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Key Points:

- Single model simulations of the pre-industrial last millennium suggest periods of heightened volcanic activity produce forced Atlantic Multidecadal Variability-like signals
- No evidence exists for internally generated oscillatory behavior on multidecadal timescales in the North Atlantic
- The North Pacific Ocean, in contrast to the North Atlantic, shows considerable internal variability

Supporting Information:

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

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Multidecadal Temperature Variability in the Community Earth System Model Last Millennium Ensemble

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Abstract We investigate the characteristics of inter- and multidecadal temperature variability in the Community Earth System Model Last Millennium Ensemble through spatiotemporal spectral analysis of forced and internal fields. We find high spectral density in North Atlantic (NA) and global temperature that is concurrent with periods of high volcanic activity, suggesting a forced origin. There is no evidence in the ensemble of an internally-generated and time-persistent signal for Atlantic Multidecadal Variability (AMV), the dominant mode on those timescales. The spatial patterns of low-frequency variability indicate activity throughout the North Pacific, where signals persist to a greater extent after the forced signal is removed, in contrast with the NA where only the subpolar region associated with deep water formation is active. Subtropical and tropical NA regions are strongly associated with forced responses, suggesting the canonical AMV pattern is comprised of both internal and forced components, with the latter being the main driver.

Plain Language Summary Climate change results from a combination of externally forced changes and internal, random variability. We used a series of simulations of Earth's temperature evolution during the pre-industrial last millennium (850–1850 CE) from a single model to investigate the Atlantic Multidecadal Variability (AMV), a purported mode of potentially oscillatory climate variability detected in various climate data sets and thought to be the most influential mode in multidecadal timescales. By determining the forced component of variability using the mean of all simulations, we explore the extent to which AMV is internally generated or externally forced and identify its spatial expression. Our results indicate that during periods of high volcanic activity, a multidecadal oscillation can be detected. However, this signal is not present in the internal fields, suggesting that the real-world AMV is externally forced. Our methods allow for the spatial pattern reconstruction of any detected signals globally, which leads us to find more evidence for internal variability in the North Pacific than in the Atlantic. These findings support growing evidence that AMV is a combination of externally forced and internally generated variability, in which the forced component is dominant, hindering the prospect of its predictability.

1. Introduction

Characterizing multidecadal climate variability and its underlying physical mechanisms is one of the greatest challenges for robust assessment of uncertainty in climate model simulations (Deser et al., 2012; Hawkins & Sutton, 2009; Lehner et al., 2020). Central to this challenge has been the difficulty in identifying and predicting low-frequency internal variability in the North Atlantic (NA) region, which influences climatic conditions in the surrounding North American and Eurasian continents (Semenov et al., 2010; Sutton & Hodson, 2005), Atlantic hurricane activity (Goldenberg et al., 2001; Ting et al., 2019), the northeast Brazil and Sahel/Indian monsoons (Knight et al., 2006; R. Zhang & Delworth, 2006), and has been linked to the so-called warming hiatus of the early 21st Century (Li et al., 2020; Yang et al., 2020). Originally named the Atlantic Multidecadal Oscillation (AMO; Kerr, 2000) due to a purported narrowband pattern of oscillatory behavior (Delworth & Mann, 2000; Folland et al., 1986), the term Atlantic Multidecadal Variability (AMV) is now preferred to describe the dominant mode of sea surface temperature (SST) variability over the NA. This allows for a wider range of temporal and spatial expressions (R. Zhang, 2017), as well as implicitly including both internal oscillatory and non-oscillatory behavior and Atlantic surface temperature responses to external forcing (Frankignoul et al., 2017). As the dominant mode of NA and global climate variability in multidecadal timescales (Chylek et al., 2014), the AMV has also been observed to have an impact on the Pacific Decadal Oscillation (PDO) or Interdecadal Pacific Oscillation (IPO), through extratropical (e.g., R. Zhang & Delworth, 2007; L. Zhang & Zhao, 2015) or tropical

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(e.g., Meehl et al., 2021; Ruprich-Robert et al., 2017) atmospheric teleconnections. The spatial and temporal expressions and climate impacts of AMV have been documented through studies of observations, proxy data and model simulations (e.g., Enfield et al., 2001; Michel et al., 2022; Wang et al., 2017), yet the specific mechanisms that underlie this pattern are still subject to debate (Bellucci et al., 2017; Delworth & Mann, 2000; Schlesinger & Ramankutty, 1994).

