The impacts of different surface boundary conditions for sea surface salinity on simulation in an OGCM

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ABSTRACT

An OGCM, LICOM2.0, was used to investigate the effects of different surface boundary conditions for sea surface salinity (SSS) on simulations of global mean salinity, SSS, and the Atlantic Meridional Overturning Circulation (AMOC). Four numerical experiments (CTRL, Exp1, Exp2 and Exp3) were designed with the same forcing data-set, CORE.v2, and different surface boundary conditions for SSS. A new surface salinity boundary condition that consists of both virtual and real salt fluxes was adopted in the fourth experiment (Exp3). Compared with the other experiments, the new salinity boundary condition prohibited a monotonous increasing or decreasing global mean salinity trend. As a result, global salinity was approximately conserved in EXP3. In the default salinity boundary condition setting in LICOM2.0, a weak restoring salinity term plays an essential role in reducing the simulated SSS bias, tending to increase the global mean salinity. However, a strong restoring salinity term under the sea ice can reduce the global mean salinity. The authors also found that adopting simulated SSS in the virtual salt flux instead of constant reference salinity improved the simulation of AMOC, whose strength became closer to that observed.

1. Introduction

The surface boundary condition for sea surface salinity (SSS) plays an important role in realistically simulating the SSS and Atlantic Meridional Overturning Circulation (AMOC) when using OGCMs (Rahmstorf, Marotzke, and Willebrand 1996; Griffies et al. 2005, 2009). A small perturbation of salt can modify the ocean’s meridional circulation (Bryan 1986; Marotzke, Welander, and Willebrand 1988; Marotzke and Willebrand 1991; Weaver and Sarachik 1991; Weaver, Sarachik, and Marotzke 1991; Hofmann and Rahmstorf 2009) and cause a persistent climate drift (Rahmstorf, Marotzke, and Willebrand 1996). Many previous studies have shown that both the mean state and climate variability can be more realistically captured when an OGCM adequately represents freshwater flux (F_w) forcing (e.g. Stouffer et al. 2006; Zhang and Busalacchi 2009; Zhang et al. 2012). Therefore, a proper surface boundary condition for SSS is important for the performance of an OGCM. The combination of salinity relaxation and virtual salt flux is widely used in most climate ocean models as the surface boundary condition for SSS. Relatively strong salinity restoration is required to stabilize the AMOC and control the sea salinity drift in OGCMs (Griffies et al. 2005). In addition, weak salinity restoration is often used to correct the F_w at the sea surface, especially for precipitation (Griffies et al. 2005; Jin et al. 2016). However, the salinity restoring condition has no physical basis, whereby its purpose is to prevent the modeled SSS from departing from the observed climatological distribution of surface salinity. Besides, Beron-Vera, Ochoa, and Ripa

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(2000) indicated that this kind of restoring condition does not guarantee the conservation of total salt in the ocean. The common technical method in ocean models is to remove the global mean restoring salt flux at each time step for the purpose of conserving the total salt. The surface salinity is often replaced by a reference salinity (often assumed to be 34.7 psu) in the virtual salt flux to formulate a better-posed problem (Roulet, Guillaume, and Madec 2000). However, this can cause significant biases in regions where SSS obviously differs from the reference state.

New formulations of the salinity boundary condition can be adopted, which can improve upon the commonly used virtual salt flux with constant reference salinity by allowing for spatial correlations between $F_w$ flux and SSS (Zeng and Mu 2002). The purpose of this study is to compare the simulated results when adopting different surface boundary conditions for SSS, especially for SSS and the AMOC, and to identify the effects of the different terms in the salinity boundary condition on the OGCM. Following this introduction, Section 2 briefly introduces the model and experiments. In Section 3, we present results from four experiments, and a brief summary of our results is provided in Section 4.

