Development of ocean general circulation model to understand an aquaplanet climate and preliminary numerical experiment

Author: Yuta Kawai[1,2]

Supervisors: Hirofumi Tomita[2], Seiya Nishizawa[2], Yoshi-Yuki Hayashi[1], Yoshiyuki O. Takahashi[1], Kensuke Nakajima[3], Shin-ichi Takehiro[4], Masaki Ishiwatari[5]

[1] Graduate School of Science, Kobe University, [2] RIKEN Advanced Institute for Computational Science, [3] Faculty of Sciences, Kyushu University [4] Research Institute for Mathematical Sciences, Kyoto University, [5] Graduate School of Science, Hokkaido University

1. Introduction

- **Exploring diversities of planetary climates**
  - As a number of extrasolar planets (exoplanets) have been discovered, their climates attract attention from more planetary atmospheric scientists. By numerical experiments, the distinctive features are becoming clear (for example, Showman ***et al.***, 2009). On exoplanet, if it has atmosphere and ocean, it is highly probable that their heat transports are important for determining and maintaining their climates. However, it is difficult to understand how they have an impact on planetary climates.
- **Aquaplanet experiment**
  - In order to help us the role of atmosphere and ocean circulation on determining planetary climates, some numerical experiments of climates on an idealized planet, such as a planet globally covered by ocean (aquaplanet), have been performed.

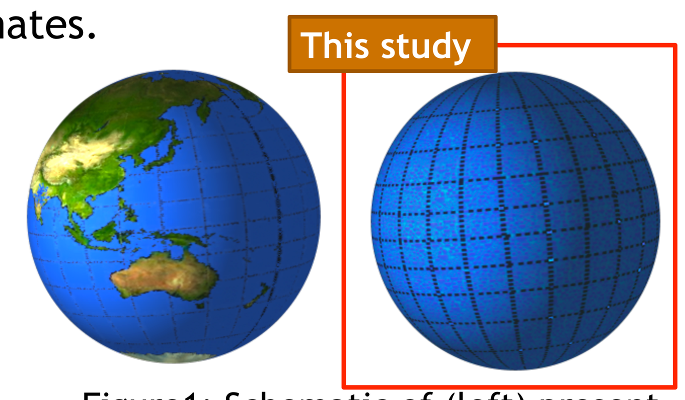

Figure1: Schematic of (left) present Earth, and (right) aquaplanet

- **Previous studies of aquaplanet climates**
  - Smith et al. (2006) is a first study of an aquaplanet climate with coupled atmosphere-ocean-sea ice model, and discussed the characteristics. Enderton ***et al***. (2009) and Rose (2015) investigated solar constant dependence of the aquaplanet climate. However, in order to confirm the robustness of climate features they found, further studies (for example, resolution dependence or intercomparison of results from different models) are required.
- **This study**
  - Our research group (GFD-DENNOU club) has been developing atmospheric and ocean general circulation models, and sea ice thermodynamics model to simulate planetary climates. The author is mainly in charge of developing ocean and sea ice models, and coupling three models.
  - In the near future, we plan to examine solar constant dependence of aquaplanet climates in our developing coupled model, and to consider the role of the atmosphere and ocean circulation on the climate.
  - Here ocean general circulation in an aquaplanet configuration calculated with our ocean model is shown as preliminary result.

2. Description of model

- **Dynamical core**
  - Boussinesq primitive equations with a spectral Eulerian method
- **Parameterization of sub-grid scale processes**
  - Mesoscale eddy mixing scheme (Redi, 1982; Gent and McWilliams, 1990)
  - Convective adjustment scheme (Marotzke, 1991)
- **Sea ice processes**
  - Three layer thermodynamics model (Winton, 2000)

