Thermodynamics of irreversible transitions in the oceanic general circulation

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[1] In this study, we investigate a transition process among multiple steady states of oceanic circulation under the same set of boundary conditions, and clarify the relationship between entropy production and the strength and direction of fresh water perturbations. Our results are found to be consistent with “the principle of maximum entropy production (MEP)” in non-equilibrium thermodynamics, and can be understood in a consistent manner by a concept of “dynamic potential” that regards the rate of entropy production as a kind of thermodynamic potential. MEP could be a general thermodynamic principle that determines the behavior of oceanic circulation in response to external perturbations, leading to a better understanding of abrupt climate changes such as the Younger Dryas event and Dansgaard–Oeschger oscillations. Citation: Shimokawa, S., and H. Ozawa (2007), Thermodynamics of irreversible transitions in the oceanic general circulation, Geophys. Res. Lett., 34, L12606, doi:10.1029/2007GL030208.

1. Introduction

[2] Computer simulations suggest that global warming can weaken or stop oceanic general circulation, resulting in global climate change [Alley, 2004]. Such weakening was in fact observed in the Atlantic meridional overturning circulation recently [Bryden et al., 2005]. Changes of this sort of the oceanic general circulation can be abrupt, thereby, significantly affecting our future. However, the change mechanism of the oceanic circulation is not yet fully understood.

[3] The ocean system can be seen as an open dissipative system connected with surrounding systems mainly via heat and salt fluxes. The surrounding systems consist of the atmosphere, the Sun and space. Because of the curvature of the Earth’s surface and the inclination of its rotation axis relative to the Sun, there are net gains of heat and salt in the equatorial region, and net losses of heat and salt in the polar regions. The heat and salt fluxes bring about an inhomogeneous distribution of temperature and salinity in the ocean system. This inhomogeneity produces the circulation, which in turn reduces the inhomogeneity. In this respect, the formation of the circulation can be regarded as a process leading to final equilibrium of the whole system: the ocean system and its surroundings. In this process, the rate of approach to equilibrium, i.e., the rate of entropy production by the oceanic circulation, is an important factor.

[4] In this paper, we focus on a thermodynamic variational principle of maximum entropy production (MEP) that was proposed in the field of non-equilibrium thermodynamics by Sawada [1981]. According to Sawada, a nonlinear system which is in contact with thermal reservoirs far from equilibrium tends to follow a path of evolution with a maximum rate of entropy production among a manifold of dynamically possible paths. This principle has been called MEP, and confirmed to be valid for mean states of a variety of nonlinear fluid systems, e.g., the global climate system of the Earth [Paltridge, 1975, 1978; Grassl, 1981; Noda and Tokioka, 1983; Ozawa and Ohmura, 1997], those of other planets [Lorenz et al., 2001], thermal convection and shear turbulence [Ozawa et al., 2001], and turbulent transport of heat and momentum in the atmospheric boundary layer [Kleidon et al., 2006]. The ocean system has been known to possesses multiple steady states of circulation under the same boundary conditions [Stommel, 1961; Marotzke and Willebrand, 1991]. Our recent numerical simulations suggest that MEP is also valid for transitions of the circulation among these multiple steady states [Shimokawa and Ozawa, 2001, 2002, 2005]. Hence it would seem that this MEP principle can stand for a universal principle for time evolution of non-equilibrium systems [Lorenz, 2003; Whitfield, 2005; Kleidon and Lorenz, 2005; Martyushev and Seleznev, 2006]. While some attempts have been made to seek a theoretical framework of MEP [Paltridge, 2001; Dewar, 2003, 2005; Ozawa et al., 2003], we remain uncertain about its physical meaning. It is therefore worthwhile to seek the mechanism of MEP by means of numerical simulations. In this paper, we examine the response of the oceanic circulation to external fresh water perturbations, and thereby investigate the underlying physical mechanism of MEP.

