
The poleward mom flux of Hadley circulation balances equatorward eddy momentum flux.

Vertical-integrated fluxes



SR dynamical process (Exp. V)

Gierasch–Rossow–Williams mechanism

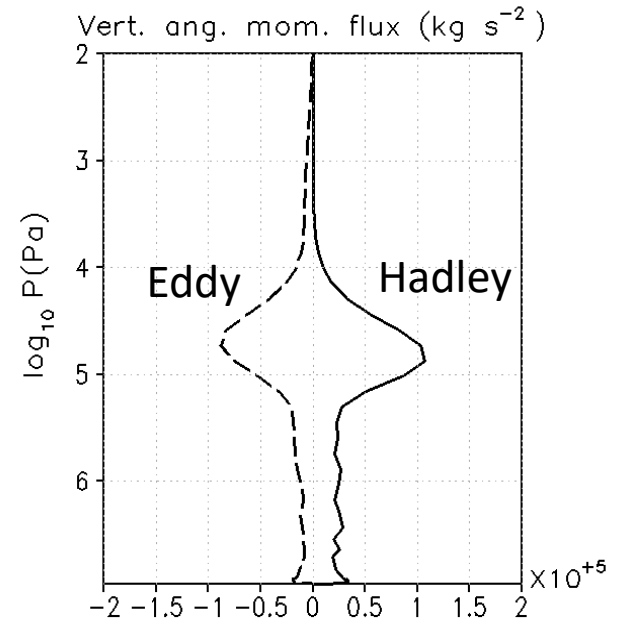


Hadley circulation globally transport both heat and momentum poleward.

Hadley circulation heat flux dominates over eddies, except for the polar region.

The poleward mom flux of Hadley circulation balances equatorward eddy momentum flux.

Global-mean Vertical AM fluxes



The upward AM flux of Hadley circulation balances the downward eddy flux.

Eddy mom flux process (Exp. V)

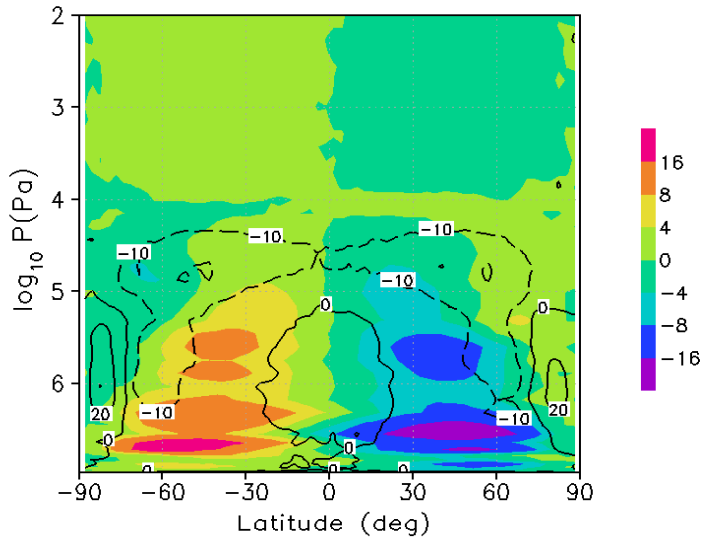


Figure 6. (a–e) Latitude–pressure distributions of zonal mean horizontal (shading) and vertical (contours) eddy angular momentum fluxes divided by the planetary radius ($\text{kg m}^{-1} \text{s}^{-2}$).

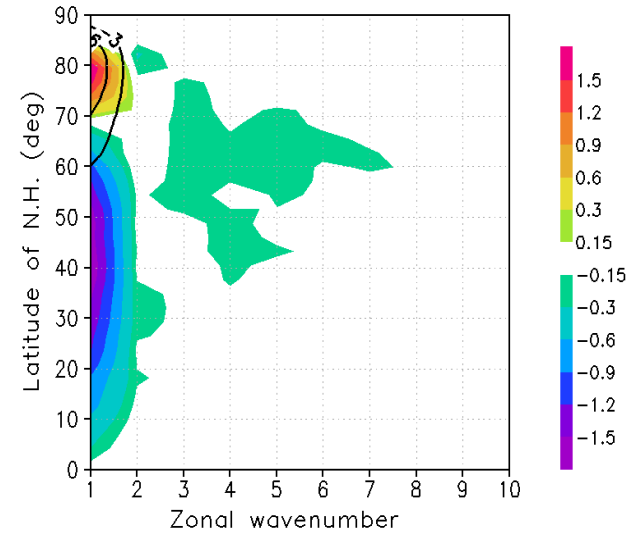


Figure 7. Zonal wavenumber–latitude distributions of zonal-mean eddy horizontal momentum flux ($\text{m}^2 \text{s}^{-2}$, shading) and heat flux (K m s^{-1} , contours) at 3.96×10^5 Pa.

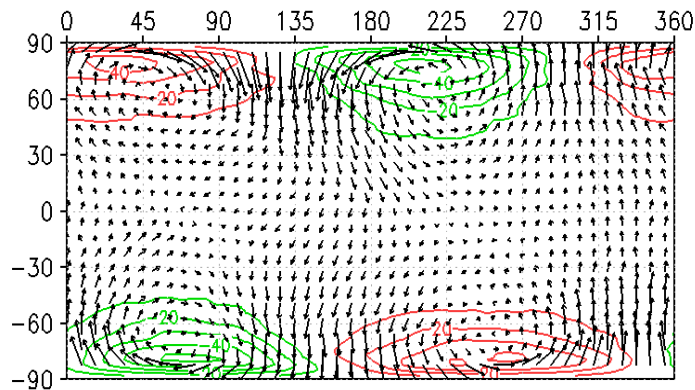


Figure B2. Longitude–latitude distributions of eddy geopotential height (m, contours) and horizontal wind velocity (m s^{-1} , vectors) at 3.96×10^5 Pa.

