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Feature of thermohaline circulation in two-layer conceptual model based on energy constraint

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The assertion that the thermohaline circulation (THC) is driven and sustained by mechanical energy has been increasingly accepted. The simplest conceptual model describing the THC is the Stommel two-box model. Given the vertical stratification in the real ocean, layered models were designed and used. In this research, using a two-layer conceptual model based on energy constraint, we studied basic features of thermal-mode and saline-mode circulations. We focused on the effects of freshwater flux and mixing energy on the intensity and multiple equilibrium states of the THC. The results show that more important than affecting the THC intensity, both the decrease of freshwater flux and increase of mixing energy can lead to an "abrupt transition" in the THC from a stable saline to a stable thermal mode, which further develops the THC energy theory.

thermohaline circulation, two-layer model, mixing energy, freshwater flux, equilibrium state

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The ocean thermohaline circulation (THC) is an important regulator of the global climate (Zhou et al., 2005; Yang, 2013). The presence of multiple equilibrium states as a significant feature of THC is thought to be closely related to abrupt climate change (Clark et al., 2002; Mu et al., 2004) and this feature can be traced in Stommel's pioneering work (Stommel, 1961). By using a hemisphere two-box model and assuming that meridional flow strength is proportional to the meridional horizontal density contrast, Stommel (1961) found three equilibrium states in the system, namely, one stable thermal mode (dominated by temperature), one unstable thermal mode, and one stable saline mode (dominated by salinity). However, in recent years, a THC driven by horizontal density contrast has had difficulty in being reproduced by experiments and numerical simulations. Among those, Wang et al.'s (2005) experimental results showed that vertical circulation driven by a horizontal temperature difference appeared only near the upper boundary layer if generalized to the actual ocean, meaning that the meridional circulation is not driven by the horizontal temperature difference. Bryan (1987) first used a numerical model to study the effect of salinity on the global THC, showing that inversion of THC can be realized only when salinity at high latitudes is altered. Counter examples have appeared in many numerical model results (Huang, 1999; Nilsson et al., 2003; Do Boer et al., 2010), in which the increase of density difference between high and low latitudes would weaken the THC. On the other hand, Marotzke et al. (1999) believed that the THC is driven by ocean mixing and not by convection. These two processes are completely different: Mixing needs the input of outside mechanical energy, but convection does not. The question of whether the

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ocean is a "heat engine" was hence given much attention by many oceanographers (Huang, 1999; Huang et al., 2008). On the basis of the energy idea, Guan et al. (2008) studied the role of mechanical mixing energy ("mixing energy" for short) in the THC using the classic Stommel two-box model (Stommel, 1961). Their results showed that the THC sustained by mixing energy has only one equilibrium state (stable) in thermal mode, but two equilibrium states (one stable the other unstable) in saline mode, very different from Stommel's result. The existence of a saline unstable equilibrium state in Guan et al.'s (2008) investigation means that THC inversion (or transition) is the result of altered salinity, providing a theoretical explanation for the numerical simulation result of Bryan (1987).

The Stommel two-box model highlights THC dependence on a meridional horizontal density gradient. However, the actual ocean is vertically layered, so in studying the influence of mixing energy related to vertical mixing on the THC, it is more reasonable to adopt a vertically layered model (Welander, 1982). Nilsson et al. (2001) studied the role of freshwater flux in the THC using a temperature-dominated, two-layer conceptual model and assuming that the mixing energy is constant. These authors later used a salinity-dominated, two-layer conceptual model to study that role, with the same assumption for mixing energy (Nilsson and Walin, 2010). In the present study, on the basis of the energy concept of Guan et al. (2008) and using Nilsson et al.'s modeling construct for reference (Nilsson and Walin, 2001, 2010), we designed two types of layered model for thermal and saline modes (Figure 1). By establishing the differential equations of temperature and salinity and analyzing the stability of equilibrium states, we explored the influences of freshwater flux and mixing energy on the intensity and multiple equilibrium states of the THC.

