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Key Points:
- Dynamical downscaling enhances decadal prediction skill of Northwest Atlantic Shelf sea surface temperatures
- A temporary respite from rapid Northwest Atlantic Shelf warming is forecast for the coming decade
- The forecast warming pause is attributed to a modest strengthening of the Atlantic meridional overturning circulation

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

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A Predicted Pause in the Rapid Warming of the Northwest Atlantic Shelf in the Coming Decade

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Abstract The capability to anticipate the exceptionally rapid warming of the Northwest Atlantic Shelf and its evolution over the next decade could enable effective mitigation for coastal communities and marine resources. However, global climate models have struggled to accurately predict this warming due to limited resolution; and past regional downscaling efforts focused on multi-decadal projections, neglecting predictive skill associated with internal variability. We address these gaps with a high resolution (1/12°) ensemble of dynamically downscaled decadal predictions. The downscaled simulations accurately predicted past oceanic variability at scales relevant to marine resource management, with skill typically exceeding global coarse-resolution predictions. Over the long term, warming of the Shelf is projected to continue; however, we forecast a temporary warming pause in the next decade. This predicted pause is attributed to internal variability associated with a transient, moderate strengthening of the Atlantic meridional overturning circulation and a southward shift of the Gulf Stream.

Plain Language Summary The Northwest Atlantic Shelf is experiencing a rapid rise in ocean temperatures, one of the fastest globally, impacting the region's marine resources. Global coupled models struggle to accurately simulate this regional warming and have large uncertainties associated with the future evolution of this warming. To address this issue, we developed a high-resolution decadal prediction system for the Northwest Atlantic Shelf which downscales global decadal predictions using a high-resolution regional ocean model. The downscaled simulations accurately predict past oceanic variability and forecast a temporary pause in warming over the next decade due to natural changes in the Atlantic meridional overturning circulation and the position of the Gulf Stream. This predictive capability could pave the way for the implementation of effective mitigation strategies, benefiting coastal communities and marine resources alike.

1. Introduction

The Northwest Atlantic (NWA) Shelf has warmed rapidly in recent decades (Z. Chen et al., 2020; Forsyth et al., 2015; Pershing et al., 2015). This warming has had severe impacts on marine ecosystems and coastal communities (Mills et al., 2013; Pershing et al., 2015). Understanding the drivers of this warming and predicting whether it will continue is thus important for mitigating or adapting to future impacts.

Changes in ocean circulation patterns have strengthened radiatively-forced warming trends associated with accumulating greenhouse gases to generate the rapid warming. Such changes include weakening of the Atlantic meridional overturning circulation (AMOC) (Caesar et al., 2018; Saba et al., 2016), shifting of the jet stream position (K. Chen et al., 2014), enhanced Gulf Stream eddy shedding (Gangopadhyay et al., 2019), variability associated with the North Atlantic Oscillation (Karmalkar & Horton, 2021), and northward migration of the Gulf Stream and associated water mass exchanges (Brickman et al., 2018; Gonçalves Neto et al., 2021; Seidov et al., 2021). These features are poorly represented in coarse resolution global models, which also struggle to capture the rapid warming of the Northwest Atlantic. High resolution global coupled models (Saba et al., 2016) and regional ocean models (Alexander et al., 2020; Shin & Alexander, 2020) emphasize the importance of adequate representation of fine topography and shelf dynamics, such as the position of the Gulf Stream and mixing of water masses along the shelf break, in order to accurately represent the interaction of the basin-scale signals with the shelf.

Whether this rapid warming will continue, diminish or further accelerate in the coming decade is an important yet unexplored question, particularly for management of living marine resources (Melbourne-Thomas et al., 2023;

Mills et al., 2013). An understanding of decadal prediction skill for coast and shelf regions and its sources, including predictable forced change and internal variability, is critical to enable climate-informed decisions on this critical time horizon.

Here, we address this challenge by dynamically downscaling an ensemble of decadal predictions from a global prediction system using a regional 1/12° configuration of the Modular Ocean Model (MOM6) for the NWA ocean (see Section 2). We run a suite of retrospective ocean simulations and hindcasts to assess prediction skill and the sources of predictability. Comparison with the parent global prediction system allows us to distill the added value in dynamical downscaling. We show how basin-scale ocean circulation signals are transmitted onto the shelf differently in the regional and global prediction systems, resulting in substantially different sea surface temperature (SST) forecasts for the next decade.

2. Methods

We designed a 1/12 regional MOM6 ocean model of the Northwest Atlantic Ocean for decadal prediction (`MOM6_NWA12`) based on Ross et al. (2023). This model is forced at its surface and at the lateral open ocean boundaries (see Figure 1a) with data from `SPEAR_LO`, a coarse resolution global coupled model.

2.1. The SPEAR_LO Global Coupled Model

The Seamless System for Prediction and Earth System Research (SPEAR) is a modeling system for seasonal to multidecadal prediction and projection (Delworth et al., 2020). SPEAR consists of coupled atmosphere and land (Zhao et al., 2018), and ocean and sea ice (Adcroft et al., 2019) models. For decadal predictions, SPEAR was run in its low resolution (approximately 1.0° in the ocean) `SPEAR_LO` configuration (Yang et al., 2021).

2.2. The MOM6_NWA12 Regional Ocean Model

We downscaled the `SPEAR_LO` simulations using a 1/12° ocean and sea ice model of the Northwest Atlantic, `MOM6_NWA12` (Ross et al., 2023), The model uses a 75-layer z* vertical coordinate (Adcroft & Campin, 2004) and three open boundaries (Figure S1 in Supporting Information S1) using a Flather-Orlanski radiation boundary scheme. A detailed description of the model configuration and an extensive evaluation of various performance metrics are provided in Ross et al. (2023). The only modifications to `MOM6_NWA12` here were decreasing the front length scale governing restratification due to submesocale processes to 1,000 m and increasing the tidal self attraction and loading parameter to 0.05.

2.3. The MOM6_NWA12 Decadal Prediction System Design

To develop a high resolution analysis to initialize the downscaled decadal predictions, we forced the `MOM6_NWA12` model with daily atmospheric forcing (2 m temperature and humidity, sea level pressure, 10 m wind, surface precipitation and radiation) and monthly ocean boundary conditions (temperature, salinity, SSH, velocity) derived from the `SPEAR_LO`-based global coupled reanalysis (Yang et al., 2021). Each of the 10 members from the `SPEAR_LO` reanalysis was downscaled to obtain a 10-member ensemble of regional ocean simulations (hereafter `MOM6_NWA12`). All simulations were started on 1st January 1958 from `SPEAR_LO` ocean initial conditions. We don't use the first 7 years during which the high resolution model adjusts to the `SPEAR_LO` forcing.

