Irreversible transition to a state with higher entropy production in oceanic general circulation

Shinya Shimokawa * and Hisashi Ozawa **
* National Research Institute for Earth Science and Disaster Prevention, Tsukuba 305-0006, Japan
** Frontier Research System for Global Change, Yokohama 236-0001, Japan

Summary The mechanism of transitions among multiple steady states of thermohaline circulation is investigated from a thermodynamic viewpoint by using an oceanic general circulation model. All the results of the simulations tend to support the hypothesis that a nonlinear system, when perturbed, is likely to move to a state with maximum entropy production.

1. Introduction

It is well known that thermohaline circulation has multiple steady states under the same set of boundary conditions (Stommel, 1961). However, the mechanism which regulates the selection of a realistic solution from multiple steady states and the transitions among them is not yet fully understood. It has been suggested that the rate of entropy production associated with an open dissipative system is related to the stability of the system. Sawada (1981) stated that the entropy of thermal reservoirs connected via a nonlinear system will increase along an evolutionary path, favoring the maximum entropy production among manifold possible paths (the principle of maximum entropy production). However, there is no study that tests the principle of maximum entropy production for the ocean system. The objective of this study is to examine the principle for the transitions among the multiple steady states of thermohaline circulation by using an oceanic general circulation model.

2. Model description and Experimental method

The numerical model used in this study is the Geophysical Fluid Dynamics Modular Ocean Model (GFDL MOM) version 2. The model domain is a rectangular basin with a cyclic path, representing an idealized Atlantic Ocean. The horizontal grid spacing is 4 degrees. The depth of the ocean is 4500 m with twelve vertical levels. Our experiments (Shimokawa and Ozawa, 2002) consist of three phases: (1) spin-up under restoring boundary conditions for 5000 years, (2) integration under mixed boundary conditions with a high-latitude salinity perturbation for 500 years, and (3) integration under mixed boundary conditions without perturbation for 1000 years. As a result of phase (1), the system reaches a statistically steady state with northern sinking circulation (N_{RBC}, Fig. 1a). In phase (2), the system moves to a state which is determined by the perturbation applied. In phase (3), the system is adjusted satisfactorily to the boundary condition without perturbation. Then, in some cases, the system returns to the initial state, while in other cases, it does not, instead remaining in the state of being determined by the perturbation or moving to a different steady state which is independent of the perturbation. If a new steady state is obtained, procedures (2) and (3) are repeated using the new steady state as the initial state. If a new steady state is not obtained, these procedures are repeated using a different salinity perturbation. As a result, a series of multiple steady states of thermohaline circulation under the same set of wind forcing and mixed boundary conditions are obtained (Fig. 1). The standard salinity perturbation used in this study (Δ in Fig. 2) is 2×10^{-7} kg m^{-2} s^{-1} (= -0.1 m $year^{-1}$ fresh water flux), which is usually applied to the north of 46N and occasionally to the south of 46S.

3. Calculation method of entropy production

The rate of entropy production is calculated during the time integration for all experiments such as

$$dS/dt = \int \rho c/T\ \partial T/\partial t\ dV + \int F_h/T\ dA - \alpha k \int \partial C/\partial t\ \ln C\ dV - \alpha k \int F_s \ln C\ dA \qquad (1)$$

where ρ is the density, c is the specific heat at constant volume, T is the temperature, $\alpha=2$ is van't Hoff's factor representing the dissociation effect of salt into separate ions (Na^+ and Cl^-), k is the Boltzmann constant, C is the number concentration of salt per unit volume of sea water, F_h and F_s are the heat and salt fluxes per unit surface area, defined as positive outward, respectively; dV is the small volume element, the volume integration is taken over the whole ocean volume, dA is the small surface element, and the surface integrations are taken over the whole ocean surface. The first term on the right hand side represents the rate of entropy increase in the ocean system due to heat transport, and the second term represents that in the surrounding system. The third term represents the rate of entropy increase in the ocean system due to salt transport, and the fourth term represents that in the surrounding system. Overall, Equation (1) represents the rate of entropy increase of the whole system. This equation is applicable to a large-scale model whose scale of resolution is coarser than the dissipation scale because it dose not include a microscopic representation of the dissipation process (Shimokawa and Ozawa, 2001).