1 Model and stability analysis

1.1 Two-layer conceptual model

Guan et al. (2008) proposed that vertical mixing in stratified water requires the input of outside mechanical energy, and they introduced an energy constraint into the classic Stommel two-box model. However, the structure of that model highlights the relationship between the THC and a meridional horizontal density gradient, not a vertical density gradient. In the study of the influence of vertical density difference or vertical mixing on the THC, it is crucial to use a layered model to describe the stratified ocean. Thus, the ocean is simply separated into two layers (Figure 1). By using Nilsson et al.'s (2001) modeling concept regarding temperature-dominated circulation, we designed a thermal mode, two-layer model as shown in the figure. In panel (a), layer 1 absorbs a large amount of heat from the sea surface and with a higher temperature, the density of layer 1 is less than layer 2. This corresponds to a steady temperature stratification and the water flows clockwise. Using Nilsson and Walin's (2010) model of a salinity-dominated circulation, a saline mode two-layer model is designed as shown in panel (b). Here, a large amount of freshwater is injected into layer 2, which gives that layer very low salinity. Hence, the density of this layer is less than layer 1, which corresponds to a steady salinity stratification and the water flows counter-clockwise. In the figure, p is freshwater flux in m a^{-1}, W is overturning water in Sv, U is meridional volume transport in Sv, T_1^* and T_2^* are sea surface reference temperatures of layers 1 and 2 respectively, and D is stratification depth.

1.2 Differential equations of temperature and salinity

When the THC flows clockwise in the thermal mode as shown in Figure 1(a), the differential equations of temperature and salinity in each layer are as follows

$$V_1 \frac{dT_1}{dt} = WT_2 - UT_1 + L^2\Gamma(T_1^* - T_1), \qquad (1a)$$

$$V_2 \frac{dT_2}{dt} = UT_1 - WT_2 + bL^2\Gamma(T_2^* - T_2), \qquad (1b)$$

$$V_1 \frac{dS_1}{dt} = WS_2 - US_1, \qquad (1c)$$

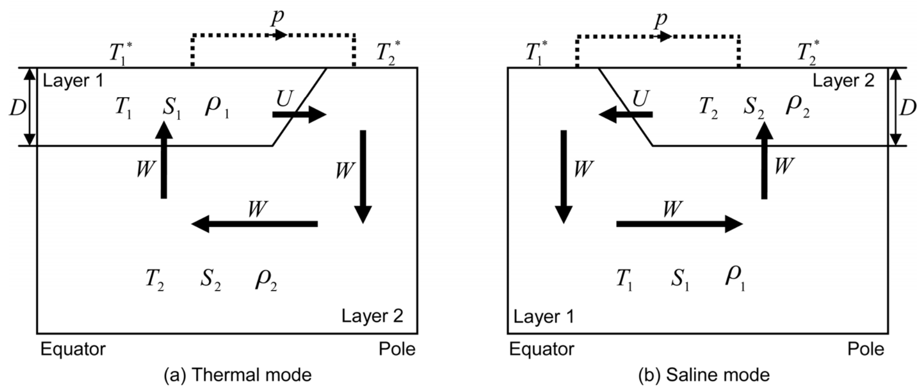

Figure 1 Two-layer conceptual model of THC. (a) For thermal mode; (b) for saline mode.

$$V_2\frac{dS_2}{dt}=US_1-WS_2, \tag{1d}$$

where L^2 is surface area of layer 1, bL^2 is that of layer 2, Γ is the surface relaxation constant (Haney, 1971), and V_i, T_i and S_i are volume, temperature and salinity in each layer.

The continuity equation is

$$W=U+L^2p, \tag{2}$$

the salt conservation equation is

$$V_1S_1+V_2S_2=(V_1+V_2)S_0^*, \tag{3}$$

where S_0^* is the mean reference value of salinity of the seawater.