2.4. Initialized Hindcasts

A downscaled 10-member ensemble of 10-year long retrospective predictions (hindcasts, hereafter `MOM6_NWA12_HIND`) was started every year on 1st January from 1965 to 2022. The ocean initial conditions for these decadal hindcasts were taken from the corresponding member of the `MOM6_NWA12` regional analysis, while the atmospheric forcing and open boundary conditions were taken from the corresponding member of the `SPEAR_LO`-based decadal hindcasts (hereafter `SPEAR_LO_HIND`). `SPEAR_LO_HIND` fields were not bias-corrected before downscaling to maintain dynamical consistency. A lead-year dependent mean bias was, however, removed from both the global and regional decadal hindcasts before analysis.

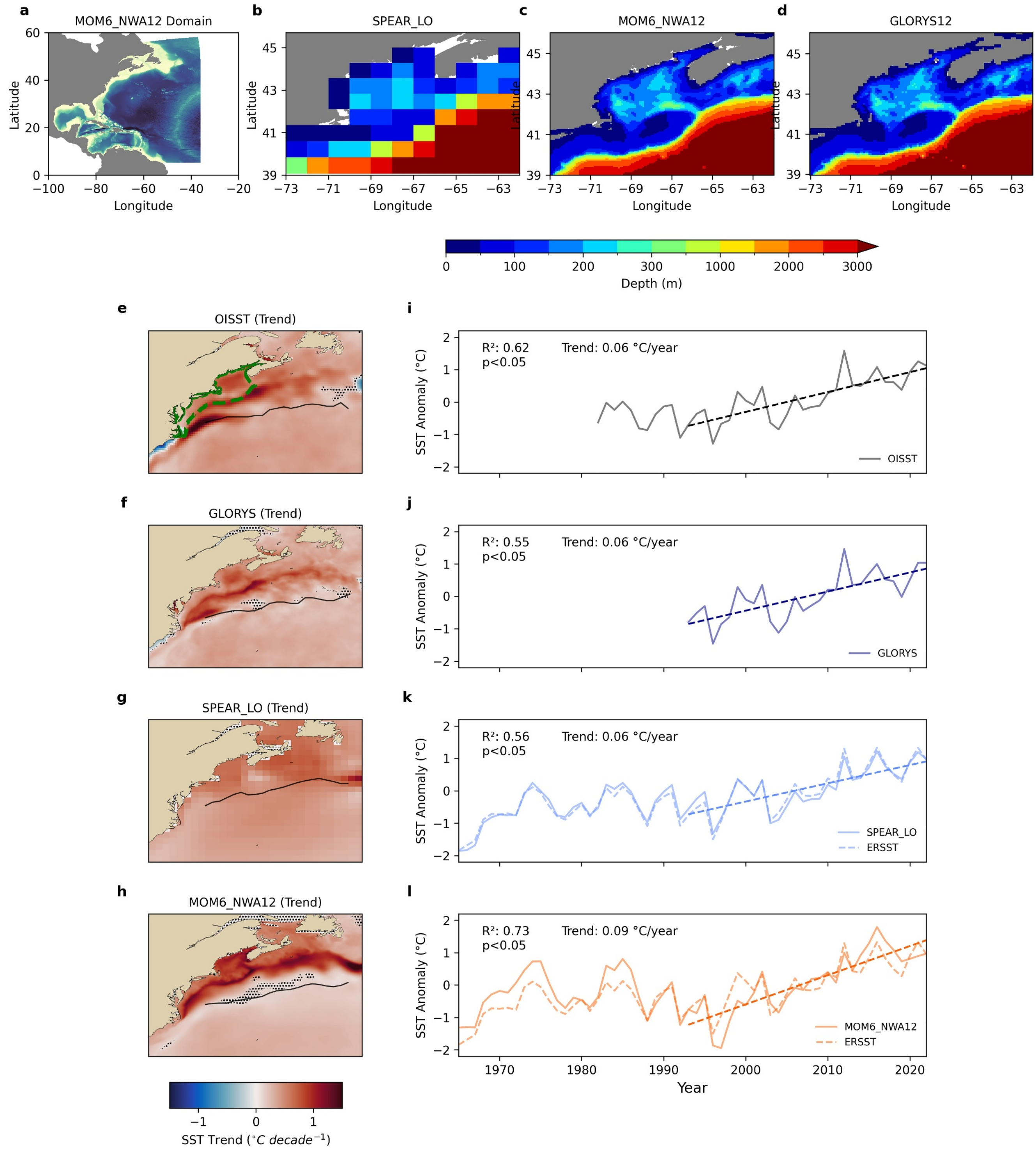

Figure 1. (a) The domain of the MOM6_NWA12 regional model and the bathymetry along the NWA Shelf in (b) SPEAR_LO, (c) MOM6_NWA12 and (d) GLORYS12. 30-year (1993–2022) linear trend in annual mean sea surface temperature (SST) anomalies from (e) NOAA_OISST, (f) GLORYS, (g) SPEAR_LO and (h) MOM6_NWA12. Black stippling denotes regions where the trend is not statistically significant at the 95% confidence level based on the Mann-Kendall test. The black line represents the mean position of the Gulf Stream in each data set (see Section 2; using satellite altimetry for e). (i–l) The time series of SST anomalies for the Northeast US large marine ecosystem (the region enclosed in the green dashed line segments in (e)) from (i) NOAA_OISST (j) GLORYS, (k) SPEAR_LO and (l) MOM6_NWA12. The dashed straight lines show the linear SST trend for the period 1993–2022.

2.5. Uninitialized Simulations

To quantify the forced climate change signal, we generated a 10-member ensemble of uninitialized ocean simulations (hereafter `MOM6_NWA12_HIST`) by dynamically downscaling the first 10 members of the 30-member ensemble of `SPEAR_LO` historical climate simulations (hereafter `SPEAR_LO_HIST`). The `SPEAR_LO_HIST` simulations cover 1850 to 2100 with future greenhouse gas concentrations from the SSP585 emissions scenario, noting that differences between climate change scenarios are minimal over the 10 years time horizon considered herein (Masson-Delmotte et al., 2021).

2.6. Forced Response and Internal Variability

We decomposed forecast SST anomalies into components representing the radiatively forced response and internal variability. The forced response is the ensemble mean of the SST anomalies (relative to 1982–2022) from the full 30-member `SPEAR_LO_HIST` uninitialized ensemble. The internal variability is the difference between the ensemble mean `SPEAR_LO_HIND` anomalies and the result of regressing the forced response against the ensemble mean `SPEAR_LO_HIND` anomalies. This definition of internal variability is based on the methodology outlined in Smith et al. (2019).

2.7. Verification Data Sets, Skill Metric and Its Uncertainty

Three observation-based gridded data sets were used to assess the quality of model simulations and the skill of decadal hindcasts: the Extended Reconstructed Sea Surface Temperature version 5 (ERSSTv5, Huang et al., 2017), the 1/4° Optimum Interpolation SST (OISST v2.1, Huang et al., 2021) and the 1/12° GLORYS12 v1 ocean reanalysis (Lellouche et al., 2018). We used anomaly correlation coefficients (ACC) to quantify the skill in predicting SST. The ACC of annual SSTs was assessed spatially and for area-averaged SST over two Large Marine Ecosystems (LMEs) and four Ecological Production Units (EPUs, NOAA Fisheries, 2022a, NOAA Fisheries, 2022b) shown in Figure 2 and Figure S1 in Supporting Information S1. In addition to the three gridded data sets, we also used the observed SST time series for the EPUs from NOAA's State of the Ecosystem reports (NOAA Fisheries, 2022a; NOAA Fisheries, 2022b).

