Development of a coupled model to explore aquaplanet climates and aquaplanet simulation with zonally symmetric dynamic ocean

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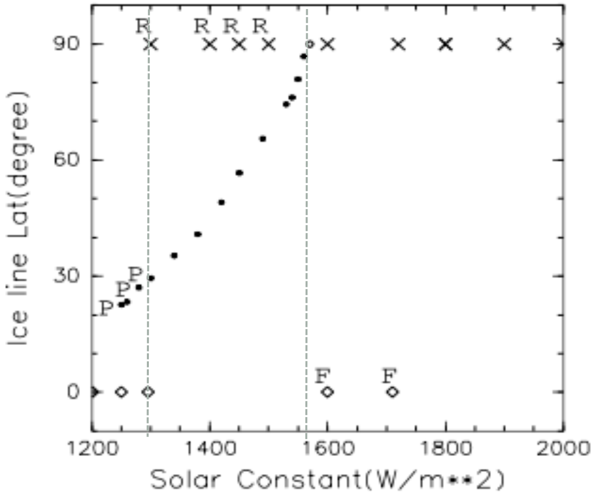
Outline of this presentation

- Background
- The purpose of our study
- Model description and experimental setup
- Results
  - An aquaplanet climate represented by our developing coupled model
  - Comparison with slab and swamp ocean experiments
- Discussion
- Conclusion

Background

- To explore the diversity of exoplanet surface environments, numerical simulations of exoplanet climates has been performed.

- Our research group has investigated the role of atmospheric general circulation on aquaplanet climates with an atmospheric general circulation model (AGCM).
  - For example
    - Ishiwatari ***et al.*** (2007) investigated the dependence of aquaplanet climates on solar constant.
- In our previous studies, the effect of ocean general circulation is **not** considered although the ocean heat transport also have an influence on determining planetary climates.

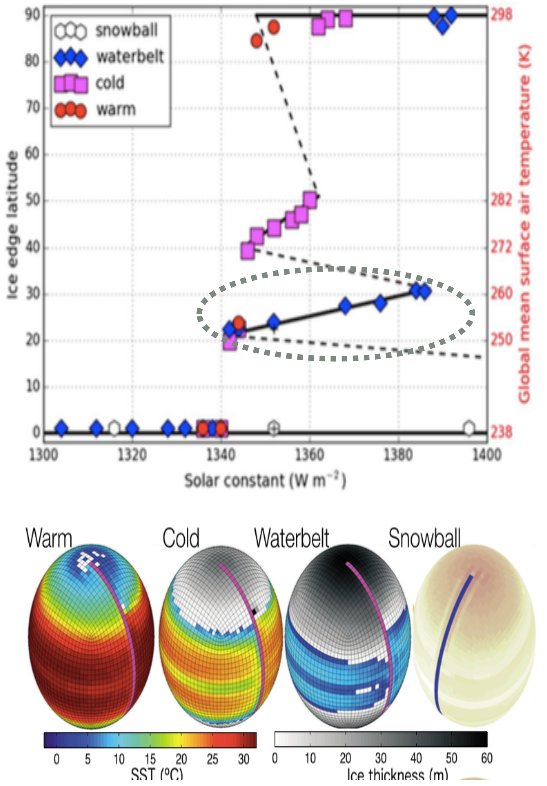


A climate regime diagram for aquaplanet climates obtained with an AGCM.
(Fig. 3 (a) in Ishiwatari et al., 2007)

Background

- Recently aquaplanet climates considering with ocean general circulation has been studied with coupled atmosphere-ocean-sea ice models.
  - For example
    - Smith ***et al***. (2006), Marshall ***et al***. (2006) : Pioneering works
    - Enderton ***et al***. (2009): Dependence of aquaplaet climates on the patterns of ocean general circulation
    - Ferreira ***et al***. (2011): Multiple equilibrium of aquaplanet climates in a coupled model
    - Rose ***et al***. (2015): Dependence of aquaplent climates on solar constant
  - Their results with coupled models indicate the importance of ocean heat transport for determining aquaplanet climates.

- However, in order to explore the diversity of exoplanet climates, we need further experiments of aquaplanet climates with coupled models in which fundamental parameters much different from that on present Earth should be set.
  - For example
    - Fresher or more salty sea water
    - Larger solar constant for which a runaway greenhouse state is obtained



A climate regime diagram for aquaplanet climates and four stable equilibrium state obtained with a coupled atmosphere-ocean-sea ice model.
(Fig. 1, 7 in Rosei et al., 2015)

The purpose of our study

- In order to explore the diversity of exoplanet climates considering with ocean circulation over wider range of planetary parameters, we started to developing ocean model and then coupled model about four years ago

- Our immediate goal
  - We perform solar constant dependence experiments in Ishiwatari et al. (2007) with considering ocean general circulation explicitly.
  - We are trying to create a climate regime diagram containing larger solar constant than that in previous study.

