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Key Points:

- Parameterization of kinetic energy backscatter reduces the North Atlantic sea surface temperature (SST) biases
- The SST response to backscatter is attributed to the effect of backscatter in different regions
- Roles of backscatter in strengthening resolved currents versus improving eddy physics are accordingly discussed

Supporting Information:
Supporting Information may be found in the online version of this article.

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Remote Versus Local Impacts of Energy Backscatter on the North Atlantic SST Biases in a Global Ocean Model

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Abstract The use of coarse resolution and strong grid-scale dissipation has prevented global ocean models from simulating the correct kinetic energy level. Recently parameterizing energy backscatter has been proposed to energize the model simulations. Parameterizing backscatter reduces long-standing North Atlantic sea surface temperature (SST) and associated surface current biases, but the underlying mechanism remains unclear. Here, we apply backscatter in different geographic regions to distinguish the different physical processes at play. We show that an improved Gulf Stream path is due to backscatter acting north of the Grand Banks to maintain a strong deep western boundary current. An improved North Atlantic Current path is due to backscatter acting around the Flemish Cap, with likely an improved nearby topography-flow interactions. These results suggest that the SST improvement with backscatter is partly due to the resulted strengthening of resolved currents, whereas the role of improved eddy physics requires further research.

Plain Language Summary Global ocean models often suffer from a lack of kinetic energy, and energy backscatter is a relatively new method designed to put kinetic energy back into the resolved flow field. It is also found to help better simulate the surface temperatures in the North Atlantic Ocean, which strongly affect the weather and climate in eastern North America and Europe but are often poorly represented by numerical simulations. Why models struggle with getting these temperatures right remains unclear, so it is important to determine mechanistic reasons for why backscatter can reduce the problem. In this study, we find that the global impact of backscatter can be separated into individual parts for different ocean regions. This regional separation of the impacts allows us to pin down the key ocean regions that give us the source of improvement and compare the roles of different ocean physical processes emphasized in previous studies. Our results point to the importance of backscatter in strengthening the resolved currents, and a need to better understand the role of eddies and their response to backscatter in the key regions identified.

1. Introduction

Current eddy-permitting ocean climate models lack the resolution to properly simulate the ocean kinetic energy level (e.g., Hewitt et al., 2020; Zanna et al., 2018), and kinetic energy backscatter is an emerging class of parameterization acting to direct the kinetic energy that is lost by grid-scale dissipation back to the resolved flows. Physically, it can be representing the collective effects of the unresolved mesoscale eddy momentum fluxes responsible for the inverse energy cascade. Alternatively, it can be interpreted to account for the implicit overdissipation due to the inaccuracy of numerics and to thus increase effective grid resolution (e.g., Danilov et al., 2019, and references therein). A common strategy to implement it in models is to use an antiviscosity term in the momentum equation, and its strength is usually modulated by grid-scale dissipation via hyperviscosity to ensure their combined use retains numerical stability. Despite different formulations, various backscatter schemes have been demonstrated to promisingly energize idealized ocean simulations (Jansen & Held, 2014; Jansen et al., 2015; Juricke et al., 2019; Klöwer et al., 2018).

Juricke, Danilov, Koldunov, Oliver, and Sidorenko (2020) recently implemented a backscatter scheme in an eddy-permitting global ocean model and showed that backscatter not only increases overall kinetic energy but also reduces long-standing sea surface temperature (SST) biases in the North Atlantic. These SST biases (see e.g., Figure 1f here), which consist of a pair of regional cold and warm biases, are associated with the inaccurate simulation of the Gulf Stream and North Atlantic Current (NAC) locations. The strip of the warm bias along the