### 2. Model and experimental design

The OGCM used in this paper is LICOM2.0 (Liu et al. 2012). The model domain is between 78.5°S and 89.5°N, with a 1° zonal resolution. The meridional resolution is refined to 0.5° between 10°S and 10°N, and increases gradually from 0.5° to 1° between 10° and 20°. There are 30 levels in the vertical direction, with 10 m per layer in the upper 150 m. This resolution can resolve equatorial waves and capture the upper mixed layer and thermocline (Lin, Yu, and Liu 2013). A detailed description of the model can be found in Liu et al. (2012).

The surface salinity boundary condition (SSBC) in LICOM2.0 is a blend of the virtual salinity flux and two restoring terms. The formula is as follows:

$$SSBC = F_w \times S_0 + WR + SR, \quad (1)$$

where $F_w = E - P - R$, in which $E$, $P$, and $R$ are evaporation, precipitation, and river runoff, respectively; $S_0$ is the reference salinity, which is assigned as a constant (34.7 psu); WR is the weak restoring salinity condition in the open ocean, with a restoring timescale of 1 yr; and SR stands for the strong restoring term under sea ice, with a timescale of 30 days.

To test the responses of the OGCM to the different surface boundary conditions for SSS, four experiments were designed, called CTRL, Exp1, Exp2, and Exp3, respectively. Descriptions of the four experiments are given in Table 1. In order to reveal the uncertainty effects of WR on simulation, the WR term is not included in Exp1. Exp2 is the same as Exp1, but the simulated SSS is used instead of the reference salinity, $S_0$. A real salt flux ($\mu S$) resulting from wind and wave breaking is added in Exp3, which is a new well-posed formulation for the SSBC and can be written as:

$$SSBC = F_w \times SSS - \mu \times SSS + SR. \quad (2)$$

The simulated SSS is used in this formula. Here, $\mu$ is parameterized as a function of the 10-m wind speed $U$ ($\mu = 0.002256U^3$).

All of the external forcings used in these experiments are from CORE.v2 (Griffies et al. 2005) from Large and Yeager (2004). Since a sea-ice model was not used in the experiments, the SSS under ice needed to be restored to the observation from WOA09 (Antonov et al. 2010), with a restoring time scale of 30 days, in all the runs. Each experiment began from the same climatological mean salinity and temperature with a rest state. The global mean $F_w$ flux was set to zero in every time step. All experiments were integrated for 500 years in order to reach a quasi-equilibrium deep circulation. The final 60 years (441–500) of the results were analyzed.

### 3. Results

Figure 1 shows the time series of global mean salinity simulated in all four experiments. There is clear distinction among the trends in global mean salinity for each experiment with a different SSBC. CTRL reached a quasi-equilibrium state with a gradually increasing trend of about
0.0024 psu/100 yr for the last 100 years of the integration, with its global mean salinity being 34.745 psu averaged in the last year. The SR term played a dominate role in reducing the trend in global mean salinity in the remaining experiments (Figure 2). Since the global mean virtual salt flux ($F_w S_0$) is approximately zero, the increasing trend in global mean salinity in CTRL was mainly attributable to the effects of WR. Exp1, in which WR was excluded, exhibited a slow monotonic decreasing trend (approximately $-0.0038$ psu/100 yr) with a 500th-year mean salinity of 34.711 psu. Moreover, the significant increasing trend in Exp2 was about $0.0071$ psu/100 yr during the last 100 years, which resulted from the evident positive relationship between $F_w$ and SSS, although the decreasing effects of SR in Exp2 were also obvious (Figure 2). The global mean salinity (34.770 psu) of the 500th year for Exp2 was the largest among the experiments. Exp3 reached a near stationary state after 100 years, with a slight negative trend of $-0.0002$ psu/100 yr for the last 100 years. During the last year, the value in Exp3 was 34.723 psu, which was the closest experimental result to the observed value of 34.728 psu (Table 1). This clearly demonstrates the importance of the real salinity flux term compared with Exp2.

Comparing the results of CTRL and Exp1, it was apparent that weak SSS restoration in the open sea increased the global mean salinity, whereas strong restoration under the sea-ice region caused a decrease.

