Climate regime diagram of ocean planet

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Center for Planetary Science

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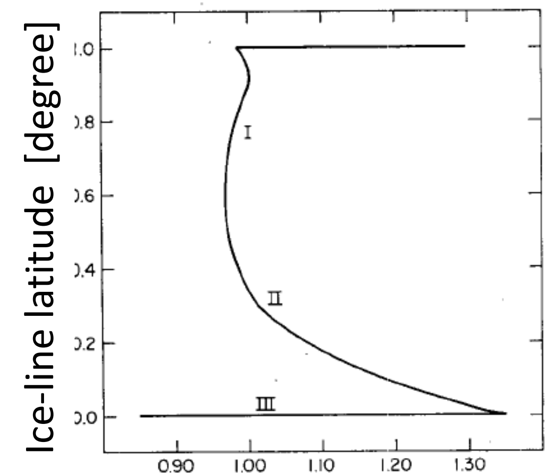
Background

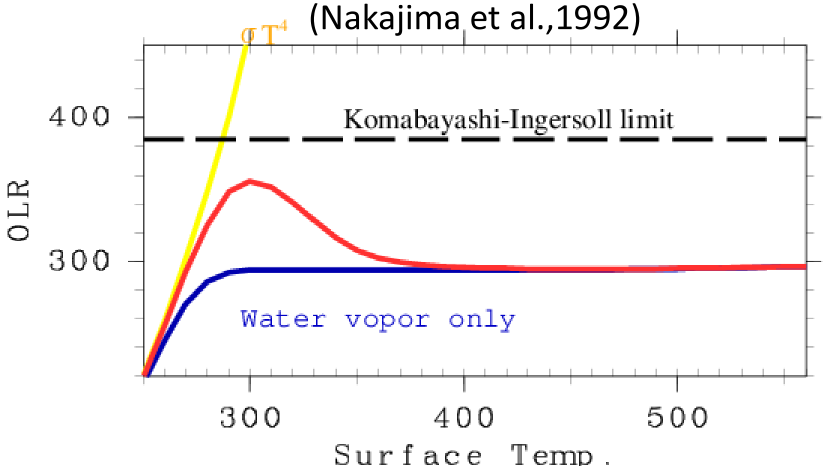
- **Variety of climate has been considered with climate regime diagram**
  - Budyko (1969), Sellers (1969), and others
  - Infrared radiation is represented as
    $$I = A + BT$$
- **Problems**
  - Effects of circulations of atmosphere and ocean
  - Influence of existence of the runaway greenhouse state
- **We consider simple system (straight forward extension of Budyko-Sellers model)**
  - ocean planet (all surface is covered with ocean)
  - Investigation with AGCM and coupled model

North (1975)



Normalized Solar constant

Radiative-convective equilibrium model (Nakajima et al.,1992)