For simplicity, we assume that $T_2^*=0$ (Guan and Huang, 2008) and $V_2=aV_1$ (Oliver et al., 2005).

In the above equations, $V_1=L^2D$, $V_2=aL^2D$, $W=L^2w$, and $U=LDu$. By introducing non-dimensional variables $t=\frac{D}{\Gamma}t'$, $w=\Gamma w'$, $u=\frac{L\Gamma}{D}u'$ and $p=\Gamma p'$, non-dimensional differential equations are obtained (accent marks of the dimensionless variables are omitted):

The non-dimensional continuity equation is

$$w=u+p, \tag{4}$$

the salt conservation equation is

$$S_1+aS_2=(1+a)S_0^*, \tag{5}$$

the non-dimensional differential equations of temperature and salinity can be expressed as follows.

$$\dot{T}_1=wT_2-(w-p)T_1+T_1^*-T_1, \tag{6a}$$

$$a\dot{T}_2=(w-p)T_1-wT_2-bT_2, \tag{6b}$$

$$\dot{S}_1=wS_2-(w-p)S_1, \tag{6c}$$

$$a\dot{S}_2=(w-p)[(1+a)S_0^*-aS_2]-wS_2. \tag{6d}$$

When THC flows counterclockwise in the saline mode as shown in Figure 1(b), L^2 is the area of layer 2 and bL^2 is that of layer 1; assuming $V_1=aV_2$, the salt conservation equation is then

$$aS_1+S_2=(1+a)S_0^*; \tag{7}$$

the non-dimensional continuity equation is

$$w=u-p; \tag{8}$$

the corresponding non-dimensional differential equations of temperature and salinity are

$$a\dot{T}_1=-wT_1+(w+p)T_2+b(T_1^*-T_1), \tag{9a}$$

$$\dot{T}_2=wT_1-(w+p)T_2-T_2, \tag{9b}$$

$$a\dot{S}_1=-wS_1+(w+p)S_2, \tag{9c}$$

$$\dot{S}_2=-(w+p)[(1+a)S_0^*-aS_1]+wS_1. \tag{9d}$$

Based on energy concept, the THC is usually considered to be "pulled" by upwelling caused by vertical mixing in stratified water. Guan et al. (2008) proposed that the outside wind and tide supplies mechanical energy to vertical mixing in such water, and further sustains a steady THC. The relationship between meridional overturning velocity and vertical density difference in Guan and Huang's study can be expressed as follows

$$w=\frac{e}{|\Delta\rho_{12}|}=\frac{e}{|\rho_0\alpha(T_1-T_2)-\rho_0\beta(S_1-S_2)|}, \tag{10}$$

where $\Delta\rho_{12}=\rho_2-\rho_1$ is the vertical density difference, ρ_0 is mean density of the seawater, α is the thermal expansion coefficient, and β is the saline expansion coefficient. Energy parameter $e=\frac{E_m}{gDL^2}$ in kg m^{-2} s^{-1} (E_m is the increase of gravitational potential energy caused by vertical mixing in stratified water per unit time, called "mixing energy" for short; L^2 is the sea surface area; D is the depth of stratification; g is gravitational acceleration). When D and L^2 are constant, e is proportional to E_m, so it is evident that e corresponds to the mixing energy input by outside wind and tide into the stratified water. For brevity, this mixing energy is represented by e hereafter.

For thermal mode, $\Delta\rho_{12}=\rho_2-\rho_1>0$ in eq. (10), so it can be written as

$$w=\frac{e}{\Delta\rho_{12}}=\frac{e}{\rho_0\alpha(T_1-T_2)-\rho_0\beta(S_1-S_2)}. \tag{10a}$$

For saline mode, $\Delta\rho_{12}=\rho_2-\rho_1<0$ in eq. (10), so it can be written as

$$w=\frac{e}{-\Delta\rho_{12}}=\frac{e}{\rho_0\beta(S_1-S_2)-\rho_0\alpha(T_1-T_2)}. \tag{10b}$$

1.3 Stability analysis

In thermal mode when the circulation is in the equilibrium state, temperature and salinity in each layer do not change with time. By combining eq. (10a) with eqs. (6a)–(6d), equilibrium solutions $\bar{T}_1$, $\bar{T}_2$, $\bar{S}_1$ and $\bar{S}_2$ can be obtained by setting the time derivative in eqs. (6a)–(6d) to zero.