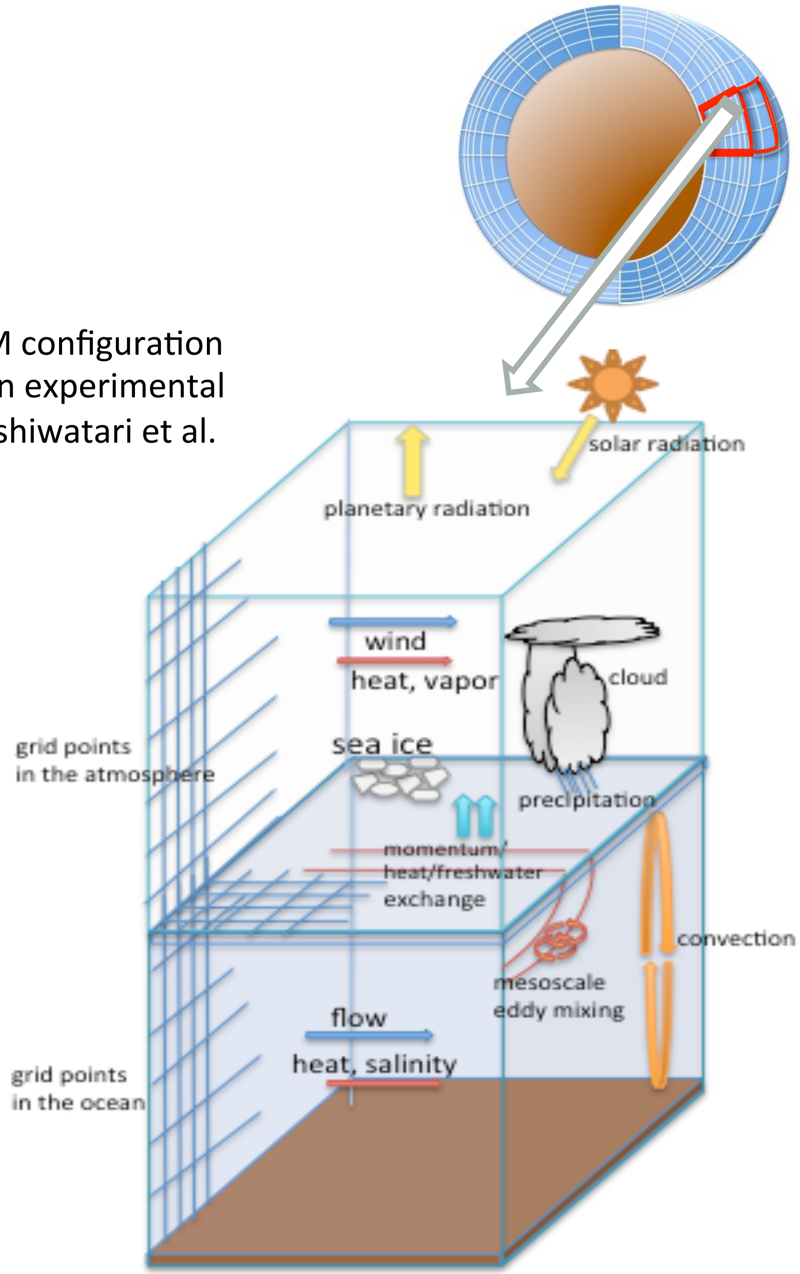
- In this presentation, our current status is presented.
  - We show some simulation results for solar constant of present Earth with our coupled model in which the setting of AGCM is same as experiments in Ishiwatari et al. (2007).
  - The result with coupled model is compared to that in slab and swamp ocean experiments in order to examine the impact of ocean large inertia and ocean heat transports.

Model description

- Atmosphere general circulation model: DCPAM (https://www.gfd-dennou.org/library/dcpam/)
  - Composition
    - dry air and water vapor
  - Dynamical process
    - 3-dimensional primitive equations, spectral Eulerian method
  - Radiation process
    - Gray radiation scheme
      - long-wave absorption coefficient for water vapor: 0.01 [m^2/kg]) (Nakajima et al., 1992)
  - Turbulent process
    - Mellor and Yamada (1982) level 2 scheme
    - Bulk formula (Louis et al., 1982)
  - Condensation process
    - Moist convective adjustment scheme (Manabe et al, 1965)
    - Large-scale condensation scheme (Manabe et al, 1965)
    - Cloud life time is set to zero.
  - Resolution: 32 x 64 x 26 (T21L26)

This AGCM configuration is based on experimental setup in Ishiwatari et al. (1998)

- Ocean general circulation model
  - Dynamical process
    - *Axisymmetric* (zonally averaged) hydrostatic boussinesq equations, spectral Eulerian method
  - Turbulent mixing process
    - Meso-scale eddy mixing scheme (Redi, 1982; Gent and McWilliams, 1990)
    - Convective adjustment scheme (Marotzke, 1991)
  - Resolution: 42 x 60
- Sea ice model
  - Thermodynamics process
    - 3-layer model (Winton, 2000)
  - The horizontal transport of sea ice is parametrized with horizontal diffusion.
- Coupler
  - Data exchange between components with Jcup (Arakawa et al., 2011)



Experimental setup

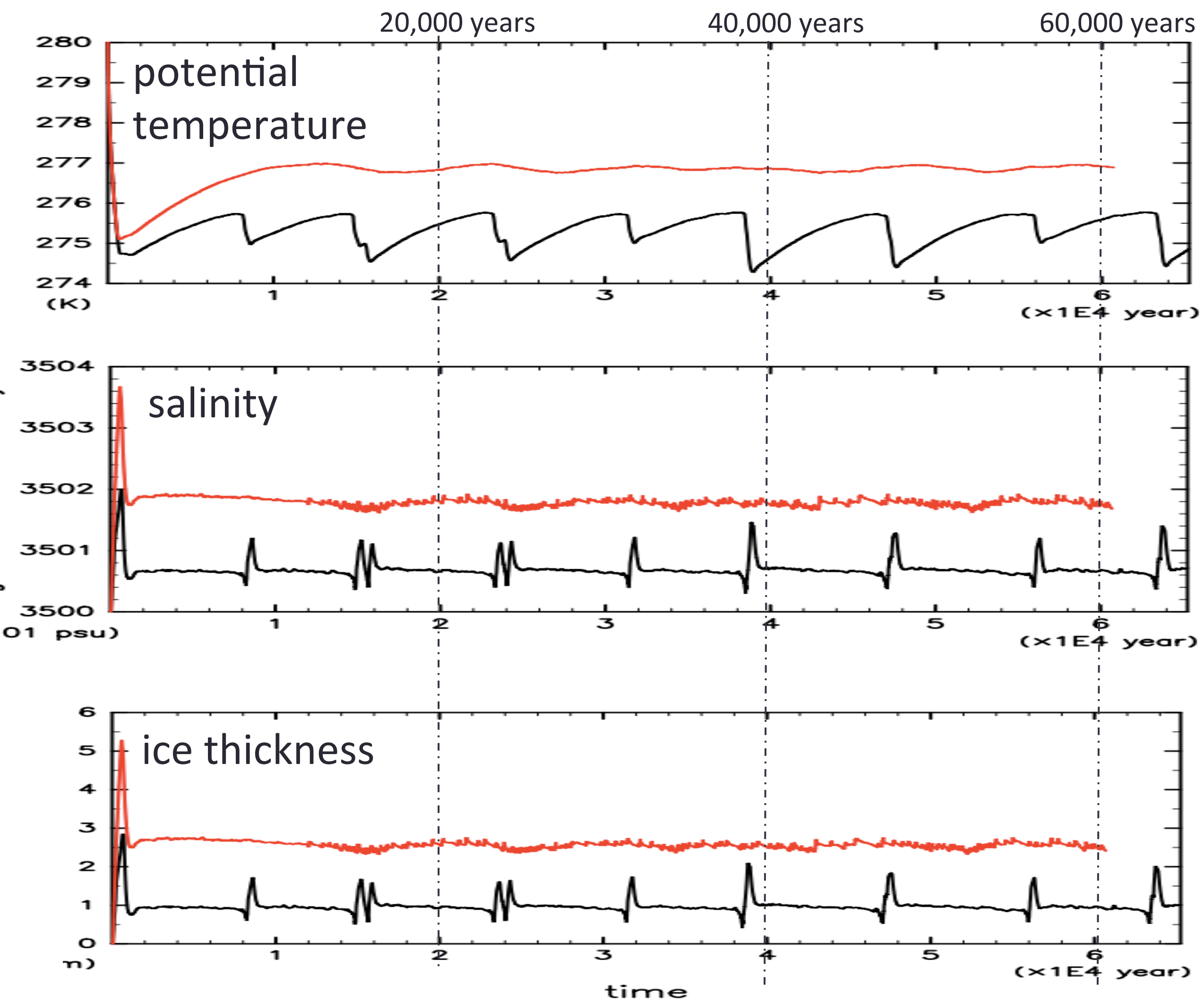
case	Ice-albedo feedback (IAF)	Ocean model	Sea-ice model	Time integration strategy for coupled model
DynOcnAxisym (CTRL)	Off	axisymmetric dynamic ocean	used	periodically coupling (Voss et al., 1998)
	On			
SlabOcnAxisym	Off	axisymmetric 60 m slab ocean	not used	pure coupling
	On			
SlabOcn	Off	60 m slab ocean	not used	N/A
	On			
SwampOcn	Off	swamp ocean (zero heat capacity)	not used	N/A
	On			

