A study on dependence of ocean planet climates on the solar constant : the effect of oceanic heat capacity and oceanic heat transport

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Outline

- Introduction
  - Background
  - The purpose of this study
- Model and Experimental setup
- Numerical results
  - control experiment
  - solar constant dependence experiment
- Discussion
- Summary

Introduction

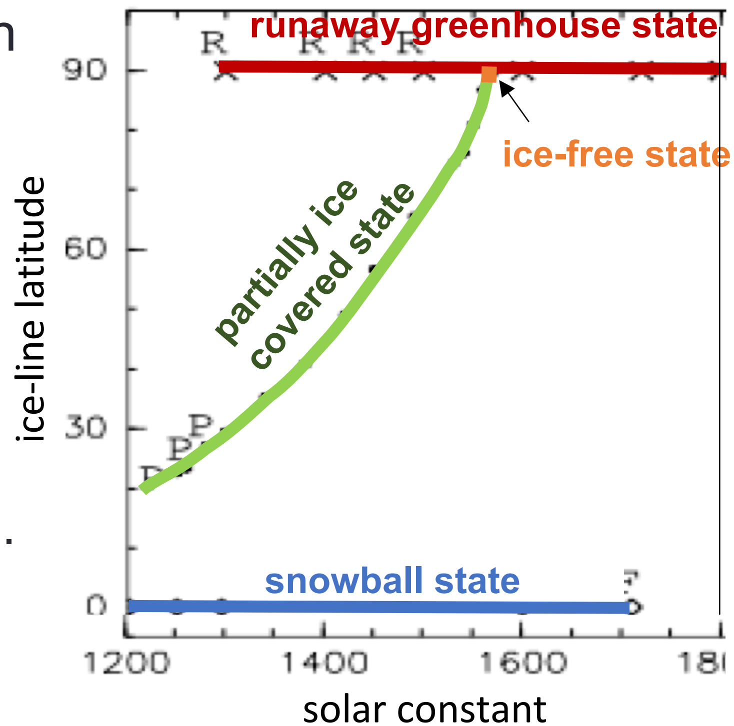
- Background
- The purpose of this study

Background

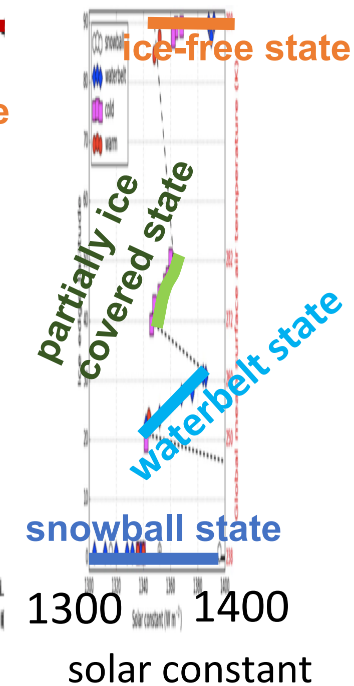
- Many exoplanets have been discovered by recent observations, and the diversity of the surface environments is expected there.
  - In order to obtain a deeper understanding of the climate diversity, some numerical studies have been performed.

- To investigate the diversity and stability of climates on terrestrial planets with water, climates on an idealized planet globally covered with ocean (***ocean planet***) have been explored numerically.
  - e.g. Solar constant dependence
    - Ishiwatari et al. (2007)
      - Atmospheric general circulation is *only* considered.
    - Rose (2015)
      - Atmospheric and oceanic general circulation is ***both*** considered.

Ishiwatari et al. (2007)



Rose (2015)



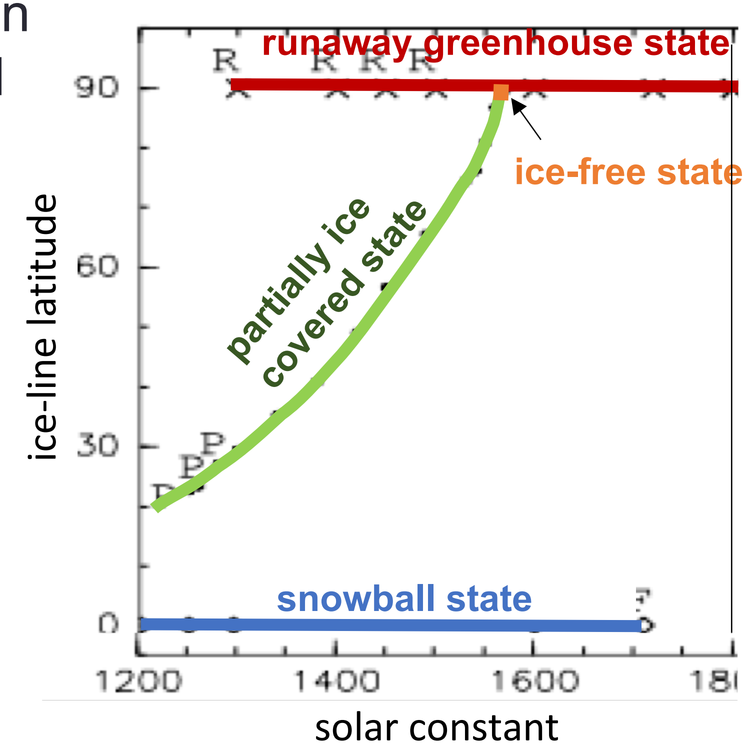
Background

- Many exoplanets have been discovered by recent observations, and the diversity of the surface environments is expected there.
  - In order to obtain a deeper understanding of the climate diversity, some numerical studies have been performed.

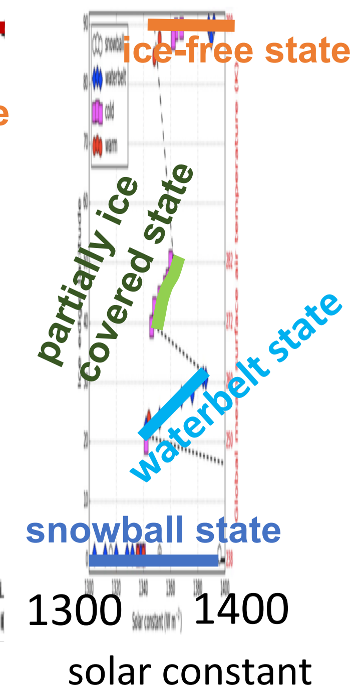
- To investigate the diversity and stability of climates on terrestrial planets with water, climates on an idealized planet globally covered with ocean (***ocean planet***) have been explored numerically.

> - Remarkable results from a coupled atmosphere-ocean-sea ice model in Rose (2015)
>   - The branch of partially ice covered state is split.
>   - Runaway greenhouse state seems not to be found.

Ishiwatari et al. (2007)



Rose (2015)



Purpose of this study

- We develop a coupled atmosphere-ocean-sea ice model to explore ocean planet climates considered ocean general circulation explicitly.
- Using our developing coupled model, we investigate dependence of ocean planet climates on solar constant.
  - The atmospheric setting in Ishiwatari et al. (2007) is extended.
  - We also examine runaway greenhouse state which seems not to be found in Rose (2015).
  - By comparing the results from swamp/slab ocean experiments, we evaluate the influence of oceanic heat capacity and oceanic heat transport on determining ocean planet climates.

Model and Experimental setup

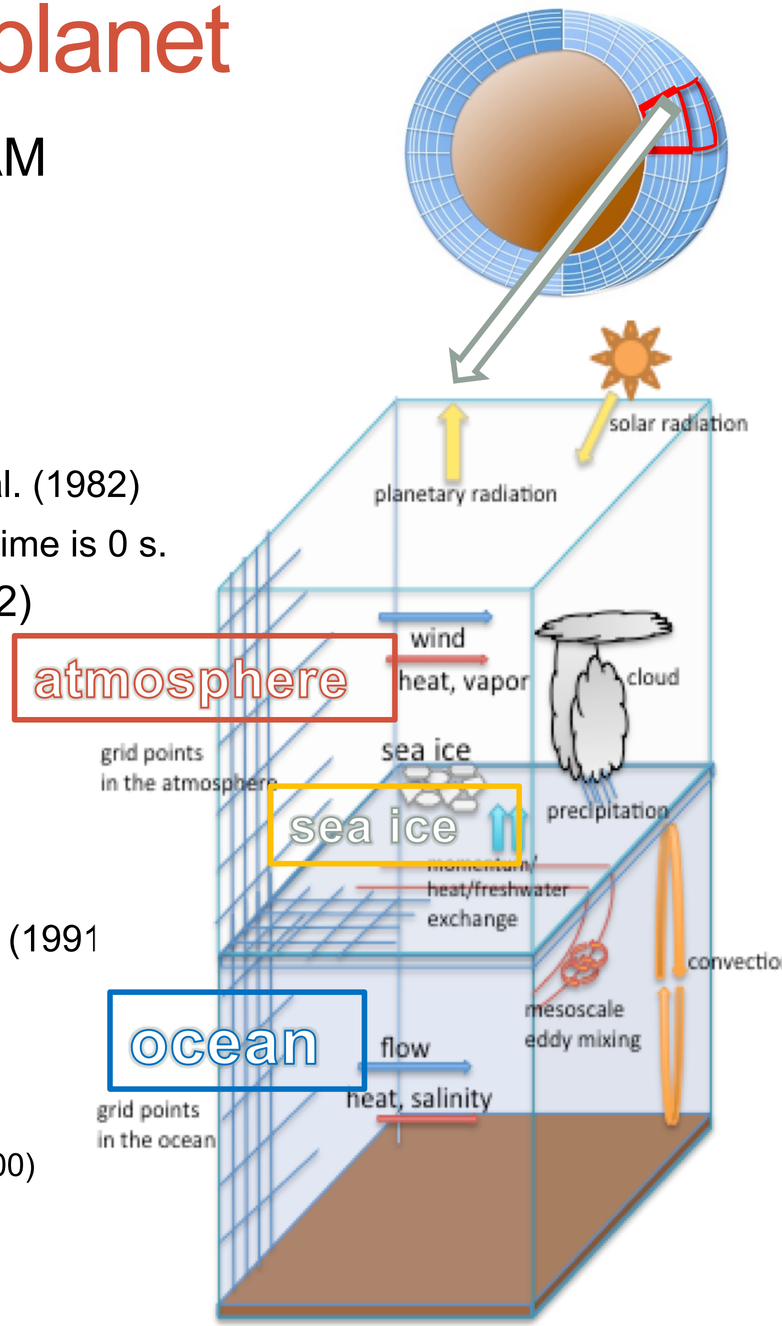
- A climate model for ocean planet
- Experimental setup

A climate model for ocean planet

- Atmospheric general circulation model: DCPAM
  - Composition: dry air, water vapor
  - Dynamical process
    - 3-dimensional primitive equations
  - Radiation process: gray radiation (Nakajima et al., 1992)
  - Turbulent process: Mellor and Yamada (1982), Louis et al. (1982)
  - Condensation process: Manabe et al. (1965), cloud life time is 0 s.
  - Spatial resolution: 64x32x16or32 (T21L16 or T21L32)

- Ocean general circulation model
  - Dynamical process
    - *Axisymmetric* hydrostatic boussinesq equations
  - Turbulent process:
    - Redi (1982), Gent and McWilliams (1990), Marotzke (1991
  - Spatial resolution: 64x60

- Sea ice model
  - Thermodynamics process: 3-layer model (Winton, 2000)
  - The horizontal transport of sea ice is parametrized with horizontal diffusion.
  - Spatial resolution: 64x3



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- Coupler
  - exchange data between models with Jcup (Arakawa et al., 2011)

Using periodically synchronous coupling (Sausen and Voss, 1998), the temporal integration is basically performed over 30,000 years.

