

# *How robust are the surface temperature fingerprints of the Atlantic Overturning Meridional Circulation on monthly time-scales?*

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## RESEARCH LETTER

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## Key Points:

- The impact of Florida Strait and Ekman transports on surface temperatures from monthly observations depends on the chosen period
- Our model suggests that 30 to 50 years of observations will be needed to robustly constrain the AMOC fingerprints on monthly time scales
- Part of the uncertainty in the simulated fingerprints is linked to stochastic variability in the atmospheric heat fluxes

## Supporting Information:

- Supporting Information S1

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## How Robust Are the Surface Temperature Fingerprints of the Atlantic Overturning Meridional Circulation on Monthly Time Scales?

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**Abstract** It has been suggested that changes in the Atlantic Meridional Overturning Circulation (AMOC) can drive sea surface temperature (SST) on monthly time scales (Duchez et al., 2016, <https://doi.org/10.1002/2017GB005667>). However, with only 11 years of continuous observations, the validity of this result over longer, or different, time periods is uncertain. In this study, we use a 120 yearlong control simulation from a high-resolution climate model to test the robustness of the AMOC fingerprints. The model reproduces the observed AMOC seasonal cycle and its variability, and the observed 5-month lagged AMOC-SST fingerprints derived from 11 years of data. However, the AMOC-SST fingerprints are very sensitive to the particular time period considered. In particular, both the Florida current and the upper mid-ocean transport produce highly inconsistent fingerprints when using time periods shorter than 30 years. Therefore, several decades of RAPID observations will be necessary to determine the real impact of the AMOC on SSTs at monthly time scales.

**Plain Language Summary** The Atlantic Meridional Overturning Circulation (AMOC) is thought to be a key element of the Earth's climate as it plays an important role in redistributing heat from the Equator toward the North Atlantic and the Arctic. Therefore, understanding how variations in the AMOC affect the wider climate is an important question for climate prediction. Unfortunately, the AMOC is difficult to measure, and it has only been continuously measured since 2004 at the latitude of 26°N. A recent paper (Duchez et al., 2016, <https://doi.org/10.1002/2017GB005667>) suggests that these observations can be exploited to predict the surface temperature of the ocean in the North Atlantic region up to 5 months ahead. However, given the short observational period (only 13 years so far), our study questions if this link is sufficiently robust. By combining the use of longer observational records, and a 120 yearlong simulation of the climate, we show that the link between the AMOC and surface temperatures is highly sensitive to the time epoch considered. Therefore, we advocate the need of continuing the current observational efforts for at least two more decades to robustly determine the AMOC potential for predicting the Atlantic several months ahead.

### 1. Introduction

Anomalies in Atlantic sea surface temperatures (SSTs) have been long thought to drive important climate impacts (Delworth et al., 1993). For example, temperature anomalies have been linked with changes in rainfall, the atmospheric circulation, and the frequency of Hurricanes on multidecadal time scales (e.g., Zhang & Delworth, 2006). Changes in SSTs in the Gulf Stream extension have been reported to affect the North Atlantic atmospheric jet stream (O'Reilly et al., 2017), and a dipole pattern in North Atlantic SSTs is thought to influence the variability of the North Atlantic Oscillation (Czaja & Frankignoul, 1999). Tropical North Atlantic SST patterns have also been associated with global impacts on rainfall on interannual to decadal time scales (Kushnir et al., 2010; Polo et al., 2008; Ruprich-Robert et al., 2017; Sutton & Hodson, 2007).

Although changes in the atmosphere are important for driving SST variability (i.e., via accumulated surface fluxes; Czaja & Frankignoul, 2002; Schneider & Fan, 2012) some of the SST variability is thought to be linked to changes in the ocean circulation. For example, changes in Ekman surface currents drive changes in upper ocean heat content, particularly on interannual time scales (Eden & Willebrand, 2001). Changes in the strength of the horizontal gyre circulation and the AMOC are also strongly linked to changes in upper ocean temperature, particularly on multiannual to decadal time scales (Häkkinen, 2000; Knight et al., 2005). These coherent patterns of response to the ocean circulation are generally known as fingerprints (Zhang, 2008).

RAPID observations are now beginning to shed light on the relative importance of AMOC at 26°N for changes in ocean heat content (Bryden et al., 2014; Cunningham et al., 2013; Sonnewald et al., 2013). However, understanding their relationship and the processes involved has been hindered by the short observational records.

