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Special Section:
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Key Points:
- Global salinity and temperature climatology are generated from the WOD for better assessing Earth system models in coastal regions
- Several methods to treat river runoff and estuary processes in the CESM are evaluated with the newly created climatology
- Salinity and stratification errors near major rivers and coasts are reduced by implementing the improved treatment of river inputs

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Assessing the Skill of the Improved Treatment of Riverine Freshwater in the Community Earth System Model (CESM) Relative to a New Salinity Climatology

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Abstract Recent studies have explored the sensitivity of global ocean model simulations to the treatment of riverine freshwater and the representation of estuarine processes via an estuary box model applied within Community Earth System Model (CESM). This study builds on these efforts by assessing the model skill score relative to a new salinity climatology. The new climatology averages the original observational data of the World Ocean Database directly onto the CESM ocean component tracer grid cells without spatial interpolation, smoothing, or other gap-filling techniques to mitigate coastal ocean salinity bias present in the World Ocean Atlas. The mean square error for coastal upper ocean salinity relative to climatology is reduced by up to 14%, and the mean square error of near-surface salinity stratification is reduced by up to 28% near major river mouths in the simulations with improved treatments of river runoff. The improvement in upper ocean bulk salinity is attributed primarily to focusing runoff as point sources thereby avoiding the artificial horizontal spreading of the control run and to applying a locally varying instead of a global constant reference salinity for riverine virtual salt fluxes. The improvements in near-surface salinity stratification are primarily attributed to adding parameterized estuarine mixing with the estuary box model. Salinity and salinity stratification skill improvements are achieved not just near large rivers but also along the global coast and skill improvements extend far offshore. Despite these improvements, many other sources of model-climatology mismatch in coastal salinity and stratification remain and merit further attention.

1. Introduction

The exchange of freshwater between rivers and oceans in the estuaries represents a unique scale interaction in the climate system. The local variability in the terrestrial hydrologic cycle is integrated by rivers over potentially large drainage basins (up to semicontinental scales) and is then imposed on the coastal ocean at the scale of a river mouth. Consequently, appropriately treating riverine freshwater discharge into the oceans in Earth system models is a challenging problem. The riverine freshwater is often discharged into the ocean component of Earth system models with zero salinity and applied to the ocean surface as a vertical flux of “augmented precipitation” over a specified ocean region (often hundreds of kilometers wide) surrounding the actual river mouth (Griffies et al., 2005). Virtual salt flux (VSF) formulations are also commonly used (including in the Community Earth System Model, CESM), to handle river inputs by removing salt from the ocean surface rather than adding freshwater volume. Tseng et al. (2016) find that water column stability near river mouths can be significantly changed by choosing different spreading functions for riverine runoff and/or a different reference salinity for VSF calculations. Sun et al. (2017) develop a physically based estuary box model (EBM) to parameterize the unresolved estuarine mixing processes and resulting estuarine exchange flow in the Earth system models. The EBM is implemented globally in the Parallel Ocean Program version 2 (POP) of the CESM. Their results show that the salinity field of world ocean and its seasonal cycles near the river mouths are affected by the estuarine mixing. It is unclear, however, which choice for treating the riverine freshwater in Earth system models performs best relative to observations. A quantitative comparison with a global salinity climatology with appropriate values near coasts is required.

The climatology of the World Ocean Atlas (WOA; Locarnini et al., 2013; Zweng et al., 2013) is widely used for initial conditions or restoring data (e.g., Balmaseda et al., 2013; Voldoire et al., 2013), model assessment (e.g., Schmidtko et al., 2013; Stammer et al., 2014), and theoretical studies (e.g., Yaremchuk, 2006; Yu, 2011), but it has limitations for the present application. The WOA provides a global large-scale climatology, but the data processing methods (described below) can lead to local climatology distortions where the salinity changes sharply, such as near major river plumes. Furthermore, horizontal smoothing and data gap filling at the scale of hundreds of kilometers likely induces salinity biases. The nearshore salinity in the WOA can have high positive bias, as offshore seawater is often saltier than the coastal water. The use of WOA for coastal applications is thus problematic.

In this study, a new salinity and temperature climatology with better representation of the coastal ocean is generated based on the original observational data in the World Ocean Database (WOD). The spatial resolution of the original data is largely preserved by avoiding any secondary statistical processing, such as interpolating and correlating to fill spatiotemporal data gaps and large-scale horizontal smoothing. The nominally one-degree POP tracer grid (T-grid) structure is employed to create the gridded climatology (WOD2POP). The nominally one-degree POP grid (in midlatitude) converges toward the Arctic and the equator, where the tracer grid cell volume can change by a factor of 3. The vertical resolution of POP grid cells is 10 m thick for the upper 15 levels and is stretched to 250 m at the ocean bottom. Generating the climatology directly onto the one-degree POP grid facilitates the evaluation of model results. Model runs compared to WOD2POP include a control case with rivers imposed as horizontally spread surface forcing, an intermediate case based on the point source with vertically distributed river inputs, and an advanced case that adds the estuarine circulation to the intermediate case via the EBM. The sensitivity of the solutions to additional options for treating riverine freshwater and estuarine processes is further assessed. Skill score is calculated based on the mean square errors (MSEs) from the climatology of the intermediate and advanced POP cases relative to the control case. The skill score assesses the model performance and examines different treatments of riverine freshwater and estuarine processes. Although our focus is on the coastal ocean salinity, the statistical comparisons extend out to the open ocean. The construction of the new climatology and comparisons to WOA is described in the following section, followed by the model result comparisons. The last two sections include a discussion of the model assessment and major conclusions.

2. Climatology Development and Comparison

2.1. WOA

The WOA is publicly available from the National Oceanography Data Center. The original data are obtained mainly from three data management projects: Intergovernmental Oceanographic Commission (IOC) Global Oceanographic Data Archaeology and Rescue project (Levitus et al., 2005), IOC WOD project (Boyer et al., 2013), and IOC Global Temperature Salinity Profile Project (IOC, 1998). The WOD database is the most systematic and updated global ocean climatology among them. WOA processing methods are described in detail in Zweng et al. (2013) for salinity and in Locarnini et al. (2013) for temperature; some key processing steps are described here. Several statistical, interpolation, and averaging methods are employed to generate the gap-free and smoothly varying WOA salinity climatology. First, the original cast data are merged from the observational depths to a set of standard depths using a Lagrange polynomial or linear interpolations according to the availability of original data. Then, the data at standard levels are smoothed or filtered by three-pass analysis with influence radii of 892, 669, and 446 km for the one-degree and 321, 267, and 214 km for the quarter-degree objectively analyzed atlas. Gaps are filled through a multistep spatiotemporal process described in Zweng et al. (2013). The quarter-degree decadal objectively analyzed mean annual WOA 2013 V2 (WOA for convenience) is averaged into the POP spatial grid (specifically the tracer T-grid cells) to generate the WOA2POP climatology for salinity and temperature. Then the WOA2POP is compared with the newly developed climatology (WOD2POP), which is described next section.

2.2. WOD2POP Climatology

To generate the new WOD2POP climatology, the observational data are taken only from eight data sets of the WOD that include both temperature and salinity. The primary data quality control benefits from the rigorous data control of the WOD itself (see Appendix), and only the accepted data (with zero flags) for both cast profiles and individual observational data are admitted in the next step to create the gridded WOD2POP climatology.

The spatial grid of the POP is employed to generate the climatology for salinity and temperature from the original WOD cast records. First, the observational data are gathered into each individual POP T-grid cell for each month and under the same data set type according to their cast information of latitude-longitude

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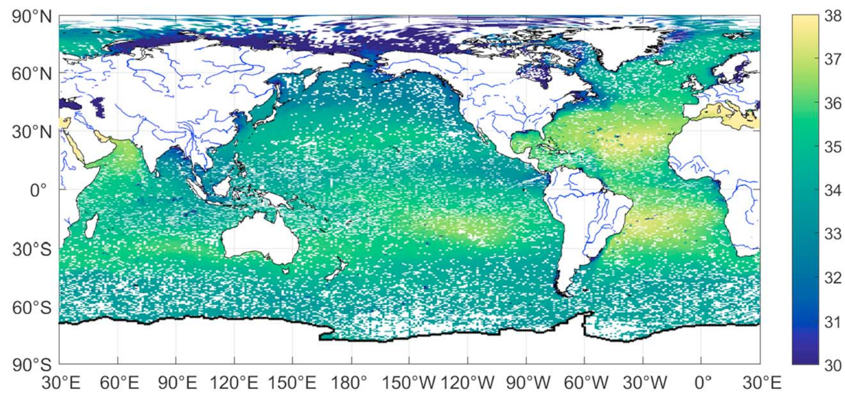

Figure 1. Mean annual near-surface salinity (centered at 5-m depth) of the WOD2POP in units of practical salinity units (PSU).

position, recording time, and observational depth. All temperatures are converted to potential temperatures relative to the sea surface to avoid pressure influence during the vertical averaging of data. The first averaging step calculates monthly averaged values for each observational data set type (Table A1) within each POP T-grid cell. Then, the corresponding monthly mean climatology is calculated over the monthly averaged values from the eight data set types. With this procedure, data sets are given equal weighting and the issue of imbalanced number of observations between data sets is avoided. Finally, the annual mean of the WOD2POP climatology is obtained by averaging over all available monthly mean values in each POP T-grid cell. None of the statistical interpolating, filtering, and gap-filling methods employed by WOA are used. Thus, the spatial scales of the WOD salinity and temperature variations are largely preserved in the WOD2POP climatology, down to the resolution of the POP grid itself.