Experimental setup

- The range of solar constants(S)
  - 900～1600 W/m^2 (S=1380 W/m^2 is set in control case)
- Planetary parameters
  - The value of the parameters (e.g., planetary radius) is same as that on present Earth.
- No seasonal and day cycles
  - The annual and daily averaged incoming solar flux is given in top of atmosphere.
- Surface albedo
  - 0.5 when surface temperature is below 263 K, otherwise 0 (step-function).
- Initial condition
  - For most of cases, a rest atmosphere and ocean with 280K.
  - To find multiple solutions, partially ice-covered, snow ball and runaway greenhouse solutions are also used.
- Ocean configurations

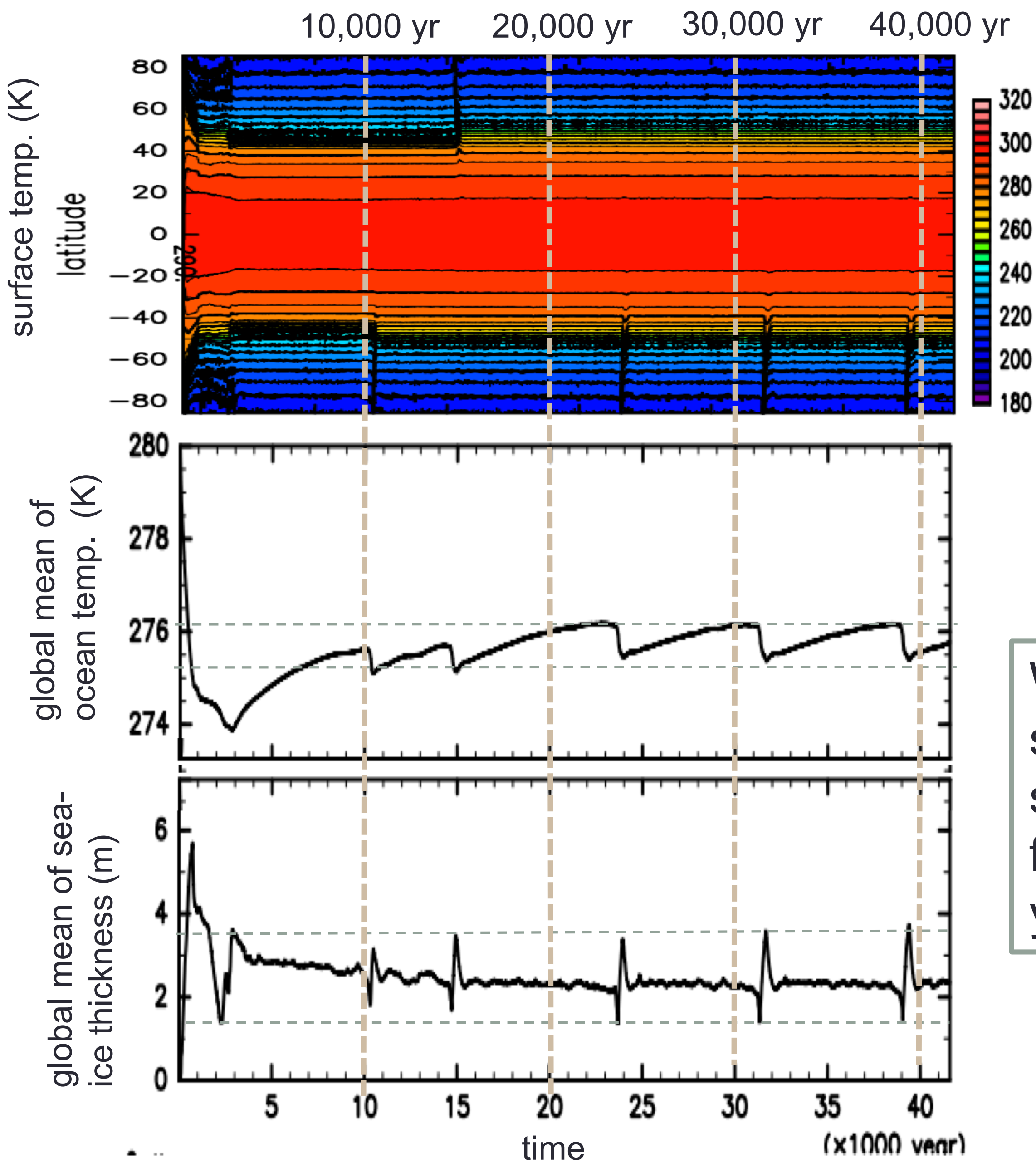
	oceanic heat capacity	oceanic heat transport
dynamic ocean*	○	○
60 m slab ocean	○	×
swamp ocean	×	×

* ocean general circulation model is used.

Numerical results

- control case (S=1380 W/m^2, dynamic ocean)
- solar constant dependence experiments

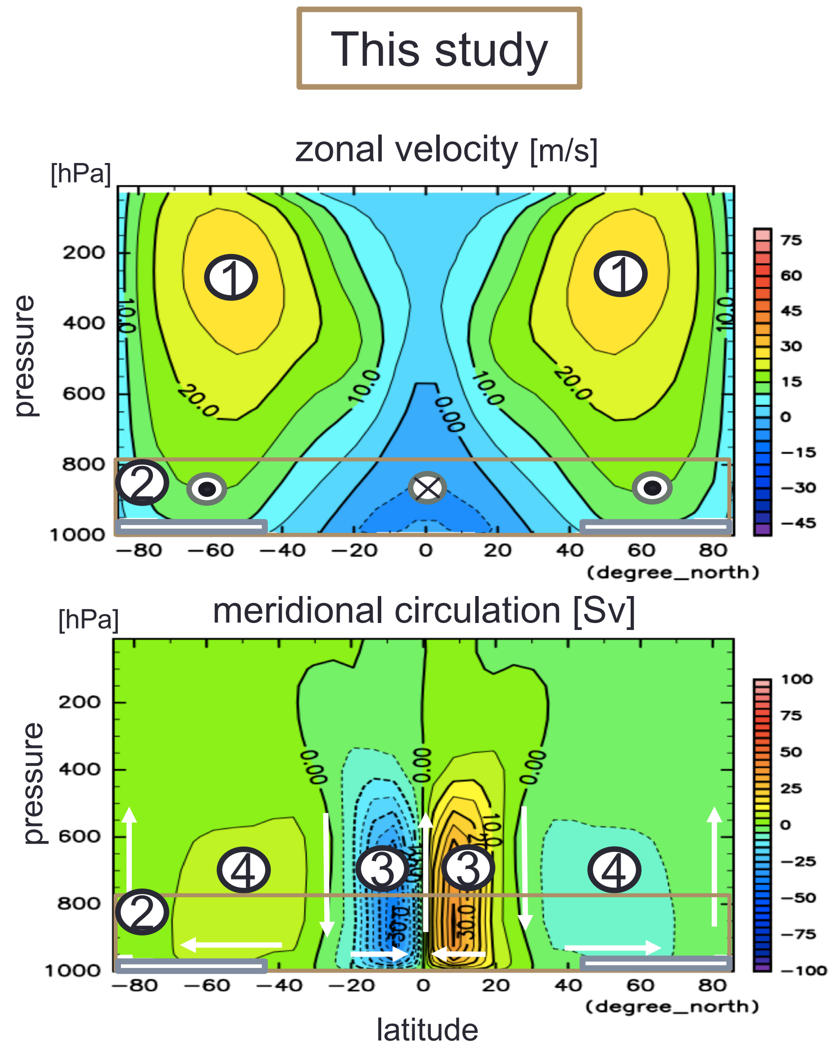
Result (control): time series

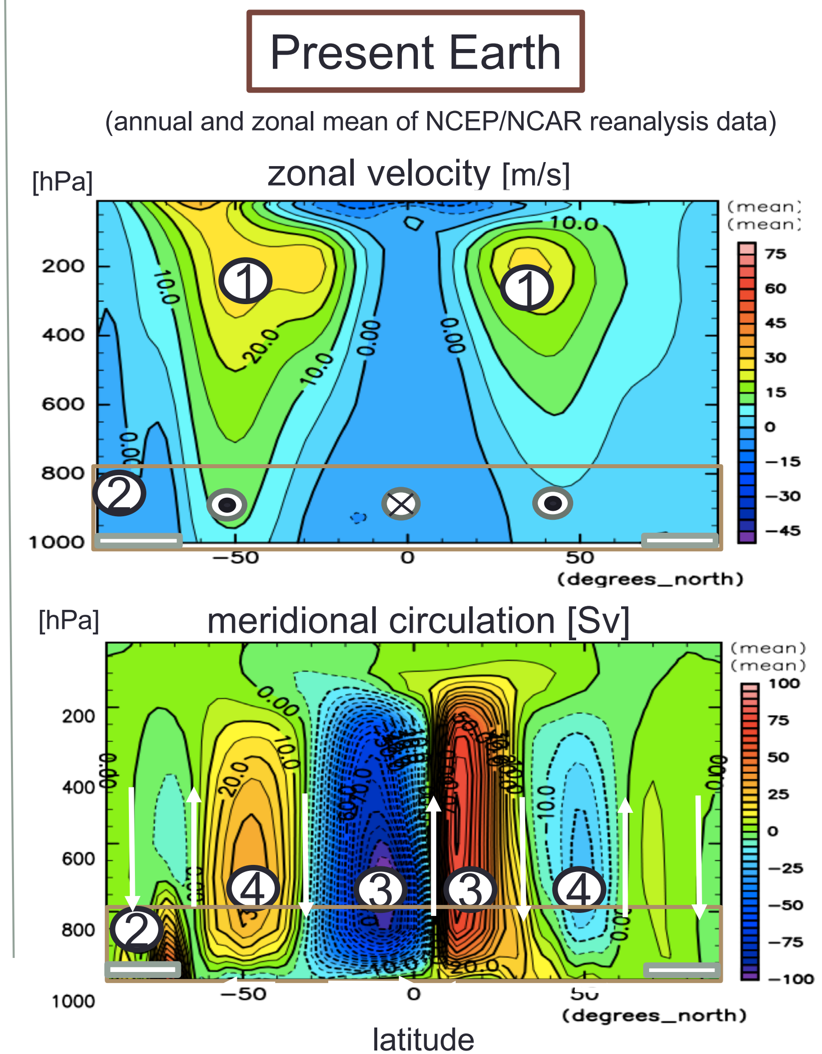


- The coupled system reaches a statistically equilibrium state after a few ten thousand years.
- After the system reached equilibrium, periodic oscillation can be seen.

We show some figures of statistically equilibrium state obtained by averaging fields over the final 20,000 years.

Result: comparison with atmospheric fields on present Earth





Some fundamental atmospheric features on present Earth are represented in our using atmospheric setting.