climate regime diagram obtained by AGCM

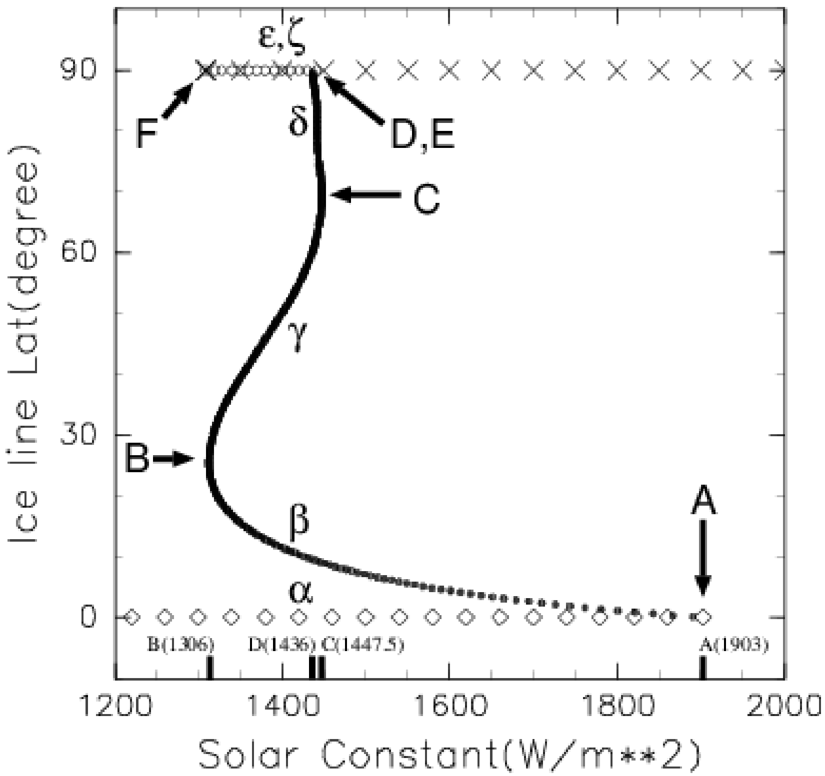
Model

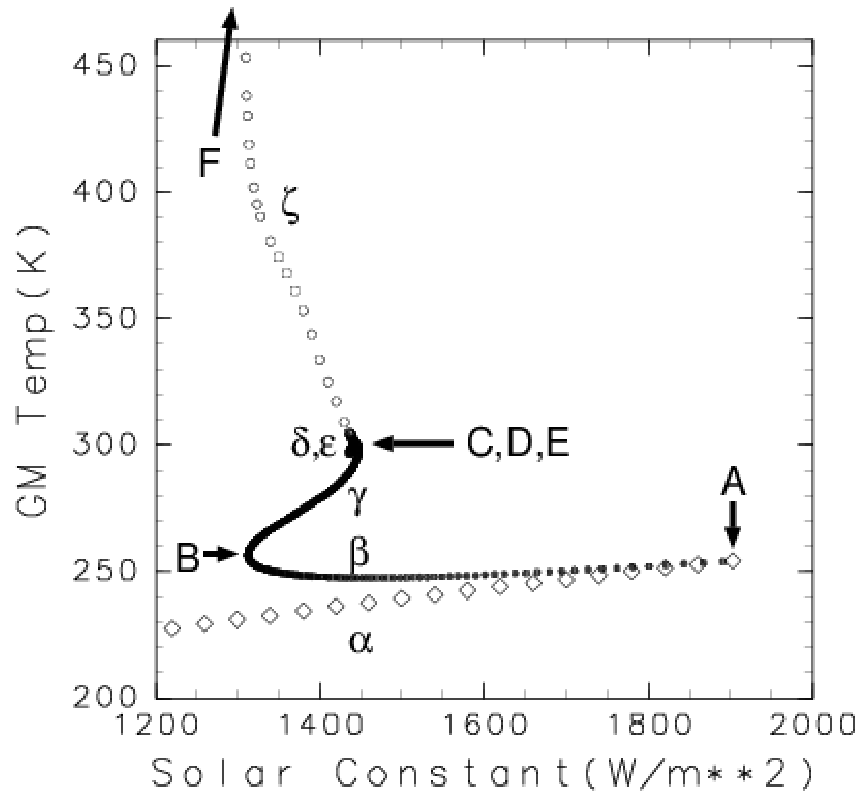
- **Energy Balance Model (EBM)**
  - Infrared radiation is calculated with result of Nakajima et al. (1992)

$$C\frac{\partial T}{\partial t} = Q\big(1-\alpha(x,x_s)\big)S(x) - I(T) + D\frac{\partial}{\partial x}(1-x^2)\frac{\partial T}{\partial x}$$

- **Atmospheric general circulation model: DCPAM**
  (https://www.gfd-dennou.org/library/dcpam/)
  - Atmospheric constituent: water vapor, dry air
  - Dynamical process： primitive equations
  - Radiation process： grey radiation (Nakajima et al., 1992)
    - Absorption coefficient: water vapor：$\kappa_v = 0.01\mathrm{m}^2/\mathrm{kg}$, dry air：$\kappa_n = 0.0\mathrm{m}^2/\mathrm{kg}$
  - Turbulent mixing: Mellor and Yamada (1982), Louis et al. (1982)
  - convection: Manabe et al. (1965), no cloud
  - Surface: swamp ocean
  - Resolution: T21L16 or T21L32
- **Experimental steup**
  - Solar constant 1200-2000 W/m2
  - Planetary radius, surface pressure, planetary rotaion rate, … are same values of Earth’s

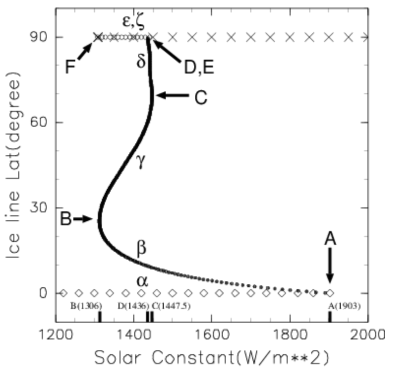
EBM regime diagram

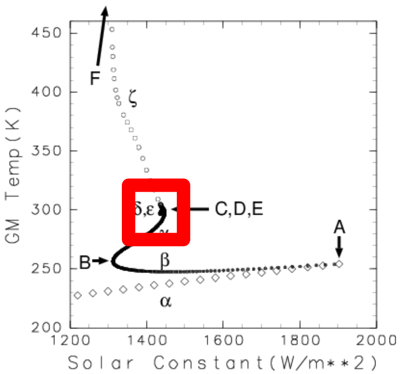




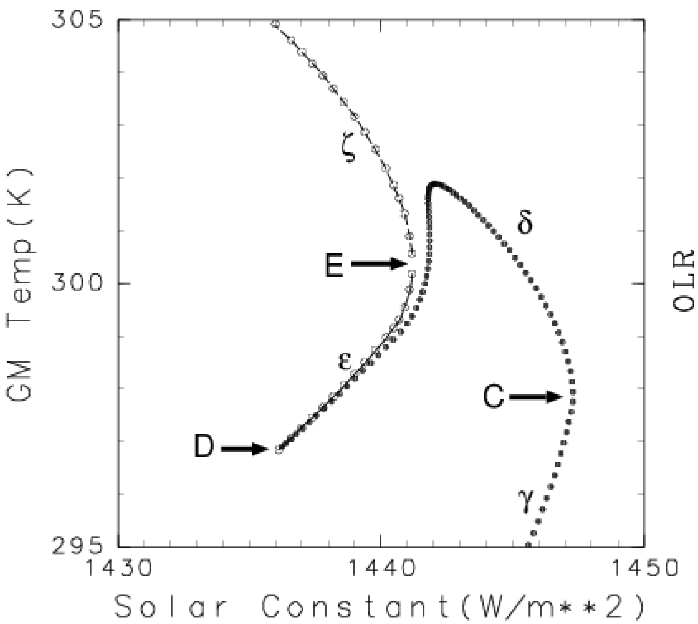
- **Branch structure is basically same as Budyko-Sellers model**
- **Ice-free state branch changes because of appearance of the runaway greenhouse state**