Although there is consensus that AMV is a combination of internally generated variability—related to the Atlantic Meridional Overturning Circulation (AMOC) and its responses to stochastic ocean-atmosphere interactions (Kim et al., 2020), or other modes of variability like the North Atlantic Oscillation (NAO; Delworth et al., 2017)—and SST responses to anthropogenic and natural forcings (Deser & Phillips, 2021; Qin et al., 2020), the extent to which internal versus external processes influence AMV is a matter of contention (Baek et al., 2022; Bellomo et al., 2018; Booth et al., 2012). A forced origin for AMV has been proposed by a number of studies wherein volcanic activity is identified as the driver of multidecadal SST variability (e.g., Birkel et al., 2018; Klavans et al., 2022; Otterå et al., 2010). Contrastingly, other groups have concluded that AMV is primarily internally driven through connections with AMOC and with a limited (or modulating) role for external forcing factors (e.g., Kim et al., 2020; Qin et al., 2020; Robson et al., 2023). Further mechanisms identified as drivers of internal AMV include stochastic atmospheric forcing (Clement et al., 2015), coupling and amplifying of the NAO (Delworth et al., 2017; Sutton et al., 2018) and cloud-radiation feedbacks (Bellomo et al., 2016; Cane et al., 2017). In a series of efforts, Mann et al. analyzed control and forced CMIP5 simulations and suggested that AMV is predominantly a response to external forcing in the Last Millennium (Mann et al., 2021) and to anthropogenic aerosol forcing in the industrial era (Mann et al., 2020).

The characterization of AMV is complicated by the lack of consensus on its defining index—commonly calculated over the entire NA basin—which leads to inconsistent results (Robson et al., 2023). Furthermore, common methods for isolating internal AMV such as linear detrending of the low pass filtered and spatially averaged NA SST timeseries (i.e., the canonical AMV index; Enfield et al., 2001), subtracting global mean SST from the NA series (Trenberth & Shea, 2006), and other methods (e.g., Steinman et al., 2015; Ting et al., 2009) have been found insufficient to varying degrees (Deser & Phillips, 2021), and more sophisticated methods have been proposed (Deser & Phillips, 2023; Frankignoul et al., 2017; Wills et al., 2020). The range of methodologies for characterizing the internal AMV, compounded with the variety of time periods in both industrial and pre-industrial data sets, have led to a range of periodicities from 20 to 40 years to as long as 60–80 years (Mann et al., 2020; Zhou et al., 2020). Observational data sets are likely too short to accurately encompass multidecadal variability (Mann et al., 2021) and are heavily influenced by anthropogenic GHG and aerosol forcing (Bellucci et al., 2017; Booth et al., 2012), while the estimation of internal variability in model simulations is known to be dependent on the choice of forcing series (Fyfe et al., 2021). When large ensembles of model simulations are available, however, the use of the single-model ensemble mean (Deser & Phillips, 2021; Mann et al., 2022), or of several models (Knight, 2009; Kravtsov & Callicutt, 2017), has been shown to adequately represent the forced signal (Frankcombe et al., 2018).

Here we characterize the spatiotemporal expressions of multidecadal variability in global surface temperature fields and explore their relationship to the canonical AMV, the main mode of variability over those timescales, by expanding on the methods and scope of Mann et al. (2020, 2021). We focus on the pre-industrial last millennium (850–1850 CE) to avoid two key issues: (a) the historical period is insufficiently long to capture more than a few cycles of a multidecadal signal, which makes the significance of any results tenuous, as the secular band is close to the upper range of AMV periodicity (Mann et al., 2020), and (b) the competing influences of anthropogenic GHG and aerosol emissions with natural forcings makes the isolation of internal signals challenging (Thompson et al., 2015). In contrast with Mann et al. (2020, 2021), we make use of a single model ensemble, thereby avoiding structural uncertainties present in multiple model comparisons and accurately determining the forced temperature signal (Frankcombe et al., 2018). Additionally, by employing Multi-taper Method Singular Value Decomposition (MTM-SVD) on the data fields, we are able to detect and reconstruct any pattern in the ensemble without calculating an AMV index and thus without any a-priori assumptions regarding its spatial and temporal characteristics. Furthermore, to explore the extent to which volcanic forcing impacts multidecadal SST variability, we also conduct spectral analyses across specific time periods of high and low volcanic forcing, by use of a moving window MTM-SVD approach, and compare resulting spectra in the NA to global fields under the assumption that changes in radiative forcing manifest themselves on a global scale while AMV-related variability would be strongest in the NA region. Lastly, we explore the global spatial patterns associated with purported oscillatory behavior over a range of timescales to assess the consistency with which the patterns are expressed across the ensemble and compare forced versus internal expressions in the NA and Pacific regions.

2. Data and Methods

2.1. Data: The CESM LME

The Community Earth System Model (CESM) Last Millennium Ensemble (LME; Otto-Bliesner et al., 2016) is the largest available set of single model simulations spanning the past millennium, thereby providing a unique testbed for exploring climate variability across multiple timescales. We focus on the "All Forcing" ensemble (henceforth "LME"; $N = 13$), forced by volcanic, solar, orbital, GHG, aerosol and land-use changes (see Otto-Bliesner et al., 2016) and estimate the forced signal as the ensemble mean ("LME-EM") which is then subtracted from each individual ensemble member to isolate the internal variability ("LME-unforced"; Frankcombe et al., 2018). The volcanic forcing series used in the LME (Gao et al., 2008) is also used in CMIP5/PMIP3 last millennium protocols (Bothe et al., 2013), allowing for direct comparison between our results and previous analyses of those data (Mann et al., 2021). The LME consists of fully coupled transient simulations using version 1.1 of CESM with the CAM5 atmospheric model (Hurrell et al., 2008), land and atmosphere resolution of ~2° and ocean and sea ice of ~1°. We analyze surface air temperature fields which are strongly correlated with SSTs and yield nearly identical results for ocean regions.

