THE STABILITY OF THERMOHALINE CIRCULATION IN A TWO-BOX MODEL

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1. INTRODUCTION

The sea surface thermal forcing, which acts in the direction of the present thermohaline circulation in the North Atlantic, is opposite to the haline forcing from the freshwater flux. The strong negative feedback between the sea surface temperature and the surface heat flux removes changes in the sea surface temperature rapidly. However, the freshwater flux, which arises from the local imbalance between precipitation and evaporation, is independent of the sea surface salinity. The difference in the boundary conditions for temperature and salinity may give rise to multiple equilibria of the thermohaline circulation under identical boundary conditions (see Weaver and Hughes 1992; Marotzke 1994; Whitehead 1995 for reviews). Therefore, the thermohaline circulation can switch from one equilibrium to another rapidly (thermohaline catastrophe) if the thermal or haline forcing is perturbed. Studies ranging fromsimple box models to fully developed primitive-equation numerical models have demonstrated the thermohaline catastrophe.

It has been suggested that the mechanism behind the thermohaline catastrophe is a large-scale advective process (Walin 1985), but the effect this advective process has on stability of the thermohaline circulation has been neglected. Instead, many studies have been focused on boundary conditions for salinity, that is, the parameterization of the air-sea freshwater exchanges and their effects. In Stommel's (1961) two-box model, a *linear mass transport relation* was assumed, and the strength of the circulation through a capillary pipe connecting two boxes, $\Psi \sim \Delta\rho$, where $\Delta\rho$ is the density difference between the two adjacent boxes. This linear relation has been used in most box models, which suggest that if freshwater flux to the Northern North Atlantic increases by a small amount, the present thermohaline circulation of North Atlantic would be reversed (Huang et al. 1992). A simple scaling analysis based on geostrophy and advective-diffusive buoyancy balance in the thermocline (Bryan and Cox 1967; Welander 1971) suggests a *nonlinear mass transport relation*, $\Psi \sim \Delta\rho^{1/3}$, for the oceanic thermohaline circulation. In this study the effects of different mass transport relation on the stability of Stommel's classical two-box model have been explored.

2. A TWO-BOX MODEL

The classical model, based on Stommel (1961), consists of a polar box and an equatorial box as shown in Fig. 1. The equations of temperature and salinity in each box are

$$
\begin{aligned}
V_P\dot{T}_P &= C_{TP}(\hat{T}_P - T_P) + |\Psi|(T_E - T_P)\\
V_P\dot{S}_P &= V_P H_{SP} + |\Psi|(S_E - S_P)\\
V_E\dot{T}_E &= C_{TE}(\hat{T}_E - T_E) + |\Psi|(T_P - T_E)\\
V_E\dot{S}_E &= V_E H_{SE} + |\Psi|(S_P - S_E).
\end{aligned}
$$

The subscripts P and E denote quantities for the polar and equatorial boxes, respectively. The restoring condition is used for temperature boundary condition and the quantities with a caret denote reference temperature. The restoring timescale for temperature $t_T=V_i/C_{Ti}$, where the volume of a box is V_i. Virtual salt flux H_{Si}, where i=E or P, is from the commonly used restoring condition or the interactive condition by Nakamura et al. (1994). The volume transport Y in this study is either on of the following:

$$
\Psi \equiv \begin{cases} \Psi_G = C_G[\alpha(T_E - T_P) - \beta(S_E - S_P)]^{1/3} & \text{nonlinear} \\ \Psi_F = C_F[\alpha(T_E - T_P) - \beta(S_E - S_P)] & \text{linear.} \end{cases}
$$

where a is the thermal expansion coefficient, b is the salt expansion coefficient, and C_G and C_F are constants whose values are set to yield Ψ=10 Sv (Sv=10^6m^{3}s^{-1}) when $\Delta\rho=\Delta\rho_p$ (ΔT=20°C and ΔS=2ppt), which represents the meridional sea surface density gradient of the present North Atlantic.

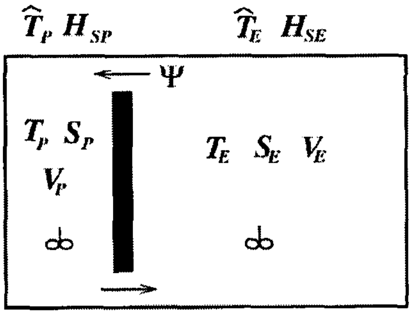

Figure 1. A two box model

3. RESULTS

In Fig. 2, hysteresis diagrams from models with the restoring salinity boundary condition are presented. In the linear model, the present thermal-model circulation (point P) becomes unstable and switches to a haline mode circulation if the haline forcing increases by 20%. This is similar to earlier box models using the linear mass transport relation such as Huang et al. (1992), in which H_S is from (E-P). In contrast, in the nonlinear model 60% increase in the haline forcing is required for the instability of the present thermal-model circulation. In this model it is less likely that a small increase in the haline forcing (or freshwater flux) would cause the catastrophic transition. Results with different thermal forcing show the same tendency.

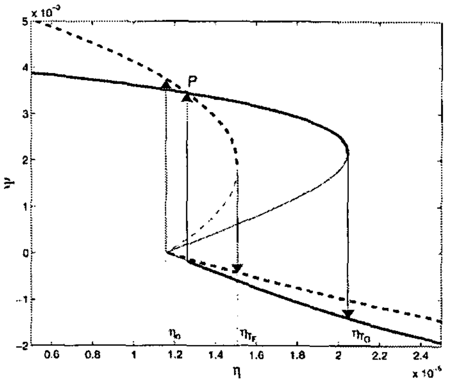

Figure 2. Hysteresis diagrams from models with the restoring salinity boundary condition.

The models with the nonlinear mass transport law show greater stability than those with the linear law when the same salinity boundary conditions are used. The largest contribution to stability is from advection related quantities so that the change in the mass transport law makes the largest change in stability. The faster circulation in the nonlinear model weakens the meridional salinity gradient and removes the salinity anomalies more effectively. The faster circulation, furthermore, prevents the water in the polar (equatorial) box from obtaining (losing) enough freshwater to build up a strong salinity gradient. Stronger haline forcing is required to reverse the thermal-mode circulation.

4. SUMMARY AND CONCLUSIONS

The Using a two-box model, the effect of mass transport on the stability of a thermal mode (high latitude sinking) circulation has been studied. The equilibrium circulation tries to remove temperature and salinity (or density) anomalies and stabilize the circulation. On the other hand, salinity anomalies try to weaken the circulation and intensify the meridional salinity gradient; this is the strongest destabilizing process. In a model with nonlinear transport, the circulation becomes relatively stronger than that in the linear model as density anomalies intensify. The stronger circulation in the nonlinear model reduces the meridional salinity gradient and removes the anomalies effectively. Thus, nonlinear models show significantly greater stability, irrespective of the freshwater flux parameterization.

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