The 90% confidence interval for the ACC skill was estimated using the percentile block-bootstrap approach with 1,000 samples (sampled with replacement) and a block length of 6 years. A simple persistence based skill, defined as the lagged autocorrelation of observed anomalies, is compared with the hindcast skill.

We also analyze ensemble spread, defined as the square root of the time mean intra-ensemble variance, and the root mean square error (RMSE) of the ensemble mean compared to OISST.

2.8. The Position of the Gulf Stream

We evaluated the mean and variability of the position of the Gulf Stream using a method developed by Pérez-Hernández and Joyce (2014) and applied by Ross et al. (2023). The mean position is defined as the latitude of highest sea surface height (SSH) variance along meridional lines spaced 1° apart between 72°W and 52°W. The Gulf Stream Index (GSI) measures variability in the position using the annual SSH anomaly (relative to the 1993–2021 mean) averaged over the points representing the mean position.

3. Results

The rapid surface warming of the NWA Ocean over the past 30 years is robust across observation-based data sets and models assessed in this study (Figure 1). OISST and `GLORYS` show the highest surface warming along the pathway of the Gulf Stream, close to its separation near Cape Hatteras, followed by the slope sea region (the oceanic region between the Gulf Stream and the continental shelf) and Gulf of Maine (Figures 1e and 1f, see also Z. Chen et al. (2020)). This spatial heterogeneity is under-represented in the low resolution `SPEAR_LO` global reanalysis but captured by the downscaled `MOM6_NWA12` regional ocean simulation (Figures 1g and 1h). Along the shelf, the warming trend over the Northeast US LME (`NEUS_LME`) is also robust across data sets and models (Figures 1i–1l), though it is overestimated by `MOM6_NWA12` (0.09°C/yr vs. 0.06°C/yr). The extended time series (Figures 1k and 1l) exhibits low frequency variations over the past six decades. For example, a period of cooling from the mid-1980s until the late 1990s was preceded by warming from 1960s to early 1980s and followed by rapid warming from the mid-1990s to the present.

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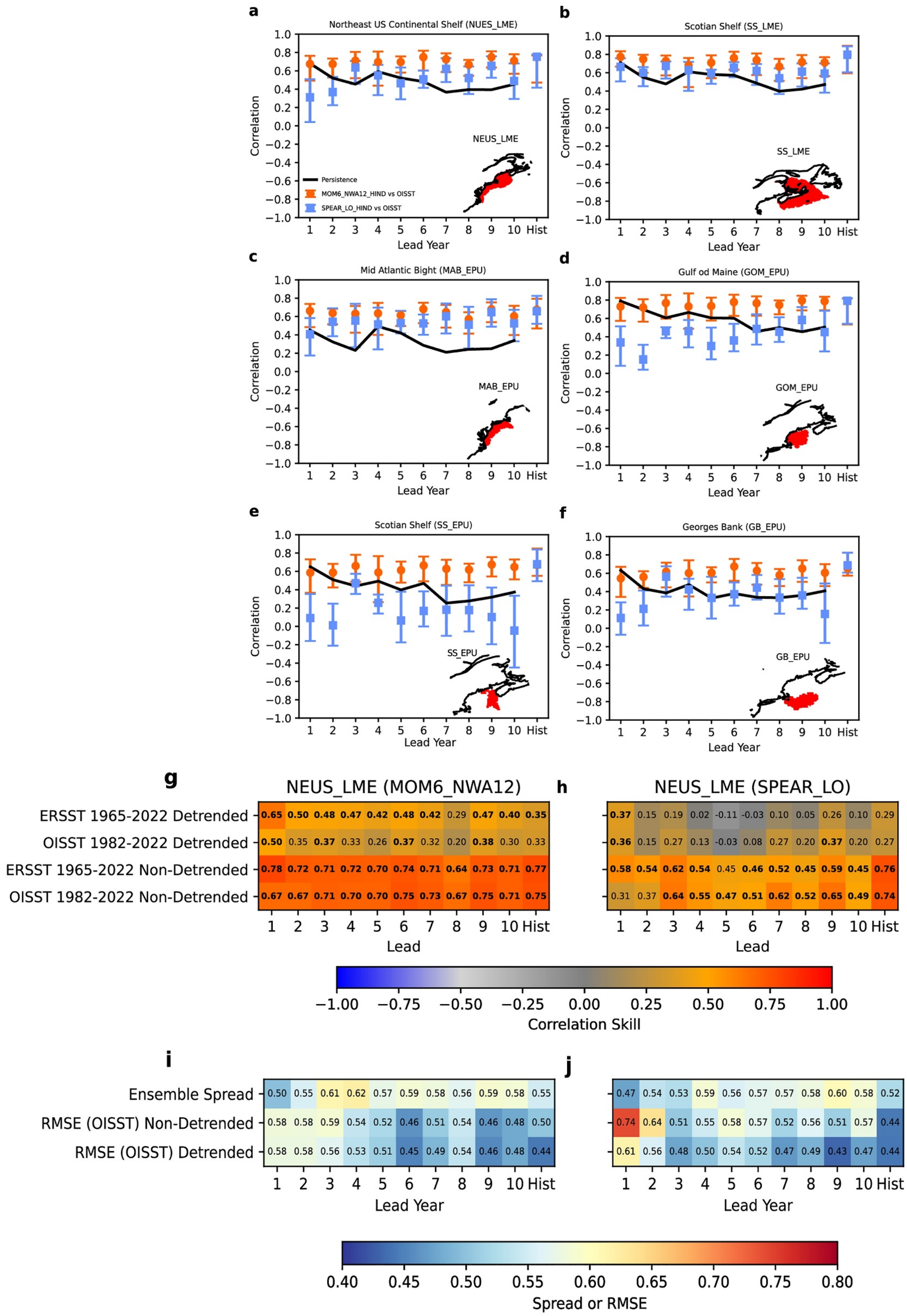

Figure 2.

SPEAR_LO_HIND predicted past variations of annual SST anomalies over the two large LMEs and the smaller EPUs (Figure 2) with skill exceeding persistence over most lead times. Over the larger LMEs, MOM6_NWA12_HIND generally has greater prediction skill than SPEAR_LO_HIND, although most confidence intervals overlap. Over the smaller EPUs of Gulf of Maine, Scotian Shelf and Georges Bank, the skill of MOM6_NWA12_HIND is often significantly greater than SPEAR_LO_HIND. MOM6_NWA12_HIND benefits from the improved bathymetry and reduced biases in the regional model (Figure 1 and Figure S1 in Supporting Information S1) as well as from the reduced drift upon initialization (Figure S2 in Supporting Information S1). The regional prediction skill is largely independent of lead time and not statistically different from the skill of the uninitialized historical predictions, suggesting external radiative forcing (due to greenhouse gasses, aerosols etc) as the primary source of prediction skill over the 1982–2022 OISST period. This is also true for the Northwest Atlantic domain where the skill is high (mostly away from the highly variable pathway of the Gulf Stream) in both initialized and uninitialized simulations (Figure S3 in Supporting Information S1).