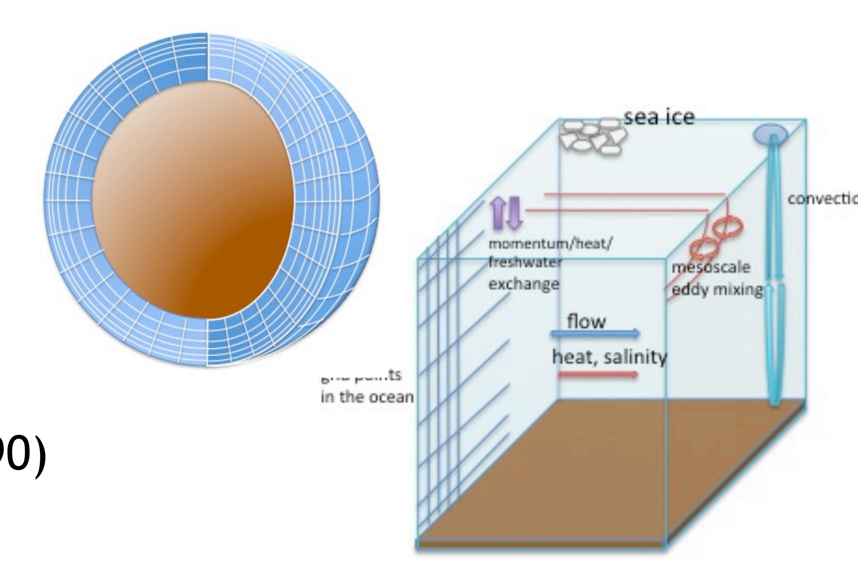

Figure 2: Schematic figure for (left) a model grid, and (right) processes included in the model.

3. Experimental design

Numerical experiments of zonally symmetric (independent of longitude) general circulation are performed.

- **Purpose**
  - To validate our developing ocean model
  - To understand fundamental features of ocean general circulation on an aquaplanet
  - To evaluate the effects of sub-grid scale parameterizations
- **Set-up**
  - The computational domain is a meridional cross section whose bottom is flat, and the depth is 5.2 km. The grid interval is about 300 km horizontally, and 90 m vertically.
  - The values of planetary radius and rotation rate are same as present Earth's ones.
  - Boundary conditions
    - At the sea surface, surface stress, temperature and salinity obtained from previous study of aquaplanet experiment (Marshall ***et al.***, 2007) are imposed (See right figures).
    - At the bottom, no-slip condition for flow and no flux condition for both of heat and salinity are imposed.
  - Experiment series

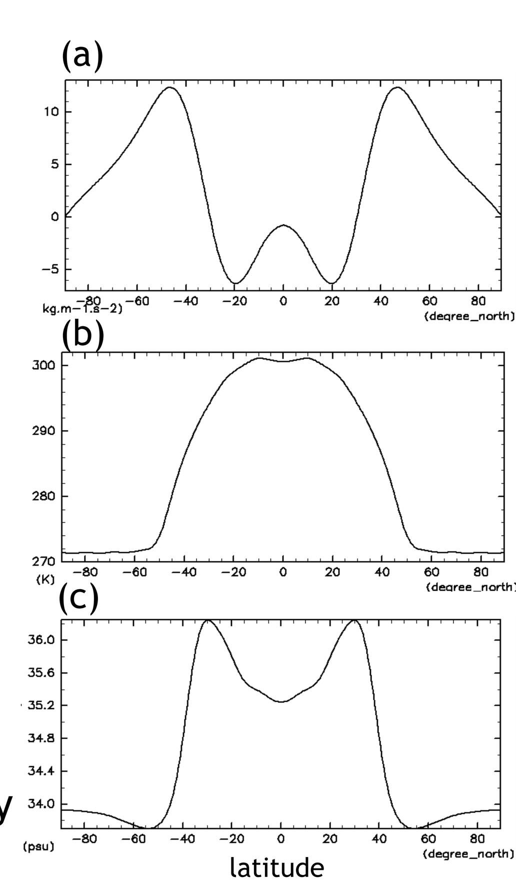

Figure 3: Meridional distribution of surface (a) stress (in N/m^2), (b) temperature (in K) and (c) salinity (in psu).

name	GM	CA	remarks
control	O	O	a standard case for comparison
const-dens	×	×	The density remains constant in the flow field.
noSGSParam	×	×	The case is same as **control** except neither GM nor CA is used.
convOnly	×	O	The case is same as **control** except GM is not used.