- Planetary parameters
  - Solar constant, planetary radius and rotation rate are same as that on present Earth.
- Surface albedo(α_s)
  - IAFOff: α_s=0 everyhwere, same as experiment in INTH98.
  - IAFOn: α_s =0.5 at Ts < 263 K and otherwise α_s=0, same as experiment in INTH07.
- Forcing
  - The annual and daily averaged incoming solar flux is given at top of atmosphere (no seasonal cycle).
- Initial conditions
  - Atmosphere
    - no motion
    - uniform temperature (280 K) and specific humidity (10^{-3} kg/kg)
  - Ocean
    - no motion
    - uniform potential temperature (280 K) , salinity (35 psu)

Results: An aquaplanet climate represented by our developing coupled model

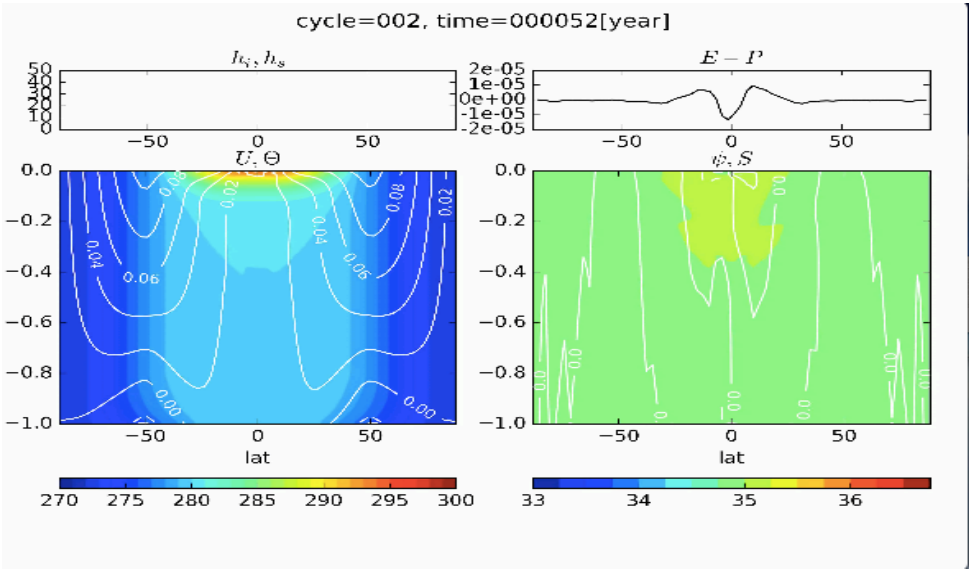
Result: Time series in DynOcnAxisym

Global-mean fields



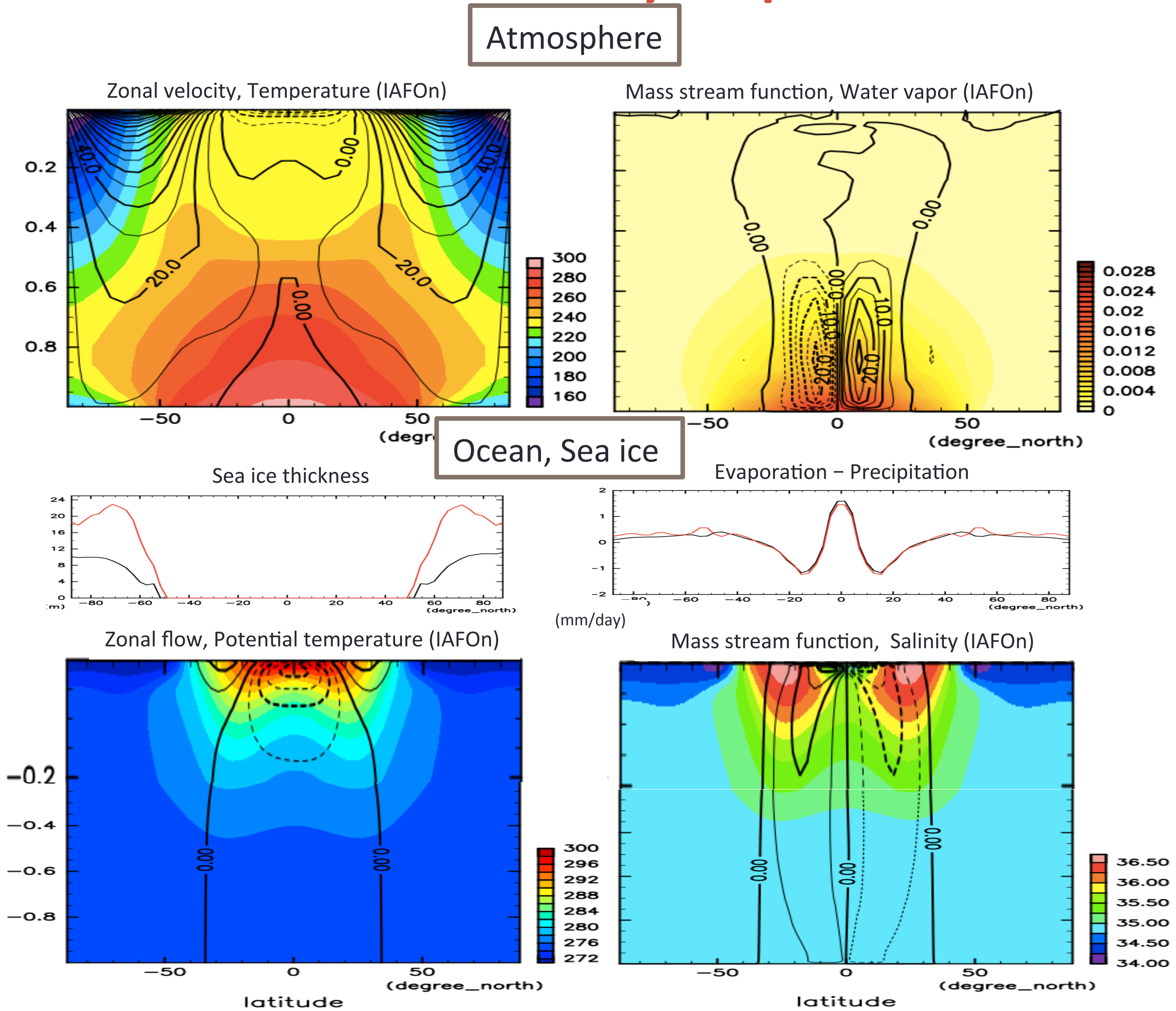
back: IAFOff
red: IAFOn

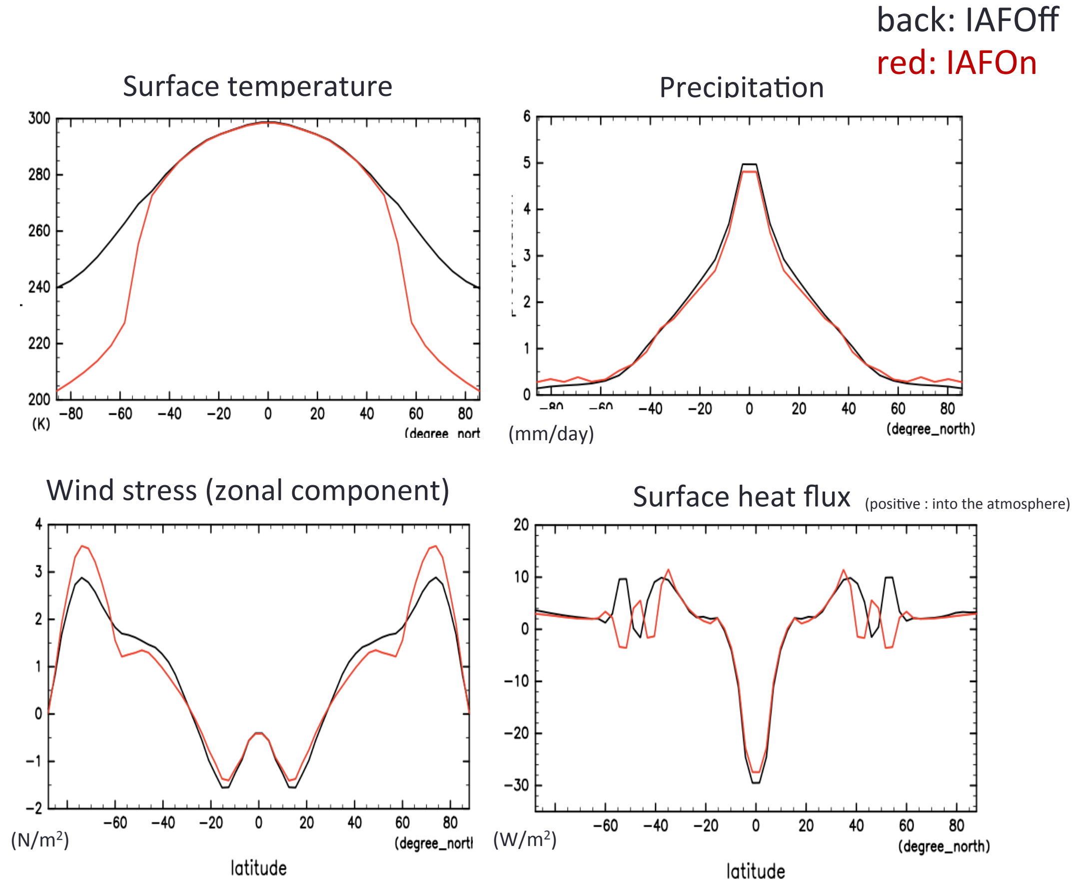
Meridional structure of ocean fields (Animation)



- After several ten thousands of years, we obtain a statistically equilibrium state with ice-line latitude about 50°.
- In the case of IAFOff, the periodic behavior of ocean fields can be seen.
  - We speculate that the sea ice in IAFOff is not enough thick to overcome the bottom melting due to the ocean heat transport.