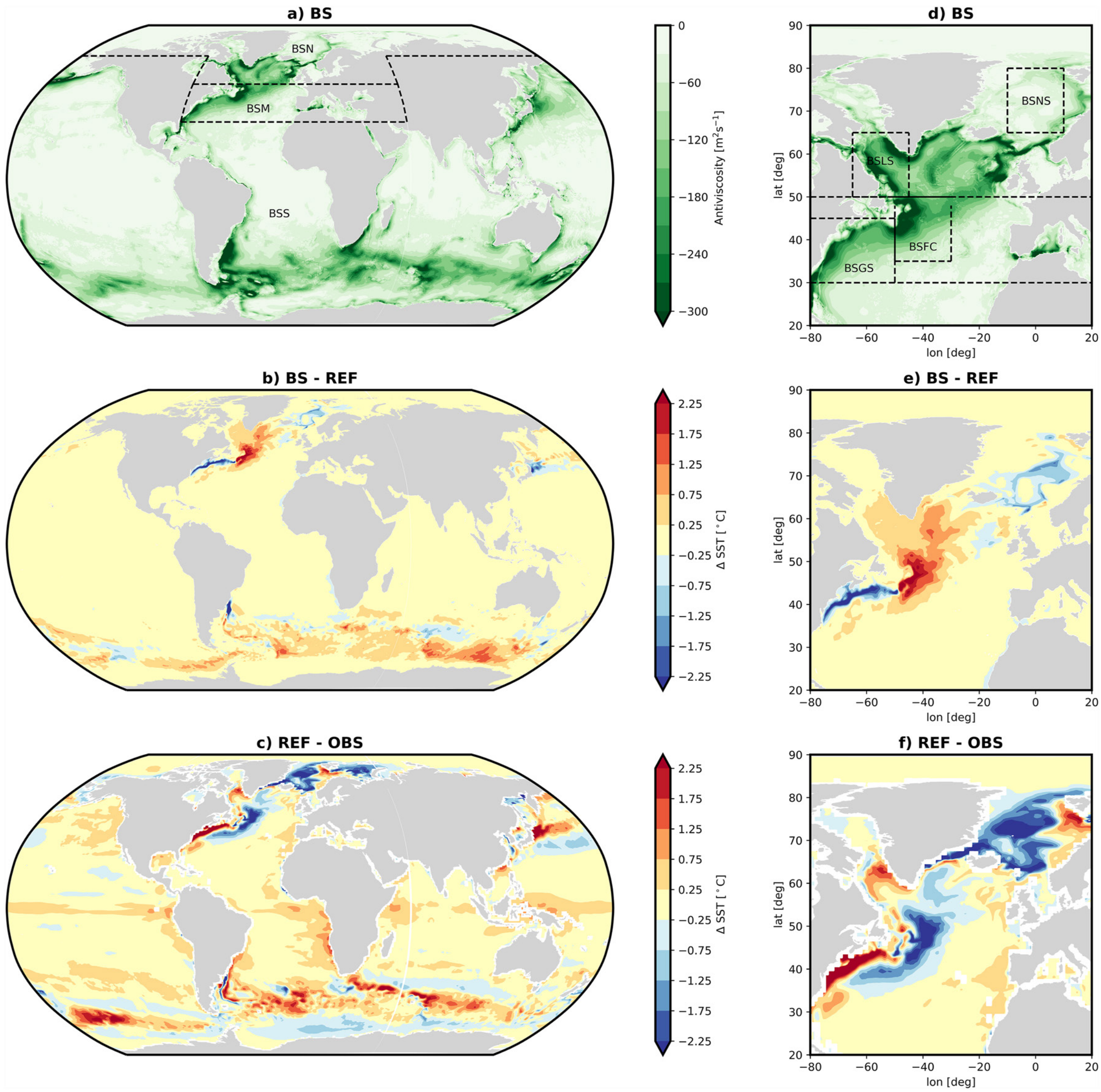

Figure 1. Backscatter and its effects on the simulated SST: (a) the Laplacian antiviscosity at 2.5 m in the BS simulation, (b) the SST response of the BS simulation with respect to the REF simulation, and (c) the SST bias in the REF simulation when compared with the observations (OBS). (d)–(f) as in (a)–(c), but for the North Atlantic only. The dashed lines in (a) separate the global domain into three subdomains, which define the BSN, BSM, and BSS simulations. The dashed lines in (d) mark the boundaries for BSM, BSGS, BSFC, BSLS, and BSNS simulations (Table S1 in Supporting Information S1). The notation Δ indicates the difference.

eastern North American coast is due to a lack of separation of the Gulf Stream from the coast, and the patch of the cold bias located east of the Flemish Cap is due to a lack of northward turn of the NAC around the southern tip of the Grand Banks. These biases have persisted across generations of coupled and ocean-only models, continuing to present challenges for climate model development (e.g., Bryan et al., 2007; Chassignet et al., 2020; C. Wang et al., 2014; Drews et al., 2015; Moreno-Chamarro et al., 2022; Roberts et al., 2019; Smith et al., 2000).

Various hypotheses for what causes the models to poorly simulate these surface currents and thus SST have been proposed. Many studies argued that the two-way interactions of the Gulf Stream and NAC with the local processes and topography at Cape Hatteras, Grand Banks, and Flemish Cap are crucial for shaping the paths themselves. These processes include continental shelf waves, mesoscale eddies, and the deep flows generated by North Atlantic Deep Water (e.g., Bower et al., 2019; Mertens et al., 2014; Schoonover et al., 2017; Spall, 1996; Stern, 1998; Tansley & Marshall, 2000), which in turn can be affected by subgrid parameterizations and model numerics (Bryan et al., 2007; Chassignet & Marshall, 2008; Ezer, 2016). In contrast to the rich fine-scale local dynamics, some studies have argued for the ultimate control by the basin-scale vertically-integrated vorticity balance and emphasized the bottom vortex stretching effect generated by the deep flows to the north. To the extent that there is limited feedback from the surface currents to the deep flows, the surface biases are then presumably set by the properties of deep flows, which is in turn determined by remote processes (e.g., Greatbatch et al., 1991; Yeager & Jochum, 2009; Zhang et al., 2011; Zhang & Vallis, 2007).