Zonal-mean eddy AM fluxes for Ro

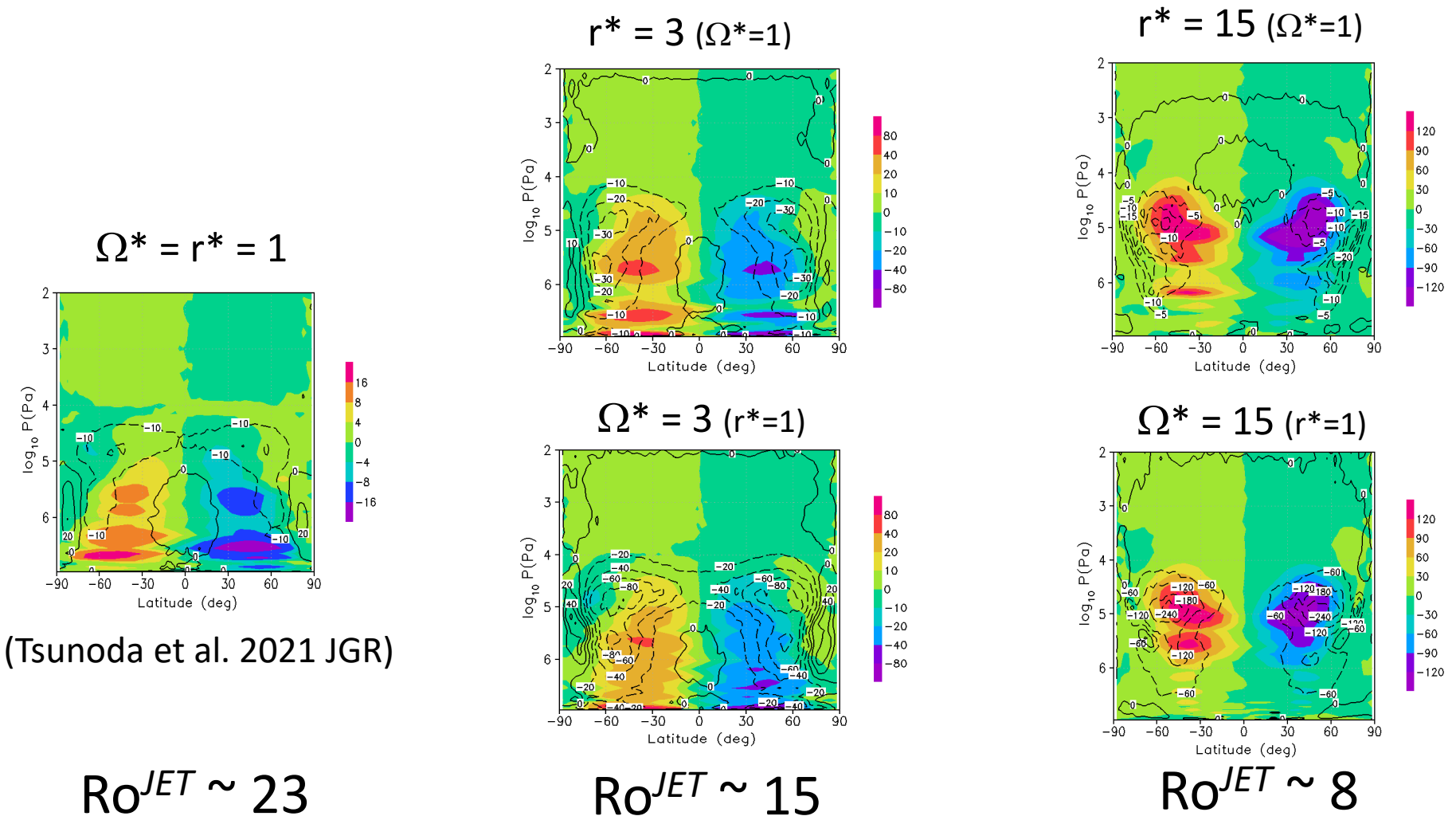


Figure 6. (a–e) Latitude–pressure distributions of zonal mean horizontal (shading) and vertical (contours) eddy angular momentum fluxes divided by the planetary radius ($\text{kg m}^{-1} \text{s}^{-2}$).