A recent study (Duchez et al., 2016; henceforth *D16*) has suggested that there is a statistically significant link between the AMOC at 26°N (as measured by the RAPID array) and SSTs on monthly time scales. In particular, they argue that changes in the upper mid-ocean component of the AMOC led a dipole of SST anomalies with negative correlations in the tropics and positive correlations in the subtropics at a lead of 5 months. Such a relationship between AMOC and SSTs, as *D16* argue, could lead to improved seasonal predictions. However, the study of *D16* relies on correlations to reveal the lagged relationship between the RAPID observations and Atlantic SST. These were calculated at the time with only ~11 years of observations, which raises the following question: are the relationships diagnosed in *D16* a robust measure of the “true” climatological-average AMOC-SST fingerprints?

In this study we will use observations and a state-of-the-art model to explore the robustness of the 5-month lagged relationships between the AMOC and Atlantic SSTs. In particular we will explore the sensitivity of the fingerprints to the length of the observational window used. Section 2 includes a discussion of the model and methods, section 3 describes the main results, and finally the conclusions are summarized in section 4.

## 2. Data and Methods

### 2.1. Observations

This study uses RAPID data from April 2004 to October 2015 (Smeed et al., 2016), extended Florida Strait Transport (FST) estimates from 1982 to 2015 (Meinen et al., 2010) and an extended Ekman Transport time series for the same period computed from ERA-Interim (Dee et al., 2011). The SST fields used to compute the AMOC fingerprints are from the Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST; Rayner et al., 2003).

### 2.2. Model Data

We use 120 years of monthly mean data from a preindustrial control experiment of the HadGEM3-GC2 model (GC2 for short), which was analyzed in Ortega et al. (2017). GC2 is a coupled atmosphere-ocean-sea ice configuration of the UK Met Office climate model (Williams et al., 2015). The atmosphere component is the Global Atmosphere version 6.0 of the Met Office Unified Model (Walters et al., 2011) and has a horizontal resolution of N216 (92 km at the equator and 60 km in middle latitudes) and 85 vertical levels. The ocean model is the Global Ocean 5.0 (Megann et al., 2014) version of the v3.4 NEMO model (Madec, 2008) includes 75 vertical levels (24 of them in the top 100 m) and runs with a nominal horizontal resolution of 0.25°. Further details on the model components and the simulation can be found in Ortega et al. (2017).

The model AMOC indices are computed to mimic the way the RAPID array observes the real ocean. Boundary density profiles are used to constrain the upper mid-ocean transport (UMOT), which is the net southward flow east of the Bahamas. The FST is estimated as the total volume transport through the Florida Strait, which is resolved in GC2. Finally, the along section wind stress at 26°N is used to calculate the Ekman transport (EkT) contribution. As in RAPID, the total simulated AMOC is defined as the sum of these three terms.

### 2.3. Data Processing and Significance Assessment

All data are processed as in *D16*; that is, they are detrended, deseasonalized, and smoothed with a 2-month running mean. In the observations we always use the whole available period to constrain the seasonal cycle more accurately. In GC2, we consider the fingerprints in different subperiods of the 120-year run from 11 to 50 years; thus, the preprocessing is applied to each subperiod separately in order to mimic the observations. The AMOC-SST fingerprints are computed as the pointwise correlations between the AMOC indices and SST fields in a given lag. Here we focus on the 5-month lagged fingerprints, as it was the lead time showing the strongest response in *D16*.

The similarity between different fingerprints (e.g., observed versus simulated) is quantified by the spatial correlation between them (e.g., Figure 2). We focus exclusively on the North Atlantic (90–0°W; 5–45°N) and mask out the Mediterranean and Baltic Seas, the Hudson Bay, and the Pacific Ocean. To only compare the large-scale features, a 5-point spatial smoothing is applied before calculating the spatial correlations.

The statistical significance of the spatial correlations is assessed with a Monte Carlo ensemble. This test is only applied in the model analysis (see, e.g., Figure 4), to compare the model fingerprints for different window lengths (section 3.3). For each window length, and each AMOC component, we produce a pool of 1,000 randomly generated synthetic indices, each of them estimated as a first-order autoregressive (AR1) process with the same lag-1 autocorrelation, variance and mean as the AMOC index from the full simulation (i.e., 120 years). Each of these time series is correlated with the corresponding SST field, and these are combined to generate an ensemble of synthetic fingerprints for each window length. These are subsequently correlated with the “true” model fingerprints, which we defined as the fingerprints computed using the whole 120-year simulation, to provide a distribution of synthetic spatial correlations. Spatial correlations are deemed significant (with  $p > 0.05$ ) when they are larger than the 95th percentile of the spatial correlations across the synthetic ensemble.

