On the links between sea level and temperature variations in the Chesapeake Bay and the Atlantic Meridional Overturning Circulation (AMOC)

Tal Ezer[1] · Teresa Updyke[1]

Abstract

Recent studies found that on long time scales there are often unexplained opposite trends in sea level variability between the upper and lower Chesapeake Bay (CB). Therefore, daily sea level and temperature records were analyzed in two locations, Norfolk in the southern CB and Baltimore in the northern CB; surface currents from Coastal Ocean Dynamics Application Radar (CODAR) near the mouth of CB were also analyzed to examine connections between the CB and the Atlantic Ocean. The observations in the bay were compared with daily Atlantic Meridional Overturning Circulation (AMOC) observations during 2005–2021. Empirical Mode Decomposition (EMD) analysis was used to show that variations of sea level and temperature in the upper and lower CB are positively correlated with each other for short time scales of months to few years, but anticorrelated on low frequency modes representing decadal variability and long-term nonlinear trends. The long-term CB modes seem to be linked with AMOC variability through variations in the Gulf Stream and the wind-driven Ekman transports over the North Atlantic Ocean. AMOC variability correlates more strongly with variability in the southern CB near the mouth of the bay, where surface currents indicate potential links with AMOC variability. For example, when AMOC and the Gulf Stream were especially weak during 2009–2010, sea level in the southern bay was abnormally high, temperatures were colder than normal and outflow through the mouth of CB was especially high. Sea level in the upper bay responded to this change only 1–2 years later, which partly explains phase differences within the bay. A persistent trend of 0.22 cm/s per year of increased outflow from the CB, may be a sign of a climate-related trend associated with combination of weakening AMOC and increased precipitation and river discharge into the CB.

Keywords Chesapeake Bay · AMOC · Sea leve · Climate Change

1 Introduction

The Chesapeake Bay (CB) is the largest estuary in the U.S., and the large population living on its shores are vulnerable to increased flooding due to sea level rise, SLR (Boon et al. 2010; Ezer and Corlett 2012; Ezer and Atkinson 2014; Sweet and Park 2014; Valle-Levinson et al. 2017; Domingues et al. 2018; Ezer 2022, 2023) and storm surges during hurricanes (Ezer et al. 2017; Ezer 2020b). In addition to global SLR (Kopp et al. 2014; Dangendorf et al. 2019) and land subsidence (Boon et al.