(GM: mesoscale eddy mixing scheme, CA: convective adjustment scheme)

- For all four cases, the ocean model is integrated to equilibrium state.

➢ **Summary**

➢ Some of planetary atmospheric scientists have been performing numerical experiments of aquaplanet climates to consider the role of atmosphere and ocean circulation on determining planetary climates.

➢ The author has been developing ocean and sea ice models, and coupling these models to atmosphere model in order to explore aquaplanet climates. With the coupled model, we plan to examine solar constant dependence of the climates.

➢ Some fundamental features of ocean general circulation on an aquaplanet and the effects of sub-grid scale parameterization are investigated with the ocean model.

4. Ocean ciruculation on an aquaplanet represented in the model

- **Control experiment**

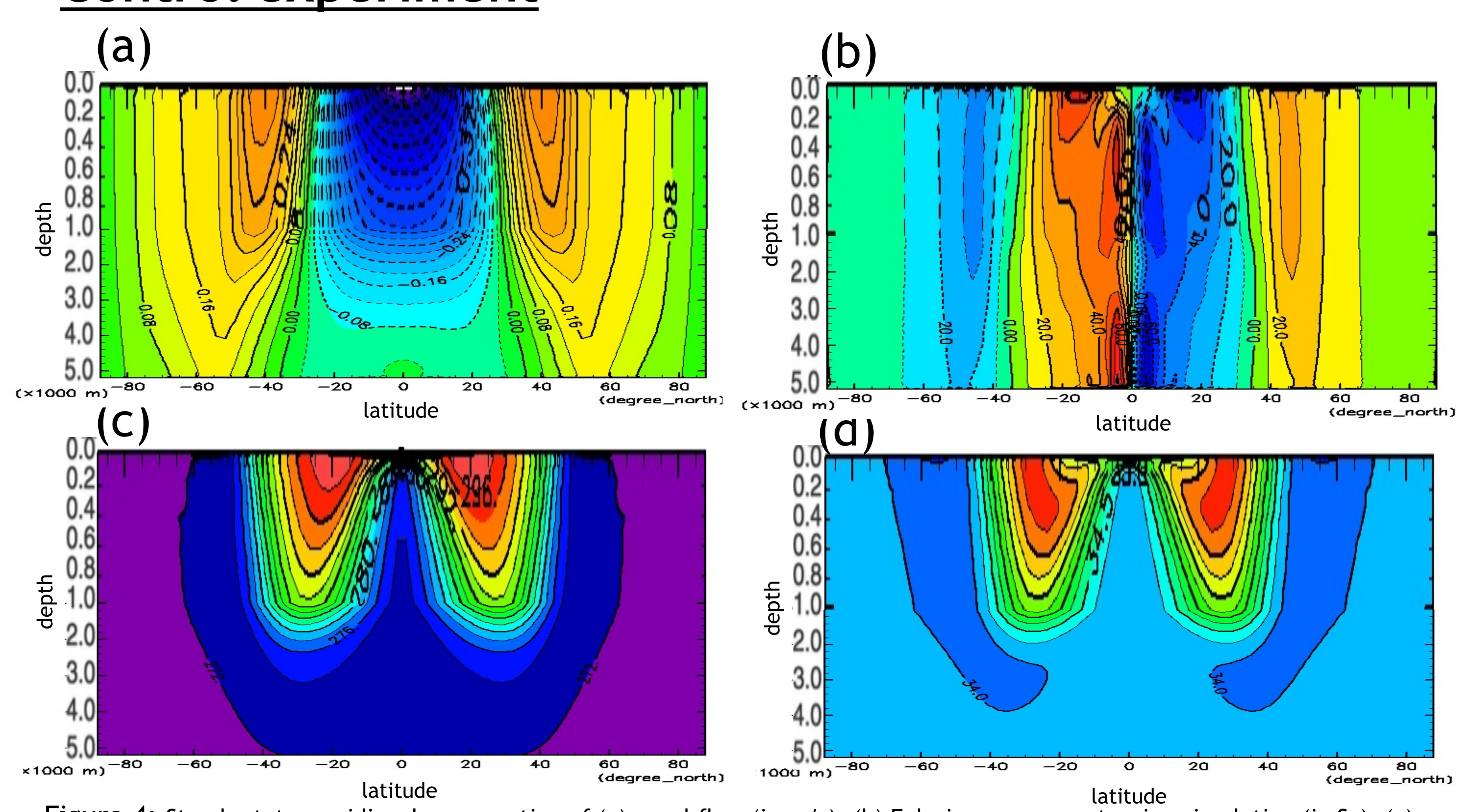

