


**OVERVIEW** OPEN ACCESS

# North Atlantic Sea Surface Temperature Variability: Impacts, Mechanisms, and Challenges

 Chengfei He<sup>1</sup> | Casey R. Patrizio<sup>2</sup> | Young-Oh Kwon<sup>3</sup> | Katinka Bellomo<sup>4</sup>

<sup>1</sup>Department of Marine and Environmental Sciences, Marine Science Center, Northeastern University, Nahant, Massachusetts, USA | <sup>2</sup>Institute for Marine and Atmospheric Research Utrecht (IMAU), Utrecht University, Utrecht, the Netherlands | <sup>3</sup>Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA | <sup>4</sup>Department of Geosciences, University of Padova, Padova, Italy

**Correspondence:** Chengfei He ([ch.he@northeastern.edu](mailto:ch.he@northeastern.edu))

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## ABSTRACT

North Atlantic sea surface temperatures (SST) exhibit variability on interannual to centennial timescales with significant regional and global impacts on Atlantic hurricane activity, marine heat waves, and other weather extremes. This review synthesizes current understanding of North Atlantic SST variability, its mechanisms, impacts, and challenges across multiple timescales with help of a conceptual stochastic climate model hierarchy and a focus on the extratropical region, where many outstanding questions remain. On interannual timescales, SST variability is driven primarily by the North Atlantic oscillation (NAO), though oceanic processes in regions like the Gulf Stream are increasingly recognized to play active roles. On decadal-to-multidecadal timescales, the relative contributions to Atlantic multidecadal variability (AMV) from internal variability versus external forcing remain debated, with emerging evidence suggesting externally forced signals may be more significant than previously thought. Fundamental disagreements also persist over whether the Atlantic Meridional Overturning Circulation (AMOC) or stochastic atmospheric forcing (e.g., NAO) drives internal AMV. At centennial scales, the North Atlantic “warming hole” emerges as a critical phenomenon, with ongoing debates whether the observed trend results from weakened AMOC or enhanced atmospheric westerlies. Growing concerns about potential collapse of the AMOC highlight the importance of understanding these longer-term variations. Major challenges persist including the respective roles of the atmosphere and ocean in these variabilities, substantial model spreads and biases, and the signal-to-noise problem, all related to how SST variability will respond to continued warming. These fundamental questions may be addressed using model hierarchy and high-resolution models.

This article is categorized under:

Paleoclimates and Current Trends > Modern Climate Change

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## 1 | Introduction

The North Atlantic Ocean plays a pivotal role in the Earth's climate system. Variability in sea surface temperature (SST)

within this region influences weather patterns, modulates atmospheric circulation, and affects marine ecosystems, with consequences for the surrounding regions and around the globe. Over the past decades, instrumental observations, along with

Chengfei He, Casey R. Patrizio, and Katinka Bellomo contributed equally.

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**TABLE 1** | Hierarchy of stochastic climate models for North Atlantic SST variability.

| Model                | Governing equation   | Key processes                         | Power spectrum  |
|----------------------|--|---------------------------------------|---|
| M1: Null hypothesis  | $C_o \frac{dT'}{dt} = -\lambda_a T' + F'_a$                              | Atmospheric forcing only              | $ T' ^2 = \frac{ F'_a ^2}{\lambda_a^2 + C_o \omega^2}$          |
| M2: Ocean processes  | $C_o \frac{dT'}{dt} = -\lambda_a T' + F'_a - \lambda_o T' + F'_o$        | Atmospheric + oceanic forcing/damping | $ T' ^2 = \frac{ F'_a ^2 +  F'_o ^2}{\lambda^2 + C_o \omega^2}$ |
| M3: External forcing | $C_o \frac{dT'}{dt} = -\lambda_a T' + F'_a - \lambda_o T' + F'_o + F'_X$ | M2 + external radiative forcing       |   |

Note: All primes denote monthly anomalies with mean seasonal cycle removed, and  $C_o = \rho C_p H$ , where  $\rho$  is density of seawater,  $C_p$  is specific heat of seawater, and  $H$  is mixed-layer depth.  $\lambda = \lambda_a + \lambda_o$  represents total damping.  $\omega = 2\pi f$  is angular frequency, with  $f$  being the frequency in cycles per unit time (e.g., cycles per month).  $F'_a$ ,  $F'_o$ , and  $F'_X$  represent atmospheric, oceanic, and external forcing, respectively.

paleoclimate reconstructions and numerical simulations, have revealed complex patterns of SST variability across a broad range of timescales. These range from interannual fluctuations related to atmospheric leading modes of variability such as the North Atlantic oscillation (NAO; Hurrell 1995) to multidecadal variability associated with the Atlantic multidecadal variability (AMV) that modulates North Atlantic hurricane activity, Sahel rainfall, and Europe temperature extremes (R. Zhang et al. 2019). At centennial scales, the emergence of a “warming hole” in the subpolar North Atlantic raises concerns about the Atlantic Meridional Overturning Circulation (AMOC) approaching a potential collapse (Rahmstorf 2024). The profound impacts of North Atlantic SST variability are starkly illustrated by the 2023/24 marine heat wave, which not only broke ocean temperature records but also contributed to extreme heat events across North America and Europe (Berthou et al. 2024; Lopez et al. 2025).

Understanding these diverse patterns requires disentangling the relative contributions of atmospheric forcing, oceanic dynamics, and external drivers across different timescales. While atmospheric variability such as NAO dominates at shorter timescales, oceanic processes become increasingly important at longer timescales (Bjerknes 1964). The challenge is further complicated by the fact that external forcing not only drives long-term trends but may also fundamentally alter these modes of internal variability (O'Brien and Deser 2022). The North Atlantic presents particularly intriguing puzzles including: (1) the respective role of atmosphere and ocean in its variabilities across timescales, (2) debates about whether AMV is internally generated or externally forced, and (3) the dominant mechanisms responsible for the warming hole in the subpolar region that defies global warming trends. Progress on these fundamental questions is essential for reducing uncertainty in SST predictions/projections and improving our ability to anticipate climate impacts on seasonal to centennial timescales. This review paper synthesizes current knowledge on North Atlantic SST variability, particularly focusing on the extratropics, aiming to document their widespread impacts, to unravel the driving mechanisms responsible for these changes and to highlight the key challenges that remain. In particular, this review addresses the following key questions: What are the respective roles of the atmosphere and ocean in driving SST variability across timescales? Is the AMV primarily an internally generated mode or a response to external forcing? What mechanisms underlie the warming hole in the subpolar North Atlantic (SPNA) in the past and future? Through a conceptual stochastic climate model hierarchy and a focus on

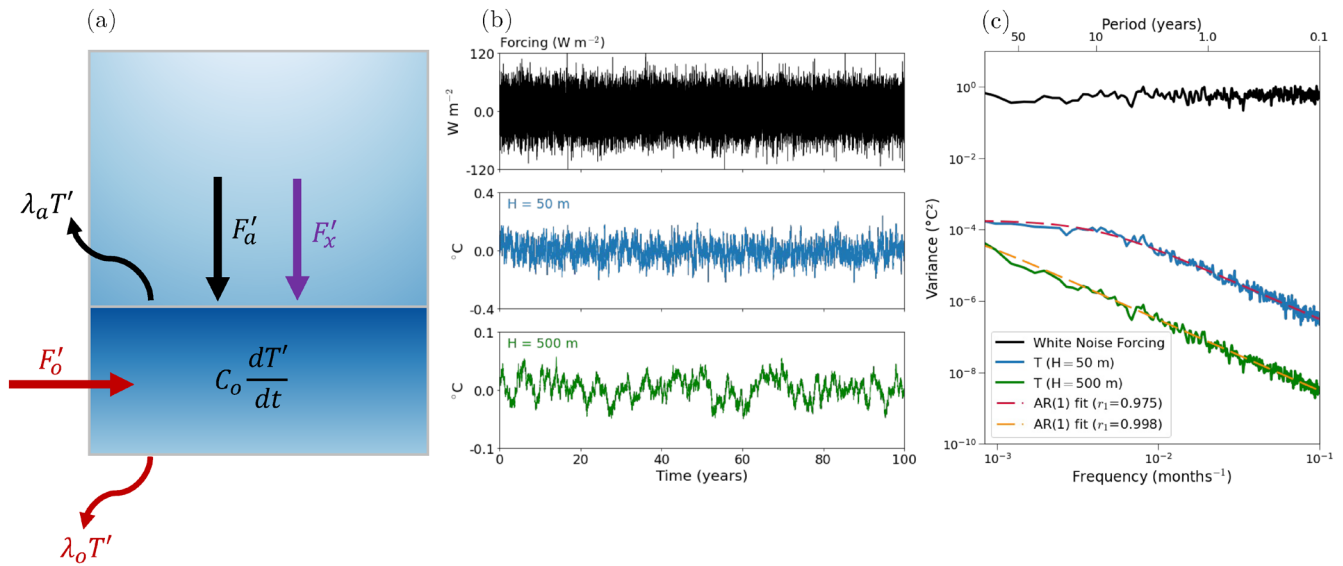
the extratropical region, we aim to provide an organizing framework for addressing these questions and identifying productive directions for future research.

## 2 | A Conceptual Model Hierarchy for Extratropical North Atlantic SST Variability

The mechanisms governing extratropical SST variability can be understood through a hierarchy of conceptualized stochastic climate models of increasing complexity, as summarized in Table 1. We begin with the simplest baseline model (M1), which is often considered as the null hypothesis for the extratropical SST variability, and progressively add oceanic processes (M2) and external forcing (M3).