Because the temperature and salinity data may not always be concurrent in the same measurement and each vertical measurement also has different vertical sampling resolution for different dates, the averaging methods (described above) could potentially create unstable water columns in the POP spatial grids. To find the problematic profiles in the WOD2POP climatology, the potential density is calculated from the salinity and temperature of the WOD2POP with the nonlinear equation of state of seawater (McDougall et al., 2003). Vertical density gradients are calculated between each two closest POP levels with climatological data. Any density inversions are eliminated by removing (i.e., replacing with a missing value) the salinity and temperature from the shallower cell.

With these treatments, the oceanic grids of POP are not fully covered by the climatology data (Figure 1). Table 1 reveals the global data coverage for different ocean regions. The WOD2POP climatology has data coverage for more than 84% of the POP cells with depths shallower than 150 m between 66.33°N and 62°S. The percentage of WOD2POP coverage slightly increases with distance from land-ocean boundary toward the open ocean. The coverage rate of all depths and the entire global ocean is lower (~75%) mainly due to fewer observations in the deep ocean. The gaps in the WOD2POP climatology are not filled in order to avoid introducing artificial data points. The climatological data coverage (Table 1) is sufficient to allow intercomparisons between different ocean regions. Seasonal sampling bias arises in the high-latitude ocean and other areas; these are described in the following section and in the section 5. Because no smoothing or despiking has been applied, the WOD2POP climatology contains some peak values that make the horizontal salinity gradients irregular in some areas (Figure 1). Those data points often have extreme values, but they are still accepted by the WOD with good data flag and are included in both the WOA and WOD2POP climatology. Again, these treatments are aimed at eliminating any artificial smoothing effects on the climatological salinity and temperature, especially in the coastal regions. Both salinity and temperature climatology in monthly and annual format are available as supporting information for this article https://opencommons.uconn.edu/marine_sci/6/.

2.3. Comparison of WOA and WOD2POP

Before the model results are compared with the WOD2POP climatology, it is important to check the original presumption that the WOA may have large distortions in the coastal ocean. The near-surface salinity

Table 1
Percent Coverages of WOD2POP Climatology Relative to Ocean POP T-Grids in Different Bands From Coasts

Upper ocean (≤150 m) and excluding the Arctic (>66.33°N) and Antarctic (>62°S)			All depths throughout global ocean		
Distance from coast (km)	Salinity	Temperature	Distance from coast (km)	Salinity	Temperature
0–150	84.6%	84.2%	0–150	75.2%	76.5%
0–300	87.2%	86.7%	0–300	76.3%	77.7%
0–500	89.5%	88.9%	0–500	76.9%	78.2%
0–1,000	91.8%	91.1%	0–1,000	78.1%	79.4%
Open ocean	93.1%	92.3%	Open ocean	80.1%	80.9%

Note. POP = Parallel Ocean Program.

differences at the POP surface layer (centered at 5-m depth) are plotted by subtracting the WOD2POP from the WOA2POP (Figure 2). The overall root-mean-quare error (*RMSE*) for the near-surface salinity is 0.77 PSU. The differences clearly show regional patterns. The large salinity distortions occur in frontal zones, where the salinity changes sharply. On the continental shelf ocean surface, the WOA2POP often has higher near-surface salinity than WOD2POP close to riverine freshwater sources, and the salinity becomes lower in the WOA2POP moving offshore. This is mainly due to the spatial smoothing and interpolating techniques used to generate WOA that artificially increase the salinity nearshore close to riverine freshwater sources and decrease salinity offshore. Similar difference patterns also can be found across some major ocean fronts (e.g., Gulf Stream). The WOA2POP climatology has overall higher near-surface salinity in the Arctic Ocean compared to WOD2POP. The time series of data coverage of the WOD show that the observational data are often collected during late boreal summer until early fall (July to October with data cover rate between 14% and 26% for the entire water depth) and less than 10% (often less than 7%) for other seasons in Arctic Ocean. Because the original data have higher coverage rate in the summer during the fresher sea ice melting period, the WOD2POP climatology tends to have lower salinity than the spatiotemporally filled WOA climatology in the Arctic.

To quantify the overall differences of salinity between WOA2POP and WOD2POP climatology, the bias is calculated as follows:

$$\mathrm{Bias} = \frac{\sum_N [(A_i - O_i)^* V_i]}{\sum_N V_i} \quad (1)$$

where A is WOA2POP, O is WOD2POP, V is the volume of POP tracer grid cell (with index i), and N is the total number of POP tracer grid cells occupied by data available in both WOA2POP and WOD2POP. To illustrate the bias changes with distance from the coast, the POP grids are masked for distances of 150, 300, 500, and 1,000 km stepwise away from the coastline (Figure 3a) until the entire open ocean is covered. The bias is

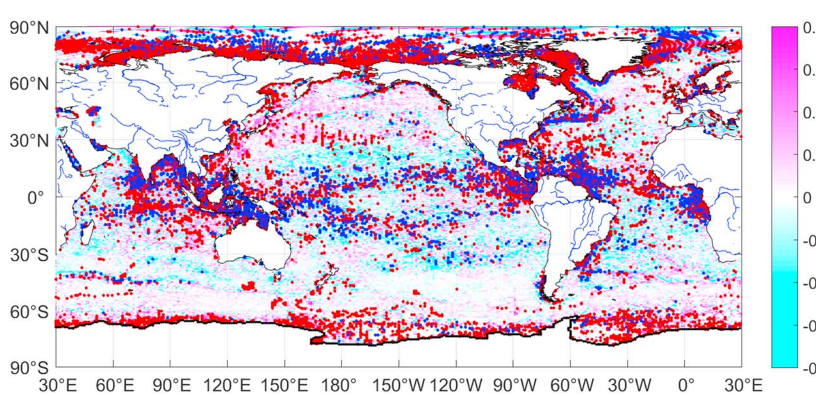

Figure 2. Near-surface mean annual salinity (centered at 5-m depth) differences by subtracting the WOD2POP from the WOA2POP, where the red dots show the near-surface salinity differences higher than 0.2 PSU, while the blue dots are the salinity differences lower than −0.2 PSU.

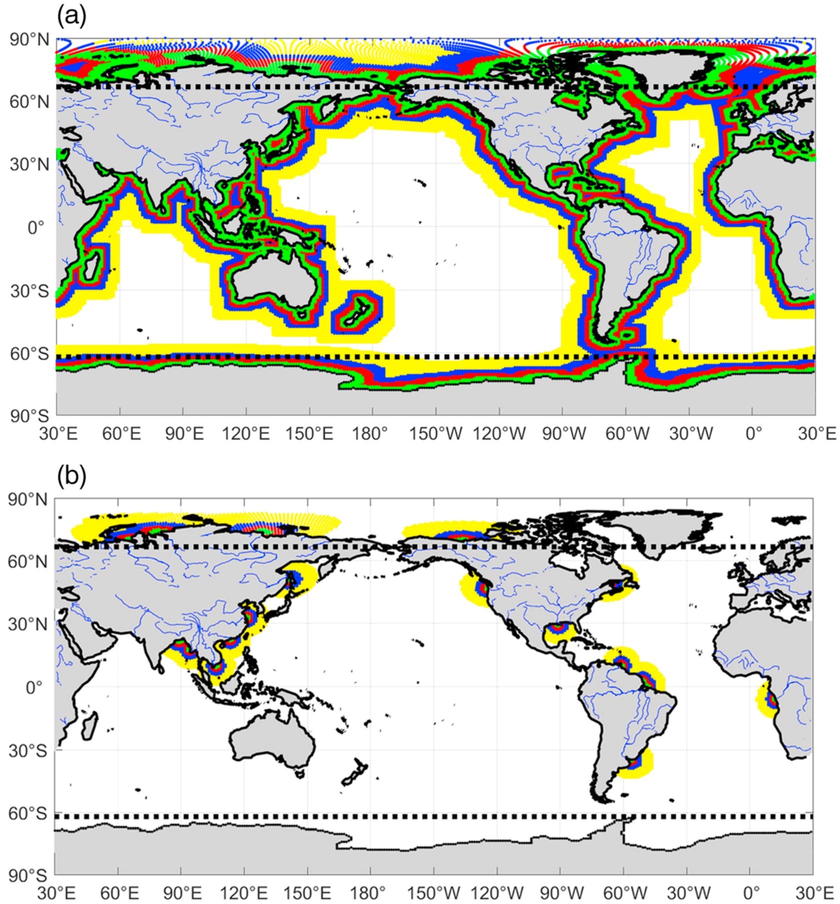

Figure 3. Coastal band masks of the Parallel Ocean Program. The distances that are 150, 300, 500, and 1,000 km away from the origins are marked with green, red, blue, and yellow color. The origins in (a) are the global land-ocean boundary, while the origins in (b) are locally centered at model runoff locations of top 20 rivers. The dashed lines indicate the northern limit (north of 66.33°N) and the southern limit (south of 62°S) for the comparisons excluding the Arctic and Antarctic. The thick black lines indicate the coastline, and the thin blue lines show the major river in the world. Gray shaded areas are not included in the analysis.

calculated for the upper 150 m (excluding north of 66.33°N for the Arctic and south of 62°S for the Antarctic) and for total depth-integrated entire ocean. Inland seas (e.g., Baltic, Black, Caspian, and Red Sea) are excluded from the masks because they are not connected to the open ocean.

The positive salinity bias rises toward the coastal ocean (Figure 4a), which is consistent with our presumption that the WOA processing methods tend to increase coastal ocean salinity. The average salinity bias in the upper ocean exceeds 0.04 PSU near the coast. The total depth-integrated ocean has similar salinity bias changes, although they are much lower than the upper ocean, because the salinity change is small in the deeper ocean. Sun et al. (2017) find the salinity changes in the coastal ocean near river mouths resulting from estuarine parameterizations are of the same order as WOA salinity bias near the coast. Therefore, the salinity bias in the WOA is not negligible when considering effects of the riverine freshwater on the global ocean. Note that the bias for salinity is not zero even for the global ocean calculation. This nonzero value may arise from the differences between the averaging methods used to construct WOD2POP and the averaging/smoothing methods for WOA. The RMSE (Figure 4b) reveals again that the errors of WOA increase toward the coast for salinity. The upper ocean is the major source of the errors, while the deep ocean water properties are not greatly affected by the statistical smoothing treatment.