2. Methods

[5] The numerical model used in this study is the Geophysical Fluid Dynamics Laboratory’s Modular Ocean Model [Pacanowski, 1995]. The model equations consist of the Navier–Stokes equations subject to the Boussinesq, hydrostatic, and rigid-lid approximations along with a nonlinear equation of state which couples two active variables, temperature and salinity, to the fluid velocity. The model domain is a rectangular basin with a cyclic path, representing an idealized Atlantic Ocean. The horizontal grid spacing is 4 degree. The depth of the ocean is 4500 m with 12 vertical levels [Shimokawa and Ozawa, 2001]. A series of multiple steady states of thermohaline circulation under the same set of mixed boundary conditions (four southern sinking circulations: S1–S4; and three northern...
sinking circulations: N1–N3, see Figure 1) are obtained by repeating two procedures: integrations under mixed boundary conditions with a high-latitude salinity perturbation for 500 years and without perturbation for 1000 years. As the standard salinity perturbation, we apply $\Delta = 2 \times 10^{-7}$ kg m$^{-2}$ s$^{-1}$ ($\approx -0.1$ m year$^{-1}$ fresh water flux) to the region between 46 degree North and 70 degree North. More details about the numerical experiments are given by Shimokawa and Ozawa [2001, 2002].

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

$$\frac{dS}{dt} = \int \rho c \frac{dT}{T} dV + \int \frac{F_h}{T} dA - \alpha k \int \frac{\partial C}{\partial t} \ln CdV$$

$$- \alpha k \int F_s \ln CdA,$$

(1)

where $\rho$ 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 respectively, defined as positive outward, and $dV$ and $dA$ are the small volume and surface elements respectively [Shimokawa and Ozawa, 2001]. The first two terms in the right-hand side represent the entropy production rate due to heat transport in the ocean, and the next two terms represent that due to the salt transport. The first and third terms vanish when the system is in a steady state since the temperature and the salinity are virtually constant ($\partial T/\partial t = \partial C/\partial t = 0$). In the steady state, entropy produced by the irreversible transports of heat and salt is completely discharged into the surrounding system through the boundary fluxes of heat and salt as expressed by the second and fourth terms in equation (1). The advantage of using this equation is that we can evaluate the entropy production rate by the boundary fluxes of heat and salt and the temperature and salinity distributions in the model, whose scale of resolution is coarser than the dissipation scale, since it does not include a microscopic representation of the dissipation process [Shimokawa and Ozawa, 2001].

3. Results and Discussion

The results of the numerical experiments are summarized in Figure 1. Each circle represents the steady state, plotted on a parameter space of the peak strength of the zonally integrated meridional stream function ($\Psi$) and the rate of entropy production ($dS/dt$). When $\Psi < 0$, the dominant circulation sinks in the Southern Hemisphere, and rises in the Northern Hemisphere. When $\Psi > 0$, the reverse is true. Each steady state can be shifted by the perturbations. The arrow in Figure 1 shows the transition from one steady state to the other state by a perturbation. Starting from S3 with a relatively low rate of entropy production, the state tends to shift to a new state (S4) with a higher rate of entropy production, by either positive or negative salt perturbation (+$\Delta$: r14 or -$\Delta$: r15). The interesting thing is that once the system reaches the state with the higher entropy production (S4), it does not go back to the initial state (S3), but tends to stay in S4, even if we apply the same-strength perturbation with opposite sign ($-\Delta$: r18 or +$\Delta$: r19). The same is true for the transition from S1 to S2 (r04, r05, r08, and r09). These transitions can be called irreversible in the direction of the increase of entropy production since no inverse transition is
possible by either positive or negative perturbations. These irreversible transitions support the validity of MEP.

[8] On the other hand, the transitions between N1 and S1 (r06, r12) or N2 and S3 (r13, r16) 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 would appear to contradict MEP. However, we can show that the decrease is caused only by the negative perturbation applied to the sinking region, which collapses the initial circulation completely. This collapse is caused by a somewhat strong perturbation applied to the sinking region of the initial circulation. After this collapse, the entropy production rate increases as the new circulation develops. This result is consistent with the concept of MEP.

[9] Let us discuss the effect of perturbation to the strength of the deep ocean circulation more closely. In general, sinking takes place in a narrow polar region whereas upwelling occurs in the broad polar region on the other side. Thus, a positive (negative) salt perturbation to the sinking region effectively enhances (suppresses) the circulation whereas the same perturbation to the upwelling region has a lesser effect on the circulation. The relative location at which the perturbation is added is therefore important, in addition to the strength and sign of the perturbation.

