Dependence of Atmospheric Meridional Heat Transports in Aqua Planets on Solar Constant

水惑星における大気南北熱輸送の太陽定数依存性

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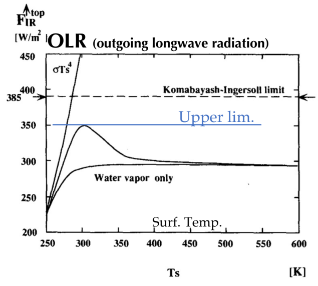
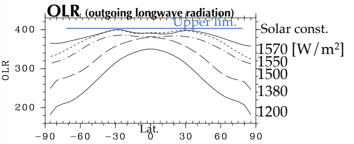
Introduction/背景

- The runaway greenhouse state is an important concept for understanding the variety of climates of the terrestrial planets.
  暴走温室状態は地球型惑星の気候を考察する上で重要な概念
- One-dimensional radiative-convective equilibrium gray atmosphere models show the existence of upper limit of outgoing longwave radiation (OLR) (Nakajima *et al.* 1992).
  灰色1次元モデルでは外向き赤外放射(OLR)に上限がある（射出限界）
- The runaway greenhouse state is a state with incoming solar radiation greater than the upper limit.
  射出限界以上に入射があるのが暴走温室状態
- A three-dimentional model also have upper limit of OLR. For solar radiation greater than the upper limit, the runaway greenhouse state appears (Ishiwatari *et al.* 2002).
  灰色3次元モデルでも OLR に上限が現れる



The relationship between surface temp. and OLR (Nakajima *et al.*, 1992, Fig. 3)



The meridional distributions of zonal mean OLR (Ishiwatari *et al.*, 2002; Fig. 4a)

Purpose/研究目的

- Decrease of meridional thermal contrast gives upper limit of OLR in three-dimentional models.
  3 次元モデルで射出限界が決まったのは南北差の減少の影響が大きかった
  - Interpretations in one-dimentional models can be applied in three-dimentional models because meridional contrast is decreased.
    3 次元系では、高温になると南北差が小さくなるので、1 次元系の解釈を適用できる
  - The increase of solar constant cuases the increase of meriodinal heat transport 灰色 3 次元モデルでは太陽定数が大きくなると南北熱輸送が大きくなっていた
- However, Ishiwatari *et al.* (2002) use idealized model. What happens in more Earth-like situation?
  Ishiwatari *et al.* (2002) は非常に理想化されているが、より地球に近い状況ではどうなるのか考察する
  - e.g. non-gray atmospheric cloud-included situation.
    具体的な設定としては、非灰色大気、雲ありの設定
- In this study, I examine what happen when solar constant increases.
  太陽定数が大きくなったときに、どのようなことが起きているか考察する
  - Do meridional thermal contrast also decrease in non-gray atmospheric model when solar constant increases?
    非灰色大気でも太陽定数が大きくなったら南北一様化が起きるのか
  - If meridional thermal contrast decrease, how meridional heat transports happen?
    南北差が小さくなるならば、どのような南北熱輸送が起きているのか

Methods/手法

- Model/利用したモデル
  - Atmospheric global circulation model (DCPAM5)/大気大循環モデル DCPAM 5
    http://www.gfd-dennou.org/library/dcpam/
- Basic equations/基礎方程式
  - 3-D primitive equations for a spherical geometry
    3 次元球殻領域のプリミティブ方程式

$$\frac{\partial \pi}{\partial t} + \boldsymbol{v}_H \cdot \nabla_\sigma \pi = -D - \frac{\partial \dot{\sigma}}{\partial \sigma}, \qquad \text{(Continuity equation)}$$

$$\frac{\partial \Phi}{\partial \sigma} = -\frac{RT_v}{\sigma}, \qquad \text{(Hydrostatic equilibrium)}$$

$$\frac{\partial \zeta}{\partial t} = \frac{1}{a}\left(\frac{1}{1-\mu^2}\frac{\partial V_A}{\partial \lambda} - \frac{\partial U_A}{\partial \mu}\right) + \mathcal{D}[\zeta], \qquad \text{(EOM1)}$$