Vertically-integrated horiz mom fluxes for Ro

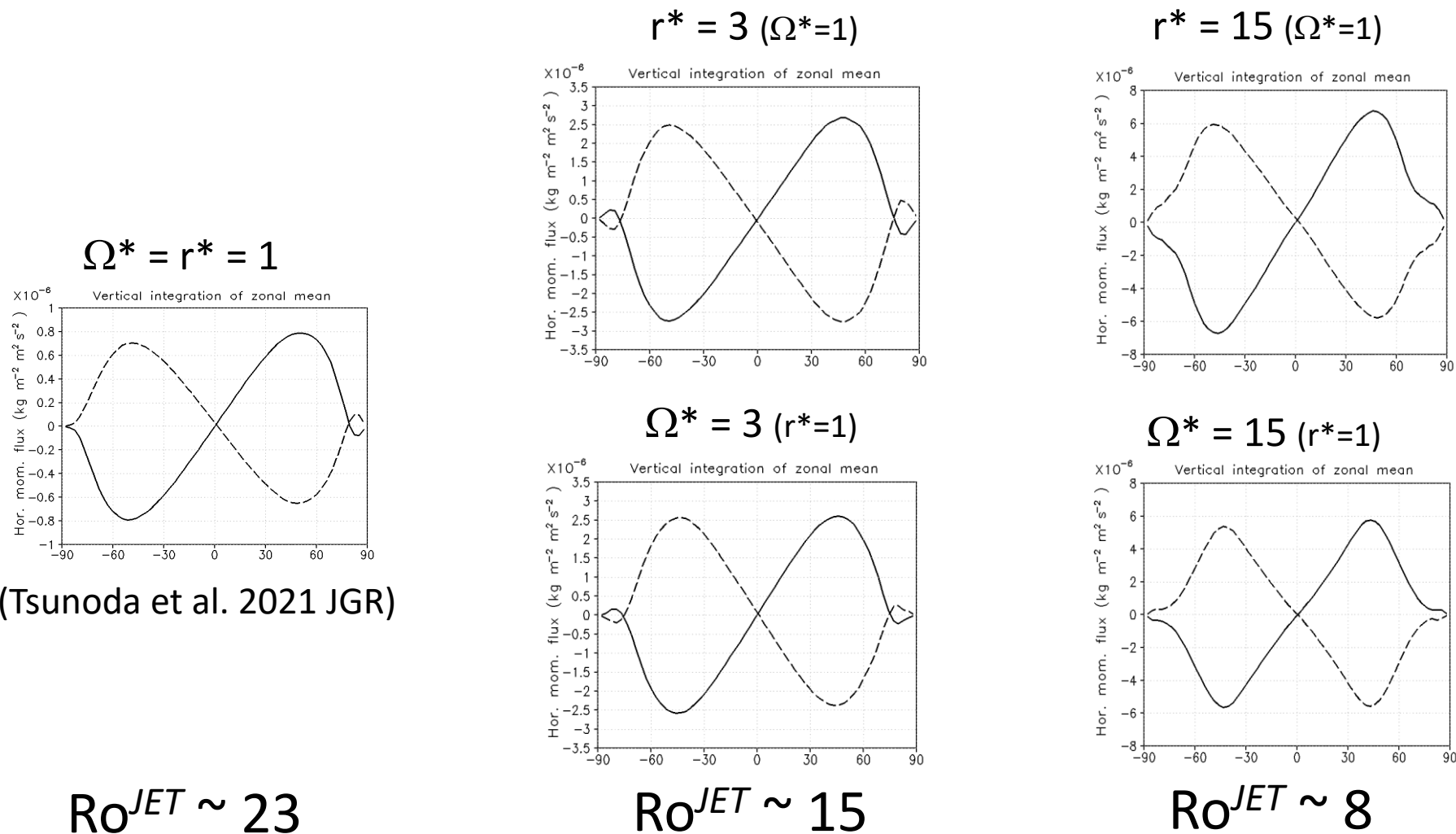
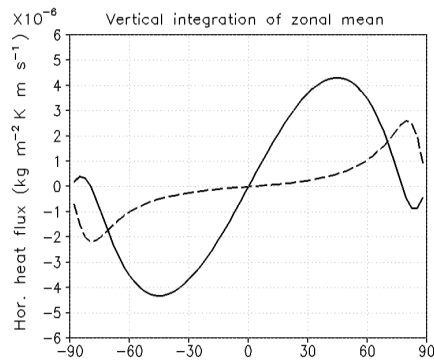


Figure 4. (f–j) Meridional distributions of vertically integrated horizontal momentum fluxes of zonal mean circulation (HMF_{ZMC} , solid curve) and eddies (HMF_{EDY} , dashed curve)

Vertically-integrated horiz heat fluxes for Ro

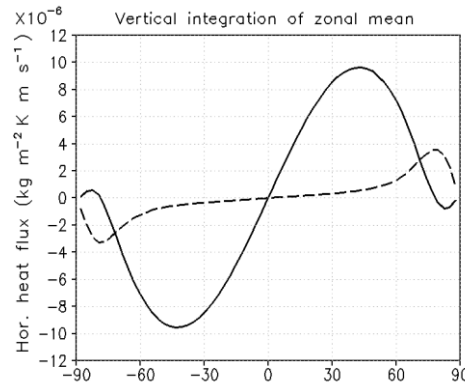
$$\Omega^* = r^* = 1$$



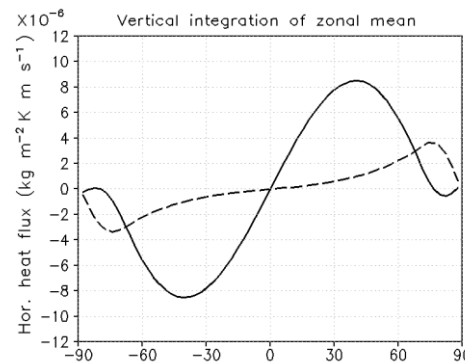
(Tsunoda et al. 2021 JGR)

$$Ro^{JET} \sim 23$$

$$r^* = 3 (\Omega^*=1)$$

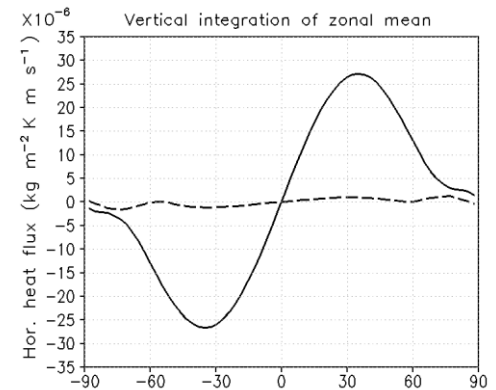


$$\Omega^* = 3 (r^*=1)$$

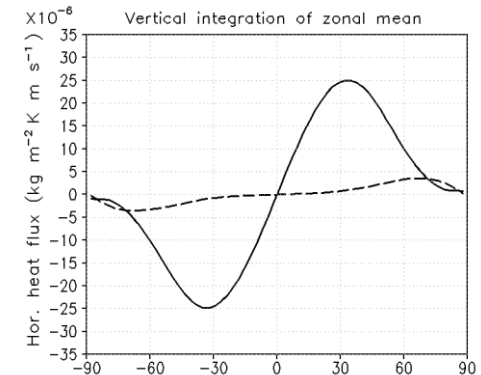


$$Ro^{JET} \sim 15$$

$$r^* = 15 (\Omega^*=1)$$



$$\Omega^* = 15 (r^*=1)$$



$$Ro^{JET} \sim 8$$

Figure 4. (a–e) Meridional distributions of vertically integrated horizontal heat fluxes of zonal mean circulation (HHF_{ZMC} , solid curve) and eddies (HHF_{EDY} , dashed curve)