2010; Eggleston and Pope 2013; Karegar et al. 2016; Bekaert et al. 2017; Buzzanga et al. 2020), local sea level variability in CB may also be affected by other factors that are not clearly understood. For example, potential weakening of the Atlantic Meridional Overturning Circulation, AMOC (Smeed et al. 2014; Robson et al. 2014; Ezer 2015) and the Gulf Stream (Ezer et al. 2013) may increase coastal SLR. There are periods when weak AMOC transport is correlated with higher sea level along the U.S. East coast (Ezer 2015; Goddard et al. 2015), but finding direct links between AMOC and coastal sea level may be elusive, since the pattern of sea level variations associated with AMOC varies by location, forcing, and timescale (Ezer 2013; Little et al. 2019; Wang et al. 2024). Piecuch et al. (2019) for example, found that anticorrelation between AMOC and sea level on the New England coast is linked to zonal wind and pressure, but not much to Gulf Stream variability. Internal variability in the Atlantic Ocean may amplify SLR along the
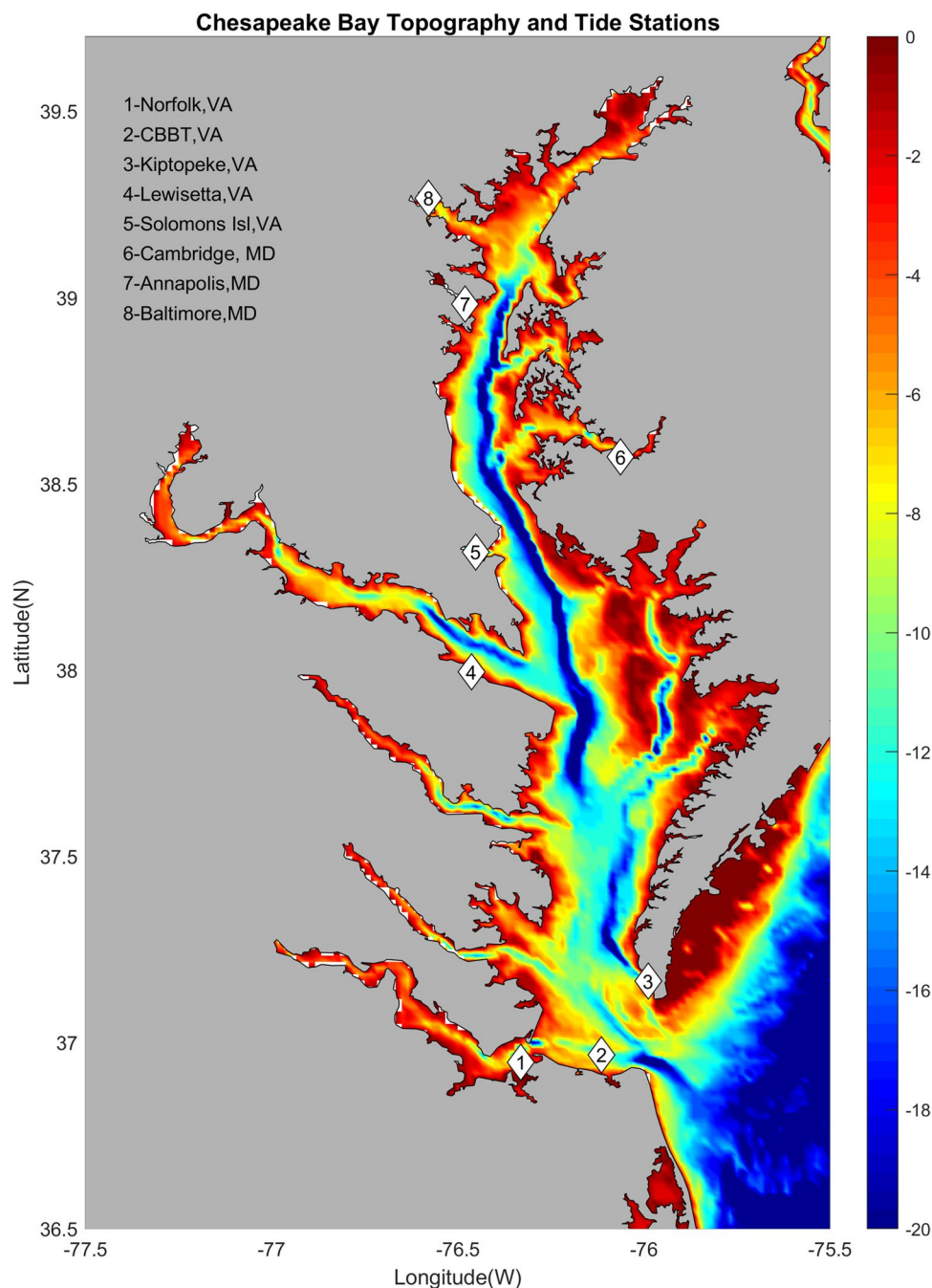
✉ Tal Ezer
  tezer@odu.edu

[1] Center for Coastal Physical Oceanography, Old Dominion University, 4111 Monarch Way, Norfolk, VA 23508, USA

East and Gulf Coasts (Dangendorf et al. 2023) through connections between the open ocean variability and the coast (Dangendorf et al. 2021). On interannual to decadal time scales, teleconnection between coastal sea level, AMOC, and Atlantic Ocean dynamics may involve large-scale heat divergence over the subtropical gyre (Volkov et al. 2019) which could influence frequency of floods along the U.S. East Coast (Volkov et al. 2023).

Unlike coasts that are directly exposed to the Atlantic Ocean, sea level variations in a semi-enclosed bay like CB is more complicated due to local estuarine dynamics, local tides, river discharge, and exchange of heat and salt across the mouth of the bay (Valle-Levinson 1998, 2003), which motivated the current study. Recent analysis of sea level in CB using NOAA tide gauges (Fig. 1) found large spatial variations within the bay and an unusual pattern of long-term sea level variability in which stations in the upper bay and stations in the lower bay are anticorrelated (Ezer 2023). On seasonal time scales, differences in sea level between the upper and lower bays were explained by the pattern of annual and semi-annual tides (Ezer 2020a, 2023), but the spatial variations within CB on interannual to decadal time