Translating our incomplete understanding into actual practices for bias reduction is difficult, and the most promising strategy so far remains simply refining the horizontal resolution. Since resolution refinement potentially affects all the processes proposed in the previous work, it helps to improve simulations but does little to enhance a process-level understanding. The newly identified SST sensitivity to backscatter opens up an opportunity to tackle the problem by introducing an alternative research tool. So long as backscatter truly acts to refine the effective resolution, it is expected to improve SST simulations analogous to refining the actual resolution. Furthermore, as we show in this study, backscatter can bring us a step closer to identifying the mechanisms given that the impact of backscatter on SST is approximately local. Hence, regionally decomposing the impact of backscatter on SST allows us to infer whether it acts via local interactions between the flows and local processes, or via remote modification of the flows.

To provide confidence in the SST bias reduction with refining resolution and backscatter, determining whether the underlying mechanisms operate locally or remotely is a step toward a full understanding of the working of these mechanisms. Here, we first confirm the robustness of backscatter in reducing the North Atlantic SST biases as well as leading to changes in simulated North Atlantic climate that resembles finer resolutions. Next, we systematically turn on the backscatter parameterization in selective geographic regions that are hypothesized as potentially key regions for the bias formation to examine the corresponding SST response. Finally, with a comparison of the previous studies, we draw on these findings to discuss the relative role of mean deep currents and mesoscale eddies in shaping the North Atlantic SST response to backscatter and propose next steps forward.

2. Impacts of Backscatter on the Surface Climate and Interior Circulation

We use the GFDL 1/4° OM4 global coupled ice-ocean model with the identical configuration to Adcroft et al. (2019) as our reference simulation (REF), which has a biharmonic grid-scale viscosity. In the other simulations, backscatter is additionally included as a Laplacian antiviscosity following Jansen et al. (2019). A vertically-integrated subgrid-scale kinetic energy is used to determine the horizontal structure of antiviscosity, and the same value is applied on all depths. All simulations are coupled ice-ocean runs initialized from the observed hydrography and integrated from 1958 to 1997 using atmospheric reanalysis as prescribed forcing. All results present are the time average of 1978–1997 (see Text S1 in Supporting Information S1 for more details).

We first look at the impacts of backscatter by comparing the REF simulation with a simulation where backscatter is turned on globally (BS). Backscatter, as indicated by antiviscosity, is generally stronger in the regions of high kinetic energy with climatologically strong resolved currents and eddy activity, including the Southern Ocean and western boundary currents (Figure 1a). Constrained by the local subgrid-scale budget, this reflects the fact that energy supplied by grid-scale dissipation of strong resolved flows is primarily scattered back locally.

While a locally strong backscatter is not always associated with a large local SST change (e.g., the Aleutian Arc), the impact of backscatter on the simulated SST is generally most pronounced in the Southern Ocean and the North Atlantic. It leads to an overall warming in the Southern Ocean with some embedded cooling patches forming dipole or tripole structures associated with the meridional shift of surface currents (Figure 1b). When compared to the observations from the reconstructed PCMDI SST data set (version PCMDI-AMIP-1.1.8 at http://esgf-node.llnl.gov/search/input4mips/), these SST responses only occasionally align with the model biases, suggesting that whether backscatter improves the Southern Ocean SST simulation varies with regions (Figure 1c).

Unlike the Southern Ocean, the backscatter induced SST change in the North Atlantic, especially the Northwest corner, is more promising as it largely projects onto the existing model biases. A cold response along the coast of eastern US marks the correction of the warm SST bias associated with the lack of Gulf Stream separation, and a warm response centered around east of the Flemish Cap and extending to the Irminger Sea marks the correction of the cold SST bias associated with the northward extension of the NAC (Figures 1e and 1f). These results are very similar to the 1/4° FESOM2 model results of Juricke, Danilov, Koldunov, Oliver, and Sidorenko (2020) (cf. their Figure 5i), indicating the robustness against details of the model and backscatter parameterization (see also Text S2 in Supporting Information S1).