### 3. Results

#### 3.1. The Simulation of the AMOC in GC2

GC2 skillfully reproduces the main features of the observed seasonal cycle of the AMOC (Figure S1 and Table S1 in the supporting information). Additionally, the features of the simulated seasonal cycle computed using all 120 years of data (dark thick orange line) appear to be well described by any given 11-year segment of the simulation (thin orange lines). The variances of the observed deseasonalized and detrended AMOC indices are also similar to the simulated variances, at both at monthly and interannual time scales (Table S2). Therefore, GC2 represents a reasonable framework to test the AMOC fingerprints and their sensitivity to the length of the “observational” window considered (section 3.3).

#### 3.2. Sensitivity of AMOC-SST Fingerprints to the Observed Time Period

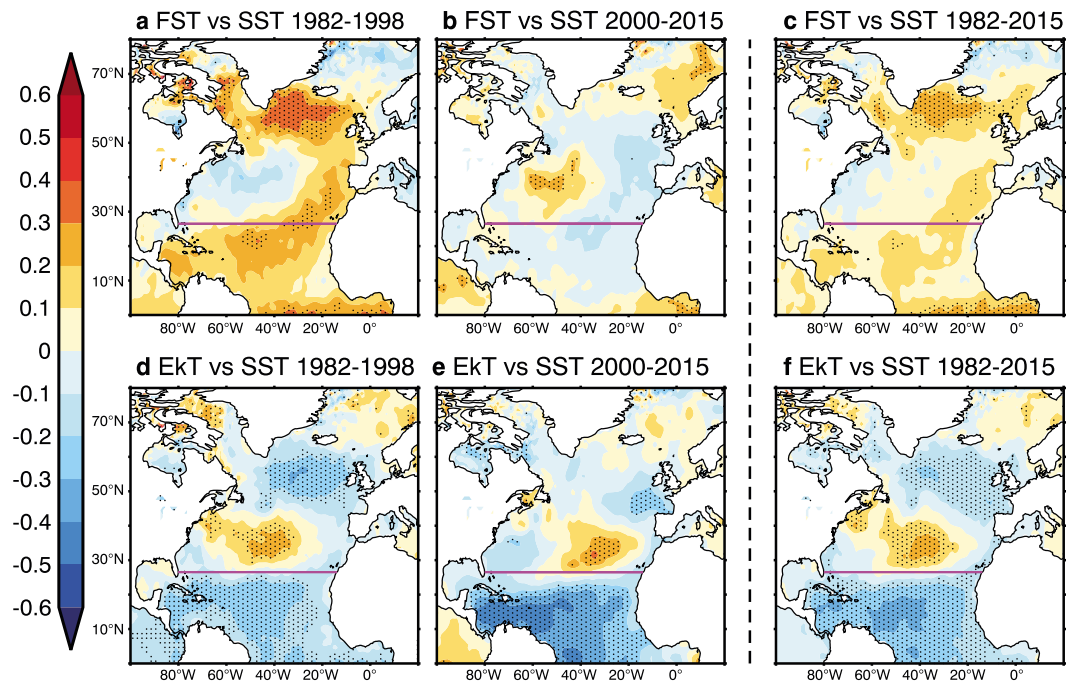
Both the FST and EkT have been observed for longer than the RAPID array has been deployed. Figure 1 shows their associated SST fingerprints during the 1982–1998 and 2000–2015 periods. Note that no FST observations are available for 1999 and that correlations from the latter period (Figures 1b and 1e) are very similar to those shown in D16 for 2004–2014. For both FST and EkT, important differences are found between the two fingerprints. For the FST fingerprint, the sign of the correlation pattern is reversed from 1982–1998 to 2000–2015. The EkT fingerprint is more similar between the periods, but changes are evident in the magnitude and location of the maximum correlations, particularly in the subpolar North Atlantic. Therefore, Figure 1 suggests that longer periods than those used in D16 are necessary to constrain the AMOC-SST fingerprints robustly.

