

# A reconstructed South Atlantic Meridional Overturning Circulation time series since 1870

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## Key Points

- A century-long reconstructed South Atlantic Meridional Overturning Circulation index from sea surface temperature is presented.
- The Interdecadal Pacific Oscillation and Atlantic Niño are the main contributors of interannual/decadal covariability of SST and SAMOC.
- SAMOC is currently in an anomalous positive phase.

## Abstract

This study reconstructs a century-long South Atlantic Meridional Overturning Circulation (SAMOC) index. The reconstruction is possible due to its covariability with sea surface temperature (SST). A singular value decomposition (SVD) method is applied to the correlation matrix of SST and SAMOC. The SVD is performed on the trained period (1993-present) for which Expendable Bathythermographs (XBT) and satellite altimetry observations are available. The joint modes obtained are used in the reconstruction of a monthly SAMOC timeseries from 1870 to present. The reconstructed index is highly correlated to the observational-based SAMOC timeseries during the trained period and provides a long historical estimate. It is shown that the Interdecadal Pacific Oscillation (IPO) is the leading mode of SAMOC-SST covariability, explaining ~85% with the Atlantic Niño accounting for

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less than 10%. The reconstruction shows that SAMOC has recently shifted to an anomalous positive period, consistent with a recent positive shift of the IPO.

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## 1. Introduction

There is currently limited knowledge about the underlying mechanisms that govern the South Atlantic Meridional Overturning Circulation (SAMOC) variability and how it might feedback into climate, partly due to the small number of direct observations in this ocean basin. Observational estimates of the SAMOC can be obtained from the beginning of the satellite altimetry period, which started in 1993 [Dong et al. 2015]. Direct observations have been confined mostly to a latitudinal transect at 34.5°S. These observations are carried out using different observing platforms; for example, High Density Expendable Bathythermographs (XBT) since 2002 [Dong et al. 2009; Garzoli et al. 2013], Argo float measurements [Dong et al. 2011, Majumder et al. 2016], and boundary array of inverted echo sounders since 2009 [Meinen et al. 2013]. The longest non-satellite observational record of the SAMOC corresponds to the time series obtained from one XBT transect since 2002, namely AX18, which runs from Buenos Aires, Argentina to Cape Town, South Africa. Motivated by the limited availability of the SAMOC observations, Dong et al. [2015] estimated the volume and heat transport in the South Atlantic using satellite altimetry and a suite of in situ measurements. In that study, they found that altimetry observations could be used to derive the SAMOC, allowing the creation of an extended observational record that starts in 1993. These estimates can be obtained given the correspondence that exists between the sea surface height and the underlying ocean temperatures, mainly below the main thermocline depth [Goni et al. 1996, 2011; Mayer et al. 2001]. In this study, the contribution

of the geostrophic and Ekman components to the total SAMOC was found to vary with time scales of 10 years or longer at different latitudes. In a similar study, Majumber et al. [2016] used Argo profiling float and satellite altimetry observations to derive three dimensional velocity profiles to estimate volume and heat transport in the South Atlantic for the period of 2000-2014 and found strong correlations between the strength of SAMOC and meridional heat transport (MHT) at 35°S, 30°S, 25°S, and 20°S.

Although the altimetry-derived SAMOC time series provides a relatively long record, decadal and multi-decadal variability of the SAMOC and its influence on climate and weather cannot be assessed due to its short temporal record. Given this, most of the current understanding of the SAMOC, and its governing mechanism, depends on the use of numerical models [e.g., Stouffer et al. 2006; Smith and Gregory 2009; Sitz et al. 2015]. The SAMOC derived from climate models has led to several hypotheses for the mechanism governing SAMOC variability. For example, Biastoch et al. [2009] and Lee et al. [2011] suggested that inter-ocean transport from the Indian into the Atlantic Ocean could be a potential source of the anomalous SAMOC variability. Yeager and Danabasoglu [2014] found that most of the SAMOC variability is accounted by changes in the Southern Ocean westerlies, although other studies showed that the influence of Southern Hemisphere wind stress onto the SAMOC depends on model representation of mesoscale eddies [Farneti and Delworth 2010]. In addition, model bias in the representation of the Southern Hemisphere wind stress field makes it difficult to understand the correct response of SAMOC to wind stress changes.

A recent study by Lopez et al. [2016a] found that low frequency variability of MHT in the South Atlantic Ocean associated with changes in the SAMOC could influence monsoon rainfall. They argue that a weaker than normal SAMOC forces an interhemispheric Hadley circulation, transporting anomalous atmospheric heat from the Northern Hemisphere

(NH) to the Southern Hemisphere (SH) and moisture from the SH to the NH, thereby modulating global monsoons. The opposite holds for the case of positive SAMOC anomalies.

This result serves as a motivation to reconstruct the SAMOC from a longer and more readily available dataset, namely sea surface temperature (SST), which can be used to monitor the state of the SAMOC and its impact on climate and weather. Our hypothesis is that the SAMOC and modes of SST variability in the South Atlantic are correlated. The reconstruction is based on the statistical relationship between the SAMOC timeseries and SST field obtained during the observed (i.e., trained) period (1993-present). There are multiple SST products available since the mid-1800s, although there are potential shortcomings with the SST records, especially for the earlier periods. Therefore, we will use several SST products to validate the results. This manuscript is organized as follows. The datasets and methodology are described in section 2. Section 3 discusses the SAMOC reconstruction from SST. Potential climate factors influencing the covariability between SAMOC and SST in the South Atlantic are presented in section 4. The summary and discussion are presented in section 5.

