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# Evidence linking satellite-derived sea-surface temperature signals to changes in the Atlantic meridional overturning circulation

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## ABSTRACT

This study explores an application of satellite-derived Sea Surface Temperature (SST) to climate studies by focusing on a connection with the Atlantic Meridional Overturning Circulation (AMOC). Here we focus on SSTs from the advanced very high resolution radiometer and report a 99% significant correlation between the changes of in situ measured AMOC transport and the variation of 1-month leading SST anomalies in the subpolar North Atlantic region (45°N–70°N) based on analyses of an 85-month period. The leading mode of the singular value decomposition analysis of SST and Sea Level Pressure (SLP) for 31 years (1981/12–2012/12) shows an apparent North Atlantic Oscillation (NAO) forcing on the SST fields. Specifically, the SST and SLP one-month phase lag covariance is notable at temporal scales of 4 to 11 months. After removing the first order component of the NAO, the residual SST (RESST) provides better estimates of the AMOC on a shorter time scale than the SST. This is because that RESST is less likely to be affected by the local SLP on these time scales. The high correlation is primarily between the RESST and variations of the geostrophic Upper Mid-Ocean transport component of the AMOC. The 31-year RESST time series in the North Atlantic subpolar region is also significantly correlated with the Gulf Stream path SST anomalies with a one-month lead, implying a fast signal transport from the subpolar North Atlantic to the Gulf Stream. A similar fast adjustment signal is also found in 500-year control simulations of the GFDL model CM2.1. These results indicate a prospective capability of satellite-derived SSTs to predict AMOC variability.

## 1. Introduction

Sea surface temperature (SST) plays a significant role in air–sea interactions and reflects both oceanic and atmospheric variability on multiple time and spatial scales. Retrieving SST from space is a relatively mature subject. For more than 30 years, the principal satellite infrared (IR) sensor, the advanced very high resolution radiometer (AVHRR), provides valuable global SST measurements, which have resulted in the longest time series of satellite SSTs available for climate research. The SST retrievals from this and other IR radiometers provide high resolution as well as accuracy to about 0.5 °C–0.3 °C (the accuracy refers to the range of scatter about a mean error, which is usually very close to zero; an example can be found in Minnett (2010). The biggest disadvantage of basin-scale IR SST fields is the data gaps caused by the presence of clouds. Although microwave SST products have the advantage of being less influenced by the presence of most clouds, such SSTs span a much shorter time period, hence microwave SST fields are less useful for extracting long term climate signals. To fill in the gaps in the IR SST measurements caused by clouds, optimum interpolation (OI) techniques have been developed by a number of researchers, of which those by Reynolds and his colleagues (Reynolds, Rayner, Smith, Stokes, & Wang, 2002; Reynolds & Smith, 1994) result in the most complete AVHRR measurements extending back to 1981. They have been used to study climate phenomena such as El-Niño Southern Oscillation (ENSO, e.g. by McPhaden and Zhang (2009)). Here, we explore another promising application of Reynolds SSTs in climate research.

The Atlantic meridional overturning circulation (AMOC) makes an important oceanic contribution to the global redistribution of heat. Variations in the AMOC are believed to be vulnerable to the consequences of a changing global climate resulting from emissions of anthropogenic greenhouse gases, and it is “very likely” that the AMOC will weaken in this century because of these emissions (Houghton et al., 2001). Robson, Hodson, Hawkins, and Sutton (2014) reported a substantial decline of the AMOC found in both in situ measurements and climate model simulations, which imply a high possibility of further decline in the future. As summarized in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) (IPCC, 2013), confidence in assessing AMOC variability is still ‘low’. Therefore, measurements of the AMOC transport to study its variability are of critical importance and have potentially profound consequences. In traditional AMOC studies, in situ data from ships and moorings are

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generally used. Instantaneous hydrographic transect measurements (Bryden, Longworth, & Cunningham, 2005) could be aliased by the seasonality of the AMOC, while continuous basin-wide measurements along 26.5°N by the RAPID-MOCHA project since April 2004 (Cunningham et al., 2007) provide measurements of AMOC seasonal variability (Kanzow et al., 2010; Zhao & Johns, 2014a). However, the question remains, can satellites provide practical measurements of the AMOC? In the North Atlantic, theoretically, the variability of AMOC transport can be reflected in changes of the extratropical upper ocean heat content, which are in large degree associated with the local SST variability. With this in mind, we compare Reynolds OI-SSTs with the transport measurements from RAPID-MOCHA to explore the climate monitoring and prediction capability of satellite-derived SST.

It remains unclear whether, in regions of the North Atlantic, SST is indicative of the AMOC. It was generally recognized that atmospheric forcing, such as characterized by the North Atlantic Oscillation (NAO), modulates air–sea interaction over the extratropics (20°N–80°N) and generates SST anomalies through both turbulent heat fluxes and wind stress (Cayan, 1992; Frankignoul, 1985). However, no consensus has been reached about the cause and effect relationship between the NAO and North Atlantic extratropical SSTs. Some recent studies found the role of North Atlantic SST anomalies on influencing the NAO (Czaja & Frankignoul, 2002), and others proposed positive feedbacks between the two (Hu & Huang, 2006; Pan, 2005). Model simulations support the concept that variations in the AMOC are reflected in large-scale SST anomalies (Delworth, Manabe, & Stouffer, 1993; Timmermann, Latif, Voss, & Grötzner, 1998). Other studies have shown that large scale averaged North Atlantic SST anomalies could be taken as a fingerprint of multidecadal AMOC variations (Knight, Allan, Folland, Vellinga, & Mann, 2005; Latif et al., 2004, 2006). Visbeck et al. (2003) estimated that only a small portion (20%–40%) of the winter-time extratropical North Atlantic SST variance can be attributed to the NAO, and suggested the oceanic role on SST has to be taken into account, and is perhaps dominant. Zhang (2007) proposed the anti-correlated relationship between the tropical North Atlantic SST and multidecadal subsurface temperature anomalies could be taken as a signature of the AMOC, through the excitation of coastal Kelvin waves by deep water formation in the subpolar region. Zhang (2008) also found that a dipole pattern in both the leading EOF mode of satellite sea surface height (SSH) data and in situ measured subsurface temperature with contrary poles in the subpolar gyre and the Gulf stream path could be a distinctive fingerprint of the AMOC variations. Similarly, a combined observation and model study proposed the Gulf Stream path index as a diagnostic variable, by showing that when the AMOC is relatively strong (weak), there is a southerly (northerly) Gulf Stream path shift (Joyce & Zhang, 2010). However, none of these studies include comparisons using continuous basin-wide in situ AMOC transport measurements.

