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

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It is well known that the ocean system has multiple steady states under the same set of boundary conditions (ref.1). 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. MEP (the principle of maximum entropy production) states that a nonlinear non-equilibrium system is stabilized at a state with maximum entropy production (ref.2). However, there is no study that tests MEP for the ocean system. The objective of this study is to examine MEP for the transitions among the multiple steady states of the ocean system by using an oceanic general circulation model.

The numerical model used in this study is the GFDL MOM. The model domain is a rectangular basin with a cyclic path, representing Atlantic Ocean. Our experiments3 consist of three phases: (a) spin-up under restoring boundary conditions for 5000 years, (b) integration under mixed boundary conditions with a salinity perturbation for 500 years, and (c) integration under mixed boundary conditions without perturbation for 1000 years. Then, if a new steady state is obtained, procedures (b) and (c) 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 boundary conditions are obtained. The standard salinity perturbation used in this study (see Fig. 1) is 0.0000002 kg/m/m/s (= -0.1 m/year fresh water flux), which is usually applied to the north of 46N.

The rate of entropy production is calculated such as (I is a integral, and d" is a partial differential): dS/dt = I[rc/T d"T/d"t] dV + I[Fh/T] dA – ak I[d"C/d"t lnC] dV - ak I[Fs lnC] dA, where r is the density, c is the specific heat at constant volume, T is the temperature, a=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, Fh and Fs are the heat and salt fluxes per unit surface area, defined as positive outward, respectively. This equation represents the rate of entropy increase of the whole system (ref.4).

The results of our experiments are summarized in Fig. 1. Starting from S3, the system moves to S4 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). We can also see the same tendency in the transition between S1 and S2. 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. 1). These results show that the transition is irreversible or directional in the direction of the increase of the rate of entropy production, and are consistent with MEP. On the other hand, starting from a northern sinking (N1 or N2) with negative perturbation (r12 or r13), the system moves to a southern sinking (S1 or S3) with lower entropy production. These results may appear to contradict MEP. 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 (ref.3). After this destruction, the entropy production is found to increase as a new circulation develops. All these results tend to support MEP.

Refferences: 1) Stommel, H. (1961) Tellus, 13, 224-230., 2) Sawada, Y. (1981) Prog. Theor. Phys., 66, 68-76., 3) Shimokawa, S. and H. Ozawa (2002) Q. J. Roy. Meteorol. Soc., 128, 2115-2128., 4) Shimokawa, S. and H. Ozawa (2001) Tellus, A53, 266-277.

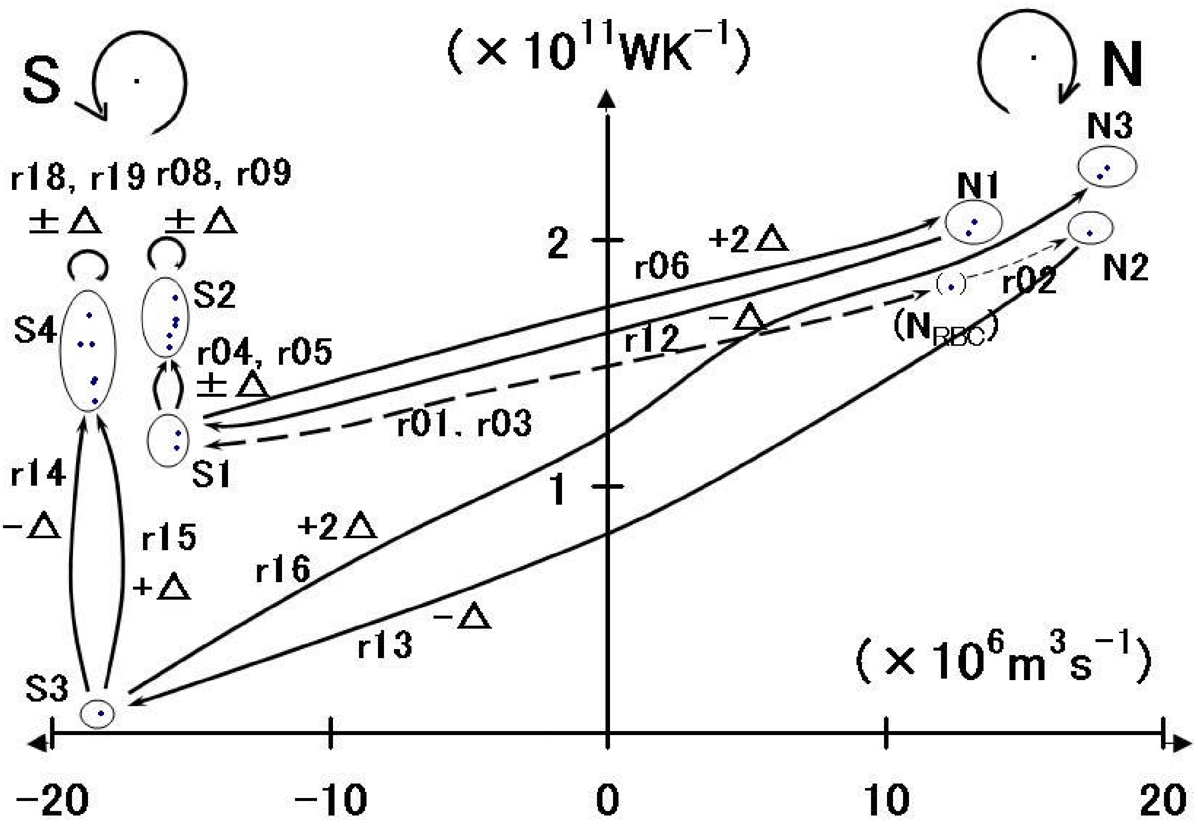

Fig.1. The relationship between transitions among multiple steady states and rates of entropy production. The vertical axis (S) indicates the rate of entropy production, and the horizontal axis (Ψ) shows the maximum value of the zonally integrated meridional stream function for the main circulation. 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 −△).