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On thermodynamics of irreversible transitions in the oceanic general circulation

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1. Introduction

In this study, we focus on a thermodynamic variational principle of maximum entropy production (**MEP**, Sawada,1981); a nonlinear non-equilibrium system tends to evolve to a state with maximum entropy production. This principle has been confirmed to be valid for various nonlinear fluid systems (e.g., Paltridge, 1975).

The ocean system can be seen as an open dissipative system connected with its surroundings mainly via heat and salt fluxes, and has been known to possesses multiple steady states under the same boundary conditions (Fig. 1). In this study, we examine MEP for the transition among multiple steady states of the oceanic general circulation (Shimokawa and Ozawa, 2001, 2002, 2007).

2. Model and Method

The numerical model used in this study is the Geophysical Fluid Dynamics Laboratory's Modular Ocean Model. The model domain is a rectangular basin with a cyclic path, representing an idealized Atlantic Ocean. A series of multiple steady states under the same boundary conditions (four Southern Sinking Circulations (**SSC**): S1–S4; and three Northern Sinking Circulations (**NSC**): N1–N3, Fig. 2) are obtained by adding salinity perturbation to the north of 46° N.

3. Results

The results are summarized in Fig. 2. Starting from S3, the system moves to S4 with higher entropy production, regardless of the sign of the perturbation (**r14 and r15**). Starting from S4, the system does not return to S3, but remains in S4, regardless of the sign of the perturbation (**r18 and r19**). **These transitions are irreversible in the increase direction of entropy production rate, and support MEP.** In r14, negative salt perturbation applied to S3 strengthens SSC (Fig. 3c). In fact, the system moves to a stronger SSC, S4, after the perturbation is removed. **This is a natural transition caused by the perturbation and is consistent with MEP.** In r15, positive salt perturbation applied to S3 weakens SSC (i.e. strengthens NSC). In fact, a NSC is developed temporarily (Fig. 3d). But, the system moves to S4 after the perturbation is removed. **This is positive evidence in support of MEP.**

Starting from N1 with negative perturbation, the system moves to S1 (**r12**). Starting from S1 with positive perturbation, the system moves to N1 (**r06**). **These transitions are irrelevant to the entropy production rate, and appear to be contradicted MEP.** In oceanic circulation, sinking occurs in the narrow polar region, and upwelling occurs in other broad regions. Therefore, a positive (negative) salt perturbation applied to a sinking region should effectively strengthen (suppress) the circulation when compared with a negative (positive) salt perturbation applied to an upwelling region. In r06, a positive salt perturbation is applied to northern high latitude region in a southern sinking (upwelling region). In this case, the SSC co-exists with a newly developed NSC, and then changes into the NSC (Fig. 3b). **The perturbation acts only as a trigger for the transition. This transition is a spontaneous transition independent of the perturbation and is consistent with MEP.** In r12, a negative salt perturbation is applied to northern high latitude region in a northern sinking (sinking region) (Fig. 3a). In this case, the NSC collapses completely, and then changes into a newly developed SSC. **The perturbation acts as a forcing to the initial circulation. This transition is an enforced transition controlled by the strong perturbation and is independent of MEP.**

4. Conclusions

The results can be explained in a consistent manner by a conceptual figure (Fig. 4a). A small perturbation can trigger the transition to a state with higher entropy production, regardless of its sign. In the situations, the entropy production rate plays a similar role to a thermodynamic potential in classical thermodynamics (Fig. 4b).

Summary

・The mechanism of transitions among multiple steady states under the same set of boundary conditions is investigated by using an numerical model of the oceanic general circulation.

・The results suggest that the transition is consistent with MEP except when the perturbation destroys the initial circulation altogether.

・ These results can be explained in a consistent manner by a conceptual figure which regards the rate of entropy production as a kind of thermodynamic potential in classical thermodynamics.