The WOA also has its own estimations of bias between "statistical mean" values and objectively analyzed mean values which are commonly used as climatology. But the statistical mean values used in the WOA already have been interpolated into the standard depths from the original WOD cast values in observational depth, while the WOD2POP is generated by simply averaging all WOD cast values within the POP T-grid

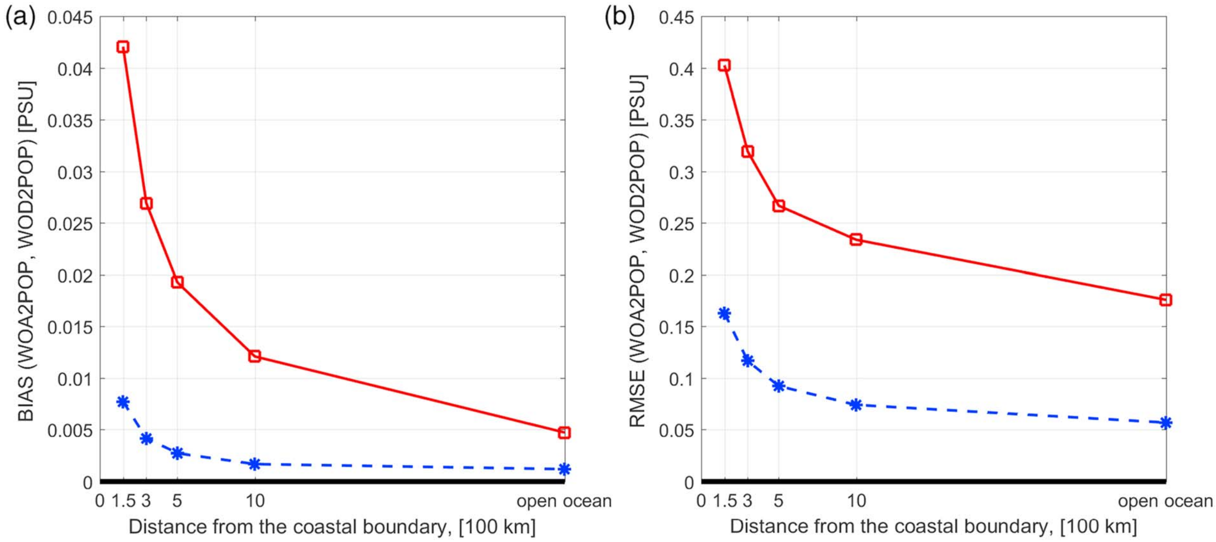

Figure 4. (a) Bias and (b) RMSE of WOA2POP from the WOD2POP for salinity. The solid lines show the upper 150-m oceans excluding the Arctic and Antarctic with coastal band masks (in Figure 3a). The dashed lines represent the entire depth-integrated ocean including the Arctic and Antarctic. RMSE = root-mean-square error.

cell. Although creating the statistical mean values from the same standard depth seems more physically reasonable, we cannot avoid the uncertainties introduced by the vertical interpolation. The uncertainty can grow in coastal regions, where salinity and temperature profiles can change greatly over small vertical scales. The WOA also has published the estimations of bias between statistical and objective means, but its estimations show clearly spatial patterns of the measurement array and track lines. The WOD2POP climatology provides an alternative way to estimate the bias of objectively analyzed climatology in WOA from its most original cast values. Furthermore, the WOD2POP climatology calculates monthly averages from each data source before averaging them together for the combined monthly average values. This method avoids artifacts such as salinity and temperature anomalies driven by high-frequency data sources (e.g., gliders) that remain apparent in the WOA "statistical mean" comparison fields.

3. Comparisons of Model Results With Climatology

CESMv1 is used in the current study with only the coupled ocean and sea ice components. The atmospheric component and river freshwater inputs are prescribed with the interannual varying 1948–2007 COREII forcing (Griffies et al., 2009; Large & Yeager, 2009). The river runoff is based on monthly Dai and Trenberth (2002). The rivers are imposed as VSFs (as described earlier). All experiments restart from the 300th year of a spin-up simulation (five cycles of forcing) and run for one cycle of the forcing (60 years). The salinity field in coastal regions responds quickly to riverine freshwater forcing changes, so the climatological averages over the last 30 years can be used for analysis. Three primary experiments that differ only by their treatment of rivers and estuaries are compared in this study. The VSFSPRD control case imposes river runoff as an outward VSF at the surface that is spread in a Gaussian distribution with *e*-folding scale of 1,000 km and maximal radius of 300 km centered at each coastal discharge point. The VSFROF intermediate case applies point-source river runoff at the closest ocean cell to each river mouth and vertically distributes river runoff over the upper two cells with total water depth of 20 m. Furthermore, this run switches from a global reference salinity for computing riverine VSFs to a local and temporally evolving reference salinity (Tseng et al., 2016). The VSFEBM advanced case includes the same treatment improvements for river runoff as in VSFROF and includes an estuarine exchange flow for salinity represented by the EBM. The estuary exchange flow removes a salt flux from lower layers and adds it to upper layers at the river runoff points. These three cases are identical to the cases with the same names in Sun et al. (2017); that paper describes the development of the EBM and includes further model details. Configuration differences among the VSFSPRD, VSFROF, and VSFEBM cases are summarized in Table 2. Two additional cases exploring

Table 2
Settings Summary for CESM Cases

Case name	River runoff mapping	Reference salinity	Estuary exchange flow
VSFSPRD (control)	Spreading with *e*-folding scale of 1,000 km, applied only at surface layer.	Global constant salinity value	NO
VSFROF (intermediate)	Point sources in single tracer cells, vertically spread over two layers.	Local tracer cell salinity value	NO
VSFEBM (advanced)	Point sources in single tracer cells, vertically spread over two layers.	Local tracer cell salinity value	YES. EBM parameters are unique for top 20 rivers, generic for others.
VSFEBM_Gen	Point sources in single tracer cells, vertically spread over two layers.	Local tracer cell salinity value	YES. EBM parameters are generic for all rivers.
VSFEBM_1010	Point sources in single tracer cells, no vertical spread (applied only at surface layer).	Local tracer cell salinity value	YES. EBM parameters are unique for top 20 rivers, generic for others. The EBM is implemented with H_U=10 m and H_L=10 m, except at Amazon river with H_L=20 m.

Note. CESM = Community Earth System Model; EBM = estuary box model.

sensitivity to EBM parameters, VSFEBM_Gen and VSFEBM_1010, are listed in Table 2 and will be discussed in section 4.

We focus on the salinity in the model comparisons with climatology, as it is most directly influenced by the treatment of riverine freshwater in the model. The near-surface salinity of the VSFEBM case and its differences from WOD2POP are represented in Figure 5 by comparing the salinities in the POP surface layer

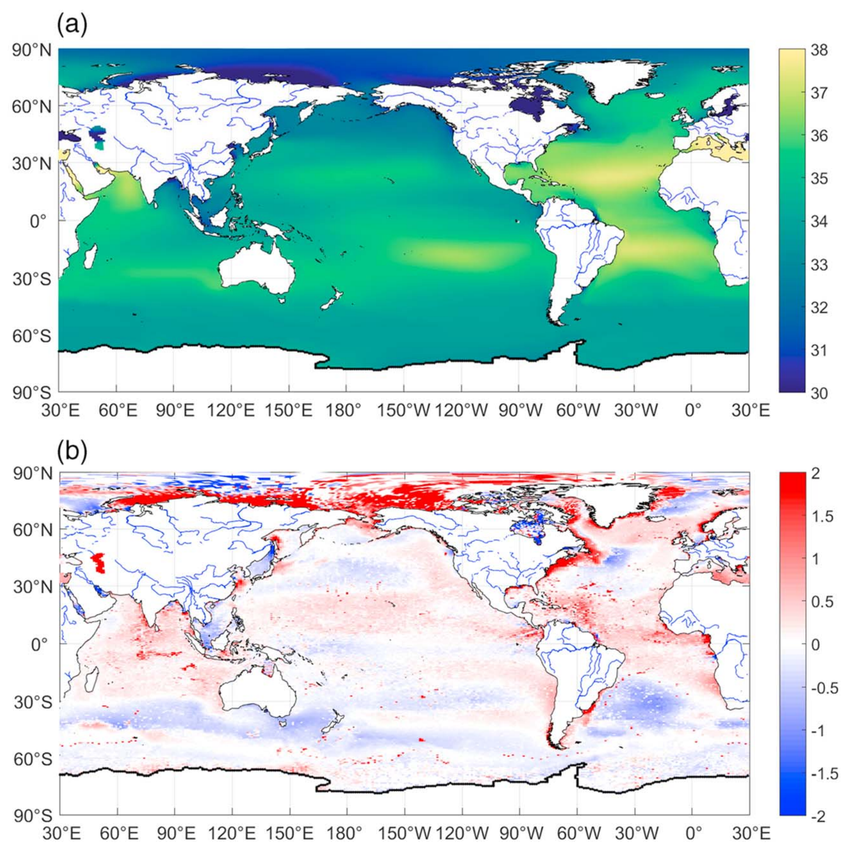

Figure 5. Near-surface salinity (centered at 5-m depth) of (a) VSFEBM, the case of Community Earth System Model with estuary box model implemented, and (b) near-surface salinity differences of VSFEBM minus WOD2POP.

(centered at 5-m depth). Many general features in the near-surface salinity are shared by the model and climatology. In the open ocean, the modeled salinity field agrees well with the climatology with differences usually less than 1 PSU. In the coastal ocean, however, the salinity differences increase considerably. The Arctic Ocean has overall higher salinity errors than other ocean basins. It is worth noting that the WOD2POP climatology has uneven seasonal data coverage in the Arctic Ocean (further discussed in section 5), so the seasonal salinity comparisons will be more reliable than the annual mean comparisons for the global ocean.