Global-mean vert mom fluxes for Ro

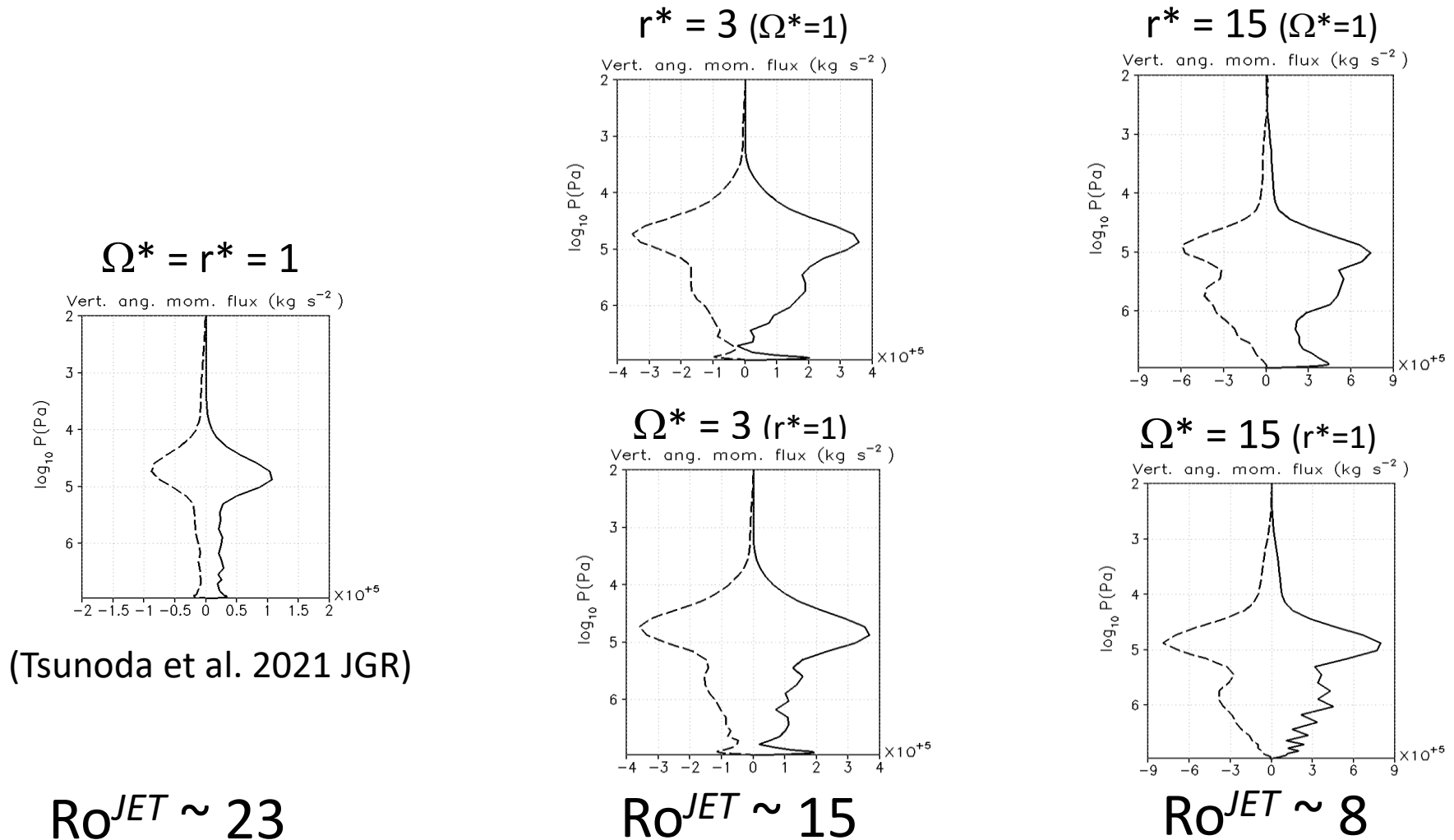
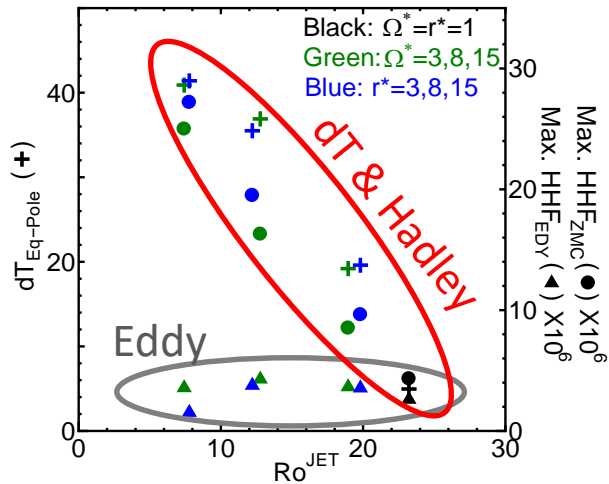


Figure 4. (k–o) vertical distributions of global-mean vertical angular momentum fluxes of zonal mean circulation (VMF_{ZMC} , solid curve) and eddies (VMF_{EDY} , dashed curve).