- ① westerly jet, ② surface wind, ③ Hadley cell, ④ Ferrel cell …

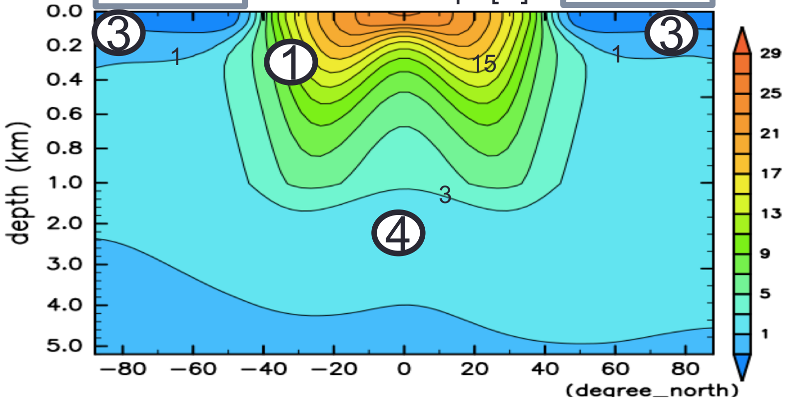
Result: comparison with oceanic fields in a previous study

This study — axisymmetric ocean model

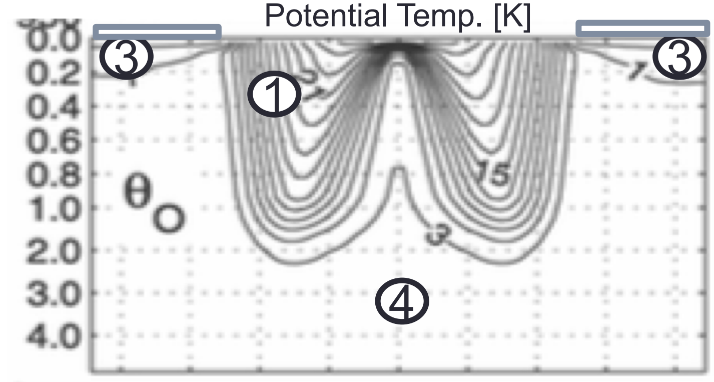
Ocean planet — 3-dim ocean model

[result with a coupled atmosphere-ocean-sea ice model in Marshall et al. (2007)]

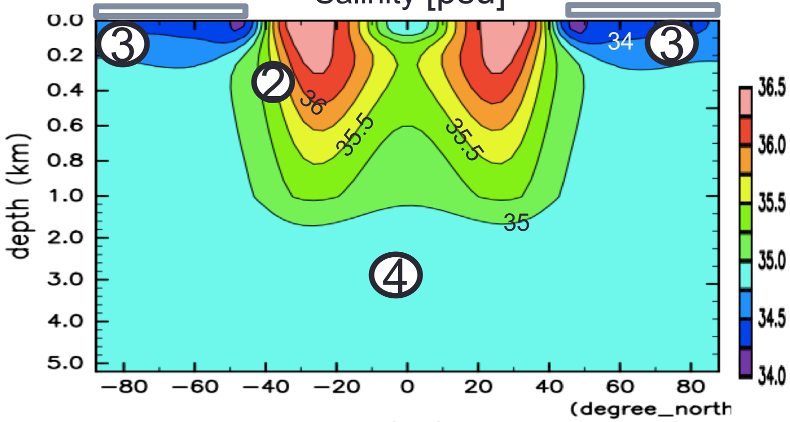
Potential Temp. [K]



Potential Temp. [K]

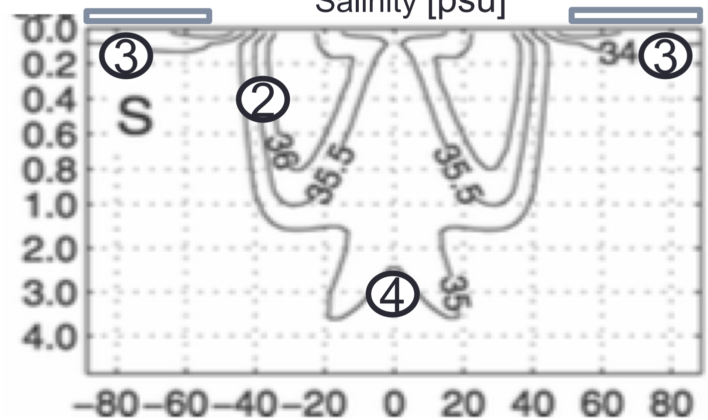


Salinity [psu]



latitude

Salinity [psu]

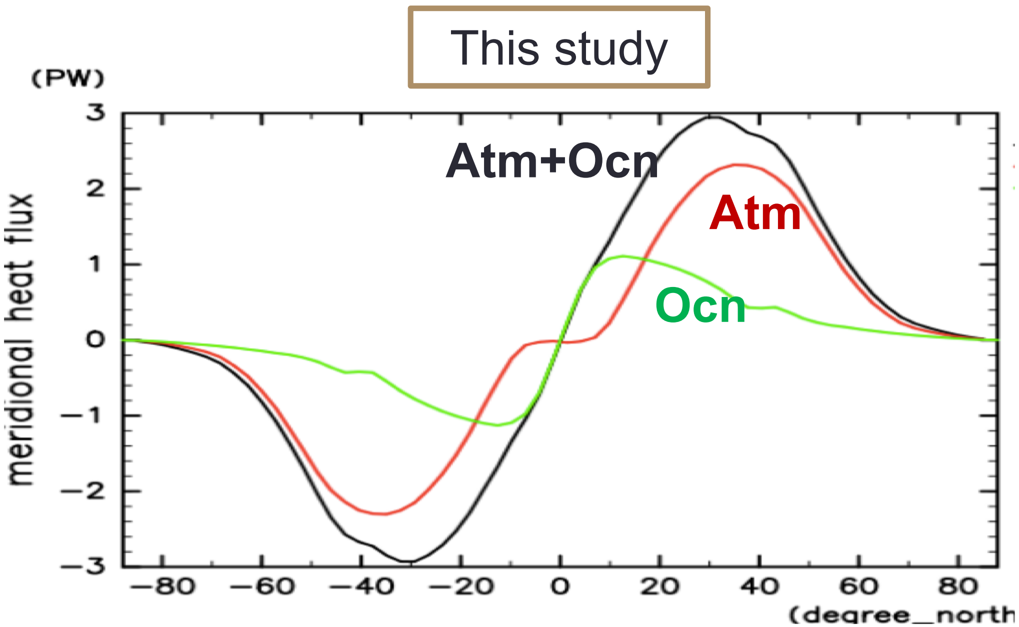


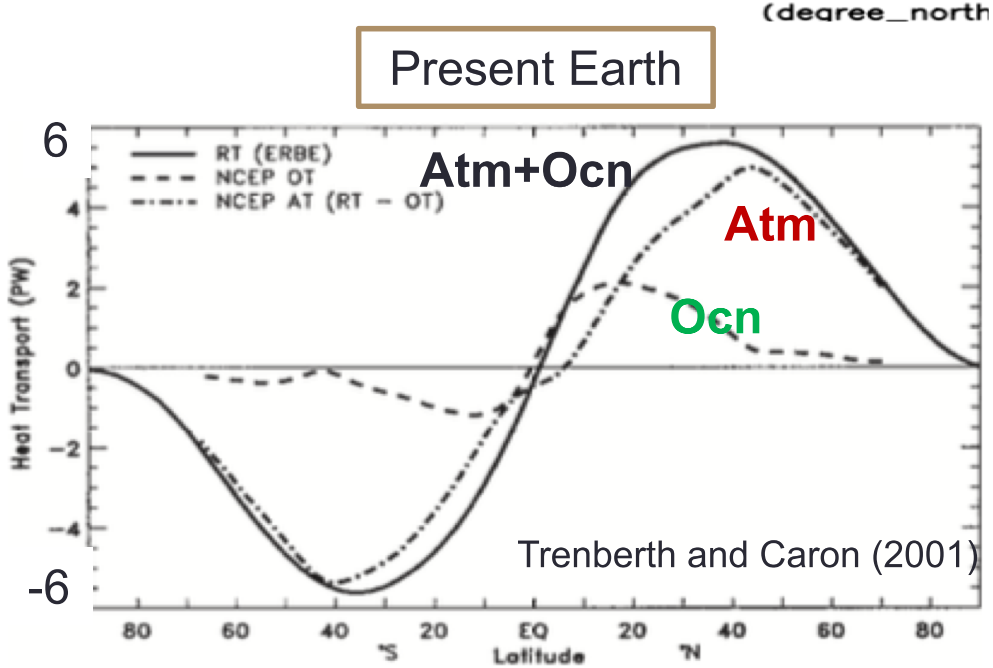
latitude

The patterns of calculated ocean fields are quite similar with results obtained from previous studies.

- ① thermocline, ② halocline, ③ stratified structure under sea-ice, ④ uniform profile in deep ocean ..

Result: meridional heat transport



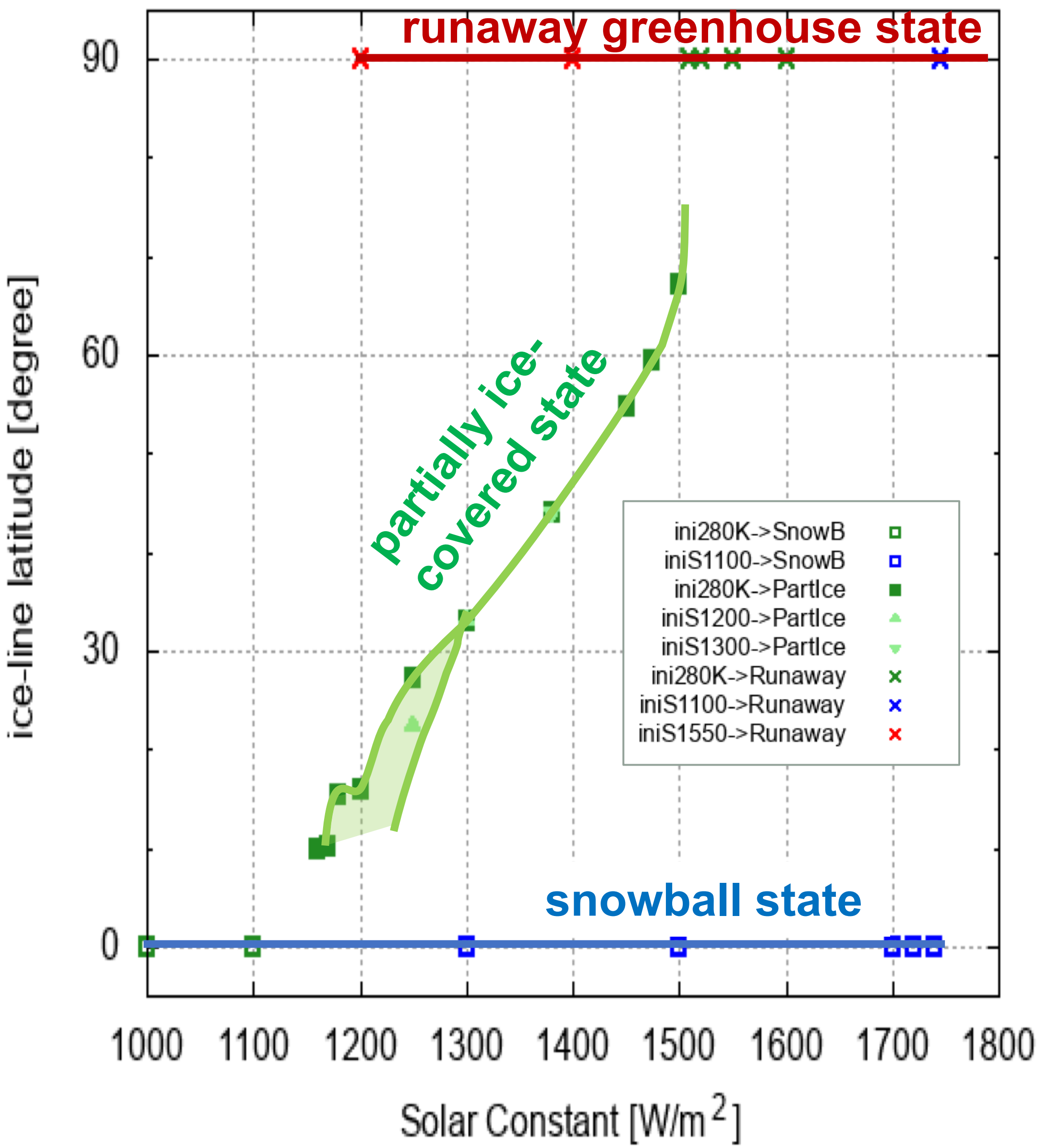


- The total (atmosphere plus ocean) heat transport reaches a maximum 3 PW at 30° N/S.
  - This amount of heat transport is about half of that in present Earth and previous studies.
- Despite nonexistence of the land, the latitudinal profiles and partitioning of meridional heat transports are similar to that on present Earth.

