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**Key Points:**

- A new multiproxy reconstruction for AMV based only on marine proxies
- AMV persists at least back to 1780
- There is a need for more marine-based proxy records

**Supporting Information:**

- Readme
- Figure S1
- Figure S2
- Table S1
- Table S2

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# Marine-based multiproxy reconstruction of Atlantic multidecadal variability

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**Abstract** Atlantic multidecadal variability (AMV) is known to impact climate globally, and knowledge about the persistence of AMV is important for understanding past and future climate variability, as well as modeling and assessing climate impacts. The short observational data do not significantly resolve multidecadal variability, but recent paleoproxy reconstructions show multidecadal variability in North Atlantic temperature prior to the instrumental record. However, most of these reconstructions are land-based, not necessarily representing sea surface temperature. Proxy records are also subject to dating errors and microenvironmental effects. We extend the record of AMV 90 years past the instrumental record using principle component analysis of five marine-based proxy records to identify the leading mode of variability. The first principal component is consistent with the observed AMV, and multidecadal variability seems to persist prior to the instrumental record. Thus, we demonstrate that reconstructions of past Atlantic low-frequency variability can be improved by combining marine-based proxies.

## 1. Introduction

In this study we reconstruct the Atlantic multidecadal variability (AMV) by combining several marine-based proxy records from the North Atlantic region. During the instrumental period, North Atlantic sea surface temperature (SST) has undergone pronounced basin-wide fluctuations, with warm and cold periods of 3–4 decades each. These variations are referred to as AMV or the Atlantic Multidecadal Oscillation [e.g., *Enfield et al*., 2001]. Studies suggest that the AMV is important for climate variability globally and has been connected to several regional climate signals. The AMV can, for instance, affect European and North American climate [e.g., *Sutton and Hodson*, 2005; *Wyatt et al*., 2012], the frequency of Atlantic hurricanes [e.g., *Goldenberg et al*., 2001], and Arctic sea ice cover [e.g., *Kinnard et al*., 2011; *Miles et al*., 2014]. It has also been linked to changes in rainfall in the African Sahel [e.g., *Zhang and Delworth*, 2006; *Wang et al*., 2012], as well as the South Asian summer monsoon [e.g., *Goswami et al*., 2006].

Whether the AMV is a persistent mode of internal variability is still disputed [*Kilbourne et al*., 2008; *Knudsen et al*., 2011]. Ocean temperature data are limited to the last 140 years by instrumental records, and the data are spatiotemporally lacking before 1950 [*Smith and Reynolds*, 2003]. The relatively short instrumental SST record can therefore only capture 1–2 cycles of AMV, and is too short to confidently study natural low-frequency variability.

High-resolution climate reconstructions based on long-lived marine biota, for instance, tropical corals, bivalve mollusks, and coralline algae, can help reconstruct SST prior to the instrumental era [*Jones et al*., 2001; *Wanamaker et al*., 2011; *Hetzinger et al*., 2012]. With such reconstructions we can investigate whether multidecadal variability of Atlantic SST is a persistent feature of the Atlantic climate. Alternative tools for studying AMV are climate models. However, state-of-the-art climate models simulate a wide range of variability because of large uncertainties in the underlying processes [*Medhaug and Furevik*, 2011; *Ba et al*., 2014].

While here we reconstruct the AMV using marine-based proxies, previous reconstructions of the AMV have mainly used land-based proxies, such as tree rings [e.g., *Gray et al*., 2004; *Mann et al*., 2009]. Many of these land-based reconstructions have also used records from regions far from the Atlantic Ocean, in noncoastal areas. How the low-frequency variability in SST is related to atmospheric temperatures is, however, not clear. The relationship between SST and tree ring proxies seems strong for the instrumental era, but this relationship may not be stable [*D'Arrigo et al*., 2008; *Vásquez-Bedoya et al*., 2012]. Therefore, we investigate

**Table 1.** Loadings on PC1 for the Proxy Records and the Correlation With the AMV-Index[a]

| Reference | Loadings on PC1 | Correlation at Zero Lag | Maximum Correlation | Lag Year |
|---|---|---|---|---|
| *Goodkin et al.* [2005] | 0.48 | 0.31 | 0.31 | 0 |
| *Kilbourne et al.* [2008] | 0.05 | 0.07 | 0.15 | −9 |
| *Saenger et al.* [2009] | 0.45 | 0.30 | 0.43 | 7 |
| *Swart et al.* [1996] | −0.28 | 0.07 | 0.21 | −9 |
| *Vásquez-Bedoya et al.* [2012] | 0.70 | 0.56 | 0.57 | 3 |
| Composite | | 0.52 | 0.52 | 0 |
| AMV from *Gray et al.* [2004] | | 0.57 | 0.61 | −3 |
| AMV from *Mann et al.* [2009] | | 0.57 | 0.59 | −2 |
| PC1 | | 0.53 | 0.57 | 3 |

