Study of the superrotation of Titan's stratosphere using a general circulation model with simple radiative processes

Motoki Sumi (WeatherNews Inc.),
Shin-ichi Takehiro (Kyoto Univ.),
Wataru Ohfuchi (Kobe Univ.),
Hideko Nomura (NAOJ), Yuka Fujii (NAOJ)

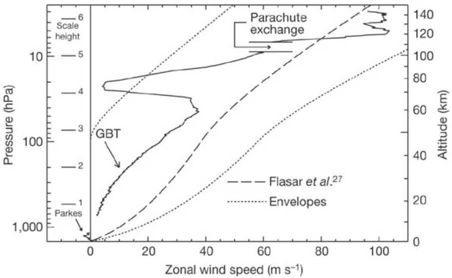
March 29th, 2024

Workshop on Venus and other related atmospheres @ CPS, Kobe Univ.

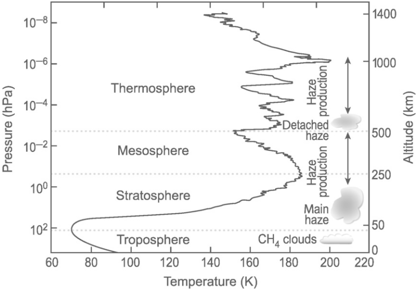
Ref: Sumi, M. et al. (2022) Astrophys. J. **928**:149
https://doi.org/10.3847/1538-4357/ac54ab

Introduction

- Titan : satellite of Saturn
  - Planetary radius : 2500km
  - Rotation period : 16 Earth days
  - Surface pressure : 1.5 atm
- Characteristics of Titan's atmosphere
  - Superrotation wind over 100 m/s in the stratosphere
  - Haze layer at the bottom of the stratosphere



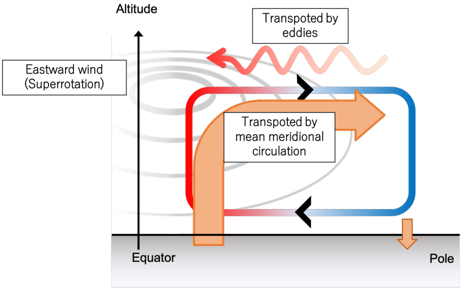
Vertical longitudinal wind profile
(Bird et al., 2005)



Vertical temperature profile
(Fulchignoni et al., 2005)

Mystery of superrotation

- Superrotation (SR) : acceleration is necessary to maintain SR
  - Meridional circulation + AM conservation
    $\Rightarrow$ subrotation at the top of the equator.
  - frictional resistance at the ground
- Gierasch mechanism (Gierasch, 1975) : a generation mechanism of SR
  - Efficient horizontal diffusion (AM transport by turbulence/waves)
  - Pumping up of AM from the planetary surface



(Sumi et al., 2022)

Purpose

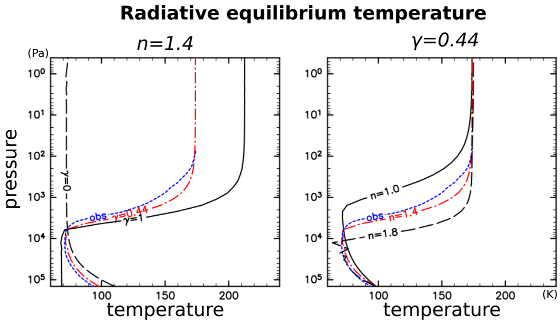
- Many studies for Titan's atmosphere using GCM with several physical processes (e.g. Newman et al,, 2011; Lebonnois et al., 2012; Lora et al., 2015)
  - Topography, seasonal variation, phase change of CH_4 etc.
  - Not clear the essential factor for SR
- Numerical experiments of GCM with simple setups are conducted
  - Investigate mechanisms for the generation/maintenance of SR in Titan's atmosphere
- Focus on effects of solar radiation absorption effect of the haze layer
  - Absorbs about 90% of solar radiation
  - Increases the temperature of the upper atmosphere
- How does the haze layer affect the generation and maintenance of SR states?
  $\Rightarrow$ Understanding the atmospheric dynamics of Earth-like planets