Numerical results

- control case (S=1380 W/m^2, dynamic ocean)
- solar constant dependence experiments

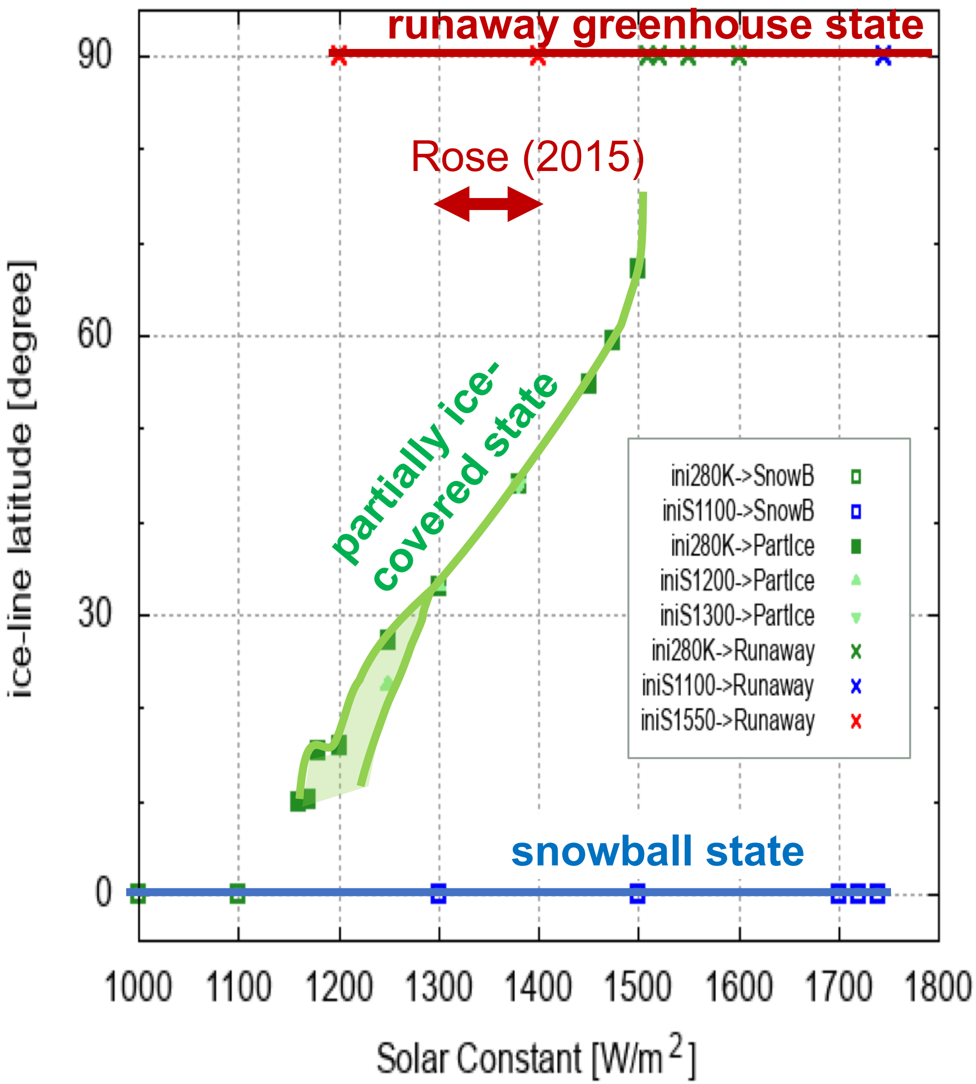
Results: climatic regime diagram (dynamic ocean case)



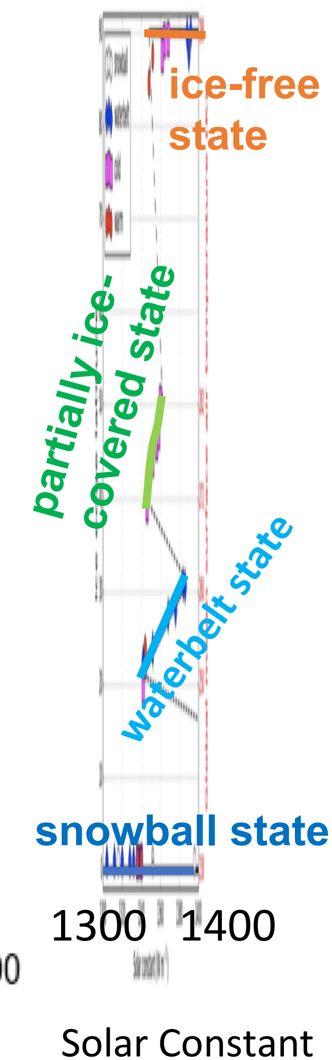
- We have obtained a climatic regime diagram for a coupled system possible to reach runaway greenhouse states.
- The number of climatic states is three: snowball, partially ice-covered and runaway greenhouse states.
  - Ice-free state is not found.
- These climatic states coexist for a solar constant between about S=1200～S1500 W/m^2 .
- Small dependence of partially ice-covered states on initial condition exists (shaded region).

Results: climatic regime diagram (dynamic ocean case)

This study

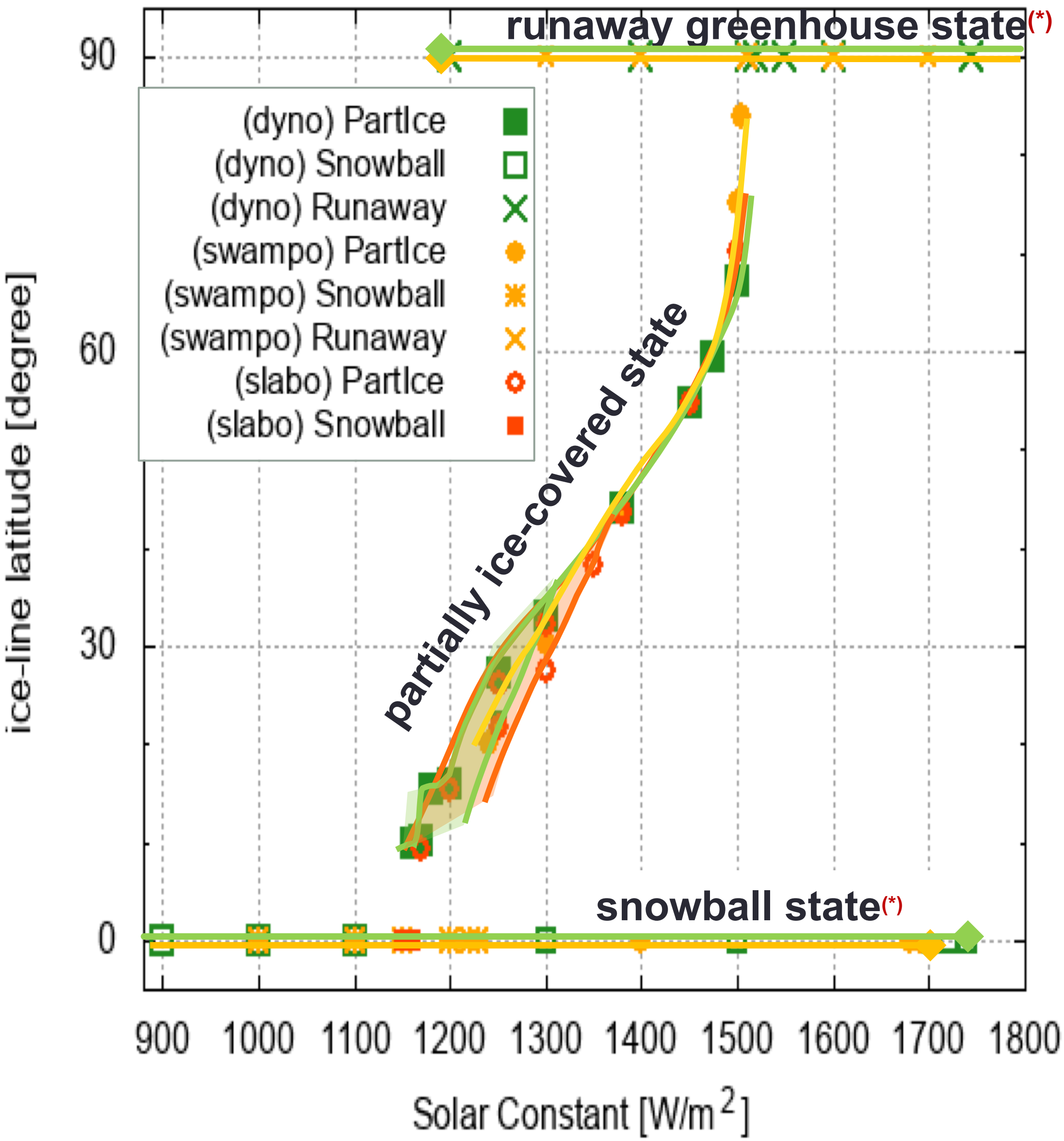


Rose (2015)



- The branch of partially ice covered state is not split unlike the regime diagram in Rose (2015).
- Compared to the result in Rose (2015), the slope of branch for partially ice-covered state is gentle which is related to weak meridional heat transports.

Results: climatic regime diagram for swamp/slab/dynamic ocean experiments



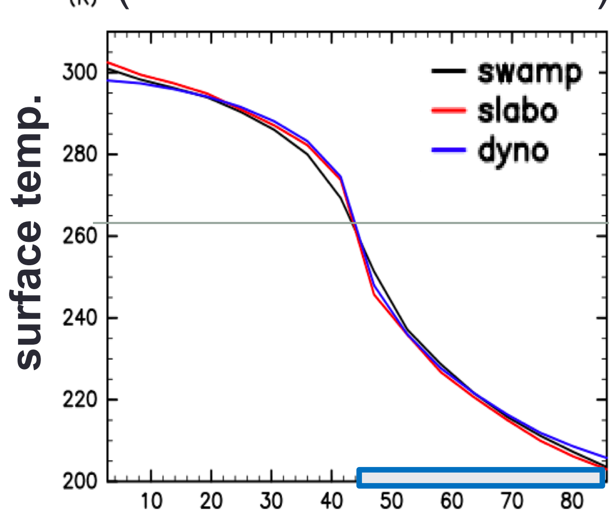
(* The branches of runaway greenhouse and snowball states in slab ocean configuration are being calculated now.)

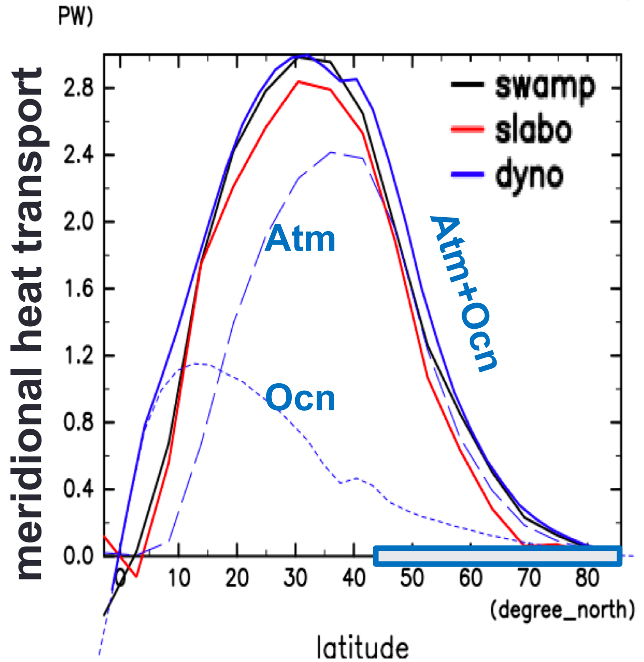
- Most of the ice-line latitudes for partially ice-covered states are nearly independent of the oceanic treatments.
    - In these experiments, oceanic capacity and oceanic heat transport have no essential impact on determining the climates.
- In slab and dynamic ocean experiments, small dependence of partially ice-covered states on initial condition can be seen.