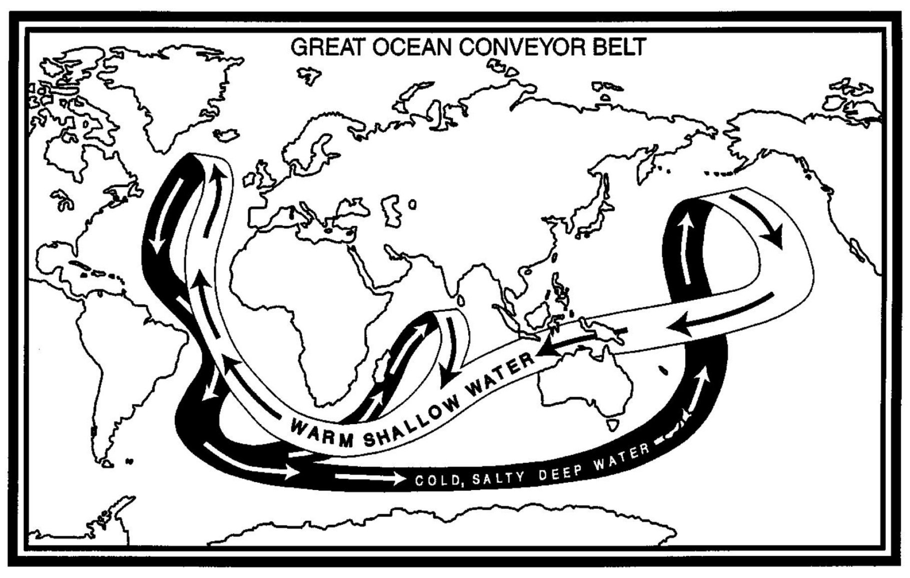

Figure 1 Conceptual figure of the oceanic general circulation at the present state of climate. The state of the circulation can be changed drastically by the state of climate, which affects on heat and fresh water (salt) fluxes.