## **2. Datasets and Methodology**

The SAMOC data used in this study are the timeseries derived from XBT and satellite altimetry at 34°S, 30°S, 25°S, and 20°S latitudes for the period of 1993-2015 [Dong et al. 2015]. These are currently the longest observational based SAMOC estimates available. Four SST products are employed, including the Hadley Centre SST (HadSST), the Extended Reconstructed SST version 3 and 4 (ERSSTv3 and ERSSTv4), and the Centennial Observational Based Estimates SST (COBE-SST) [Reynolds et al. 2002; Parker et al. 1994; Smith et al. 1996; Kaplan et al. 1998; Ishii et al. 2005]. Readers are referred to Huang et al. [2014] for a thorough description of the strength/weakness of these SST reanalysis products.

The use of multiple products brings two benefits. First, the comparison among reconstructions during the trained period (i.e., 1993-present) with the actual XBT-altimetry derived SAMOC will allow to assess each SST product. Second, the comparison among reconstructions during the untrained period (i.e., before 1993) should allow quantifying the fidelity of the reconstruction, especially prior to the satellite era.

SVD analysis is used to find coupled patterns of variability between two fields. For example, two data vectors denoted  $\mathbf{x}(t)$  (i.e., SST herein), which cover  $p$  stations or grid points over  $m$  temporal records and  $\mathbf{y}(t)$  (i.e., SAMOC herein), which covers  $q$  stations over  $n$  temporal records, are evaluated here. Thus,  $\mathbf{x}$  is a  $(p \times m)$  matrix and  $\mathbf{y}$  is a  $(q \times n)$  matrix. An SVD analysis (1) on the cross-covariance or correlation matrix  $C_{xy}$  of  $\mathbf{x}$  and  $\mathbf{y}$  can be performed. Note that  $C_{xy}$  is a  $(p \times q)$  matrix.

$$C_{xy} = U \Sigma V^T \quad (1)$$

From (1),  $U$  is a  $(p \times m)$  matrix, whose columns contain the singular vectors of  $\mathbf{x}$ , or the left field here onward.  $V^T$  is a  $(n \times q)$  matrix, which rows contain the singular vectors of  $\mathbf{y}$ , or the right field. The matrix  $\Sigma$  has dimensions of  $(m \times n)$ , which diagonal entries are the squared covariance factors or eigenvalues. Each pair of singular vectors ( $U_k, V_k$ ) corresponds to a singular eigenvalue. Given this, sets of expansion coefficients can be obtained by projecting the singular vectors to their respective data matrix (2a and 2b):

$$a_k(t) = U_k^T \mathbf{x}(t) \quad (2a)$$

$$b_k(t) = V_k^T \mathbf{y}(t) \quad (2b)$$

The temporal expansion coefficient for the left and right fields,  $a_k$  and  $b_k$  respectively, are of key value in describing the covariability between the data vectors  $\mathbf{x}$  and  $\mathbf{y}$  (Bretherton et al. 1992). For example, one can project the expansion coefficient from one field into the data vector of the other to produce heterogeneous correlation maps,  $r_{het}[b_k(t), \mathbf{x}(t)]$  and  $r_{het}[a_k(t), \mathbf{y}(t)]$ . The heterogeneous correlation map is useful to assess how well one field can be predicted from the knowledge of the state of the other field.

The methodology described above is used to perform SVD between the altimetry-derived SAMOC and SST in the South Atlantic for the period 1993-present. First, we detrend both datasets. This is done to filter long-term climate trends, as we are mainly assessing the internal variability. Interannual anomalies are obtained by removing the monthly climatology. A 13-month running average is also applied to each data vector. Lastly, the data vectors are normalized by their respective standard deviation in order to perform the SVD analysis on the correlation matrix of SST and SAMOC.

We will use the SVD patterns obtained for the 1993-present trained period to reconstruct the SAMOC for the untrained period 1870-present, which starts prior to the altimetry era constrained by the longer observed SST field (3). The reconstructed SAMOC timeseries  $\hat{y}(t)$  is readily obtained from the SST data vector  $x(t)$ , where  $t$  indicates the time index (e.g., monthly variant). Note that the relative strength of each mode is measured by the ratio of covariance and variance of each expansion coefficient. The reconstruction is limited by the smaller number of station data of the SAMOC vector (i.e.,  $q=4$  corresponding to 20°S, 25°S, 30°S, and 34°S). Thus, we can obtain a timeseries for each of these latitude points such that  $\hat{y}$  is a function of latitude and time.

$$\hat{y}(t) = \sum_{k=1}^q \frac{cov(a_k, b_k)}{var(a_k)} \mathbf{U}_k^T \mathbf{x}(t) \mathbf{V}_k, \quad q = 4, t = 1870:2015 \quad (3)$$

### 3. SAMOC Reconstruction

Figure 1 shows the heterogeneous correlation for the first joint SVD vectors from the observed SAMOC and the four SST products. Black stipples indicate where correlations are significant at 95% confidence levels. It is important to note that the leading mode explains >84% of the joint variability between SST and the SAMOC independent of the SST product used. The heterogeneous correlations resemble a meridional dipole pattern centered in the South Atlantic Subtropical Gyre. This result is consistent with Lopez et al. [2016b], who found that low-frequency variability of the SAMOC is tightly associated with the leading mode of variability of sea surface height in the South Atlantic Ocean.