Two branches of ice-free solutions

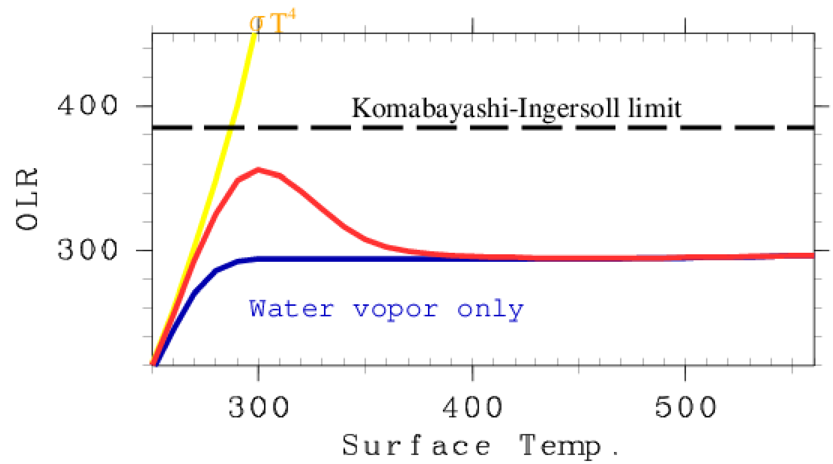




Magnified view



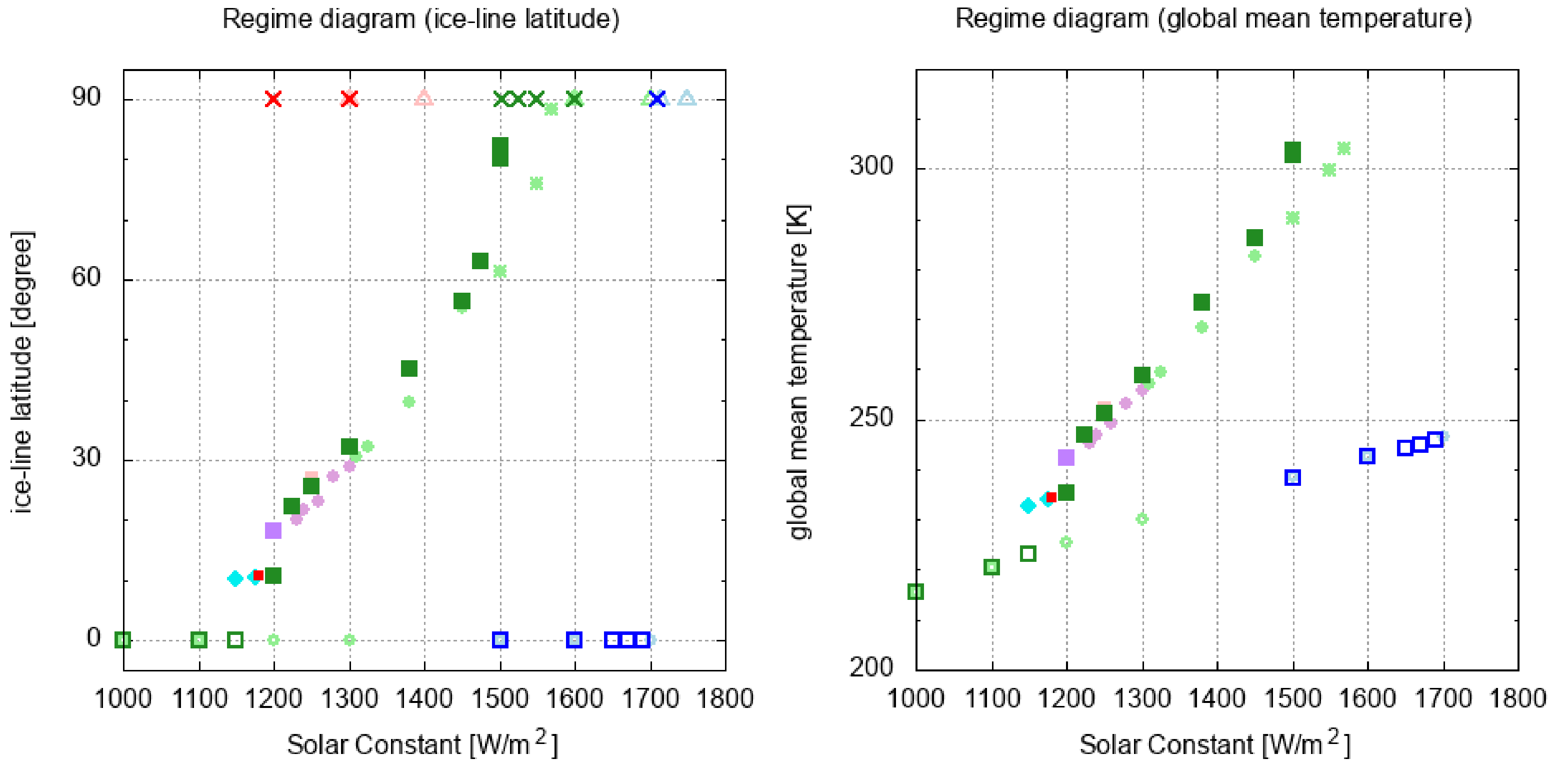
Nakajima et al. (1992)