Figure 4: Steady state meridional cross section of (a) zonal flow (in m/s), (b) Eulerian-mean overturning circulation (in Sv), (c) potential temperature (in K) and (d) salinity (in psu).

- The zonal flow is strong, while the meridional overturning circulation is weak.
- The thermocline and halocline are deeper than the ocean which has shores.
- These are fundamental features of ocean general circulation on an aquaplanet found by previous studies (Smith ***et al.***, 2006; Marshall ***et al***. 2007).

- **Constant-density experiment**

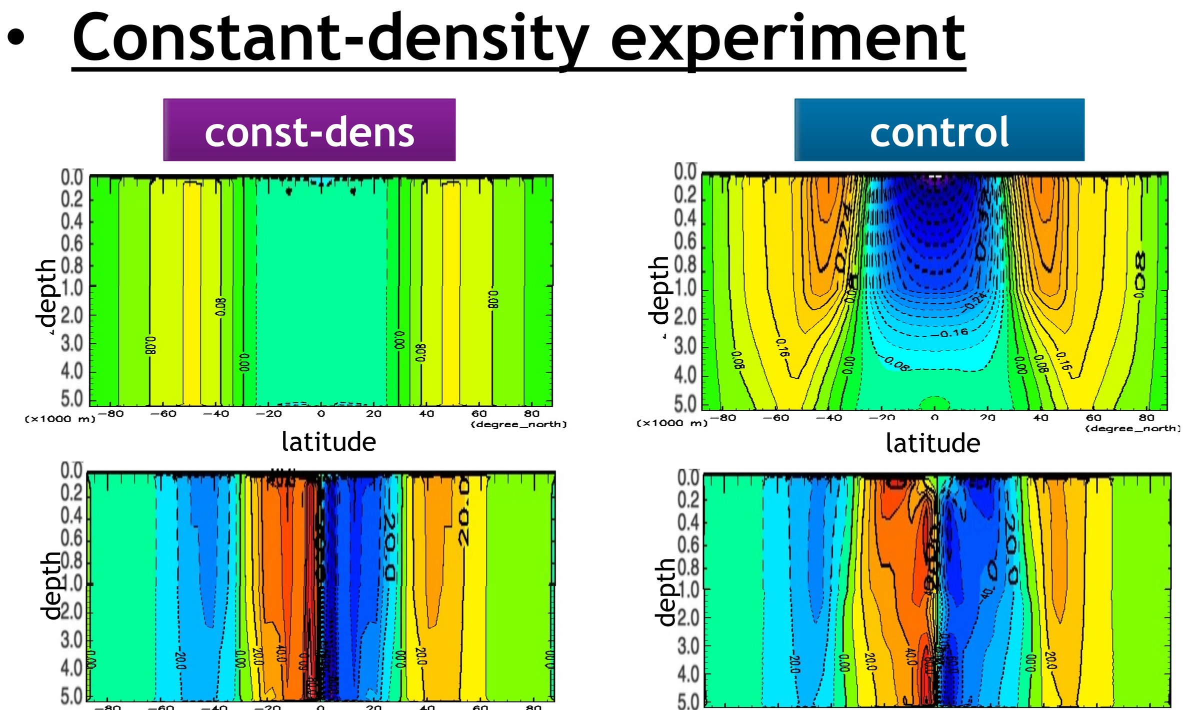

Figure 5: Steady state meridional cross section of (upper panels) zonal flow (in m/s), (lower panels) Eulerian-mean overturning circulation (in Sv)

- The structure of zonal flow dependent on ocean depth relates to horizontal variation of density field.
- The density variation seems to influence the structure of meridional overturning circulation at low latitudes, but does not at midlatitudes and high latitudes.