Model performance is statistically evaluated relative to climatology and between cases using the skill score (*SS*) involving POP tracer cell volumetric weighted MSE of salinity and salinity stratification as follows:

$$\mathrm{MSE} = \frac{\sum_N \left[(A_i - O_i)^2 * V_i\right]}{\sum_N V_i} \quad \text{and} \quad \mathrm{MSE_R} = \frac{\sum_N \left[(B_i - O_i)^2 * V_i\right]}{\sum_N V_i} \tag{2}$$

$$\mathrm{SS} = \left(1 - \frac{\mathrm{MSE}}{\mathrm{MSE}_R}\right) \times 100\% \tag{3}$$

MSE (equation (2)) compares the model run (A) to the new WOD2POP climatology observations (O), MSE_R (equation (2)) compares the reference model run (B) to the same observations, and SS assesses agreement with climatology for model run A relative to reference run B. As in equation (1), V is the volume of each POP tracer cell (with index i) and N is the total number of POP tracer cells covered by both simulation and climatological data. Positive SS (equation (3)) indicates that the agreement with the climatological salinity in the model case A is improved compared to referenced model case B. Zero SS means no change of the MSE, though the spatial distribution of errors may differ among runs. Negative SS reveals degradation of the agreement with climatology. SS based on the MSE has been applied to assess model performance in many previous studies (e.g., Murphy, 1988 & 1992; Oke et al., 2002). For all comparisons of annual mean results in this section, the Arctic Ocean and high-latitudinal Southern Ocean are excluded for the reason that the WOD2POP climatology does not have data availability in all seasons. The seasonal coverage of the WOD2POP and local SS seasonal variations is presented in section 5.

The global performance of the advanced case by including the EBM and other riverine treatment improvements (VSFEBM) is statistically assessed with SS relative to the VSFSPRD standard control case as reference. The VSFEBM case has positive SS for annual mean salinity in the upper 150-m ocean excluding the Arctic and the Antarctic (Figure 6a). The most significant improvement is found offshore of the top 20 river (Table 3) mouths with about a 14% SS and corresponding MSE reduction relative to climatology. Globally by considering all rivers, the model salinity field has a 10% SS (and MSE reduction) within 150 km from the global coastline (Figure 3a). Salinity skill improvements extend far from the coast.

Near-surface salinity stratification is calculated with salinity differences between the first and the fourth POP vertical layers in upper 40-m ocean. The corresponding salinity stratification SS is assessed for the VSFEBM case (A) relative to the VSFSPRD control reference case (B) and WOD2POP observations (O; equations (2) and (3)). Impressively, the vertical salinity stratification SS reaches 28% within 300 km of the top 20 river mouths (Figure 6c). For the global coastal ocean, the SS is up to 6%. The skill improvements for vertical stratification also extend far into the ocean.

The effects of including estuary exchange flow by implementing the EBM in the advanced VSFEBM case are isolated with SS relative to the VSFROF intermediate run as the new reference case. The changes of annual mean salinity SS by the net effects of estuarine exchange flow are in general much smaller than the effects from riverine treatment improvements included in both cases (i.e., point source river runoff and local reference salinity for riverine VSF calculations, as described in Tseng et al., 2016). Overall, the salinity SS increase in the upper 150 m ocean due to the EBM is less than 1.6% locally close to top 20 river mouths, and negligible for global coastal ocean (Figure 6b). However, parameterizing estuarine mixing has huge impacts on the upper 40-m oceanic salinity stratification (Figure 6d), where the SS is 24% close to the top 20 river mouths, which accounts for almost all of the skill improvement relative to the VSFSPRD control case (Figure 6c and described in the previous paragraph). This result suggests that close to the river mouths, the effects of estuarine mixing become the dominant factor compared to effects from other river runoff treatments. Considering the entire global coastline, however, the SS changes in stratification due to net effects of estuarine mixing are

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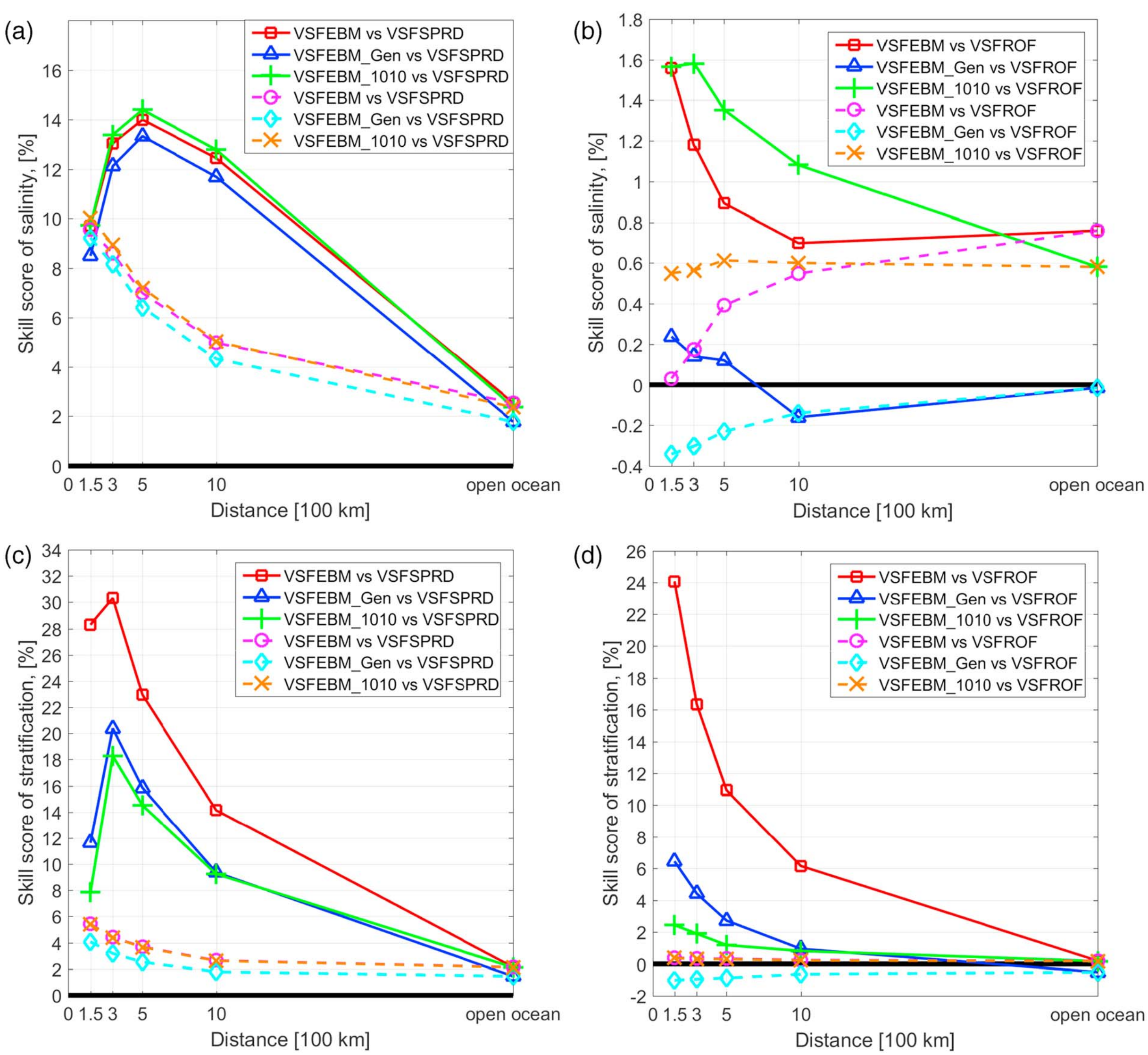

Figure 6. Skill score (SS) for model comparisons with the WOD2POP climatology salinity (a, b) and salinity stratification (c, d) by excluding the Arctic and Antarctic. Solid lines are the results from mask bands originated from the top 20 runoff locations (Figure 3b), while the dashed lines are the results from the mask bands that originated from global coastlines (Figure 3a). The legends are in the format "assessed case A versus reference case B." Case names are listed in the Table 2. The WOD2POP climatology is employed as observations for SS calculation (equation (3)). The salinity SS is calculated with the upper 150-m ocean, and the stratification SS is calculated with salinity differences from the upper 40-m ocean.

negligible, which suggests that other processes or error sources may dominate the model-climatology mismatch in coastal ocean stratification. Even if the effects of estuarine processes on global coastal ocean stratification are small, it is still necessary to include them to provide the model some physically based mixing where rivers are discharged into the ocean.