- **Two Branches of ice-free states are caused by the existence of multiple solutions of vertical one-dim model (Nakajima et al., 1992)**

GCM regime diagram

Ishiwatari et al. (2021)

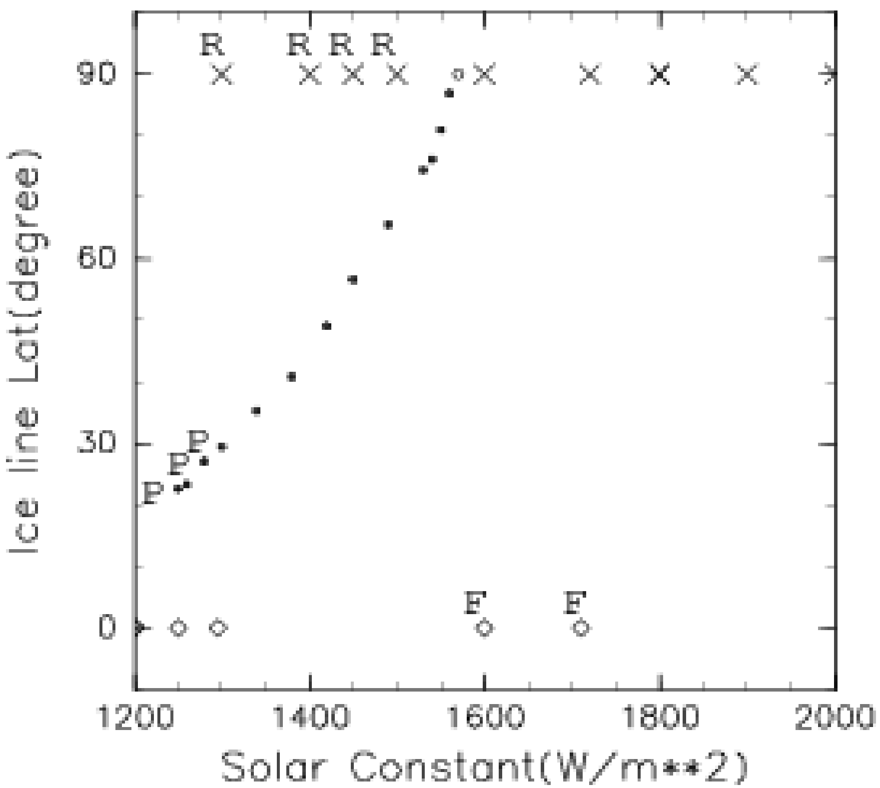


- **Branch structure is similar to EBM result**
- **Ice-free state branch changes because of appearance of the runaway greenhouse state**
- **Partially ice-covered state with large ice cap cannot be determined uniquely**

GCM regime diagram(old version)

- **Actually, the regime diagram has been updated from Ishiwatari et al. (2007)**
- **Some problems including a serious bug were discovered**

Old version (Ishiwatari et al., 2007, retracted)



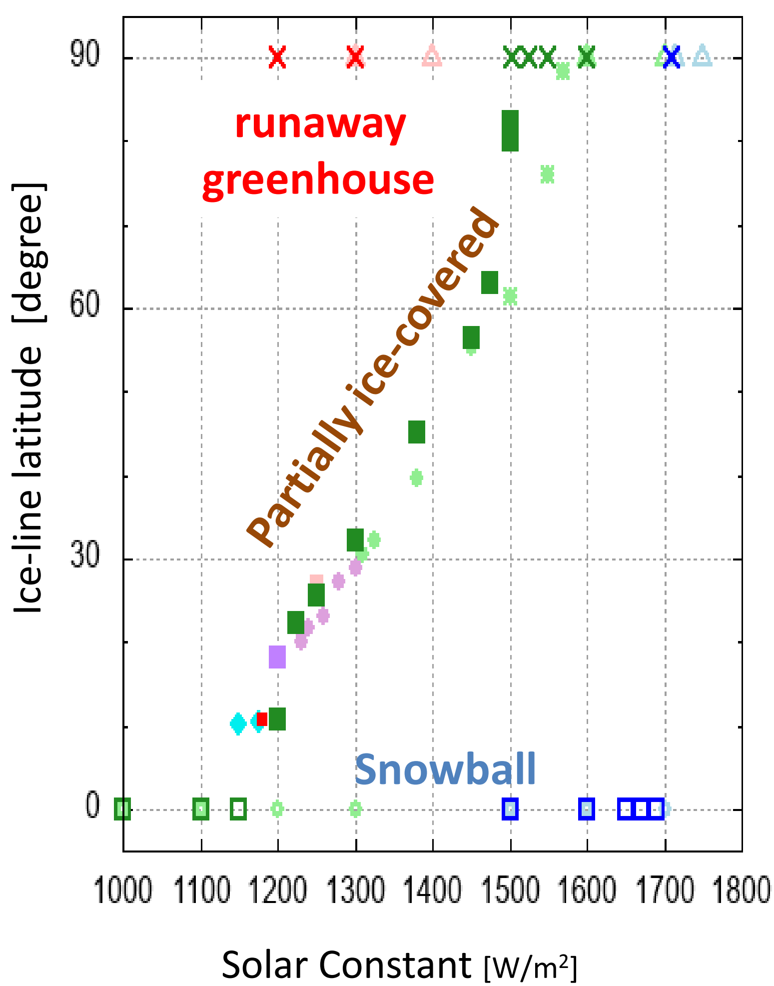
Climate regime diagram obtained by a coupled model