The second joint pattern explains <10% of the joint covariance and shows a positive loading near the South American coast and a dominant negative loading in the equatorial Atlantic, which extends into the Benguela current region (Fig. 1SI supplementary information). Most of the variability associated with the third pattern is found near the Brazil-Malvinas Confluence region (Fig. 2SI), explaining less than 7% of the joint variability between SAMOC and SST. The last pattern (Fig. 3SI) explains <1% of the covariability.

The patterns described in Fig. 1, Fig. 1SI, Fig. 2SI, and Fig. 3SI are used here, as stated in (3) to reconstruct the SAMOC timeseries from each SST product. The reconstructed monthly mean SAMOC anomalies are shown in Fig. 2 extending back to 1870. Note that the reconstructed SAMOC and the altimetry-derived SAMOC are very well correlated from 1993-present for all latitudes. This is described in Fig. 3, which shows a Taylor diagram as deterministic skill measure of the goodness of fit between the observed and reconstructed SAMOC timeseries for the trained period for all latitudes and all SST products. The root-mean-square-error (RMSE) of the reconstructed timeseries is considerably smaller than the saturation RMSE error for all cases, indicating that errors in the reconstruction are much smaller than the observed SAMOC variability. There are some marked differences in the

quality of the reconstruction regarding latitude and SST product used. For example, ERSSTv3 and ERSSTv4 show the lowest correlation (e.g.,  $0.5 < r < 0.78$  depending on latitude) but the most accurate standard deviation ( $\sigma$ ) with respect to (w.r.t) the observed  $\sigma$  as depicted by the azimuthal dashed line. The reconstruction using the COBESST presents the smallest RMSE and highest correlation w.r.t the observed (e.g.,  $0.74 < r < 0.97$  depending on latitude), although its  $\sigma$  is consistently larger than that of the observed. The HadSST reconstruction systematically lies between the COBESST and both ERSST products (e.g.,  $0.6 < r < 0.85$  depending on latitude).

This high degree of agreement is indicative of a statistical correspondence between SST and SAMOC and such correspondence is well modeled by the statistical method used here. It also provides great degree of accuracy of the reconstruction prior to the observation record. The reconstructions are very similar among SST products during the untrained period (Fig. 4SI) with the correlations exceeding 0.9 for the 20S, 25S and 30S and 0.7 for the 34.5S. The large agreement among the SAMOC indices during the untrained period adds confidence to the reconstruction. The reconstruction of the SAMOC obtained here provides valuable information that is impossible to obtain from the current observational records alone. For example, results show that there is considerable interannual variability imbedded into large multidecadal variations in the SAMOC for all four latitudes (See supplementary information Figs. 5SI, 6SI, 7SI, and 8SI). The SAMOC interannual variability in the South Atlantic is highly dependent on latitude. Wavelet analysis suggests that the volume transport at 20°S and 25°S are currently stronger than normal in a multi-decadal sense, whereas the transport at 30°S, and 34°S indicates a shift from neutral to a positive (anomalous northward) phase (supplementary information). Since the SVD analysis was trained using a detrended SST and SAMOC data, this notion of weakening/strengthening SAMOC is due to internal variability, and not be misunderstood with those associated with slowdown due to climate change.



#### 4. Factors influencing SAMOC-SST covariability

We investigate climate factors influencing SAMOC-SST covariability. Lopez et al. [2016b] showed that diabatic heating from the Interdecadal Pacific Oscillation (IPO) forces atmospheric teleconnection patterns, which eventually influence the wind stress fields over the South Atlantic modulating the SAMOC. Motivated by this, we use the expansion coefficient reconstructed in (2a) for the first 2 modes, which accounts for more than 90% of the covariability between the SST and the SAMOC. Figure 4 shows the normalized monthly mean expansion coefficient of the first two SST modes (e.g.,  $a_1$  and  $a_2$ ) and the normalized IPO and Atlantic Niño indices. The spatial correlations of interannual SST anomalies with these indices are also shown.

The IPO is multidecadal SST variability in the Pacific, different from ENSO. It shows a symmetric structure about the equator very similar in the North Pacific to the Pacific Decadal Oscillation described by Mantua et al. [1997]. The IPO is known to modulate the strength of the South Pacific Convergence Zone [Folland et al. 2002]. It is worth noting the similarity between the IPO and the leading mode that explains about 85% of the SST-SAMOC covariability. This is consistent with the relationship of the IPO and the SAMOC [Lopez et al. 2016b].