Not surprisingly, in MOM6_NWA12_HIND and SPEAR_LO_HIND, prediction skill is considerably lower when the linear trend is removed (Figures 2g and 2h). The anomaly correlation, however, remains significant at the 90% level for several leads in MOM6_NWA12_HIND. The detrended prediction skill is higher if the time period of evaluation is extended to 1965–2022 using the coarser resolution ERSST data (which has similar correlation during the recent time period). Correlation coefficients often approach or exceed 0.5 at short leads in this case (Figures 2g and 2h and Figures S4 and S5 in Supporting Information S1). These values exceed those of the uninitialized forecasts, supporting a contribution from initialization that was masked during the recent period of persistent increase (see Figures S6 and S7 in Supporting Information S1 for the full 1965–2022 time series). The detrended skill in MOM6_NWA12_HIND generally exceeds SPEAR_LO_HIND (Figure 2), supporting the added value of dynamical downscaling.

The analysis of ensemble spread reveals similarities in both MOM6_NWA12_HIND and SPEAR_LO_HIND ensembles (Figures 2i and 2j). The spread/error ratio is generally around 1, although as the lead time progresses, both ensembles shift from being slightly underdispersive to slightly overdispersive. The SPEAR_LO_HIND ensemble displays a larger RMSE in comparison to MOM6_NWA12_HIND, especially when the trend is maintained in the time series. This suggests that both model ensembles reliably represent forecast error and uncertainty.

Selected hindcasts initialized on 1st January 1982 and 2010 (Figures 3a–3f) further illustrate the capacity of predictions to correctly anticipate periods of relatively stable SSTs (1982–1991) and periods of rapid warming (2010–2019). Individual ensemble members vary and SPEAR_LO_HIND exhibit significant deviations at the EPU-scale, but the ensemble means of SPEAR_LO_HIND and MOM6_NWA12_HIND correctly predict the contrasting temperature trends for these two periods, which raises our confidence in the ability of the models to predict future temperature trends.

The most recent forecasts, initialized on 1st January 2022, predict either a cooling (SPEAR_LO_HIND) or a stagnation of the warming (MOM6_NWA12_HIND) during the next decade over the study region (Figure 3). Every ensemble member within each model is consistent with the ensemble-mean prediction of cooling or stagnation. Both the SPEAR_LO_HIND and MOM6_NWA12_HIND forecast a southward shifted Gulf Stream in the coming decade (Figure 3g) which is consistent with the forecast cooling or stagnation of warming. The forecast of a southward shifted Gulf Stream is also consistent with the modest strengthening of the AMOC that is predicted in the coming decade (Figure 3h; see Section 4). Both SPEAR_LO and MOM6_NWA12 were able to predict past changes in the Gulf Stream position. The southward progression of the Gulf Stream in the 1990s as well as the northward shift from 2010 onward was correctly simulated by the analysis and decadal hindcast simulations of both models, which raises our confidence in both models' predictions of an upcoming southward shift.

Figure 2. Correlation skill of sea surface temperature anomalies from MOM6_NWA12_HIND (orange) and SPEAR_LO_HIND (blue) hindcasts at various lead years verified against NOAA_OISST for the period 1982–2022. "Hist" represents uninitialized simulation skill. Skill shown for six regions (a–f). Whiskers show 90% confidence interval. Black line is persistence skill from NOAA_OISST. Red regions indicate areas used for sea surface temperature averaging. (g) Correlation between MOM6_NWA12_HIND and NOAA_OISST for NEUS_LME, using raw and detrended time series. Panels (h) Same as (g) but for SPEAR_LO_HIND. Bold numbers are statistically significant at 90%. (i) Ensemble spread and root mean square error for MOM6_NWA12_HIND. Panels (j) Same as (i) but for SPEAR_LO_HIND.

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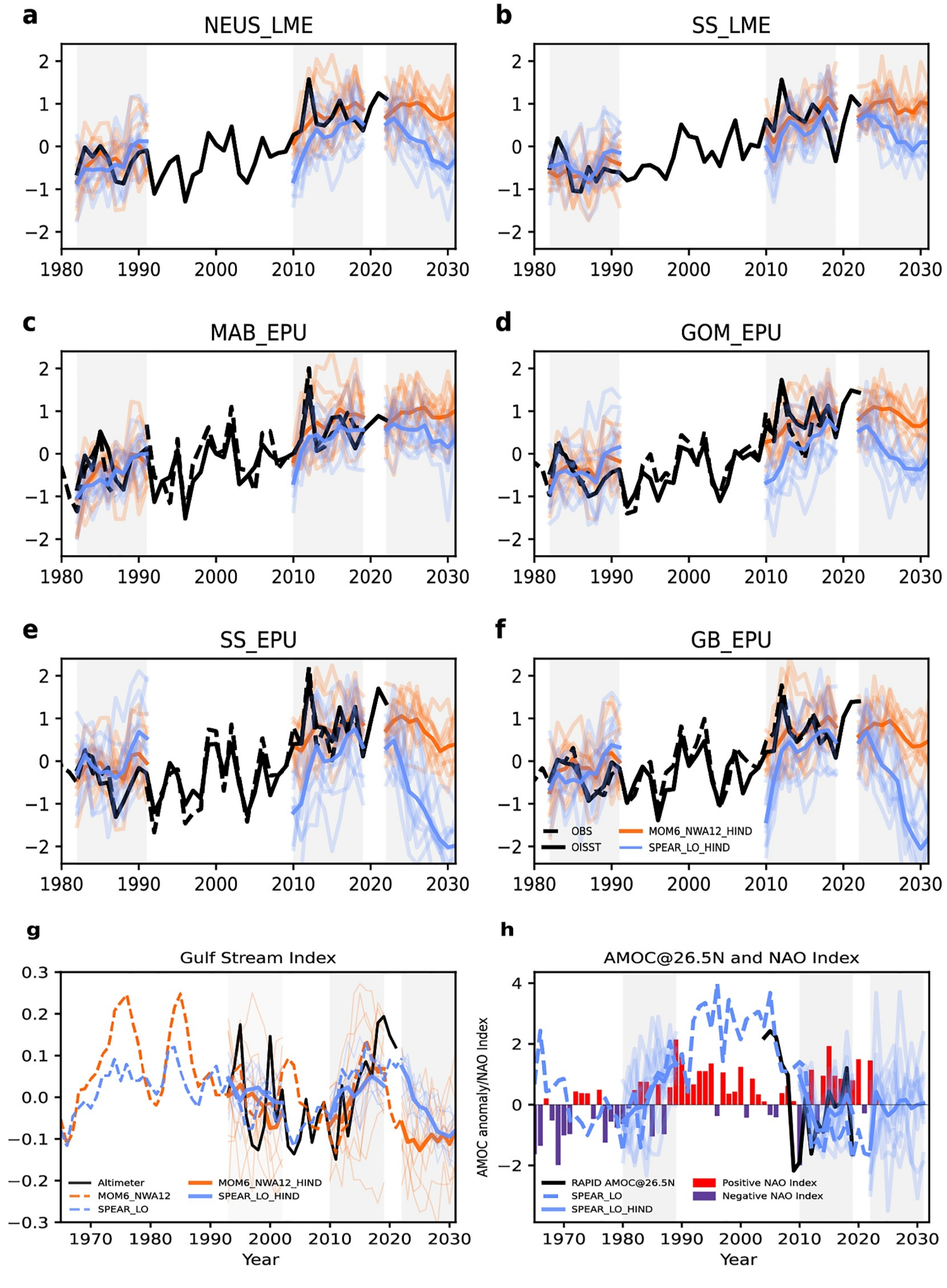