#### 3.3. Spatial Consistency of Model AMOC-SST Fingerprints With Observations

We now use the GC2 model to provide a longer context to assess the robustness of the AMOC-SST fingerprints. Their robustness is assessed by calculating the SST fingerprints for different subperiods of the 120-year model simulation. Specifically, we calculate the SST fingerprints for sections ranging from 11 to 50 years long, using all possible overlapping sections. In order to narrow down the SST anomalies that may be driven directly by the AMOC at 26°N (i.e., those discussed in D16) we focus on the 5–45°N region.

The GC2 model is able to broadly reproduce the observed AMOC-SST fingerprints when computed with 11 years of data. Figure 2a shows the model-derived AMOC-SST fingerprint (shading) that has the highest spatial correlation with the observed AMOC-SST fingerprint (contours). Generally speaking, both the observed and model-derived AMOC-SST fingerprints show the same dipole pattern following a change in the AMOC (the overall spatial correlation is 0.88), with negative correlations in the tropics and positive correlations in the subtropics. The agreement between model and observationally derived AMOC-SST fingerprints also extends to most of other 11-year segments in the control experiment. The median spatial correlation between the observed and model-derived 11-year AMOC-SST fingerprints is ~0.64.

Similar coherent features are also found between the observed and model-derived fingerprints of the individual AMOC components. Of these, the EkT-SST fingerprint has the largest spatial correlation with the observed SST fingerprint (0.88), and also the best agreement over all 11-year periods (median correlation of 0.6; Figure S2b). When we increase the length of the data used to compute the SST fingerprints to 32 years (i.e., to compare the model with Figure 1f), the median correlation increases to 0.82, and all model-derived fingerprints become positively correlated with the observed fingerprint.



**Figure 1.** Sensitivity of the observed Atlantic Meridional Overturning Circulation (AMOC)-sea surface temperature (SST) fingerprints to time period. (a–c) Correlations between the Florida Strait Transport (FST) at 26°N and the 5-month lagged SST fields, in the periods 1982–1998, 2000–2016, and 1982–2016, respectively. All data were preprocessed as in *D16* (see text). Stippling highlights correlation values significant at the 95% confidence level, according to a *t* test that takes into account the series autocorrelation. Horizontal magenta lines indicate the latitude of the RAPID array. (d–f) Same as above but for Ekman transport (EKT).

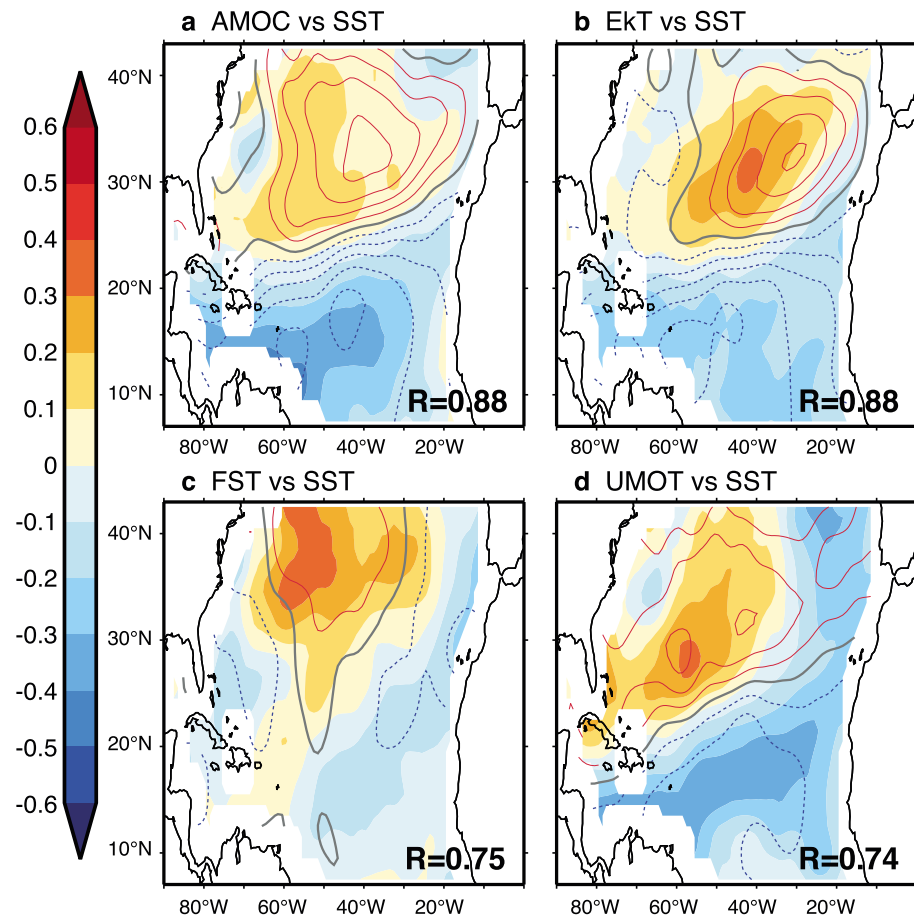
For FST-SST and UMOT-SST fingerprints, the model is broadly capable of simulating the observed SST fingerprints (Figures 2c and 2d). The largest spatial correlations between observed and model-derived SST fingerprints are equal to 0.75 and 0.74 for FST and UMOT, respectively. However, unlike for the EKT-SST, their uncertainty is much larger. In both cases the spatial correlation between simulated and observed fingerprints range from  $\sim -0.8$  to 0.8 when using all available sections (Figures S2c and S2d), and even when using 32 yearlong periods for the FST-SST. Therefore, although the model is able to recreate the observed FST-SST and UMOT-SST fingerprints, there is considerable spread between fingerprints computed from different sections of the simulation.