4. Results

The results of our experiments are summarized in Fig. 2. Starting from S1 (Fig. 1e), the system moves to S2 (Fig. 1f) regardless of the sign of the perturbation (r04 and r05); whereas starting from S2, the system does not return to S1, but remains in the initial state (S2) regardless of the sign of the perturbation (r08 and r09). In addition, starting from S3 (Fig. 1g), the system moves to S4 (Fig. 1h) regardless of the sign of the perturbation (r14 and r15); whereas starting from S4, the system does not return to S3, but remains in the initial state (S4) regardless of the sign of the perturbation (r18 and r19). When these transitions occur (r04, r05, r14 and r15), the rates of entropy production in the final states are always higher than those in the initial states (see Fig. 2). These results show that the transition from a state with lower entropy production to a state with higher entropy production tends to occur, but the transition in the inverse direction does not occur, i.e. the transition is *irreversible* or *directional* in the direction of the increase of the rate of entropy production. On the other hand, starting from N1 (Fig. 1b) with negative perturbation (r12), the system moves to S1. Starting from S1 with double positive perturbation (r06), the system moves to N1. Starting from N2 (Fig. 1c) with the negative perturbation (r13), the system moves to S3. Starting from S3 with double positive perturbation (r16), the system moves to N3 (Fig. 1d). These results show that the transitions in mutual directions between southern sinking and northern sinking are possible depending on the direction of the perturbation. In these cases, the rates of entropy production for the northern sinkings are higher than those for the southern sinkings. These results may appear to contradict the principle of maximum entropy production. However, we can show that the decrease is only caused by the negative perturbation applied to the sinking region which destroys the initial circulation altogether (Shimokawa and Ozawa, 2002). After this destruction, the entropy production is found to increase as a new circulation develops. All these results tend to support the hypothesis that a nonlinear system, when perturbed, is likely to move to a state with maximum entropy production.

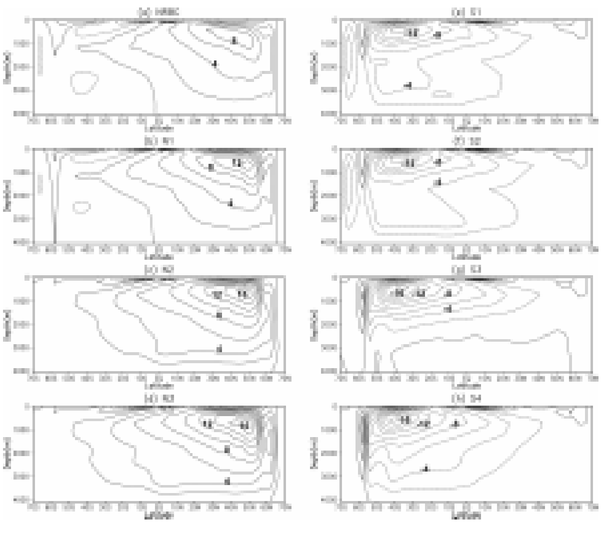

Fig. 1 All steady states obtained from this study. (a) N_{RBC}, (b) N1, (c) N2, (d) N3 (e) S1, (f) S2, (g) S3, (h) S4. Fields shown are zonally integrated meridional stream function at year 5000 for (a) spin-up and at year 1500 for (b) r06, (c) r02, (d) r16, (e) r01, (f) r04, (g) r13 and (h) r14. The contour line interval is 2 SV (10^6 m^3 s^{-1}). The capital letters "N" and "S" refer to northern sinking and southern sinking, respectively. N_{RBC} is a unique solution under restoring boundary conditions.

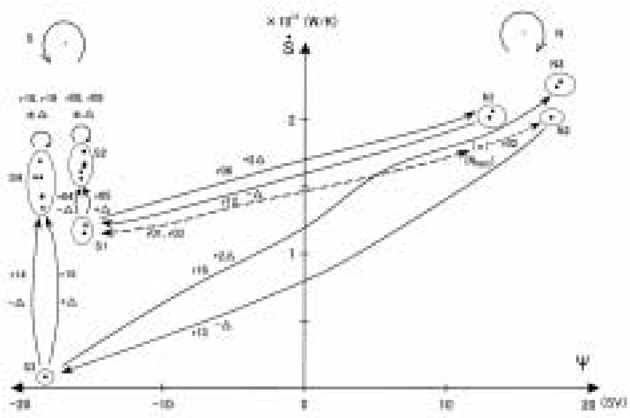

Fig. 2 The relationship between transitions among multiple steady states and rates of entropy production. The vertical axis ($\dot{S}$) indicates the rate of entropy production, and the horizontal axis (Ψ) shows the maximum value of the zonally integrated meridional stream function for the main circulation. The dots are corresponding to the steady states (initial and final states) of each experiment. The circles surrounding the dots show the circulation pattern (e.g. N1). The arrows show the direction of the transitions. The symbols besides the arrows show the experiment number and the perturbation used in the experiment (e.g. r04 and $-\Delta$).

REFFERENCES: Sawada, Y. (1981) Prog. Theor. Phys., **66**, 68-76., Stommel, H. (1961) Tellus, **13**, 224-230., Shimokawa, S. and H. Ozawa (2001) Tellus, **A53**, 266-277., Shimokawa, S. and H. Ozawa (2002) Q. J. Roy. Meteorol. Soc., **128**, 2115-2128.