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Article

Effects of different freshwater flux representations in an ocean general circulation model of the tropical Pacific

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ABSTRACT

Freshwater flux (FWF) is a major forcing that affects the ocean through several processes. The effects of FWF may be represented in ocean modeling as real freshwater flux (RFF) formulations and virtual salt flux (VSF) methods. RFF formulations have been implemented in the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model version 5 (MOM5) as a replacement for the non-physical VSF method, which is primarily used in state-of-the-art ocean models. Here, we systematically evaluated the effects of RFF-related processes on the GFDL MOM5-based simulations in the tropical Pacific. When the FWF was treated as the natural boundary condition (NBC), it directly decreased the local temperature and the salinity by changing the volume of the top model layer, and it increased the temperature in the eastern Pacific by triggering an eastward Goldsbrough–Stommel circulation in the subsurface. Moreover, the heat content induced by the FWF tended to counteract the decreasing effects of the NBC on sea surface temperatures (SSTs) in the western-central tropical Pacific. The relationships between SST perturbations and the FWF representation in ocean modeling are also discussed.

1. Introduction

As an important atmospheric forcing to the ocean, the freshwater flux (FWF) at the sea surface has significant influence on the climate system [1]. For example, FWF can have great impact on ENSO and tropical ocean dynamics through several processes particularly in the Inter Tropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ) of the tropical Pacific, where precipitation contributes to a large amount of FWF into the ocean. Apparently, FWF has direct effects on ocean salinity, which is an important variable in both the oceanic water cycle and climate. Several studies have demonstrated that FWF forcing and the associated salinity fields can play significant roles in the maintenance of Pacific climate and the low-frequency variability of the climate through their effects on horizontal pressure gradients, stratification, and equatorial thermocline [2–14]. Further investigations have indicated that FWF forcing strengthens ENSO by influencing the salinity and hence the ocean density and vertical mixing [15,16]. Moreover, in coupled general circulation models (CGCMs), the assimilation of salinity data can enhance the accuracy of ENSO seasonal forecasting [17,18].

Despite its important role, the treatment of the surface FWF in OGCMs has been paid little attention in the last several decades. In many state-of-art ocean general circulation models (OGCMs), the virtual salt flux (VSF) method is still commonly used as the default option to represent FWF forcing on the ocean. In this approach, the FWF is first converted to the VSF by multiplying the FWF by a constant reference salinity, and it is then treated as the source/sink in the salt conservation equation [19]. However, such treatment is unrealistic and can cause biases in regions where the SSS largely differs from the reference salinity [20]. In addition, this approach cannot realistically depict the adjustment of sea surface height (SSH) associated with the mass change induced by FWF [20]. To solve the above issues with the VSF approach, Huang [20] developed a more realistic method, the natural boundary condition (NBC), in which the FWF across the ocean surface is represented as the vertical velocity boundary condition, and its influence is included in the ocean continuity equation. Compared with the VSF method, the NBC method does not introduce artificial salt fluxes at the interface; thus, it physically ensures that the salt flux through the ocean surface is zero. To apply the innovative ideas of Huang [20] to more comprehensive OGCMs, Griffies et al. [21]

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further developed an RFF method, in which not only the effect of FWF on the vertical velocity but also ocean temperature, velocity, and surface buoyancy flux are comprehensively considered. In version 5.1.0 of the GFDL MOM (MOM5), the RFF method was introduced as the default scheme to represent FWF effects. In response to large external FWF forcing, ocean models that use this method produce less biases in regional salinity and global sea level compared with the conventional VSF method [22].

Although substantial improvements have been made in the representations of FWF forcing in MOM5, related processes and effects are still not completely understood. For example, FWF can affect the ocean through various processes, including vertical velocity, temperature, and surface buoyancy flux. However the processes required to represent FWF forcing in MOM5, the extent to which each process affects the SST, and the underlying physical mechanisms are not well understood. In addition, whether relationships occur among the different processes, and the potential interactive effects and physical mechanisms involved in these relationships are not clear. At present, the relationships between simulation effects and the way in which FWF is represented in ocean modeling remain elusive. Thus, it is necessary to address these issues to understand the intermingled effects of FWF forcing on ocean dynamics. Here, we used the GFDL MOM5 to perform sensitivity experiments to address these questions with a focus on the tropical Pacific.

2. Model and experiments

The MOM5 used in this study is a Boussinesq model with global coverage. It has 360 longitudinal grid cells that are evenly distributed, 200 latitudinal grid cells with enhanced resolution in the tropics (1/3° equatorward of 30° N/S), and 50 vertical levels at 10 m intervals in the upper 22 levels. The model descriptions and the details of the related physical parameterizations are described in Griffies [23].