The null hypothesis for extratropical SST variability is based on the stochastic climate model framework first proposed by (Hasselmann 1976) (M1, Table 1). In this framework (as illustrated in Figure 1a, black arrows), the SST anomaly  $T'$  is forced by stochastic fluctuations in the atmospheric circulation (i.e., weather) via surface heat fluxes  $F'_a$  (Figure 1b) and damped by surface heat flux feedback  $-\lambda_a T'$ . The corresponding power spectrum reveals the model's key behavior. On monthly and interannual timescales ( $\lambda_a^2 \ll C_o \omega^2$ ), the SST spectrum increases rapidly in proportion to  $1/\omega^2$ . On decadal and longer timescales ( $\lambda_a^2 \gg C_o \omega^2$ ), the SST spectrum flattens. Physically, this transition arises because the ocean's large heat capacity effectively integrates the white atmospheric noise, which shifts the power toward lower frequencies and hence yields a red-noise SST spectrum (Figure 1c).

The null hypothesis model without ocean processes successfully captures many key aspects of SST variability in extratropical oceans (Frankignoul 1979; Patrizio and Thompson 2022), but there are exceptions where oceanic dynamics play a crucial role (Buckley et al. 2014; Kushnir et al. 2002). For example, SST variability in western boundary current regions is forced by the oceanic circulation and damped by surface heat fluxes (Kwon et al. 2010; Smirnov et al. 2014). In the SPNA, the reemergence mechanism allows SST anomalies to persist from winter to winter through seasonal variations in vertical entrainment in the ocean (Alexander and Deser 1995; Deser et al. 2003). These oceanic mechanisms can be parameterized analogously to the respective atmospheric terms (Frankignoul et al. 2002; Patrizio and Thompson 2022), adding oceanic forcing  $F'_o$  and damping  $\lambda_o$  (red arrows in Figure 1a) to produce M2. Due to the ocean's



**FIGURE 1** | Stochastic climate model framework. (a) Schematic includes the null hypothesis model with atmospheric processes only (black arrows), additional ocean processes (red arrows), and external forcing (purple arrow). (b) Synthetic white-noise forcing (black) and associated SSTs arising from integrating the null hypothesis model with a mixed-layer depth of 50m (blue) and 500m (green) based on M1. (c) Power spectra of the forcing and SST time series in (b), with best-fit AR(1) models plotted dashed lines.

greater thermal inertia,  $F'_o$  is generally considered to have greater power toward lower frequencies (i.e., red noise), while  $F'_a$  has more uniform power across all frequencies (i.e., white noise). Thus, North Atlantic SST variability on shorter timescales is often considered to be primarily driven by the atmosphere  $F'_a$ , while the SST variability on longer timescales is often considered to be driven by the ocean  $F'_o$ , as first hypothesized by Bjerknes (1964).

Models M1 and M2 describe linear SST variability in a stable climate. In a transient climate, external forcing  $F'_x$  must be incorporated (purple arrow in Figure 1a, M3), representing anomalies from anthropogenic emissions, volcanic eruptions, or solar variations relative to a reference period. Given the stochastic nature of  $F'_a$  and  $F'_o$ , isolating the forced response to  $F'_x$  requires averaging across an ensemble of M3 integrations.

While this model hierarchy provides a useful conceptual framework for understanding North Atlantic SST variability, certain simplifications merit discussion. First, external forcing  $F'_x$  may alter the characteristics of the system (i.e.,  $\lambda_a$ ,  $\lambda_o$ ,  $C_o$ ,  $F'_a$ , and  $F'_o$ ), introducing nonlinear interactions beyond simple additive forcing. Second, the parameterization necessarily simplifies the rich spectrum of oceanic processes: Ekman transport, gyre circulations, AMOC, and mesoscale eddies are all represented within  $F'_o$ , though they operate on different spatial and temporal scales and interact in complex ways. This simplification, while essential for analytical insight, means that process-specific responses may require more detailed investigation. Third, the stochastic climate models treat forcing and damping as independent processes for mathematical tractability, though in reality they are often coupled through multiple feedbacks in the climate system (e.g., cloud-SST feedback). In particular, models M1–M3 (Table 1) assume one-way atmospheric influence on the ocean, but air-sea interactions are inherently two-way. This was partially addressed by Barsugli and Battisti (1998), who introduced two-way air-sea interaction to the stochastic model framework

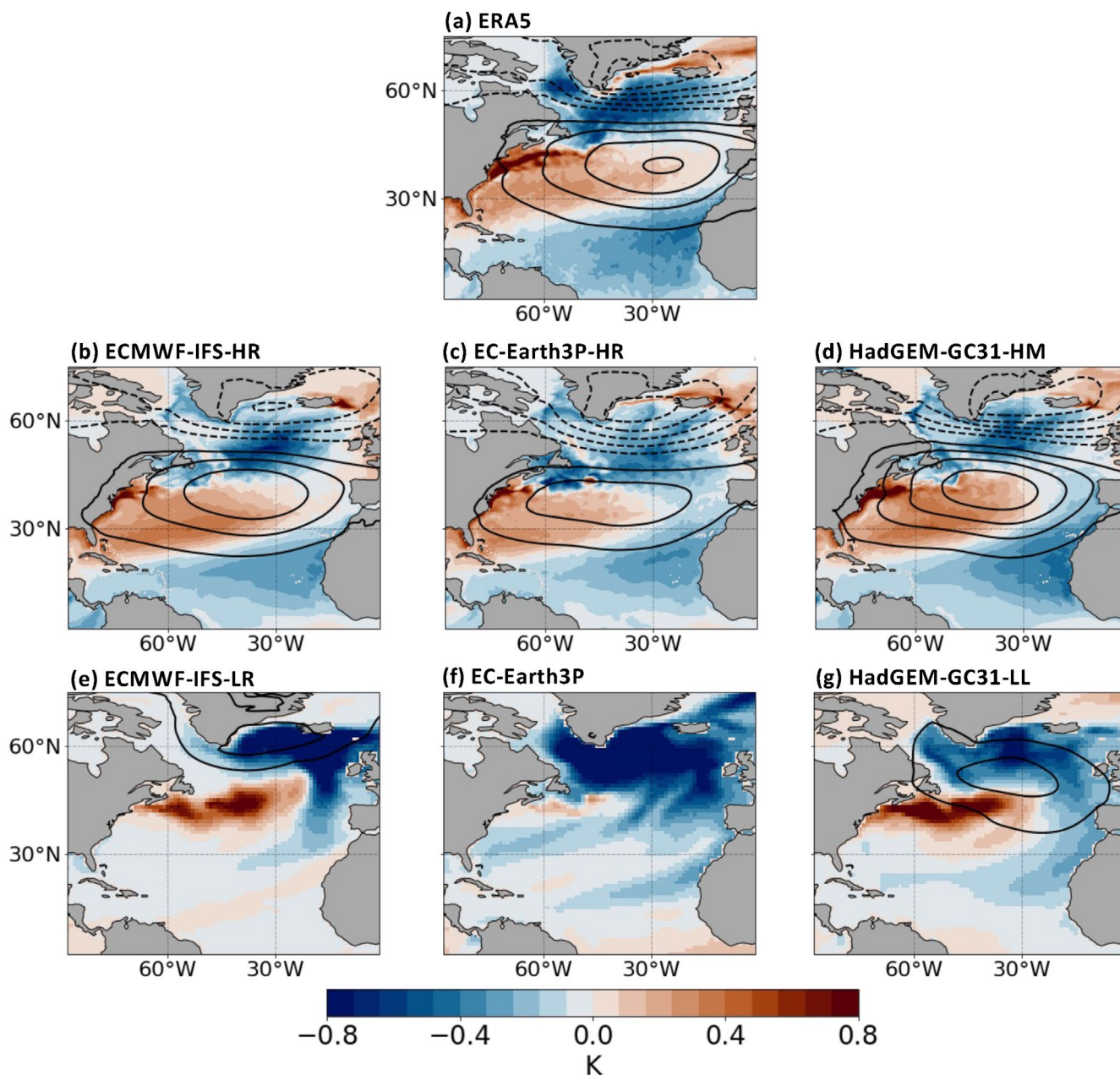
via surface heat exchange. This coupling, proportional to the ocean–atmosphere temperature difference, reduces turbulent heat flux damping at decadal timescales and thus significantly enhances decadal SST variability compared to the stochastic climate models with one-way interactions. Despite these simplifications, this hierarchy provides essential theoretical grounding for interpreting complex model results and observations. These models offer a baseline understanding of SST variability mechanisms, with their transparent assumptions helping identify when and where additional complexity is needed. Throughout this review, we will reference these conceptual models as organizing principles while highlighting phenomena that require extensions beyond this framework.

### 3 | Interannual SST Variability

North Atlantic SST variability on interannual timescales is predominantly driven by the NAO, which typically results in a tripole SST pattern anomaly (Figure 2a), with profound impacts on regional weather patterns (Y. Liu et al. 2014; R. Wu et al. 2011). While traditionally viewed as a passive oceanic response to stochastic atmospheric variability, recent advances in observational networks and high-resolution modeling have revealed a more nuanced picture where ocean processes play an increasingly active role. This section examines the mechanisms driving interannual SST variability, the critical importance of model resolution in capturing these processes, and insights gained from extreme events such as the 2023/24 marine heat wave that illuminate the interplay between natural variability and anthropogenic warming.

#### 3.1 | Mechanisms

As outlined in Section 2, a widely accepted view attributes the North Atlantic SST variability to the thermodynamic response



**FIGURE 2** | Leading empirical orthogonal function (EOF) patterns of winter-mean (DJFM) SST anomalies (shading; K) calculated over the North Atlantic ( $0^{\circ}$ – $70^{\circ}$  N,  $0^{\circ}$ – $90^{\circ}$  W), and SLP anomalies regressed onto the respective normalized principal component time series (contours; 0.6 hPa interval and dashed contours are negative) for (a) ERA5 (1959–2021) as well as (b–d) three different high-resolution model simulations and (e–g) corresponding low-resolution simulations performed over the 1950–2014 period from HighResMIP (replotted from Patrizio et al. 2023). For low-resolution simulations, the oceanic grid spacing is 100 km and the atmospheric grid spacing at  $50^{\circ}$  N is 71, 50, and 135 km for ECMWF-IFS-LR, EC-Earth3P, and HadGEM-GC31-LL, respectively. For high-resolution simulations, the oceanic grid spacing is 25 km and the atmospheric grid spacing at  $50^{\circ}$  NN is 25, 36, and 25 km for ECMWF-IFS-HR, EC-Earth3P-HR, and HadGEM-GC31-HM, respectively.

of the ocean mixed-layer to stochastic atmospheric variability ( $F'_a$  in M1), supported by numerous observational and modeling studies. The leading pattern of monthly SST anomalies reflects the atmospheric forcing most clearly in winter when the extratropical atmospheric circulation is most vigorous (Cayan 1992; Visbeck et al. 2003). These anomalies form a tripole pattern anomaly due to surface heat flux associated with the NAO (Figure 2a) (Hurrell 1995; Hurrell and Deser 2010).