Objective

- **Climate regime diagram with considering ocean circulation**
  - Rose (2015)
    - 3-dim ocean model
    - Water belt state is found
- **What is climate regime diagram for atmosphere-ocean system with Nakajima et al. (1992)'s grey radiation?**

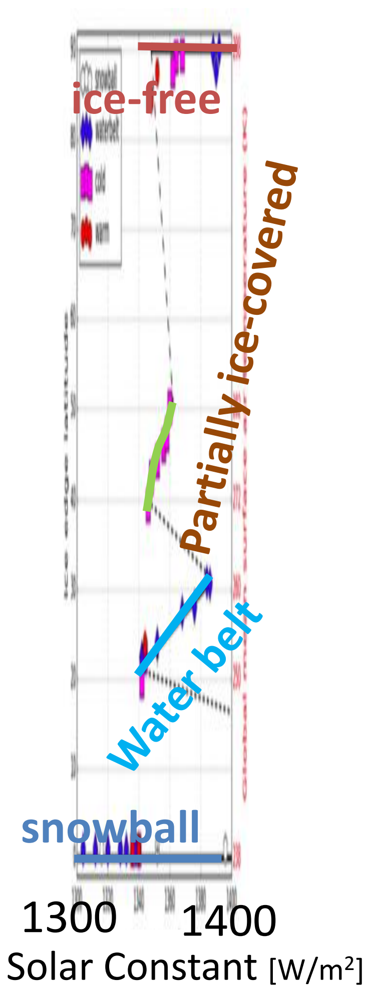
Ishiwatari et al. (2021)

- grey radiation
- Swamp ocean



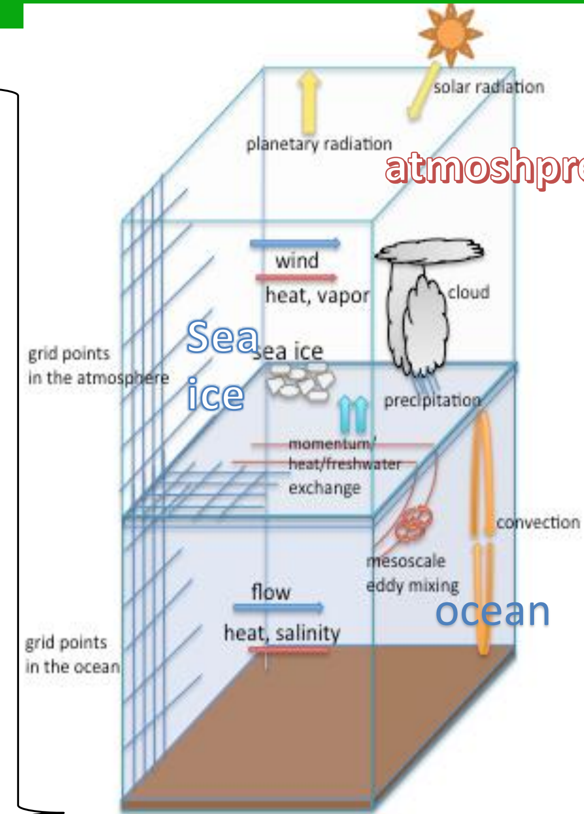
Rose (2015)

- 4-band rad.
- 3-dim ocean model



Atmosphere-ocean coupled model

- **AGCM ： DCPAM**
  (https://www.gfd-dennou.org/library/dcpam/)
  - Atmospheric constituent: water vapor, dry air
  - Dynamical process ： primitive equations
  - Radiation process ： grey radiation (Nakajima et al., 1992)
  - Turbulent mixing: Mellor and Yamada (1982), Louis et al. (1982)
  - Convection: Manabe et al. (1965), no cloud
  - Resolution: T21L16 or T21L32
- **Ocean ciruculation model**
  - Dynamical process ： axisymmetric hydrostatic Boussinesq equations
  - Turbulent mixing ： Redi (1982), Gent and McWilliams (1990), Marotzke (1991)
  - Resolution ： horizontal 3 degree, vertical 60 levels
- **Sea ice model**
  - Thermodynamical process ： 3-layer model (Winton, 2000)
  - Horizontal transport: diffusion type
  - Resolution : horizontal 3 degree



- Coupler
  - Data exchange between models: Jcup (Arakawa et al., 2011)