For the VSF scheme, the virtual salt flux (F_v) at the ocean surface is calculated as:

$$F_v = -fwf \cdot S, \tag{1}$$

where, the fwf is the net surface FWF, and the S is the reference salinity which is often designated as a constant value. In this method, the FWF changes the salinity of the sea water parcel by changing its salt content while keeping its volume constant. This method is relatively simple and only includes the processes of converting the FWF (fwf) into the salinity source term (F_v) of the salt conservation equation. In comparison to this, the RFF scheme includes four methods of representing the FWF effect on the ocean in MOM5 [21,23,24]. A brief description of these processes is provided, and a schematic is shown in Fig. 1. More detailed information, including the formula derivation, can be found in Griffies et al. [21]. (1) The FWF is represented as the vertical velocity boundary condition ($w_0 = fwf$) from the ocean continuity equation, namely the NBC in Huang [20]. In this process, the FWF is equivalent to the mass source/sink in the mass conservation equation, thus leading to the balance of mass per unit area of an oceanic column, or the momentum density in the direction normal to the ocean surface [21]. (2) The FWF is assumed to have the same temperature as the SST, thus directly leading to a change in ocean heat content ($fwf \cdot sst$). The influence of FWF on the ocean temperature tendency ($\frac{\partial T}{\partial t}$) is manifested through the ocean heat conservation equation (this process is hereafter referred to as HCT). (3) The difference between the tracer concentration (temperature and salinity) in the FWF and that in the surface ocean leads to a change in the surface ocean buoyancy flux, which is a factor that influences the vertical mixing in the upper ocean [25]. Given that the FWF is assumed to be pure water and the same temperature as the SST, the heat contained in the FWF has no effect on the buoyancy flux. As such, the turbulence flux of salt ($-fwf \cdot \mathrm{sss}$) in the upper ocean can be modulated by FWF, thus leading to changes in surface buoyancy fluxes ($\frac{\partial B}{\partial t}$) and consequently to changes in the vertical mixing in the upper ocean boundary layer (the process is referred to as VMX). (4) The FWF is considered to have the same horizontal velocity as the sea surface current, thereby representing the vertical flux of horizontal momentum at the ocean surface ($fwf \cdot U_{sur}$), and it exerts its influence on the horizontal momentum conservation equation (the process is referred to as HM).

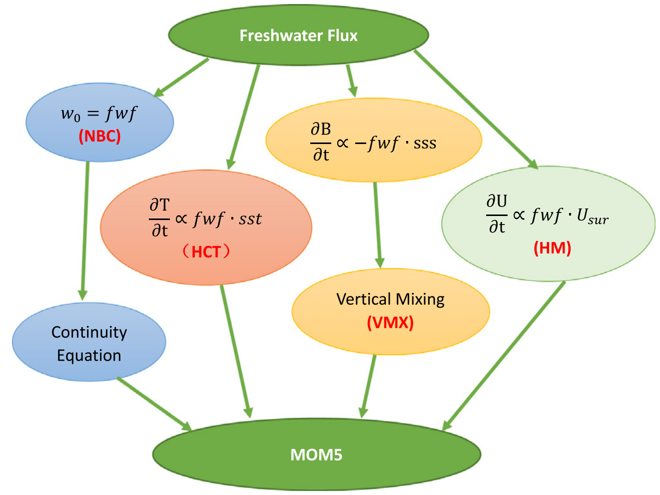

Fig. 1. Schematic diagram illustrating the four processes (NBC, HCT, VMX and HM) used by the FWF to exert its influence on the ocean in MOM5. For the NBC process, the FWF is represented as a vertical velocity boundary condition (w_0), which further influences the ocean through the ocean continuity equation. For the HCT process, the FWF is assumed to have the same temperature as the SST. Thus, its effect on the ocean can be represented as a heat source ($fwf \cdot sst$) affecting the ocean heat tendency ($\frac{\partial T}{\partial t}$). For the VMX process, the FWF and SSS together influence the tendency of the surface ocean buoyancy flux ($\frac{\partial B}{\partial t}$), which is a factor that affects the vertical mixing. For the HM process, the FWF is assumed to have the same velocity as that of sea surface current (U_{sur}) and thus serves as a momentum source at the ocean surface to affect the horizontal momentum tendency ($\frac{\partial U}{\partial t}$).

In this study, we first conducted a 50-year spin-up run by using MOM5 forced by the climatological atmospheric fields provided by Large and Yeager [26]. Using the near-equilibrium model ocean state, we further conducted a group of sensitivity experiments with pre-determined FWF perturbations to investigate the oceanic responses to different representations of FWF forcing in the model. The first experiment was run without FWF into the ocean, the so-called control experiment (CTL). A series of perturbation experiments were conducted with the FWF perturbation described as follows:

$$fwf = 8.0 \times e^{-\left(\frac{y}{10.0}\right)^2} \times e^{-\left(\frac{x-180.0}{30.0}\right)^2}, \tag{2}$$

where x is the longitude and y is the latitude, both in degrees. Under this method, the FWF perturbation exhibits an extended elliptical zone along the equator with the maximum values (8.0 mm/day) located on the International Date Line, and it decreases as a function of the distance from the maximum location (Fig. 2a). This designed FWF perturbation resembles a very simplified representation of FWF in the mature phase of an El Niño event in the tropical Pacific. As ENSO itself exhibits large diversity, the related FWF pattern in each El Niño event can change significantly. Thus, differences between the sensitivity simulations and the CTL can be reasonably considered to be oceanic responses to the FWF forcing during an El Niño event. Four sensitivity experiments (each including only one of the four FWF processes) were conducted to investigate the role