The equilibrium solutions may be stable or unstable. When the circulation is in a stable equilibrium state, even in the presence of an external disturbance, it can return to the equilibrium state. However, when the circulation is in an unstable equilibrium state, a slight external disturbance will cause increasing deviation from the equilibrium state. It is clear that the unstable equilibrium solution has no practical significance (Ye and Yang, 1985), so it is necessary to analyze the stability of the equilibrium state.

We apply the stability theory of differential equations (Ye and Yang, 1985) and retain the Taylor expansion of eqs. (6a)–(6d) at equilibrium point ($\overline{T}_1$, $\overline{T}_2$, $\overline{S}_1$, $\overline{S}_2$) and the first degrees. Then, the approximate linear equations are obtained as follows

$$\dot{T}_1' = w'\overline{T}_2 + \overline{w}T_2' - w'\overline{T}_1 - \overline{w}T_1' + pT_1' - T_1', \tag{11a}$$

$$a\dot{T}_2' = w'\overline{T}_1 + \overline{w}T_1' - pT_1' - w'\overline{T}_2 - \overline{w}T_2' - bT_2', \tag{11b}$$

$$\dot{S}_1' = w'\overline{S}_2 + \overline{w}S_2' - w'\overline{S}_1 - \overline{w}S_1' + pS_1', \tag{11c}$$

$$a\dot{S}_2' = w'(1+a)S_0^* - w'(a+1)\overline{S}_2 - \overline{w}(a+1)S_2' + paS_2', \tag{11d}$$

where $\overline{w}$ and w' can be derived from eq. (10a)

$$w' = \frac{e[\rho_0\beta(S_1'-S_2') - \rho_0\alpha(T_1'-T_2')]}{[\rho_0\alpha(\overline{T}_1-\overline{T}_2) - \rho_0\beta(\overline{S}_1-\overline{S}_2)]^2},$$

$$\overline{w} = \frac{e}{\rho_0\alpha(\overline{T}_1-\overline{T}_2) - \rho_0\beta(\overline{S}_1-\overline{S}_2)}.$$

Eqs. (11a)–(11d) can be written in matrix form

$$\frac{\partial}{\partial t}\begin{pmatrix} T' \\ S' \end{pmatrix} = A\begin{pmatrix} T' \\ S' \end{pmatrix}. \tag{12}$$

Based on the aforementioned stability theory of differential equations, the stability of equilibrium state is determined by the eigenvalues of A, which is a 4×4 matrix. There are two types of equilibrium state solutions, which are characterized by the plus or minus sign of the real part of A. If the real parts of the eigenvalues of A are all negative, then the equilibrium state is stable; if the real part of some eigenvalue of A is positive, then that state is unstable.

For saline mode, combining eq. (10b) with eqs. (9a)–(9d), the equilibrium solutions $\overline{T}_1$, $\overline{T}_2$, $\overline{S}_1$ and $\overline{S}_2$ can be obtained by setting the time derivative in the latter equations to zero. Corresponding linear equations for perturbations at equilibrium point ($\overline{T}_1$, $\overline{T}_2$, $\overline{S}_1$, $\overline{S}_2$) are as follows

$$a\dot{T}_1' = w'\overline{T}_2 + \overline{w}T_2' - w'\overline{T}_1 - \overline{w}T_1' + pT_2' - bT_1', \tag{13a}$$