2.2. Method: Spectral Analysis of Climate Timeseries and Fields

We perform power-spectral-density analysis (PSD) via the Multi-taper Method (MTM; Thomson, 1982) on global and NA (defined as the region bound by 80°W–0°E) area-weighted average temperature series to detect broad spatial-scale signals and for the sake of comparison with similar studies (Ba et al., 2014; Bellomo et al., 2018; Miao et al., 2024). Additionally, we apply wavelet analysis (Torrence & Compo, 1998) to LME-EM, allowing for visualization of the spectral density in individual timeseries as it changes through time. Due to the limitations in detecting periodic signals that may weakly project onto global or regional averages (like AMV), we employ the MTM-SVD method, which was designed for the detection of narrowband spatiotemporal signals in climate data fields (Mann & Park, 1994, 1999). Unlike data decompositions in the time domain such as PCA/EOF, MTM-SVD performs PSD analysis on each timeseries, transforming the data into the frequency domain before detecting patterns of variability through SVD. The process is done over a bandwidth $\pm pf_r$, where f_r is the minimum resolvable frequency ($f_r = 1/N\,\Delta t$; N samples Δt timestep) and p is a bandwidth parameter determined by $p = K - 1$, with K being the number of tapers in MTM. The Local Fractional Variance (LFV) is the signal detection variable whose magnitude indicates the relative level of spatiotemporal activity in a specific frequency band. Under the assumption that a red noise spectral background varies modestly in the narrow bandwidth of the analysis and thus locally approximates white noise, significance limits are calculated through bootstrapping wherein LFV spectra are calculated for temporally randomized fields. Once a signal is identified, it may be reconstructed from the complex SVD decomposition. Percent-variance-explained maps of the reconstructed signal versus the original fields are calculated to construct the spatial patterns. See Supporting Information S1 for a full description of the method.

3. Results and Discussion

We first apply PSD and wavelet analysis to investigate signals that may have a significant imprint on North Atlantic mean surface temperatures and that are persistent throughout the length of the simulations. The timeseries analyzed here are analogous to the canonical AMV index (area-weighted mean surface temperatures; Figure 1a Top). MTM analysis on each LME and LME-unforced ensemble member characterizes the total variability and internal-only components of the ensemble, while LME-EM corresponds to the forced-only signal (Figure 1b Right). Wavelet analysis of LME-EM (Figure 1b, Left) represents the temporal evolution of spectral power of the forced signal and is directly related to the MTM spectrum of LME-EM. Two distinct periods of enhanced forced activity, 1200–1300 CE and 1600–1850 CE, both due to high rates of volcanism, are evident in the wavelet analysis. Note that these periods show heightened activity across a wide range of periodicities but are temporally bounded by relative volcanic quiescence. MTM spectra of the LME ensemble and LME-EM show enhanced power in the ~40- and ~60-year periodicities, which is absent in the unforced data. Indeed, diminished spectral density through all frequencies is observed in the LME-unforced series, suggesting that through the last