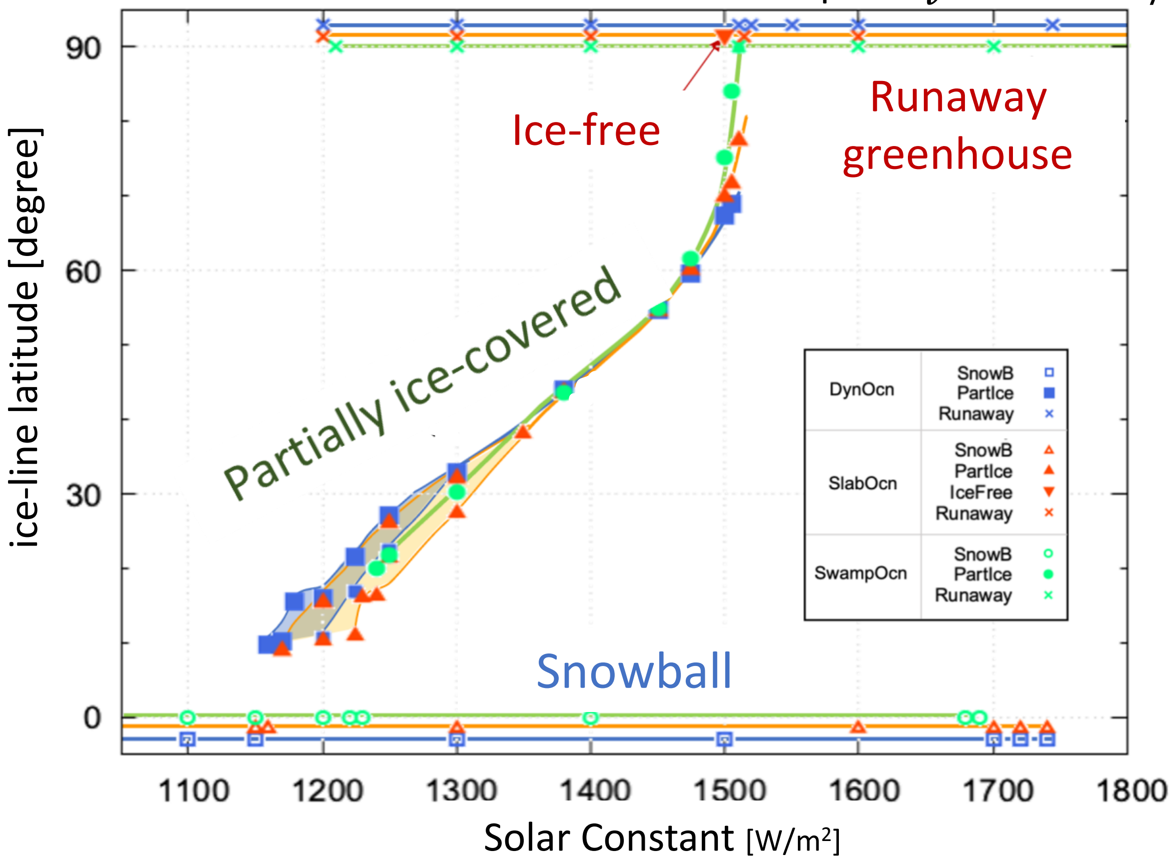
Using Periodically synchronous coupling (Sausen and Voss, 1996), coupled system is integrated for 30 thousand years

Experiment configuration

- Solar constant: 1000〜1750 W/m^2
- Atmospheric absorption coefficient
  - Case with same configuration as Ishiwatari et al. (2021) :
    water vapor : $\kappa_v = 0.01 \mathrm{m}^2/\mathrm{kg}$ dry air : $\kappa_n = 0.0 \mathrm{m}^2/\mathrm{kg}$
  - Case with large absorption coefficient
    water vapor : $\kappa_v = 0.1 \mathrm{m}^2/\mathrm{kg}$ dry air : $\kappa_n = 10^{-5} \mathrm{m}^2/\mathrm{kg}$
    (Based on Byrne and O'Gorman (2013), Vallis et al. (2018))
- Ocean model
  - Dynamic ocean, 60m slab ocean, Swamp ocean
- Planetary parameters (Planetary radius, gravitational acceleration, ...): Same values with Earth's
- No seasonal change, no diurnal cahnge
- Surface albedo
  - 0.5 (Ts below 263K), 0 (otherwise)
  - Calculated with considering sea ice concentration
- Initial condition
  - Basically, isothermal state (280 K)
  - Calculated runaway greenhouse states, sonwball states, partially ice-covered state

Regime diagram for case with Ishiwatari et al. (2021) configuration

vapor : $\kappa_v = \mathbf{0.01}\,\mathrm{m^2/kg}$ dry air : $\kappa_n = \mathbf{0.0}\,\mathrm{m^2/kg}$



3 types of ocean model

Dynamic ocean

60m slab ocean

swam

- **Multiple kinds of solutions are obtained regardless of ocean model**
  - **Runaway greenhouse state, Snowball state, Partially ice-covered state (Water belt state does not appear)**
- **Branch structures are almost independent of ocean model**

Reason for indepence of branch structures on ocean model

- **Meridionally 1-dim EBM (Sellers-type) with ocean heat transport**

$$0 = \boxed{Q\big(1-\alpha(x,x_s)\big)S(x)}\;\boxed{-(A+BT)}\;\boxed{+D\,\frac{\partial}{\partial x}(1-x^2)\frac{\partial T}{\partial x}}\;\boxed{+F_o(x)}$$