$$\frac{\partial D}{\partial t} = \frac{1}{a}\left(\frac{1}{1-\mu^2}\frac{\partial U_A}{\partial \lambda}\right) - \nabla_\sigma^2(\Phi + R\bar{T}\pi + KE) + \mathcal{D}[D], \qquad \text{(EOM2)}$$

$$\frac{\partial T}{\partial t} = -\frac{1}{a}\left(\frac{1}{1-\mu^2}\frac{\partial UT'}{\partial \lambda} + \frac{\partial VT'}{\partial \mu}\right) + T'D - \dot{\sigma}\frac{\partial T}{\partial \sigma}$$
$$+ \kappa T_v\left(\frac{\partial \pi}{\partial t} + \boldsymbol{v}_H \cdot \nabla_\sigma \pi + \frac{\dot{\sigma}}{\sigma}\right) + \frac{Q}{C_p} + \mathcal{D}[T] + \mathcal{D}'[\boldsymbol{v}], \qquad \text{(Thermodynamics)}$$

$$\frac{\partial q}{\partial t} = -\frac{1}{a}\left(\frac{1}{1-\mu^2}\frac{\partial Uq}{\partial \lambda} + \frac{\partial Vq}{\partial \mu}\right) + qD - \dot{\sigma}\frac{\partial q}{\partial \sigma} + S_q + \mathcal{D}[q]. \qquad \text{(Water Vapor)}$$

- Physical Process/物理過程
  - Radiation prosess for East/地球用放射過程 (Chou and Lee, 1996; Chou *et al.*,1998)
  - Turbulent mixing/乱流混合 (Mellor and Yamada, 1982)
  - Dry convection adjustment/乾燥対流調節 (Manabe *et al.*, 1965)
  - Relaxed Arakawa–Schubert (Moorthi and Suarez, 1992)

φ, λ	Latitude and longitude
$\sigma := p/p_s$	σ coordinate height
t	Time
$\pi := \ln[p_s]$	
T	Temperature
q	Specific humidity
a	Radius of planet
f	Coriolis parameter
ζ	Vorticity
D	Divergence
u, v	Eastward, northward wind
$(U, V) := (u\cos\varphi, v\cos\varphi)$	
$KE := (U^2 + V^2)/(2(1-\mu^2))$	
$\Phi := gz$	Geopotential
$\mathcal{D}$	Horizontal diffusion
$\mathcal{D}'[v]$	Frictional heat
$\mathcal{F}$	Small-scale movement process
Q	Heating
S_q	Water vapor source
R	Gas constant of dry air
c_{pn}	Specific heats at constant press. of dry air
$\kappa := R/c_{pn}$	
ϵ_v	Water vapor moleculars weight ratio
$\bar{T}$	Temperature level
$T' := T - \bar{T}$	
$T_v := T(1 + (\epsilon_v^{-1} - 1)q)$	
$T_v' := T_v - \bar{T}$	

Experimental design/実験設定

- Experimental design/実験設定
  - Aqua Planet/水惑星
  - Paramters/パラメータ

Parameters	Value
Radius of planet	$a = 6.37 \times 10^7$ m
Rotation angular velocity	$\omega = 7.292 \times 10^{-5}$ /s
Gravitational acceleration	$g = 9.8\,\mathrm{m/s^2}$
Gas constant of dry air	$R_n = 287.1\,\mathrm{J/kg/K}$
Gas constant of water vapor	$R_v = 461.5\,\mathrm{J/kg/K}$
Specific heat at constant press. of dry air	$c_{pn} = 1004\,\mathrm{J/kg/K}$
Specific heat at constant press.ure of water vapor	$c_{pv} = 1810\,\mathrm{J/kg/K}$
Molecular weight of dry air	$m_n = 28.96 \times 10^{-3}$ kg/mol
Molecular weight of water vapor	$m_v = 18.02 \times 10^{-3}$ kg/mol
Latent heat of water vapor	$L = 2.50 \times 10^6$ J/kg
Albedo of ocean	$A = 0.1$