Sensitivity of SR dynamical process to Ro

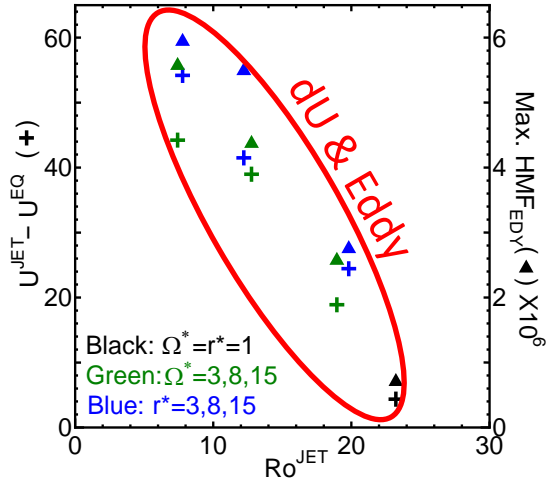
Horiz. heat transport



南北温度差と帯状平均子午面循環熱輸送はRoの増加とともに、減少する。

帯状平均渦熱輸送はRoにあまり依存しない

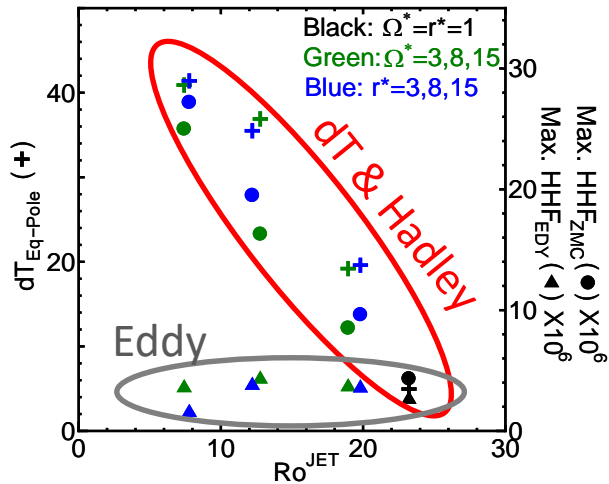
Horiz. mom. transport



南北の風速差と帯状平均渦運動量輸送は、Roの増加とともに、減少する。

Sensitivity of SR dynamical process to Ro

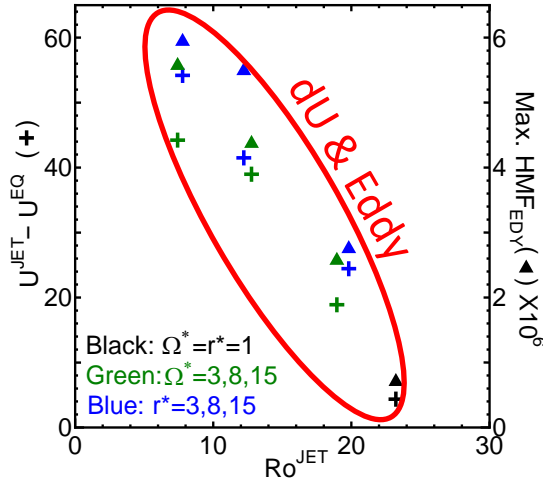
Horiz. heat transport



南北温度差と帯状平均子午面循環熱輸送はRoの増加とともに、減少する。

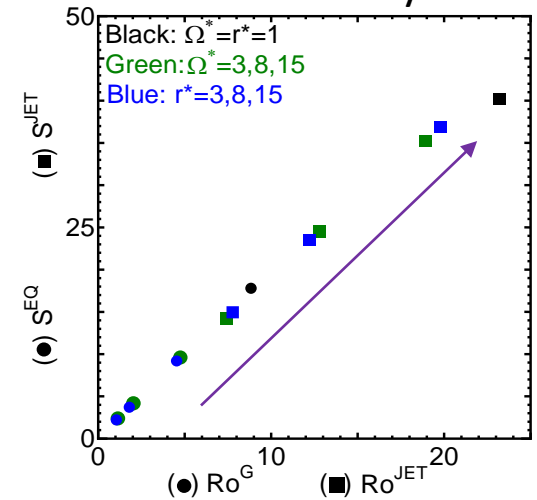
帯状平均渦熱輸送はRoにあまり依存しない

Horiz. mom. transport



南北の風速差と帯状平均渦運動量輸送は、Roの増加とともに、減少する。

SR intensity



Roが増加に伴い、渦角運動量輸送と子午面循環熱輸送は弱いが、超回転強度は強まる。



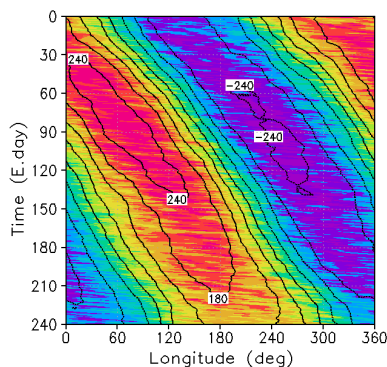
高Roでは、弱い輸送で効率よく超回転が発達する。

Sensitivity of wave and its mechanism to Ro

Time-longitude cross-sections of eddy geo-potent height (m, color shade)

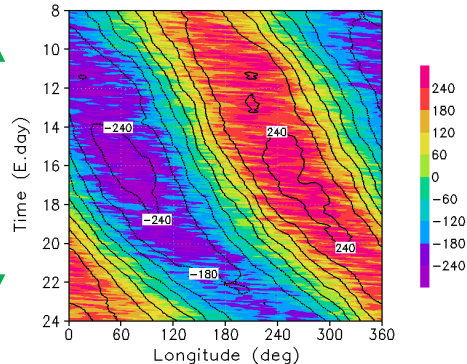
$Ro \sim 8$

$r^* = 15$ ($\Omega^* = 1$)



$Ro \sim 8$

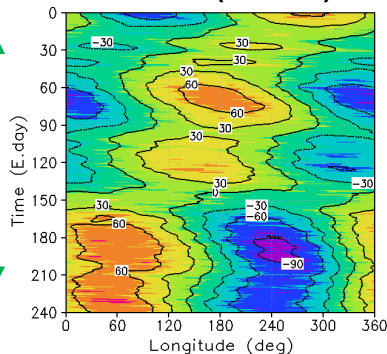
$\Omega^* = 15$ ($r^* = 1$)



Continuous,
Long wave period
for low Ro

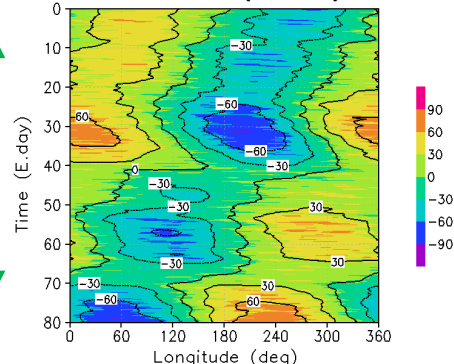
$Ro \sim 15$

$r^* = 3$ ($\Omega^* = 1$)



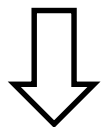
$Ro \sim 15$

$\Omega^* = 3$ ($r^* = 1$)



Intermittent,
Short wave period
for high Ro

Time-scale
is normalized
by planet. rot.
period.



Planet. Rot. period

Planet. Rot. period

Wave structures
are also similar
for the same Ro.

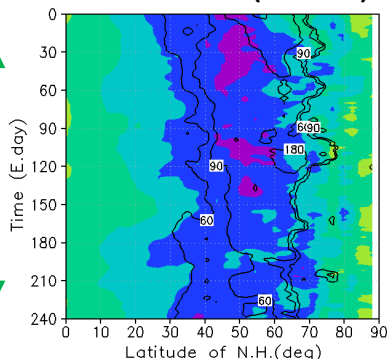
They are quite
different between
high and low Ro.