Model

- DCPAM : GCM for planetary atmospheres developed by GFD-Dennou Club (Takahashi et al., 2018)
  - primitive system (hydrostatic approx.)
  - Dynamic processes in the horizontal direction are descretized by the spectral method using spherical harmonics
- A grey atmospheric radiation model with parameters to express greenhouse effect due to atmospheric gases and attenuation of sunlight due to haze (McKay et al., 1999)
- No methane phase change, topography, and seasonal cycle

Radiation model and haze effects

- Radiation model : two-parameters, γ, n
  - Grey atmosphere, two-stream approx.(solar and infrared)
  - Optical thickness proportional to the power of pressure : $\tau_L(p) = \tau_{\mathrm{surf},L}(p/p_{\mathrm{surf}})^n$
- γ : ratio of solar radiation absorption of the haze layer
- n : parameter for the height of the haze layer
- Suitable parameters for Titan : $(\gamma, n) = (0.44, 1.4)$



(Sumi et al., 2022)

Setup for numerical experiments

- Resolution : Number of grids (lon. lat. height) = (32,16,55)
- ∇^6-type hyper-diffusion
  Diffusion time for max. wavenumber component : 1 day
- Radiation parameters : 5 cases

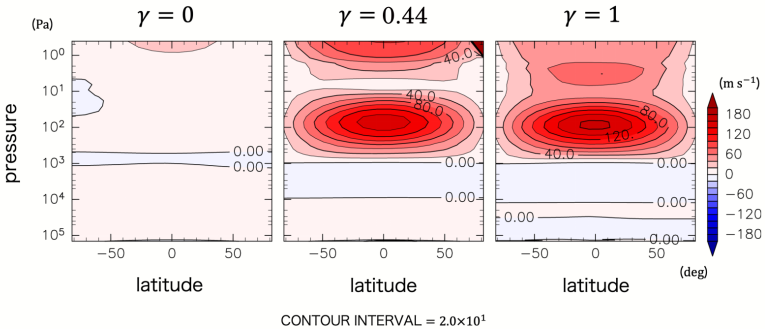
	γ		
	0.0 (No haze)	0.44	1.0 (Perfect haze)
$n = 1.0$ (higher haze layer)		∘	
$n = 1.4$	∘	Titan	∘
$n = 1.8$ (lower haze layer)		∘	

- Initial condition : no motion, radiative equilibrium temperature
- Analyze the states after 10^5 days time integration

Results : γ dependence ~ mean zonal flows

- The cases with $n = 1.4$
- $\gamma = 0.44$ and 1 : sunlight is absorbed at the haze layer
  - SR over 100m/s in the stratosphere
  - Weak counter wind just below the SR area
- $\gamma = 0$: no sunlight absorption by the haze, no SR in the stratosphere

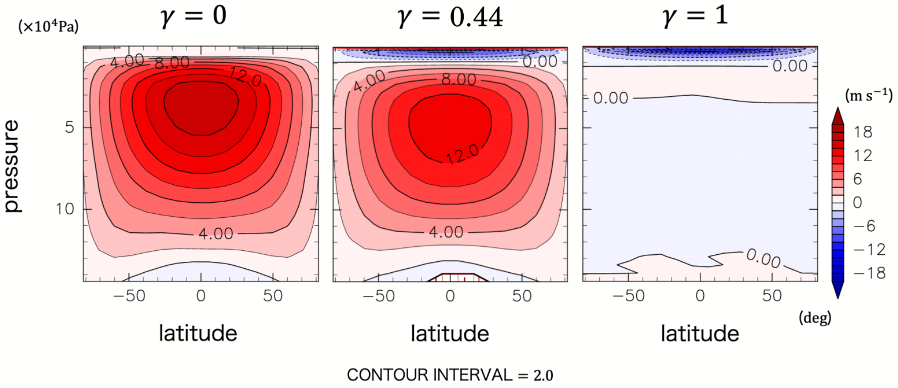
Zonal mean zonal wind



(Sumi et al., 2022)

γ dependence ~ zonal flow (lower altitudes)