[a] The correlation with the AMV-index is calculated for the included proxy records, the composite of the proxy records, the AMV reconstruction from *Gray et al.* [2004] and *Mann et al.* [2009], and PC1, for the period 1871–1986.

low-frequency variability of North Atlantic SST using marine-based proxies, as these are a more direct measure of SST compared to land-based proxies.

There are several annual-resolution marine-based proxy records that capture the AMV signal [e.g., *Hetzinger et al.*, 2008; *Kilbourne et al.*, 2008; *Saenger et al.*, 2009; *Halfar et al.*, 2011]. Many of these proxy records are relatively short, not extending past the instrumental era, but their consistency with the instrumental record indicates that these types of records can be used to reconstruct past SST. However, individual records will be subject to sampling and dating errors as well as microenvironmental effects. Principle component analysis (PCA) can be used to reduce these uncertainties by extracting the leading patterns of variability [*Storch and Zwiers*, 2002]. While this method is common for land-based proxies, its application to marine-based proxies has been limited [*Ault et al.*, 2009]. Here we successfully apply this method to reconstruct AMV 90 years past the instrumental data period.

## 2. Data and Method

We analyze five published marine-based proxy records from the North Atlantic sector (Table 1). These records are chosen on the basis that they all have annual resolution, are longer than the instrumental record, and are proxies for SST. The proxy records stem from massive-growing tropical coral colonies. Two of the records are based on growth [*Saenger et al.*, 2009; *Vásquez-Bedoya et al.*, 2012], two are based on the Sr/Ca ratios [*Goodkin et al.*, 2005; *Kilbourne et al.*, 2008], and one is based on the skeletal $\delta^{18}$O composition [*Swart et al.*, 1996]. The locations of these proxy records are illustrated in Figure 1a, and their properties are summarized in Table S1. The records used in the analysis are all from the western tropical Atlantic. Cooler temperatures in the eastern Atlantic lead to slower coral growth rates, hampering the formation of large and long-lived colonies of massive growing coral. Thus, no long-term coral-based proxies exist at the moment from the eastern Atlantic, as well as at higher latitudes.

The five coral records from the tropical Atlantic are combined with PCA, where the individual records have been detrended and normalized prior to the analysis. Combining these records gives us an overlapping time span of 206 years from 1781 to 1986. For validation of our AMV reconstruction we compare our results with the SST data from Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) [*Rayner et al.*, 2003]. We also compare our results with two other AMV reconstructions [*Gray et al.*, 2004; *Mann et al.*, 2009]. Both these records are multiproxy reconstructions, but neither focuses on marine proxies. The reconstruction from *Gray et al.* [2004] is composed of 12 tree ring chronologies located in North America, Europe, and the Middle East between 30°N and 70°N [*Gray et al.*, 2004]. Although the reconstruction from *Mann et al.* [2009], which is composed of several different types of records, includes some marine records from the North Atlantic, none of them has continuous annual resolution [*Mann et al.*, 2009].

## 3. Results and Discussion

The first principal component (PC1) from the PCA explains 32% of the variance in the records and exhibits a close correspondence to the observed AMV-index (Figure 1b). The AMV-index is defined as the detrended and normalized annual averaged low-frequency (11 year running mean) Atlantic SST averaged over the region 0–60°N and 75°W–7.5°W [*Enfield et al.*, 2001; *Wyatt et al.*, 2012]. The time series of PC1 is consistent with