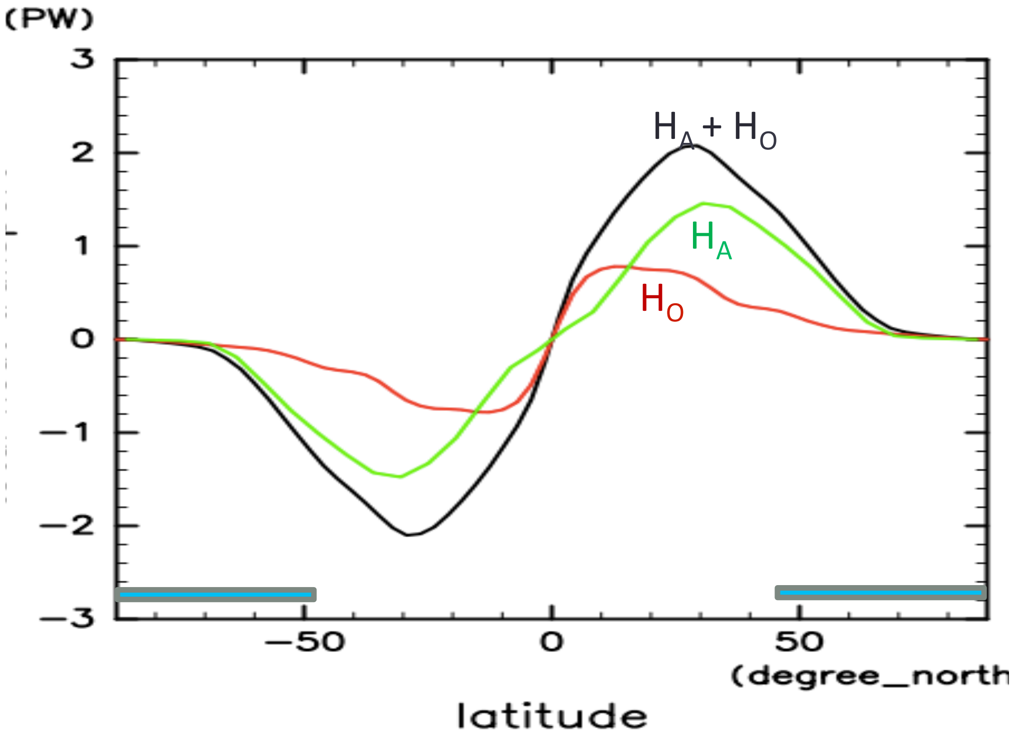
Result: Statistically equilibrium state in DynOcnAxisym





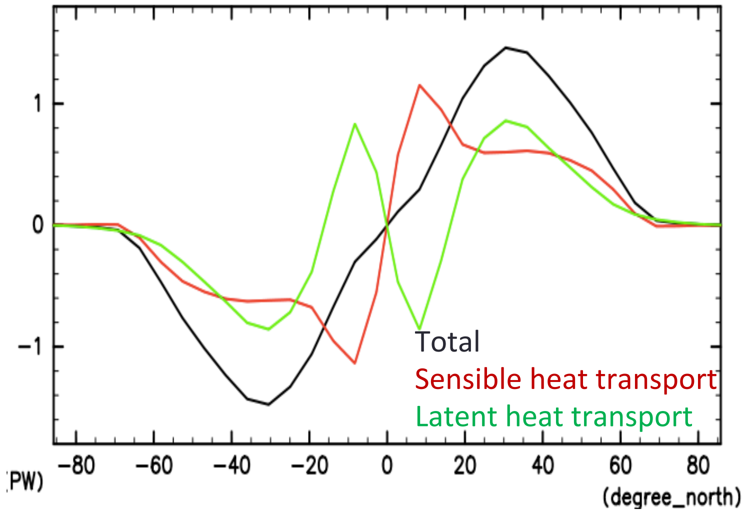
- The major patterns of atmospheric and ocean fields are similar with that in Marshall et al. (2007).
- On the other hand, the strength of circulations is quite weaker, about 1/3.

Result: Meridional heat transports in DynOcnAxisym (IAFOn)



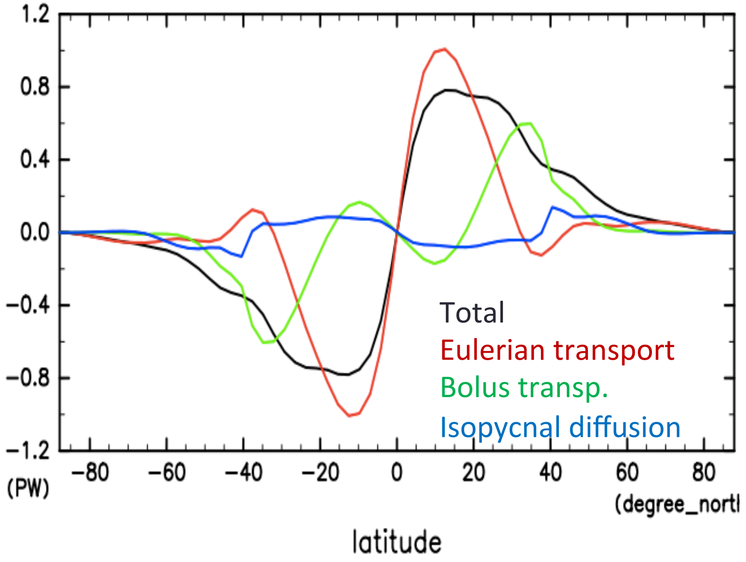
- The total (atmosphere plus ocean) heat transport reaches a maximum 2.2 PW at 30˚ N/S.
  - This amount of heat transport is about 1/3 of that in Marshall et al. (2007).
- Atmospheric heat transport dominates in mid-latitude, while ocean heat transport dominates in low-latitude.

Atmospheric heat transport (H_A)



- In low-latitude, poleward sensible heat transport is poleward, but mostly compensated by latent heat transport.
- In mid-latitude, both of heat transports is poleward.

Oceanic heat transport (H_O)

