# The coupling procedure of air-sea freshwater exchange in climate system models

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**Abstract A coupling procedure of air-sea freshwater exchange in climate system models is reported in this note. The first stage of the procedure is to force OGCM to equilibrium under strong restoring surface condition on salinity, then increase the relaxing coefficient and get another steady state. The second stage is to switch the forcing on salinity from the weak restoring condition to the flux condition, and then finish a long-term spinning-up integration. After finishing these OGCM spinning-up stages, the last stage is to couple the OGCM with an active atmosphere, i.e. AGCM. Verification with the Global-Ocean-Atmosphere-Land-System model developed at the State Key Laboratory of Atmospheric Sciences and Geophysical Fluid Dynamics (LASG) shows that the preferred procedure is successful in including the air-sea freshwater exchange process.**

**Keywords: freshwater flux, air-sea coupling.**

The climate system of the Earth can be broken down into a number of components, and permeating all of the climate components is water. There exists robust freshwater exchange between ocean and atmosphere, and it is regarded as one of the most important processes of air-sea interaction, especially for ocean circulation changes on decadal to millennial time-scales[1, 2]. Coupled models are powerful tools for the community of climate variability studies, and the including of air-sea freshwater exchange is undoubtedly important for the improvement of the models in reproducing the actual climate system.

The air-sea coupling process is the interaction of modeled atmosphere with modeled ocean at their interface. For the AGCM, it needs the forcing of SST and sea ice from the OGCM. For the OGCM, it needs the forcing of heat flux, momentum and freshwater flux from the AGCM. The oceanic stratification is determined by the density of seawater, since the effect of freshwater on density is larger than that of heat flux, oceanic general circulation models (OGCMs) are sensitive to the forcing of freshwater at sea surface. Thus, in the process of developing coupled models, one used to ignore air-sea freshwater exchange, only including momentum and heat flux exchange. Inspections on the sensitivity of OGCM to surface freshwater or salinity forcing edified us to design a coupling procedure for air-sea freshwater exchange. Experiments with the Global Ocean-Atmosphere-Land System model (GOALS)[3] developed at the LASG, the Institute of Atmospheric Physics, the Chinese Academy of Sciences show that the procedure is suitable for the implementation of air-sea freshwater coupling. This note is a brief report on the work in this regard.

## 1 The coupling procedure for air-sea freshwater exchange

In the ocean model, freshwater flux at ocean surface is represented as a surface boundary condition on salinity. The most commonly used boundary condition for salinity is a Newtonian type relaxation condition, which can be expressed as

$$S_f = \lambda_S (S^* - S_0), \tag{1}$$

where $S^*$ is the reference salinity and the climatological mean sea surface salinity is often used for it, $S_0$ is the modeled sea surface salinity, and $\lambda_S$ is the restoring coefficient.

The restoring condition was originally constructed for the forcing of atmospheric heat flux[4], and was subsequently used on salinity. However, there is less physical justification for the use of the condition on salinity[5]. In ideal circumstances, one would like to use a fixed salinity flux, which is based on observed evapora- tion and precipitation rate. This is often impractical since it has been argued that the convergence of numerical model salinity fields, when a flux boundary condition is used, is extremely slow[6]. As a consequence, to reproduce the ocean climate, the Newtonian type condition on salinity is still used universally.

For the convenience of climate variability studies, the so-called flux condition for salinity is designed[7, 8]. The commonly used procedure is: spinning up the model ocean to a steady state by restoring the surface salinity to the present day climatologies, diagnosing the corresponding salt flux required to maintain the steady state, and then switching the restoring boundary condition on salinity to the diagnosed salt flux. Thus in further integration, this diagnosed surface salinity flux is used as a fixed-flux surface boundary condition. The flux condition can be expressed as

$$S_f = S_f^0, \tag{2}$$

where $S_f^0 = \lambda_S (S^* - S_0)$, it is the salt flux diagnosed from the quasi-equilibrium state attained by parameterizing the upper boundary conditions for salinity in terms of restoring conditions. This kind of flux condition can represent the actual surface freshwater flux to some extent. Jin et al.[9] integrated a thirty-layer OGCM under a restoring condition for salinity to equilibrium, and found that the equivalent freshwater pattern of surface salinity deviation is quite similar to the observational pattern presented in ref. [1]. In fact, the deviation field is the flux condition on salinity shown in formula (2).