Figure 3 presents the biases in annual mean SSS against WOA09 (Antonov et al. 2010) for the different experiments.
The most evident features are two large freshening SSS biases in Exp1 (Figure 3(b)): one appears between 40°S and 10°S in the Pacific and Atlantic, and the other is located between 30°N and 45°N in the Pacific. These large biases also occurred in Exp3 (Figure 3(d)). The root mean square difference (RMSD) was 0.686 psu in Exp3, which was closer to the CTRL value of 0.505 psu, as compared to that of Exp1 (Table 1). The two large freshening SSS biases were mainly due to biases of the forcing field, such as precipitation and/or RH, in CORE.v2 (Jin et al. 2016). These large biases were partly reduced in Exp2 (Figure 3(c)), especially for the subtropical western Pacific. The reason may have been due to the biases of CORE.v2 being partly compensated by the positive relationship between $F_w$ and SSS. Compared with CTRL, the only difference was the exclusion of the WR term in Exp1. This shows that the WR term in LICOM2.0 plays an important role in reducing the SSS bias.

However, some common biases also appeared in the four experiments. All the experiments exhibited a saltier SSS in the Laptev Sea and East Siberian Sea compared to observation, which was associated with the absence of a sea-ice component in our model. In the North Atlantic subpolar region, the SSS simulated in all of the four experiments exhibited obvious fresh biases. This was mainly because the simulated path of the Gulf Stream could not reach the North Atlantic subpolar region. As a result, there was less transportation of warm, salty water to higher latitudes. A more specific study on this issue is needed. The corresponding SST simulated in all of the experiments was also colder in this region, as compared with WOA09 (figure not shown). This would have reduced the simulated evaporation flux, leading to a fresher SSS.

Figure 4 illustrates the Atlantic meridional overturning stream-function for CTRL, Exp1, Exp2, and Exp3. All of the four experiments reflected the main structure of the AMOC well, indicating an upper cell between 500 m and 3,000 m and a bottom cell below. The former is related to the North Atlantic Deep Water (NADW) and the latter to the Antarctic Bottom Water.
The most striking difference between the different experiments was the strength of the AMOC simulated. The results from Exp2 and Exp3 (Figure 4(c) and (d)) presented the most vigorous AMOC, while CTRL (Figure 4(a)) was the weakest among the four experiments. The maximum NADW at 731 m and 36°N in CTRL was 10.8 Sv, whereas it was 11.3, 13.2, and 13.0 Sv for Exp1, Exp2, and Exp3, respectively. This strengthening is mainly related to the saltier seawater in the Labrador Sea and Norwegian Sea, but these maximum values of NADW for Exp2 and Exp3 were closer to the observed value of ~15 Sv at about 40°N (Ganachaud and Wunsch 2000, 2003; Lumpkin, Speer, and Koltermann 2008). This indicates that the depicted AMOC strength can be improved with the virtual salt flux by adopting predicted SSS instead of the constant reference salinity. Besides, compared with Exp2, the AMOC simulated in Exp3 did not change much, since the SSS difference between Exp2 and Exp3 was minimal in the high latitudes of the North Atlantic (figure not shown).

4. Discussion and conclusion

This study investigated the effects of different surface boundary conditions for SSS on simulations of global mean salinity, SSS and the AMOC, using an OGCM (LICOM2.0). It was found that, in the default salinity boundary condition setting in LICOM2.0, the WR term in the open sea plays an essential role in reducing the simulated SSS bias and increasing the global mean salinity, while the SR term under the sea-ice region decreases the global mean salinity. The new surface salinity boundary condition consisting of both virtual and real salt fluxes at the oceanic surface prohibited a monotonous increasing or decreasing global mean salinity trend, and basically preserved the long-term conservation of global mean salinity. Furthermore, the simulated AMOC strength was also much closer to observations, although the freshening SSS bias was large without the WR term.

A number of biases caused by ocean dynamics were also detected, such as freshening biases in the North Atlantic and subtropical regions in the Pacific, and a weak NADW; although, both Exp2 and Exp3 offered some improvements in this regard. The causes of these biases need further investigation.

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