Fig. 1 A topographic map (depth in meters) of the Chesapeake Bay and locations of tide gauge stations. Stations 1 and 8 at the two ends of the bay were used in this study

Chesapeake Bay Topography and Tide Stations

1-Norfolk,VA
2-CBBT,VA
3-Kiptopeke,VA
4-Lewisetta,VA
5-Solomons Isl,VA
6-Cambridge, MD
7-Annapolis,MD
8-Baltimore,MD

scales could not be explained. Therefore, the goal of this study is to assess these long-term variabilities in the bay in the context of large-scale Atlantic variability as captured by the latest AMOC observations (Moat et al. 2023). Two stations, one in the upper bay (Baltimore) and one in the lower bay (Norfolk) were compared to examine potential mechanisms and forcing that may explain the different response to Atlantic Ocean variability at the two ends of CB. Surface currents near the mouth of the CB were also analyzed to see if there are long-term variations or trends in the exchange processes connecting the Atlantic Ocean and the CB.

The study is organized as follows. First, the data sources and analysis methods are described in Section 2, then results are presented in Section 3, focusing on variations in sea level, water temperature, and surface currents, finally a summery and conclusions are offered in Section 4.

2 Data sources and analysis methods

Water level and water temperature records from CB tide gauge stations (Fig. 1) are available from NOAA (https://tidesandcu rrents.noaa.gov/). Data at 6-min intervals for 2005–2021 were obtained for Norfolk and Baltimore from the NOAA server (https://opendap.co-ops.nos.noaa.gov/axis/webservices/). The data were first detrended (removing linear trend for the period of our data) and then daily and yearly mean anomalies were calculated. A 10-day low-pass filter was applied to the daily data (Fig. 2a and b) to be consistent with the AMOC data that were filtered at the source (the filter is similar, but not necessarily identical to that used by the RAPID/AMOC group). The climate related linear trends were neglected in the analysis of the anomaly data shown in Fig. 2. It is of interest to acknowledge that the removed trend from 2005 to 2021 was downward -0.1 Sv/y for AMOC, and upward SLR rate of 6.33 mm/y for Baltimore and 6.83 mm/y for Norfolk. These SLR rates are about twice the global SLR rates due to land subsidence in the region (Boon et al. 2010; Eggleston and Pope 2013; Karegar et al. 2016; Bekaert et al. 2017; Buzzanga et al. 2020). Moreover, SLR is accelerating in CB- for example, SLR rates since 1975 were lower, at 4.5 mm/y and 6.1 mm/y for Baltimore and Norfolk, respectively (Ezer 2023). These two stations were chosen following the analysis of Ezer (2023) which shows the different patterns of sea level at the north and south edges of the CB.

The AMOC observations for 2005–2021 at 26°N are available at twice daily intervals from the AMOC-RAPID site (https://rapid.ac.uk/; see Moat et al. 2023, for the latest data release). Daily and yearly mean anomalies were calculated for each of the AMOC components: the Gulf Stream (GS) transport (measured at the Florida Strait), the wind-driven Ekman transport (EKM) the density driven upper