The NAO also drives interannual SST anomalies via surface wind-stress anomalies that affect the ocean circulation (Visbeck

et al. 2003; Lohmann et al. 2009). For instance, the positive phase of the NAO is associated with Ekman heat flux divergence in the subpolar gyre and convergence in the subtropical gyre, which cools and warms those regions, respectively (Deser et al. 2010; Marshall et al. 2001). The path of the Gulf Stream also responds to surface wind stress curl anomalies associated with the NAO (de Coëtlogon et al. 2006; Marshall et al. 2001), leading to SST anomalies on the interannual to decadal timescales (Joyce et al. 2009).

While atmospheric variability such as the NAO influences SST anomalies through both local surface heat fluxes and its impact

on ocean circulation, recent studies indicate that the ocean itself plays a more active role in shaping interannual SST variability, beyond the surface heat flux-driven response (e.g., M2, Table 1). Enhanced observational capabilities, including expanded Argo float coverage, satellite altimetry, and in situ measurements, combined with improved model resolution more clearly reveal that ocean heat advection via mesoscale eddies, and vertical mixing, strongly influence interannual SST variability, especially around the Gulf Stream and the North Atlantic subpolar gyre (Deser et al. 2003; Buckley et al. 2014, 2015; Roberts et al. 2017; Patrizio and Thompson 2021; Josey and Sinha 2022). This active role of the ocean is reinforced by idealized climate model studies incorporating ocean processes with varying complexity. By comparing SST variability between models with different ocean representations—from simple extensions of stochastic climate models similar to those discussed in Section 2 (e.g., Bishop et al. 2017; Liu, Kwon, et al. 2023) to atmosphere–slab-ocean models that lack explicit ocean dynamics (e.g., Patrizio and Thompson 2022) to fully-coupled eddy-resolving models (Figure 2a–d)—these findings underscore ocean dynamics in shaping extratropical SST variability on interannual timescales than previously understood.

Despite this growing evidence for an active oceanic role, the extent to which such extratropical SST anomalies influence the atmospheric circulation remains a subject of debate. This stands in contrast to the tropical Atlantic, where SST variability is well recognized as arising from coupled ocean–atmosphere interactions (see Xie and Carton (2004) and Cabos et al. (2019) for reviews of tropical Atlantic variability). In the extratropics, the atmospheric circulation response to SST anomalies has often been considered small compared to the internal atmospheric variability (e.g., Saravanan 1998; Kushnir et al. 2002). Theoretical scaling analysis indicates one degree of SST anomaly, could only induce 20–30 m response in geopotential height at 500 hPa, far less than the standard deviation of the total responses (Kushnir et al. 2002). The small impact of the SST anomaly on atmosphere also extends to longer timescales (See Section 6.2). Nevertheless, numerous studies have detected influences of interannual SST variability on the atmospheric circulation. For instance, both modeling and observation-based studies suggest that the tripole SST pattern may exert weak positive feedback to the NAO through turbulent heat fluxes (Czaja et al. 2003; Gastineau and Frankignoul 2015; Kolstad and O'Reilly 2024). This is broadly consistent with coupled interactions described by Barsugli and Battisti (1998), in which the atmosphere and ocean thermally couple based on their temperature differences. While limited to the local interaction and thus unable to fully capture the large-scale NAO–SST tripole feedback, the Barsugli and Battisti (1998)'s thermally coupled model represents key atmosphere–ocean feedbacks more realistically than the stochastic climate models based only on internal atmospheric variability (M1).

Another prominent area of research on extratropical ocean–atmosphere interactions has focused on the Gulf Stream. Building upon earlier work showing the *climatological* Gulf Stream's strong influence on the free troposphere (Minobe et al. 2008, 2010), recent studies provide both observational and modeling evidence for atmospheric impacts of Gulf Stream variability—particularly when model resolution is sufficiently fine to resolve

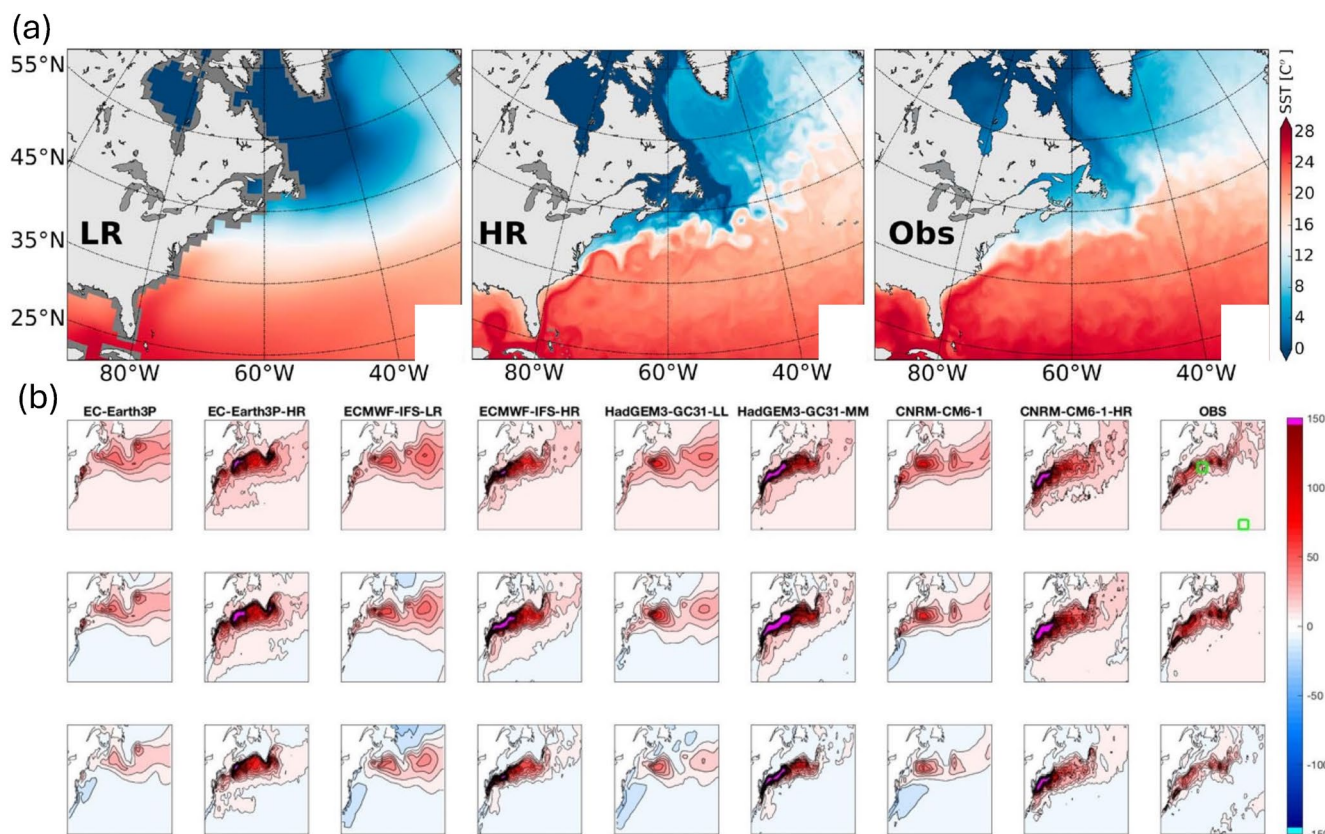
small-scale (< ~25 km) interactions (Parfitt et al. 2016; Famooss Paolini et al. 2022; Wills et al. 2024; Larson, Thompson, and Hurrell 2024). Such extratropical SST influences have important implications for seasonal to interannual climate predictions over the North Atlantic sector (e.g., Dunstone et al. 2016; Weisheimer et al. 2017; Kido et al. 2023) and possible inter-basin interactions (e.g., Kohyama et al. 2021).

### 3.2 | Role of Model Resolution

Interannual extratropical North Atlantic variability simulated by climate models often deviates from observed variability, particularly around the Gulf Stream region (e.g., Small et al. 2019). This discrepancy largely stems from insufficient resolution in both ocean and atmosphere model components. Standard resolution models typically use  $\sim 1^\circ$  grids, whereas adequately resolving the sharp Gulf Stream front requires  $\sim 0.1^\circ$  ocean resolution. These coarse-resolution models fail to capture critical features such as the sharp Gulf Stream front, associated ocean mesoscale eddy activity, ocean–atmosphere heat exchange along the narrow front, and the ocean-basin topography that affects circulation patterns, including the Gulf Stream's separation near Cape Hatteras and the path of its extension (Chassignet and Xu 2017). These limitations often contribute to large SST biases in the extratropics (Danabasoglu et al. 2016; Athanasiadis et al. 2022), but they can also be mitigated by increasing model resolution (Chassignet and Marshall 2008), as illustrated by instantaneous snapshots of the SST field in a high-resolution ( $\sim 0.1^\circ$  horizontal resolution for the ocean) climate model (Figure 3a; Siqueira and Kirtman 2016). Crucially, this high-resolution more accurately captures fine-scale features along the Gulf Stream front and the northeastward pathway of the Gulf Stream extension compared to its low-resolution ( $\sim 1.0^\circ$ ) counterpart.