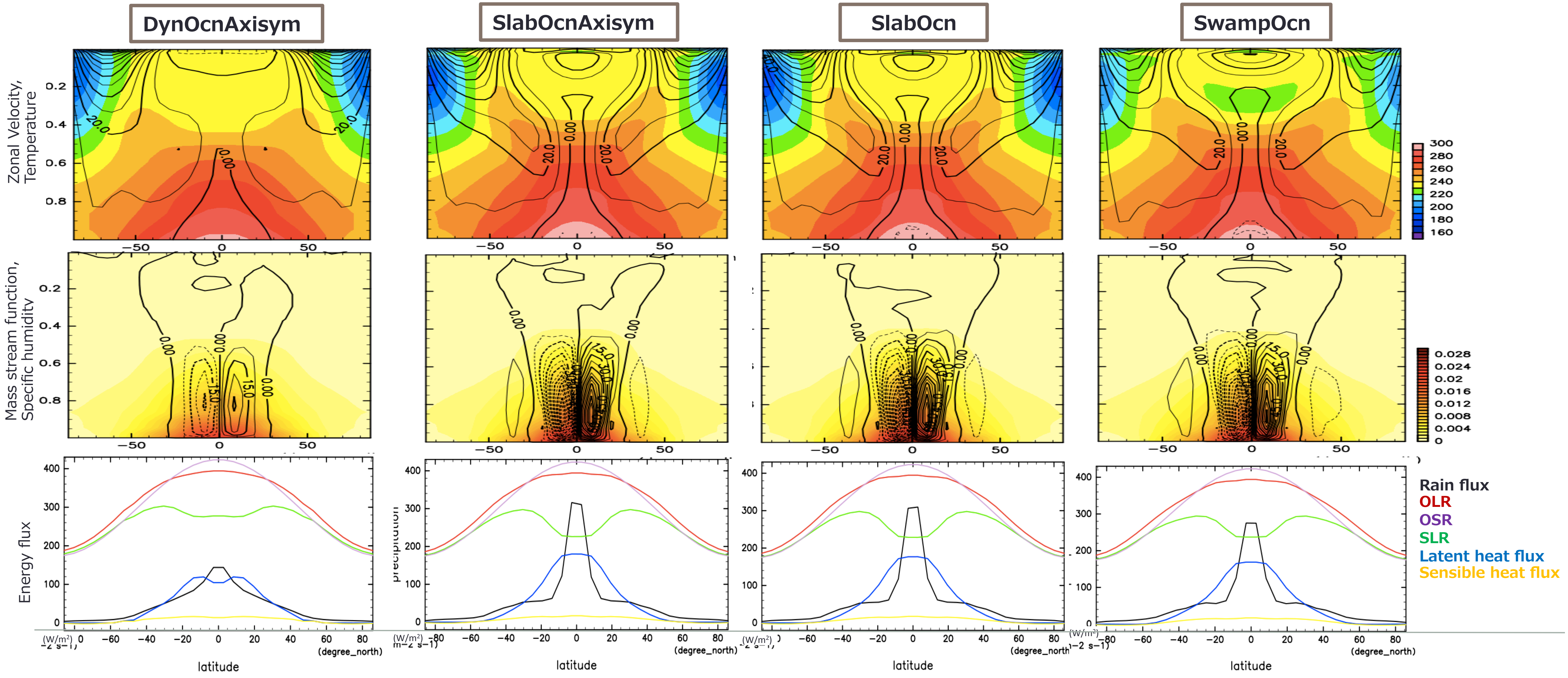


- In low-latitude, H_O is dominated by Eulerian mean overturning which is partially compensated by bolus transport.
- In mid-latitude, H_O is dominated by bolus transport.

Results

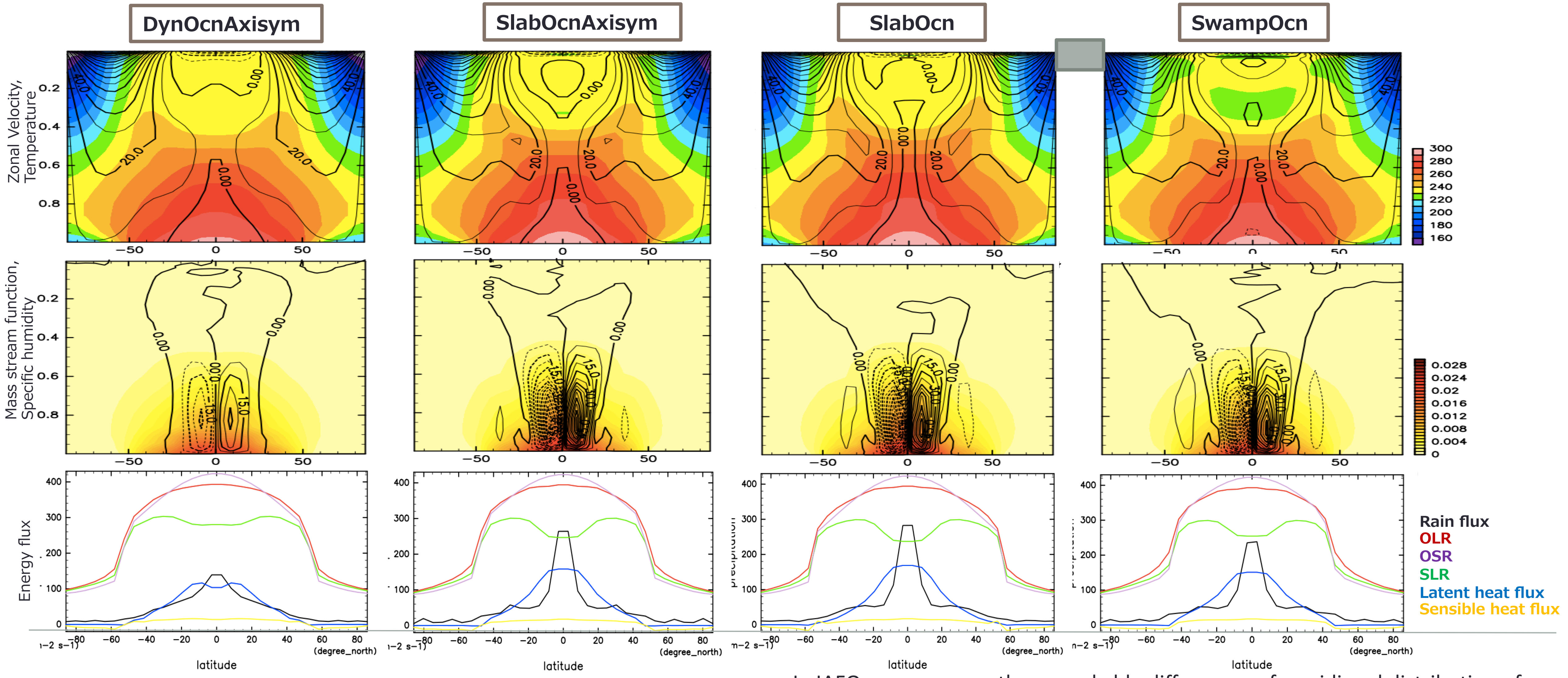
~ Comparison with the results of slab and swamp ocean experiments

Result: Comparison of statistically equilibrium state without IAF



- By considering ocean dynamics, the strength of atmospheric meridional overturning circulation becomes weak, and precipitation around equator decreases.
- The difference between results of slab and swamp ocean experiments are small in the absence of ice-albedo feedback.