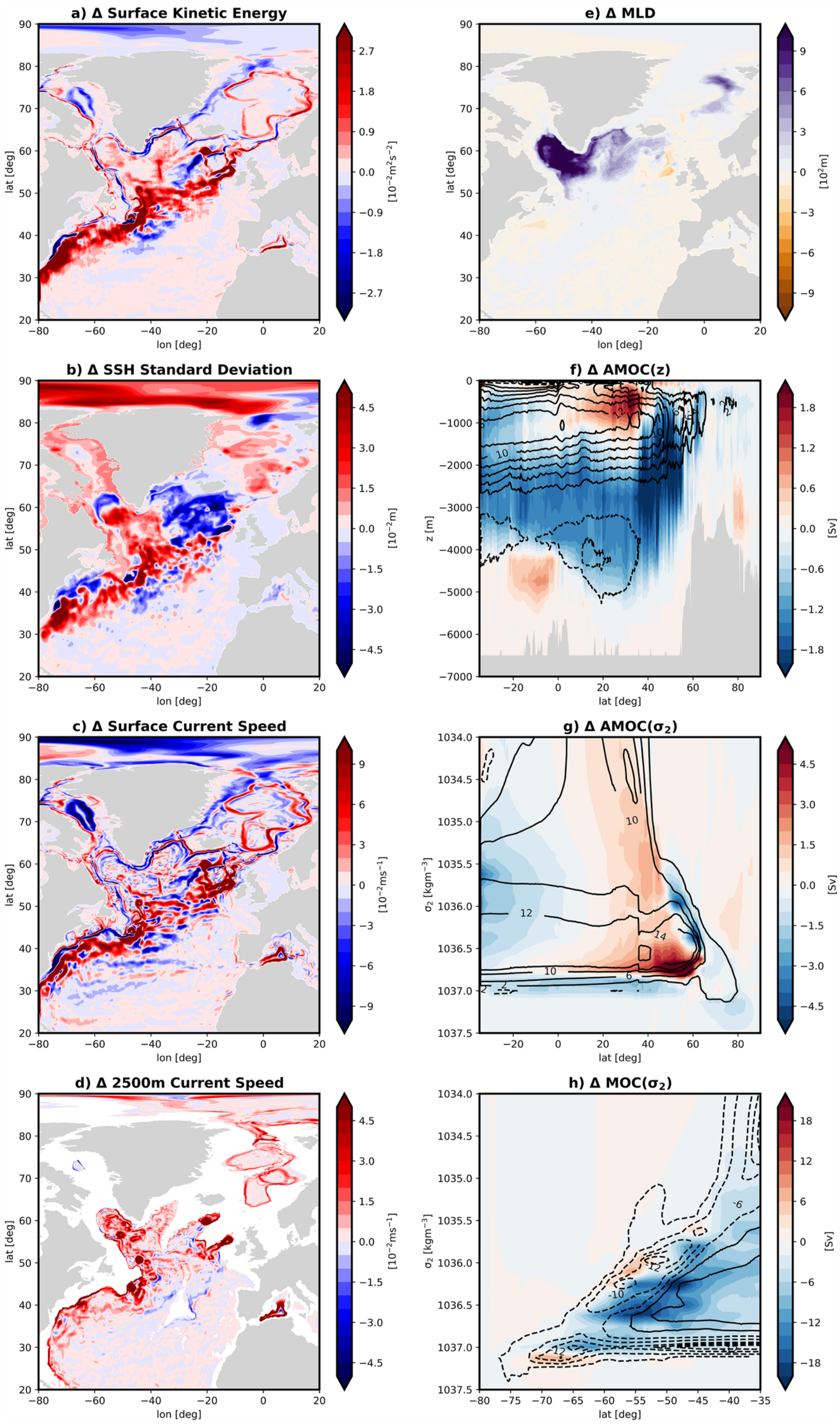

Figure 2. Effects of backscatter on the simulated surface climate and ocean circulation in the North Atlantic: response of (a) surface kinetic energy, (b) standard deviation of daily mean sea surface height (SSH), (c) surface 20-year mean current speed, (d) 20-year mean current speed at 2,500 m, (e) MLD, (f) AMOC in the depth coordinate, (g) AMOC in the density coordinate (potential density referenced to 2000db, σ_2), and (h) global meridional overturning circulation in the σ_2 coordinate, in the BS simulation with respect to the REF simulation (shading). In (f)–(h), the contours show the circulation in the REF simulation.

Along with a reduction in the North Atlantic SST biases, backscatter also leads to changes in other large scale surface fields that are generally seen with refined resolution. Specifically, it increases the simulated resolved surface kinetic energy (Figure 2a), which is contributed to by both a generally more vigorous transient eddy

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activity (Figure 2b) and stronger time-mean currents (Figure 2c). Notable location shift of the surface currents is also identified. The weakening of the mean currents and eddy activities extending from Cape Hatteras (35°N, 75°W) along the coastline to the north indicates the mean position of the Gulf Stream is located farther away from the coast. The weakening of the mean currents and eddy activities extending from where the Gulf Stream separates into the NAC and Azores Current (40°N, 45°W) into the east suggests the shift of the transport from the eastward Azores Current to the northward NAC.