[10] In the case with a negative salt perturbation to the sinking region of the circulation N1 (r12), the northern sinking circulation collapses completely, and then new southern-sinking circulation develops afterwards (Figure 2a). This means that the perturbation plays a crucial role in the transition, and the transition is said to be an enforced one. The similar situation can be seen for the transition from N2 to S3 (r16). These enforced transitions can, in principle, be independent of the concept of MEP. On the other hand, in the case with a positive salt perturbation to the upwelling region of the southern-sinking circulation S1 (r06), the initial circulation co-exists with newly developed circulation, which then grows into the dominant circulation N1 (Figure 2b). In this case, the perturbation acts just as a trigger for the transition, and the transition is said to be a natural one. This natural transition is associated with an increase of entropy production, and is consistent with MEP. In the case with a negative salt perturbation to the upwelling region of the circulation S3 (r14), the circulation is enhanced, and grows into a stronger circulation S4 with a higher rate of entropy production (Figure 2c). This is a natural transition caused by the perturbation, and is consistent with MEP. In the case of a positive salt perturbation to the upwelling region of the same circulation S3 (r15), the southern sinking circulation is temporarily suppressed by a newly formed northern-sinking cell (see the arrow in Figure 2d), but the initial circulation grows into the stronger circulation S4 after the perturbation is removed (Figure 2d). This means that the circulation tends to grow into the stronger circulation with the higher rate of entropy production even though the applied perturbation has the suppression effect on the initial circulation. This result suggests the validity of MEP. In the case with a positive salt perturbation to the upwelling region of the circulation S4 (r19), the circulation is temporarily suppressed by a newly formed northern-sinking cell (Figure 2e). The suppressed circulation, however, does not go back into the original circulation S3 with the lower rate of entropy production, but remains in the same state of S4, after the perturbation is removed. The transition from S3 to S4 is therefore irreversible, and is consistent with the concept of MEP.

[11] The overall results obtained from our experiments can be summarized schematically in Figure 3a, in which entropy production is shown as positive downward. The ordinate represents a sort of “dynamic potential” that is supposed to indicate stability of an externally driven fluid system like the ocean. In general, such a system is driven by external supply of energy and materials, and the amount of energy that is available for mechanical energy is called available energy. It is shown in our recent study that the generation rate of the available energy as well as its dissipation rate tends to increase by a feedback growth process of kinetic energy in the fluid system [Ozawa et al., 2003]. Thus, one can infer that the increasing process of the dissipation rate (entropy production) is identical to the decreasing process of the “dynamic potential” shown in Figure 3a. The most stable steady state of this dynamic system can then be expected at the minimum of its “dynamic potential” as if it were the case of equilibrium minimum in the thermodynamic potential (Gibbs free energy) for a static system (Figure 3b). A static thermodynamic system tends to reduce its thermodynamic potential so that its final equilibrium state corresponds to the one with the minimum thermodynamic potential (i.e., maximum entropy). While the system’s state can be shifted to other states by strong external perturbations, the most stable equilibrium state is expected at the one with the minimum thermodynamic potential. Likewise, a dynamic fluid system tends to reduce its “dynamic potential” by the feedback growth of the dissipation rate so that its most stable steady state should be the one with the minimum “dynamic potential” (i.e., MEP). This schematic concept is consistent with our experimental results that, when an ocean system is subjected to perturbations, the system tends to change its state towards a state with higher entropy production except for the case of enforced transitions due to strong directional perturbations.

[12] Past abrupt climate changes have been attributed to rapid changes in the oceanic circulation caused by external freshwater fluxes [Broecker, 1997]. For example, reducing the meridional overturning of the oceanic circulation caused by melting of the Laurentide ice sheet has been proposed as a possible mechanism of the Younger Dryas cold event [Broecker and Denton, 1989]. Also, it has been proposed that the 8.2 ka cold event was triggered by catastrophic fresh water discharge from the Laurentide lakes to the Labrador Sea [Alley et al., 1997]. The Dansgaard–Oeschger oscillations [Dansgaard et al., 1982] and the Palaeocene/Eocene thermal maximum [Nunes and Norris, 2006] are also considered to be related to the changes in the oceanic circulation. In all these cases, the response of the oceanic circulation to external perturbations is of certain importance. It can be said from our numerical experiments that the present northern-sinking circulation is possible and stable one as the oceanic general circulation. But this circulation is sensitive to a negative salt (i.e., fresh water) perturbation in its sinking region, and can collapse or be changed into

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completely different circulation by such a perturbation. The newly formed circulation may be less stable with low entropy production, and can be changed into more active circulation with higher entropy production via external perturbations. Although our study remains to be on a qualitative interpretation of the changes in the oceanic circulation, we can suspect that MEP could be a general thermodynamic principle governing the stability and
changes of the oceanic circulation in response to external perturbations, leading to a better understanding of the past and future climate changes.

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