The spatial pattern associated with mode 2 is a dipole in SST with a loading over the tropical Eastern Atlantic and a pole of opposite sign over the southwestern subtropical South Atlantic (Fig. 4d), which is similar to the so-called Atlantic Niño [Zebiak 1993; Keenlyside and Latif, 2007] shown in Fig. 3f. The expansion coefficient  $a_2$  in Fig. 4b is multiplied by minus one for easy comparison with the Atlantic Niño index. These two indices show large anti-correlation ( $r=-0.92$ ) in their temporal variability as well as their correlation with global SST anomalies.

The Atlantic Niño is the equivalent to the Pacific Niño but peaks during the boreal summer [Zebiak 1993; Keenlyside and Latif, 2007]. A positive Atlantic Niño is characterized by warm SST anomalies over the tropical eastern Atlantic. While this mode of SST variability has been widely studied, the underlying mechanisms are still not well understood. One view is that ocean dynamics may be a key factor in the growth of the Atlantic El Niño through positive Bjerknes feedback mechanism [Zebiak 1993; Ding et al. 2010; Hu et al. 2013], equatorial Kelvin waves [Brandt et al. 2011], or meridional temperature advection [Richter et al. 2013]. A competing view is that ocean dynamics only plays a minor role and that atmospheric stochastic forcing is responsible for the growth of tropical Atlantic SST anomalies [Trzaska et al. 2007; Wang and Chang, 2008].

The meridional SST structures associated with the Atlantic Niño (Figs 4d and 4f) are similar to the so-called South Atlantic Subtropical Dipole (SASD, Venegas 1996; Haarsma et al. 2005; Morioka et al. 2011). There is still debate whether the Atlantic Niño and the SASD are part of the same mode or independent from each other. For example, Nnamchi et al. [2011] argued that these two modes are independent. On the other hand in a separate study, the same author demonstrated that the Atlantic Niño can be viewed as the equatorial branch of the SASD, and that the southern pole of the SASD is significantly anticorrelated with the Atlantic Niño [Nnamchi et al. 2016]. Regardless of the origin of the Atlantic Niño or whether it is independent of the SASD, the Atlantic Niño appears to play a secondary role to the IPO in terms of the SST\_SAMOC variability. The variance explained by this mode is much smaller than that associated with the IPO. Overall, the IPO [Lopez et al. 2016b] dominates with covariance explained higher than 85% for all SST products.

## 5. Discussion

Using a reconstructed AMOC timeseries in the South Atlantic, it was shown that while decadal variability of the SAMOC is coherent at 20°S and 25°S, there are larger differences with respect to those at 30°S and 34°S. There is also considerable differences in the interannual variability. Figure 5 shows the linear projection between the reconstructed SAMOC at different latitudes (labeled colored axes) and the first two SST expansion coefficients  $a_1$  (horizontal axis) and  $a_2$  (vertical axis) for the period of 1870-2015. Recall that  $a_1$  is explained by the IPO and  $a_2$  is explained by the negative Atlantic Niño. The variability of the SAMOC at 30°S is mostly explained by the first SST expansion coefficient (e.g., the red axis is parallel to the horizontal axis with correlation of 0.95 for  $a_1$  and 0 for  $a_2$ ). Similarly, the SAMOC at 25°S has a correlation of 0.97 for  $a_1$  and 0.10 for  $a_2$ . Also, the SAMOC at 20°S is significantly correlated with  $a_1$  (0.87) and  $a_2$  (0.53). Note that the SAMOC at 34°S is significantly correlated with both expansion coefficients, although it has a negative relation to mode 2. In summary, the SAMOC is positively correlated with the IPO at all four latitudes. In contrast, the relationship of SAMOC and the Atlantic Niño is dependent on latitude, with positive correlation with SAMOC at 20°S, negative correlation at 34°S, and little correlation at 25°S and 30°S.

It is important to note that the SAMOC at 34°S is nearly orthogonal to the SAMOC at 20°S. This is true from the reconstructed (e.g., correlation  $r=0.18$ ) as well as from the observed (correlation  $r=0.19$ ) period, which advocates for the implementation of observing systems at different latitudes. This finding is consistent with Dong et al. [2015], which found that the correlation of SAMOC at 34°S with all other three latitudes discussed here were below the 95% significant level. In that study, they hypothesized potential factors influencing these low correlations, including the Brazil and Benguela Currents and the Agulhas leakage,

although their relative short temporal record limited further assessments for identifying drivers of meridionally-asymmetric SAMOC behavior.

The latitudinal coherence (e.g., meridional structure) of the reconstructed SAMOC is very similar to the observed SAMOC given that their correlation differences do not pass a significance test at 95% confidence level for any latitude pair (See Table. 1SI of supplementary information). So we can reject the null hypothesis and confirm that the meridional coherence is similar between the observed and reconstructed SAMOC. These results are consistent with those shown in Fig. 5, adding fidelity to the reconstruction.

The high degree of accuracy of the reconstruction presented here may allow for more comprehensive studies on SAMOC variability and potential influence on climate and weather to carry out additional research on the impact of the South Atlantic on global climate and extreme weather events, similar to Lopez et al [2016a]. Future work on this topic will include the assessment of physical mechanism driving the distinction between the SAMOC at 34°S and elsewhere and the latitudinal symmetric (asymmetric) relationship with the IPO (Atlantic Niño). Dong et al. [2015] also pointed out that the relative influence of the Ekman and geostrophic components varies on interannual timescales. This non-stationary behavior could be investigated using the reconstructed datasets presented here. Multi-decadal variability of the SAMOC and its influence on extreme weather will also be investigated in future studies, partially motivated by the findings of Lopez et al. [2016a].