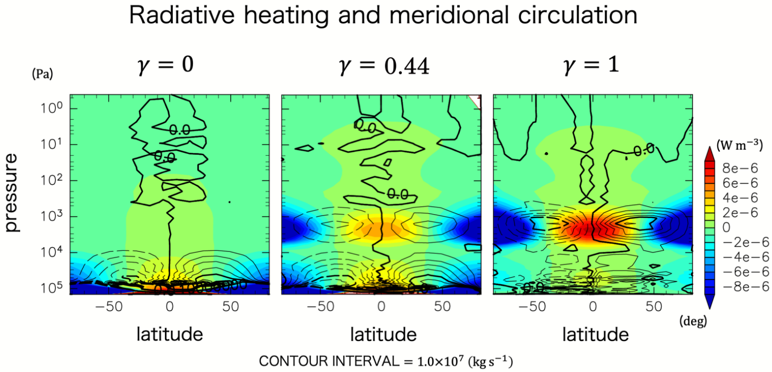
- The cases with $n = 1.4$
- $\gamma = 0$: all sunlight reaches the planetary surface
  - Strong SR in the troposphere (~ 20m/s)



(Sumi et al., 2022)

γ dependence : meridional circulation, radiative heating

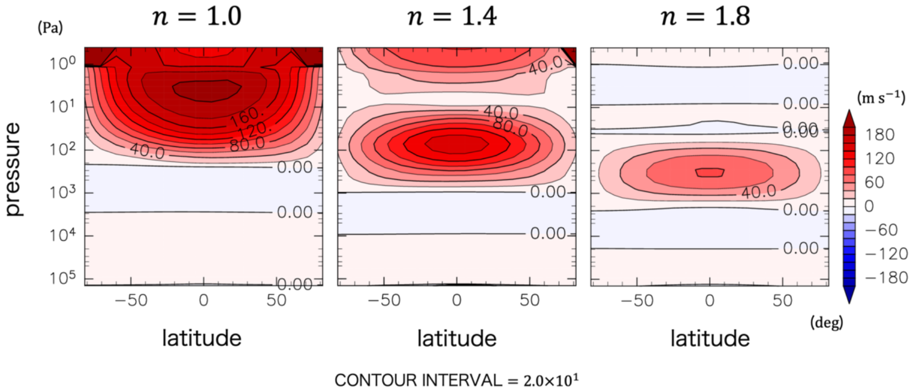
- The cases with $n = 1.4$
- $\gamma = 0.44$ and 1 : sunlight is absorbed at the haze layer
  - Stratosphere : heating at equator, cooling at polar region, 1-cell circulation
- $\gamma = 0$ and 0.44 : sunlight reaches at the ground
  - Troposphere : heating at equator, cooling at polar region, 1-cell circulation



(Sumi et al., 2022)

n dependence : mean zonal flows

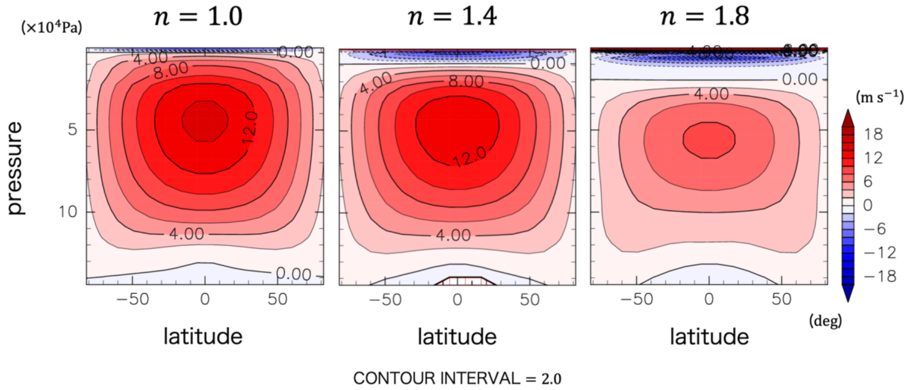
- The cases with $\gamma = 0.44$
- n increase : the haze layer lowered
  - SR region lowered
  - SR weakening



(Sumi et al., 2022)

n dependence : zonal flow (lower altitudes)