$$\dot{T}_2' = w'\overline{T}_1 + \overline{w}T_1' - w'\overline{T}_2 - \overline{w}T_2' - (p+1)T_2', \tag{13b}$$

$$a\dot{S}_1' = w'\overline{S}_2 + \overline{w}S_2' - w'\overline{S}_1 - \overline{w}S_1' + pS_2', \tag{13c}$$

$$\dot{S}_2' = -w'(1+a)S_0^* + w'(a+1)\overline{S}_1 + \overline{w}(a+1)S_1' + paS_1', \tag{13d}$$

where $\overline{w}$ and w' can be derived from eq. (10b)

$$w' = \frac{e[\rho_0\alpha(T_1'-T_2') - \rho_0\beta(S_1'-S_2')]}{[\rho_0\beta(\overline{S}_1-\overline{S}_2) - \rho_0\alpha(\overline{T}_1-\overline{T}_2)]^2},$$

$$\overline{w} = \frac{e}{\rho_0\beta(\overline{S}_1-\overline{S}_2) - \rho_0\alpha(\overline{T}_1-\overline{T}_2)}.$$

Eqs. (13a)–(13d) can be written in matrix form

$$\frac{\partial}{\partial t}\begin{pmatrix} T' \\ S' \end{pmatrix} = B\begin{pmatrix} T' \\ S' \end{pmatrix}. \tag{14}$$

Stability of the equilibrium state in saline mode is determined by the eigenvalues of B in eq. (14).

1.4 Parameters

Fixed model parameters used in all experiments are shown in Table 1.

Table 1 Fixed parameters of the model

Parameter	Symbol	Value
Sea surface reference temperature of layer 1	T_1^* (°C)	20
Sea surface reference temperature of layer 2	T_2^* (°C)	0
Mean reference salinity	S_0^* (psu)	35
Surface relaxation constant	Γ (m s^{-1})	9.03×10^{-6}
Thermal expansion coefficient	α (°C^{-1})	1.5×10^{-4}
Saline expansion coefficient	β (psu^{-1})	8.0×10^{-4}
The surface area of layer 1 (layer 2) in thermal (saline) mode	L^2 (m^2)	3.2×10^{13} (2.4×10^{13})
The value of V_2/V_1 (V_1/V_2) in thermal (saline) mode	a	8
The value of Area2/Area1 (Area1/Area2) in thermal (saline) mode	b	1/8 (1/2)
Average density	ρ_0 (kg m^{-3})	1.02×10^3
Specific heat capacity	c_p (J kg^{-1} °C^{-1})	3.81×10^3

2 Results

2.1 Influence of freshwater flux on THC equilibrium state

The THC regulates the global climate through its meridional heat transport, which is closely related to the meridional overturning rate. The meridional overturning velocity of the THC driven by mixing energy is determined by eq. (10).

In thermal mode, eq. (10) can be written as eq. (10a), and the corresponding meridional heat transport is

$$Q = c_p \rho_0 L^2 (w - p)(T_1 - T_2) . \qquad (15)$$

In saline mode, eq. (10) can be written as eq. (10b), and the corresponding meridional heat transport is

$$Q = c_p \rho_0 L^2 (w + p)(T_1 - T_2) . \qquad (16)$$

Figure 2(a) and (b) shows the equilibrium state responses of overturning rate W and meridional heat transport Q to freshwater flux p, respectively. The figure also shows that there is only one equilibrium state (stable) in thermal mode and two such states (one stable and the other unstable) in saline mode. It was found that the stable thermal overturning rate strengthens with increase of freshwater flux (indicated by heavy lines in Figure 2(a)), consistent with Nilsson et al. (2001) from their two-layer model with constant mixing energy. In Figure 2(b), meridional heat transport in thermal mode almost increases linearly with the increase of freshwater flux (indicated by heavy lines in Figure 2(b)). The most significant feature of saline mode is the existence of a threshold (indicated by circles in Figure 2). There are two equilibrium states in saline mode, which exist only when freshwater flux exceeds the threshold. One is stable (indicated by thin solid lines in Figure 2) and the other unstable (thin dotted lines in that figure).