The statistical reconstruction shows that SAMOC is currently in an anomalous positive (i.e., stronger than normal) phase. Concurrently, the IPO has recently shifted to a positive phase [Burgman et al., 2016]. Given this, and according to the mechanism presented in Lopez et al. [2016b], anomalous tropical Pacific convection associated with the positive phase of the IPO forces robust stationary Rossby wave patterns, modulating the wind stress curl over the South Atlantic Ocean. This in turn increases the westerlies over the South

Atlantic, which intensifies the strength of the Subtropical Gyre in the South Atlantic and thus the SAMOC. This physical mechanism aligns with the results presented here and the current state of the SAMOC.

To conclude, it is worth noting that the reconstruction presented here is not a replacement of the current observing systems. In fact, it is a testament of the effort in sustaining several key ocean observational platforms, such as XBTs and Argo floats, and the importance of their joint analysis with satellite altimetry observations, which allowed for studies such as the one presented here to be carried out.

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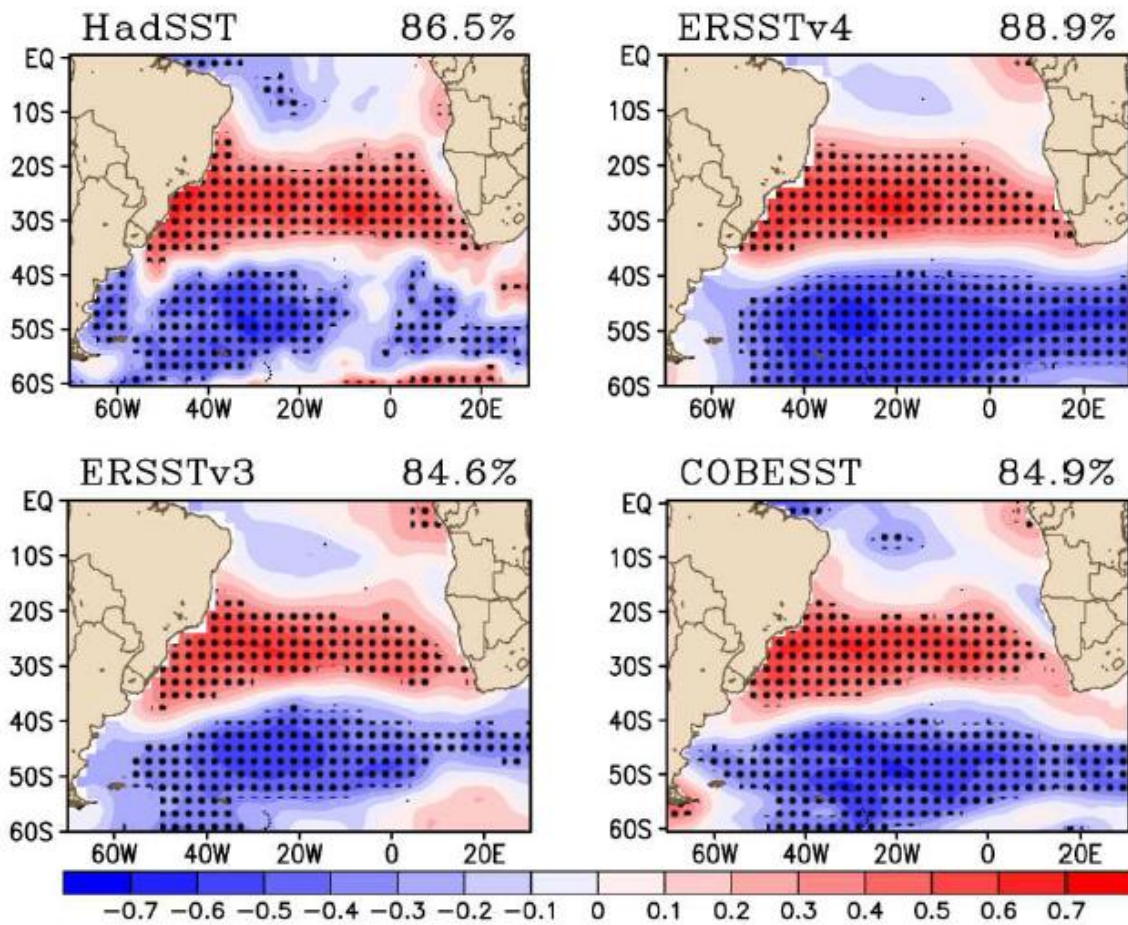


Figure 1. SAMOC time series obtained from altimetry (black) and those reconstructed from SST and SAMOC joint variability (color). All time series were normalized by their standard deviation. The trained period is highlighted by a grey box.