- **Experiments to evaluate the effects of sub-grid scale parameterizations**

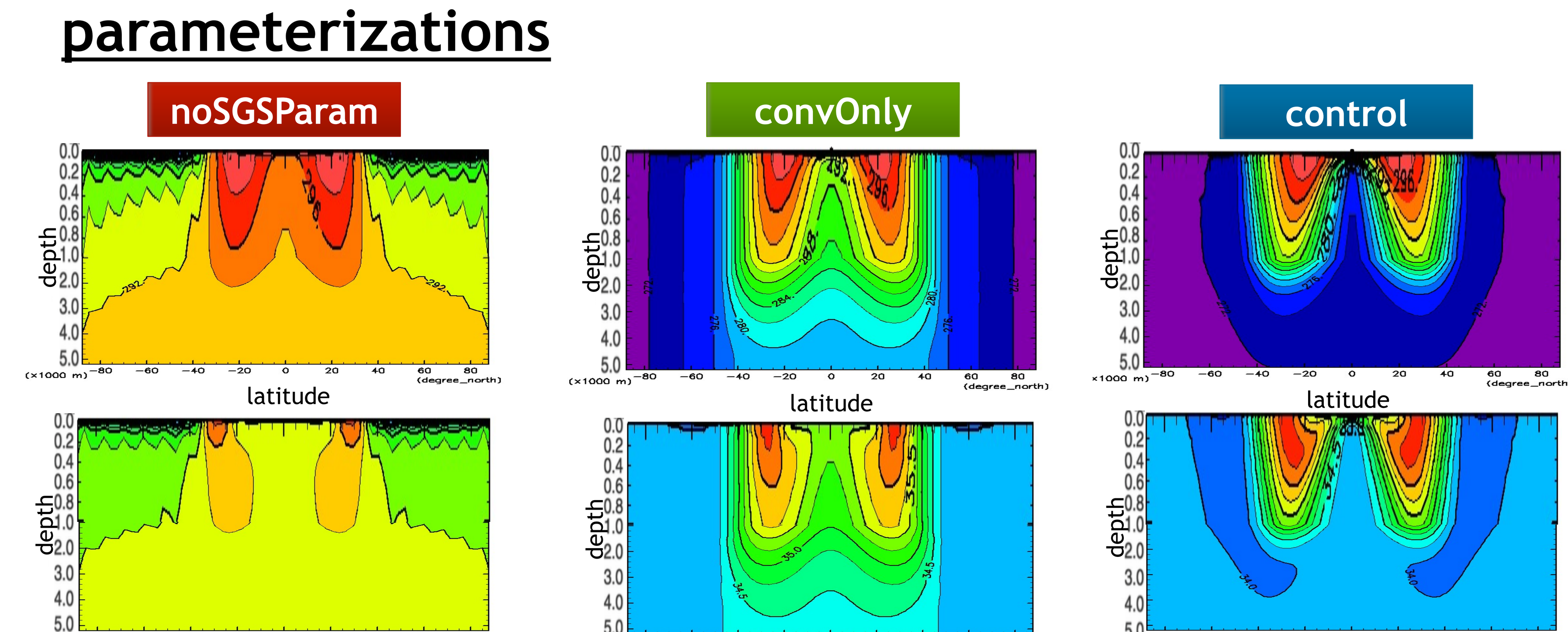

Figure 6: Steady state meridional cross section of (upper panels) potential temperature (in K) and (lower panels) salinity (in psu).

- The comparison between **noSGSParam** and **convOnly** cases shows that convective adjustment scheme plays a role in efficient vertical mixing at high latitudes.
- The comparison between **convOnly** and **control** cases shows that mesoscale eddy mixing scheme maintains the sharp vertical gradients of thermocline and halocline.