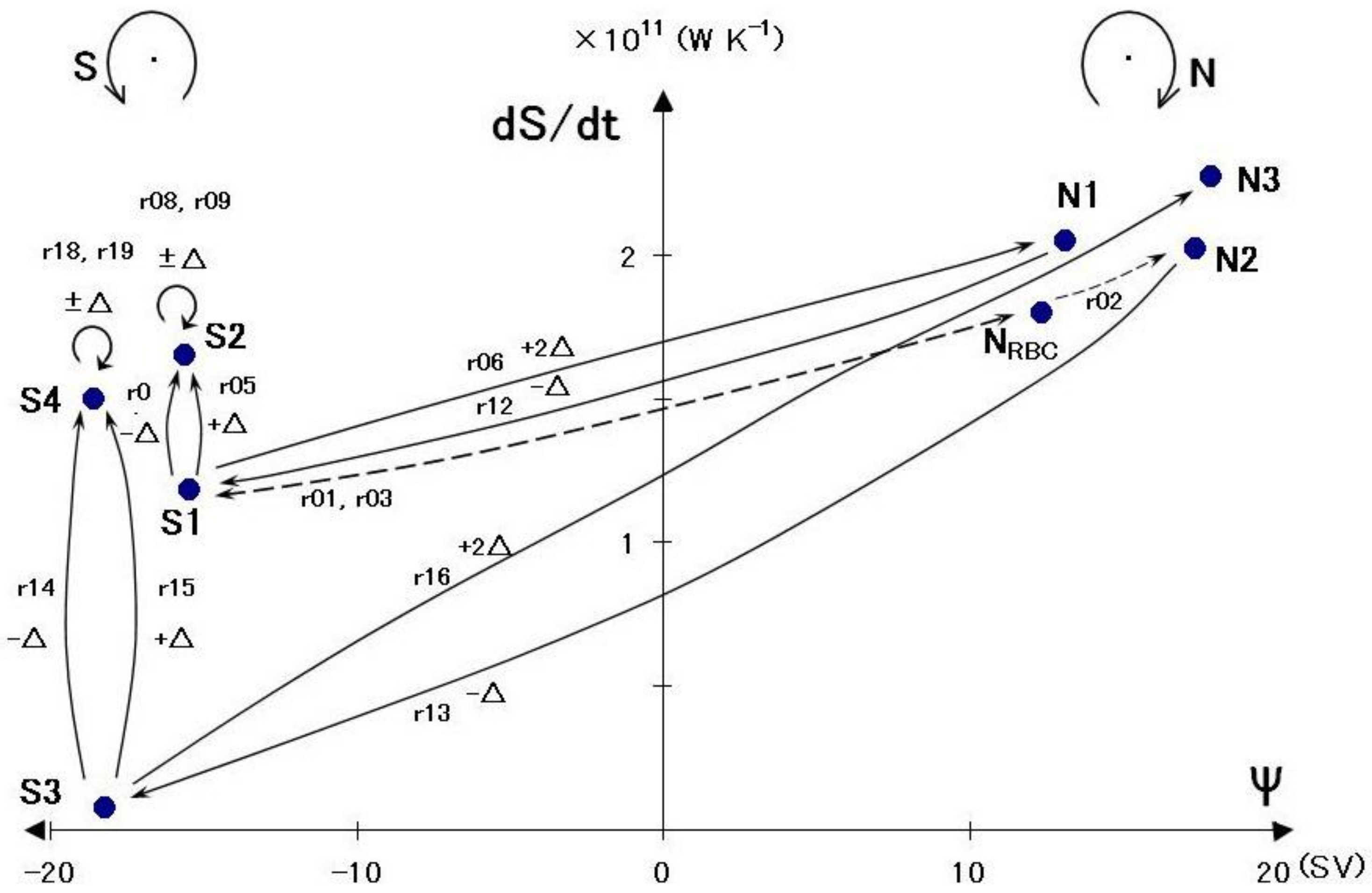

Figure 2 Summary of the results obtained from the numerical simulations: the relationship between transitions among multiple steady states and rates of entropy production. The y axis (dS/dt) indicates the rate of entropy production (W K^{-1}), and the x axis (Ψ) shows the maximum value of the zonally integrated meridional stream function for the main circulation (SV = 10^6 m^3 s^{-1}). The dots correspond to the steady states (initial and final states) of each experiment (e.g., N1). The arrows show the direction of the transitions. The symbols beside the arrows show the experiment number and the perturbation used in the experiment (e.g. r04 and −Δ). The standard salinity perturbation, Δ is 2 × 10^{-7} kg m^{-2} s^{-1}, which is applied north of 46° N. N_{RBC} is a unique solution under another boundary conditions. The dashed lines show the transition from or to N_{RBC} with the changes of boundary conditions.