Sensitivity of wave and its mechanism to Ro

Time-latitude cross-sections of horiz eddy mom (shade) and heat (contour) fluxes

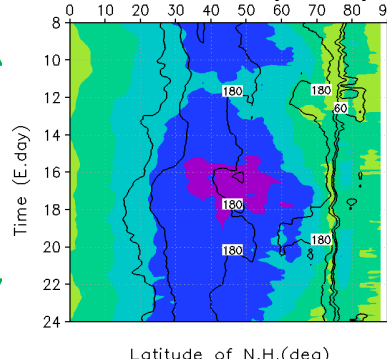
$Ro \sim 8$

$r^* = 15 (\Omega^*=1)$



$Ro \sim 8$

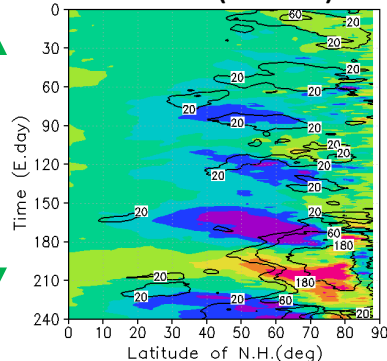
$\Omega^* = 15 (r^*=1)$



Continuous,
equatorward (blue)
momentum flux
for low Ro

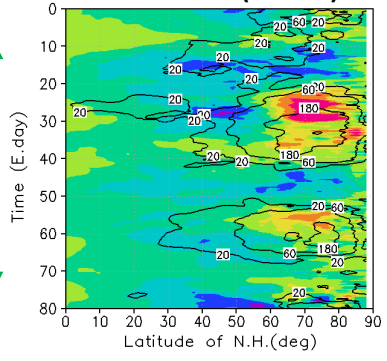
$Ro \sim 15$

$r^* = 3 (\Omega^*=1)$



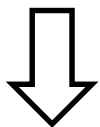
$Ro \sim 15$

$\Omega^* = 3 (r^*=1)$



Intermittent,
equatorward (blue)
momentum flux
for high Ro

Time-scale
is normalized
by planet. rot.
period.



Planet. Rot. period



Wave structures
are also similar
for the same Ro.

They are quit
different between
between high and
low Ro.

Planet. Rot. period



Sensitivity of wave and its mechanism to Ro

We introduce energy conversions from zonal-mean to eddy energies.

- Barotropic kinetic energy conversion

$$CK(s) = -\frac{1}{r} \int_V (\partial \bar{u} / \partial \varphi + \bar{u} \tan \varphi) \overline{u'(s)v'(s)} dV$$

The horizontal zonal-wind shear induces eddies when $CK > 0$ (e.g., Barotropic instability or Spherical horizontal shear instability).