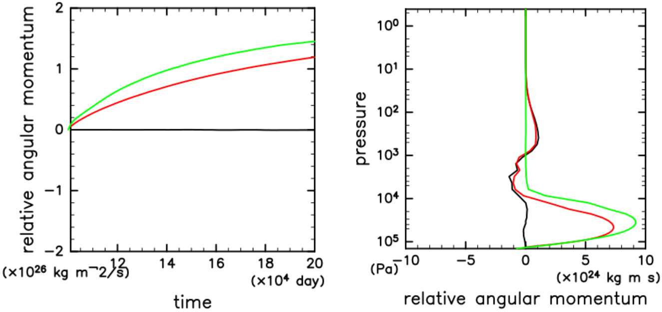
- The cases with $\gamma = 0.44$
- n increase : the haze layer lowered
  - SR region lowered
  - SR weakening



(Sumi et al., 2022)

Relative angular momentum

- $\gamma = 1$: AM ~ 0
  - AM redistribution inside the atmosphere
  - AM transport from bottom to top at an altitude of 10^3 Pa
- $\gamma = 0$: AM accumulation in the troposphere from solid planets
- $\gamma = 0.44$: similar to both $\gamma = 1$ and $\gamma = 0$



Time variation of AM   Vertical distribution of AM

(Sumi et al., 2022)

Wave analysis

- TEM equations, longitudinal component of EOM

$$\frac{\partial \overline{u}}{\partial t} = \underbrace{-\frac{\overline{v}^*}{a\cos\varphi}\frac{\partial}{\partial\varphi}(\overline{u}\cos\varphi) - \overline{w}^*\frac{\partial\overline{u}}{\partial z} + f\overline{v}^*}_{①} + \overline{\mathcal{F}_\lambda} + \underbrace{\frac{1}{\rho_0 a\cos\varphi}\nabla\cdot\boldsymbol{F}}_{②}$$

  - ① : acceleration by meridional circulations, ② : acceleration by waves

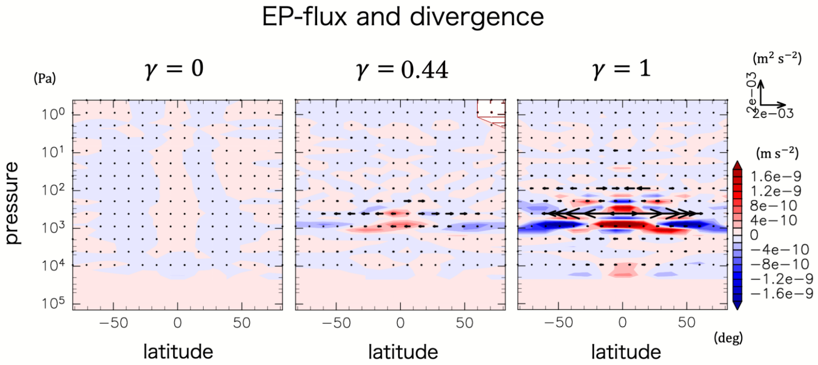
- $\boldsymbol{F} = (0, F_\varphi, F_z)$: Eliassen-Palm flux (EP flux)
  - Indicator of wave activity
  - Inverse direction to the AM flux

$$F_\varphi = \rho_0 a\cos\varphi\left(\frac{\partial\overline{u}}{\partial\overline{z}}\frac{\overline{v'\theta'}}{\frac{\partial\overline{\theta}}{\partial z}} - \overline{u'v'}\right),$$

$$F_z = \rho_0 a\cos\varphi\left(\left[f - \frac{\frac{\partial\overline{u}\cos\varphi}{\partial\varphi}}{a\cos\varphi}\right]\frac{\overline{v'\theta'}}{\frac{\partial\overline{\theta}}{\partial z}} - \overline{u'w'}\right),$$

Wave analysis : EP flux

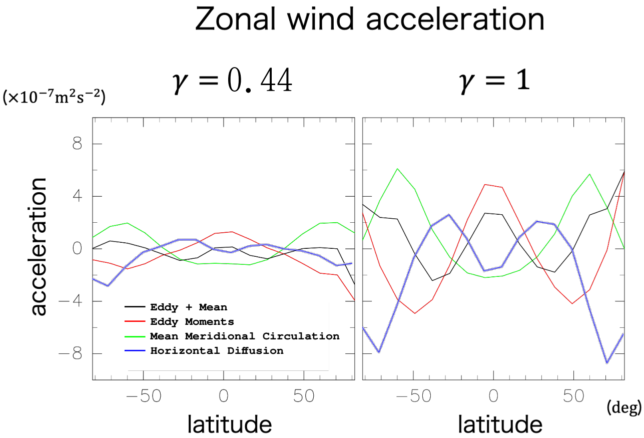
- The cases with $n = 1.4$
- $\gamma = 0.44,\ 1$: Sunlight absorption by the haze layer
  - Wave activity above 10^3 Pa height
  - AM transport from the poles to the equator