Figure 3. (a–f) Time series of observed sea surface temperature anomalies from NOAA_OISST (solid black) and NOAA Fisheries (2022a), NOAA Fisheries (2022b) (dashed black). Gray shades show periods of 10-year predictions from MOM6_NWA12_HIND (orange) and SPEAR_LO_HIND (blue) initialized on 1 Jan 1982, 2010 and 2022. Light lines are ensemble members, bold lines ensemble mean. Regions used are as in Figure 2. (g) Gulf Stream Index from altimeter (black), model reanalysis (dashed), and initialized hindcasts (solid). (h) Annual Atlantic meridional overturning circulation (AMOC) depth-max anomalies (Sv) at 26.5°N from 10-member SPEAR_LO reanalysis (dashed blue) and SPEAR_LO_HIND for 1980, 2010, 2022 initializations (members in light blue, mean in dark blue). RAPID AMOC (black) and standardized winter NAO index (bars, from https://www.cpc.ncep.noaa.gov/) also shown. Anomalies are with respect to 2005–2020 mean for AMOC, 1950–2023 for NAO.

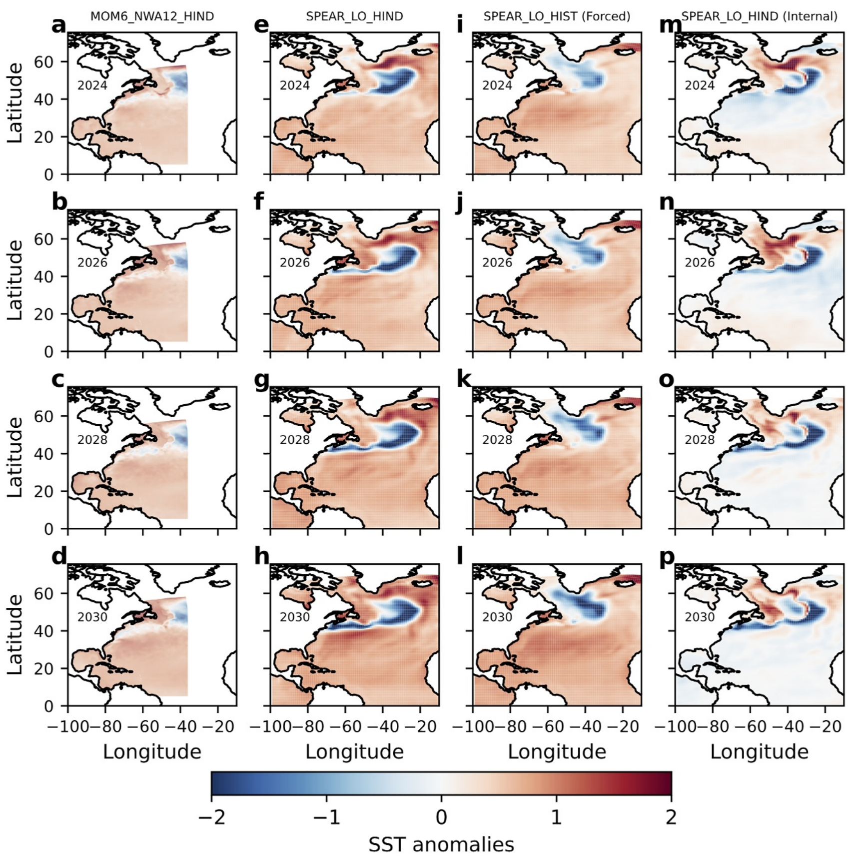

Figure 4. Forecast sea surface temperature (SST) anomalies from (a–d) `MOM6_NWA12_HIND`, (e–h) `SPEAR_LO_HIND`, (i–l) `SPEAR_LO_HIST`-based forced response and (m–p) Internal component of SST anomalies in `SPEAR_LO_HIND`.

The forecast cooling is spatially linked to a broad cooling pattern in the subpolar North Atlantic SSTs (Figure 4 and see Figure S8 in Supporting Information S1 for full 10-year forecast). Both models display a band of cool anomalies stretching from the subpolar North Atlantic to the Northwest Atlantic Ocean Shelf, intensifying and moving further west over time. Decomposing these forecast anomalies into external forcing and internal variability contributions indicates that the cool forecast anomalies in the subpolar North Atlantic result from external forcing, while the cool anomalies north of the Gulf Stream path and extending toward the shelf result from internal variability (Figure 4). In the regional model, these anomalies decrease in magnitude closer to the NWA Shelf.

Finally, we emphasize that the predicted pause in the rapid warming is a temporary feature driven by internal variability. Over the long term, warming is projected to continue under a high emissions scenario (Figure S9 in Supporting Information S1).

4. Discussion

A key challenge for predicting future Northwest Atlantic coastal ocean climate is sufficient representation of regional ocean features controlling the interaction of the shelf with basin-scale changes. We addressed this challenge by using the regional `MOM6_NWA12` ocean model to dynamically downscale a suite of ocean simulations from the `SPEAR_LO` global model. Over the next 10 years, the high resolution regional model, `MOM6_NWA12_HIND`, forecasts a pause in the rapid warming of the NWA Shelf which it inherits from the parent `SPEAR_LO_HIND` global model forecasts. However, the strong forecast cooling in the `SPEAR_LO_HIND` is damped in the `MOM6_NWA12_HIND`, which predicts that the SST will remain above the 1982–2022 average for most of the region.

Our results advance coastal ocean prediction capabilities by showing that SSTs over the LMEs and EPUs of the NWA Shelf are predictable at the decadal time horizon, where proper initialization of the ocean is comparably important as accurate prediction of the effects of changes in external forcing (Meehl et al., 2009). To the best of authors' knowledge, this is the first high resolution regional decadal prediction system for any region of the world ocean. Other downscaling efforts have primarily aimed at multi-decadal climate change timescales (Alexander et al., 2020; Drenkard et al., 2021; Rutherford et al., 2023; Shin & Alexander, 2020), with the goal of predicting the response of the ocean to greenhouse gases and other external climate forcings, and subseasonal and seasonal timescales (Jacox et al., 2020; Siedlecki et al., 2016) with the goal of predicting how the ocean will evolve from its initial state.