- Barotropic potential-energy conversion

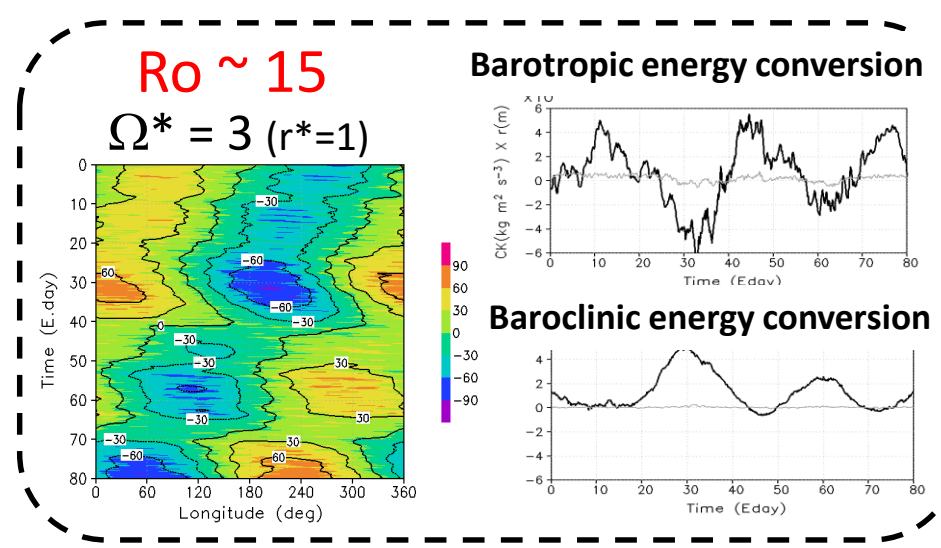
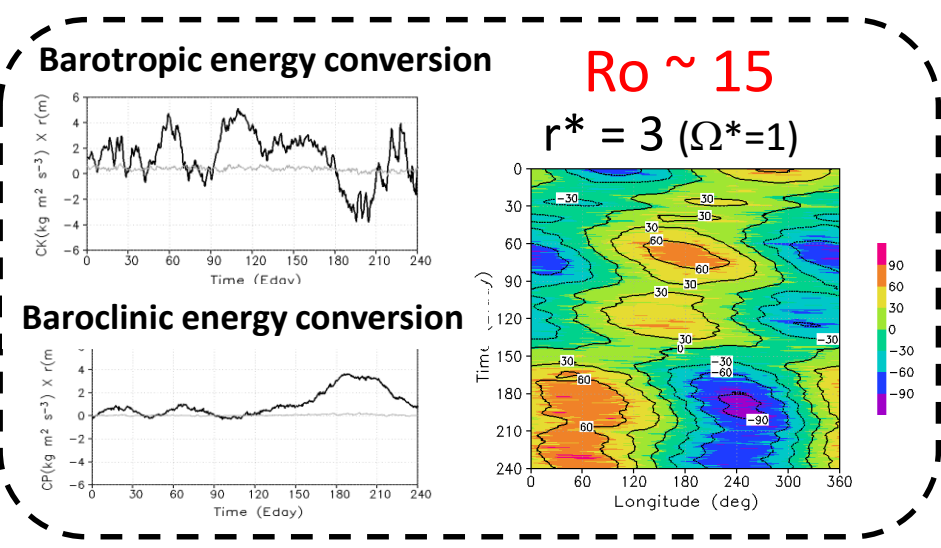
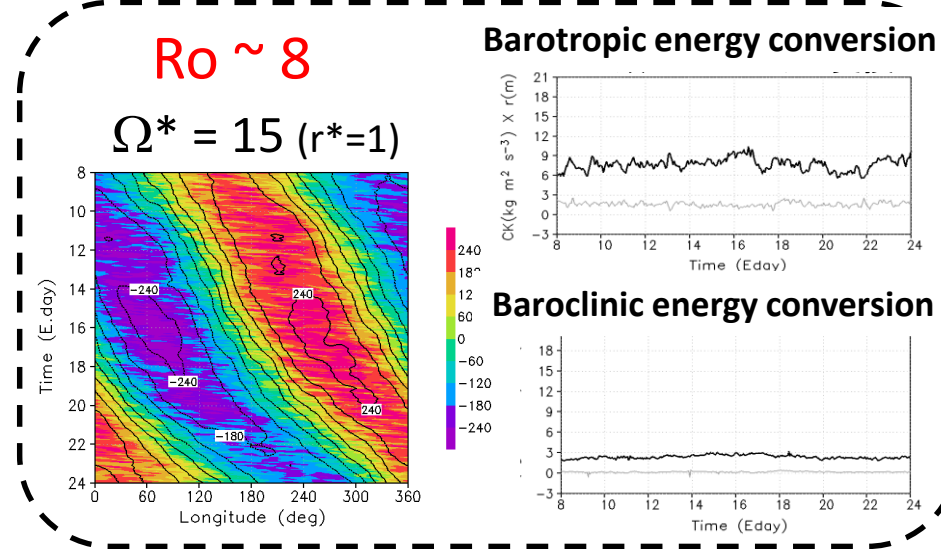
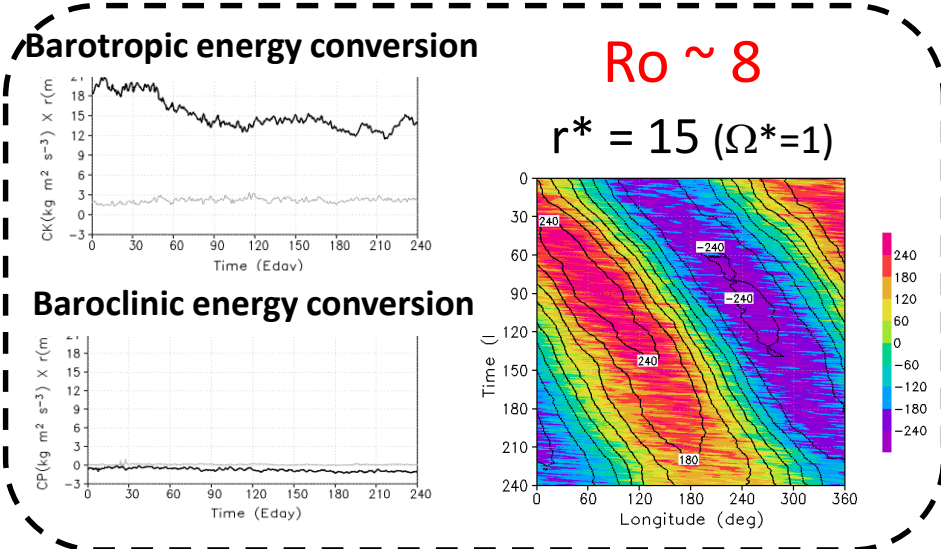
$$CP(s) = -\frac{1}{r} \int_V \frac{\partial \bar{T}}{\partial \varphi} \left(\frac{R}{NH} \right)^2 \overline{T'(s)v'(s)} dV$$

The horizontal temperature gradient induces eddies when $CP > 0$ (e.g., Baroclinic instability).

Here, s indicates zonal wavenumber.

Sensitivity of wave and its mechanism to Ro

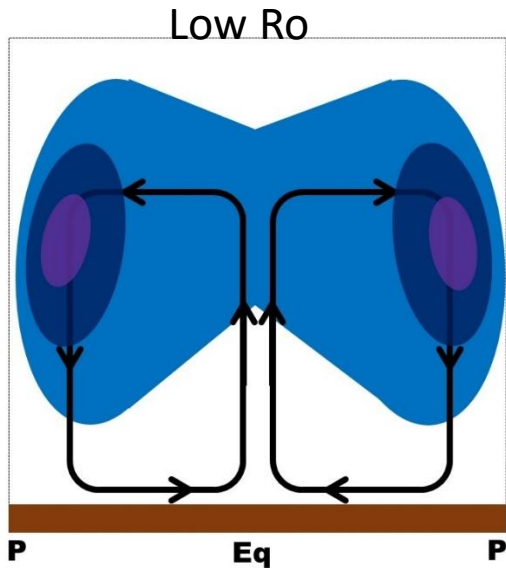
Time-longitude cross-sections of eddy geo-potent height (m, color shade)