(Sumi et al., 2022)

Wave analysis : acceleration distribution

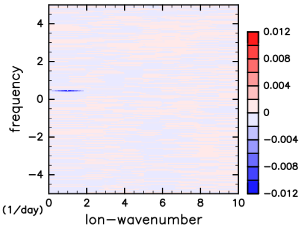
- Comparison of acceleration around 800 Pa height ($n = 1.4$)
  - Around equator : acceleration by waves $\Rightarrow$ generation/maintenance of SR
  - Poler region : AM transport by meridional circulation



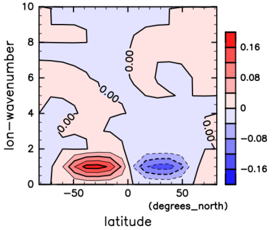
(Sumi et al., 2022)

Wave analysis : UV cospectrum

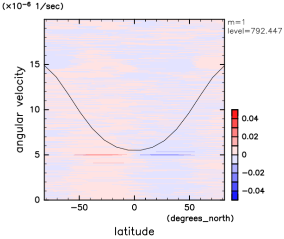
- Analysis around 800 Pa height $(\gamma = 1.0, n = 1.4)$
- AM transport : waves with zonal wave number 1 dominates
- Angular velocity : slower than zonal flows $\Rightarrow$ Rossby waves?



lon.wavenumber vs frequency (40N latitude)



latitude vs lon.wavenumber

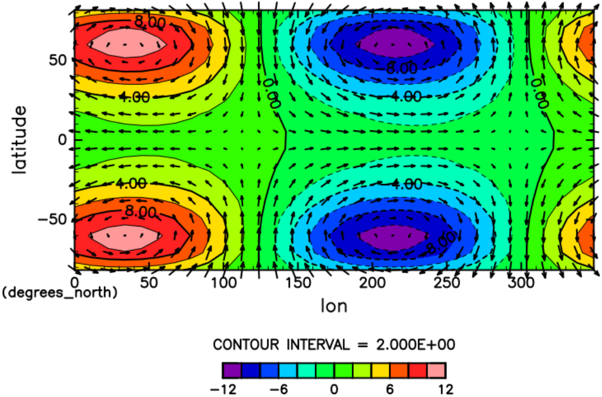


latitude vs angular velocity $(m = 1)$

(Sumi et al., 2022)

Wave analysis : wave structure

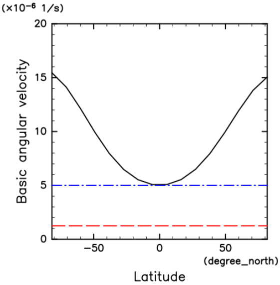
- Tilting of horizontal vortices : ⇒ equatorward AM transport
- Height and horizontal velocity : geostrophic balance ⇒ Rossby waves?
- Excitation mechanism : barotropic instability?



Height (tone and contour) and horizontal velocity (arrows) around 800Pa height (Sumi et al., 2022)

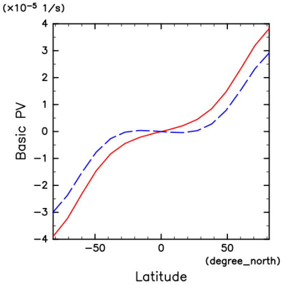
Linear stability analysis

- 2D barotropic rotating sphere model + hyper viscosity
- Basic field : zonal mean height field at 800Pa of the numerical result.
- No inflection point in the PV distribution



Angular velocity

(basic zonal flow, unstable mode, wave analysis)