The role of model resolution in representing extratropical atmosphere–ocean interactions on monthly to interannual timescales has been supported through multi-model analyses of High Resolution Model Intercomparison Project (HighResMIP; Haarsma et al. 2016). For instance Bellucci et al. (2021) showed that high-resolution models from HighResMIP represent the positive covariance between monthly SST and air–sea turbulent heat flux anomalies more realistically than the low resolution models in the Gulf Stream region (Figure 3b). This aforementioned result reflects enhanced oceanic forcing of SSTs in this region with increased resolution. Contextually, Patrizio et al. (2023) showed that HighResMIP models also tend to exhibit a more realistic leading pattern of large-scale interannual SST anomalies that is strongly linked to the NAO as in observations (Figure 2b–g), reflecting enhanced atmospheric forcing of large-scale SST variability with increased resolution. Together, these findings show that application of our conceptual understanding of midlatitude air–sea interactions—that is, whether the ocean plays a passive (e.g., M1) or active role (e.g., M2)—is strongly dependent on the model resolution and the specific region considered.

The reduction of SST biases in the extratropics arising from increased model resolution may have widespread implications (e.g., R. W. Lee et al. 2018), including improved representation of the extratropical atmospheric circulation, such as atmospheric



**FIGURE 3** | (a) Snapshot of monthly mean sea surface temperature (°C) for a given month in the North Atlantic region in a low horizontal resolution global climate model (left), corresponding high-resolution global climate model (middle), and observations (right) from Jet Propulsion Laboratory Multiscale Ultra-high Resolution Sea Surface Temperature (adapted from Siqueira and Kirtman 2016). (b) Spatial patterns of the covariance between SST and turbulent surface heat fluxes in the North Atlantic (°C W m<sup>-2</sup>), computed for [-1, 0, +1]-month lag (top, middle, bottom row, respectively) for HighResMIP models and observations. SST leads for the negative lags (adapted from Bellucci et al. 2021).

blocking (Athanasiadis et al. 2022; Michel et al. 2023; Scaife et al. 2011), and enhanced seasonal to interannual climate predictions over the North Atlantic (Roberts et al. 2020, 2021). However, higher resolution does not always guarantee substantial improvements in simulating interannual SST variability across the extratropical North Atlantic. For instance, climate models with relatively high (~0.25°) ocean resolution frequently overestimate mixed-layer depths in the Labrador Sea, adversely affecting the representation of interannual SST variability in this region (Koenigk et al. 2021). Warm SST biases in the Gulf Stream persist in higher resolution models (G. Xu et al. 2022). Addressing these challenges may require advancements in model physics and/or further increases in resolution.

### 3.3 | Extreme Events: The 2023/24 North Atlantic Marine Heat Wave

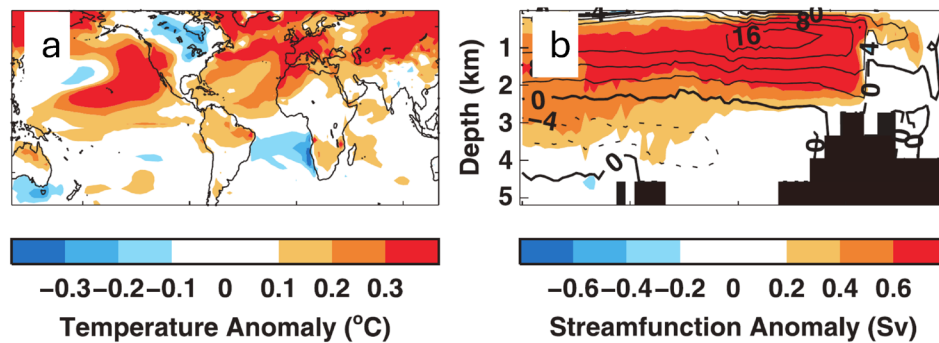
While much of our understanding of interannual SST variability comes from examining mean patterns and standard deviations, extreme events provide critical insights into the processes driving SST anomalies. The 2023/24 North Atlantic record-breaking marine heat waves, characterized by a tripole pattern SST anomaly, exemplifies the complex interplay between atmospheric forcing ( $F'_a$ ), oceanic preconditioning ( $C_o$ ), and potentially climate change ( $F'_x$ ) influences. England et al. (2025)

identified a combination of anomalously weak surface winds, reduced cloud cover, and shallowed ocean mixed-layer preconditioned by climate change as primary drivers, while Guinaldo et al. (2025) demonstrated that internal variability amplified by climate change created conditions conducive to this extreme event. The heat wave's impacts extended beyond the ocean, with Lopez et al. (2025) showing how the anomalously warm Atlantic fueled record-breaking heat waves in western North America, and Berthou et al. (2024) documenting the northwest European marine heat wave contributed to breaking land temperature records. These events underscore how extreme SST anomalies can arise from the convergence of multiple factors operating on seasonal-to-interannual timescales, with their amplitude potentially enhanced by the warming background state.

## 4 | Decadal to Multidecadal Variability

### 4.1 | AMV and Its Widespread Impacts

North Atlantic SST variability on decadal and multidecadal timescales is often referred to as the Atlantic multidecadal variability (AMV), characterized by a horseshoe pattern in the North Atlantic (Figure 4). AMV has been linked to widespread impacts on global climate, weather, and both marine and terrestrial ecosystems. In particular, AMV has



**FIGURE 4** | Joint multi-taper method-singular vector decomposition (MTM-SVD) analysis of simulated decadal mean surface temperature and Atlantic meridional overturning circulation (AMOC) streamfunction for model years 400–900 from a 1400-year coupled climate model simulation. Panels (a) show the signal in surface temperature anomaly in the frequency band from  $(70\text{years})^{-1}$  to  $(180\text{years})^{-1}$ , when the surface temperature anomaly peaks in the Northern Hemisphere. Panels (b) show the corresponding phases of the covarying signal in AMOC streamfunction anomaly in the same band. The climatological AMOC streamfunction is shown by contours. Adapted from Knight et al. (2005).

been shown to influence South American, East Asian, and North African monsoon rainfall via meridional shift of Intertropical Convergence Zone (ITCZ; Mohino et al. 2024; Monerie et al. 2024; Moreno-Chamarro et al. 2020), North Atlantic hurricane activity (Goldenberg et al. 2001), and atmospheric blocking over the North Atlantic sector (Häkkinen et al. 2011; Kwon et al. 2020). It has also been associated with temperature extremes in North America and Europe (Börgel et al. 2023; Ruprich-Robert et al. 2018), as well as marine and terrestrial heat waves (von Kietzell et al. 2022; Qasmi et al. 2021) that affect ecosystems (Faillietaz et al. 2019; Nye et al. 2014) and increase wildfire risk (Kitzberger et al. 2007), carrying implications for human health (Bonomo et al. 2019; Majeed et al. 2020).

AMV also affects global climate by interacting with SST in other ocean basins. In the tropics, AMV can modulate El Niño events (Dong et al. 2006; D. Kim et al. 2020) and the Walker circulation (Meehl et al. 2020; Ruprich-Robert et al. 2017) and, by extension, the global hydrological cycle (Z. He et al. 2021; Hong et al. 2022). In the extratropics, Pacific Decadal Variability (PDV) interplays with AMV via multiple atmospheric and oceanic pathways (McGregor et al. 2018; Meehl et al. 2020). Depending on the phase of AMV and PDV, different teleconnection patterns can develop. When they are out of phase, a zonally-oriented circumglobal pattern tends to form, while an in-phase relationship favors a great-circle wave train. These patterns affect the jet stream (Huang et al. 2019), East and South Asian summer monsoon rainfall (Kayano et al. 2019; Z. Zhang et al. 2018), and droughts in the United States (McCabe et al. 2004).

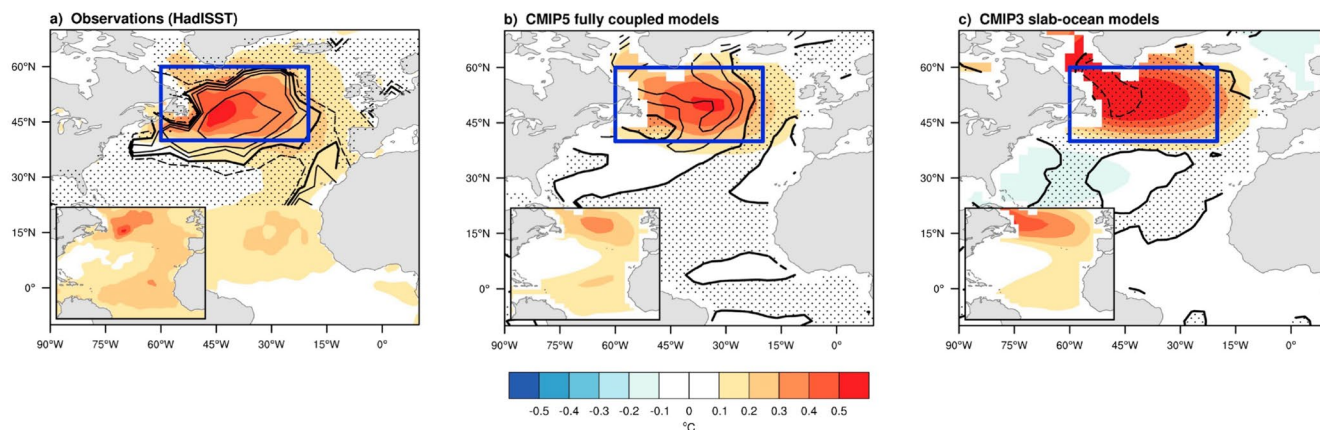
#### 4.2 | Mechanism of AMV: Role of Internal Variability

Despite its widespread impacts, the mechanisms governing decadal to multidecadal variability of North Atlantic SST remain poorly understood due to the limited length of instrumental observations relative to AMV's long periodicity. Climate model simulations with fixed external forcings (i.e., preindustrial control runs) demonstrate that AMV can arise purely from internal dynamics. In these simulations, internal variability of

AMOC emerges as a primary driver of AMV (e.g.,  $F'_0$  in M2). An intensified AMOC is associated with enhanced meridional heat transport to the North Atlantic, leading to warming in the SPNA (Figure 4), which is compensated by a moderate cooling in the South Atlantic (R. Zhang et al. 2019). This subpolar warming propagates to the tropics via cloud–SST interactions (Bellomo et al. 2015, 2016; Yuan et al. 2016), wind–evaporation–SST feedback (Senapati et al. 2024) and dust–SST feedback (Wang et al. 2012), forming a characteristic basin-wide horseshoe pattern (Figure 4a).