In addition to the surface circulation, deep ocean flows change significantly with backscatter. As for the surface currents (Figure 2c), backscatter strengthens the deep western boundary current (DWBC) at most locations where it flows along the continental slope, from the Labrador Sea to the Florida Straits (Figure 2d). The strengthening of the DWBC is likely a combined result of less dissipation along its path as well as enhanced deep water formation in the Labrador Sea, as indicated by the deepening of the maximum monthly mean mixed layer depth (MLD; Figure 2e). Deeper MLD has also been found in other models when the resolution is refined in the eddy-permitting regime, despite enhancing existing model biases (Marzocchi et al., 2015; Talandier et al., 2014). Multiple processes, including eddy restratification and the preconditioning associated with surrounding boundary currents, are responsible for setting the Labrador Sea MLD, so its net response may be sensitive to competing effects (e.g., Rieck et al., 2019) and therefore dependent on model details (e.g., Treguier et al., 2023).

Another intriguing aspect of deep circulation responses to backscatter relates to the Atlantic Meridional Overturning Circulation (AMOC) changes, which have a complicated spatial structure. Despite the strengthening of the Gulf Stream, NAC, and DWBC (Figures 2c and 2d), the strengthening of the AMOC is confined between 20°N and 40°N and above 1,000 m when evaluated as the meridional overturning streamfunction zonally integrated at constant depth (Figure 2f). In contrast, a more general AMOC strengthening is seen when evaluated in density coordinates (Figure 2g). The difference appears to be associated with a change in the Northern Hemisphere AMOC pathways seen in finer resolution simulations (Hirschi et al., 2020). In the Southern Hemisphere, the AMOC weakens along with a strengthening of the abyssal overturning (Figure 2f). This change is a direct result of the stronger eddy-driven counterclockwise overturning in the Southern Ocean (Figure 2h) as backscatter energizes the Southern Ocean mesoscale eddies (Jansen et al., 2015). The hemispheric asymmetry of the AMOC response is somewhat different from the consistent AMOC strengthening across all latitudes found with resolution refinement (Roberts et al., 2020). A direct comparison may however be hindered by our short model integration, so the reason for the discrepancy remains unclear.

Taken together, these results indicate that backscatter generally leads to similar changes in the North Atlantic climate as seen for resolution refinement in eddy-permitting models. As discussed in the introduction, refined grid spacing can improve many physical processes together, making it difficult to distinguish their relative importance in controlling SST patterns. To the extent that these processes primarily operate in distinct geographic regions, we can use a regional mask to limit the backscatter effect to these regions. This motivates the regionally masked simulations discussed below.

3. Regional Decomposition

The extent to which the impact of backscatter on the SST can be linearly decomposed into the contributions from the different geographic regions is studied here. We compare the SST response in BS with three regionally masked simulations where backscatter is separately applied in the subpolar North Atlantic and Arctic (BSN), subtropical North Atlantic (BSM), and the rest of the globe (BSS) (see Figure 1a for the exact boundaries). The sum of the SST responses in these three simulations (Figures 3a–3c) recovers most of the SST response in the BS simulation (Figure 1e), with a residual appearing as a cold response south of the Newfoundland (45°N, 60°W) and a warm response in the southern Irminger Sea (55°N, 35°W) (Figure 3d). Additional simulations showed that the residual amplitude can be sensitive to the boundary chosen to separate the subpolar and subtropical simulations (Figure S2 in Supporting Information S1), pointing to some nonlocal interactions among the processes within the intergyre region. We consider this nonlinearity to be relatively moderate so a regional decomposition remains useful to distinguish the effects of backscatter from different regions. In the following, we discuss how these regionally masked simulations help shed light on the potential processes controlling SST response to backscatter.

We first discuss the cold response extending from south of the Grand Banks to Cape Hatteras, which seems to be contributed to by the effect of backscatter from multiple regions. Specifically, this response is seen in BSN and