While the southward shift of the Gulf Stream is forecast by both SPEAR_LO_HIND and MOM6_NWA12_HIND, the global model predicts a substantial cooling (1.5°–2°C) of the Northwest Atlantic in response to this shift, whereas the downscaled model predicts a damped response. Several pieces of evidence suggest that the downscaled model is more reliable at predicting the response of ocean temperatures to regional ocean circulation changes. First, the substantially higher resolution of MOM6_NWA12 provides a more accurate representation of the bathymetry, shelf-scale dynamics, as well as the mean Gulf Stream Position and shelf-adjacent water masses (Figure 1, Figure S1 in Supporting Information S1). Second, MOM6_NWA12 is more skillful at predicting past SST variations over the NWA Shelf (Figure 2 and Figures S4 and S5 in Supporting Information S1), although a larger sample size is needed to establish statistical certainty. Lastly, and perhaps most critically, SPEAR_LO tends to overestimate the relationship between the Gulf Stream position and temperature anomalies on the shelf (Figure S1 in Supporting Information S1). A northward Gulf Stream position is modestly correlated with warmer NEUS_LME SST in observations ($r = 0.37$–0.47). This correlation is substantially overestimated by SPEAR_LO ($r = 0.85$), and slightly underestimated by MOM6_NWA12 ($r = 0.19$).

We propose that internal variability of the AMOC and associated shifts in the Gulf Stream position is the main cause of this forecast warming pause in the coming decade. Three pieces of evidence establish the dynamical basis of the forecast and provide confidence in the muted degree of cooling in the MOM6_NWA12_HIND forecasts. First, the SPEAR_LO_HIND forecasts a modest strengthening of the AMOC associated with internal variability (that temporarily counteracts projected AMOC declines associated with climate change). We derive confidence in this forecast from (a) the performance of the model in simulating past variations in the AMOC (Figure 3h), (b) the dominant positive phase of the observed winter NAO in the past decade (Figure 3h) which is thought to favor a lagged response of strengthening AMOC (Danabasoglu et al., 2016; Delworth & Zeng, 2016; Eden & Jung, 2001; Xu et al., 2019) and (c) the observed (2013–2015) intense water mass transformation at higher latitudes which is expected to cause an AMOC recovery at 26.5°N (Moat et al., 2020). A stronger AMOC is understood to be associated with cool upper ocean anomalies in the NWA Ocean (Caesar et al., 2018; Zhang, 2008).

Second, there is a southward shift in the Gulf Stream in both the SPEAR_LO_HIND and MOM6_NWA12_HIND forecasts, which is consistent with the predicted modest strengthening of the AMOC and the observed and modeled response of the Gulf Stream position to changes in the AMOC (Caesar et al., 2018; Joyce & Zhang, 2010; McCarthy et al., 2018; Sanchez-Franks & Zhang, 2015; Zhang, 2008). Furthermore, the southward shift of the Gulf Stream in the MOM6_NWA12_HIND forecast suggests that the large-scale ocean circulation changes are properly transmitted across the regional model boundaries.

Third, the southward shift of the Gulf Stream alters the advection of water masses which then largely determine the temperature anomalies on the NWA Shelf. The southward shift, particularly near the Tail of Grand Banks region, leads to more Labrador Slope Water flowing southward and limits the northward extent of Warm Slope Waters (Brickman et al., 2018; Gonçalves Neto et al., 2021; Saba et al., 2016; Seidov et al., 2021), both of which would favor a cooling of the NWA Shelf.

We also underscore remaining uncertainties in downscaled regional predictions. First, despite the regional model's success in reducing Gulf Stream position bias and capturing low-frequency variability, both global and regional models struggled with past high-frequency variability, indicating potential for further improving Gulf Stream dynamics (Figure S1 in Supporting Information S1). Second, while our results suggest merits in initializing the ocean, consistent with the role of the AMOC in driving the basin-wide Atlantic Multidecadal Variability (AMV) pattern of SSTs, there is an ongoing debate about the extent to which other processes (like volcanic forcing, atmospheric noise etc.) also drive the AMV (Clement et al., 2015; Kim et al., 2020; Mann et al., 2021; Robson et al., 2023; Zhang et al., 2019). If the AMOC-AMV relationship were to change or weaken in the future, the decadal prediction skill in the Northwest Atlantic Ocean might drop as well (Bellucci et al., 2022). Finally, there is a large spread in forecasts of the next decade for the North Atlantic among the operational global decadal prediction systems, with some predicting continued rapid warming (Hermanson et al., 2022). A natural next step would be to assess the processes driving this uncertainty and the impact of diverse global model forcings on dynamically downscaled forecasts for the NWA Shelf.

The decadal forecasts of SSTs over the NWA Shelf can inform the development of effective fisheries management and mitigation strategies in the face of a changing climate. While our models predict a respite from rapid warming, multi-decadal projections under a high emissions scenario suggest that warming from continued increases in radiative forcing and projected weaker AMOC will reassert itself over time (Figure S9 in Supporting Information S1). The warming respite suggested by our predictions, however, is consequential for numerous management decisions (Link et al., 2023; Melbourne-Thomas et al., 2023) and would provide additional time to formulate measures to adapt to future ocean changes. Yearly updates of the decadal outlooks presented herein are also imperative for dynamic modulation of adaptation strategies with changing ocean conditions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The model data generated and analyzed in this work is available at Koul (2023). The Observations-based data sets — NOAA-OISSTv2.1, NOAA-ERSSTv5 and GLORYS12V1 are publicly available. NOAA-OISSTv2.1 is available at https://www.ncei.noaa.gov/products/optimum-interpolation-sst, NOAA-ERSSTv5 is available at https://www1.ncdc.noaa.gov/pub/data/cmb/ersst/v5/netcdf/ and GLORYS12V1 is available at https://doi.org/10.48670/moi-00021.