mid-ocean transport (UMO), and the total transport of the meridional overturning circulation (MOC) (Fig. 3).
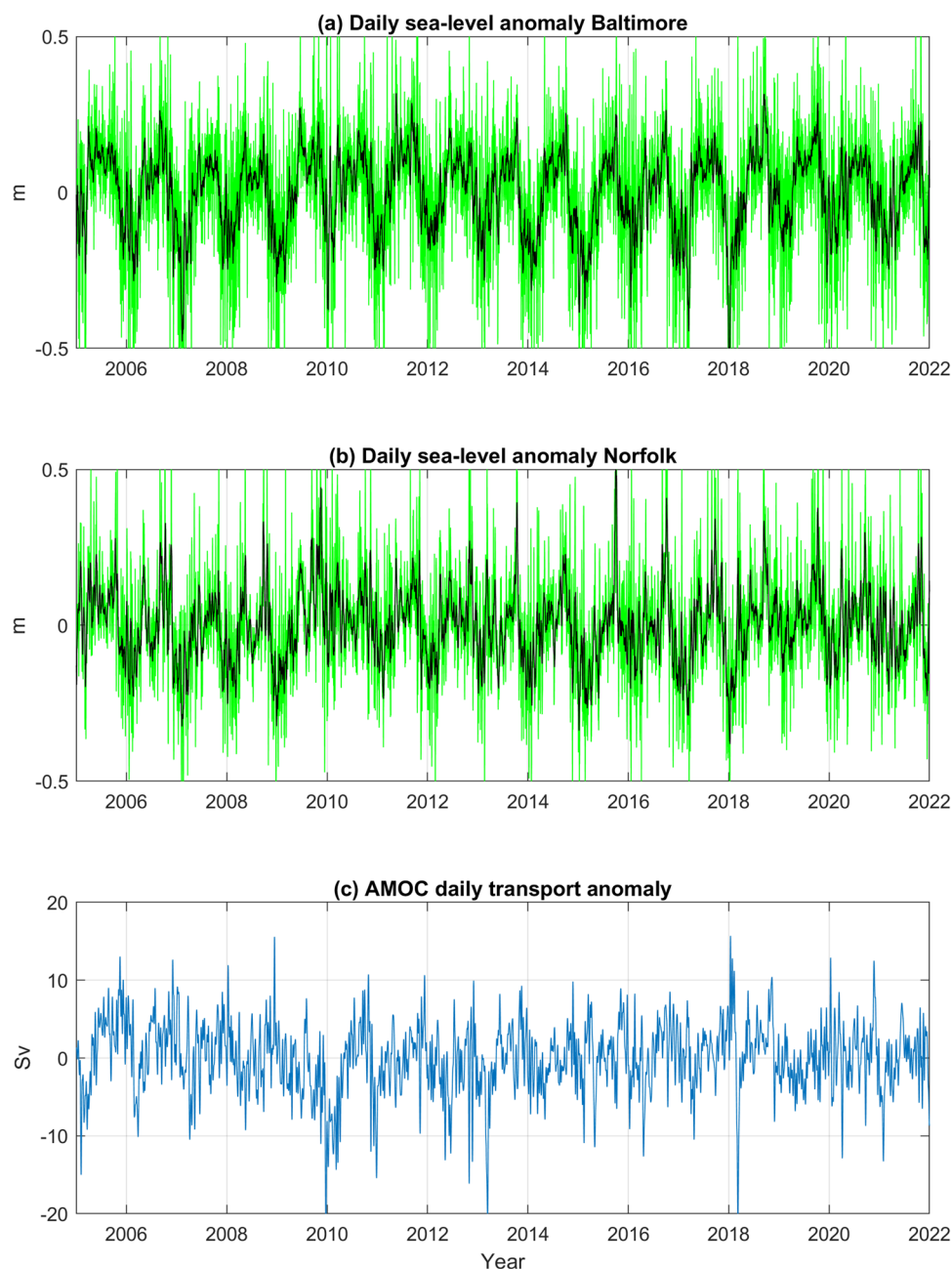
To obtain information on the inflow/outflow at the mouth of the CB, hourly surface currents in this region were obtained from the Coastal Ocean Dynamics Application Radar (CODAR; http://www.ccpo.odu.edu/currentmapping/); 197 spatial data points were averaged to create time series of surface currents (see Atkinson et al. 2009 and Ezer et al. 2022, for details). The current vectors were transformed by rotating the axis 45° southeastward so that negative values represent currents out of the bay (like most estuaries, due to river discharge into the bay there is a mean outflow, i.e., mean current is negative). Daily and yearly detrended mean anomalies were also calculated to be compared with the other data. Monthly river streamflow into the CB (2007–2021) was obtained from USGS (https://www.usgs.gov/media/ images/estimated-monthly-mean-streamflow-entering-chesa peake-bay).

Empirical Mode Decomposition (EMD; Huang et al. 1998; Wu et al. 2007; Wu and Huang 2009) was used to analyze modes of variability on different time scales. EMD is a nonstationary nonlinear method that breaks time series records into Intrinsic Mode Functions (IMFs) representing oscillations with time-dependent amplitudes and frequencies, $C_i(t)$, and a long-term trend, $r(t)$. Therefore, the time series is represented by.