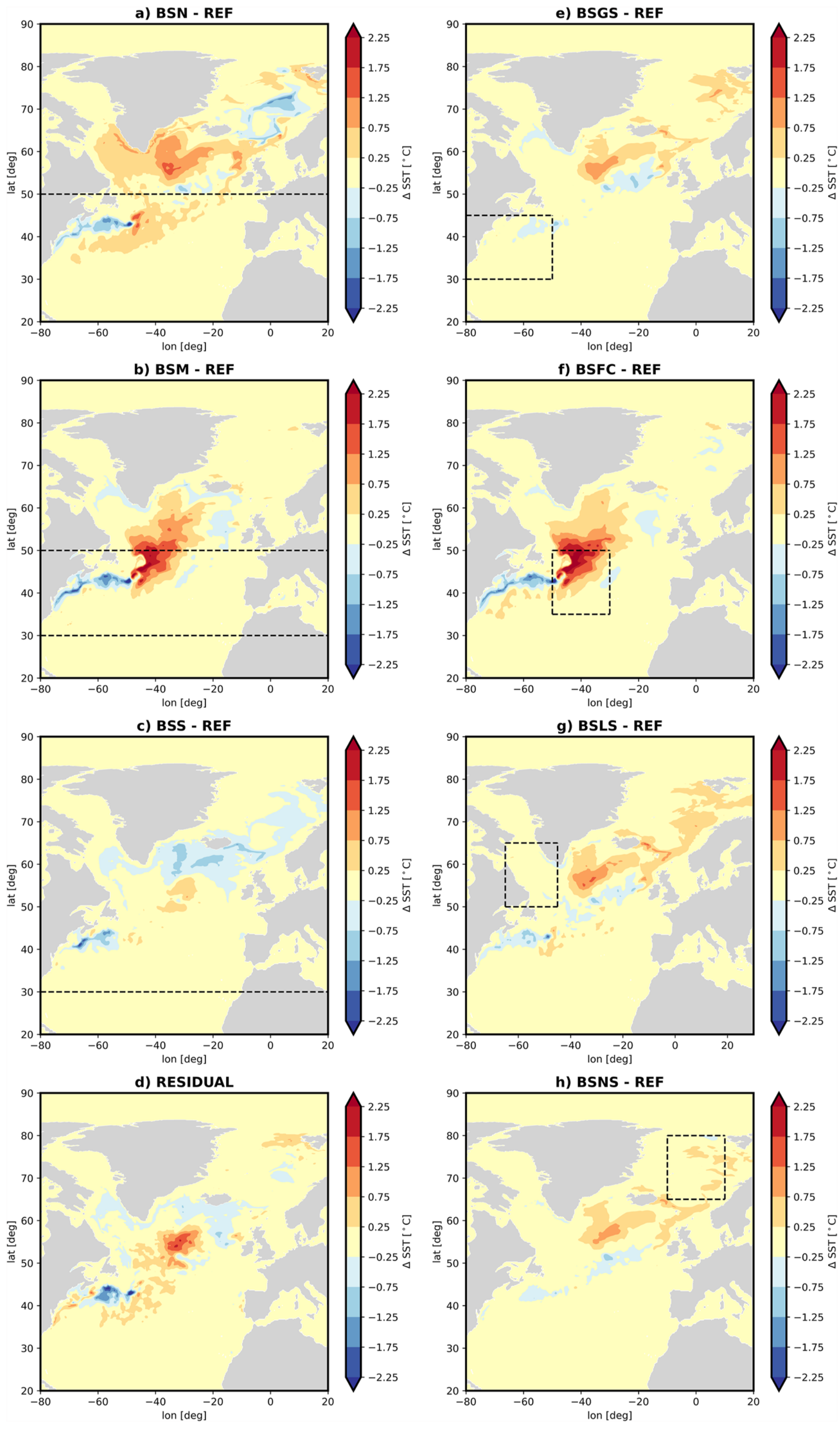

Figure 3. As in Figure 1e, but for the regionally masked backscatter simulations: (a) BSN, (b) BSM, (c) BSS, (e) BSGS, (f) BSFC, (g) BSLS, and (h) BSNS simulations. The dashed lines indicate the boundaries of the corresponding mask. The residual shown in (d) is the sum of SST responses in BSN, BSM, and BSS (i.e., (a)–(c)) subtracting the response in BS (i.e., Figure 1e).

BSM (Figures 3a and 3b), with less signal in BSS (Figure 3c). Comparing BSM with two additional simulations where backscatter is applied along the Gulf Stream path (BSGS; Figure 3e) and around the Flemish Cap (BSFC; Figure 3f) suggests that most of the backscatter effect in the subtropical region is dominated from the remote Flemish Cap region as apposed to its local effect on the Gulf Stream.

The BSN and BSFC simulations together support the hypothesis that this remote source of the cold SST response is the strengthening Northern Recirculation Gyre (NRG), which in turn results from a stronger DWBC (e.g., Greatbatch et al., 1991; Held et al., 2019; Yeager & Jochum, 2009; Zhang & Vallis, 2007). In a sensitivity study of a global ocean model, Zhang et al. (2011) showed that the North Atlantic SST biases can be improved by correcting the excess dilution of overflows in the Denmark Strait. A less diluted overflow forms a stronger DWBC and generates bottom vortex stretching when flowing down the continental slope along the Flemish Cap and Grand Banks, enhancing the cyclonic surface circulation east of the Flemish Cap as well as the NRG. They argued that these two anomalous circulations control the locations of nearby surface boundary currents, with the former leading to a westward shift of the NAC and the latter a southward shift of the Gulf Stream.

Both the BSN and BSFC simulations have backscatter applied along the path of DWBC before it reaches the southern tip of the Grand Banks. This feature helps to reduce dissipation experienced by the DWBC and maintains its strength (Figures 4a and 4f). A stronger DWBC then leads to a stronger NRG and southward Gulf Stream shift, and a cold SST response, consistent with the mechanism proposed by Zhang et al. (2011). The downstream DWBC also strengthens along the northeastern continental slope, which can contribute to the NRG strengthening as well. However, this effect is minor since the same appears in the BSGS simulation (Figure 4e), where little SST change is seen (Figure 3e). In the BSGS simulation, the DWBC indeed becomes slightly stronger in the upstream regions, but this nonlocal influence of backscatter is limited in affecting SST.