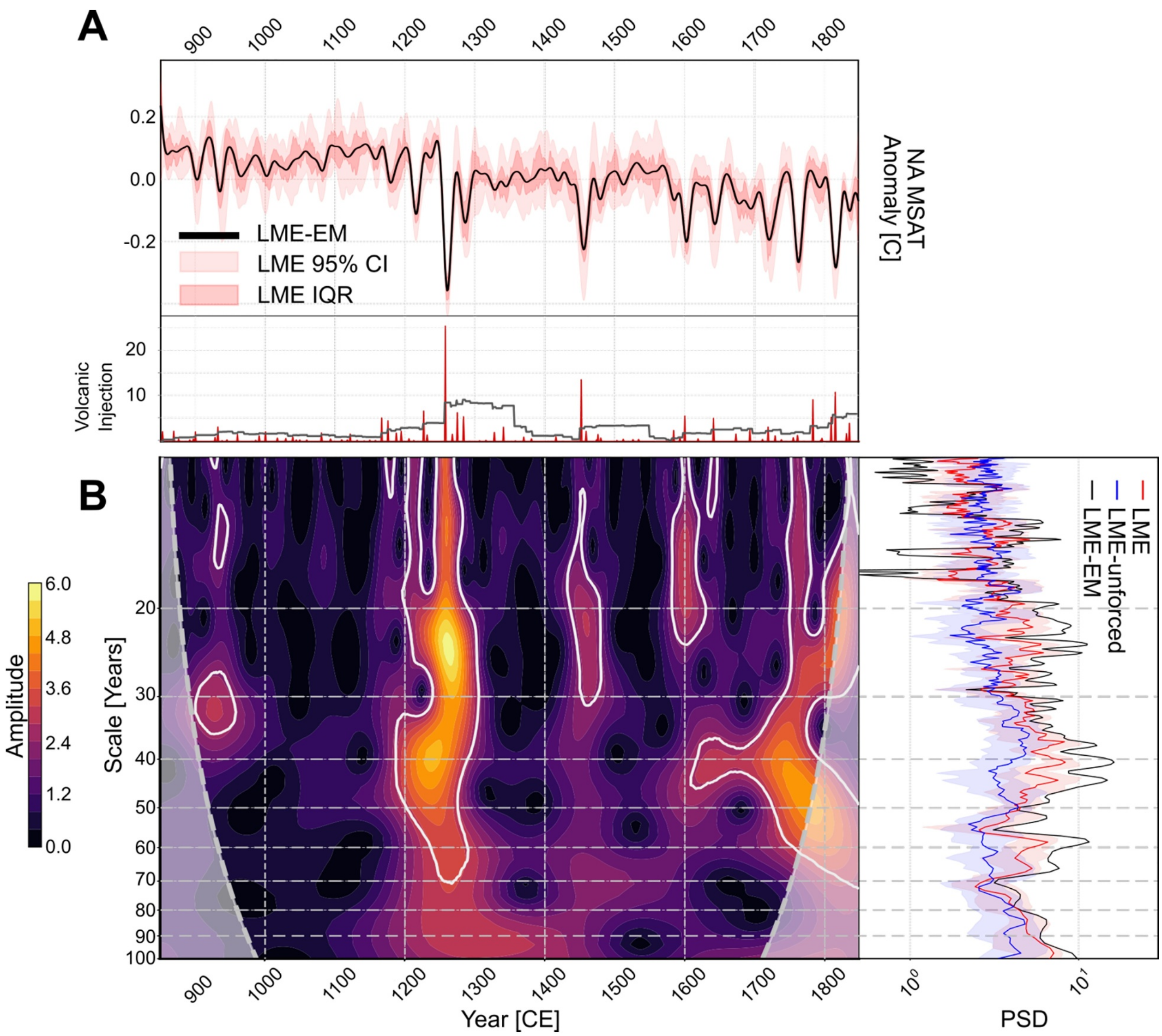

Figure 1. (a) Top: LME Ensemble Mean (LME-EM) North Atlantic mean surface air temperature (NAMSAT) anomaly timeseries (black line) and spread of the LME ensemble (IQR and 95% spread in dark and light red, respectively). All timeseries are 20-year lowpass filtered only for visualization. Bottom: Gao et al. (2008) global stratospheric volcanic aerosol injection standardized series (z-scored; red) and 100-year trailing average of the same data (dark gray) to highlight centennial-scale fluctuations. (b) Left: Continuous wavelet transform of the LME-EM. Light gray outlines represent 90% confidence levels. Right: MTM spectrum mean (solid) and IQR (shading) for LME, LME-unforced and LME-EM.

millennium a large proportion of oscillatory or pseudo-oscillatory behavior in mean NA SST (and thus AMV index) is driven by external forcing. Figure S1 in Supporting Information S1 shows the same analysis applied to global temperature series, wherein similar spectral features are present in the volcanically active periods of the last millennium, further suggesting that volcanic forcing is the main driver of multidecadal variability.

Studies comparing output from CESM and other models, paleoclimate proxy data and reanalysis products have reported enhanced spectral density in the ~60–80-year band for NA SSTs for the second half of the last millennium (post 1250 CE), but not before then (Dai et al., 2022; Mann et al., 2021; Miao et al., 2024). Our results suggest that these observations are likely due to high volcanic activity during the 13th, 17th, and 18th Centuries that manifests over a broad band of frequencies. Importantly, a comparison between the MTM spectra and the wavelet reveals that spectral peaks in certain frequencies do not correspond to signals consistently expressed through time, but are localized temporally near the high-volcanism periods. This suggests that multidecadal variability attributed to the AMV in PSD analyses may be the result of time-varying forcing mechanisms whose