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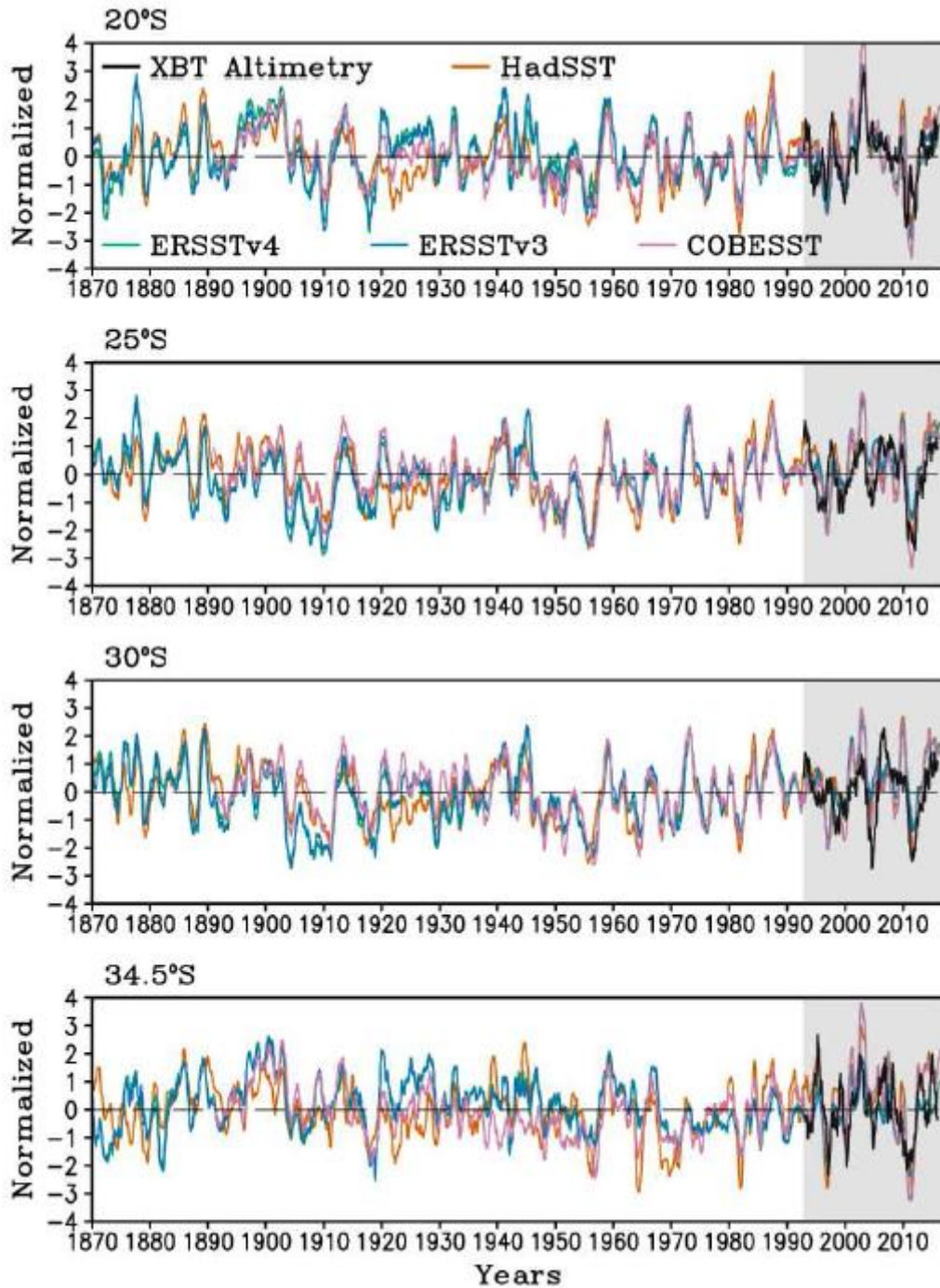


Figure 2. SAMOC time series obtained from altimetry (black) and those reconstructed from SST and SAMOC joint variability (color). All time series were normalized by their standard deviation. The trained period is highlighted by a grey box.