In addition to making the DWBC less dissipative, we also investigate whether backscatter can affect the DWBC strength by changing the deep water formation, as indicated by the MLD changes (Figure 2e). When we isolate backscatter to the Labrador Sea (BSLS), a cold response is indeed seen which hints at some role of the Labrador Sea convection on the SST response via changing the DWBC (Figures 3g and 4g). On the other hand, the effect of backscatter on the deep water formation in the Nordic Sea appears to play a negligible role (BSNS; Figures 3f and 4f). Along with little improvement on the simulated depth of DWBC (Figure S3 in Supporting Information S1), backscatter unfortunately does not correct the model deficiency in not generating dense enough overflows that is also responsible for the associated model biases (see discussion in Zhang et al. (2011)).

Unlike the cold response, the warm response east of the Flemish Cap in our simulations is not solely controlled by the changing strength of the DWBC as proposed by Zhang et al. (2011). This warm response is primarily attributed to the local effect of backscatter around the Flemish Cap, since it is seen in BSFC (Figure 3f) but not BSN, where backscatter is applied in the north (Figure 3a). An investigation of the deep current speed in BSN and BSFC confirms that the deep flows become stronger around Flemish Cap and Grand Banks in both cases, despite less in BSN than BSFC (Figures 4a and 4f). This result prompts the question why the deep flow response translates to the surface response in one case but not the other. Recall that in Zhang et al. (2011)'s argument, the shift of NAC involves the formation of an anomalous surface cyclonic circulation east of the Flemish Cap, which is associated with enhanced bottom vortex stretching when stronger deep currents flow down the continental slope. It is possible that the deep flows in the BSN simulation strengthen but generally become more aligned with bottom topography, which in turn weakens vortex stretching and the associated impact on surface circulation.

In addition, changes of bottom vortex stretching can be connected to surface circulation changes only when the associated bottom pressure torque is the dominant term in the vertically-integrated vorticity balance. Diagnosis of the vorticity budget by Y. Wang et al. (2017) using high resolution simulations suggested that the primary balance between the bottom pressure torque and planetary vorticity advection is satisfied for NRG but not the circulation east of the Flemish Cap and Grand Banks. For the latter, bottom pressure torque is largely compensated by inertial and eddy terms. How these extra terms respond to backscatter is unclear due to the limited understanding of the dynamics governing the flows in these regions. More likely, the nontrivial vorticity balance is a manifestation of intricate relationships and feedbacks among the NAC, eddies, deep currents, and bathymetry collocated here, making it conceptually difficult to attribute the shift of the NAC simply to the strengthening of the deep flows. Nonetheless, the result that having backscatter act locally around the Flemish Cap is a promising way to recover the warm SST response, and confirms the importance of local processes.

4. Conclusions

To study the impacts of backscatter on the North Atlantic SST biases, we investigate a series of eddy-permitting global ocean model simulations with various setups of a backscatter parameterization. Consistent with previous