Result: Comparison of statistically equilibrium state with IAF

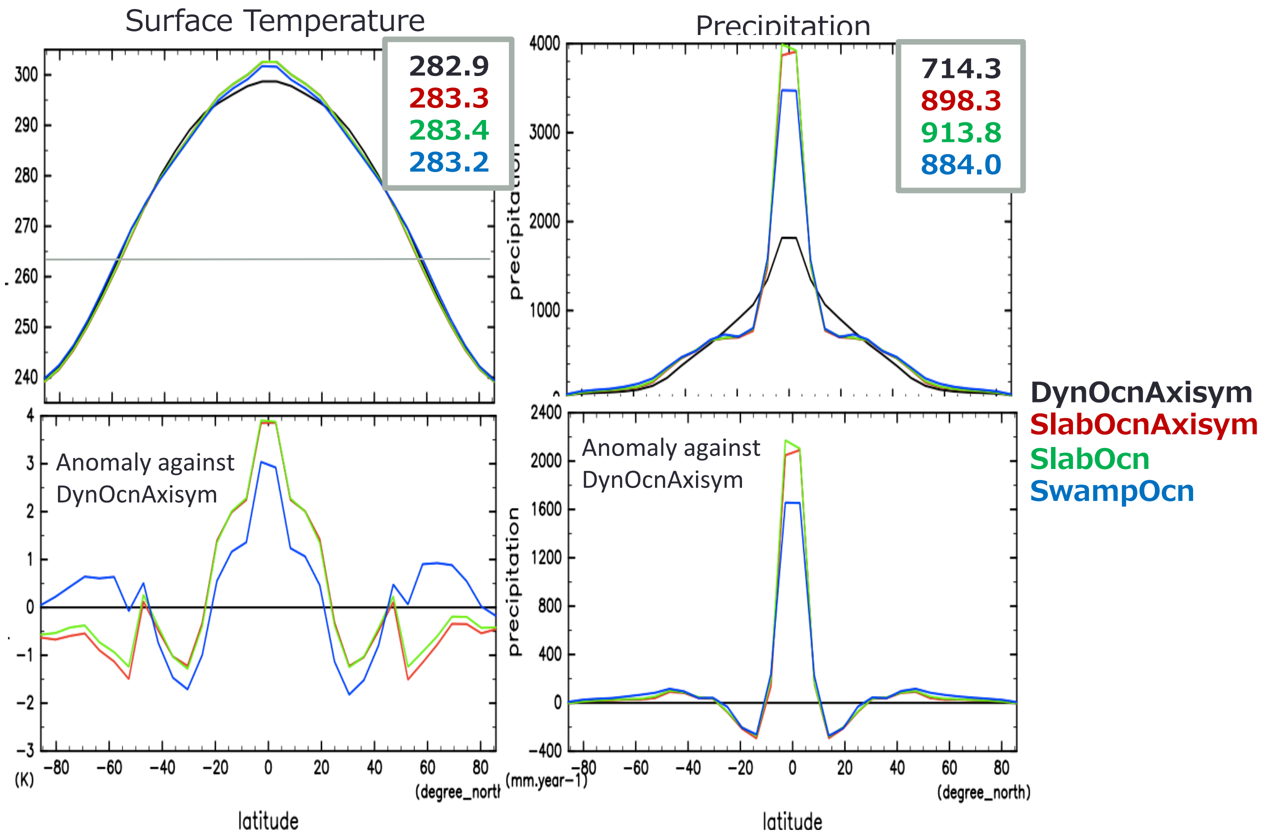


- As experiments without IAF, the effect of ocean general circulation is the reduction of MOC strength and precipitation at equator.

- In IAFOn , we can see the remarkable differences of meridional distribution of OLR and OSR between the results of swamp and other ocean model experiments.
    - Correspondingly, SST around ice-line latitude is quite different as shown next slide.

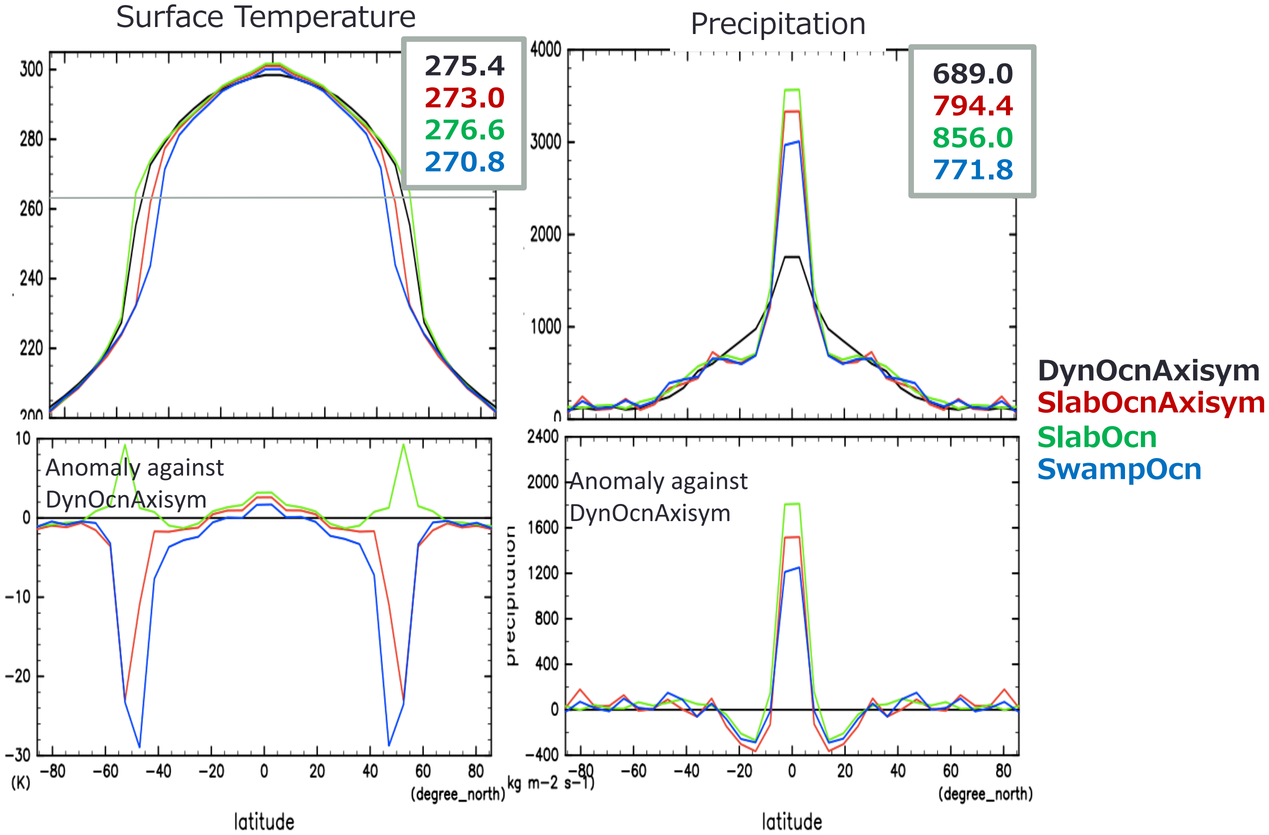
Comparison with swamp and slab ocean experiments

Without ice-albedo feedback



- The ocean heat transport decreases the temperature difference between middle and low latitudes by about 5 K.
- However, the ice-line latitude and global mean SST are almost same in all cases.

