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A low latitude paleoclimate perspective on Atlantic multidecadal variability

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ABSTRACT

Traces of environmental conditions found in natural archives can serve as proxies for direct climate measurements to extend our knowledge of past climate variability beyond the relatively short instrumental record. Such paleoclimate proxies have demonstrated significant multidecadal climate variability in the Atlantic sector since at least the mid-1700s. However, Atlantic multidecadal climate variability is primarily defined by fluctuations in sea surface temperature (SST) and the proxy evidence comes from a variety of sources, many of which are terrestrial and are not directly recording sea surface temperature. Further analysis into the causes and consequences of Atlantic multidecadal climate variability requires development of a spatial network of decadal resolution proxy SST records with both low and high latitude contributions. An initial attempt at a low latitude Atlantic SST reconstruction found only 4 sites with ≤5 year resolution data, demonstrating the paucity of appropriate data available. The 4-site average correlated significantly with instrumental average SST and the Atlantic Multidecadal Oscillation (AMO). The full record, 1360–2000 C.E., and a shortened version 1460–1850 C.E., had significant multidecadal variability centered at a 60-year period. Comparing our reconstruction with reconstructions of SST anomalies in the North Atlantic shows that there is no consensus yet on the history of Atlantic multidecadal variability.

1. Introduction

Multidecadal-scale sea surface temperature (SST) anomalies in the North Atlantic, often called the Atlantic Multidecadal Oscillation or AMO, after the editorial article by Kerr (2000), are a subject of great research interest. The AMO has been connected to physical processes such as African rainfall (Folland et al., 1986), Atlantic sector hurricane frequency (Goldenberg et al., 2001), and precipitation in North America (Enfield et al., 2001), as well as ecological processes such as lower trophic-level productivity and fish migration patterns (Lehodey et al., 2006; Nye et al., 2014-in this issue).

The widely used AMO index by Enfield et al. (2001) defines the phenomenon as a detrended SST anomaly in the North Atlantic but a rotated EOF analysis of global SST variability shows a horseshoe pattern of correlation over a broad region of the North Atlantic (Goldenberg et al., 2001). The EOF analysis produces two centers of action for multidecadal SST variability, one in the northern North Atlantic at about 45–60°N latitude, and one in the tropical North Atlantic south of about 20°N latitude (Goldenberg et al., 2001). The mid-latitude western Atlantic (about 20–45°N) does not correlate highly with the rest of the basin on these time scales and some areas may even have negative correlation with the rest of the basin (Goldenberg et al., 2001).

Understanding the past behavior and mechanisms behind this multidecadal temperature variability in the North Atlantic contributes toward improved forecasts of the climate system and the related climatologic and ecologic processes. The leading hypothesis for the cause of the North Atlantic temperature anomalies invokes changes in ocean circulation and ocean heat transport (Delworth et al., 2007). Atlantic Meridional Overturning Circulation (AMOC), transports heat from the southern hemisphere to the northern hemisphere, driving hemispheric surface temperature anomalies (Vellinga and Wu, 2004). AMOC includes a warm, salty northward flowing surface circulation that moves along with the wind-driven surface currents, including the Gulf Stream. This surface flow replaces water at higher latitudes that cools, looses buoyancy, and sinks to depth in the North Atlantic. The cold deep water moves southward in a deep western boundary current, contributing to the net northward heat flow. AMOC is likely not the only process affecting North Atlantic sea surface temperature (SST) on these time scales, but it has the potential to be a primary driver (Zhang et al., 2007). Evidence for the link between AMOC and AMO is primarily from modeling experiments (e.g., Knight et al., 2005), because the required long-term ocean circulation observations have only begun to be collected in recent years (Johns et al., 2010; Kanzow et al., 2010). Correlations between AMO and changes in water masses thought to be associated with AMOC provide circumstantial evidence for a connection between overturning circulation and AMO during recent decades (Kilbourne et al., 2007; Zhang et al., 2011), though the

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uncertainty inherent in the analyses leaves room for alternative explanations.

A major stumbling block for exploring the causes of the AMO is the relatively short length of instrumental records compared to the time scale of the phenomenon (Johns et al., 2010). The global SST record only goes back about 160 years, representing a little over two oscillations between negative and positive phases. Direct ocean circulation observations targeting AMOC from programs such as the RAPID-MOCA observation array have only been made for a few years (Johns et al., 2010). Such short record lengths make it difficult to determine the frequency of oscillatory cycles and to fully characterize the related processes. Thus, the name Atlantic Multidecadal Oscillation may be a misnomer because there is not enough evidence that the phenomenon is oscillatory with such a short instrumental record (Vincze and Janosi, 2011). Many authors describe the phenomenon as Atlantic Multidecadal Variability (AMV) instead of AMO; though for consistency with other papers in this volume we will continue using AMO in this paper.

Natural records of climate variability, known as paleoclimate proxies can supplement existing instrument-based observations to extend our records of climate to earlier periods. This paper describes recent contributions of paleoclimate work to our understanding of the AMO and highlights open questions. An analysis of existing data demonstrates the hurdles we still need to overcome and provides guidance for future research.

2. Summary of the paleoclimate literature addressing the AMO

The scientifically diverse audience for this paper warrants a brief explanation of paleoclimate data before delving into the nature of the AMO as evidenced in paleoclimate data. Climate system processes leave traces in natural archives such as marine and lake sediments, shells of marine organisms, glacial ice, and cave deposits. Different chemical, biological, and physical variables measured in these natural archives provide many types of information including ocean and air temperature, relative precipitation amounts, and changes in ocean circulation patterns. The chemical, biological and physical variables measured in natural archives are often referred to as “proxies” because they provide information in proxy to direct measurements of climate variables.