For the coupling of air-sea freshwater exchange in numerical models, if one ran an OGCM under restoring condition for salinity to quasi-equilibrium, and then coupled it directly to an AGCM, the great change of surface forcing would lead to the collapse of the ocean circulation. Since the implied surface freshwater forcing of flux condition is similar to that provided by an active atmosphere (i.e. AGCM), a preferred method for conducting air-sea water flux coupling is to run an OGCM under the flux condition for salinity to equilibrium, then couple it to an AGCM. In this condition, the relatively weak variation of surface forcing may be not robust enough to cause the occurrence of climate drift in theory. Accordingly, the air-sea freshwater coupling in GOALS is conducted in the following ways: First, run the ocean component under restoring condition (i.e. force the model toward sea surface salinity climatologies) for 1 700 years with a restoring time of 20 days, which can speed up the convergence of the ocean. Second, increase the salinity restoring time to 150 days and run the ocean model for further 8 000 years to a new steady state. Third, diagnose the salt flux required to maintain the steady state of the 4 700 model year and further integrate OGCM for 2 000 years under the diagnosed surface salinity flux. Fourth, couple the OGCM with the atmospheric component from the 1960 model year of flux forcing spinning-up by the daily flux anomaly coupling scheme[10], and finish another 100-year long-term coupled integration.

Notice that we did not switch the restoring condition directly to flux condition after the first stage, since we found this would lead to the collapse of the ocean circulation in less than 100 years. In a theoretic study of Tziperman et al. it is suggested that the steady solution of OGCM under restoring conditions may be either stable or unstable upon transition to the salt flux condition, depending on the magnitude of the salinity restoring time used to obtain this steady solution[11]. Thus, we increase the restoring time from 20 to 150 days in the second stage and finish another long-term spinning-up integration rather than switching it directly to the flux condition.

It should be noted that the Haney type formula for temperature is used throughout the ocean spinning-up stage. During the air-sea coupling stage, the daily flux-anomaly-coupling scheme of Yu et al. (1998) is used not only for freshwater flux but also for heat flux.

## 2 Model verification of the preferred air-sea freshwater coupling procedure

We examine the coupling procedure stated above by the GOALS model. For the convenience of inspecting the response of ocean circulation to the changes of surface water or salinity forcing, the time series of North Atlantic overturning circulation index (hereafter referred to as THC, which is defined as the maximum value of downwelling branch around 60°N) during OGCM spinning-up stages and air-sea freshwater coupling stage are shown in fig. 1.

