Freshening biases in the freshwater flux of CORE data

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ABSTRACT
The authors investigate biases in the freshwater flux (FWF) of CORE.v2—a common data-set for stand-alone ocean models—based on the results of a set of experiments using an OGCM. The authors identify freshening biases in the FWF in the subtropical regions of the North Pacific, South Pacific, and South Atlantic, which may be caused by the weak surface wind, high specific humidity, or high precipitation in the CORE.v2 data. The authors also find biases in sea surface salinity that are caused by ocean dynamics, such as in the North Atlantic, and that cannot be corrected by correcting surface forcing.

1. Introduction
Stand-alone OGCMs are driven by the observed surface momentum flux (or wind stress), heat flux, and freshwater flux (FWF), which usually include precipitation, evaporation, and river runoff. Many studies have identified the important effects of surface wind stress and heat flux on OGCMs (e.g. Yu et al. 2001; Chen, Zhang, and Li 2011). FWF forcing also has significant effects on OGCM simulations. Griffies et al. (2009) reported that errors in the FWF directly forced a large drift in ocean salinity in an OGCM. Ocean salinity modulates the oceanic density and mixed layer depth, both of which can further modify surface currents and the SST (e.g. Thompson, Gnanaseelan, and Salvekar 2006; Wu et al. 2010; Zhang, Wang et al. 2010; Zhang, Zheng et al. 2012; Ma, Wu, and Li 2013; Zhi et al. 2015). The FWF is also a very crucial factor in maintaining and altering thermohaline circulation (Bryan 1986; Sévellec and Fedorov 2011). Huang and Mehta (2005) presented related changes in salinity-associated FWF forcing as playing a crucial role in maintaining the Pacific climate and low-frequency variability. However, because there is no direct feedback to the boundary conditions of the surface FWF in ocean models, the accumulation of errors in FWF data may lead to serious drift in models. This drift occurs not only in salinity, but also in circulation. Therefore, it is worth evaluating the uncertainty of the forcing data-set with respect to the surface FWF. Because of the lack of observational reference data, a direct evaluation of these uncertainties is difficult. An alternative is to evaluate FWF data by evaluating OGCM results. For this purpose, we expect the FWF data to yield more accurate sea surface salinity (SSS) values and less drift in global mean salinity.

CORE.v2 (Griffies et al. 2009; Large and Yeager 2009) contains normal-year forcing datasets that are widely used by the OGCM development community. CORE.v2 data are based on NCEP Reanalysis-1 and other in situ and satellite observation datasets. In these datasets, precipitation is based on the combined monthly data from 1979 to 2006, the details of which can be found in Large and Yeager (2009). Evaporation is computed using atmospheric state variables (prescribed specific humidity and vector winds from NCEP Reanalysis-1) and SST values predicted by OGCMs. Therefore, any bias in evaporation may be attributable to errors in not only the atmospheric state variables,
but also the simulated SST. Another important component of the FWF is runoff, which is distributed only around ocean coastal regions and adjacent to river mouths.

The purpose of this study is to use results from an ocean model to evaluate FWF data errors in CORE.v2. In Section 2, we briefly introduce the model and the experiments. In Section 3, we present the results from the three experiments. And in Section 4, we provide a brief summary of the study’s findings.

2. Model and experiment design

The OGCM used in the study was LICOM2.0 (Liu et al. 2012). LICOM2.0 has 30 levels in the vertical direction, with 10 m per layer in the upper 150 m. The model domain ranges from 78°S to 87°N, with a 1° zonal resolution. The nominal 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°. More details on LICOM2.0 can be found in Liu et al. (2012).

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

\[ \text{SSBC} = (E - P - R) \times S_0 + WR + SR, \]

where \( E, P, \) and \( R \) are evaporation precipitation, and river runoff, respectively. \( S_0 \) is the reference salinity, which is assigned as 34.7 psu. \( WR \) is the weak restoring salinity condition, with a piston velocity of 12.5 m yr\(^{-1}\) in the open ocean. In addition to the observational constraint of the SSS, \( WR \) may also be partially considered as a correction of the surface forcing. \( SR \) stands for the strong restoring term under sea ice, with a piston velocity of 120 m yr\(^{-1}\), or a restoration time scale of 30 days.