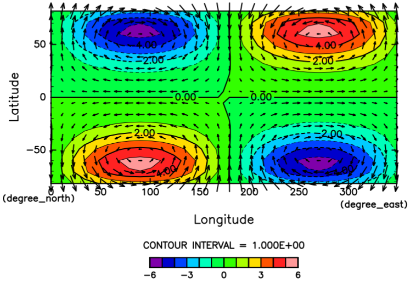


PV, vorticity

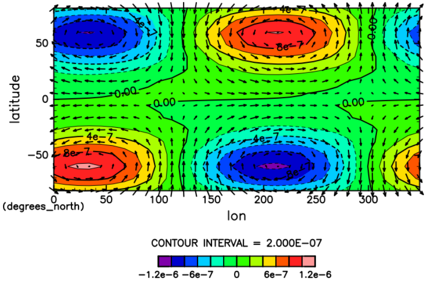
(Sumi et al., 2022)

Linear stability analysis

- Unstable mode (left), wave analysis (right) : similar structure
  - zonal wavenumber $m = 1$, growth rate $\sigma = 2.5 \times 10^{-8}$ day^{-1}, frequency $\omega = 1.24 \times 10^{-8}$ day^{-1}.
  - No critical latitude!
- Unstable mode disappears when hyper viscosity is switched off



Unstable mode



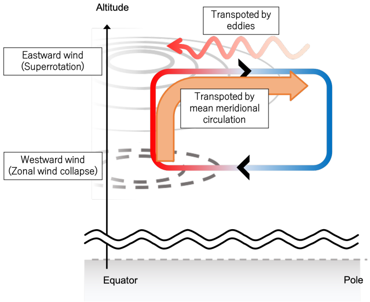
Wave analysis

(Sumi et al., 2022)

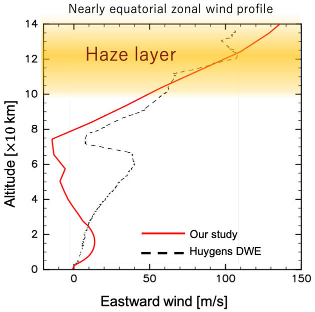
Summary

- SR in stratosphere : sunlight absorption by the haze layer
- Gierasch mechanism + no effect of the planetary surface
  - AM distribution inside the atmosphere
  - Counter flow below SR region

  $\Rightarrow$ consistent with observation? Wind collapse region?



Schematic figure of AM transport



Vertical distribution of mean zonal flows

Obs (black dotted), num.exp.(red solid)

(Sumi et al., 2022)

References

Sumi, M., Takehiro, S., Ohfuchi, W., Nomura, H., Fujii, Y., Superrotation of Titan's Stratosphere Driven by the Radiative Heating of the Haze Layer. Astrophys. J. (2022), **928**:149 (18pp) `https://doi.org/10.3847/1538-4357/ac54ab`

Bird, M. K., Allison, M. Asmar, S. W., Atkinson, D. H. Avruch, I. M., Dutta-Roy, R., Dzierma, Y.. Edenhofer, P., Folkner, W. M., Gurvits, L. I., Johnston, D. V., Plettemeier, D., Pogrebenko, S. V., Preston, R A., Tyler, G, L., Nature (2005), **438**, 800–802.

Fulchignoni, M., Ferri, F., Angrilli, F. et al., 2005: In situ measurements of the physical characteristics of Titan's environment. Nature, **438**, 785–791.

Gierasch, P. J., Meridional circulation and the maintenance of the Venus atmospheric circulation. J. Atmos. Sci. (1975), **32**, 1038–1044.

Newman, C. E., Lee, C., Lian, Y., Richardson, M. I., Toigo, A. D., Stratospheric superrotation in the TitanWRF model, Icarus (2011), **213**, 636–654.

Lebonnois, S., Burgalat, J., Rannou, P., Charnay, B. Titan global climate model: A new 3-dimensional version of the IPSL Titan GCM, Icarus (2012), **218**, 707–722.

Lora, J. M., Lunine, J. I., Russell, J. L., GCM simulations of Titan 's middle and lower atmosphere and comparison to observations, Icarus (2015), **250**, 516–528.

Takahashi, Y. O., H. Kashimura, S. Takehiro, M. Ishiwatari, S. Noda, M. Odaka, T. Horinouchi, Y.-Y. Hayashi, DCPAM Devlopment Group, DCPAM: planetary atmosphere model, GFD Dennou Club (2018), http://www.gfd-dennou.org/library/dcpam/

McKay, C. P,. Lorenz, R. D., Lunine, J. I., Analytic Solutions for the Antigreenhouse Effect: Titan and the Early Earth. Icarus (1999), **137**, 56–61.