### 3.4. Robustness of AMOC-SST Fingerprints in the Model

To further quantify the uncertainty in AMOC-SST fingerprints, we focus exclusively on GC2 to assess the reproducibility of the model's own fingerprints. In particular, we assess whether the SST fingerprints computed from the different 11-year subsections of the GC2 control have the same sign as the “true” model fingerprints (see section 2.3).

Figure 3a presents the “true” simulated AMOC-SST fingerprint, which shows some consistency with observations (i.e., as shown in *D16* and Figure 2a), particularly the tropical cooling and subtropical warming. The tropical cooling between  $\sim 10$ – $20^\circ\text{N}$  is largely robust, because it is found in  $>95\%$  of all simulated 11-year segments (gray contours). However, the warm subtropical anomaly is weaker than in the observed fingerprint, and, although it is significant based on a Student's *t* test (indicated by the stippling), it is not a robust feature across all simulated 11-year subperiods (i.e., the warm anomalies are not found in  $>95\%$  of segments). Other less restrictive thresholds (75% and 66% of the segments) suggest that there is an overall agreement in the sign of the anomalies over the subtropical region (Figure S3).

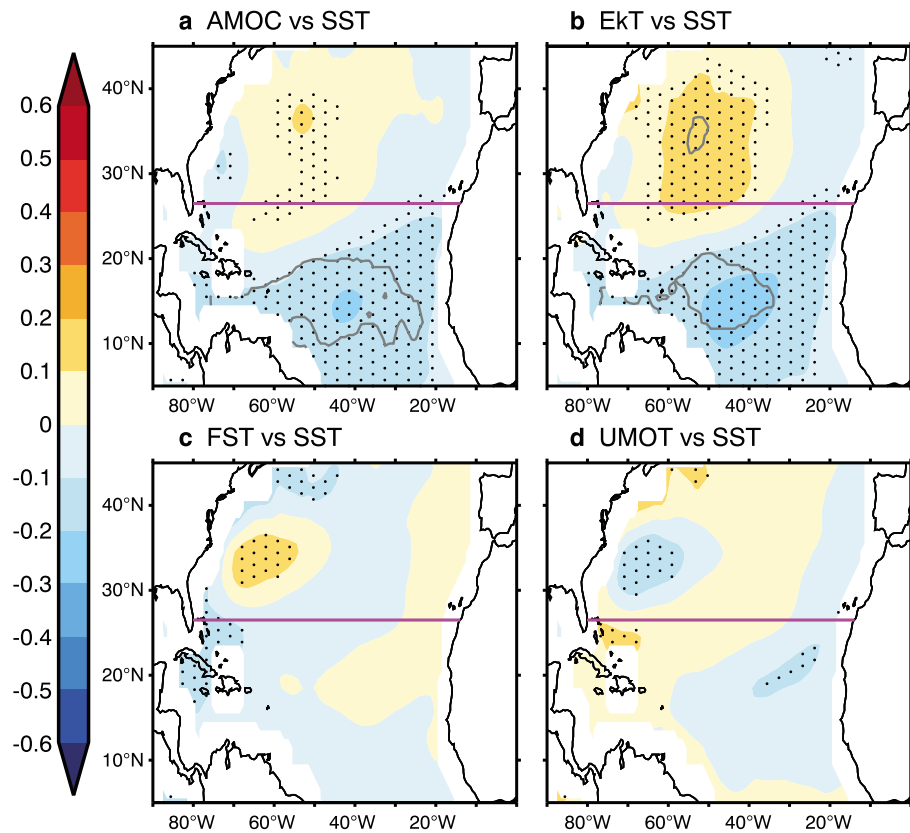
The main contributor to the “true” model-derived AMOC-SST fingerprint, in terms of magnitude and the most robust features, is the EKT-SST fingerprint (Figure 3b). It is also the most consistent with the observed fingerprints (Figures 2b versus 3b) and shows robust features in both the tropics and subtropics. In