Comparisons between model cases and WOD2POP climatology can be further described with the model bias (using equation (1)), R^2 (equation (7)), standard deviation error (STDE; equation (8)) of salinity, and RMSE (equation (9), the square root of the MSE defined in equation (2)).

$$\mu_A = \frac{\sum_N (A_i V_i)}{\sum_N V_i} \text{ and } \mu_O = \frac{\sum_N (O_i V_i)}{\sum_N V_i} \tag{4}$$

$$\sigma_A^2 = \frac{\sum_N \left[(A_i - \mu_A)^2 * V_i\right]}{\sum_N V_i} \text{ and } \sigma_O^2 = \frac{\sum_N \left[(O_i - \mu_O)^2 * V_i\right]}{\sum_N V_i} \tag{5}$$

Table 3
Name of Top 20 Rivers Ranked by Their Runoff in the POP of CESM

Rank	River name
1	Amazon
2	Congo
3	Orinoco
4	Changjiang
5	Brahmaputra
6	Mississippi
7	Yenisey
8	Parana
9	Lena
10	Mekong
11	Tocantins
12	Ob
13	Ganges
14	Irrawaddy
15	St. Lawrence
16	Amur
17	Xingu
18	Mackenzie
19	Xijiang
20	Columbia

Note. POP = Parallel Ocean Program; CESM = Community Earth System Model.

$$\sigma_{AO} = \frac{\sum_N [(A_i - \mu_A)^*(O_i - \mu_O)^* V_i]}{\sum_N V_i} \tag{6}$$

$$R^2 = \left(\frac{\sigma_{AO}}{\sigma_A \sigma_O}\right)^2 \tag{7}$$

$$\text{STDE} = \sigma_A - \sigma_O \tag{8}$$

$$\text{RMSE} = \sqrt{\text{MSE}} \tag{9}$$

The μ is mean, the σ is standard deviation, and the V_i is the volume of each POP T-grid cell with WOD2POP data. The σ_A^2 and σ_O^2 are POP T-grid cell volumetric weighted variances of model results (A) and the WOD2POP climatology observations (O), and the σ_{AO} is volumetric weighted covariance. The statistics reported in Table 4 are for the upper 150-m ocean annual mean salinity with the Arctic Ocean and high latitudinal Southern Ocean excluded. For the comparisons within the 300-km global coastal band, there are no significant statistical differences between the VSFEBM advanced case with the VSFROF intermediate case, which indicates that the effects of estuarine mixing are overall small for the global coastal salinity. However, compared to the VSFSPRD control case, the integrated effects of all improvements to the treatment of riverine freshwater can be seen from decreases in RMSE (as described before in terms of the SS and MSE) and STDE. Within the 500-km radius from top 20 river mouths, the negative bias in the VSFSPRD control case compared to climatology agrees with the original presumption that artificially spreading river runoff makes the upper ocean too fresh in coastal regions. It is important to point out that the bias, RMSE, and R^2 of WOA2POP with WOD2POP within the 300-km global coastal band indicate a closer match between climatologies than between any of the model runs and climatology.

4. Assessment of Additional Test Cases

4.1. Setting EBM With Generic Parameters

Table 4
Statistics of Model Salinity to Climatology Comparisons for Upper 150-m Ocean Within the 300-km Band Originated From Global Coastlines (Figure 3a) or 500 km From Top 20 River Mouths (Figure 3b) Excluding the Arctic and Antarctic Regions

Band and distances	Case A name	Bias	R^2	STDE	RMSE
300-km band from global coastlines	VSFSPRD	0.070	0.84	0.082	0.606
	VSFROF	0.080	0.85	0.067	0.580
	VSFEBM	0.078	0.85	0.066	0.579
	VSFEBM_Gen	0.079	0.85	0.068	0.581
	VSFEBM_1010	0.080	0.86	0.064	0.578
	WOA2POP	0.027	0.91	−0.076	0.319
500-km band form top 20 river mouths	VSFSPRD	−0.072	0.71	−0.073	0.993
	VSFROF	0.020	0.74	−0.107	0.925
	VSFEBM	0.005	0.74	−0.112	0.921
	VSFEBM_Gen	0.017	0.74	−0.108	0.924
	VSFEBM_1010	0.019	0.75	−0.120	0.919
	WOA2POP	0.074	0.58	0.013	0.535

Note. The compared model case name is noted as A and annual mean salinity climatology as O, which are indicated as subscripts in the equations (1), (7), (8), and (9). STDE = standard deviation error; RMSE = root-mean-square error.

The EBM requires five independent parameters (as described in Sun et al., 2017). For each river/estuary, three of them are used to prescribe the width, total depth, and lower layer thickness of the two-layer box. The other two parameters are the adjustable dimensionless vertical and horizontal mixing constants. In the VSFEBM case, the EBM parameters are specified for the global top 20 rivers (Table 3) ranked by their mean annual runoff, while generic parameters are applied for the other 2,343 rivers in the model. Sun et al. (2017) represent these lower-ranked rivers by optimizing the generic parameters based on the observational data from 13 estuaries (Geyer, 2010). Because the total runoff of the top 20 rivers is about half of the global annual riverine freshwater runoff into the ocean, the EBM parameter specifications aim to improve the accuracy of the estuarine mixing for these large rivers with appreciable influences on the coastal stratification. Under some circumstances (e.g., for paleoclimate applications), however, the parameters for the largest rivers are hard to constrain, so specifying appropriate individualized parameters is difficult. From the model sensitivity point of view, it is also interesting to see if customizing EBM parameters for individual rivers is necessary or not. In the VSFEBM_Gen test case (Table 2), the EBM for all runoff points (including the global top 20 rivers) uses the same generic parameters, while all other model settings are kept same as the VSFEBM case.

The annual mean salinity field in the VSFEBM_Gen case has a positive SS compared to the VSFSPRD control case in the upper 150-m ocean excluding the Arctic and Antarctic regardless of the distance from the coast (Figure 6a). The SS for the VSFEBM_Gen relative to the VSFSPRD control reference case is about 2% lower than the analogous SS for the VSFEBM case near the top 20 rivers and 1% lower along the global coastal band. The negative SS between the VSFEBM_Gen test case and the VSFROF intermediate case (Figure 6b) and little change in other statistical measures (Table 4) reveals that applying the EBM with only generic parameters for all rivers provides no statistical benefit in the representation of the salinity field globally in coastal ocean, but the SS still shows limit improvement locally 500 km from the top 20 river mouths. In contrast, the positive salinity SS for the VSFEBM advanced case relative to the VSFROF case, further highlights that the customization of EBM parameters for top 20 river is necessary to improve the salinity predictions of the POP. The Atlantic is the most affected ocean basin by using generic parameters. The model salinity bias increases in North Atlantic chiefly because of weak mixing in Amazon and Orinoco Rivers with generic EBM parameters.

For the salinity stratification in the upper 40-m ocean, the VSFEBM_Gen case has a positive SS compared to the VSFSPRD control case, but the SS is only two thirds the analogous SS in the VSFEBM case within 300 km from the top 20 river mouths. In the regions with radius of 150 km from the river mouths, the SS of VSFEBM_Gen case in salinity stratification is less than a half the VSFEBM case SS (Figure 6c). These skill reductions are primarily due to weaker mixing, as the comparisons with VSFROF intermediate case show considerable decreases in SS for the isolated estuarine processes (Figure 6d) locally within 150 km from top 20 river mouths. At the global scale, the SS in salinity stratification is also reduced by using generic parameters for the EBM in the VSFEBM_Gen case. Overall, the EBM with generic parameters does little harm to the model globally, although the comparisons with VSFROF intermediate case show small degradations in salinity field and for vertical salinity stratification. In the circumstances of paleoclimate studies (e.g., for river-borne isotopes) where custom EBM parameters are unavailable, the VSFEBM_Gen can provide more realistic conditions than without including parameterized estuarine mixing. When available, customized EBM parameters for major rivers improve SS and therefore are preferable for simulating modern-day and near-future periods.

4.2. Sensitivity of EBM Implementation Depth

In nature, the estuarine exchange is observed as real volume fluxes through the river mouth with brackish oceanward (tidally averaged) near-surface flow and salty landward near-bottom flow. In POP, however, the freshwater input is treated as VSF. A salt sink tendency term is applied in the salinity tracer equation at the surface layers of water column close to river mouths in order to mimic riverine freshwater input. The net effect of estuarine mixing is represented as a salt source tendency term in surface layers and a salt sink tendency term in subsurface layers of the same water column. The water column integral of the salt flux tendencies due to estuarine mixing equals zero, as the mixing only vertically redistributes the salt. The water depths have to be specified for the salt flux tendencies when the estuarine mixing is implemented in the POP. H_U is the implementation depth associated with the salt sinks corresponding to riverine freshwater inflow and the salt sources due to estuarine mixing in the surface layers. H_L is the depth below H_U associated with the salt sinks corresponding to estuarine mixing in subsurface layers. More detailed descriptions and mathematical formulae can be found in Sun et al. (2017).

The sensitivities of SS with different implementation depths of the EBM for upper ocean salinity are further studied. In the VSFEBM advanced case, the implementation depths are set to $H_u = 20$ m (two surface POP layers) for riverine freshwater runoff distributions, and $H_L = 20$ m or 10 m (two subsurface layers or one subsurface layer, depending on the available local water depth) for estuary exchange flow. The implementation depth in the VSFEBM_1010 case (Table 2) is reduced to 10 m (the first POP layer) for H_U and 10 m (the second POP layer) for H_L, which are expected to better represent the shallow depths of riverine freshwater from river mouth. The one exception is the Amazon River mouth, where H_L is set to 20 m (the second and third POP layers) due to the exceptionally large magnitude of the Amazon sources and sinks. The SS to assess the VSFEBM_1010 case is shown in Figure 6.