With ice-albedo feedback



- The ocean large inertia and ocean heat transport retreats ice-line latitude by about 10° N/S, and correspondingly global mean SST increases by about 5 K.
- Locally, ocean heat transport decreases SST in tropics, while ocean heat transport and large thermal inertia increase temperature in mid-latitude.

Discussion

- When an atmospheric setting in Ishiwatari et al. (2007) is used, the maximum of total meridional heat transport is about 2 PW. This value is only 1/3 of total heat transport in some previous studies (i.e., Marshall et al., 2007).
  - Why does the total meridional heat transport decrease ?

- In the case including ice-albedo feedback, SST around ice-line latitude in slab experiment is higher than that in swamp experiment althogh I expect that the statistically equilibrium state for slab ocean setting is not so different from that for swamp ocean setting.
  - What is the reason ?

Conclusion

- We have been developed a coupled atmosphere-ocean-sea ice model to explore exoplanet climates.
- Using coupled model, we perform solar constant dependence experiments in Ishiwatari et al. (2007) with considering ocean general circulation, and the role of ocean general circulation on the climates are focused.
- In this presentation, as our current status, we present some simulation results for present Earth solar constant, and the results are compared to slab and swamp ocean experiments.
  - The ocean heart transport reduces the meridional temperature difference between middle and low latitudes.
  - The large ocean inertia and ocean heat transport have more significant influence on ice-line latitude when ice-albedo feedback is included.

Reference

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- Ferreira, D., Marshall, J., Rose, B., 2011: Climate Determinism Revisited: Multiple Equilibria in a Complex Climate Model. *J. Climate*, **24**, 992–1012.
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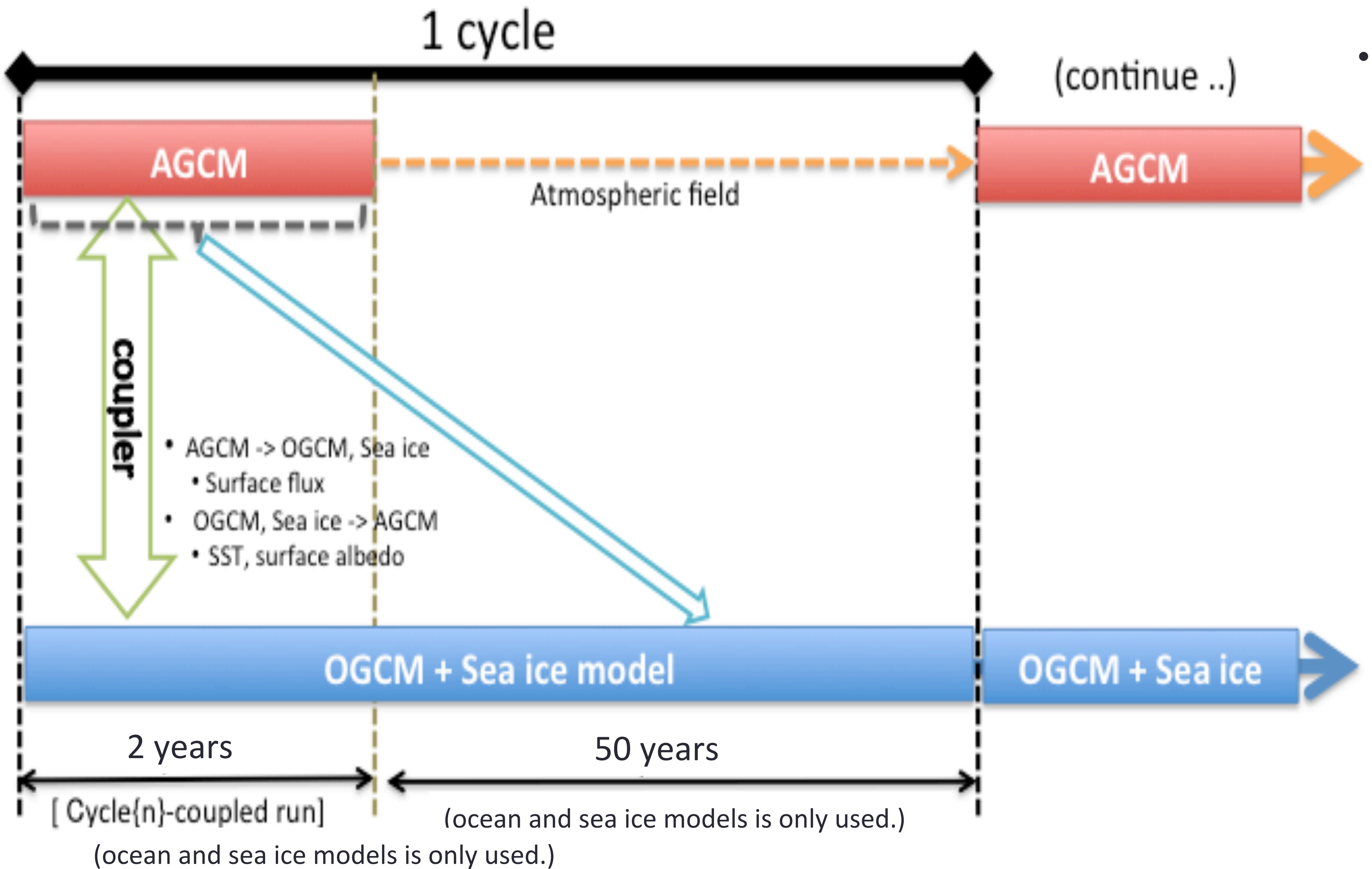
Appendix

Strategy for efficient time integration of a coupled model



- The periodically synchronously coupled integration (Voss et al., 1998) is applied.