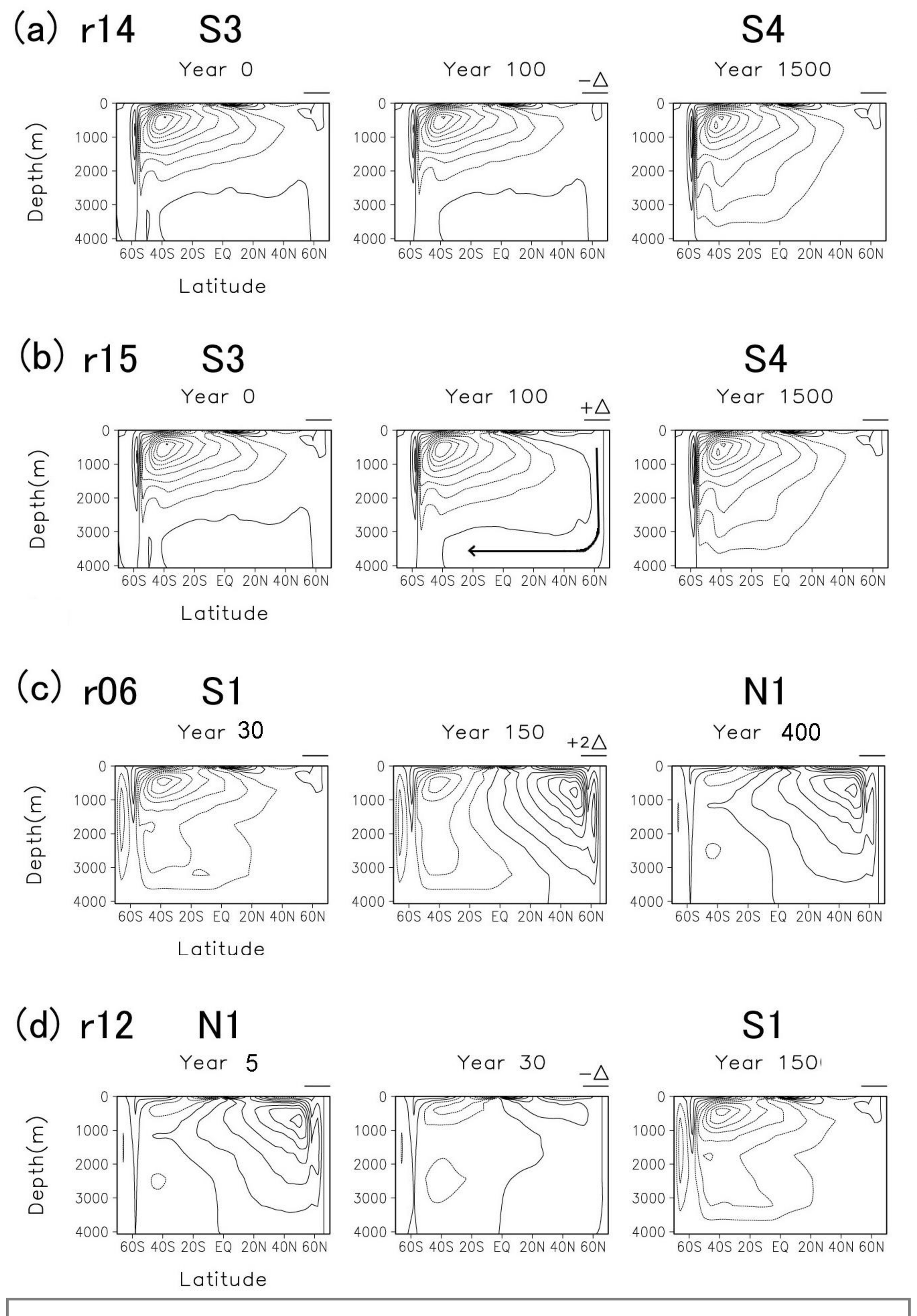

Figure 3 Evolution of the zonally integrated meridional stream function in five experiments: (a) r14; (b) r15; (c) r06; (d) r12. The contour interval is 2.0 SV (10^6 m^3 s^{-1}). The arrow in the middle of (b) indicates the development of the NSC (see left text).

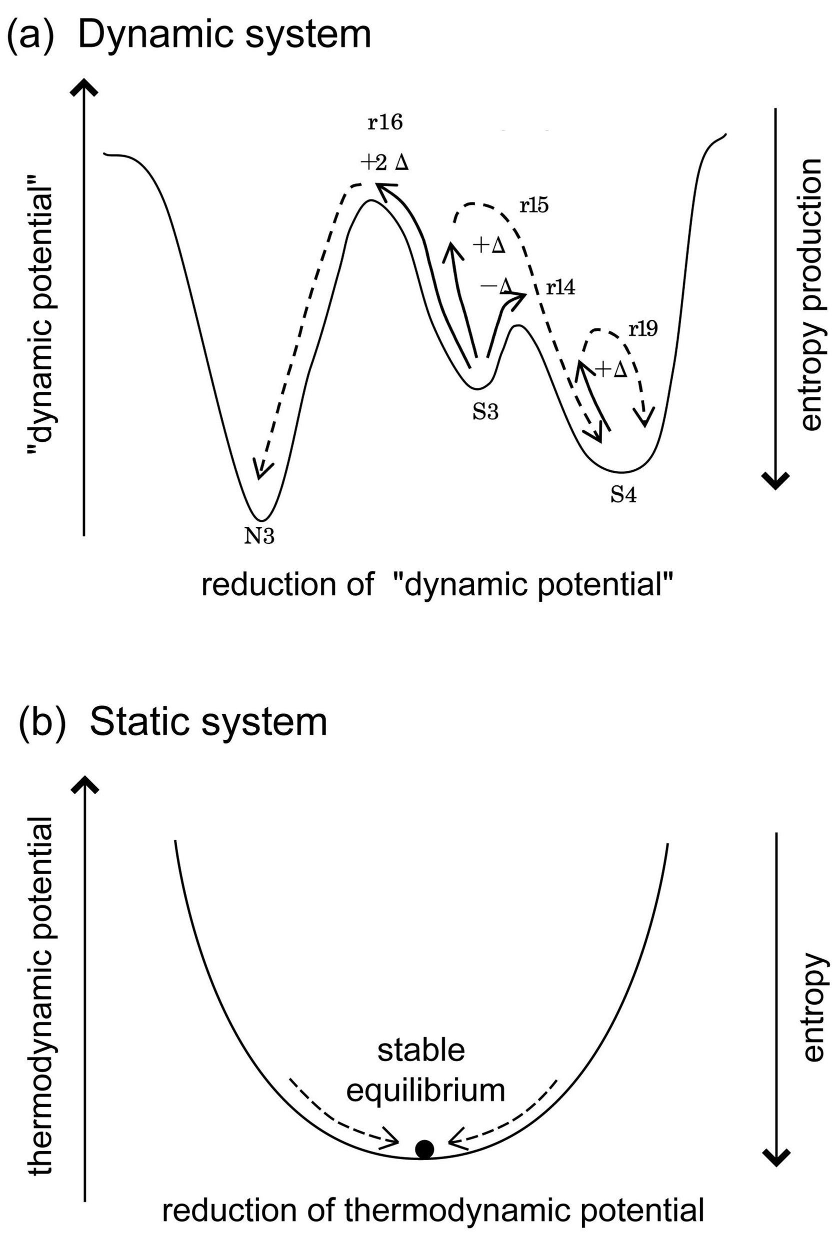

Figure 4 Schematic diagrams showing the stability of (a) a dynamic system and (b) a static system. The most stable steady state corresponds to a minimum in the dynamic potential (i.e., MEP) in (a) and a minimum in the thermodynamic potential (i.e., maximum entropy) in (b).

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