In the VSFEBM_1010, the effects of riverine freshwater and estuarine mixing are more constrained to the sea surface and smaller regions near river mouths, which makes the model results closer to the WOD2POP

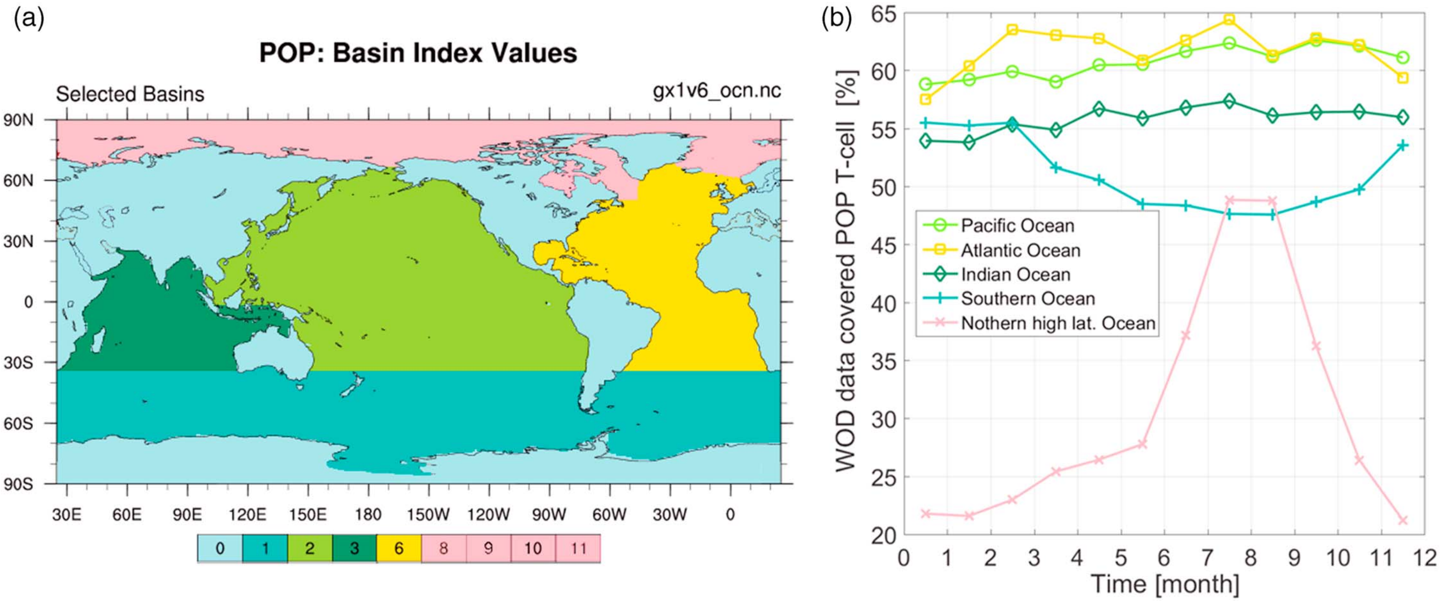

Figure 7. POP ocean basin colored index (a; https://www.ncl.ucar.edu/Applications/popmask.shtml) with modified colors for northern high-latitude oceans and monthly POP ocean tracer cell coverage rate by the WOD salinity data for each basin in the upper 150 m (b). The northern high-latitude ocean includes the basins with indices 8–11. POP = Parallel Ocean Program; WOD = World Ocean Database.

salinity climatology and also closer to the natural conditions, where the river plumes usually are shallow. With this advantage of a shallower implementation depth, the upper 150-m salinity SS of VSFEBM_1010 is slightly higher than the VSFEBM compared to the VSFSPRD standard control case (Figure 6a). TheVSFEBM_1010 has a much better SS and the lowest RMSE (Table 4), compared to the VSFROF intermediate case than the advanced VSFEBM case offshore of the top 20 river mouths. Globally, the VSFEBM_1010 case also shows higher SS than the advanced VSFEBM case within 1,000 km from coastline (Figure 6b). For the vertical salinity stratification in upper 40-m ocean (Figures 6c and 6d), however, the VSFEBM_1010 case does not show improved SS. As a result, the offshore salinity field in the VSFEBM_1010 case has higher SS than the VSFEBM case, but it shows less improvement in the vertical salinity stratification than the VSFEBM case referred to the control and intermediate cases.

Overall, changing the implementation depth is less important than either including point source river runoff and using local reference salinity or including the EBM as originally implemented.

5. Discussion

The new WOD2POP provides advantages over the WOA in representing the scales of salinity variability in coastal areas. Nevertheless, gaps remain unfilled in the new climatology (i.e., ocean grid cells without observations) and uneven seasonal sampling tends to bias the mean annual climatology in higher latitudes and potentially other regions. The mean annual data, which are calculated by averaging all available monthly mean values, have relatively high global coverage rates (Table 1). Besides the varying data coverage with distance from the coast, the coverage also changes with time and different basins. The monthly data coverage rate for the salinity in upper 150 m is plotted for individual ocean basins (Figure 7). The Pacific, Atlantic, and Indian Oceans have relatively small seasonal changes in data coverage rate. The Southern Ocean has clear seasonal changes with higher data coverage rate in southern summer. The seasonal sampling bias is even larger in the northern high-latitude ocean, where the data in July and August have more than double the coverage rate as compared with the boreal winter. The mean annual climatology value is assigned in WOD2POP, even if there is only one cast data available in the WOD in single month in a POP grid cell. Therefore, in areas with large seasonal sampling bias, the WOD2POP climatology cannot represent the actual mean annual value in that cell, especially if it is in a region with high seasonal salinity or temperature variations. The WOD data occupancy of

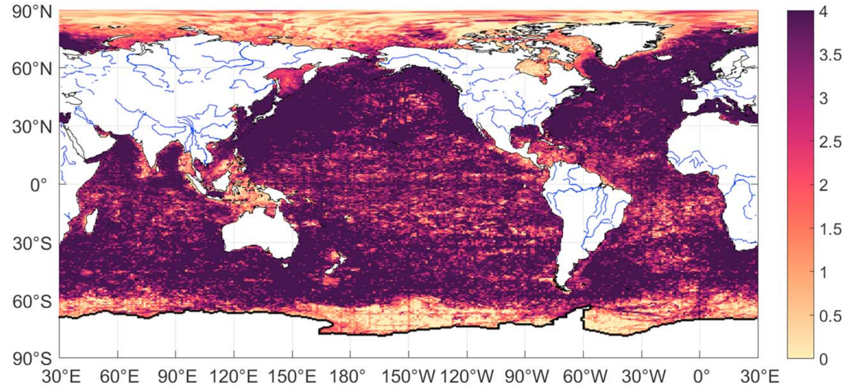

Figure 8. Seasonal World Ocean Database (WOD) data coverage for upper 150 m of the ocean. The dark color shaded areas have WOD observations available from all four seasons, and light colored areas do not have any WOD data available.

seasons is calculated for the POP ocean; ideally, all grid cells have data for all four seasons and severe seasonal sampling bias can occur when only one season or two seasons have data. For the upper 150-m ocean (Figure 8), the coastal ocean usually has been covered with data available from all four seasons. But some seasonal sampling bias can still be found in regions, such as the northeastern Brazil coast, Caribbean Sea, eastern coast of northern tropical Pacific Ocean, Banda Sea, Andaman Sea, and the Sea of Okhotsk. The high-latitude ocean (north of the Arctic Circle 66.33°N or south of 62°S) clearly lacks full seasonal data coverage, so the mean annual comparisons of model results with the original WOD in these regions should be trusted less than comparisons excluding high-latitude regions. Instead, the global summer seasonal climatology is useful to assess the entire ocean. The spatial and monthly data coverage rate of WOD2POP reveals that this climatology has good representation of mean annual salinity in coastal oceans. Improvements beyond the WOD2POP climatology can be made to avoid the coastal salinity bias in WOA. One possible alternative is to use more sophisticated objective mapping methods than simple bin averaging as used in WOD2POP. Applying the interpolation methods of Dunn and Ridgway (2002) and Ridgway et al. (2002) can sufficiently reduce the influence of offshore observations on coastal analyses. Furthermore, it is best to develop a climatology that is independent of the target model grid (such as POP in the present study) so that it can be more readily applied to other Earth system models.

Seasonal variability in the salinity SS is checked for the upper 150-m ocean for global spring, summer, fall, and winter by excluding the high-latitude ocean, while the SS for Arctic Ocean is only looked at in fall. The SS relative to the VSFSPRD control case shows great seasonal variation with positive values in spring, summer, and winter, while there is some degradation in fall very close to top 20 river mouths within the 150-km radius (Figure 9a). The variations of SS are primarily due to the seasonal cycles of river runoff, because the skill improvement with estuarine mixing provided by the EBM relative to the VSFROF intermediate case is relatively small (Figure 9b). The fall season SS in the Arctic Ocean in both reference cases is negative, which reveals that the EBM and other river runoff treatments do not benefit the salinity field around the largest Arctic rivers (Ob, Yenisey, Lena, and Mackenzie Rivers). Further investigation of the treatment of these rivers in CESM is warranted. Large salinity biases resulting from processes other than river runoff, for example, sea ice freezing and melt, also make this a challenging simulation problem.

Close to major rivers and the global coast, the VSFEBM advanced case has higher skill than the VSFSPRD reference case, and it is closer to the natural system with point source runoff treatment, local reference salinities, and parameterized estuary mixing. But there are other sources of errors that remain and may have more significant influences on model-climatology mismatch near the coastal ocean. First, the locations of ocean currents near shelf regions are often not appropriately represented in the POP ocean. The near-surface salinity (in the POP surface layer centered at 5-m depth) of the VSFEBM case and its differences from WOD2POP are shown in Figure 5. Compared to the corresponding near-surface salinity plot of WOD2POP in Figure 1, the separation point of Gulf Stream is clearly shifted from its natural position