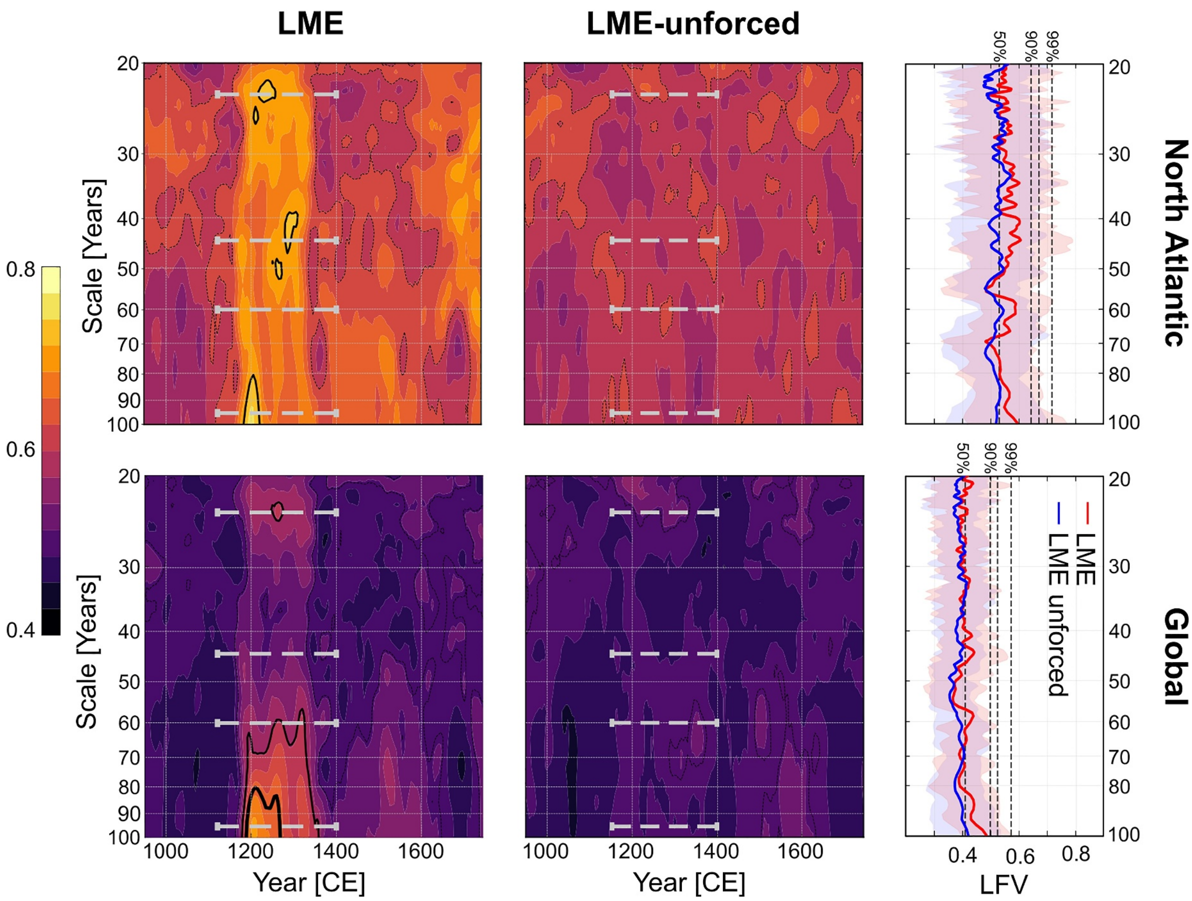

Figure 2. Left and Middle: Moving-window (200-year) LFV spectra of North Atlantic and global temperature fields from the LME and LME-unforced. Dashed, thin solid and thick solid contours represent 50%, 90%, and 95% confidence levels, respectively. Thick horizontal ranges denote the periods of analysis for subsequent signal reconstruction (Figure 3). Right: LFV spectra of NA and global temperature fields for LME (red) and LME-unforced (blue). Mean and 2σ range of spectra represented by thick lines and shading.

impacts in distinct periods may be sufficient to produce to a spectral peak for the full series. In analyzing the mean spectrum of all simulations, as well as the spread of individual spectra, we find no common periodic behavior in the CESM LME NA mean surface temperature series that points to a mode of internal variability expressed on the timescales of interest. This indicates that CESM, in contrast to other models, does not produce significant internal, multidecadal variability in the North Atlantic (Ba et al., 2014; Fang et al., 2021; Mavilia et al., 2018).

The internal portion of the AMV is thought to be a redistribution of heat over the NA, and it may not necessarily project strongly onto mean temperature series (Mann et al., 2021) such as the AMV index or global series. To explore the spectral power of the temperature fields as a whole, we perform MTM-SVD analysis (Mann & Park, 1994) to spatially and temporally characterize any prevalent signal. By analyzing both NA and global fields we are able to discern if an AMV-like pattern is due to global variability (e.g., cooling due to volcanism) or localized phenomena (ocean circulation). Though the mean LFV spectra of the simulations (Figure 2, Right) show no statistically significant narrow-band signal through the last millennium, a moving-window MTM-SVD analysis reveals that apparent oscillatory behavior in the temperature fields is detected in all realizations only during times of strong forcing (Figure 2, Left). Signals above the 90% confidence level are absent in the NA analysis except for short ranges of time within ~100 years of the Samalas eruption of 1,257 CE, the largest eruption in the Gao et al. (2008) volcanic forcing record, and the global analysis shows highly significant signals close to the secular band (100 years) at the same time. A similar analysis of a much smaller ($N = 5$) ensemble of experiments forced only by volcanism shows similar trends in all time periods and spectral bands (Figure S2 in Supporting Information S1), further indicating that volcanism drives any apparent periodic behavior in CESM. Once internal variability is isolated, no spatiotemporally coherent signal exists that is common to all experiments and that can be distinguished from a colored noise null hypothesis (Figure 2 Middle). Time-slice comparison of LFV spectra in the LME and volcanic-only simulations produces similar results, wherein discernible differences between the forced and unforced fields are only present in periods of high volcanism (Figure S2 in Supporting Information S1).