**Figure 2.** Consistency between the observed and simulated Atlantic Meridional Overturning Circulation (AMOC)-sea surface temperature (SST) fingerprints. (a–d) Correlations between the different AMOC components and the 5-month lagged SST fields in GC2 (shaded) and the RAPID observations (contours). For GC2, shows the SST fingerprint calculated from 11 years of data with the highest spatial correlation with the observed RAPID fingerprints (the corresponding spatial correlation is shown at the bottom). Note that the simulated fingerprints for the different components are from different 11-year periods.

contrast, the “true” model-derived FST-SST and UMOT-SST fingerprints (Figures 3c and 3d) are quite different to the observed ones. For the “true” UMOT-SST fingerprint in particular, there is no warm anomaly in the subtropics and none of the significant correlations are consistent across all the 11-year segments. Therefore, an interesting question is: how long do we have to observe the model to robustly estimate the “true” AMOC-SST fingerprints? We first assess this for the whole tropical and subtropical Atlantic box in Figures 2 and 3. This is done by calculating the AMOC-SST fingerprints for all 11 to 50 yearlong subperiods of the control simulation and calculating their respective spatial correlation with the “true” model fingerprint. In order to conclude that a particular subperiod length would yield a robust SST fingerprint we assume that >95% of SST fingerprints need to be significantly correlated (see section 2.3) with the “true” SST fingerprint.

Figure 4 shows this distribution of spatial correlations from different time periods. Generally, there is a wide spread of spatial correlations for short time periods (i.e., 11 years), but as the length of the time period increases, the median spatial correlation increases and the spread decreases. Figure 4a suggests that the model’s “true” AMOC-SST fingerprint requires ~27 years of data to be robustly estimated at the 95% level. This characterization is again largely due to the robustness of the EKT-SST fingerprint, which is robustly defined after ~25 years of data (Figure 4b). Note that Ekt explains twice as much of the AMOC and SST variance than the other indices. The FST-SST and UMOT-SST fingerprints are less well constrained and require ~48 or > 50 years respectively to be robustly estimated (Figures 4c and 4d). For a 75% (100%) threshold,



**Figure 3.** Robustness of the simulated sea surface temperature (SST)-Atlantic Meridional Overturning Circulation (AMOC) fingerprints. (a–d) Correlations between the different AMOC components and the 5-month lagged SST fields, using the 120 years of GC2. Stippling highlights correlation values significant at the 95% confidence level. Gray contour lines enclose regions where the sign of the correlation is consistent in more than 95% of the 11-year segments. FST = Florida Strait Transport; UMOT = upper mid-ocean transport; Ekt = Ekman transport.

section lengths of approximately 19, 17, and 32 (30, 27, and >50) years are required for the AMOC-SST, Ekt-SST, and FST-SST fingerprints, respectively. The UMOT-SST fingerprint cannot be robustly defined with less than 50 years of data.