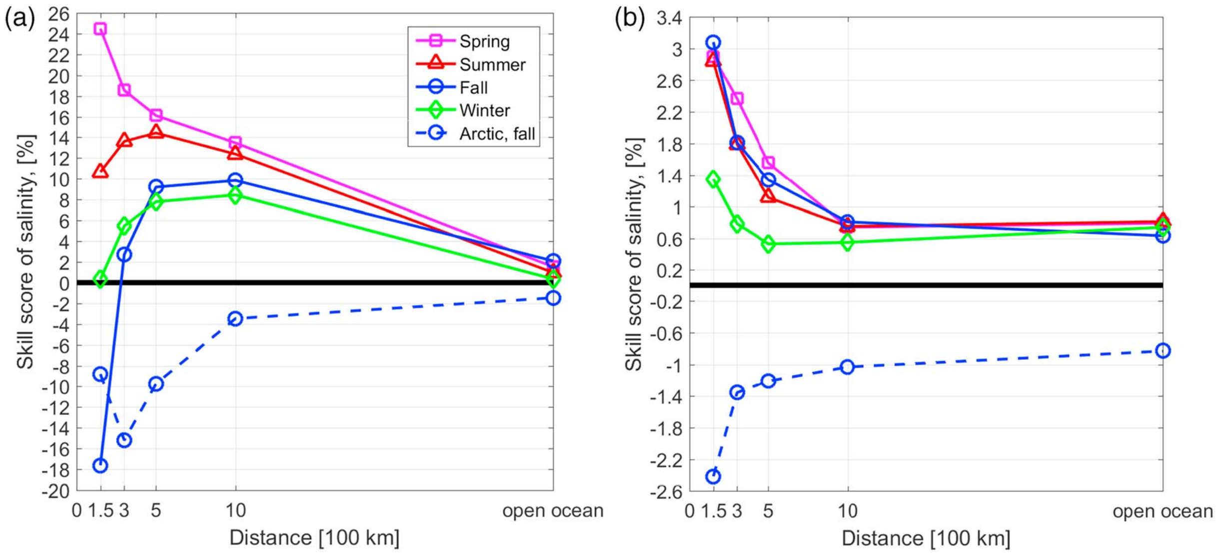

Figure 9. Seasonal salinity skill score (SS) calculated with top 20 river coastal band (Figure 3b) for model comparisons with the WOD2POP climatology (equation (3)). For curves in (a), the assessed case is VSFEBM and the reference case is VSFSPRD, while the curves in (b) have the assessed case of VSFEBM and the reference case of VSFROF (Table 2). The solid lines show the SS for four seasons excluding the high-latitude oceans, while the dashed lines are the SS for Arctic Ocean in fall.

near Cape Hatteras to Cape Cod in the model. Late separation of western boundary currents is a well-known problem in one-degree global ocean models (e.g., Gent et al., 2011; Griffies et al., 2005). The entire U.S. eastern coastal ocean has high salinity bias, shown in Figure 5b, chiefly because of the mismatch of Gulf Stream location. The Kuroshio Current has a similar issue that induces a positive near-surface salinity bias on the Japanese eastern coastal ocean north of Cape Nojima-zaki. Second, the shelf and slope current properties are not well represented in POP. The Labrador Current is much saltier in the model than in the climatology (Figure 5b). This may also contribute to the mismatch of Gulf Stream location in the model and in the climatology, because both currents interact on the Middle Atlantic Bight. Another issue is the locations of many river mouths in model differ from their actual geographic positions. Significant near-surface salinity differences in a dipole form can be seen in the northern Sea of Japan and in the southern Sea of Okhotsk (Figure 5b). In POP, the strait connecting both seas is closed due to coarse horizontal resolution, so the runoff of Amur River freshwater is artificially discharged into the Sea of Japan. In reality, the Amur River discharges into Amurskiy Liman, which acts as the Amur River estuary, and its flow directions are controlled by the background sea level difference between Sea of Japan and Sea of Okhotsk (Abrosimova et al., 2009). The flow direction of Amurskiy Liman water changes due to seasonal wind reversals. Overall, the Sea of Okhotsk receives more freshwater originating from Amur River than the Sea of Japan. This kind of mismatch of river mouth location induces the positive near-surface salinity bias in southern Sea of Okhotsk and negative bias in entire Sea of Japan. Similar positioning issues can also be found for the Ob, Irrawaddy, Changjiang, and Columbia Rivers and others. Some of them (e.g., Ob, Changjiang, and Columbia) have their mouth shifted a couple of degrees away from their natural locations. Others (e.g., Xingu, Xijiang, Ganges, and Brahmaputra) have separated runoff into the POP coastal ocean, but in nature they have confluences before reaching the ocean, that is, the Xingu is a tributary of Amazon, Xijiang is a tributary of Zhujiang River, and Ganges and Brahmaputra are combined with Meghna River before discharging into the Bay of Bengal. All these coastal ocean issues in POP create mismatch with the coastal salinity climatology that the estuarine mixing parameterizations of EBM cannot improve. Consequently, significant challenges remain in representing the coastal ocean in Earth system models.

The VSFEBM_Gen test case with generic EBM parameter values applied to all global rivers has lower SS than the VSFEBM case that has individualized parameter values for the 20 largest rivers. The test cases are run to reveal both the sensitivity associated with EBM parameter values and the viability for climate scenario applications for which specific rivers and their parameter values can be difficult

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to determine. Since the SS is higher for the VSFEBM case than the VSFEBM_Gen test case, it points to the importance of customizing EBM parameter values for the 20 largest rivers, and this also suggests that customizing parameter values for additional rivers may further improve model skill. Nevertheless, representing estuarine exchange flow, even in this generic fashion, may still be of benefit if other model tracers (e.g., nutrients, carbon, and ideal age) are cycled with the exchange flow. The sensitivity test of implementation depth (VSFEBM_1010) shows that the salinity SS close to coast can be improved by reducing the vertical spreading depth of riverine freshwater and estuarine exchange flow. Yankovsky and Chapman (1997) show that there are two different types buoyancy-driven river plumes: bottom-advected and surface-advected plumes. For the bottom-advected type, freshwater occupies the entire water column with depths much greater than the river mouth depth. And the plume depth increases as it extends offshore until the alongshore velocity in the bottom boundary layer is reversed. The surface-advected type forms a freshwater plume with large offshore extent but with shallow thickness that typically is less than or equal to the river mouth depth near shore and reduces to zero toward the offshore plume front. In general, the plume types depend on river discharge, river outflow depth, coastal water depth, Coriolis, and density anomaly from ambient coastal seawater. In the POP, however, the finest vertical resolution at sea surface is 10 m, which already exceeds the total depth of most rivers at their mouth. If the vertical estuarine circulation is taken into account, then the riverine outflow depth is even shallower than the total depth of river mouth. Therefore, the representation of riverine freshwater in the ocean is still limited by the POP model vertical resolution, particularly for rivers with surface-advected plumes.

6. Conclusions

Climatological salinity and temperature fields have been generated from the original observational data of WOD with the POP tracer grid cells as the spatial frame to facilitate comparisons to model results. To avoid any artificial distortions of data in the coastal ocean, no spatial interpolation, smoothing, or other gap-filling techniques are applied; this sets the new WOD2POP climatology apart from the WOA. Comparisons between WOA and the new WOD2POP climatology reveal that the WOA salinity fields at frontal zones, such as on the shelf and along ocean currents, have relatively high bias. Globally, the positive salinity bias of WOA increases toward the land-ocean boundary. Therefore, the new WOD2POP climatology is better suited to evaluating Earth system model performance in the coastal ocean, especially where WOD observations span all seasons and seasonal sampling biases (most common at high-latitudes and at deeper depths) are avoided.

Assessment of model performance focuses on CESM ocean-ice coupled model runs that differ in their treatment of riverine freshwater. The advanced case includes horizontally focused and vertically distributed runoff forcing, local reference salinities for riverine VSFs, and estuarine exchange flow for salinity calculated by the EBM. This case has positive SS in its agreement to the new WOD2POP climatology relative to the standard control case with horizontally spread surface runoff forcing, a global reference salinity for VSFs, and no representation of estuarine exchange flow. The SS grows larger toward the coast and reflects a 10% reduction in the model MSE of salinity relative to climatology. Close to the river mouths, especially the top 20 rivers, the SS increases tremendously for both upper ocean salinity (about 14% within 500 km) and stratification (30% within 300 km). Most of the skill improvement for salinity is associated with horizontally and vertically remapping river runoff closer to its natural distribution. While including estuarine mixing with the EBM is a secondary factor in improving salinity skill, the EBM is the major factor in the large skill improvement in salinity stratification near the top 20 river mouths. Applying customized EBM parameter values for the top 20 largest rivers is an important step because a test case with generic EBM parameter values for all rivers had lower SS than the customized EBM case and the intermediate case without the EBM. The sensitivity test with shallow implantation depth of the EBM, but customized parameters for the top 20, has some improvement for salinity in the global coast but makes less change to the stratification. Though SS increases have been achieved by improving the representation of riverine freshwater, there are many other sources of disagreement between model and climatology in the coastal ocean (e.g., more accurate locations for river mouths, improved representations of coastline geometry and bathymetry, and better solutions for ocean currents) that merit further attention.

Appendix A

A1. Introduction of Primary Data Quality Control in the WOD

The profiling data are organized into 11 data sets with similar instruments and depth resolutions in WOD 2013. There are only eight data sets that contain both salinity and temperature measurements in casts: ocean station data, conductivity-temperature-depth data, profiling floats data, moored buoy data, drifting buoys data, undulating ocean recorder data, surface-only data, and glider data. The total number of cast profiles and the temporal coverage are listed in the Table A1.

The data used for climatology calculations undergo strict quality control by the IOC. First, the data are converted to the standard units of the WOD (practical salinity units, PSU, for salinity, Celsius for temperature, and meters for depth), and the cast location and time are also verified. Then the cruise information and a number for identifications are assigned to each cast profile. Duplicated cast profiles and duplicated observational depth within casts are identified. The duplicated data are either omitted or merged. Finally, the quality control flags for both statistic and stability checks are applied either for single observational value (Table A2) or for the entire cast profile (Table A3). The primary data quality control benefits from the rigorous data control of the WOD itself, and only the data with flag number "0" (accepted data) for both entire profile (Table A3) and individual observations (Table A2) are used in the WOD2POP climatology.