$$\eta(t) = \sum_{i=1}^{N} C_i(t) + r(t) \tag{1}$$

where N is the total number of oscillating modes. Note that since here linear trends have been removed from all data, the trend $r(t)$ represents the remaining nonlinear trend that points for example of sea level acceleration (Ezer and Corlett 2012; Ezer 2023). The EMD method has been used in many studies of sea level variability (Ezer and Corlett 2012; Ezer et al. 2013; Ezer 2013, 2015). Here EMD is used to explore the relation and correlation between different data sets and to see at which time scales different data are linked or not. Note that each EMD mode may not represent a specific process, so often several modes within a window of frequencies are added together, for example, high-frequency, middle-frequency, and low-frequency modes. Ensemble EMD was used to calculate the statistical significance of EMD modes following Wu and Huang (2009), and the statistical significance of correlations between EMD modes was estimated based on the degrees of freedom dependency on autocorrelation scales following the method of Thiebaux and Zwiers (1984). However, one should keep in mind that estimated confidence levels on low-frequency modes may not be as accurate as for high-frequency modes. Note that unlike standard spectral analysis that can only find cyclic variability of constant frequency at each frequency band and is limited to periods much shorter than the record length, in the EMD

Fig. 2 Daily sea level anomaly (detrended) for **a** Baltimore and **b** Norfolk; green lines are the raw data and black lines are 10-day low-pass filtered data. **c** AMOC daily total transport anomaly (also after 10-day low-pass filtered at the source)

3 Results

3.1 Modes of variability in daily sea level and AMOC data

Qualitatively, the daily sea level anomaly (Fig. 2a, b) and AMOC (Figs. 2c and 3) data show considerable variations on a wide range of scales including apparent seasonal variations, but also high-frequency variations and inter-annual variability; the sea level variations represent combined impacts from many potential factors such as tides, winds, storm surges, river discharge, and thermal changes. A particular interesting period with significant anomalies is 2009–2010 when AMOC was especially weak and sea level in Norfolk especially high. This period, during a low phase of the North Atlantic Oscillation (NAO), has been mentioned in past studies (Ezer 2015; Goddard et al. 2015). To further investigate the nonlinear nonstationary variability at different time scales, the ensemble EMD analysis (Wu and Huang 2009) was employed, producing 10 modes (Eq. 1)
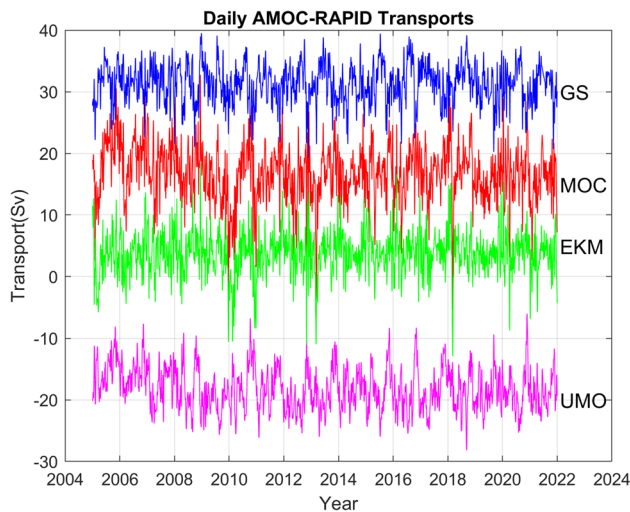

analysis frequency can change within each mode and non-linear trends with incomplete cycles can also be detected.

Fig. 3 The components of the AMOC transport: the Gulf Stream transport at the Florida Strait (GS), the Ekman wind-driven transport (EKM), the density-driven upper mid-ocean transport (UMO) and the total transport (MOC)

for each daily time series. Figure 4 shows the normalized spectral energy of the EMD modes of sea level (Fig. 4a) and the AMOC components (Fig. 4b). High frequency modes with periods less than ~1 month are not significant due to the 10 days low pass filter (high-frequency modes of sea level before the filtering are significant, but not discussed here). Sea level variability in Baltimore has higher relative energy only around the annual cycle, while in the lower bay, in Norfolk, relative energy is higher in all other time scales (especially large difference between the stations is seen for the longest time scales). As discussed later, this may indicate source of variability in the lower CB that originated from the Atlantic Ocean, while the upper bay is more influenced by local dynamics. The energy of the AMOC components shows that the wind-driven Ekman transport is relatively more energetic at short-term monthly time scales (weather systems), while the Gulf Stream and mid-ocean transports are more energetic at longer time scales. The relatively high energy of the total AMOC at decadal time scales seems to be a combination of low-frequency modes of several of its components, especially the mid-ocean transport associated with long-term density variations. For periods longer than 5 years, sea level is several orders of magnitude more energetic at Norfolk than at Baltimore (Fig. 4a), which suggests that the long-term variability seen in Norfolk may have originated outside the CB and potentially linked with AMOC (Fig. 4b).

