Thermodynamics of the oceanic general circulation

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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 of the transitions among the multiple steady states is not yet fully understood. It is also known that a nonlinear system will evolve along a path favoring the maximum entropy production among manifold possible paths (the principle of maximum entropy production, Sawada, 1981). However, there is no study that tests the principle for the ocean system. The objectives of this study are to develop a method evaluating the rate of entropy production in large-scale circulation models and to examine the principle for the ocean system by applying to the method to an oceanic general circulation model.

2. Calculation method of entropy production

The rate of entropy production is calculated in large-scale circulation systems 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. 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 circulation 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).

3. Model description and Experimental method

The numerical model used in this study is the 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 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 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}, which is applied to the north of 46N or the south of 46S.

4. Results of the spin-up experiment

The oceanic circulation becomes statistically steady after the year 4000 and its flow pattern shows a basic one in the idealized Atlantic Ocean (N_{RBC}, Fig. 1a). In the steady-state after the year 4000, for both heat and salt transports, the entropy increase rates for the ocean system are zero whereas those for the surrounding system show positive values. The zero increase rates represent the fact that the ocean system is in a steady-state. Heat and salt are transported from equatorial (hot and salty) to polar (cold and less salty) regions by the steady-state circulation. These irreversible transports contribute to the entropy increase in the surrounding system. In this sense, the surrounding system is not in a steady state, even though the ocean system is in a steady-state.

5. Results of the transition experiments

The results of the transition 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). Likewise, the system moves from S3 to S4 (r14 and r15), whereas it does not return to the initial state (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, transitions in mutual directions between southern sinking and northern sinking are possible depending on the direction of the perturbation (r06, r12, r16 and r13). 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 the 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.
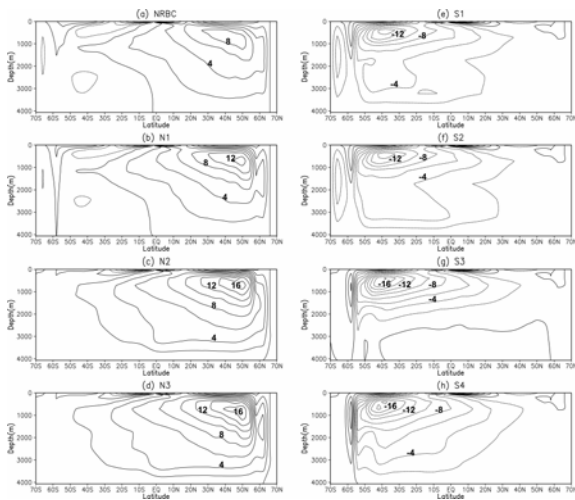

Fig. 1 All steady states obtained from this study. (a) N_{RBC}, (b) N1, (c) N2, (d) N3 (e) S1, (f) S2, (g) S3, (h) S4. Fields shown are zonally integrated meridional stream function at year 5000 for (a) spin-up and at year 1500 for (b) r06, (c) r02, (d) r16, (e) r01, (f) r04, (g) r13 and (h) r14. The 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.
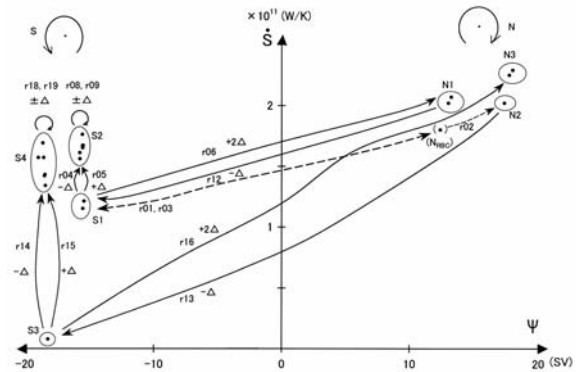

Fig. 2 The relationship between transitions among multiple steady states and rates of entropy production.

The vertical axis (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 -Δ).

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