More important than changing THC intensity, the change of freshwater flux can lead to an "abrupt transition" in the THC from one mode to another, which was fully embodied in the Mu et al. (2004) two-box model based on Stommel's assumption specifically, the study by Mu et al. (2004) showed that the increase of freshwater flux in a stable thermal mode can produce an abrupt transition in the THC from stable thermal mode to a stable saline mode; if the freshwater flux in a stable saline mode circulation continually decreases, then that mode will abruptly shift into a stable thermal mode. In our study, THC was assumed to be driven by mixing energy (Figure 2). Decrease of freshwater flux in a stable saline mode circulation would lead to the abrupt shift of that mode into a stable thermal mode (indicated by arrows in Figure 2(a) and (b)). It is seen that if we consider only the abrupt transition in THC modes caused by freshwater flux, our conclusion based on energy constraint is somewhat consistent with Mu et al.'s (2004) conclusion.

Another influence of freshwater flux on THC is portrayed in Figure 3 in which red lines correspond to freshwater flux p=1 m yr^{-1} and green lines to freshwater flux p=0.5 m yr^{-1}. It is shown that greater freshwater flux produces a larger threshold of mixing energy in saline mode, i.e., increase of such flux strengthens the stability of the saline mode circulation with the perturbation of mixing energy.

2.2 Influence of freshwater flux on THC equilibrium state

Figure 3(a) and (b) shows equilibrium state responses of overturning rate W and meridional heat transport Q of the THC to energy parameter e, respectively. It is shown that the stable thermal overturning rate strengthened with increase of mixing energy (indicated by heavy lines in Figure 3(a)), consistent with the result of Guan et al. (2008) from Stommel's two-box model and of Huang (1999) from numerical experimentation. Figure 3(b) shows that meridional heat transport in thermal mode almost increases linearly with increase of mixing energy (heavy lines in that figure), which provides theoretical evidence for the numerical experiment result of Huang (1999), i.e., poleward heat flux almost linearly proportional to strength of the energy flux.

Equilibrium state responses of the THC to mixing energy in saline mode show that only when mixing energy is less

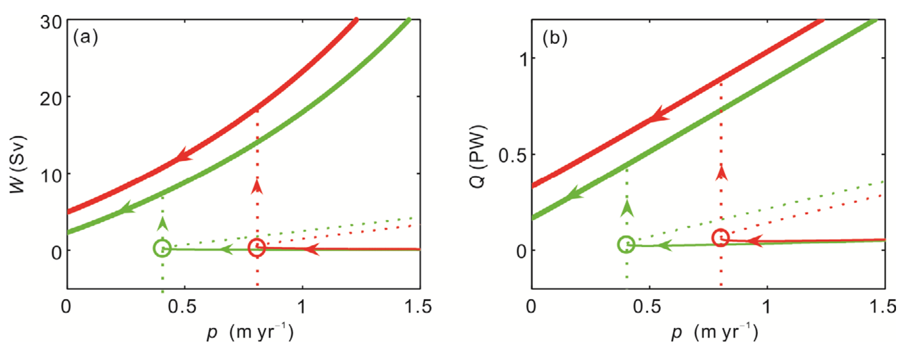

Figure 2 Equilibrium state responses of overturning rate W (a) and meridional heat transport Q (b) of THC to freshwater flux p. Heavy lines indicate thermal mode and thin lines saline mode. Thin solid lines indicate stable states and dotted lines unstable states. Red lines correspond to energy parameter e=4×10^{-7} kg m^{-2} s^{-1} and green lines to energy parameter e=2×10^{-7} kg m^{-2} s^{-1}.