After assessing the level of spectral power across different time periods in the CESM LME, we further leverage MTM-SVD to characterize the spatial patterns associated with prominent signals. We analyze temperature fields during the period of highest LFV spectral density related to heightened volcanic activity (~1150–1400 CE) and calculate mean %-variance-explained maps that show the dominant spatial patterns in the ensemble. As no spatial regressions or correlations are necessary to characterize spatial patterns of variability in a particular frequency slice, no assumptions about the relationship between forced and unforced signals with any indexes or features in the data are needed (Mann et al., 2021), providing an unbiased view of the locations where significant temperature variability occurs. Furthermore, because the MTM-SVD method is capable of reconstructing a signal regardless of its relative amplitude or spatial extent, we are able to produce global maps of variance explained that provide context as to other manifestations of low-frequency temperature variability outside of the NA, particularly in the Pacific, and that do not dampen signals exclusive to the NA (Figure S4 in Supporting Information S1). We focus on bidecadal (~23 years), interdecadal (~44 years), multidecadal (~60 years) and centennial (~95 years) periodicities (Figure 3), chosen with the goal of capturing the highest LFV values in the evolutive spectra (Figure 2). Though the multidecadal slice does not show heightened spectral density in the MTM-SVD analysis, we show it due to its prevalence in previous works (Dai et al., 2022; Lapointe et al., 2020; Mann et al., 2021; Miao et al., 2024).

The signal reconstruction and resulting variance-explained maps of the forced ensemble (Figure 3 Left) display general similarities across the selected timescales such as heightened activity in the Gulf of Mexico, tropical and subtropical NA and subtropical Pacific. Previous studies characterizing spatial patterns of variability due to volcanism show similar spatial distributions on decadal and multidecadal timescales (Bellomo et al., 2018; Deser & Phillips, 2021; Fang et al., 2021; Watanabe & Tatebe, 2019). As the global impacts of volcanic cooling in CESM have been shown to strongly influence tropical oceans (Otto-Bliesner et al., 2016), observed activity in the tropical and southern Atlantic and Indian Oceans are expected in the forced fields. The NA activity seems to disappear, or attenuate significantly, in the internal fields (Figure 3, Right), suggesting that it is not predominantly the result of the model's reproduction of internal variability in the form of oceanic circulation or interactions with atmospheric phenomena. An exception is the subpolar NA region where the internal signal is relatively strong, likely because of internal variability related to AMOC and other ocean-atmosphere circulation patterns like the NAO (Frankignoul et al., 2017; McCarthy et al., 2015).

Although volcanic eruptions typically have a short-term direct effect on polar NA SSTs through sea ice expansion, when clustered they can have longer lasting impacts due to the ice-albedo feedback, which ultimately results in freshwater injection that lowers salinity and slows AMOC convection (Dai et al., 2022; Slawinska & Robock, 2018). In effect, it is suggested that a series of large eruptions in the late 13th Century, starting with the Samalas event, triggered the centuries-long cooling that led to the Little Ice Age (LIA; Miller et al., 2012). Our MTM-SVD analysis captures decadal and multidecadal processes in this subpolar region that are a combination of internal variability and long-term responses to volcanic forcing, though there appears to be no significant narrow-band periodicity to the signal. Thus, our results suggest that the long-lasting impacts of heightened volcanism during the 13th and 14th centuries leads to an amplification of NA SST variance by modulating AMOC activity through sea-ice expansion, reduced heat loss and freshwater injection, which would impact convection (Delworth & Mann, 2000). Periods in the last millennium with higher volcanic activity, as well as single large volcanic events, appear to have a greater AMOC variability on both annual and interdecadal timescales (Figure S5 in Supporting Information S1). Otto-Bliesner et al. (2016) similarly document how some eruptions have an immediate cooling influence on AMV followed by a decadal-scale warming, highlighting how volcanic effects influence surface temperatures and ocean circulation on different timescales.