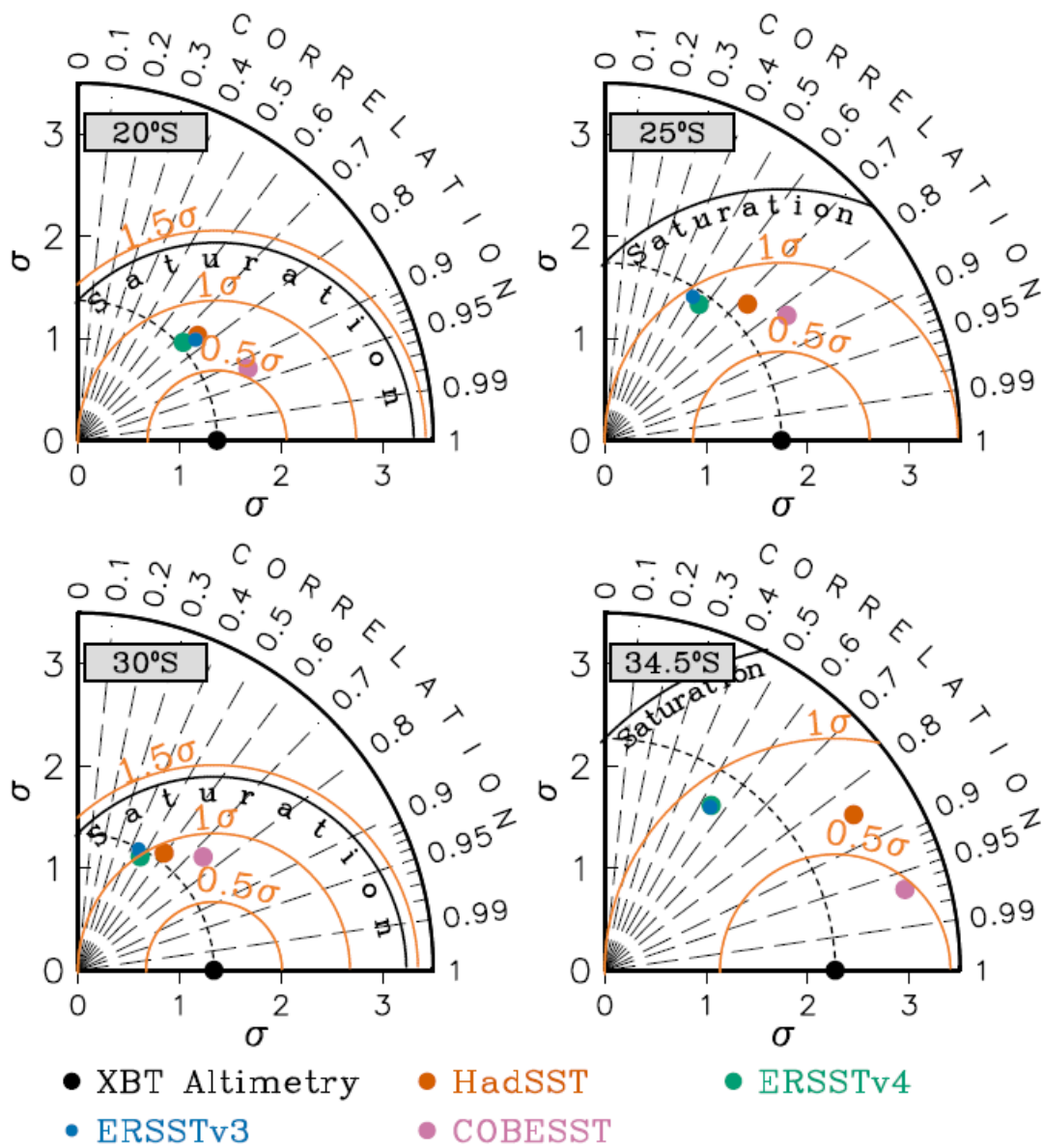


Figure 3. Taylor diagram for the reconstruction of the MOC using different SST products with respect to the observed XBT-altimetry derived MOC (black dot). Note that the radial axes describe standard deviation ( $\sigma$ ) in Sverdrup and the azimuthal axis indicates correlation. The concentric orange circles with respect to the observed MOC indicate root-mean-square-error (RMSE) in standard deviation units. That is, the closer a point is to the observed MOC, the better the reconstruction. The RMSE for all reconstructions are significantly smaller than the saturation RMSE (RMSE equal to  $\sqrt{2}\sigma$ ) shown by black semicircle.



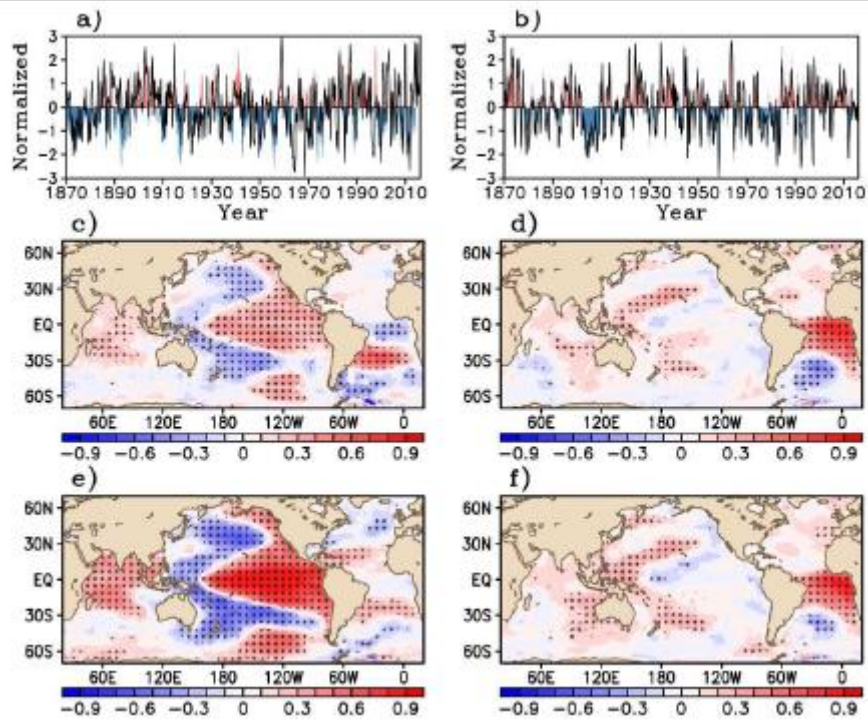


Figure 4. a) Normalized expansion coefficient ( $\mathbf{a}_1$  from eq. 2a) for the first mode of SST and SAMOC variability (black) and the normalized Interdecadal Pacific Oscillation Index, IPO (color). Both timeseries are smoothed by a three-month running average. b) Same as a) but for the normalized (negative) expansion coefficient ( $\mathbf{a}_2$  from eq. 2a) for the second mode of SST and SAMOC variability (black) and the normalized Atlantic Niño Index (color). Panels c, d, e, and f) show the correlation between SST anomaly and:  $\mathbf{a}_1$ , negative  $\mathbf{a}_2$ , IPO index, and Atlantic Niño index respectively. Hatching indicates regions of significant correlation at a 95% confidence level.