Figure 5 shows the correlation between the EMD modes of sea level in Norfolk and Baltimore. The overall correlation of daily detrended anomalies between the two locations is R = 0.8; while this correlation is significant at over 95% confidence, it also means that about 33% of the variability
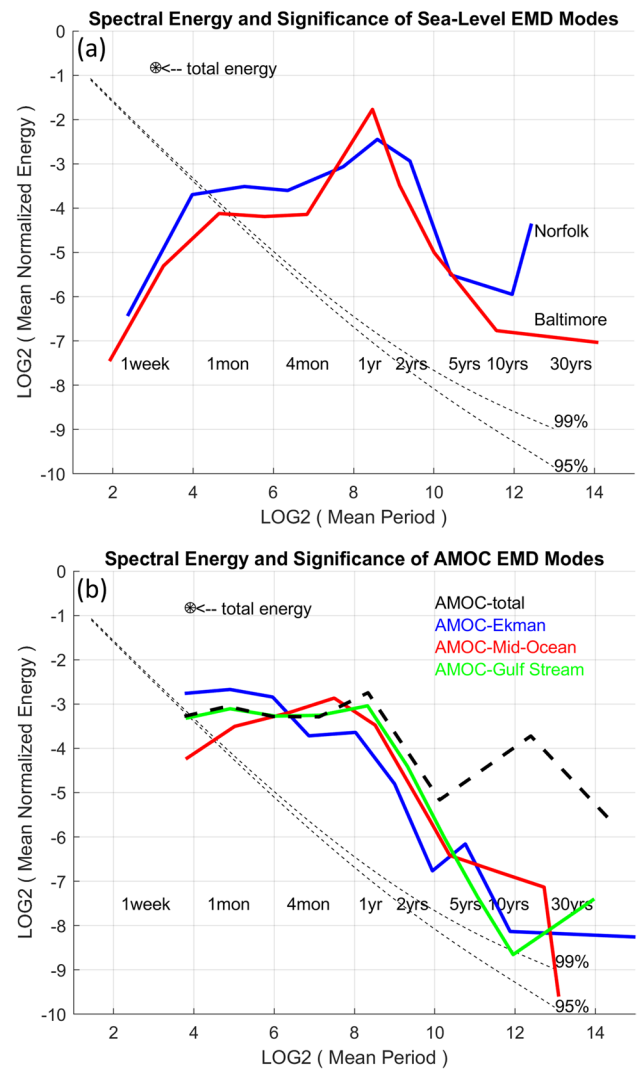

Fig. 4 Spectral energy (normalized) of EMD modes calculated from ensemble simulations of **a** daily sea level for Norfolk (blue) and Baltimore (red), and **b** AMOC components. The estimated mean periods are indicated, as well as the significance level

cannot be explained by a common forcing (i.e., involved local forcing or local estuarine dynamics). The highest positive correlation is near the annual cycle, which is expected, though it is interesting to note that the seasonal sea level cycle in CB is driven mostly by the annual and semiannual tides and not by the seasonal temperature cycle (Ezer 2020a, 2023). Except the annual cycle, positive, but not very high correlations (~0.2–0.4), are seen in modes representing variability with periods of weeks to interannual, demonstrating that local forcing within the CB has significant spatial variability (local rivers, winds, etc.). The very high negative correlation of the lowest frequency mode was indicated before (Ezer 2023), but not fully explained yet. Since AMOC has significant energy at low-frequency modes (dash line in
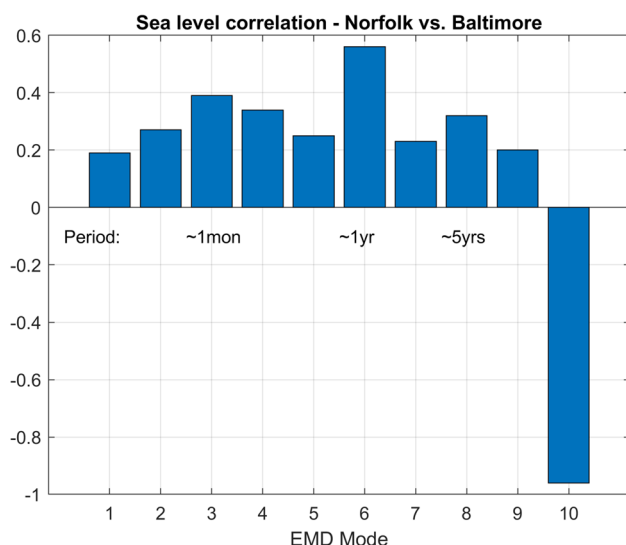
Fig. 5 Correlation between EMD modes of daily sea level of the two locations. Estimated mean periods are indicated

Fig. 4b), the link of AMOC with CB variability is further explored below.