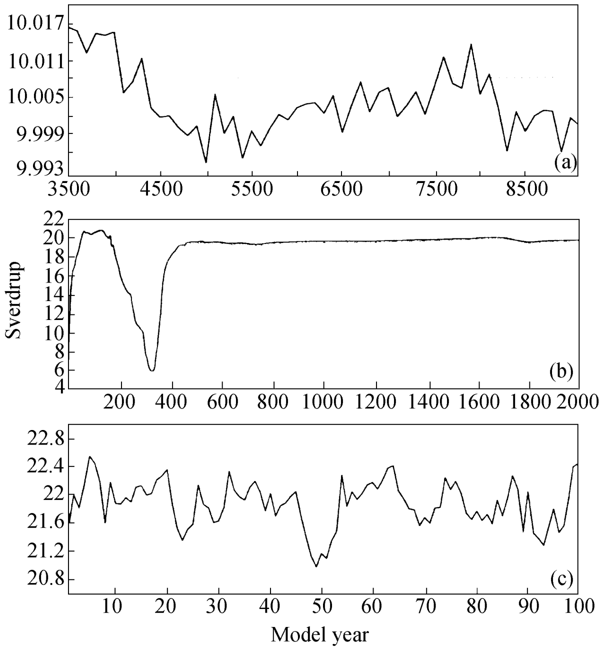

Fig. 1. Time series of North Atlantic overturning circulation (in $10^6$ m$^3$/s). (a) Under restoring condition on salinity with a relaxation coefficient of 150 days; (b) under a flux condition on salinity; (c) after coupling with the atmospheric model.

When the constraint on salinity is relaxed, i.e. the restoring coefficient is increased from 20 to 150 days, the maximum value of downwelling branch of North Atlantic Deep Water (NADW) experienced a decrease in the first 3 000 years. Then in the following 5 000 years or so, as shown in fig.1(a), the variation of NADW is relatively weak and the model-ocean comes up to equilibrium.

Upon switching from the restoring forcing to flux condition, the oceanic meridional circulation undergoes impetuous adjustment. As shown in fig. 1(b), the intensity of THC first increases from $10.0\times10^6$ m$^3$/s to $21.0\times10^6$ m$^3$/s sharply, then decreases to $6.0\times10^6$ m$^3$/s in 100 years or so, and then once again increases to $20.0\times10^6$ m$^3$/s in dozens of years. After the adjustment of amplifying-bating-amplifying, the oceanic circulation comes up to a near-steady state. In the following 1 500 years, the intensity maintains on the value of $20.0\times10^6$ m$^3$/s or so. Thus, from the model year of 1960, an active atmosphere replaces the forcing of flux condition on salinity, i.e. the OGCM is coupled to the AGCM. Notice that not only freshwater but also momentum and heat flux is included in the coupling process.

As shown in fig. 1(c), during the 100 years coupled integration, the strength of oceanic circulation is stable The thermohaline circulation oscillates on interannual and decadal time scales with an annual mean intensity of 21.0

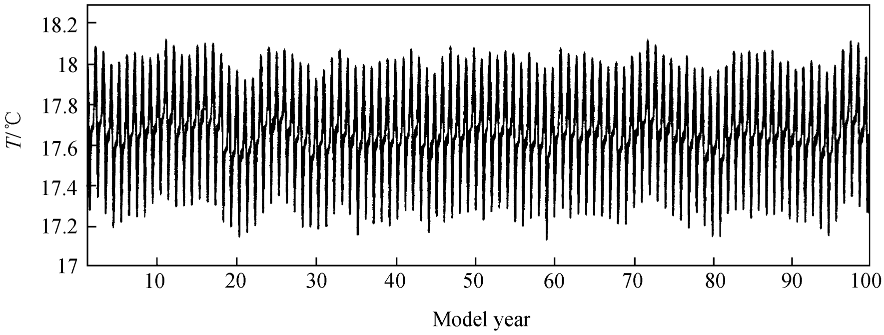

Fig. 2. Globally averaged monthly sea surface temperature in 100 years coupled integration.

$\times 10^6$ $m^3$/s. Thus, the procedure designed for air-sea freshwater coupling of GOALS is fairly successful in controlling climate drift. The results also demonstrate that the flux-anomaly coupling scheme provided by Yu et al. (1998) is suitable not only for daily air-sea momentum and heat flux coupling but also for daily freshwater coupling.

Another most commonly used criterion for detecting climate drift in coupled models is the globally averaged sea surface temperature. The time series of globally averaged monthly SST is shown in fig. 2. Visual inspection shows that over the 100 years coupled integration, the globally averaged sea surface temperatures are remarkably stable and exhibit no obvious drift trend. There are significant seasonal and interannual variations superimposed on the climatological mean state. Thus, the process of air-sea freshwater exchange is included successfully in the GOALS model by using our preferred coupling procedure.

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