A new well-posed formulation of the SSBC was made prior to this study, as follows:

\[ \text{SSBC} = (E - P - R) \times S - \mu S + WR + SR. \]

The predicted SSS, \( S \), is adopted in this SSBC. \( \mu S \) is the upward or exiting salt flux resulting from wind, which may cancel out globally integrated ocean salt from the correlation between the FWF and the predicted SSS. \( \mu \) is parameterized as a function of the 10-m wind speed. Because \( \mu S \) is relatively small, the pattern of the first two terms of Equation (2) is actually dominated by \( (E - P - R) \) (figure not shown). The magnitudes of \( \mu S \) are only significant in the Southern Ocean and midlatitudes where the surface winds are strong.

We carried out three experiments in this study, including a control and two sensitivity experiments, called CTRL, Exp1, and Exp2, respectively. The SSBC formulas for the three runs are listed in Table 1. Our objective in the experiments was to evaluate the uncertainty of the FWF data forcing in CORE.v2 by comparing the different model biases in salinity among the three experiments. Exp1 used no WR term, in order to show the uncertainty effects in the FWF data for CORE.v2 in the simulation. Exp2 was the same as Exp1, but we added the term \( q_w (= WR / S) \) in the surface FWF to correct for biases in the observational data. The term \( q_w \) was calculated from the annual-mean WR term for CTRL during years 461–500. The spatial pattern of WR was close to the biases in SSS in Exp1 (figure not shown). Because a sea-ice model is not included in LICOM2.0, we used SR in each experiment. All other settings for the three experiments were the same. We initialized the experiments from the climatic mean temperature and salinity with no motion, and integrated them for a period of 400 years.

3. Results

Figure 1(a) shows the time series of the global mean SSS for the three experiments. The global mean SSS for CTRL and Exp2 reached quasi-equilibrium after the 400-year integration. The linear trends were 0.002 and 0.015 psu/100 yr during the last 100-year period (Table 1), respectively. However, Exp1 showed a much stronger trend, 0.056 psu/100 yr, during the last 100-year period. Because the restoring term was included in CTRL, the results from the CTRL experiment were closer to the observational value. Figure 1(b) shows the global volume-mean salinity from the three experiments. The weak freshening trends were about 0.0001 and 0.0004 psu psu/100 yr for the Exp1 and Exp2 runs in the last 100-year period, respectively. The annual global mean salinities for Exp1 and Exp2 during the 400th year were the same—about 34.723 psu—which differed less than 0.005 psu from that in the World Ocean.
In summary, for both the global mean SSS and salinity results, we found that although Exp1 obtained results nearing equilibrium, like those of Exp2, the biases and trends of the global mean SSS were relatively bigger than in the other two experiments. Because the restoring term was omitted in Exp1 without making any correction, the freshening drift may be related to biases in the forcing data. To identify the specific reasons for this drift, the spatial patterns of the SSS biases in SSS must be further investigated.

Figures 2(a)–(c) compare the biases of the annual-mean SSS that were simulated in the three experiments with those from WOA09 (Antonov et al. 2010). The RMSs of the SSS for CTRL, Exp1, and Exp2 were 0.505, 0.671, and 0.520 psu (Table 1), respectively. That is, Exp1 generally yielded a relatively larger SSS bias than did the other two experiments. In the CTRL run, large SSS biases occurred both in the North Atlantic along the Gulf Stream and in the northern coast of the Eurasian continent in the Arctic Ocean. The former was a freshening bias and the latter was salty. However, the biases in Exp1 had the same pattern as in the CTRL experiment, but with larger magnitudes. Freshening biases (less than −0.6 psu) were found in the subtropical regions of the North Pacific, South Pacific, and South Atlantic. The same kind of bias pattern can also be found in some other models forced by CORE.v2 data (Figure 8 in Griffies et al. 2009); for instance, the models of the MPI and KNMI, which use very weak salinity restoration. This also indicates that the freshening biases may be caused by the data-set itself, not the biases of the model processes. After introducing the correction term in Exp2, the freshening biases poleward of the subtropical regions almost