Model simulations show that the AMOC itself responds to multiple forcing mechanisms: surface winds associated with NAO perturb turbulent heat fluxes in the SPNA, influencing deep-water formation and, with some delay, the AMOC (Delworth et al. 2017; Kwon and Frankignoul 2014); sea ice–atmosphere interactions modify heat fluxes in regions like the Labrador Sea (Deng and Dai 2022; Hao et al. 2025); and freshwater export from the Arctic or South Atlantic disrupts density gradients critical for deep convection (F. Liu et al. 2022; Wei and Zhang 2022). These AMOC-induced SST anomalies can in turn drive atmospheric responses, creating two-way coupled interactions between AMV, the AMOC, and atmospheric circulation (Wills et al. 2019; Årthun et al. 2021; Omrani et al. 2022; Vacca et al. 2025).

Continuous observations of the AMOC only began in 2004 and remain spatially limited with the RAPID array at  $26.5^\circ\text{N}$  (McCarthy et al. 2020) and the OSNAP array across the subpolar gyre since 2014 (Fu et al. 2025). This limited observational coverage motivates the use of climate model simulations and indirect observational indicators to explore its apparent linkages with AMV. These so-called fingerprints of AMOC variability (also discussed in Section 6.4) include sea surface salinity, upper ocean heat content, subsurface temperature, and surface turbulent heat flux (Gulev et al. 2013; Moat et al. 2024; R. Zhang 2017). These fingerprints have primarily been identified in model simulations, where they are correlated with AMOC variability (O'Reilly et al. 2016; Yan et al. 2019). However, inconsistencies between model simulations and observations complicate attribution of AMV, though limited instrumental records may complicate robust validation (Alexander et al. 2014). For instance, the persistence of AMV



**FIGURE 5** | Annual SST anomalies regressed onto AMV index (shading), defined as SST in SPNA (blue box), and the surface heat flux anomaly (contours) averaged over the 10 years prior to the year of the AMV indices, in (a) observations (1880–2007); (b) ensemble mean of the CMIP5 preindustrial control simulations; (c) ensemble mean of the CMIP3 slab ocean control simulations. Dashed (solid) contours denote positive (negative) anomalies. Surface heat flux is defined as positive downwards and contoured at  $-0.5, 0, 0.5, 1$  and  $2 \text{ W m}^{-2}$ . SST anomalies for AMV indices calculated over the whole North Atlantic ( $80^{\circ}\text{--}0^{\circ}\text{W}$ ,  $0^{\circ}\text{--}60^{\circ}\text{N}$ ) are shown in the bottom left of each panel. Adapted from O'Reilly et al. (2016).

in current models is consistently weaker than in observations (Lv et al. 2023; Qasmi et al. 2017; Robson et al. 2023), and the lead–lag relationship between AMOC and AMV varies widely across multi-model ensembles (Ba et al. 2014; Lai et al. 2022; L. Zhang and Wang 2013; Zhao et al. 2024) and even within a single-model large ensemble after removing externally forced components (Frankignoul et al. 2017).

Although the AMOC has been regarded as a key driver of AMV, some studies have questioned the role of ocean dynamics in AMV. Clement et al. (2015) demonstrated that GCMs coupled to slab ocean models (i.e., a motionless ocean equivalent to the null hypothesis model, M1) can simulate AMV with similar persistence as in fully-coupled atmosphere–ocean models, but with too large amplitudes (Figure 5). This result implies that AMV can be passively forced as red noise by stochastic white atmospheric noise, notably the NAO. In fact, time integral of the NAO reconstructions yields a time series that aligns closely with AMV observations (O'Reilly et al. 2019; Smeed et al. 2014). Liu, Kwon, et al. (2023) further demonstrated that the AMV spatial pattern can be reproduced if a realistic spatial coherence is retained for the white noise atmospheric forcing, using a hierarchy of stochastic models in direct comparison with a set of GCM simulations coupled to slab ocean or fully dynamic ocean. However, they also suggested a role for ocean dynamics, both vertical and lateral, in generating the AMV with realistic amplitude.

The relative roles of atmospheric and oceanic circulation in driving AMV have also been inferred by relationships between SST and surface heat fluxes. A positive correlation between observed SST variability and downward surface heat fluxes on interannual time scales has been interpreted as atmospheric forcing of SSTs, whereas an inverse correlation on multidecadal timescales has been interpreted as indicative of SSTs primarily driven by ocean processes (Gulev et al. 2013). This phase relationship inversion is also evident in fully-coupled atmosphere–ocean model simulations (Garuba et al. 2018; O'Reilly et al. 2016; R. Zhang et al. 2016), supporting Bjerknes' hypothesis (Bjerknes 1964). It is not, however, present in slab-ocean simulations that do not include ocean dynamics (Figure 5).

Nevertheless, interpretations of the SST–heat flux relationship are nontrivial and remain debated, adding further complexity to our understanding of the drivers of AMV. Cane et al. (2017), using a simple model similar to M1, argued that the sign of the heat flux–SST correlation does not necessarily imply causality, as even a weak oceanic influence can produce correlations that indicate ocean-driven SST variability. Similarly, Patrizio and Thompson (2021) cautioned that the SST–surface heat flux correlation alone is insufficient to infer the role of ocean dynamics. In contrast, R. Zhang (2017) extended Cane et al. (2017)'s framework by incorporating ocean damping (as in M2), demonstrating that the observed spectral characteristics and phase relationships of AMV can only be reproduced when ocean dynamics are explicitly included in the model. This finding highlights the ocean's essential role in shaping AMV characteristics. Building on this, Liu, Gu, and Delworth (2023) further emphasized that red-noise ocean forcing is necessary to explain the low-frequency phase reversal in the SST–surface heat flux relationship, though they concluded that both oceanic and atmospheric processes contribute comparably to AMV.

Other studies have also used stochastic models to quantify the oceanic forcing and damping of North Atlantic SST variability. Gu, Liu, and Delworth (2024) reported that decadal oceanic forcing is stronger than atmospheric forcing ( $F'_o > F'_a$ ) in the mid- and high-latitude ocean, yet this oceanic forcing appears to arise from wind-driven circulation—potentially linked to gyre circulation—rather than the AMOC (Khatri et al. 2024; McCarthy et al. 2015), although the gyre circulation and the overturning circulation (especially when density is used as the vertical coordinate instead of depth) are highly coupled in SPNA (Straneo 2006). Using a simple stochastic model analogous to M2, Patrizio and Thompson (2022) similarly found that oceanic forcing variance exceeds the atmospheric forcing variance in the midlatitudes across a wide range of timescales, yet they also found that, overall, ocean processes substantially damp SST variance at low-frequency timescales. The net damping role of ocean dynamics is supported by results from fully-coupled model simulations that exhibit weaker amplitude AMV compared to their respective

slab-ocean configurations (Liu, Kwon, et al. 2023; Patrizio and Thompson 2022; Murphy et al. 2021). However, this result is inconsistent with studies using similar simple models (L. Li et al. 2020) and state-of-the-art climate model simulations where ocean dynamics are argued to act as a net forcing of AMV rather than damping (Garuba et al. 2018; W. M. Kim et al. 2018; Oelmann et al. 2020). While the debate is still open, a common perspective that has emerged is that while climate models that neglect ocean dynamics (e.g., slab-ocean models) are capable of generating AMV (Clement et al. 2015), they likely omit crucial ocean processes that act in reality. It remains to be determined whether these missing ocean processes are fundamental in driving or damping AMV.

The ongoing debate about atmospheric and oceanic influences on the internal AMV reflects the complexity and regional dependencies of potential underlying mechanisms. It has been more recently shown that vertical mixing and ocean mixed-layer entrainment are crucial for partially reconciling differences in North Atlantic SST variability between slab ocean and full ocean coupled models, particularly in the SPNA (Liu, Kwon, et al. 2023). In particular, a deepening (shallowing) of the mixed-layer affects the upper ocean heat capacity thus decreasing (increasing) SPNA SST variability (Senapati et al. 2024; Yamamoto et al. 2020). AMV has also been shown to drive large-scale atmospheric responses that project onto the NAO through multiple mechanisms, such as stratosphere-troposphere interactions (Peings and Magnusdottir 2016), eddy activity (Ruggieri et al. 2021), and atmospheric blocking (Kwon et al. 2020). While many aspects of the interactions between AMV and the extratropical atmospheric circulation are still to be clarified, cloud-SST interaction and wind-evaporation-SST feedback have been shown to be essential for the existence of tropical AMV (Brown et al. 2016; Oelmann et al. 2020).

### 4.3 | Role of External Forcing

#### 4.3.1 | Attribution of AMV to External Forcings

Although the prevailing view has been that AMV is primarily an internal variability, emerging evidence suggests that external forcings ( $F'_x$  in M3), particularly anthropogenic and volcanic aerosols, may be the main drivers of both recent and paleo AMV (Bellomo et al. 2018; Bellucci et al. 2017; Birkel et al. 2018; Booth et al. 2012; Dai et al. 2022; Dunstone et al. 2013; C. He et al. 2023; Klavans et al. 2022; Mann et al. 2020, 2021; Murphy et al. 2017, 2021; Otterå et al. 2010; Rousseau-Rizzi and Emanuel 2022; Watanabe and Tatebe 2019). In CMIP6 model historical simulations, the externally forced component of AMV—typically calculated from the ensemble mean—shows high correlation with observations in recent decades (Figure 6a). Importantly, the associated impacts on, for example, Sahel rainfall and hurricane activity, also show strong agreement between the forced response and observations (Figure 6b,c), suggesting that external forcing drives not only the AMV itself but also its teleconnections (C. He et al. 2023).