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References

Adcroft, A., Anderson, W., Balaji, V., Blanton, C., Bushuk, M., Dufour, C. O., et al. (2019). The GFDL global ocean and sea ice model OM4. 0: Model description and simulation features. *Journal of Advances in Modeling Earth Systems*, *11*(10), 3167–3211. https://doi.org/10.1029/2019ms001726

Adcroft, A., & Campin, J.-M. (2004). Rescaled height coordinates for accurate representation of free-surface flows in ocean circulation models. *Ocean Modelling*, *7*(3–4), 269–284. https://doi.org/10.1016/j.ocemod.2003.09.003

Alexander, M. A., Shin, S.-i., Scott, J. D., Curchitser, E., & Stock, C. (2020). The response of the Northwest Atlantic Ocean to climate change. *Journal of Climate*, *33*(2), 405–428. https://doi.org/10.1175/jcli-d-19-0117.1

Bellucci, A., Mattei, D., Ruggieri, P., & Famooss Paolini, L. (2022). Intermittent behavior in the AMOC-AMV relationship. *Geophysical Research Letters*, *49*(17), e2022GL098771. https://doi.org/10.1029/2022gl098771

Brickman, D., Hebert, D., & Wang, Z. (2018). Mechanism for the recent ocean warming events on the Scotian shelf of eastern Canada. *Continental Shelf Research*, *156*, 11–22. https://doi.org/10.1016/j.csr.2018.01.001

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., & Saba, V. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature*, *556*(7700), 191–196. https://doi.org/10.1038/s41586-018-0006-5

Chen, K., Gawarkiewicz, G. G., Lentz, S. J., & Bane, J. M. (2014). Diagnosing the warming of the Northeastern US Coastal Ocean in 2012: A linkage between the atmospheric jet stream variability and ocean response. *Journal of Geophysical Research: Oceans*, *119*(1), 218–227. https://doi.org/10.1002/2013jc009393

Chen, Z., Kwon, Y.-O., Chen, K., Fratantoni, P., Gawarkiewicz, G., & Joyce, T. M. (2020). Long-term SST variability on the Northwest Atlantic continental shelf and slope. *Geophysical Research Letters*, *47*(1), e2019GL085455. https://doi.org/10.1029/2019gl085455

Clement, A., Bellomo, K., Murphy, L. N., Cane, M. A., Mauritsen, T., Rädel, G., & Stevens, B. (2015). The Atlantic Multidecadal oscillation without a role for ocean circulation. *Science*, *350*(6258), 320–324. https://doi.org/10.1126/science.aab3980

Danabasoglu, G., Yeager, S. G., Kim, W. M., Behrens, E., Bentsen, M., Bi, D., et al. (2016). North Atlantic simulations in coordinated ocean-ice reference experiments phase II (Core-II). Part II: Inter-annual to decadal variability. *Ocean Modelling*, *97*, 65–90. https://doi.org/10.1016/j.ocemod.2015.11.007

Delworth, T. L., Cooke, W. F., Adcroft, A., Bushuk, M., Chen, J.-H., Dunne, K. A., et al. (2020). Spear: The next generation GFDL modeling system for seasonal to multidecadal prediction and projection. *Journal of Advances in Modeling Earth Systems*, *12*(3), e2019MS001895. https://doi.org/10.1029/2019ms001895

Delworth, T. L., & Zeng, F. (2016). The impact of the North Atlantic oscillation on climate through its influence on the Atlantic meridional overturning circulation. *Journal of Climate*, *29*(3), 941–962. https://doi.org/10.1175/jcli-d-15-0396.1

Drenkard, E. J., Stock, C., Ross, A. C., Dixon, K. W., Adcroft, A., Alexander, M., et al. (2021). Next-generation regional ocean projections for living marine resource management in a changing climate. *ICES Journal of Marine Science*, *78*(6), 1969–1987. https://doi.org/10.1093/icesjms/fsab100

Eden, C., & Jung, T. (2001). North Atlantic interdecadal variability: Oceanic response to the North Atlantic oscillation (1865–1997). *Journal of Climate*, *14*(5), 676–691. https://doi.org/10.1175/1520-0442(2001)014<0676:naivor>2.0.co;2

Forsyth, J. S. T., Andres, M., & Gawarkiewicz, G. G. (2015). Recent accelerated warming of the continental shelf off New Jersey: Observations from the CMV o Leander expendable bathythermograph line. *Journal of Geophysical Research: Oceans*, *120*(3), 2370–2384. https://doi.org/10.1002/2014jc010516

Gangopadhyay, A., Gawarkiewicz, G., Silva, E. N. S., Monim, M., & Clark, J. (2019). An observed regime shift in the formation of warm core rings from the Gulf Stream. *Scientific Reports*, *9*(1), 12319. https://doi.org/10.1038/s41598-019-48661-9

Gonçalves Neto, A., Langan, J. A., & Palter, J. B. (2021). Changes in the Gulf Stream preceded rapid warming of the Northwest Atlantic shelf. *Communications Earth & Environment*, *2*(1), 74. https://doi.org/10.1038/s43247-021-00143-5

Hermanson, L., Smith, D., Seabrook, M., Bilbao, R., Doblas-Reyes, F., Tourigny, E., et al. (2022). WMO global annual to decadal climate update: A prediction for 2021–25. *Bulletin of the American Meteorological Society*, *103*(4), E1117–E1129. https://doi.org/10.1175/bams-d-20-0311.1

Huang, B., Liu, C., Banzon, V., Freeman, E., Graham, G., Hankins, B., et al. (2021). Improvements of the Daily Optimum Interpolation Sea Surface Temperature (DOISST) version 2.1. *Journal of Climate*, *34*(8), 2923–2939. https://doi.org/10.1175/jcli-d-20-0166.1

Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., et al. (2017). Extended Reconstructed Sea Surface Temperature, Version 5 (ERSSTV5): Upgrades, validations, and intercomparisons. *Journal of Climate*, *30*(20), 8179–8205. https://doi.org/10.1175/jcli-d-16-0836.1

Jacox, M. G., Alexander, M. A., Siedlecki, S., Chen, K., Kwon, Y.-O., Brodie, S., et al. (2020). Seasonal-to-interannual prediction of North American coastal marine ecosystems: Forecast methods, mechanisms of predictability, and priority developments. *Progress in Oceanography*, *183*, 102307. https://doi.org/10.1016/j.pocean.2020.102307

Joyce, T. M., & Zhang, R. (2010). On the path of the Gulf Stream and the Atlantic meridional overturning circulation. *Journal of Climate*, *23*(11), 3146–3154. https://doi.org/10.1175/2010jcli3310.1

Karmalkar, A. V., & Horton, R. M. (2021). Drivers of exceptional coastal warming in the Northeastern United States. *Nature Climate Change*, *11*(10), 854–860. https://doi.org/10.1038/s41558-021-01159-7

Kim, W. M., Yeager, S., & Danabasoglu, G. (2020). Atlantic multidecadal variability and associated climate impacts initiated by ocean thermohaline dynamics. *Journal of Climate*, *33*(4), 1317–1334. https://doi.org/10.1175/jcli-d-19-0530.1

Koul, V. (2023). Model output accompanying "a predicted pause in the rapid warming of the northwest Atlantic shelf in the coming decade" [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.10412704

Lellouche, J.-M., Le Galloudec, O., Greiner, E., Garric, G., Regnier, C., Drevillon, M., et al. (2018). The Copernicus marine environment monitoring service global ocean 1/12 physical reanalysis Glorys12v1: Description and quality assessment. In *EGU general assembly conference abstracts* (Vol. 20).19806.

Link, J., Thur, S., Matlock, G., & Grasso, M. (2023). Why we need weather forecast analogues for marine ecosystems. *ICES Journal of Marine Science*, *80*(8), 2087–2098. https://doi.org/10.1093/icesjms/fsad143

Mann, M. E., Steinman, B. A., Brouillette, D. J., & Miller, S. K. (2021). Multidecadal climate oscillations during the past millennium driven by volcanic forcing. *Science*, *371*(6533), 1014–1019. https://doi.org/10.1126/science.abc5810

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., et al. (2021). Climate change 2021: The physical science basis. In *Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change* (Vol. 2).