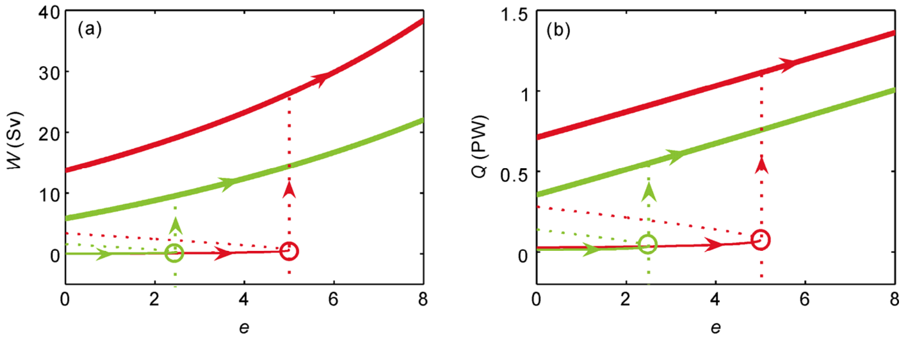

Figure 3 Equilibrium state responses of overturning rate W (a) and meridional heat transport Q (b) of THC to energy parameter e. Heavy lines indicate thermal mode and thin lines saline mode. Thin solid lines indicate stable states and dotted lines unstable states. Red lines correspond to p=1 m yr^{-1} and green lines to p=0.5 m yr^{-1}. Energy parameter e has unit 10^{-7} kg m^{-2} s^{-1}.

than the threshold (indicated by circles in Figure 3), there exist two equilibrium states in that mode, one stable (thin solid lines in the figure) and the other unstable (thin dotted lines in the figure). Therefore, in addition to altering THC intensity, variation of mixing energy can also generate the abrupt transition of the THC from a stable saline to stable thermal mode (indicated by arrows in Figure 3(a) and (b)). This is very consistent with the conclusion of Guan et al. (2008).

Another influence of mixing energy on the THC is depicted in Figure 2, in which red lines correspond to energy parameter e=4×10^{-7} kg m^{-2} s^{-1} and green lines to energy parameter e=2×10^{-7} kg m^{-2} s^{-1}. Greater mixing energy produces a larger threshold of freshwater flux in saline mode, i.e., decrease of that energy strengthens the stability of the saline mode circulation with the perturbation of freshwater flux.

3 Discussion and summary

The present study revealed the following. Overturning rate and meridional heat transport increased with freshwater flux in stable thermal mode. In saline mode, two equilibrium states (one stable and the other unstable) exist only when freshwater flux exceeds a threshold, i.e., decrease of freshwater flux can lead to an abrupt transition of the THC from a stable saline to stable thermal mode. Regarding the influence of mixing energy on THC, the following was found. Overturning rate and meridional heat transport increased with mixing energy in stable thermal mode. In saline mode, two equilibrium states (one stable and the other unstable) disappear with mixing energy greater than the threshold, i.e., the increase of mixing energy can produce the abrupt transition of THC from a stable saline to stable thermal mode. It was also found that increase of freshwater flux strengthened the stability of saline mode THC with the perturbation of mixing energy, and a decrease of mixing energy strengthened the stability of saline mode THC with the perturbation of freshwater flux.

Compared with the results of Nilsson et al. (2001, 2010) from their two-layer conceptual model, the present study focused on analysis of the abrupt transition of THC from one stable mode to another and the influences of freshwater and mixing energy on this transition process. The character of THC driven by mixing energy in our two-layer conceptual model is consistent with the conclusion of Guan et al. (2008), and provides a theoretical explanation for the numerical simulation result of Huang (1999). The present work supports the viewpoint that the THC is driven and sustained by external mechanical energy. Ocean stratification has been simulated by more sophisticated three-box (Oliver et al., 2005; Shen et al., 2011) and four-box (Tziperman et al., 1994) models, as well as by more complex ocean circulation models (Cimatoribus et al., 2014). Energy constraint parameterization has been used in many ocean numerical models (Huang, 1999; Nilsson et al., 2003), but many theoretical conceptual models still use Stommel's buoyancy constraint assumption. The present study further develops the THC energy concept (Guan and Huang, 2008) and furthers understanding of THC dynamic features.