- Initial state/初期状態
  - Temp./温度一様 280 K
  - Specific Humidity/比湿一様 0
  - Resting Atmosphere/静止大気
- List of experimets/実験リスト

Expt.	Solor const. S [W/m^2]	Cloud lifetime [s]	Integrate time [year]
S1366	1366	13500	41
S1500	1500	13500	11
S1600	1600	13500	11
S1800	1800	13500	11
S2000	2000	13500	21

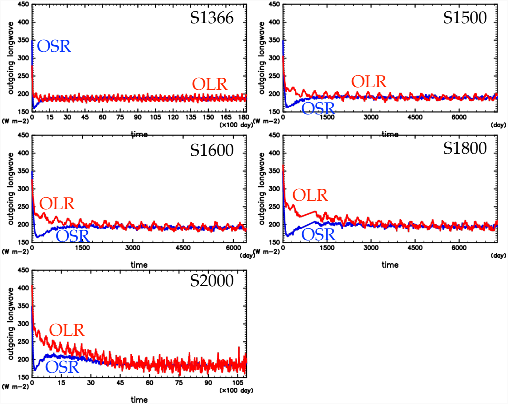
Result—Emargence of equilibrium stats/結果—平衡状態に達しているか

- The atmosphere reaches equilibrium states in S1366 to S1800, because OLR (outgoing longwave radiation) become equal to OSR (outgoing shortwave radiation).

  S1366 から S1800 までは OLR と OSR が一致して平衡状態になっている

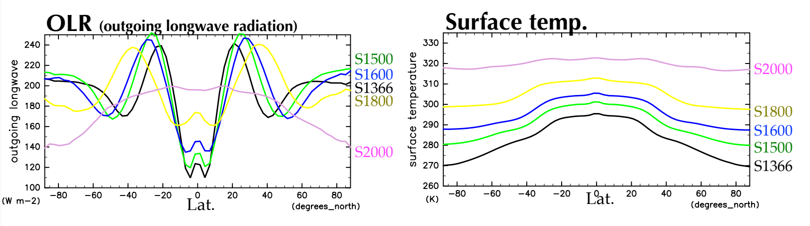
- For S2000, more integration seems to be necessary to determine whether the system reaches is equilibrium state.

  S2000 は積分期間を長くしなければ平衡状態になっているか判断できない



Time evolutions of global mean OLR and OSR.

Results—Decreaseing meridional thermal contrast/結果—南北差の減少



Meridional distributions of zonal mean of OLR and surface temp.

- Meridional contrasts of zonal mean OLR and surface tempraure decrease as solar constant increases in equilibrium state.
  非灰色大気でも太陽定数が増大すると OLR の東西平均と地表面温度の東西平均の南北差が小さくなる
  - OLR at the equator increases and OLR at mid-latitude decreases as solar constant increases.
    太陽定数の増大に従って、赤道の OLR は増加し、中緯度の OLR は減少する

Meridional heat transports/南北熱輸送

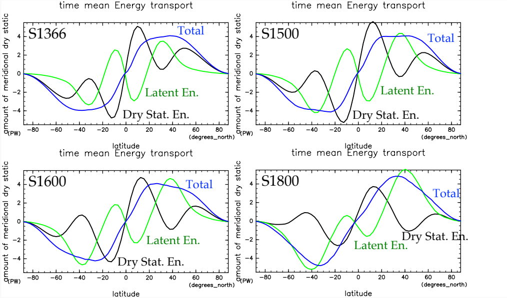
- Meridional energy transports F_T is written $F_L + F_D$.
  南北方向の熱輸送 F_T は $F_L + F_D$ と書ける

$$F_T = F_L + F_D$$

$$F_L = \int_0^{2\pi} \int_0^{p_s} Lqv \, dp \, d\lambda, \qquad \text{(Latent energy)}$$