In the sections that follow, we first discuss the satellite and in situ data and the analysis methods. In Section 3, major results are presented. We explore the NAO–SST link and describe the temporal and spectral characteristics, with a discussion of the comparisons between appropriate indices and the AMOC transport. Possible mechanisms leading to the correlation between the AMOC Upper Mid-Ocean transport and the residual SST (RESST), a SST signal after removing the first-order-component correlated the NAO (see details in Section 2), are interpreted in Section 4. In Section 5, conclusions and possible implications of our results are summarized.

## 2. Data and methods

We start by re-examining the NAO–SST relationship in the extratropical region. Based on previous studies, there is a potential for subpolar SST fields to connect with changes in the AMOC, as proposed by Zhang (2008). Therefore the domain of this investigation includes the extratropical North Atlantic (XNA, 20°–70°N, 90°W–0°) and within this, the subpolar North Atlantic (SPNA, 45°–70°N, 90°W–0°). The maps of the two regions are shown in Fig. 1a.

We used Reynolds fields based on AVHRR data rather than SST fields based on AMSRE-E, because the AMSR-E record is too short to reveal the signals of the NAO-driven spatial pattern and time series in a meaningful fashion. The 1° × 1° Reynolds analysis SST data (Reynolds et al., 2002), was then selected as this provides the longest satellite-measured time series. It is an optimum interpolation (OI.v2) product, and is thus spatially complete. It is derived by combining satellite SST data from the AVHRR (Pathfinder data: September 1981 through

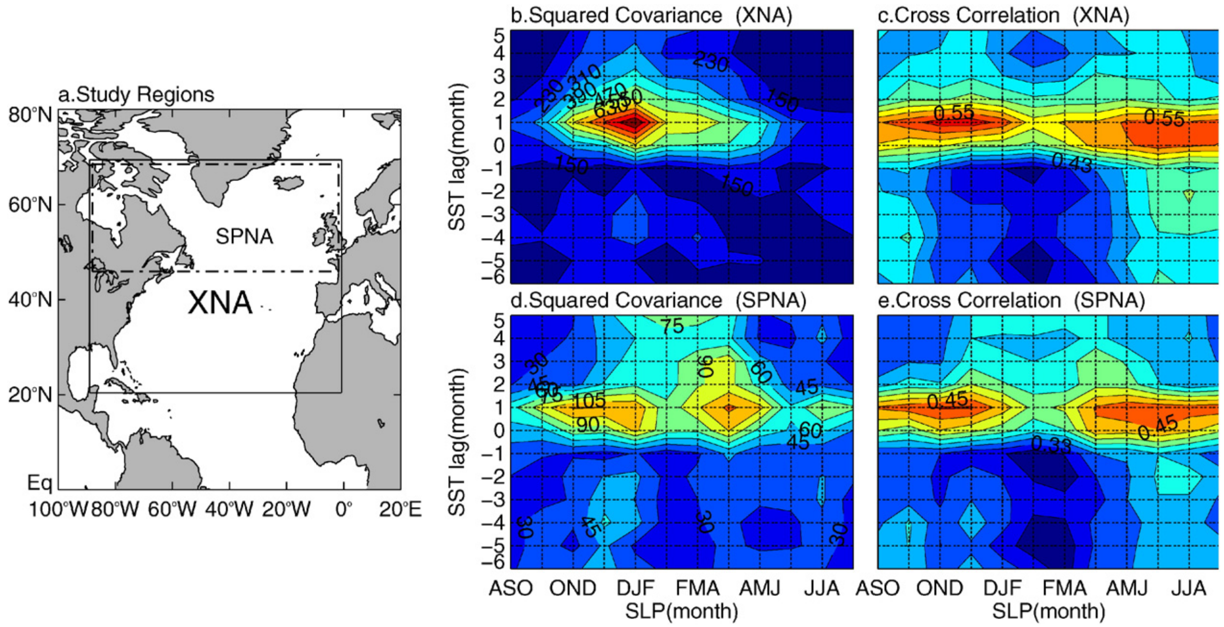

**Fig. 1.** a: The studied two regions of extratropical North Atlantic (XNA) and subpolar North Atlantic (SPNA). b–d: Squared Covariance and Cross Correlation distributions of the SVD result of lagged covariance between SST and SLP fields (1981/12–2012/12) in the two regions. The squared covariance is dimensionless as the SST and SLP fields have been normalized (see Section 2). Positive lag means SST-S1 lags the SLP (i.e., the ocean lags the atmosphere). The contour interval for cross correlation is 0.02. Notice the squared covariance structure is more coherent and has a smaller gradient across all seasons in the SPNA region.