Solar radiation | Infrared radiation | Atmospheric heat transport | Ocean heat flux

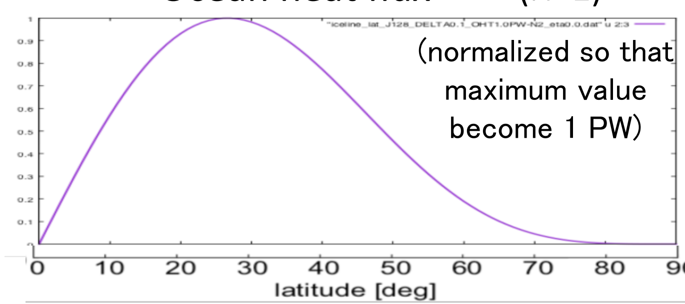
(x: sine-latitude, T: Temperature, Q: (Solar constant)/4, α : Albedo, S(x)=1+s2 P2(x))

$$F_o(x) = -\frac{1}{2\pi R^2}\frac{\partial H_o}{\partial x},$$

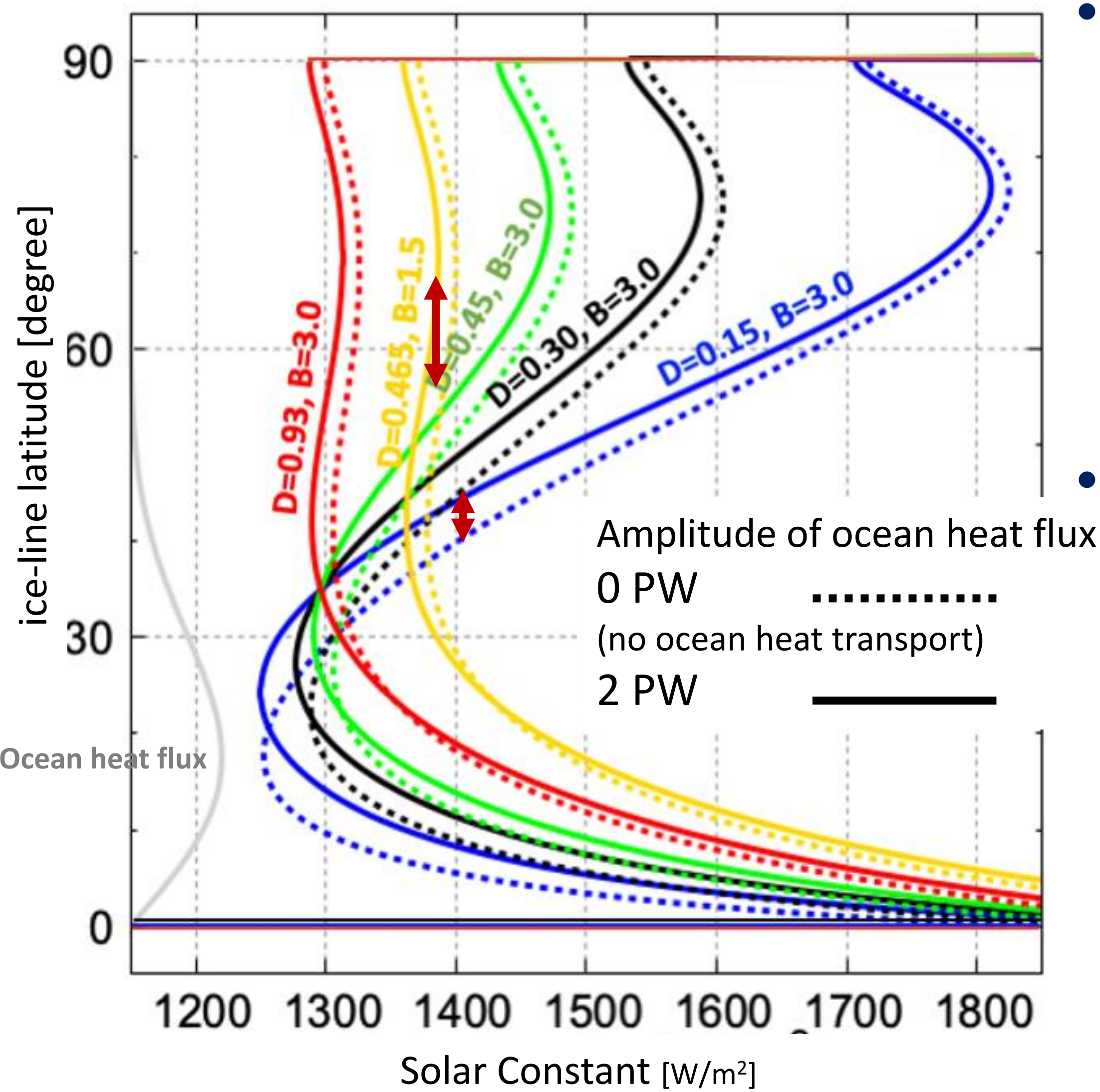
$$H_o(x) = \Psi_o x(1-x^2)^N$$

- **Experiment setup**
  - D/B (heat transport coefficient/coefficient in infrared radiation)
    - 0.1 (corresponds to Ishiwatari et al., 2021)
    - 0.3 (North, 1975)
  - Ocean heat flux is specified
    - Determined with the result obtained by coupled-model
    - Latitude dependence : N=2
    - Amplitude : 1 [PW] (from result of dynamic ocean model)