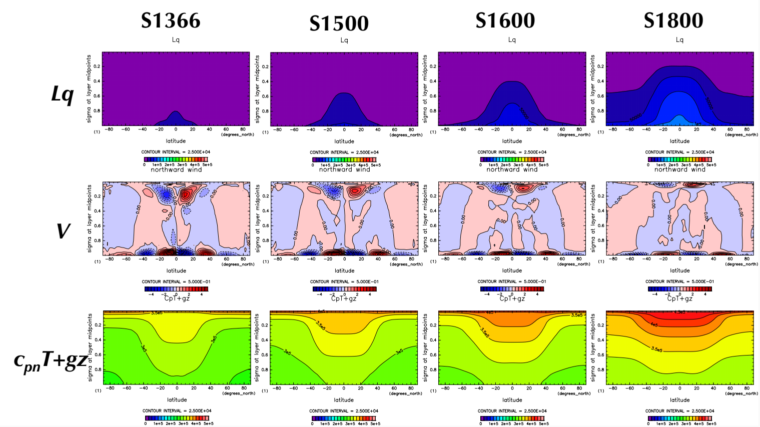
$$F_D = \int_0^{2\pi} \int_0^{p_s} (c_{pn}T + gz)v \, dp \, d\lambda. \qquad \text{(Dry static energy)}$$

Results—Zonal time mean of meridional heat transports
結果—南北熱輸送の東西時間平均



- Total energy transport increases as solar constant is increased.
- Latent energy transport increases as solar constant is increased.
  南北熱輸送の合計と潜熱輸送は太陽定数が増大すると増大する
- Dry static energy transport has maximun in S1500 but increasing solar constant over S1600 cause decrease dry static energy flux.
  乾燥静的エネルギーの輸送は S1500 で最大になり、それ以降太陽定数が大きくなると小さくなる。

Zonal time mean of latent energy and dry static energy
各実験での潜熱と乾燥静的エネルギーの東西平均



- Northward wind on upper atmosphere decrease as solar constant increases over S1600. This makes dry static energy transport decrease.
  S1600 以上では太陽定数が増大すると大気上層の南北風が小さくなるので乾燥静的エネルギーの輸送が小さくなる

Next problem/現在取り組んでいる問題

- Disaggragate the transports three part.
  それぞれの輸送を次の 3 つによるものの和に分ける

$$[\overline{xv}] = \underbrace{[\bar{x}][\bar{v}]}_{\text{mean meridional flow}} + \underbrace{[\bar{x}^*\bar{v}^*]}_{\text{stationary eddy}} + \underbrace{[\overline{x'v'}]}_{\text{transient eddy}} \quad (x = Lq \text{ or } (c_{pn}T + gz)).$$

  $\bar{\bullet}$: time mean; $[\bullet]$ zonal mean; $\bullet' = \bullet - \bar{\bullet}$, $\bullet^* = \bullet - [\bullet]$: deviations from means
- I'm trying to figure out how each term affects the other.
  それぞれの項がどう影響しているか調べている
  - When solar constant is large, latent heat is transported by low and high pressure systems.
    太陽定数が大きいとき、潜熱輸送は低気圧・高気圧に依る部分が大きい
  - When solar consttabt is large, latent heat is transported by mean meridional flow.
    太陽定数が大きいとき、乾燥静的エネルギーの輸送は平均子午面の循環に依るところが大きい

まとめ/Conclution

- Dependence of atmospheric meridional heat transports on solar constant using three-dimentional spherical non-gray atmospheric model is examined.
  3 次元非灰色大気モデルで、太陽定数と南北熱輸送の関係を調べた
- Increase of solar constant cause decrease of meridional thermal contrast.
  太陽定数が増大すると南北差が小さくなる
- Increase of solar constant cause total meridional heat transports increases.
  太陽定数が増大すると南北熱輸送が大きくなる
  - Dry static energy transport has maximun in $S = 1500\,\mathrm{W/m^2}$ but increasing solar constant over $S = 1600\,\mathrm{W/m^2}$ cause decrease dry static energy flux.
    乾燥静的エネルギーの輸送は、$S = 1500\,\mathrm{W/m^2}$ で最大になって、それより大きい太陽定数では小さくなる
  - Latent energy transports increases as solar constant increases.
    潜熱輸送は太陽定数が増大すると、乾燥静的エネルギー輸送の減少にまして大きくなる