Discussion: Why does the difference between oceanic treatments have no essential influence on climates?

- In fact, there are some differences of surface temperature latitudinal profiles between three ocean treatments.
  - The surface energy budget partitioning also changes significantly.
- But, heating due to ocean heat transport is not enough to retreat sea ice and maintain ice-line.
  - The magnitude itself or meridional convergence is weak.
- Furthermore, in radiative and cloud setting of INTH07, unless ice-line moves, the profile of absorbed solar radiation does not change.
  - Then, a total of atmospheric and oceanic heat transports is independent of oceanic treatments.
- Consequently, we consider that the introduction of oceanic heat capacity and transport have no essential influence on planetary climates.

(case of S=1380 W/m²)





Summary

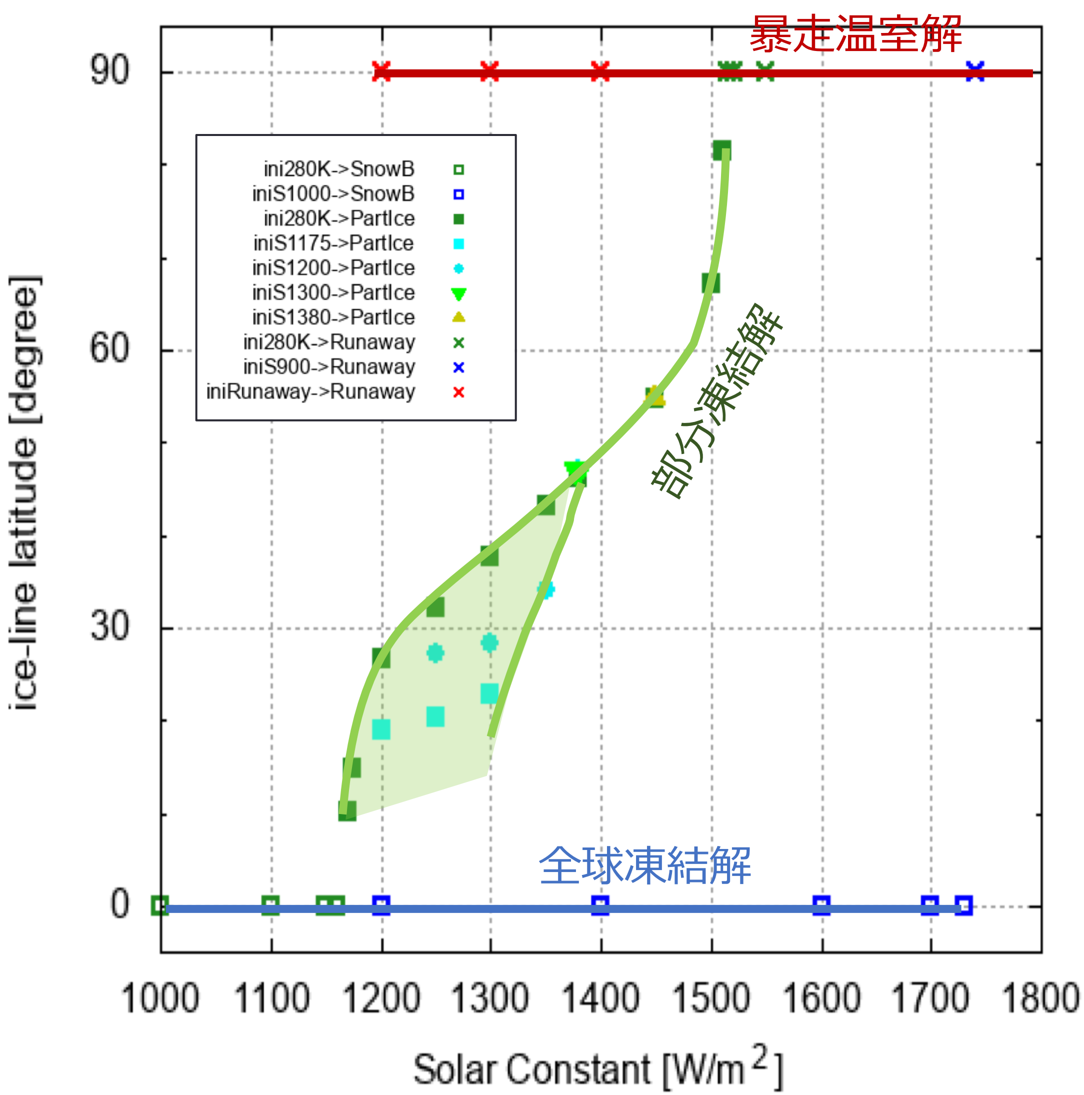
- Using our developing coupled atmosphere-ocean-sea ice model with the atmospheric setting in Ishiwatari et al. (2007), we investigate the dependence of ocean planet climates on solar constant.
  - In control case (S=1380W/m^2), our model represents typical features of atmospheric fields on present Earth and oceanic fields obtained by previous studies.
  - Increasing and decreasing the solar constant, we have obtained a climatic regime diagram for a coupled system possible to reach runaway greenhouse states.
    - Snowball, partially ice-covered and runaway greenhouse states are found.
    - These states coexist over about S=1200～S1500 W/m^2.
  - In order to examine the role of ocean more closely, we also conduct swamp/slab/dynamic ocean experiments.
    - In the experimental setting of INTH07, the introduction of oceanic heat capacity and oceanic heat transport has no essential impact on determining ocean planet climates.

References

- Budyko, M. I., 1969: The effect of solar radiation variations on the climate of the earth. *Tellus*, **21**, 611–619.
- Ferreira, D., J. Marshall, and B. Rose, 2011: Climate determinism revisited: multiple equilibria in a complex climate model. *J. Climate*, **24**, 992–1012.
- Ishiwatari, M., K. Nakajima, S.-i. Takehiro, and Y.-Y. Hayashi, 2007: Dependence of climate states of gray atmosphere on solar constant: From the runaway greenhouse to the snowball states. *J. Geophys. Res*., 112.
- Rose, B. E., 2015: Stable“ waterbelt ”climates controlled by tropical ocean heat transport: A nonlinear coupled climate mechanism of relevance to snowball earth. *J. Geophys. Res*., **120**, 1404–1423.
- Sellers, W. D., 1969: A global climatic model based on the energy balance of the earth-atmosphere system. *J. Appl. Metor.*, **8**, 392–400.

Appendix 1: climatic regime diagram obtained with solar constant experiments in the case of using surface albedo scheme in INTH07

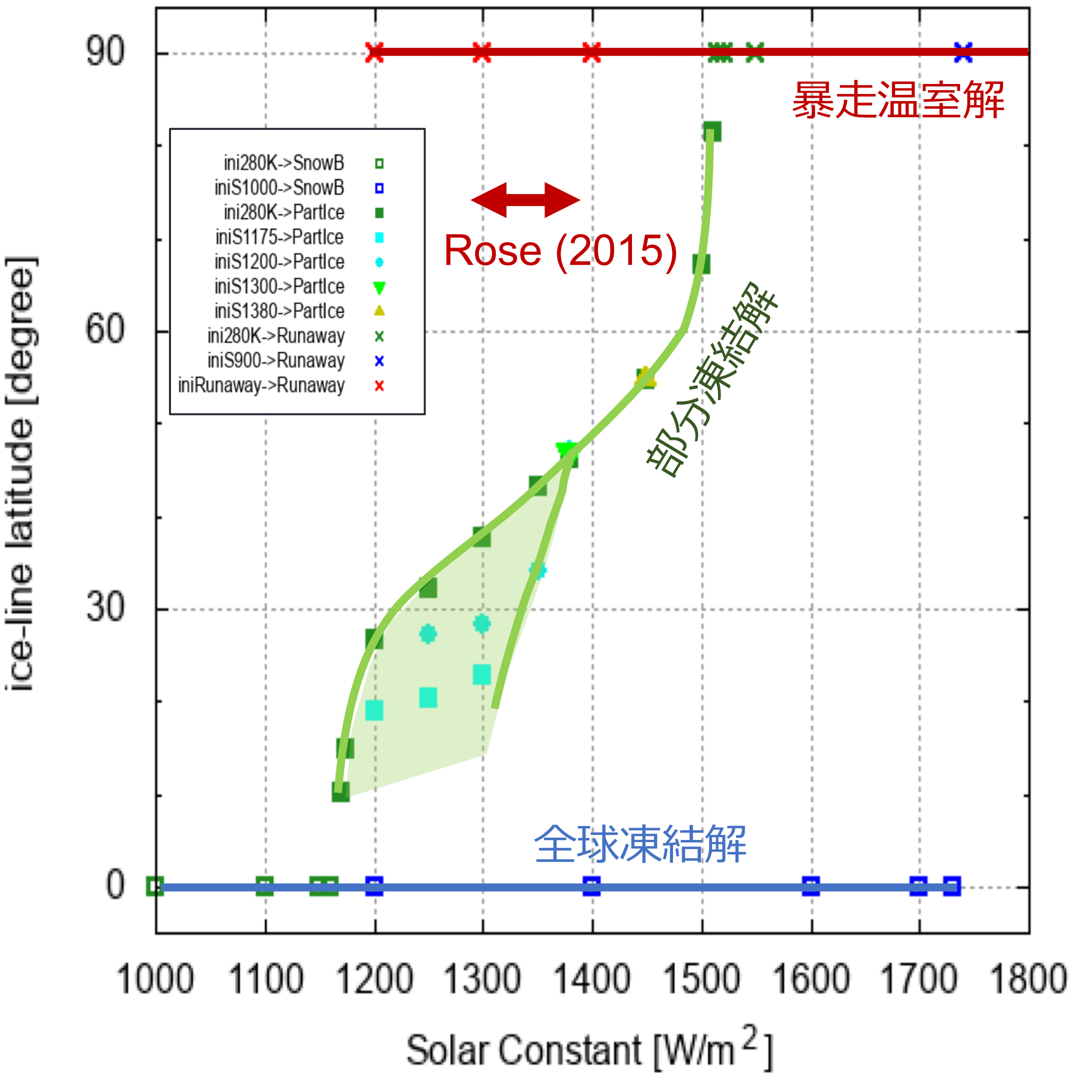
太陽定数増減実験: 気候レジーム図 (dynamic ocean 実験の場合)



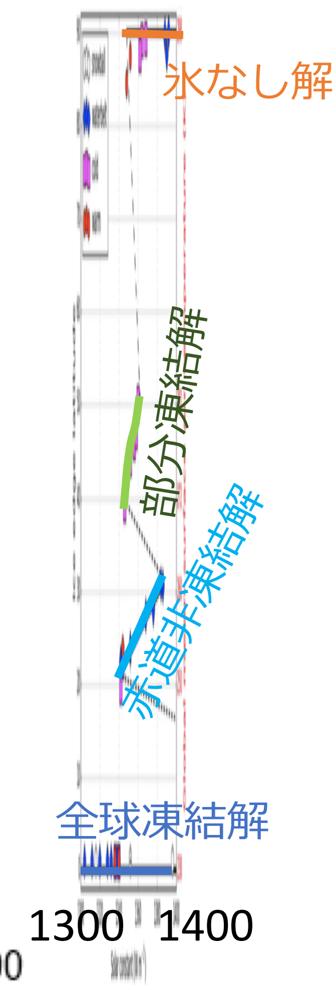
- 全球凍結解, 部分凍結解, 暴走温室解が得られる.
  - 氷なし解は見つからない.
- 約 S=1200〜S1520 W/m^2 の範囲で, 同じ太陽定数に対して 3 つの解が共存する.
- 部分凍結解には初期値依存性が見られる.