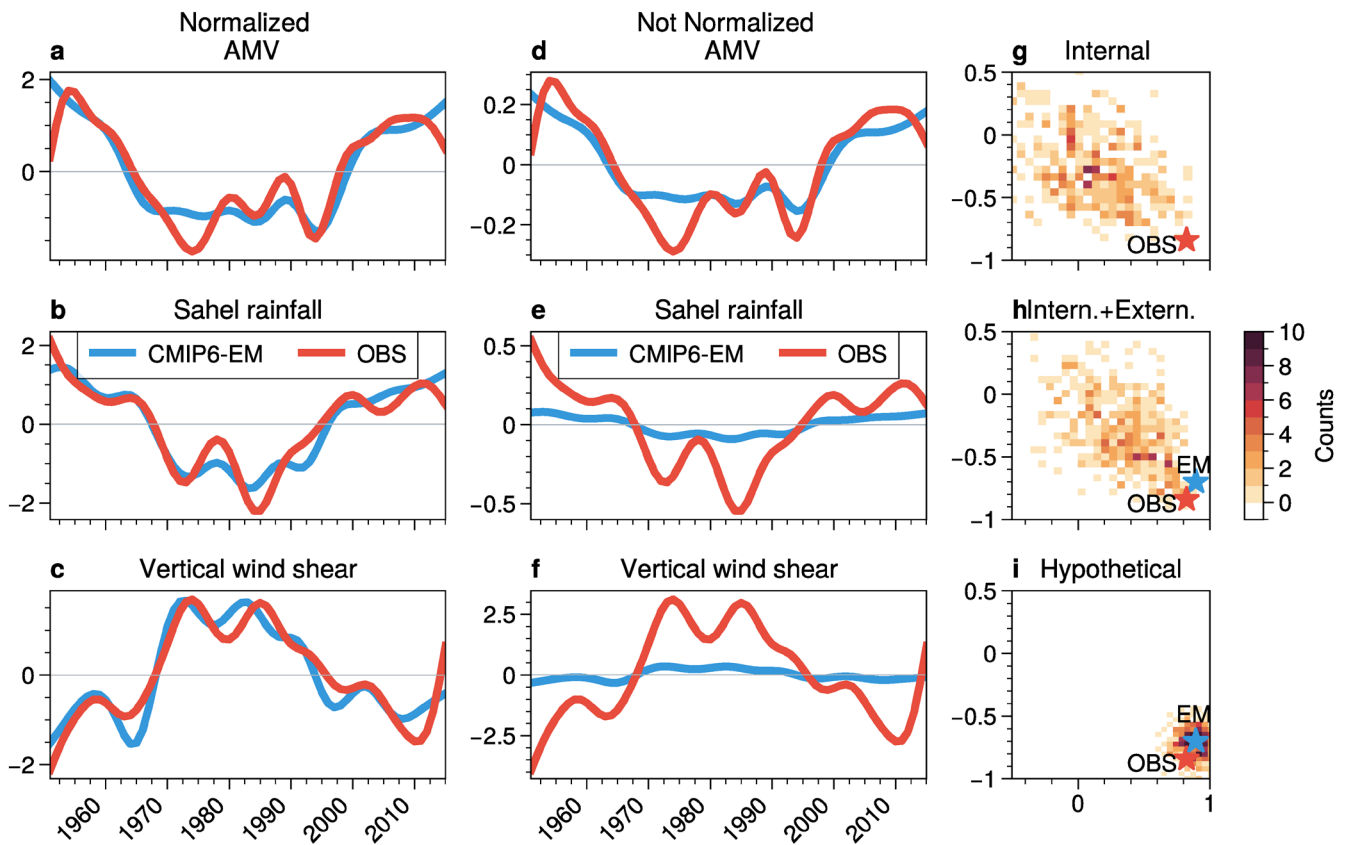
The agreement between observations and simulated forced responses can help pinpoint the driver of the AMV, but it alone

cannot definitively exclude a role for internal variability, similarly for the case of internal AMV simulated by slab ocean models (Section 4.2). Multiple studies have shown that the amplitude of externally forced AMV is much weaker than observed, leading to the hypothesis that observed AMV may result from a mix of internal variability and external forcing, with internal variability likely playing a dominant role (Hua and Dai 2024; Qin et al. 2020; Robson et al. 2023). Consistently, Figure 6d–f demonstrates that the amplitude of the modeled forced AMV and its impacts in CMIP6 are weaker than the observation, seemingly supporting this hypothesis.

However, amplitude-based attribution faces its own challenges. The total variance of AMV and its impacts in historical simulations is systematically weaker than observed, indicating that models may underestimate either the forced response, internal variability, or both (Murphy et al. 2017). This underestimation complicates attribution of AMV in the real world. As an alternative, studies start to explore whether the correlation structure between AMV and its associated climate impacts can provide additional constraints on attribution (C. He et al. 2023). The rationale is that if internal variability dominates AMV, the co-variability between AMV and its downstream impacts, such as Sahel rainfall and Atlantic hurricane activity, should be robust in model-simulated internal variability, even if the amplitudes are biased (as correlations are independent of amplitude). In practice, however, the correlations between internally generated AMV and these impacts in CMIP6 models are noticeably weaker and more broadly distributed than in observations (Figure 6g), partly because other modes of variability such as ENSO and PDV also influence Sahel rainfall and hurricane activity (W. Li et al. 2015; Pielke and Landsea 1999), diluting the AMV-impact coherence in any single realization. In contrast, the ensemble-mean forced response aligns more closely with observed correlations (Figure 6h), suggesting that external forcings may play a larger role in shaping the observed AMV and its climate impacts than the weak amplitude of the forced signal in models would imply (Figure 6d–f, C. He et al. 2023). This discrepancy between the apparent strength of the forced signal in observations and its weak amplitude in models is closely related to the signal-to-noise problem discussed in the following section (Section 4.3.2).

#### 4.3.2 | Signal-To-Noise Problem in Attribution

Strong correlation with observations but weaker amplitude points to what Clement et al. (2025) recently termed the “signal-to-noise problem” in climate attribution. In this framework, the radiatively forced response (the “signal”) is remarkably smaller than internal variability (the “noise”) in any single realization of models, while observations suggest the opposite relationship. This “signal-to-noise problem” is also evident in the correlations between AMV and its impacts across model ensembles. The transition from Figure 6g,h reveals that external forcing in CMIP6 simulations hardly shifts the correlation distribution, indicating that external forcing plays a much weaker role than internal variability in individual model realizations. If models correctly represented the dominance of external forcing suggested by observations, the



**FIGURE 6** | Externally forced AMV, Sahel rainfall, and vertical wind shear (as a measure of hurricane activities) since 1950. (a) Normalized AMV from the ensemble mean of CMIP6 simulations (light blue) and an observation (red). (b, c) As in (a) but for the Sahel rainfall and vertical wind shear, respectively. (d–f) As in (a–c), but for time series without normalization. Units: K, mm/day, m/s, respectively. (g) Two-dimensional histogram of the correlations of the AMV versus Sahel rainfall (x axis) and AMV versus the vertical wind shear (y axis) in each model realizations after forced responses removed (i.e., internal variability). (h) As in (g) but including the forced responses (i.e., internal variability + externally forced signals). (i) As in (h) but forced response in model realizations has been artificially scaled up to match the observation following Smith et al. (2020), such that all model members have a high signal-to-noise ratio (i.e., a hypothetical case). The light blue star (EM) is the correlation associated with the forced responses. The red star (OBS) is the correlation from observation. Replotted from C He et al. (2023).

correlation distribution should concentrate near the forced response (blue star, Figure 6i).

While the causes of the signal-to-noise problem in the modeled AMV have not yet been fully determined, model deficiencies in ocean–atmosphere interactions may play a role. For instance, the low signal-to-noise ratio in the simulated tropical AMV may be attributed to the weak cloud- and dust-SST feedback mechanisms in response to the external forcing in climate models. Incorporation of enhanced cloud-SST feedback in models is shown to amplify the AMV signal in the tropical North Atlantic (Bellomo et al. 2016; Brown et al. 2016; Yuan et al. 2016).

Note this “signal-to-noise problem” in climate attribution is related to, but differs from, the well-documented “signal-to-noise paradox” in climate prediction. The prediction paradox, identified mainly in interannual and decadal NAO predictions using initialized models, reveals that nature appears more predictable than models suggest (Scaife and Smith 2018; Smith et al. 2020). In those initialized experiments, the “signal” encompasses both the radiatively forced component and the response to initial conditions. By contrast, the attribution

studies discussed here employ free-running, uninitialized models where the “signal” derives entirely from radiative forcing, with no contribution from initial conditions. Borchert et al. (2021) compared initialized and uninitialized simulations for SPNA SST after 1980 and found that while radiative forcing explains the majority of observed SST changes, historical simulations underestimate the amplitude of observed sub-polar SST variations, which could be substantially improved through initialization in CMIP6. The persistence of signal-to-noise errors in these uninitialized simulations at decadal timescales thus points directly to deficiencies in how models respond to external forcing, with different implications for our understanding of climate variability and their impacts (e.g., Figure 6; Clement et al. 2025).

## 5 | Centennial Variability and Trends

At longer timescales, SST variability is influenced by internal modes of variability on centennial timescales which can overlap with long-term external forcings. In particular, recent studies have raised concern about the possibility of the AMOC crossing a tipping point (Rahmstorf 2024), which would have strong

effects on North Atlantic SSTs, including features such as the warming hole.