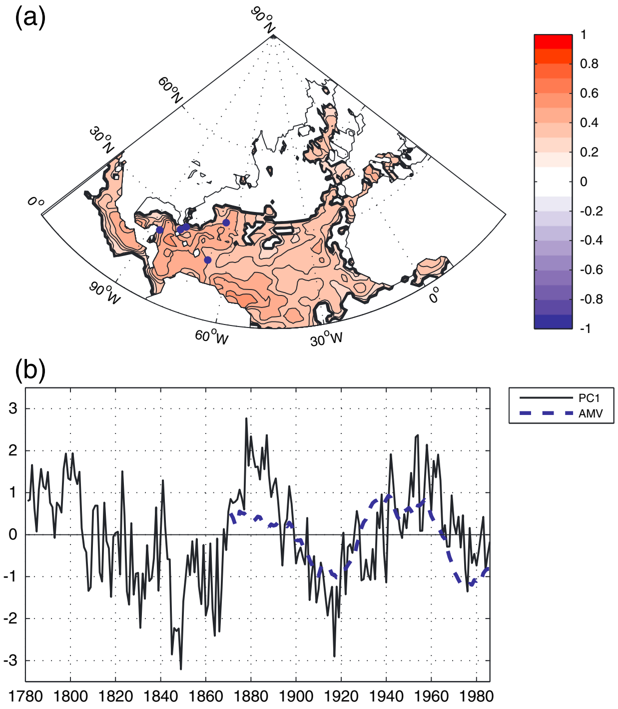

**Figure 1.** (a) Correlation between PC1 and annually averaged observed SST (HadISST), showing only values at a 95% confidence level for the effective degrees of freedom. Blue dots indicate the sampling sites. (b) PC1 (solid black line) and the AMV-index from HadISST data (dashed blue line).

the instrumental SST record from the Atlantic with warm periods from 1860 to 1890 and 1940 to 1970, and a cold period from 1900 to 1930. The time series have a correlation of 0.53 at a zero lag. This and other correlations discussed below are summarized in Table 1. PC1 captures an additional cold period in the 1930s that is not present in the observed AMV-index. This cooling is present in four out of the five proxy records included in our analysis, suggesting that this cold period is a tropical signal. However, this cooling is not present in the observed records for the western tropical Atlantic. Prior to the instrumental record, PC1 has a cold period from 1820 to 1860 and a warm period from the beginning of the record (1781) to 1820. When we repeat the PCA for the five coral records without detrending the records first, PC1, now explaining 35% of the variability, captures the same periodicity and timing of warm and cold periods as for the detrended records (not shown). In addition, there is a positive linear trend. PC1 provides evidence that the multidecadal variability in Atlantic SSTs may have persisted prior to the instrumental record.

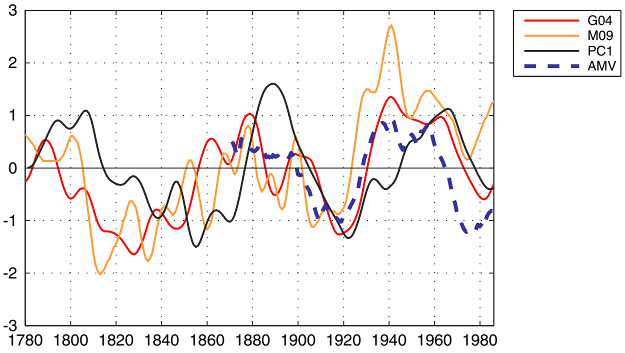

**Figure 2.** Normalized decadally filtered PC1 (solid black line), AMV reconstructions from *Gray et al.* [2004] (G04, red line) and *Mann et al.* [2009] (M09, orange line), and the AMV-index from HadISST data (dashed blue line).

PC1 is also comparable to the AMV reconstruction from both *Gray et al.* [2004] (G04) and *Mann et al.* [2009] (M09), but the reconstructions are somewhat displaced in time (Figure 2). For instance, the first warm period in the beginning of PC1 ends later than the corresponding warm period in the land-based reconstructions; hence, the cold period that lasts until about 1860 starts later in PC1 (Figure 1b). The cross correlation between PC1 and the AMV reconstruction from *Gray et al.* [2004] has a maximum value of 0.44 when PC1 lags the reconstruction by 11 years. At a zero lag the correlation is 0.26. The cross correlation between PC1 and the AMV reconstruction from *Mann et al.* [2009] has a maximum value of 0.39 when PC1 lags the reconstruction by 12 years. At a zero lag the correlation between PC1 and the reconstruction from *Mann et al.* [2009] is 0.33, slightly higher than that for the reconstruction from *Gray et al.* [2004]. The lags are similar when the reconstructions are 10 year low-pass filtered, as seen in Figure 2.