太陽定数増減実験: 気候レジーム図

本研究 (dynamic ocean 実験)

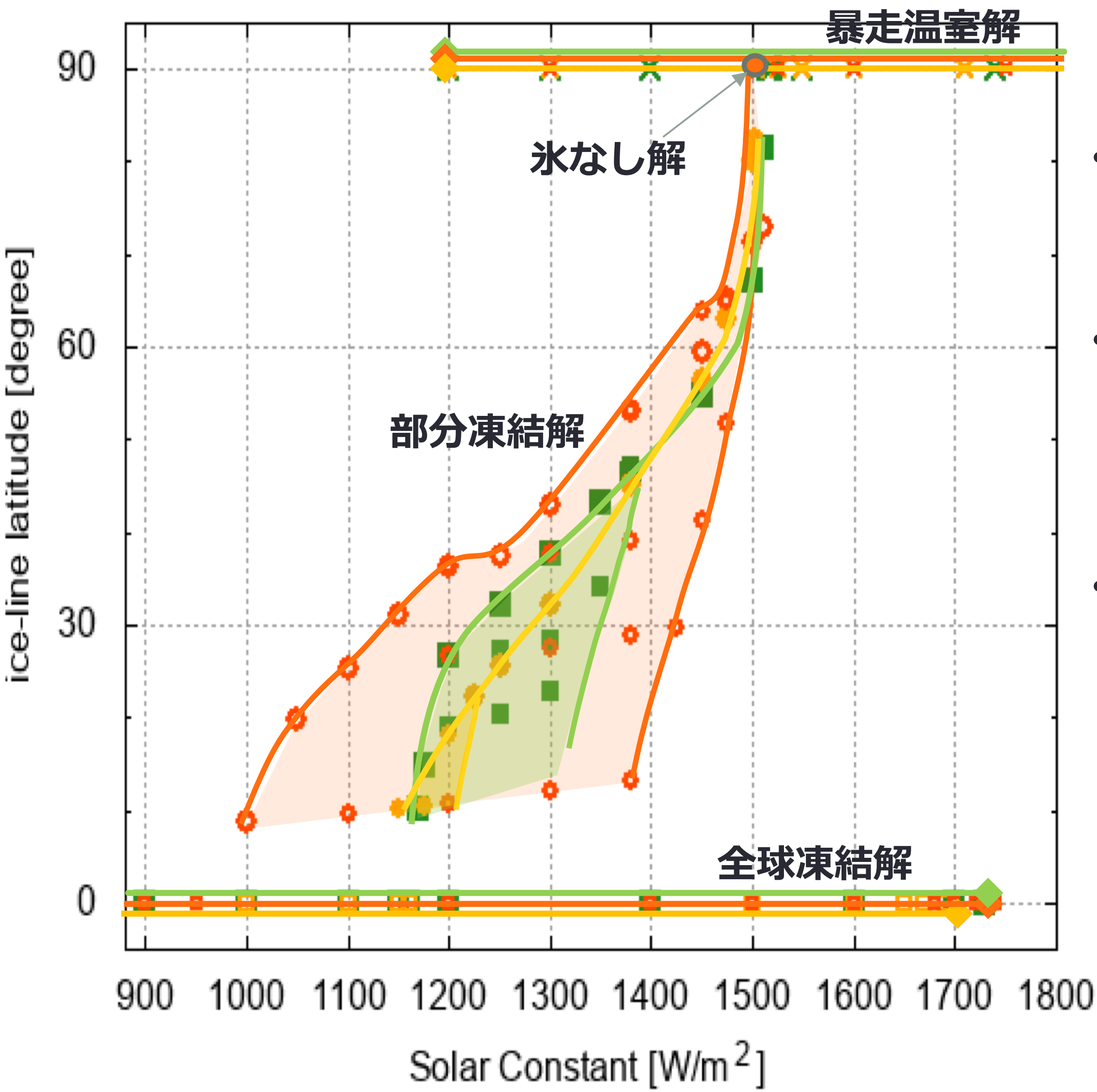


Rose (2015)



- Rose (2015) が示唆した, 海洋熱輸送による部分凍結解のブランチの分断は見られない.
- Rose (2015) と比べると, 太陽定数に対する氷線緯度の変化が小さい.

太陽定数増減実験: 海洋熱容量・海洋熱輸送の効果

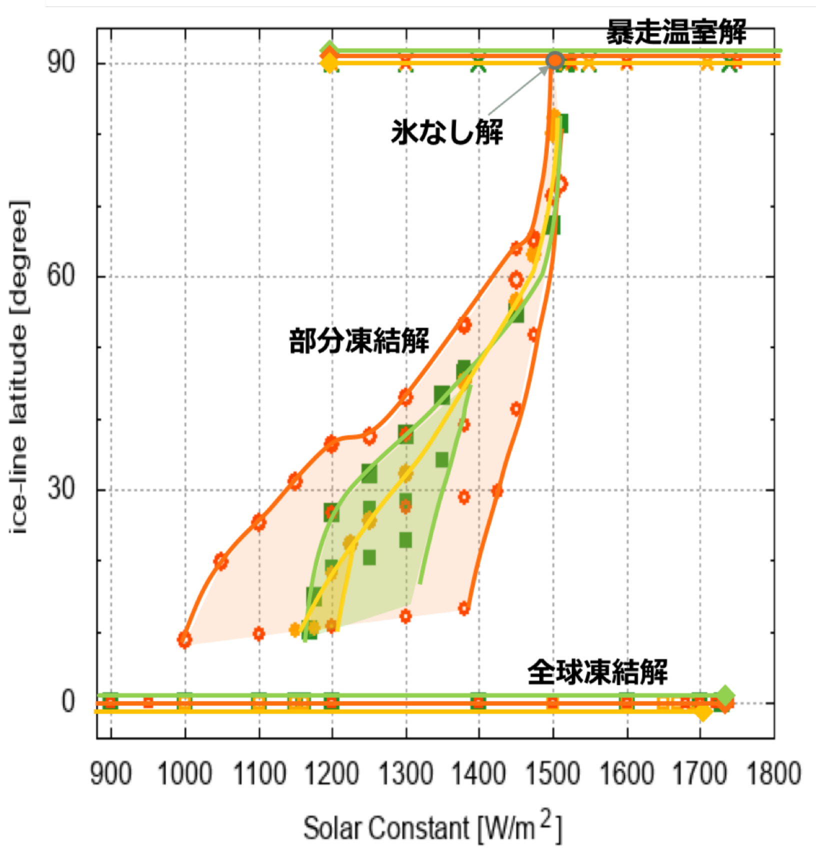


緑: dyno (海洋熱輸送あり・海洋熱容量あり)
橙: slabo (海洋熱輸送なし・海洋熱容量あり)
黄: swampo (海洋熱輸送なし・海洋熱容量なし)

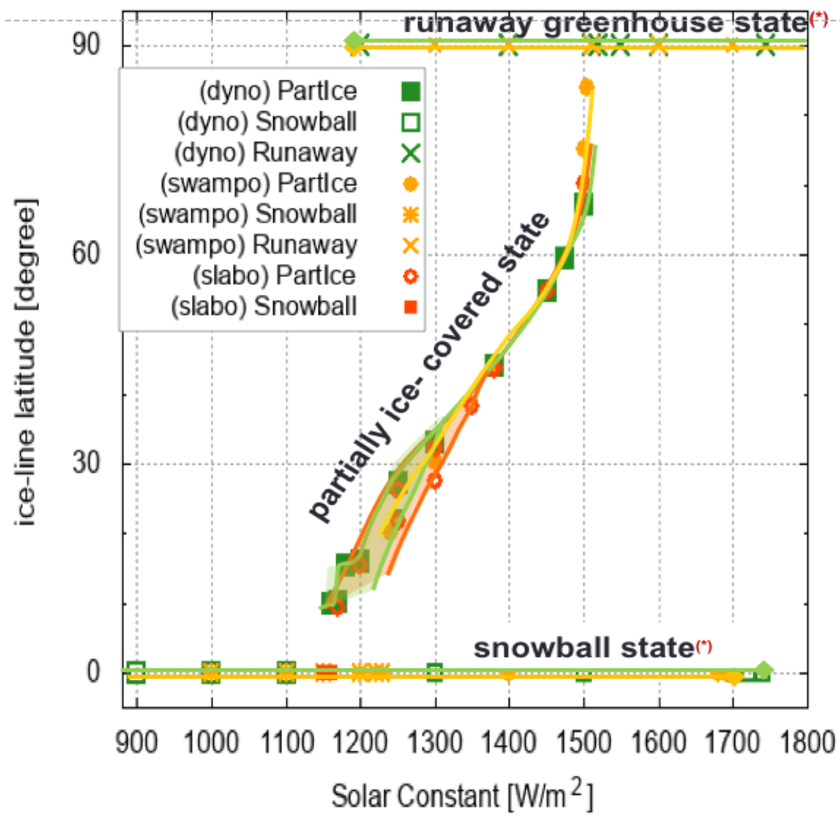
- 海洋熱容量・海洋熱輸送によって, 部分凍結解のブランチの構造は劇的には変化しない.
- 部分凍結解の初期値依存性が大きいため, 海洋の取り扱いに伴う氷線緯度の差を議論することは難しい
- この問題は, 表面アルベドを決める表面温度の不連続性とモデルの南北低解像度に起因する.
  - Held and Suarez (1974) での議論と本質的に同じ
  - 南北一次元エネルギー・バランスモデルによる検証から, セル内の海洋・海氷面積比を考慮して表面アルベドを決定すれば, 初期値依存性を軽減できることが分かってきた.