3.2 Comparison of sea level and AMOC

To look at the relationship between AMOC and sea level at different time scales, the EMD modes were composed into three bands, high-frequency modes (mean periods of weeks to ~ 6 months), mid-frequency modes (mean periods of ~ 2–5 years), and low-frequency modes (mean periods of ~ 10 year and longer nonlinear trends). The mode representing the annual cycle (mode 6 in Fig. 5) was not used. The comparisons of the EMD modes of sea level anomaly and AMOC are shown for Baltimore (Fig. 6) and Norfolk (Fig. 7); cross correlations were also shown to indicate potential lags (in the bottom two panels vertical stem-lines are dense, looking like a solid plot). Negative correlations between sea level and AMOC are expected due to the relation with the Gulf Stream (Ezer et al. 2013, 2017; Ezer and Atkinson 2014; Ezer 2020b) and is seen in the high-frequency modes (upper panels of Figs. 6 and 7). The mid- and low-frequency modes show very different AMOC-sea level relations between Baltimore and Norfolk with *positive* lag of 3–5 years for Baltimore and similar *negative* lag for Norfolk. In fact, the nonlinear trends in the low-frequency modes of sea level (blue lines; bottom panels of Figs. 6 and 7) are almost in opposite phase (minimum sea level in Baltimore around 2018, but maximum sea level in Norfolk around 2016, about 5 years after maximum in AMOC).
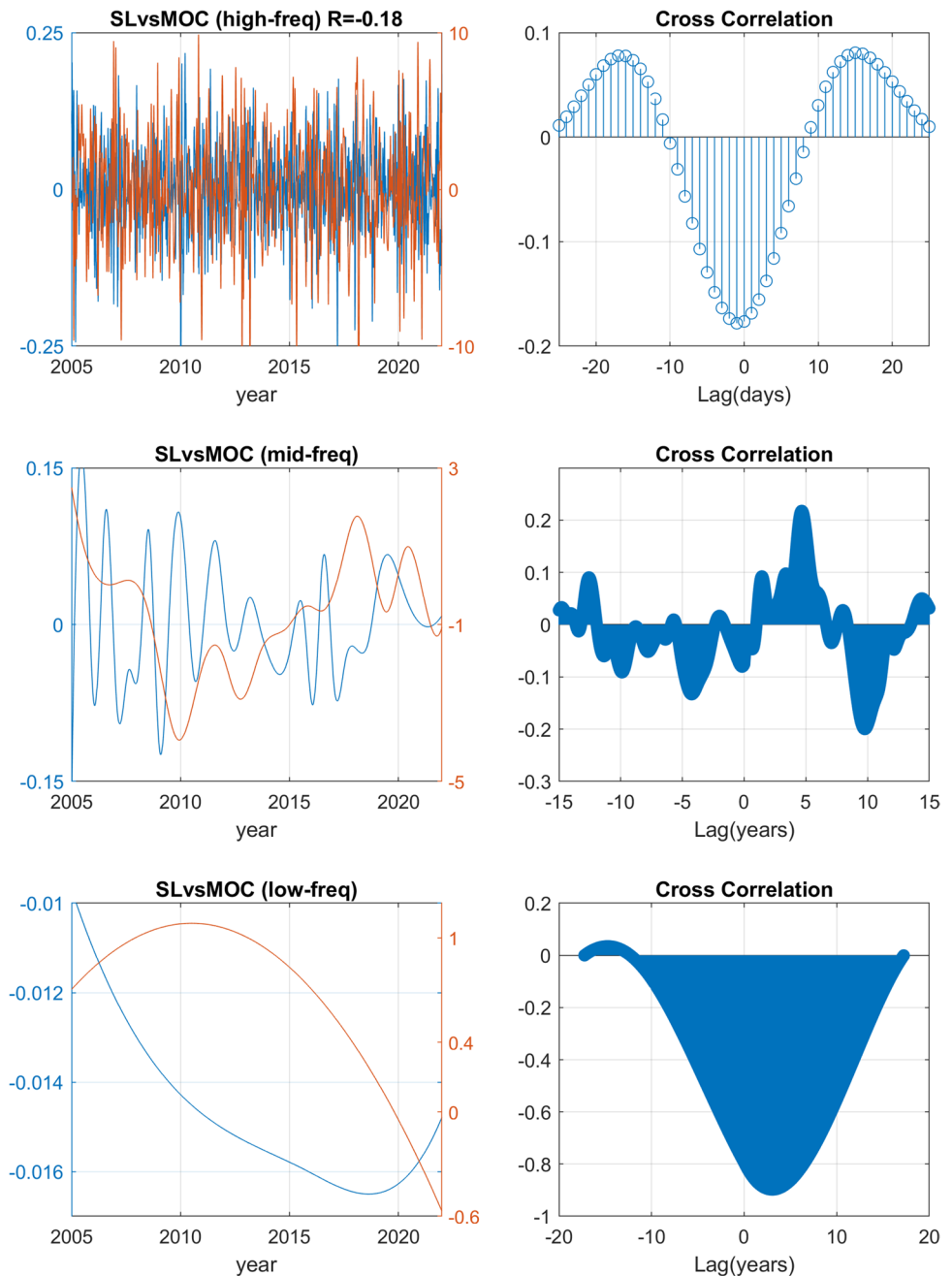
Figure 8 examines how the 3 components of AMOC (Fig. 3) linked with sea level at the two locations (Norfolk/Baltimore in left/right panels; frequency bands from high