## 5.1 | Internal Longer-Term Variability

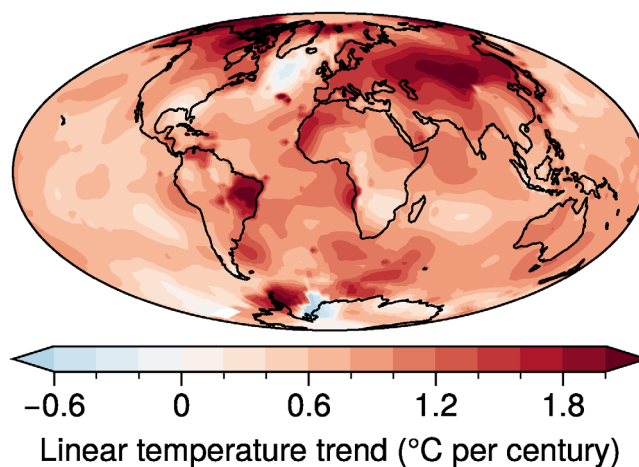
Climate variability at centennial timescales is often associated with internal fluctuations of the AMOC (e.g., Bakker et al. 2022; Ellerhoff et al. 2022; von der Heydt et al. 2021).

AMOC variability on centennial scales, though less studied than multidecadal fluctuations (Buckley and Marshall 2016), can still impact climate and human policy planning over relevant timescales (Bonnet et al. 2021; Kelson et al. 2022). However, there is greater uncertainty in identifying and characterizing modes of internal climate variability at centennial and longer timescales compared to shorter timescales (Laepple et al. 2023). This uncertainty stems from both the scarcity of paleoclimate reconstructions with sufficient spatiotemporal resolution and the computational constraints limiting the length of model simulations needed to capture these long-period oscillations (Lippold et al. 2019; Little et al. 2020).

Emerging studies have leveraged new thousand-year long simulations from CMIP6 preindustrial control runs and LongRunMIP (Eyring et al. 2016; Rugenstein et al. 2019) to study internal variability in the North Atlantic at timescales longer than AMV. This centennial variability is strongly linked to large internal fluctuations in AMOC strength originating from the North Atlantic or the Southern Ocean (e.g.,  $F'_0$  in M2 (Delworth and Zeng 2012; Martin et al. 2013, 2015)). Interestingly, this centennial variability is more prominent in some models, especially those that include the NEMO ocean model (Martin et al. 2015; Mehling et al. 2023, 2024). Notably, Mehling et al. (2024) found that six of nine CMIP6 models displayed significant centennial-scale AMOC variability, compared to only one of six CMIP5 models, with the variability linked to a two-way interaction between AMOC strength and Arctic Ocean freshwater content. They showed that only models with positive sea ice bias in the Labrador Sea exhibited strong centennial-scale AMOC oscillations, suggesting that inter-model differences in sea ice mean state modulate this variability (see also (Jiang et al. 2021; Meccia et al. 2023; Waldman et al. 2021)). In addition to local North Atlantic processes, several studies have identified remote Southern Ocean forcing as an alternative driver of the AMOC and then centennial North Atlantic SST variability, through northward propagation of salinity anomalies (Delworth and Zeng 2012) or compensation between Antarctic Bottom Water and North Atlantic Deep Water (Martin et al. 2015).

## 5.2 | Forced Long-Term Trends

In addition to fluctuations in centennial SST variability, there is a pronounced long-term warming trend in North Atlantic associated with increasing concentrations of greenhouse gases in the atmosphere. However, this warming trend is not spatially uniform but features a cold blob of no or reduced temperature increase in SPNA that is commonly referred to as the “warming hole” (Figure 7) (Rahmstorf et al. 2015). The observed warming hole is characterized by a cooling trend with an



**FIGURE 7** | Linear trends of annual surface temperature since AD 1901. Replotted from Rahmstorf et al. (2015).

average intensity of  $\sim 0.3\text{K century}^{-1}$  in the SPNA during the past century (L. Li et al. 2022). The persistence of the warming hole has important implications for regional climate (Gervais et al. 2020). Atmospheric general circulation models driven by fixed SST patterns show that the warming hole projects onto the positive NAO phase, enhancing and elongating the jet stream eastward (Gervais et al. 2019; Kramer et al. 2024). The warming hole also affects temperature, precipitation patterns, and marine heat waves across the North Atlantic basin (Gervais et al. 2020; Ren and Liu 2021).

The mechanisms driving the observed historical warming hole remain controversial. A weakening AMOC has been proposed as the primary driver (Caesar et al. 2018; K.-Y. Li and Liu 2025), though Keil et al. (2020) argued that historical AMOC weakening is indistinguishable from internal variability, instead attributing the warming hole to enhanced heat transport by the subpolar gyre. Recent studies increasingly point to atmospheric forcing as the primary driver, including jet stream intensification (C. He et al. 2022), increased storminess (L. Li et al. 2022), enhanced wind-induced Ekman transports (Hu and Fedorov 2020), and reduced downward clear-sky longwave radiation (Fan et al. 2025). For example, C. He et al. (2022) demonstrated that a warming hole emerges in slab-ocean model simulations (M1 with additional  $F'_X$ ) despite absent ocean dynamics, with enhanced turbulent heat flux driven by increased westerly winds cooling the SPNA. Li et al. (2022) similarly reproduced the warming hole using a one-dimensional ocean model forced only by observed atmospheric conditions, while Hu and Fedorov (2020) linked the enhanced westerlies to tropical Indian Ocean warming teleconnections.

While the historical warming hole mechanisms remain debated, there is greater consensus about the processes driving warming hole formation under global warming, though the specific location, intensity, and timing of the cooling vary between models (Menary and Wood 2018) and are influenced by internal variability (Gu, Gervais, et al. 2024). It is worth noting that the warming hole is typically defined as a region of reduced warming relative to the global mean, rather than absolute cooling; although some models do show cooling in the subpolar North Atlantic, nearly all project a persistent and intensifying minimum in

the warming pattern under continued greenhouse gas forcing. Model projections consistently show that increased freshwater input from Greenland ice sheet melting and Arctic sea ice loss will stratify the upper ocean, weakening deep convection in the Labrador and Irminger Seas (Gervais et al. 2018; Sévellec et al. 2017). This freshening-induced stratification reduces AMOC strength by inhibiting the formation of North Atlantic Deep Water, decreasing northward heat transport and creating a relative cooling in the SPNA despite overall warming (Bellomo et al. 2021; W. Liu et al. 2020). In addition to AMOC-driven cooling, abrupt subpolar gyre convection collapse events, distinct from AMOC shutdown, can independently trigger rapid cooling of  $\sim 2^{\circ}\text{C}$ – $3^{\circ}\text{C}$  within a decade in both CMIP5 and CMIP6 models (Sgubin et al. 2017; Swingedouw et al. 2021). Ghosh et al. (2023) further demonstrated the complex interplay between the subpolar gyre and AMOC under warming: while both initially cool the SPNA, gyre-driven warming eventually erodes this cooling, leading to SST recovery and depletion of the warming hole despite sustained AMOC weakening. Additionally, external radiative forcings play contrasting roles: anthropogenic greenhouse gases enhance the warming hole, while aerosol emissions tend to reduce it (Chemke et al. 2020; Dagan et al. 2020; Qasmi 2023).

## 6 | Challenges and Future Directions

### 6.1 | Respective Roles of the Atmosphere and Ocean

While substantial progress has been made in the past decades to elucidate the respective roles of the atmosphere, ocean, and their coupling in North Atlantic SST variability, fundamental questions on their respective roles persist across all timescales. At interannual timescales, strong ocean dynamics in regions like the Gulf Stream have recently been shown to drive atmospheric responses, yet how extratropical SST anomalies influence the general atmospheric circulation requires further investigation (Kushnir et al. 2002). At multidecadal timescales, the relative contributions of atmosphere and ocean to internal AMV remain actively debated, in both fully-coupled climate models and stochastic models (e.g., Liu, Gu, and Delworth 2023; Patrizio and Thompson 2021), with even the same stochastic model yielding contradictory results (L. Li et al. 2020; Patrizio and Thompson 2022). At centennial timescales, the cause of the historical warming hole, particularly the role of the AMOC, remains elusive (Section 6.4).

Moving forward, hierarchical modeling approaches offer promising pathways for disentangling these complex interactions. A recently developed model hierarchy in the CESM begins with the “null hypothesis”, a slab ocean model (M1), and progressively incorporates additional processes (M2) (Kwon et al. 2011; Hsu et al. 2022). This architecture resembles the simplified stochastic model hierarchy (Table 1), but with full physics that enable a stepwise investigation of oceanic dynamics. Complementary atmospheric model hierarchies (Medeiros et al. 2016) could similarly isolate how the atmosphere responds to extratropical SST anomalies, where significant uncertainties persist.

Several emerging techniques, though still underutilized in the North Atlantic, offer considerable promise to disentangle

atmosphere–ocean interactions. Surface heat flux partial coupling experiments and mechanically decoupled simulations can isolate specific atmospheric and oceanic contributions (Garuba et al. 2018; Larson, McMonigal, et al. 2024), while interactive ensembles help determine the extent to which internal atmospheric variability forces SST anomalies (Schneider et al. 2023). In particular, eddy-resolving high-resolution models have shown significant improvements in representing air–sea coupling (Siqueira et al. 2024) and atmospheric blocking related to multidecadal SST variability (Hao et al. 2025). Regionally refined simulations, which are less computationally demanding than global eddy-resolving models, have been used to explore the atmospheric response to SST anomalies in the North Atlantic (Wills et al. 2024). Combining some of these approaches may offer a path toward better constraining the relative roles of atmosphere and ocean in SST variability across timescales and improving the predictability of North Atlantic climate variability.

### 6.2 | Model Deficiencies and Spreads

While increased model resolution has generally improved the representation of interannual SST variability in climate models, particularly around the Gulf Stream (Athanasiadis et al. 2022; Patrizio et al. 2023), substantial biases persist (Simpson et al. 2025). A key open question is whether increased resolution alone is sufficient to address most of these biases, or if concurrent improvements to model physics are also necessary. Future research should diagnose the sources of these biases, including deficiencies in air–sea coupling and the representation of mesoscale ocean eddies and their atmospheric interactions (Parfitt et al. 2016, 2017; Czaja et al. 2019; Wills et al. 2024). Coordinated model experiments that systematically vary key parameters or further refine resolution (e.g., Haarsma et al. 2016) may help identify crucial processes required for more realistic simulations of North Atlantic SST variability.