太陽定数増減実験: 表面アルベドの与え方を工夫した場合

表面アルベド工夫なし



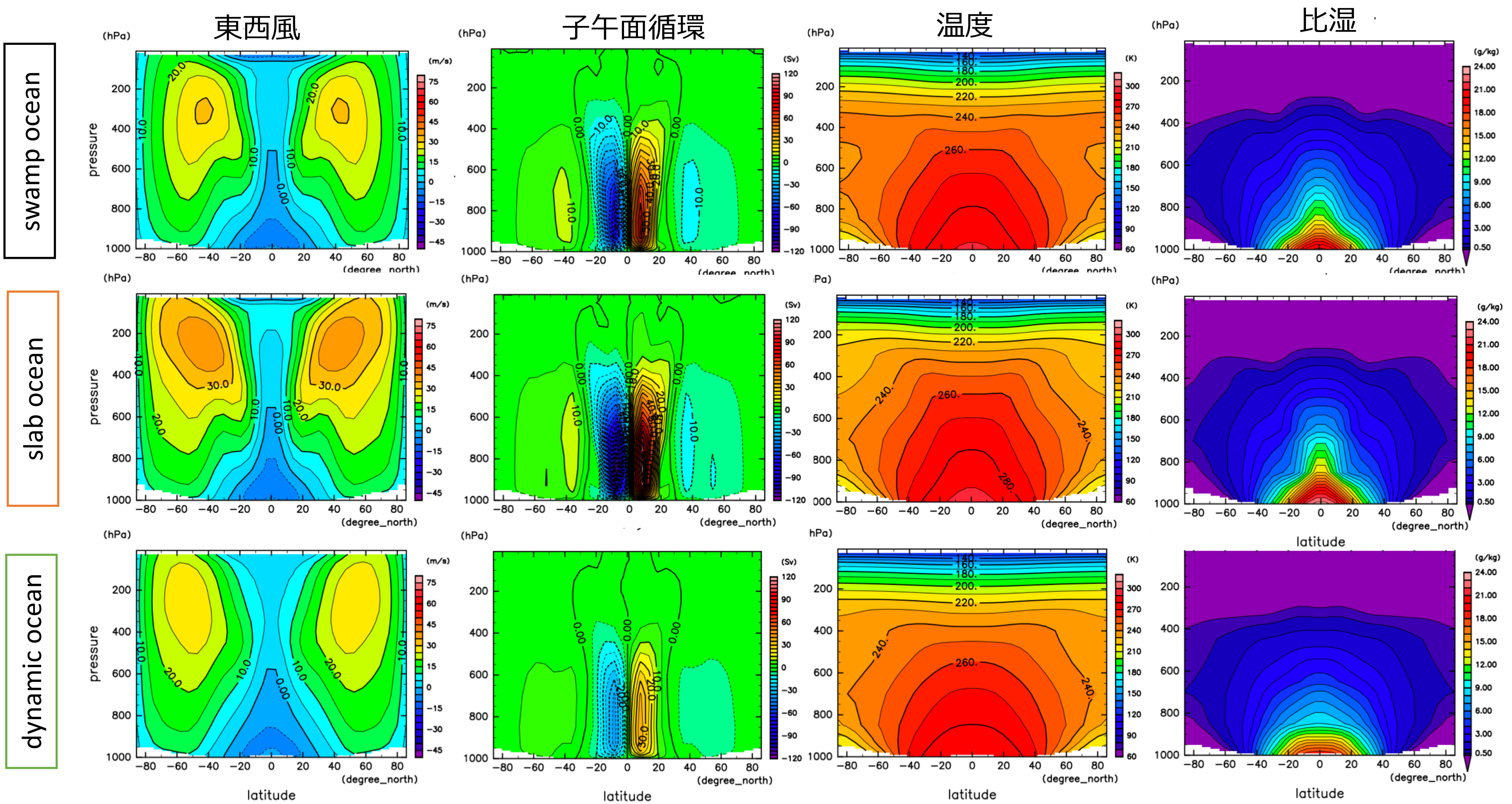
表面アルベド工夫あり



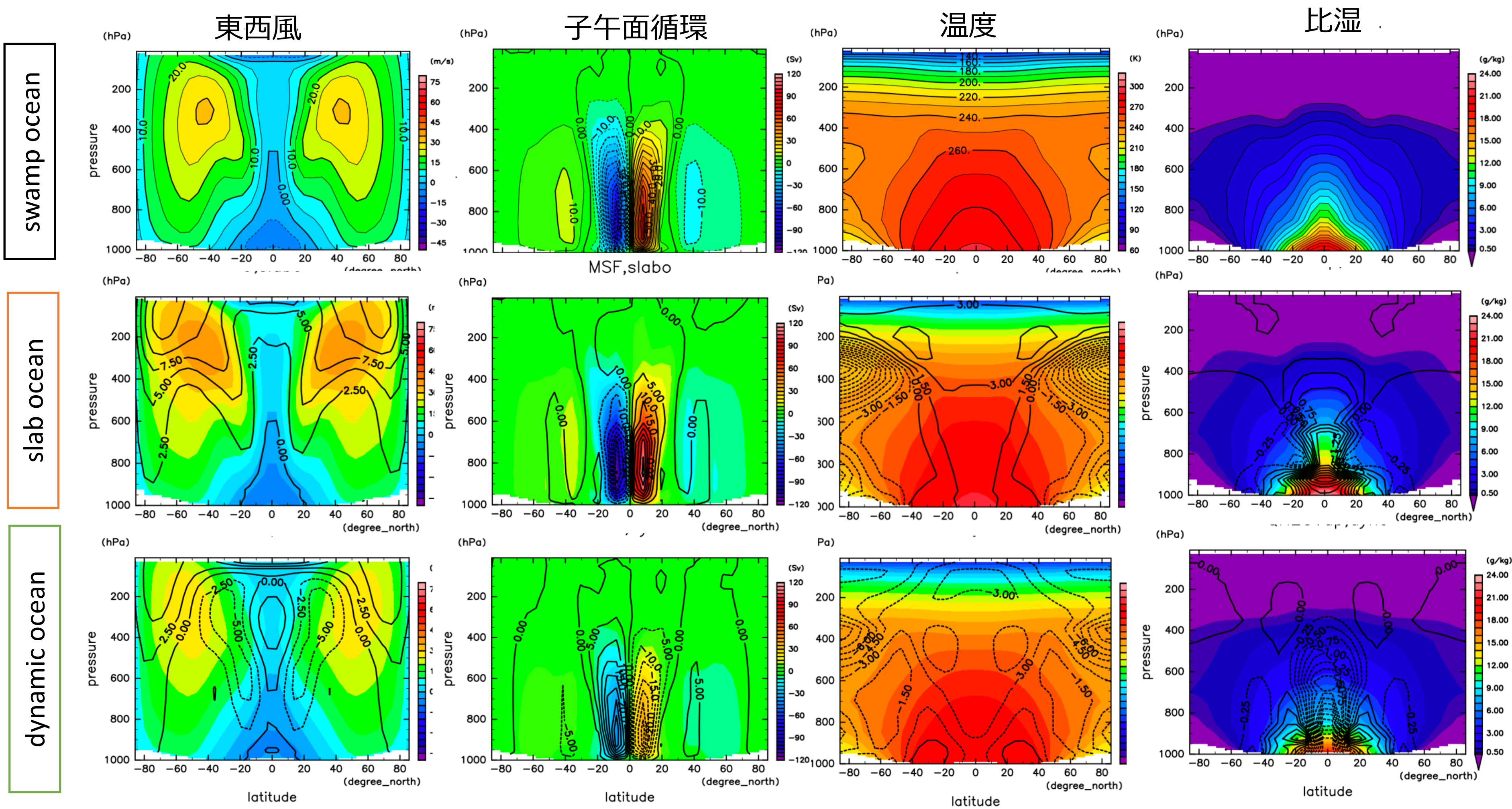
- 部分凍結解の初期値依存性が大幅に小さくなるが, slab/dynamic ocean 実験で多少残る.
- 部分凍結解の氷線緯度は, 海洋の取り扱いにあまり依らない.
  - 海洋熱容量・海洋熱輸送の有無が, 気候決定に本質的な影響を及ぼしていない.

Appendix 2: Comparison with atmospheric fields obtained from three oceanic configurations

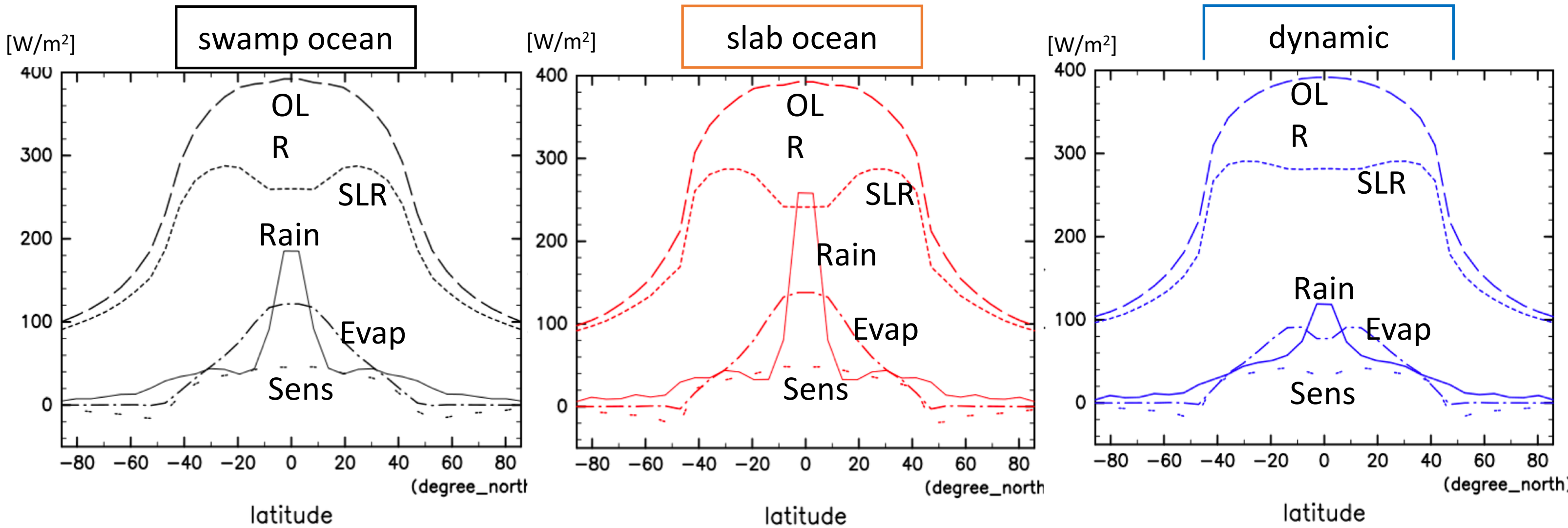
[参考] S=1380 W/m^2 に対する大気場

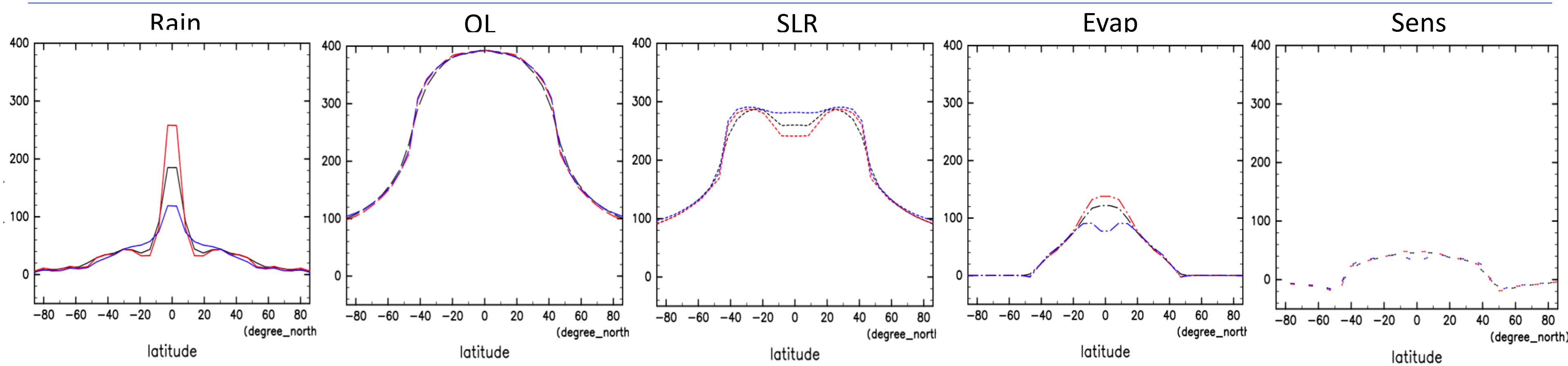


[参考] S=1380 W/m^2 に対する大気場, (コンター: swampo との差)