Ocean heat flux (N=2)



Result of EBM



- **Parameter exp. By EBM**

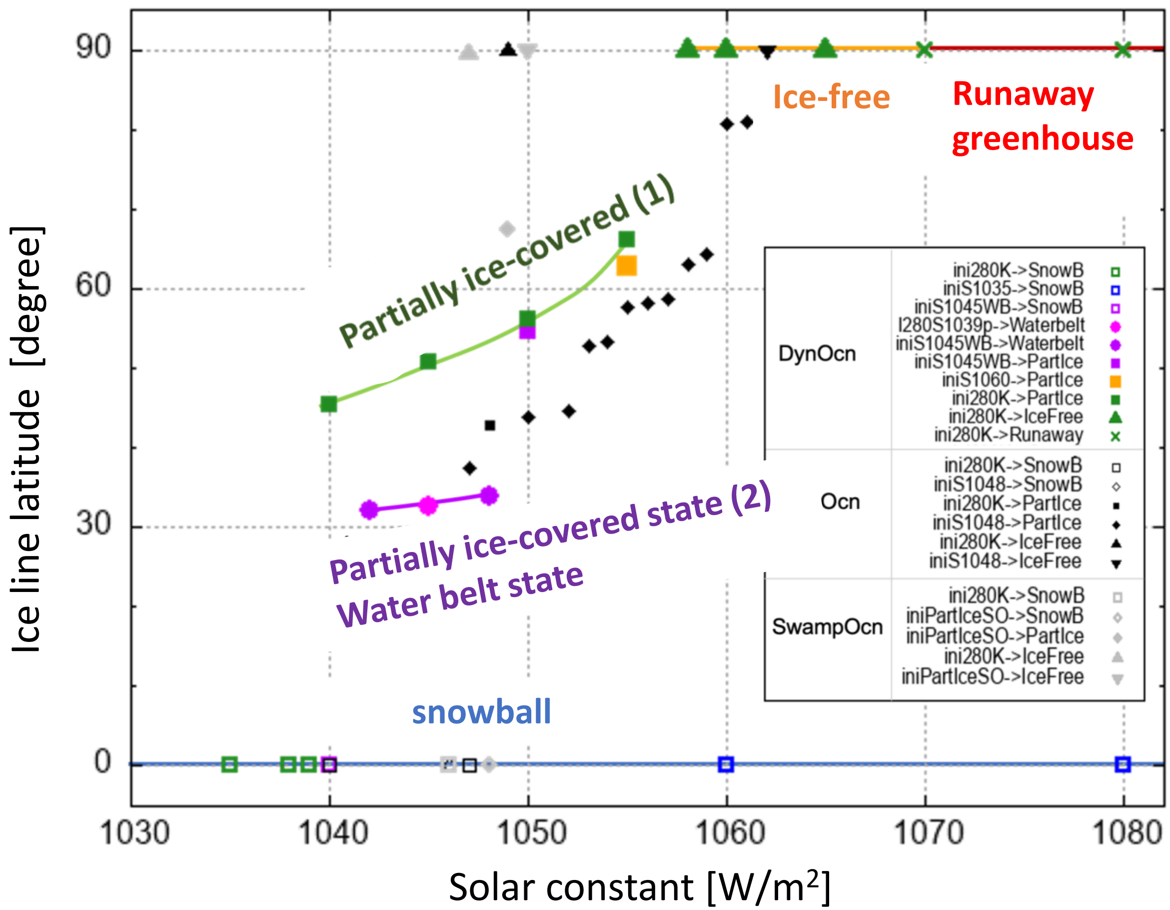
  $\frac{D}{B} \sim \frac{\text{heat trancport coefficient}}{\text{coefficien in infrared radiaion}}$ is small,

  change of ice-line latitude is smaller for cases with ocean heat transport

- **The reason why branch shape is almost independent of ocean model is that the effect of atmospheric heat transport is weak than cooling effect by infrared radiation**

Climate regime diagram with large absorption coefficient

Absorption coefficient: for vapor, $\boldsymbol{\kappa}_{\mathbf{v}} = \mathbf{0.1}\mathrm{m}^2/\mathrm{kg}$ for dry air, $\boldsymbol{\kappa}_{\mathbf{n}} = \mathbf{10}^{-5}\mathrm{m}^2/\mathrm{kg}$



- Five kinds of solutions
  - Ice–free state
  - Two kinds of partially ice–covered state
  - Runaway greenhouse state
- Coexistence of two kinds of partially ice–covered states and snowball state for the same value of solar constant
- Solar constant range for existence of partially ice–covered state becomes narrower

Summary

- Climate regime diagram is obtained by atmosphere-ocean coupled model with grey radiation
- Cases with small absorption coefficient
  - Solar constant dependence of branch structures is almost independent of ocean model
  - One kind of partially ice-covered state
- Cases with large absorption coefficient
  - Branch structures are changes according to ocean model
  - When ocean heat transport exist,
    - Solar constant range for existence of partially ice-covered states becomes narrower
    - Another kind of partially ice-covered state appers: water belt state