The patterns of variability in the Pacific Ocean are more persistent between the LME and LME-unforced fields in contrast with the NA, with the strongest signal resembling the extratropical boundaries between the PDO dipoles (Hua et al., 2018; Takahashi & Watanabe, 2016; Xu et al., 2024). This could suggest that ocean circulation has a stronger influence on surface temperatures in the Pacific and therefore a weak or non-existent causal relationship between the AMV and IPO/PDO. This supports the results of Frankignoul et al. (2017), who suggest a larger

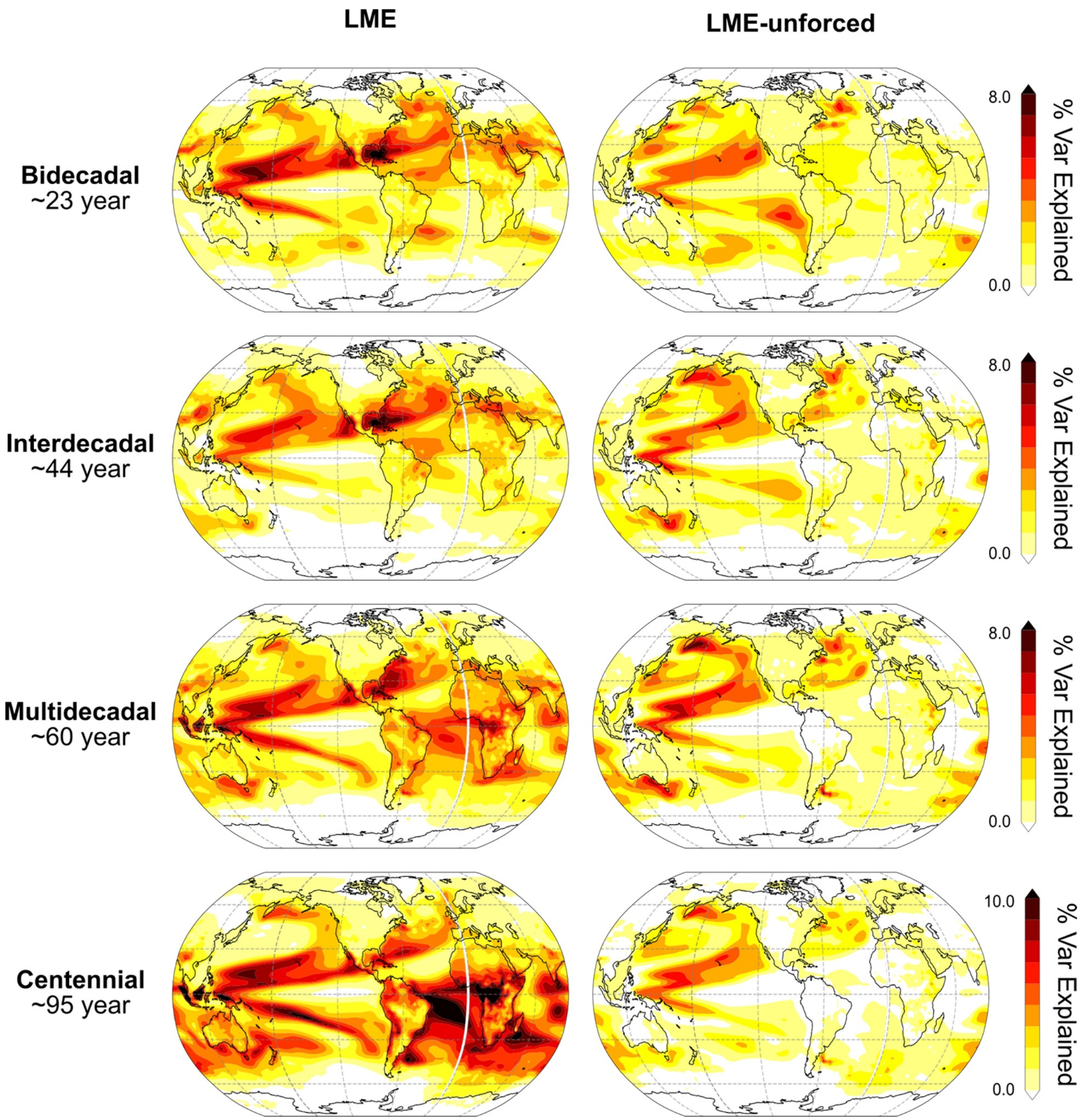

Figure 3. Mean spatial patterns of %-Variance Explained by reconstructed signals at each of the periocities identified in Figure 2 for LME (left) and LME-unforced (right) temperature fields across all 13 ensemble members during 1150–1400 CE.

proportion of Pacific variability to be internal compared to the AMV, and whose estimate of the PDO pattern is similar to our interdecadal and multidecadal results. The lack of signal concentrated in the tropical Pacific suggests that the impact of ENSO variability on lower frequency Pacific patterns is reflected at higher latitudes in the chosen timescales. Furthermore, the concentration of explained variance in the subtropics has a spatial pattern resembling that of the Pacific Meridional Mode (PMM; Amaya, 2019; Sanchez et al., 2019). Two regions of the Pacific show enhanced activity in the unforced fields: the western subtropical Pacific (off the coast of Japan), and the southern subtropical eastern Pacific (west Peru and northern Chile), regions usually associated with the PDO (Newman et al., 2016). The enhanced signal in the internal fields suggests CESM generates internal variability in the Pacific to a greater extent than in the NA.