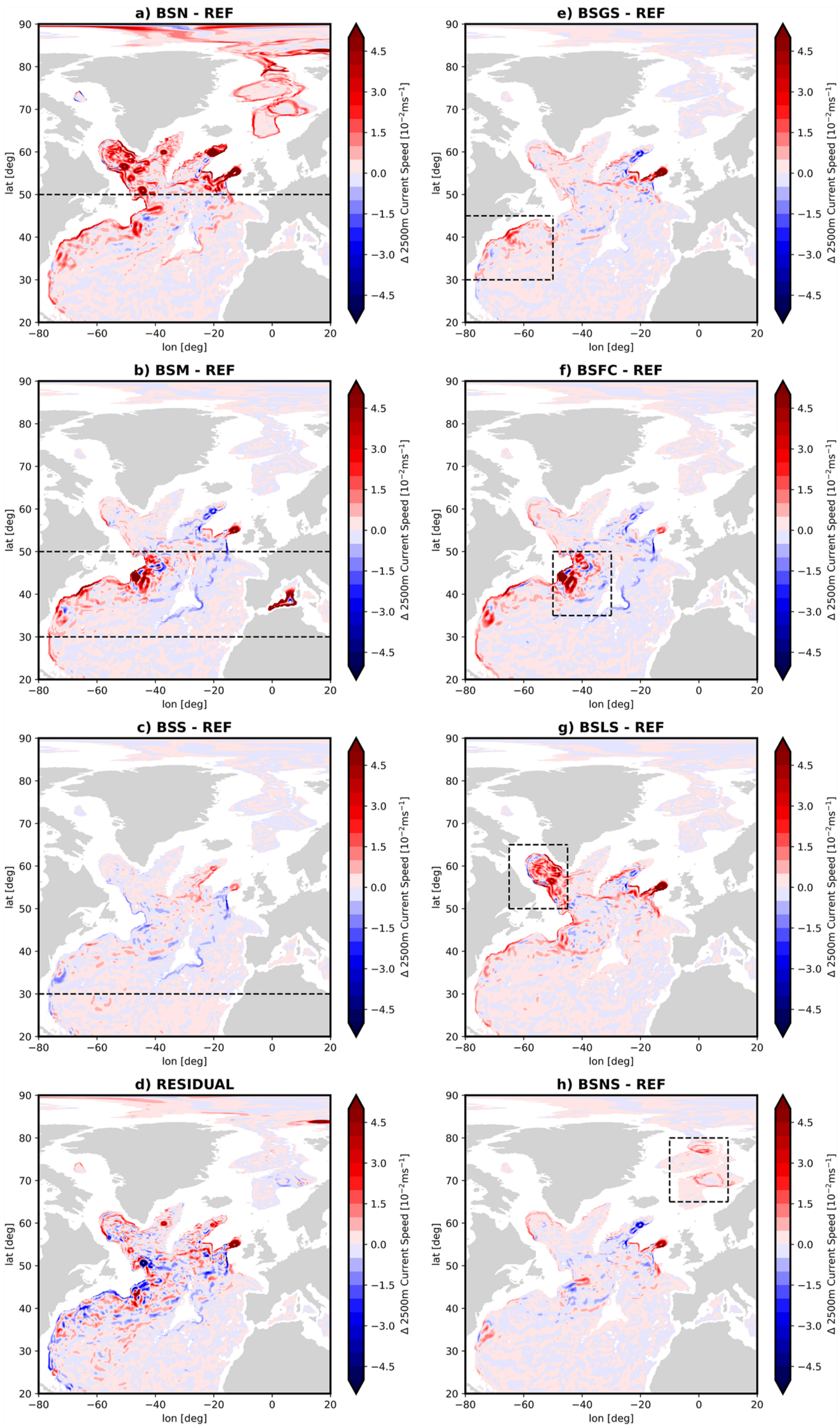

Figure 4. As in Figure 3, but for the 20-year mean current speed at 2,500 m.

work, we find that having backscatter acting globally leads to a promising reduction in the North Atlantic SST biases and generally makes the simulated North Atlantic surface climate and interior circulation look similar to what we expect from finer resolution simulations. Additional simulations where backscatter is applied in selective geographic regions help distinguish the dynamics underlying the warm SST bias along the northeastern coast versus the cold SST bias east of Flemish Cap. We find that the warm bias is affected by backscatter in remote regions but insensitive to the local backscatter, and vice versa for the cold bias. Compared with the mechanisms proposed by earlier studies, our results indicate that the warm bias is more readily attributed to the model deficiency in simulating the strength of DWBC, while the origin of the cold bias remains to be understood but is likely to do with its nearby topography-flow interactions. The key implication of our results are therefore two-fold. First, the reason why backscatter reduces the North Atlantic SST biases in our simulations is partly due to its strengthening of resolved currents. Second, the role of mesoscale eddies around the Flemish Cap is potentially important and needs to be better clarified.

Our ability to mechanistically understand the role of mesoscale eddies in setting North Atlantic SST patterns is fundamentally limited by our understanding of how backscatter modifies the resolved eddies and how eddies shape circulation in the North Atlantic. Existing studies of mesoscale eddy parameterizations have focused on idealized models with zonally reentrant channel and/or double-gyre configurations, which incorporate Southern Ocean and/or gyre dynamics only (e.g., Jansen et al., 2019). However, our results suggest that a model suitable for studying their impacts on the North Atlantic surface boundary currents should capture their interactions with interior flows and bottom bathymetry around Flemish Cap and Grand Banks. Given the robust North Atlantic sensitivity to backscatter, a mindful design and investigation of a North Atlantic process-oriented model would benefit the future parameterization development (e.g., Le Bras et al., 2018; Stewart et al., 2021). It would also grant us with a better theoretical and diagnostic framework to study the underlying dynamics in these regions critical to climate changes (e.g., Buckley & Marshall, 2016).

Relative to its use for energizing eddies, the strengthening of mean boundary currents with backscatter in our results is perhaps more easily justified by its undoing of numerical overdissipation on these currents. In this sense, the use of backscatter would improve the simulations even if it is designed to improve only the numerics with limited reference to eddy dynamics, as has also indicated by Juricke, Danilov, Koldunov, Oliver, Sein, et al. (2020). To account for the lack of resolution and energy, various competing ideas sharing the same reasoning like stochastic and gradient models have also been proposed (e.g., Porta Mana & Zanna, 2014; Jansen & Held, 2014; Anstey & Zanna, 2017, and references therein). Conducting a similar process-level analysis on the North Atlantic SST simulations with these alternative approaches would help verify the above hypothesis and rationalize their use in global ocean models.

Data Availability Statement

The data and scripts used to generate the figures are available at the Zenodo repository, Chang et al. (2023).

Acknowledgments

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