Paleoclimate proxy data have their advantages and disadvantages, like any other kind of data. The primary reason we use paleoclimate proxies is that they give us the ability to look back in time and extend our knowledge of Earth's systems to before we were widely recording measurements. One major advantage of paleoclimate data in relatively recent samples is that the recording processes only change on evolutionary and geologic time scales, unlike instrumental data where observation methods often shift through time and can cause increased uncertainty in identifying long-term processes. A challenge of paleoclimate data is limited spatial and temporal resolution. Each archive is sensitive to specific climate variables (e.g., temperature, salinity, water mass mixing), has a specific spatial distribution (e.g., tropics, high altitudes, mid-latitudes) and has a characteristic time domain (e.g., summer only temperatures, interannual resolution, 100–300 year length), limiting the spatial and temporal resolution of some types of information. Another challenge is that paleoclimate proxies are not perfect recorders of climate variables and it is important to acknowledge and address the uncertainties in the records during interpretation.

Like direct measurements of the climate system, local synoptic variations can impact variations at any given site, but the relatively broad spatial and temporal correlation of ocean and atmospheric variations can be utilized to represent larger scale processes. Just like the atmospheric pressure difference between Tahiti and Darwin, Australia represents the Southern Oscillation in the climate system, well-placed proxy measurements can be used to reconstruct specific climate processes such as the El Niño-Southern Oscillation, or in the case of this paper, the AMO.

One of the most common methods of reconstructing past temperatures is by determining the oxygen isotopic composition in biogenic $CaCO_3$, a method that was first proposed by Harold Urey (1947). The oxygen isotopic composition of inorganic $CaCO_3$ precipitated in equilibrium is a function of both the temperature of precipitation and the isotopic composition of the water from which it precipitates. Some organisms, including sclerosponges and foraminifera (Druffel and Benavides, 1986; Erez and Luz, 1983) precipitate their skeleton at or close to isotopic equilibrium with the surrounding seawater and behave similarly to inorganic $CaCO_3$ (Druffel and Benavides, 1986; Erez and Luz, 1983). Other organisms, such as corals have an isotopic composition with a mean offset from equilibrium but the skeletal isotopic *variations* respond to temperature and water isotopic composition just like the organisms that precipitate in equilibrium with the water (Weber and Woodhead, 1972). Isotope data are reported in delta notation, which expresses the isotopic ratio ($^{18}O/^{16}O$) in a sample (R_{smp}) relative to the isotopic ratio of a standard (R_{std}). The standard for marine carbonates is Pee Dee Belemenite (PDB). Delta notation is defined by the following equation.

$$\delta^{18}O = 1000 \times \frac{R_{std} - R_{smp}}{R_{std}}$$

Empirical and experimental equations have been determined that quantify the relationship between the three variables, temperature, water isotopic composition and carbonate isotopic composition for different taxonomic groups included in this study (e.g., Erez and Luz, 1983; Leder et al., 1996; Rosenheim et al., 2009). Seawater oxygen isotopic composition is primarily determined by salinity in the tropics over recent centuries, but water mass changes and global ice volume contribute over longer time scales. Oxygen isotopic data alone provide a convolved signal of temperature and water isotopic composition that can be de-convolved with an independent measure of temperature or water oxygen isotopic composition.

An independent method of determining temperature using $CaCO_3$ involves measuring Sr/Ca or Mg/Ca ratios in biogenic carbonates. These elements tend to substitute for the Ca in $CaCO_3$, with a distribution coefficient between the water and the mineral that is a function of temperature (Beck et al., 1992; Rosenthal et al., 1997). The distribution coefficient (D) in this case is defined as the ratio of the Sr/Ca molar ratio in the aragonite (Sr/Ca_A) to the Sr/Ca molar ratio in the liquid (Sr/Ca_L):

$$D = \frac{Sr}{Ca_A} \bigg/ \frac{Sr}{Ca_L}$$

after equation (1) in (Kinsman and Holland, 1969).

The concentration of the elements in seawater is also important as the above equation makes clear, but is usually assumed to be constant for conservative elements with long residence times in the open ocean such as Mg and Sr. Although this is the traditional view of Mg and Sr, some variations in seawater Sr/Ca exist (de Villiers, 1999) and this could be a source of significant error in some records. $CaCO_3$ has two common mineral forms at Earth's surface temperature and pressure, aragonite and calcite. Sr/Ca ratios are used for paleotemperature reconstructions from aragonitic corals and sclerosponges, whereas Mg/Ca ratios are used in reconstructions from calcitic foraminifera. Empirical calibration studies provide the quantitative relationships between $CaCO_3$ element/Ca ratios and temperature (e.g., Rosenheim et al., 2005; Rosenthal et al., 1997; Swart et al., 2002). The rest of this section highlights recent contributions of paleoclimate work using these proxies to our understanding of the AMO.

A major focus of recent paleoclimate work on multidecadal time scales has been to generate proxy records with enough length and time resolution to robustly capture multidecadal-scale signals and use those records to characterize past behavior of the AMO. One of the early attempts to characterize multidecadal variability in paleoclimate data was Delworth and Mann (2000). These authors used the 5th eigenvector of a multi-proxy global climate reconstruction to demonstrate