4. Conclusions

We employed the MTM-SVD method of spatiotemporal signal detection and reconstruction, coupled with single timeseries PSD and wavelet analysis, to assess evidence in the CESM LME for periodic or oscillatory signals in North Atlantic and global surface temperature fields, with a focus on the AMV. Our results build on those of Mann et al. (2020, 2021) by performing single-series spectral analysis on the AMV index used in other studies (Bellomo et al., 2018; Dai et al., 2022; Miao et al., 2024), performing signal reconstructions on both forced and unforced fields, implementing a moving window spectrum allowing for signal detection in distinct time intervals, and performing global signal reconstructions over a range of timescales and thereby comparing internal versus forced signals in both the NA and the Pacific. We found spectral peaks in the LME ensemble temperature fields that are absent in LME-unforced and that are exclusively present both in NA and global temperature series during time periods of high volcanic activity (Figure 1, Figure S1 in Supporting Information S1), agreeing with previous studies that suggest a strong role of forcing on AMV (e.g., Birkel et al., 2018; Clement et al., 2015; Otterå et al., 2010). Our results indicate that apparent oscillatory behavior in the NA is due to external forcing, specifically volcanic activity during the 13th and, to a lesser extent, the 17th and 18th centuries, as similar spectral behavior is evident in analyses of global fields (Figure 2), which indicates a common underlying mechanism to both. Previous studies comparing the spectral density in AMV indices prior to the Medieval Climate Anomaly and into the Little Ice Age report similar results, suggesting a shift from weak interdecadal to strong mulitidecadal periodicities of the AMV concurrent with the strengthening of volcanic forcing that led to the onset of the LIA (Dai et al., 2022; Miao et al., 2024). By identifying periods of high spectral density in multidecadal bands that are not persistent through time, and that are common to global and NA fields, as well as to both the LME and Volcanic-only experiments (Figure 2, Figures S2 and S3 in Supporting Information S1), we conclude that no internal mode of variability with any characteristic or predictable frequency can be detected in the climate as simulated by the CESM model.

After determining the spectral characteristics of the ensemble, we leveraged MTM-SVD signal reconstruction on global fields in order to disentangle the spatial patterns associated with any periodic behavior. Our results (Figure 3) agree with previous studies that have attributed a larger proportion of AMV variability to NA responses to external forcing than to internal climate dynamics (Frankignoul et al., 2017; Murphy et al., 2017; Watanabe & Tatebe, 2019) and show a spatial expression of variance explained that has commonalities with previous studies characterizing the AMV and/or Pacific SST variability (Knight et al., 2005; O'Reilly et al., 2019; Takahashi & Watanabe, 2016). The subpolar Atlantic region in particular shows evidence of internally generated temperature variability, while the rest of the canonical "horseshoe" shape often attributed to the AMV appears to be related to the Atlantic's response to radiative forcing, particularly in the tropical NA (Frankignoul et al., 2017). There is, however, no evidence that internal variability in the subpolar NA is oscillatory. Thus, we suggest that multidecadal variability on timescales commonly attributed to the AMV is due to different mechanisms: an internally generated source of temperature variability (overprinted by external forcing) that occurs in the subpolar region of NA deep water formation but is not consistently periodic through the last millennium, and an exclusively forced region of temperature variability related to the response of the NA to volcanic activity, localized in the subtropical (~20–30°N) NA and Gulf of Mexico and that extends to the eastern branch of the canonical AMV pattern.

We further find that the spatial expressions of decadal and multidecadal patterns in the Pacific (IPO/PDO) are both stronger and more consistently expressed in the forced and unforced fields compared to those in the Atlantic, suggesting ocean and atmosphere dynamics exert a greater control on Pacific low-frequency variability in the LME. However, these observations may also be due to the long-term impact that volcanism has on the extent and characteristics of ENSO activity (McGregor et al., 2020; Pausata et al., 2023), which itself is strongly correlated with lower-frequency IPO variability in both observations (Heidemann et al., 2024) and model simulations (Capotondi et al., 2020).

The apparently strong dependence of inter- and multidecadal variability in NA SSTs to external forcing in CESM suggests that there is limited predictability for an AMV-like mode that could be used to reduce uncertainty in climate projections, though some skill has been found in initialized model experiments related to subpolar NA heat content and gyre circulation (Yeager, 2020). It has been shown, however, that CESM does not fully capture low frequency internal variability related to the AMV and NAO (O'Reilly et al., 2019) and that it is highly sensitive to volcanic radiative forcing (Otto-Bliesner et al., 2016). Thus, additional large simulation ensembles from different models, and from which internal variability could be isolated, would help elucidate the extent to which the internal component of the AMV has changed through time and the degree to which multidecadal variability in the NA is a direct consequence of internal ocean-atmosphere dynamics versus external forcing.

Conflict of Interest

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

Data Availability Statement

All CESM LME simulations are publicly available and can be found at https://www.cesm.ucar.edu/community-projects/lme. Code for MTM and MTM-SVD analysis of the data is publicly available as a Zenodo software release (Fernandez, 2024).

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