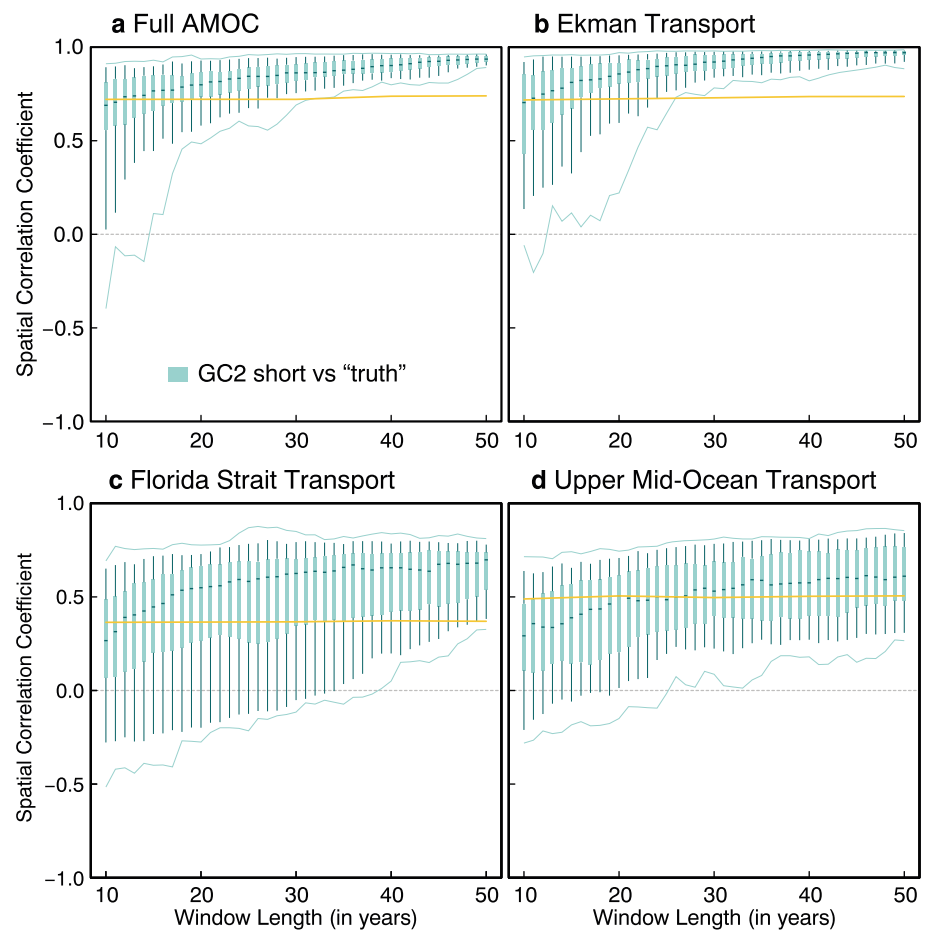
At the local scale, the consistency of the AMOC-SST fingerprints across different subperiods can increase considerably with the length of the subperiod (Figures S4a–S4d). For the Ekt-SST fingerprint, we find that coherent anomalies of the fingerprint are found in >95% of 30-year sections, including the subtropics (Figure S4b). However, the subtropical anomalies are still not consistent in >95% of 50-year segments for the AMOC-SST fingerprint, which likely reflects the larger uncertainty in the other AMOC components. Although some regional anomalies of similar sign are found in more than >95% of 30-year sections for the FST-SST and UMOT-SST fingerprints (Figures S4c and S4d), 50-year sections are needed to resolve the majority of the significant SST anomalies for both of these fingerprints.

### 3.5. Source of Uncertainty in AMOC-SST Fingerprints

We have shown that the AMOC-related SST fingerprints are unreliable if using short time periods to compute them, but what is the source of this uncertainty? Here we assess the role of surface heat fluxes (SHFs) by accumulating them over the previous 5 months (i.e., the SHFs that have occurred since the change in AMOC).

We first assess the spatial correlation of the model-derived “true” AMOC-SHF fingerprints, with the respective AMOC-SST fingerprints. Their overall correlation is high for the AMOC and Ekt (Figures S4a, S4b, S4e, and S4f; 0.86 and 0.84, respectively), suggesting that SHFs are an important driver of the overall AMOC-SST fingerprints. The similarity is especially large in the tropical North Atlantic for both AMOC and Ekt components, with cool SSTs associated with cooling SHFs—which is consistent with the large-scale atmospheric





**Figure 4.** Sensitivity of sea surface temperature-Atlantic Meridional Overturning Circulation (AMOC) fingerprints to the simulated “observational” period. (a) Box-and-whisker plots describing the spatial correlation between the AMOC-SST fingerprint using all 120 years of GC2 data (referred to as “truth”) and the equivalent fingerprints using segments of shorter “observational” lengths. The whisker (box) comprises the 5th–95th (25th–75th) percentiles of the distribution, and the thin blue lines span between the minimum and maximum values. (c and d) Same as in (a) but for the individual components. All fingerprints are obtained against the 5-month lagged sea surface temperature fields. Horizontal orange lines show the  $p < 0.05$  significance threshold (see section 2.3).