A significant positive correlation between PC1 and the observed SST is found for the whole tropical North Atlantic (Figure 1a). The same correlation pattern is found for PC1 with the records not detrended prior to the analysis (not shown). The highest correlations are found in the tropics in the region where the corals are situated. This bias in the location of the coral records may distort our results, with PC1 capturing a tropical rather than an extratropical North Atlantic signal. The correlation of PC1 with observed North Atlantic SSTs averaged over the tropics (0–30°N, 75°W–7.5°W) and the subtropics (30–60°N, 75°W–7.5°W) are 0.59 and 0.47, respectively. The correlation of PC1 with observed North Atlantic SSTs averaged over western (0–60°N, 75°W–45°W) and eastern (0–60°N, 45°W–7.5°W) North Atlantic are 0.53 and 0.52, respectively. The correlation between the 10 year low-pass filtered PC1 and observed SSTs show a similar pattern; however, the correlations are lower (see Figure S1 in the supporting information). We do not see such a strong tropical bias in the correlation pattern between the other two land-based multiproxy AMV reconstructions and observed Atlantic SST (Figure S1). For the observed SSTs, correlations are also high in the tropics; however, there are also high correlations in the subtropics that are not visible in the correlation with PC1 (Figure S2). The observed SST pattern is also subject to uncertainty [*Alexander et al*., 2013], and in particular the patterns for the period prior to and following the 1940s differ markedly (Figure S2). Interestingly, the pattern prior to the 1940s resembles that associated with PC1.

Correlations between the observed AMV-index from HadISST with each individual proxy record, the composite of the records, the two land-based AMV reconstructions [*Gray et al*., 2004; *Mann et al*., 2009], and PC1 is given in Table 1. The correlation with PC1 is 0.57 and is higher than the correlation with any of the individual proxy records alone, except for the record from *Vásquez-Bedoya et al*. [2012]. This gives indications that PC1 is an improved reconstruction of AMV compared to individual proxy records. The correlations for the observed AMV-index with the two AMV reconstructions from *Gray et al*. [2004] and *Mann et al*. [2009] are slightly higher than for the correlation with PC1. This might be because these reconstructions have been calibrated to the observed SST field [*Gray et al*., 2004; *Mann et al*., 2009]. In addition, the 12 tree ring chronologies used in the reconstruction from *Gray et al*. [2004] have been chosen due to their strong link to Atlantic SSTs in the observational record.

PC1 is the optimally weighted average of the records, with loadings given in Table 1, while a composite is a simple average of the proxy records. Thus, PCA extracts the common variability in the proxy records, and can act as a filter to eliminate higher frequencies of variability. The correlation of the observed AMV-index with PC1 is equal to the correlation of the observed index with the composite (unweighted average) of the proxy records, and PC1 is not necessarily an improved AMV reconstruction compared to the composite. Nevertheless, PCA may give more reliable results than an unweighted average because PCA allows some records to be lightly weighted or even negatively weighted.

When working with proxy records, there is always the possibility that the proxy may not actually be reflecting the variable of interest. In our study we are interested in temperature, but the marine-based proxies may also be influenced by, for instance, salinity. However, we find that our reconstruction is able to successfully reproduce the variability seen in the instrumental SST record, and also by combining several records using PCA we may be able to extract the SST signal as a dominant mode of low-frequency variability.

## 4. Conclusion

Here we propose a different method for reconstructing low-frequency variability in North Atlantic SST based on records from long-lived marine biota. We combine several annual resolution marine-based proxy records, extending 90 years further back in time than the instrumental record, with PCA to extract the low-frequency variability and limit microenvironmental effects and sampling errors. We find that PC1 is consistent with the observed AMV, and that the AMV persists throughout the record. This suggests that our method is able to capture the Atlantic low-frequency variability, and we conclude that this method is adequate for reconstructing SST on multidecadal timescales.

We find a discrepancy in the timing of the variability between our marine-based reconstruction and other land-based multiproxy AMV reconstructions, with the land-based AMV reconstructions leading 11–12 years to the marine-based reconstruction, indicating that we have to be careful about using proxies for reconstructing multidecadal SST variability in the Atlantic. There are also discrepancies related to the location of the proxies used. For our marine-based reconstruction we find higher correlations in the tropics and an additional cold period in the late 1930s. These discrepancies reflect differences in using proxies from high and low latitudes and of various types, as well as errors and uncertainties in the records. However, there are at present relatively few high-resolution long marine proxy records from the Atlantic sector, and the existing records are mainly from the tropics. Longer marine records, including records from the subtropics, are needed to reconstruct the AMV even further back in time. Additional high-resolution marine-based proxy records will also improve the confidence in AMV reconstructions, and will help constrain climate models and in turn predictions. Such reconstructions can also be used to investigate the persistence of observed AMV teleconnections. This record is freely available for use.

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