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Bryan F. 1987. Parameter sensitivity of primitive equation ocean general circulation models. J Phys Oceanogr, 17: 970–985
Cimatoribus A A, Drijfhout S S, Dijkstra H A. 2014. Meridional overturning circulation: Stability and ocean feedbacks in a box model. Clim Dyn, 42: 311–328
Clark P U, Pisias N G, Stocker T F, et al. 2002. The role of the thermohaline circulation in abrupt climate change. Nature, 415: 863–869
De Boer A M, Gnanadesikan A, Edwards N R, et al. 2010. Meridional density gradients do not control the atlantic overturning circulation. J Phys Oceanogr, 40: 368–380
Guan Y P, Huang R X. 2008. Stommel's box model of thermohaline circulation revisited—The role of mechanical energy supporting mixing and

the wind-driven gyration. J Phys Oceanogr, 38: 909–917
Haney R L. 1971. Surface thermal boundary condition for ocean circulation models. J Phys Oceanogr, 1: 241–248
Huang R X. 1999. Mixing and energetics of the oceanic thermohaline circulation. J Phys Oceanogr, 29: 727–746
Huang J F, Guan Y P, Liu Y. 2008. Centennial debating: Is Ocean a heat engine?—100th anniversary review for Sandström's theorem (in Chinese). Prog Nat Sci, 18: 747–755
Marotzke J, Scott J R. 1999. Convective mixing and the thermohaline circulation. J Phys Oceanogr, 29: 2962–2970
Mu M, Sun L, Dijkstra H A. 2004. The sensitivity and stability of the Ocean's thermohaline circulation to finite amplitude perturbations. J Phys Oceanogr, 34: 2305–2315
Nilsson J, Broström G, Walin G. 2003. The thermohaline circulation and vertical mixing: Does weaker density stratification give stronger overturning? J Phys Oceanogr, 33: 2781–2795
Nilsson J, Walin G. 2001. Freshwater forcing as a booster of thermohaline circulation. Tellus Ser A-Dyn Meteorol Oceanol, 53: 629–641
Nilsson J, Walin G. 2010. Salinity-dominated thermohaline circulation in sill basins: Can two stable equilibria exist? Tellus Ser A-Dyn Meteorol Oceanol, 62: 123–133
Oliver K I, Watson A J, Stevens D P. 2005. Can limited ocean mixing buffer rapid climate change? Tellus Ser A-Dyn Meteorol Oceanol, 57: 676–690
Shen Y, Guan Y P, Liang C J, et al. 2011. A three-box model of thermohaline circulation under the energy constraint. Chin Phys Lett, 28: 059201
Stommel H. 1961. Thermohaline convection with two stable regimes of flow. Tellus, 13: 224–230
Tziperman E, Toggweiler J R, Bryan K, et al. 1994. Instability of the thermohaline circulation with respect to mixed boundary conditions: Is it really a problem for realistic models? J Phys Oceanogr, 24: 217–232
Wang W, Huang R X. 2005. An experimental study on thermal circulation driven by horizontal differential heating. J Fluid Mech, 540: 49–73
Welander P. 1982. A simple heat-salt oscillator. Dynam Atoms Oceans, 6: 233–242
Yang H J. 2013. Assessing the meridional atmosphere and ocean energy transport in a varying climate. Chin Sci Bull, 58: 1737–1740
Ye Z Z, Yang W L. 1985. Ordinary Differential Equations and Stability Theory of Motion (in Chinese). Tianjin: Tianjin University Press. 78–92
Zhou T J, Yu R C, Liu X Y. 2005. Weak response of the Atlantic thermohaline circulation to an increase of atmospheric carbon dioxide in IAP/LASG climate system model. Chin Sci Bull, 50: 592–598