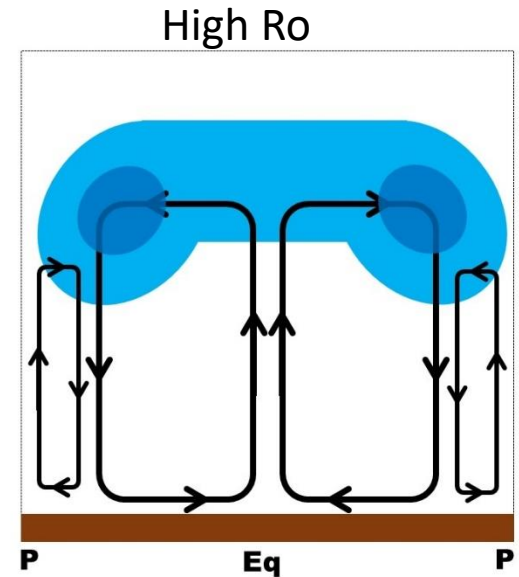
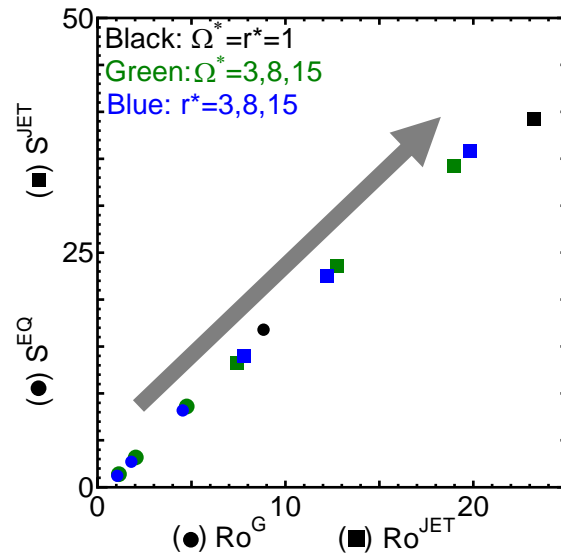
(Tsunoda et al. 2021 JGR)

Summary

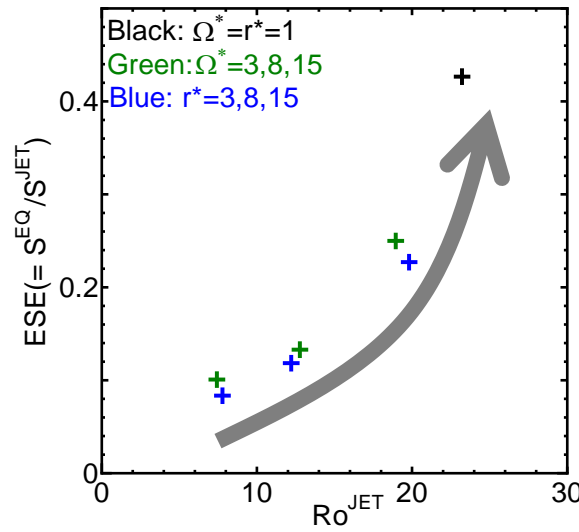
We confirmed dynamical similarity to the same Ro in the GRW mechanism. The sensitivity of SR to Ro is summarized as follows.



- Strong mom flux
- Strong zonal wind
- Low SR intensity
- *Slow* Rossby wave *continuously* produces equatorward mom flux



- Weak mom flux
- Weak zonal wind
- High SR intensity
- *Fast* Rossby wave *intermittently* produces equatorward mom flux



まとめ

金星型大気超回転の高ロスビー数($Ro^{JET} > 1$)依存性を調査した.

○低ロスビー数($Ro^{JET} \sim 8$)

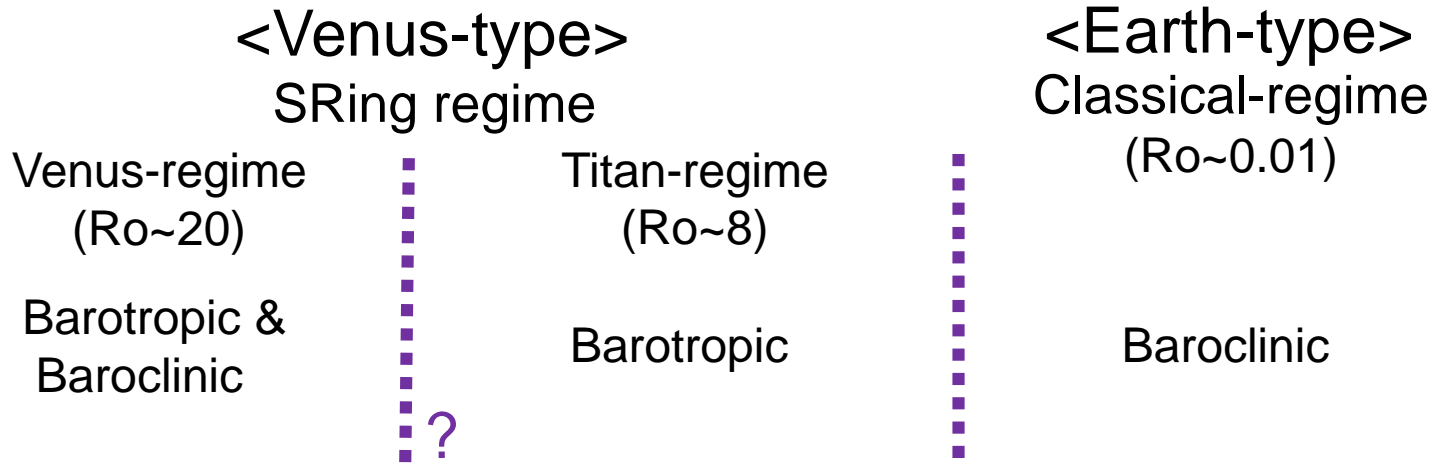
- ・順圧エネルギー変換に伴い、自転よりも遅いロスビー波が、連続的な赤道向き運動量輸送を生み出す.
 - ・帯状平均流は中高緯度ジェットが卓越する.
 - ・帯状風速と赤道向き渦運動量輸送は大きいですが、赤道超回転は十分に発達しない.
- ⇒超回転強度Sと赤道超回転効率ESEが小さい

○高ロスビー数($Ro^{JET} \sim 20$)

- ・順圧エネルギー変換と傾圧エネルギー変換に伴い、ロスビー波の運動量および熱輸送が短い周期で間欠的に増幅する.
 - ・帯状平均流は中低緯度で概ね同速分布に近い赤道超回転となる.
 - ・間欠的で弱い運動量輸送だが、赤道超回転が効率よく発達する.
- ⇒超回転強度Sと赤道超回転効率ESEが大きい

Future works

The present work suggests the following three-regimes based on the energy conversion. Venus-type SRing regime is newly classified into Venus-regime and Titan-regime.



(1) We must elucidate **the regime boundaries** and their dynamical characteristics on Venus-type planets.

(2) We must elucidate the spin-up process of SR.

(3) We must elucidate the sensitivity of SR to diffusion (Yamamoto & Takahashi 2022 JGR).