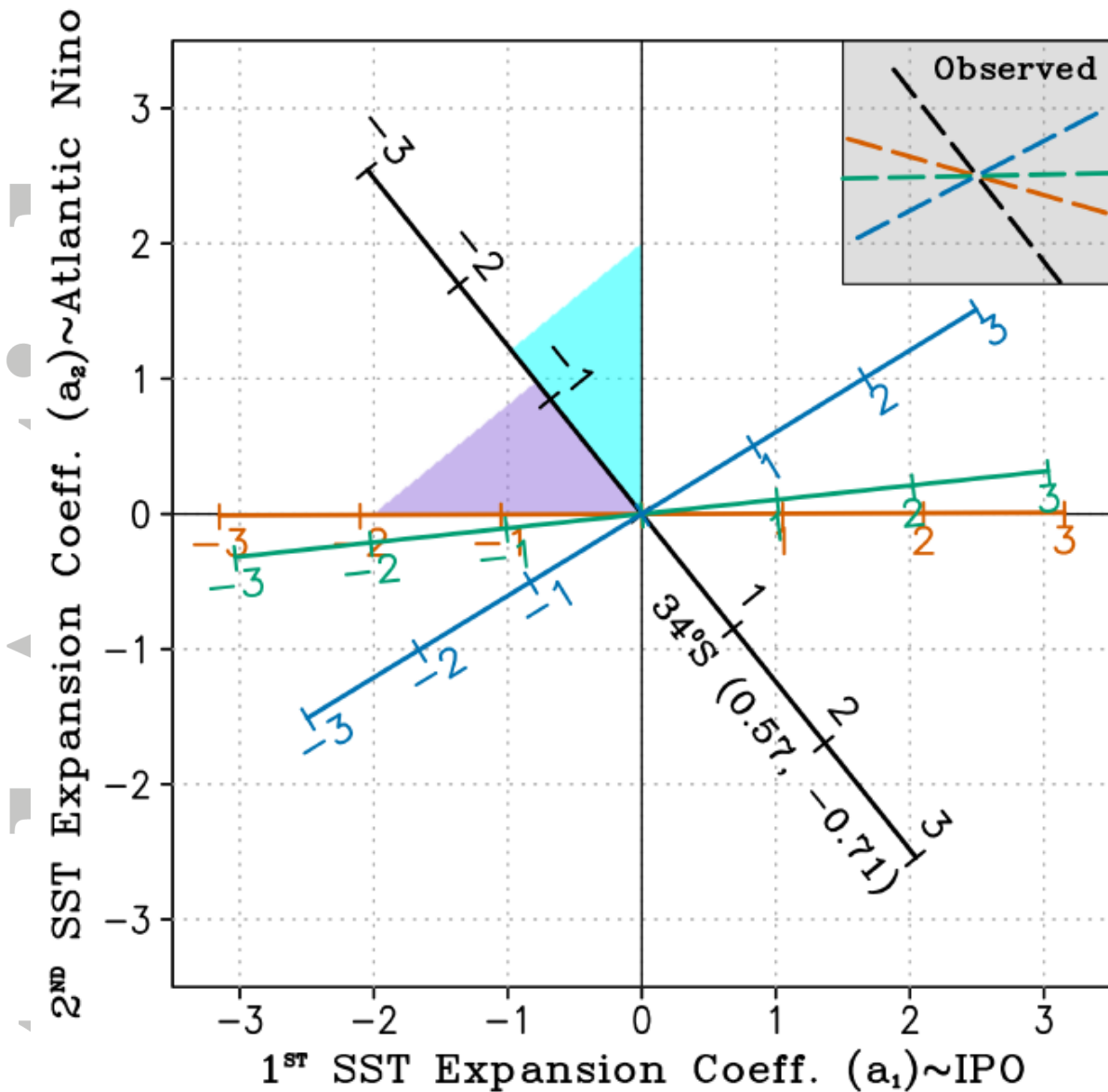


Figure 5. Linear projection between the reconstructed SAMOC at different latitudes (labeled colored axes) and the first two SST expansion coefficients  $a_1$  (horizontal axis) and  $a_2$  (vertical axis). The projection between any two axes indicates their correlation. Note that  $a_1$  and  $a_2$  are orthogonal. For illustration purpose, the purple (aqua) triangle indicates the projection between  $a_1(a_2)$  and the AMOC at 34S. The gray rectangle in the upper-right serve to illustrate that the relationship between first two SST expansion coefficients and the observed AMOC at different latitudes is similar.