Stabilization of thermohaline circulation by wind-driven and vertical diffusive salt transport

Abstract The stability of the thermohaline circulation is investigated using an ocean general circulation model coupled to a simple atmospheric model. The atmospheric model is so developed that it represents the wind stress and the freshwater flux more realistically than existing energy balance models. The coupled model can reproduce the realistic deep ocean circulation without any flux adjustment. Effects of the wind stress and the vertical diffusion on the thermohaline circulation are studied by conducting various experiments with the coupled model. The Ekman upwelling between 60°N and 90°N brings up salt to the sea surface, while the compensation flow of the Ekman transport and the wind-driven gyre circulation between 30°N and 60°N carry salt horizontally to the high latitudes. By carrying out experiments where the wind stress is completely or partly removed, it is demonstrated that either of the vertical or the horizontal salt transport prevents the halocline formation at high latitudes and maintains the thermohaline circulation. For an experiment in which the vertical diffusivity is enhanced at high latitudes, it is shown that the vertical diffusion at high latitudes also prevents the halocline formation and stabilizes the thermohaline circulation. It is also shown that the value of the vertical diffusivity at high latitude affects the existence of the multiple equilibria of the thermohaline circulation.

1 Introduction

The Atlantic deep circulation is one of the most important factors controlling the climate. For the present Atlantic deep circulation, the deep sinking is taking place in the northern North Atlantic and the deep water is flowing southward at 2000 to 3000 m depths. The heat transport associated with this circulation plays an important role in maintaining the present state of the climate. However, some studies show that the Atlantic deep circulation in other climate states can be different from the present. For example, there is geological evidence that the Atlantic deep circulation at the Last Glacial Maximum (LGM) was weaker and shallower than the present one (e.g. Labeyrie et al. 1992). Manabe and Stouffer (1988) obtained two stable equilibria in their atmosphere-ocean coupled model: one with the active Atlantic deep circulation as at present and the other without any deep water formation in the northern North Atlantic. However, it is not clear what makes those states different and what causes the transition between each state.

Many studies on the stability of the thermohaline circulation have been conducted by using ocean general circulation models (OGCMs) with mixed boundary conditions. For example, multiple equilibria of the thermohaline circulation were obtained in some studies (e.g. Bryan 1986; Marotzke and Willebrand 1991; Hughes and Weaver 1994) and the variability of the thermohaline circulation was investigated (e.g. Weaver et al. 1993; Winton and Sarachik 1993). However, the mixed boundary conditions cannot represent the realistic air-sea feedback, and they make the thermohaline circulation unrealistically unstable (Rahmstorf et al. 1995). Use of a coupled ocean-atmosphere model is necessary for realistic representation of the air-sea feedback. Although the best way is to use an OGCM coupled to an atmospheric general circulation model (AGCM) as Manabe and Stouffer (1988) did, its computational cost is so high that case studies on the thermohaline circulation, which require long-term integration, are difficult to carry out. Recently some studies have been conducted by using simpler atmospheric models such as energy balance models (EBMs) for
AGCMs (e.g. Fanning and Weaver 1996; Lohmann et al. 1996). There are some problems in existing EBMs, e.g., since they cannot represent the rainfall at low latitudes or the wind stress. We need an atmospheric model which resolves these problems.

In the present work, we develop a new atmospheric model which parametrizes the freshwater flux and the wind stress in terms of the surface air temperature, and then couple it to an OGCM to examine mechanisms maintaining the present thermohaline circulation and controlling its stability. It has been shown that the thermohaline circulation driven by sinking of the cold water at high latitudes stops when the low-salinity water covers the sea surface at high latitudes, forming the halocline there (e.g. Bryan 1986; Marotzke and Willebrand 1991). In most of the previous studies, the halocline formation was discussed from the standpoint of the freshwater boundary condition, i.e., the behaviour of the thermohaline circulation was examined under various patterns of freshwater flux (e.g. Weaver et al. 1991; Rahmstorf 1995). For the present study, we focus on effects of the wind stress and the vertical diffusion on the halocline formation, and examine how they stabilize the global thermohaline circulation.