Table A1
Total Number of Cast Profiles and Time Span for Each Data Set Type of WOD Which Contains Both Salinity and Temperature Measurements (Boyer et al., 2013)

Data set		Number of cast profiles	Time coverage
Ocean station data (OSD)	Temperature	2,382,296	(1873–2012)
	Salinity	2,382,296	(1873–2012)
Conductivity-temperature-depth (CTD)	Temperature	847,566	(1961–2012)
	Salinity	819,675	
Profiling floats data (PFL)	All variables	1,020,213	(1994–2012)
Moored buoy data (MRB)	All variables	1,411,762	(1980–2012)
Drifting buoys data (DRB)	All variables	154,900	(1985–2013)
Undulating ocean recorder data (UOR)	Temperature	88,170	(1992–2004)
	Salinity	86,454	
Surface-only data (SUR)	Temperature	506,062[a]	(1867–2010)
	Salinity	1,958,361[a]	
Glider data (GLD)	All variables	103,798	(2004–2012)

Note. WOD = World Ocean Database.
[a]For the SUR the number indicates the total number of observations.

Table A2
WOD Flags for Individual Observation (Boyer et al., 2013)

Flag	Description
0	Accepted value
1	Range outlier (outside of broad range check)
2	Failed inversion check
3	Failed gradient check
4	Observed level "bullseye" flag and zero gradient check
5	Combined gradient and inversion checks
6	Failed range and inversion checks
7	Failed range and gradient checks
8	Failed range and questionable data checks
9	Failed range and combined gradient and inversion checks

Note. WOD = World Ocean Database.

Table A3
WOD Flags for Entire Cast Profile (Boyer et al., 2013)

Flag	Description
0	Accepted cast
1	Failed annual standard deviation check
2	Two or more density inversions (Levitus, 1982, criteria)
3	Flagged cruise
4	Failed seasonal standard deviation check
5	Failed monthly standard deviation check
6	Failed annual and seasonal standard deviation check
7	Bullseye from standard level data or failed annual and monthly standard deviation check
8	Failed seasonal and monthly standard deviation check
9	Failed annual, seasonal and monthly standard deviation check

Note. WOD = World Ocean Database.

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References

Abrosimova, A., Zhabin, I., & Dubina, V. (2009). Influence of Amur River discharge on hydrological conditions of the Amurskiy Liman and Sakhalin Bay of the Sea of Okhotsk during a spring-summer flood. *PICES Scientific Report*, *36*, 180–184.

Balmaseda, M. A., Mogensena, K., & Weaverb, A. T. (2013). Evaluation of the ECMWF ocean reanalysis system ORAS4. *Quarterly Journal of the Royal Meteorological Society*, *139*, 132–1161.

Boyer, P. T., Antonov, I. J., Baranova, K. O., Coleman, C., Garcia, E. H., Grodsky, A., et al. (2013). In S. Levitus, & A. Mishonov (Eds.), NOAA Atlas NESDIS 72*World ocean database 2013*. Silver Spring, MD: NOAA Printing Office.

Dai, A., & Trenberth, K. E. (2002). Estimates of freshwater discharge from continents: Latitudinal and seasonal variations. *Journal of Hydrometeorology*, *3*(6), 660–687. https://doi.org/10.1175/1525-7541(2002)003<0660:EOFDFC>2.0.CO;2

Dunn, J. R., & Ridgway, K. R. (2002). Mapping ocean properties in regions of complex topography. *Deep Sea Research Part I: Oceanographic Research Papers*, *49*(3), 591–604. https://doi.org/10.1016/S0967-0637(01)00069-3

Gent, P. R., Danabasoglu, G., Donner, L. J., Holland, M. M., Hunke, E. C., Jayne, S. R., et al. (2011). The Community Climate System Model Version 4. *Journal of Climate*, *24*(19), 4973–4991. https://doi.org/10.1175/2011JCLI4083.1

Geyer, R. W. (2010). Estuarine salinity structure and circulation. In A. Valle-Levinson (Ed.), *Contemporary issues in estuarine physics, transport and water quality*, (pp. 12–26). New York: Cambridge University Press. https://doi.org/10.1017/CBO9780511676567.003

Griffies, S. M., Biastoch, A., Böning, C., Bryan, F., Danabasoglu, G., Chassignet, E. P., et al. (2009). Coordinated Ocean-ice Reference Experiments (COREs). *Ocean Modelling*, *26*(1-2), 1–46. https://doi.org/10.1016/j.ocemod.2008.08.007

Griffies, S. M., Gnanadesikan, A., Dixon, K. W., Dunne, J. P., Gerdes, R., Harrison, M. J., et al. (2005). Formulation of an ocean model for global climate simulations. *Ocean Science*, *1*(1), 45–79. https://doi.org/10.5194/os-1-45-2005

IOC. (1998). Global Temperature-Salinity Profile Programme (GTSPP)—Overview and future. Paris: Intergovernmental Oceanographic Commission, IOC Technical Series 49.

Large, W. G., & Yeager, S. G. (2009). The global climatology of an interannually varying air–sea flux data set. *Climate Dynamics*, *33*(2–3), 341–364. https://doi.org/10.1007/s00382-008-0441-3

Levitus, S. (1982). *Climatological Atlas of the World Ocean*, NOAA Professional Paper 13. Washington, DC: U.S. Government Printing Office.

Levitus, S., Sato, S., Maillard, C., Mikhailov, N., & Caldwell, P. (2005). *Building ocean profile-plankton databases for climate and ecosystem research*. Wash., D.C.: NOAA Techn. Report NESDIS 117: U.S. Gov. Printing Office.

Locarnini, R. A., Mishonov, A. V., Antonov, J. I., Boyer, T. P., Garcia, H. E., Baranova, O. K., et al. (2013). World Ocean Atlas 2013, volume 1: Temperature. In S. Levitus (Ed.), Mishonov, A. Technical*NOAA Atlas NESDIS 73*, (p. 40). Silver Spring, MD: National Oceanographic Data Center. https://data.nodc.noaa.gov/woa/WOA13/DOC/woa13_vol1.pdf

McDougall, T. J., Jackett, D. R., Wright, D. G., & Feistel, R. (2003). Accurate and computationally efficient algorithms for potential temperature and density of seawater. *Journal of Atmospheric and Oceanic Technology*, *20*(5), 730–741. https://doi.org/10.1175/1520-0426(2003)20<730:AACEAF>2.0.CO;2

Murphy, A. H. (1988). Skill scores based on the mean square error and their relationships to the correlation coefficient. *Monthly Weather Review*, *116*(12), 2417–2424. https://doi.org/10.1175/1520-0493(1988)116<2417:SSBOTM>2.0.CO;2

Murphy, A. H. (1992). Climatology, persistence, and their linear combination as standards of reference in skill scores. *Weather and Forecasting*, *7*(4), 692–698. https://doi.org/10.1175/1520-0434(1992)007<0692:CPATLC>2.0.CO;2

Oke, P. R., Allen, J. S., Miller, R. N., Egbert, G. D., Austin, J. A., Barth, J. A., et al. (2002). A modeling study of the three-dimensional continental shelf circulation off Oregon. Part I: Model–data comparisons. *Journal of Physical Oceanography*, *32*(5), 1360–1382. https://doi.org/10.1175/1520-0485(2002)032<1360:AMSOTT>2.0.CO;2

Ridgway, K. R., Dunn, J. R., & Wilkin, J. L. (2002). Ocean interpolation by four-dimensional weighted least squares—Application to the waters around Australasia. *Journal of Atmospheric and Oceanic Technology*, *19*(9), 1357–1375. https://doi.org/10.1175/1520-0426(2002)019<1357:OIBFDW>2.0.CO;2

Schmidtko, S., Johnson, G. C., & Lyman, J. M. (2013). MIMOC: A global monthly isopycnal upper-ocean climatology. *Journal of Geophysical Research: Oceans*, *118*, 1658–1672. https://doi.org/10.1002/jgrc.20122

Stammer, D., Ray, R. D., Andersen, O. B., Arbic, B. K., Bosch, W., Carrère, L., et al. (2014). Accuracy assessment of global barotropic ocean tide models. *Reviews of Geophysics*, *52*, 243–282. https://doi.org/10.1002/2014RG000450

Sun, Q., Whitney, M. M., Bryan, F. O., & Tseng, Y.-h. (2017). A box model for representing estuarine physical processes in Earth system models. *Ocean Modelling*, *112*, 139–153. https://doi.org/10.1016/j.ocemod.2017.03.004

Tseng, Y.-H., Bryan, F. O., & Whitney, M. M. (2016). Impacts of the representation of riverine freshwater input in the community earth system model. *Ocean Modelling*, *105*, 71–86. https://doi.org/10.1016/j.ocemod.2016.08.002

Voldoire, A., Sanchez-Gomez, E., Salas yMélia, D., Decharme, B., Cassou, C., Sénési, S., et al. (2013). The CNRM-CM5.1 global climate model: Description and basic evaluation. *Climate Dynamics*, *40*(9-10), 2091–2121. https://doi.org/10.1007/s00382-011-1259-y

Yankovsky, A. E., & Chapman, D. C. (1997). A simple theory for the fate of buoyant coastal discharges. *Journal of Physical Oceanography*, *27*(7), 1386–1401. https://doi.org/10.1175/1520-0485(1997)027<1386:ASTFTF>2.0.CO;2

Yaremchuk, M. (2006). Sea surface salinity constrains rainfall estimates over tropical oceans. *Geophysical Research Letters*, *33*, L15605. https://doi.org/10.1029/2006GL026582

Yu, L. (2011). A global relationship between the ocean water cycle and near-surface salinity. *Journal of Geophysical Research*, *116*, C10025. https://doi.org/10.1029/2010JC006937

Zweng, M. M., Reagan, J. R., Antonov, J. I., Locarnini, R. A., Mishonov, A. V., Boyer, T. P., et al. (2013). World Ocean Atlas 2013, volume 2: Salinity. In S. Levitus (Ed.), Mishono,. A. Technical*NOAA Atlas NESDIS 74*, (p. 39). Silver Spring, MD: National Oceanographic Data Center. http://data.nodc.noaa.gov/woa/WOA13/DOC/woa13_vol2.pdf/