circulation patterns driving both the Ekman transport and SHFs. There is also a similarity in the subtropics, with warm SST anomalies associated with warming SHFs. However, the agreement is weak over the Gulf Stream extension, suggesting that SHFs are less important in that region for driving the “true” AMOC-SST and EKT-SST fingerprints. There is also less agreement between the SHF and SST “true” model fingerprints for the FST and UMOT, with spatial correlations equal to  $-0.59$  and  $0.08$ , respectively. Furthermore, regions with the strongest correlations in the SST fingerprints in the Gulf Stream extension region are anticorrelated with the colocated SHF fingerprints, suggesting that for these components, the ocean is the main driver of the SHFs, and not vice versa.

Although SHFs do not explain the “true” SST fingerprints for the FST and UMOT, the uncertainty in the SHFs does contribute to the spread in the SST fingerprints for different subsections. We find that SST fingerprints are more similar to the “true” SST fingerprints when the respective SHF fingerprints are also more similar to the “true” SHF fingerprints, and vice versa (see Figure S5). This is indicative of an important impact of stochastic atmospheric variability in driving the spread in the AMOC-related SST fingerprints on monthly time scales.

#### 4. Conclusions

This paper investigates the role of the AMOC as a predictor of SST changes in the tropical and subtropical Atlantic 5 months in advance, using both observational estimates and model outputs from a preindustrial

experiment with GC2. The simulation was used to explore the sensitivity of AMOC-SST fingerprints to the “observational window” considered. GC2 can represent the mean annual cycle of the AMOC, and the range of monthly and interannual variability of the different components as measured by the RAPID array. The major conclusions of this study are the following:

1. The AMOC-SST fingerprints calculated using short time periods (~11 years) are very sensitive to the period used to compute them. This is particularly true for the observed FST, where the sign of the fingerprint can reverse but is also seen in the model. The model suggests that more than 50 years might be necessary to consistently constrain the “true” large-scale SST fingerprints associated with FST and UMOT on monthly time scales. However, ~30 years might suffice to do it at the local scale, in particular in the regions where the maximum SST responses occur.
2. The main robust feature between observations and GC2 is a cooling south of 26°N that lags a peak in the full AMOC. In the model this is mostly associated with changes in the EkT and SHFs. GC2 suggests that ~25 years of data are enough to constrain the EkT-SST fingerprint.
3. Atmosphere-driven variability in surface ocean heat fluxes contributes to part of the uncertainty in the AMOC-related SST fingerprints.

Although we have assessed the robustness of AMOC-SST fingerprints it is important to note that the results can be somewhat sensitive to the exact details of the analysis. The smoothing applied to the SST fields and the size of the domain considered both affect the magnitude of the spatial correlations. Nevertheless, the general results, including the lack of robustness for short time series (<20–30 years), and the relative robustness of the EkT-SST fingerprint, are not sensitive to these differences. Additional tests in GC2 to address the sensitivity to the particular lead time considered (Figure S6) suggest that the 5-month lead time does not yield the strongest fingerprints, but results remain consistent for other similar lead times. Determining the lead time of maximal correlation might also prove difficult for short observational windows and is likely reflected in the uncertainties when defining the fingerprints.

Our model analysis suggests that on average, the impact of the AMOC on SST on monthly time scales is rather weak. However, an important caveat is that the analysis relies on only one model. Although GC2 can reproduce some general aspects of the observed AMOC and SST fingerprints, it will be important to investigate these findings in other models. Furthermore, with the available data we cannot rule out the possibility that the long-term SST fingerprints in GC2 might differ from those in the real world. If the real-world SST fingerprints for UMOT were stronger than those found in GC2, then less data would be required for the SST fingerprint to become robust. Many interesting questions also remain regarding whether the AMOC-SST fingerprints vary with different seasons or what processes lead to differences in the fingerprints between epochs. Therefore, extending RAPID observations is not only crucial to unveil the true potential of the AMOC to predict the North Atlantic SST several months ahead but also to assess and understand climate models ability to reproduce the observed fingerprints. Longer RAPID time series will additionally open the possibility to address year-to-year climate fingerprints and predictions for which the sample size is currently too small. Ultimately, more process-oriented studies are crucial to understand the robustness of any derived fingerprints.

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