Greater challenges emerge at longer timescales. Simulated AMV in climate models often differs substantially from observations in amplitude and persistence (Mann et al. 2020; Robson et al. 2023; X. Xu et al. 2019). The diverse AMOC–AMV relationships across models raise critical questions about the underlying physical processes responsible for this inter-model spread. Similarly, at centennial timescales, the presence of strong internal AMOC oscillations in some models but not others (Mehling et al. 2024) points to fundamental differences in the representation of ocean and sea-ice processes. The warming hole’s location and intensity also vary considerably across models, further highlighting these representational uncertainties.

The atmospheric response to North Atlantic SST anomalies is typically small but exhibits considerable diversity across models on decadal and longer timescales (Vacca et al. 2025). Ruprich-Robert et al. (2017) demonstrated opposing North Atlantic storm track responses to the AMV between models, highlighting fundamental uncertainties in atmospheric circulation to underlying SST anomaly. Si et al. (2023) similarly showed that downstream atmospheric teleconnections vary substantially among models. The Cold Blob Model Intercomparison Project (ColdBlobMIP) further revealed substantial inter-model spread in sea level pressure responses to the North Atlantic warming hole, with

different physical mechanisms dominating in individual models (Kramer et al. 2025).

These discrepancies emphasize the need for systematic inter-model comparisons of North Atlantic SST variability on multidecadal and longer timescales. Paleoclimate proxies indicate that the disparity between models and observations is even greater at centennial and multi-centennial timescales compared to shorter timescales (Laepple et al. 2023; Laepple and Huybers 2014), presenting persistent challenges for simulating low-frequency SST variability. Direct comparison between modeled proxy and observation (e.g., water isotopes) is encouraged in paleoclimate modeling to better identify and address the origins of these biases.

### 6.3 | Internal or Externally-Forced AMV

The debate over whether AMV is driven by internal variability or external forcing remains one of the most contentious issues in North Atlantic climate research. Both internal and external mechanisms can reproduce certain aspects of observed AMV, yet neither fully captures all its characteristics.

Under the hypothesis that AMV is internally generated, several key discrepancies remain. Modeled internal variability struggles to reproduce the observed amplitude, persistence, and apparent periodicity of AMV (Mann et al. 2020; Robson et al. 2023; R. Zhang 2017), but the short instrumental record limits robust evaluation (Alexander et al. 2014). In addition, simulated atmospheric circulation responses to internally generated AMV differ from observations (Si et al. 2023; Ting et al. 2014), with models likely underestimating AMV's influence on the extratropical circulation (Bracegirdle 2022; W. M. Kim et al. 2018; Simpson et al. 2018). These systematic discrepancies may reflect misrepresentations of fundamental processes, including those associated with the model biases discussed in the previous section.

The hypothesis that AMV is externally forced raises a different set of issues, particularly the timing of when external forcings become dominant. C. He et al. (2023) proposed that external forcing became dominant after 1950, though this temporal division likely requires refinement. Further investigation is needed whether externally-forced AMV reproduces observed AMOC-related fingerprints, including sea surface salinity, upper ocean heat content, and surface heat flux, during the post-1950 period. Additionally, the observed AMV spatial pattern differs from externally-forced patterns in models and more closely resembles patterns associated with internal variability (Robson et al. 2023; Yan et al. 2019). Multidecadal SST-heat flux relationships are also seemingly inconsistent between models and observations.

Most critically, the signal-to-noise problem in climate models demands explanation on its root causes, including potential deficiencies in atmosphere–ocean interactions (e.g., involving the NAO, see Patrizio et al. 2025) and weak positive feedbacks (e.g., cloud feedbacks, see Yuan et al. 2016). Enhanced resolution, improved model physics, and better initialization strategies may help resolve these issues. Additionally, the development of new metrics to evaluate prediction performance beyond simple correlations, particularly those focused on climate impacts, would

be valuable for both scientific understanding and practical applications. Emerging tools such as artificial intelligence and machine learning also offer promising avenues for improving the decadal prediction of North Atlantic SST variability (e.g., Q. Gu and Gervais 2021; Liu, Wang, and Kwon 2023).

### 6.4 | Fingerprint of the AMOC

Despite the complex interplay between atmospheric and oceanic processes driving the warming hole, SST indices in the SPNA have been widely used as surface fingerprints to estimate AMOC strength and variability (Caesar et al. 2018). While the relationship between AMOC and SPNA SST is well-established (e.g., Drijfhout et al. 2012), deriving an SST index that accurately represents the underlying meridional overturning circulation remains challenging, particularly for the past century (e.g., Chafik and Lozier 2025; Terhaar et al. 2025). On one hand, the strength of AMOC-SST coupling appears to be timescale-dependent, with internal variability introducing varying degrees of atmosphere–ocean coupling even within a given timescale (Bellucci et al. 2022). On the other hand, recent studies have highlighted fundamental limitations of SST-based fingerprints (Ben-Yami et al. 2024; McMonigal et al. 2025; Zhu and Cheng 2024) and proposed improved fingerprints (Ferster et al. 2023; Zhu and Liu 2020).

Moving forward, systematically validating the assumptions underlying commonly used AMOC fingerprints is critical. Research should assess the strengths and limitations of various fingerprinting methods while developing integrated approaches that combine multiple lines of evidence for more robust reconstructions. Since these fingerprints are typically developed and validated using climate model simulations, continued progress depends on improving model fidelity.

### 6.5 | Global Warming

Projections of how SST variability will evolve under global warming remain highly uncertain across persistence, amplitude, and spatial patterns. Recent studies report seemingly contradictory trends: some find increased persistence of daily SST anomalies in the subpolar and subtropical North Atlantic linked to decreased oceanic damping rates ( $\lambda_o$  in M2) (C. Lee et al. 2025; J. Li and Thompson 2021), while others document reduced persistence at interannual timescales (Shi et al. 2022). Resolving these discrepancies is crucial for understanding future extreme events, including marine heat wave duration and intensity (e.g., Oliver et al. 2019).

While the forced AMV depends on the timescale and intensity of external forcings, the response of internal AMV to global warming is contentious. Several studies using CMIP5 and CMIP6 models report reduced AMV amplitude under warming (Qin et al. 2022; S. Wu and Liu 2020; Zanchettin and Rubino 2024), attributed primarily to an increased damping ( $\lambda/\rho C_p H$ ) as enhanced upper-ocean stratification develops from surface-intensified warming. This stratification also increases buoyancy frequency ( $N^2$ ), accelerating baroclinic Rossby waves and thereby shortening the AMV period (Cheng et al. 2016; S. Wu

and Liu 2020). Conversely, S. Li et al. (2025) found that elevated CO<sub>2</sub> increases both AMV amplitude and period, arguing that mixed-layer shoaling reduces effective upper-ocean heat capacity, amplifying SST fluctuations, while a weakened AMOC extends the timescale needed for AMV development. Adding to this complexity, Brown et al. (2017) found no change in AMV characteristics under increased CO<sub>2</sub> in their model simulations.

These conflicting results highlight fundamental gaps in our understanding of how changing mean states affect SST variability. For example, the influence of projected AMOC decline on interannual-to-multidecadal SST variability remains particularly uncertain. Future research must clarify the physical links between mean-state changes—including mixed-layer depth, stratification, circulation patterns, and jet stream/storm track positions—and changes in SST variability characteristics. Leveraging both idealized and comprehensive hierarchical climate models will be essential for disentangling these complex interactions and improving projections of North Atlantic SST variability under continued warming.

## 7 | Conclusion

This review has synthesized current understanding of North Atlantic SST variability across multiple timescales, revealing a complex interplay of atmospheric forcing, oceanic dynamics, and external drivers that remains incompletely understood despite decades of research. Through the lens of a stochastic climate model hierarchy, we have shown that:

- On interannual timescales, atmospheric forcing predominantly shapes the tripole SST pattern in the North Atlantic driven by the NAO. However, improvements in observations and model resolution increasingly reveal active oceanic roles at these shorter timescales, particularly in dynamically active regions, for example, the Gulf Stream.
- At decadal-to-multidecadal timescales, where oceanic processes, particularly the AMOC, have traditionally been considered dominant to the AMV, we now recognize that atmospheric stochastic forcing and external forcings also play crucial roles, with the exact partitioning of these contributions remaining actively debated.
- On even longer time scales, the SST variability is dominantly driven by the AMOC variability. The emergence of the warming hole in the SPNA, however, exemplifies the complex interplay in the atmosphere and ocean dynamics.

While substantial progress has been made in characterizing patterns of variability and their impacts, from the NAO-driven tripole pattern to the basin-scale AMV and the centennial warming hole, fundamental questions persist:

- The respective roles of atmospheric and oceanic processes in driving these patterns of variability, their interactions across timescales, and how these mechanisms will evolve under continued global warming.
- Substantial spread and biases in climate models, particularly in simulating AMV amplitude and persistence,

inconsistent AMOC-AMV relationships across models, and varying responses of atmospheric circulations to the SST anomaly across timescales.

- The signal-to-noise problem, where models systematically underestimate the amplitude of externally forced responses relative to internal variability, challenges our fundamental understanding of climate attribution and prediction.
- The validity and reliability of AMOC fingerprints used to reconstruct past AMOC variability and predict its future change, given limited direct observations and strong atmospheric processes dependencies.

Resolving these fundamental questions is essential for improving our ability to predict and prepare for changes in North Atlantic SST variability, with implications extending far beyond the ocean basin itself to affect weather patterns, ecosystems, and human societies across the globe.

### Author Contributions

**Chengfei He:** conceptualization (lead), project administration (lead), writing – original draft (lead), writing – review and editing (lead). **Casey R. Patrizio:** conceptualization (equal), writing – original draft (equal), writing – review and editing (supporting). **Young-Oh Kwon:** writing – review and editing (supporting). **Katinka Bellomo:** conceptualization (equal), writing – original draft (equal), writing – review and editing (supporting).

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### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

### Related WIREs Articles

[Equatorial Atlantic variability—Modes, mechanisms, and global teleconnections.](#)

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