McCarthy, G. D., Joyce, T. M., & Josey, S. A. (2018). Gulf Stream variability in the context of quasi-decadal and multidecadal Atlantic climate variability. *Geophysical Research Letters*, *45*(20), 11–257. https://doi.org/10.1029/2018gl079336

Meehl, G. A., Goddard, L., Murphy, J., Stouffer, R. J., Boer, G., Danabasoglu, G., et al. (2009). Decadal prediction: Can it be Skillful? *Bulletin of the American Meteorological Society*, *90*(10), 1467–1486. https://doi.org/10.1175/2009bams2778.1

Melbourne-Thomas, J., Tommasi, D., Gehlen, M., Murphy, E. J., Beckensteiner, J., Bravo, F., et al. (2023). Integrating human dimensions in decadal-scale prediction for marine social–ecological systems: Lighting the grey zone. *ICES Journal of Marine Science*, *80*(1), 16–30. https://doi.org/10.1093/icesjms/fsac228

Mills, K. E., Pershing, A. J., Brown, C. J., Chen, Y., Chiang, F.-S., Holland, D. S., et al. (2013). Fisheries management in a changing climate: Lessons from the 2012 ocean heat wave in the Northwest Atlantic. *Oceanography*, *26*(2), 191–195. https://doi.org/10.5670/oceanog.2013.27

Moat, B. I., Smeed, D. A., Frajka-Williams, E., Desbruyères, D. G., Beaulieu, C., Johns, W. E., et al. (2020). Pending recovery in the strength of the meridional overturning circulation at 26 n. *Ocean Science*, *16*(4), 863–874. https://doi.org/10.5194/os-16-863-2020

NOAA Fisheries. (2022a). 2022 state of the ecosystem: Mid-Atlantic (Tech. Rep.).

NOAA Fisheries. (2022b). 2022 state of the ecosystem: New England (Tech. Rep.).

Pérez-Hernández, M. D., & Joyce, T. M. (2014). Two modes of Gulf Stream variability revealed in the last two decades of satellite altimeter data. *Journal of Physical Oceanography*, *44*(1), 149–163. https://doi.org/10.1175/jpo-d-13-0136.1

Pershing, A. J., Alexander, M. A., Hernandez, C. M., Kerr, L. A., Le Bris, A., Mills, K. E., et al. (2015). Slow adaptation in the face of rapid warming leads to collapse of the gulf of Maine cod fishery. *Science*, *350*(6262), 809–812. https://doi.org/10.1126/science.aac9819

Robson, J., Sutton, R., Menary, M. B., & Lai, M. W. (2023). Contrasting internally and externally generated Atlantic multidecadal variability and the role for AMOC in CMIP6 historical simulations. *Philosophical Transactions of the Royal Society A*, *381*(2262), 20220194. https://doi.org/10.1098/rsta.2022.0194

Ross, A. C., Stock, C. A., Adcroft, A., Curchitser, E., Hallberg, R., Harrison, M. J., et al. (2023). A high-resolution physical-biogeochemical model for marine resource applications in the Northwest Atlantic (MOM6-cobalt-NWA12 v1. 0). *Geoscientific Model Development Discussions*, *2023*(23), 1–65. https://doi.org/10.5194/gmd-16-6943-2023

Rutherford, K., Fennel, K., Garcia Suarez, L., & John, J. G. (2023). Uncertainty in the evolution of Northwest North Atlantic circulation leads to diverging biogeochemical projections. *EGUsphere*, *21*(1), 301–314. https://doi.org/10.5194/bg-21-301-2024

Saba, V. S., Griffies, S. M., Anderson, W. G., Winton, M., Alexander, M. A., Delworth, T. L., et al. (2016). Enhanced warming of the Northwest Atlantic ocean under climate change. *Journal of Geophysical Research: Oceans*, *121*(1), 118–132. https://doi.org/10.1002/2015jc011346

Sanchez-Franks, A., & Zhang, R. (2015). Impact of the Atlantic meridional overturning circulation on the decadal variability of the Gulf Stream path and regional chlorophyll and nutrient concentrations. *Geophysical Research Letters*, *42*(22), 9889. https://doi.org/10.1002/2015gl066262

Seidov, D., Mishonov, A., & Parsons, R. (2021). Recent warming and decadal variability of gulf of Maine and slope water. *Limnology & Oceanography*, *66*(9), 3472–3488. https://doi.org/10.1002/lno.11892

Shin, S.-I., & Alexander, M. A. (2020). Dynamical downscaling of future hydrographic changes over the Northwest Atlantic Ocean. *Journal of Climate*, *33*(7), 2871–2890. https://doi.org/10.1175/jcli-d-19-0483.1

Siedlecki, S. A., Kaplan, I. C., Hermann, A. J., Nguyen, T. T., Bond, N. A., Newton, J. A., et al. (2016). Experiments with seasonal forecasts of ocean conditions for the northern region of the California current upwelling system. *Scientific Reports*, *6*(1), 27203. https://doi.org/10.1038/srep27203

Smith, D., Eade, R., Scaife, A., Caron, L.-P., Danabasoglu, G., DelSole, T., et al. (2019). Robust skill of decadal climate predictions. *npj Climate and Atmospheric Science*, *2*(1), 13. https://doi.org/10.1038/s41612-019-0071-y

Xu, X., Chassignet, E. P., & Wang, F. (2019). On the variability of the Atlantic meridional overturning circulation transports in coupled CMIP5 simulations. *Climate Dynamics*, *52*(11), 6511–6531. https://doi.org/10.1007/s00382-018-4529-0

Yang, X., Delworth, T. L., Zeng, F., Zhang, L., Cooke, W. F., Harrison, M. J., et al. (2021). On the development of GFDL'S decadal prediction system: Initialization approaches and retrospective forecast assessment. *Journal of Advances in Modeling Earth Systems*, *13*(11), e2021MS002529. https://doi.org/10.1029/2021ms002529

Zhang, R. (2008). Coherent surface-subsurface fingerprint of the Atlantic meridional overturning circulation. *Geophysical Research Letters*, *35*(20), L20705. https://doi.org/10.1029/2008gl035463

Zhang, R., Sutton, R., Danabasoglu, G., Kwon, Y.-O., Marsh, R., Yeager, S. G., et al. (2019). A review of the role of the Atlantic meridional overturning circulation in Atlantic multidecadal variability and associated climate impacts. *Reviews of Geophysics*, *57*(2), 316–375. https://doi.org/10.1029/2019rg000644

Zhao, M., Golaz, J.-C., Held, I., Guo, H., Balaji, V., Benson, R., et al. (2018). The GFDL global atmosphere and land model AM4. 0/LM4. 0: 1. Simulation characteristics with prescribed SSTS. *Journal of Advances in Modeling Earth Systems*, *10*(3), 691–734. https://doi.org/10.1002/2017ms001208