Figure 1. The (a) global mean SSS and (b) volume-mean global ocean salinity (units: psu) for the CTRL (green), EXP1 (blue), and EXP2 (red) runs with LICOM2.0. Note: The dashed lines are the observed values from WOA09 (Antonov et al. 2010).

Figure 2. Annual-mean SSS (contours) and their biases (color-shaded) for (a) CTRL, (b) EXP1, and (c) EXP2, with respect to WOA09 (Antonov et al. 2010). (d) Difference in SSS between EXP2 and EXP1. The model output is taken from the last 50 years (years 351–400).
A comparison between the two experiments indicates that there is much more freshwater entering the subtropical regions for CORE v2. That is, less water has evaporated or more precipitation has fallen over these regions.

Figure 3(a) shows the value of the correction term, $q_w$. The positive (negative) values stand for water exiting (entering) the ocean. Large positive centers are located close to the freshening biases in Figure 2(b). This further confirms that the biases in the subtropical regions in the North Pacific, South Pacific, and South Atlantic are mainly due to errors in the forcing datasets. But without in situ observational data, we cannot determine if the errors are caused by evaporation or precipitation.

Because the evaporation values in LICOM2.0 are computed using both observed atmospheric state variables (vector winds at 10 m and specific humidity at 10 m) and simulated SST by LICOM2.0, it is also possible that the biases in the simulated SST caused the freshening biases in these regions. We further investigated the differences in the evaporation between Exp1 and the CORE.v2 data, using the observational SST (Figure 3(b)) for our computations. We found that the spatial pattern in the subtropics differed from the SSS bias and the correction term, but was the same as the SST bias (not shown). That is, the evaporation biases in the subtropics are not caused by biases in the simulated SST, but rather by the data-set itself, such as the weak vector winds at 10 m and/or the high specific humidity at 10 m.

It is interesting that the spatial pattern of the SSS biases for Exp2 was the same as that for CTRL. Two large bias centers remained in the North Atlantic along the Gulf Stream and in the northern coast of the Eurasian continent in the Arctic Ocean. This suggests that these biases may not be caused by errors in the forcing data, but by dynamic ocean processes in LICOM2.0. For instance, the freshening biases in the North Atlantic may be related to the biases of the Gulf Stream simulated in LICOM2.0, and the salinity errors in the Arctic Ocean may be associated with sea-ice processes. Some of the SSS errors in the North Atlantic were caused by biases in the SST (Figure 3(b)).
4. Summary and discussion

We investigated biases in the FWF of CORE.v2 via a set of experiments using an OGCM. We found that the freshening biases in the subtropical regions in the North Pacific, South Pacific and South Atlantic for Exp1 could be corrected by using a correction term for the surface forcing. We are certain that these biases are caused by freshening biases in CORE.v2, since the SST biases cannot affect evaporation in these regions. However, without further investigation, we cannot determine if the errors are caused by evaporation or precipitation. The freshening biases may be caused by the weak surface wind, high specific humidity, or high precipitation in the CORE.v2 data. To further clarify these biases, in situ observations must be used for observational reference.

We also found SSS biases caused by ocean dynamics, such as in the North Atlantic. These biases cannot be corrected by correcting the surface forcing. These processes include salinity advection, vertical mixing and entrainment of the mixed layer. The causes of these kinds of biases will also require further investigation.

Acknowledgements

Discussions with Dr LIN Pengfei and Mr YU Yi were very helpful during the course of this work.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Basic Research Program of China (grant number 2013CB956204); and the Strategic Priority Research Program of the Chinese Academy of Sciences (grant numbers XDA11010403 and XDA11010304).

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