Some recent studies examined the relationship between the wind stress and the thermohaline circulation. Winton and Sarachik (1993) results showed that the long-term self-sustaining oscillations of the thermohaline circulation appear when the wind stress is switched off. Hughes and Weaver (1994) showed that the deep water formation in the Southern Hemisphere stops when the wind stress is eliminated in the Southern Ocean. Schiller et al. (1997) pointed out that the wind stress contributes to the recovery of the thermohaline circulation weakened by freshwater discharge to the deep water formation region, because the wind-driven circulation removes freshwater capping at high latitudes. Toggweiler and Samuels (1994) conducted experiments where the strength of the wind stress in the Southern Ocean is varied and found that the strength of the Atlantic deep circulation is strongly affected by the wind stress there. Tsujino and Suginohara (1999) clarified a mechanism that provides a connection between the wind forcing and the thermohaline circulation by using an idealized basin model: the Ekman upwelling enhances the sea surface heating and its heating is balanced by the enhanced cooling in the deep-water formation region due to the warmed deep water, thus enhancing the thermohaline circulation. Hasumi and Suginohara (1999a) clearly demonstrated that the relation between the wind stress in the Southern Ocean and the Atlantic deep circulation is accounted for by the mechanism suggested by Tsujino and Suginohara (1999). Their results explain how the present thermohaline circulation is maintained, but cannot answer the question of how the thermohaline circulation really responds to changes in wind stress because their experiments were conducted under fixed restoring boundary conditions and air-sea feedback was not considered. Rahmstorf and England (1997) showed that the change of the wind stress in the Southern Ocean did not affect the Atlantic deep circulation so much when air-sea thermal feedback is considered. However, the freshwater flux is prescribed in their experiments and the air-sea feedback is not fully represented.

For the present study, we conducted experiments in which the wind stress is completely or partly removed to examine wind stress effects on the thermohaline circulation. These effects are discussed in terms of salinity balance at high latitudes and the halocline formation there. We also discuss effects of the vertical diffusion by conducting an experiment in which the vertical diffusivity is enhanced at high latitudes.

In Sect. 2, the model description is given. Results and discussion of various experiments are described in Sect 3. Finally, concluding remarks are presented in Sect. 4.

2 Model description

2.1 Atmospheric model

This model predicts the surface air temperature by solving the vertically integrated energy balance equation. The surface wind is diagnosed from the distribution of the surface air temperature. The freshwater flux is diagnosed from the convergence of atmospheric water transport.

2.1.1 Prediction equation for surface air temperature

The equation for the vertically integrated energy balance is

$$C_a \frac{dT}{dt} = Q_{lw} - Q_{sw} + Q_i - F_r \ ,$$

(1)

where $C_a$ is the heat capacity of the air column, $T$ is the surface air temperature, $t$ is time, $Q_{lw}$ and $Q_{sw}$ are the net incoming shortwave and the outgoing longwave radiation at the top-of-the-atmosphere, $Q_i$ is the convergence of the horizontal heat transport by the atmosphere, and $F_r$ is the net downward heat flux at the sea or land surface. The net incoming shortwave radiation is estimated by prescribing the time independent planetary albedo,

$$Q_{sw} = \frac{S_0}{4} S(\theta)(1 - \alpha(\theta)) \ ,$$

(2)

where $S_0$ is the solar constant, $S$ is the annual distribution of the shortwave radiation intersecting the top of the atmosphere, $\theta$ is the latitude, and $\alpha$ is the latitudinally dependent planetary albedo. We do not consider the seasonality of $Q_{sw}$ in this model because an annually averaged steady state is assumed in some of the parameterizations. The outgoing longwave radiation is represented by a linear function of $T$, as in traditional EBMs (e.g. North 1975),

$$Q_{lw} = A + BT \ ,$$

(3)

where $A$ and $B$ are constant values. The convergence of the horizontal heat transport by the atmosphere is represented by the form of the diffusion term,

$$Q_i = C_i \nabla \cdot (\kappa \nabla T) \ ,$$

(4)

where $\kappa$ is the heat diffusion coefficient.

The net downward heat flux at the sea surface is represented by

$$F_r = Q_{lw} - (Q_{lo} - Q_{lw}) - Q_{sh} - Q_{ls} \ ,$$

(5)

where $Q_{lw}$ is the net downward shortwave radiation, $Q_{lo}$ and $Q_{lw}$ are the upward and the downward longwave radiation, and $Q_{sh}$ and $Q_{ls}$ are the sensible and the latent heat flux from the ocean. At the land