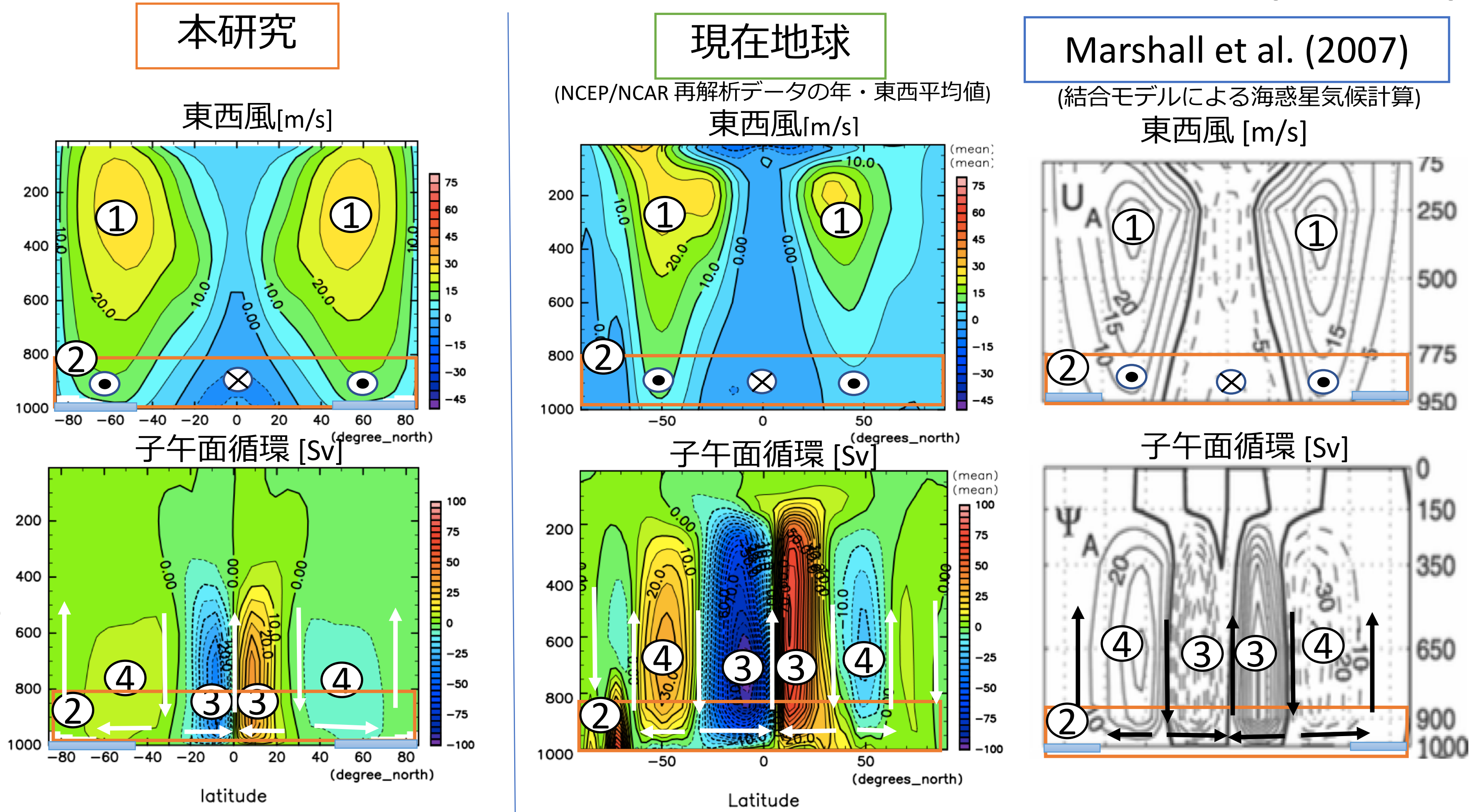
$S=1380\ W/m^2$ の場合 (氷線緯度 約 45 度)





Appendix 3: Other atmospheric fields in control case of dynamic ocean experiment

標準実験の結果: 先行研究との比較 (大気)



- ①西風ジェット, ②地表風速パターン, ③ ハドレー・セル, ④フェレル・セル 等 の現在地球で見られる基本的な大気大循環の特徴を再現する.
- 子午面循環の強度が弱い特徴は, 灰色大気設定に起因する.
- 海洋大循環を駆動する大気下層の循環パターンは, Marshall et al. (2007) が得たパターンと定性的には同じである.

標準実験の結果: 先行研究との比較 (大気)

本研究

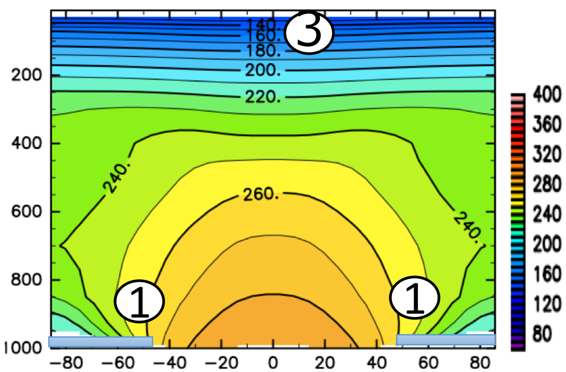
現在地球

(NCEP/NCAR 再解析データの年・東西平均値)

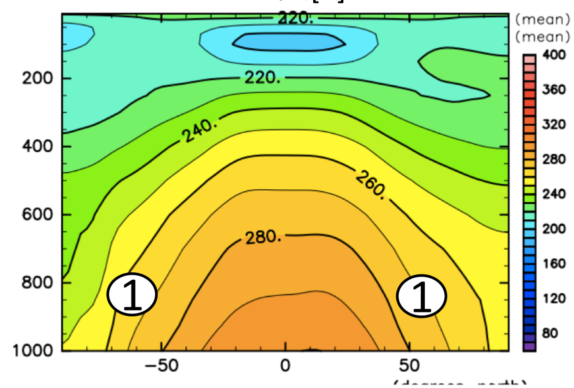
Marshall et al. (2007)

(結合モデルによる海惑星気候計算)

温度[K]

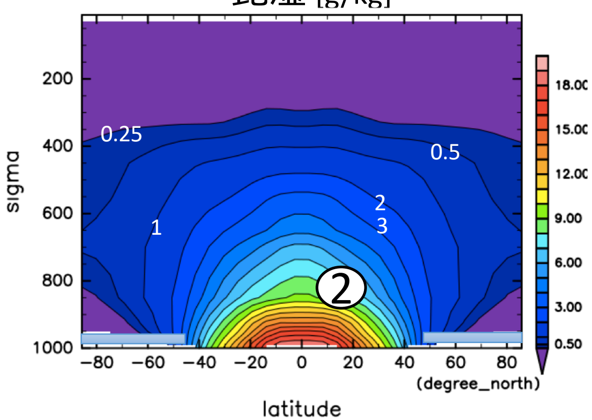


温度[K]

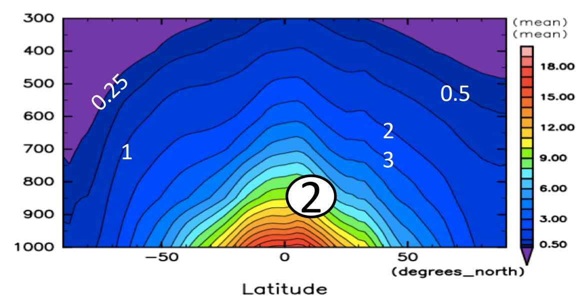


図の掲載なし

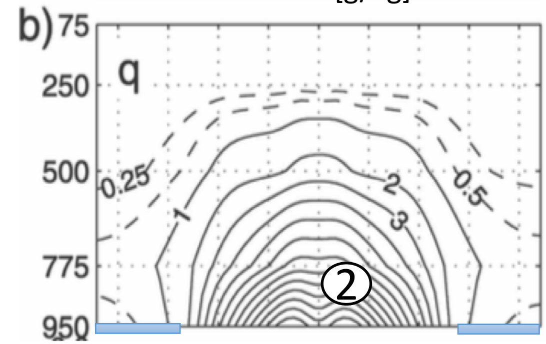
比湿 [g/kg]



比湿 [g/kg]



比湿 [g/kg]

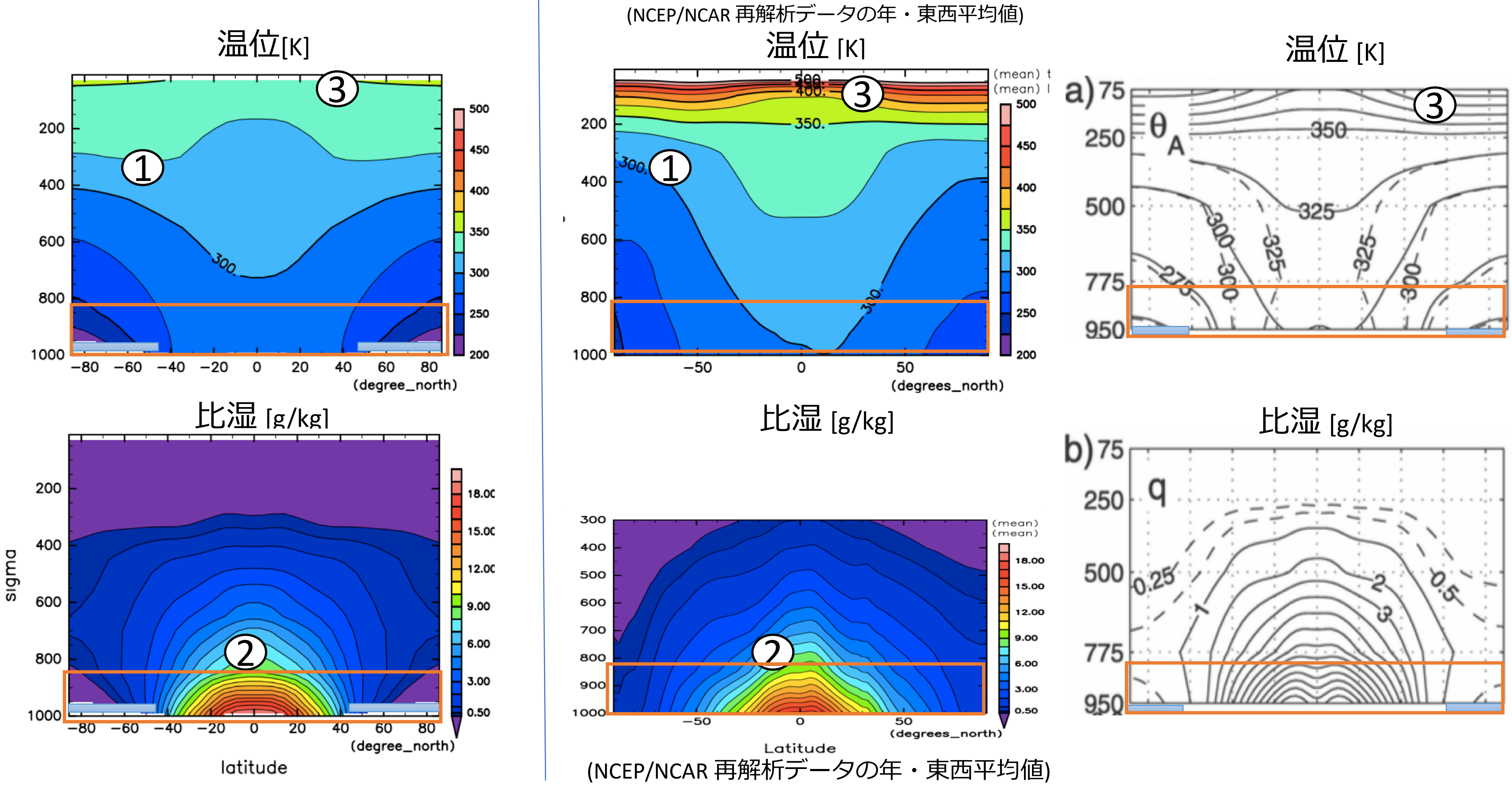


(NCEP/NCAR 再解析データの年・東西平均値)

- ① 南北温度勾配, ②赤道下層の高い比湿域 といった基本的特徴は, 現在地球の特徴を押さえている.

標準実験の結果: 先行研究との比較 (大気)

本研究 | 現在地球 | Marshall et al. (2007)



- 現在地球や Marshall et al. (2007) の結果と比較すると, 大気上層の温度場が放射過程の設定に起因して低温となる (③).
- しかし, 定性的な大気中層・下層の特徴は再現されている.