to low in top to bottom panels). Almost all correlations are higher in Norfolk than Baltimore, suggesting that the AMOC influence affects the CB through exchange in the mouth of the bay in the south (Fig. 1). High-frequency Gulf Stream variability (Fig. 8a) and mid-frequency wind-driven Ekman transport variability (Fig. 8c) have especially significant correlation with sea level in Norfolk. The pattern of AMOC-sea level correlations in the low-frequency band is exactly opposite in sign between Norfolk and Baltimore for all three components (Fig. 8e and f), owing to the phase difference in sea level at the two ends of the CB as seen before (Figs. 6 and 7). It should be noted however that the estimated confidence level for the low-frequency modes is probably not very accurate, but the sign of the correlation is of interest. For this low-frequency band, higher mid ocean transport is linked with lower sea level in Norfolk and higher sea level in Baltimore, but higher Gulf Stream and Ekman transports are linked with higher sea level in Norfolk and lower sea level in Baltimore. The impact of the Gulf Stream on low-frequency sea level in Norfolk (green bar in Fig. 8e) is interestingly opposite to its impact on high-frequency variability (green bar in Fig. 8a), pointing to a different mechanism than the simple geostrophic argument of sea level slope across the GS, as found in past studies (Ezer et al. 2013; Ezer 2015). It is important to acknowledge that correlation does not necessarily means cause and effect, and the mechanism involved could be a complex combination of several factors.

3.3 Comparison of temperature variability and AMOC

Climatic change and variability over the North Atlantic can affect the CB through local atmospheric heat fluxes and heat transport exchange through the mouth of the bay—temperature changes can also affect steric sea level in the bay. Studies also show that remote influence from wind pattern and heat exchange over the subtropical gyre can impact the coast (Piecuch et al. 2019; Volkov et al. 2019, 2023; Wang et al. 2024). Therefore, daily water temperature records for Norfolk and Baltimore were analyzed. While dominated by the seasonal cycle, temperature variations from year to year are significant (Fig. 9). The seasonal range of temperature is larger in Baltimore than Norfolk, which is consistent with the larger energy at seasonal time scales in Baltimore (Fig. 4a). To remove the dominant seasonal cycle, yearly mean values of AMOC components are compared with sea level (Fig. 10a) and temperature (Fig. 10b); shown are only the AMOC components with significant correlations with either sea level or temperature. On annual basis, sea level correlation between Norfolk and Baltimore is larger (R = 0.84) than temperature correlation (R = 0.6). Both correlations are significant at the 95% confidence level, but temperatures seem to be affected more by
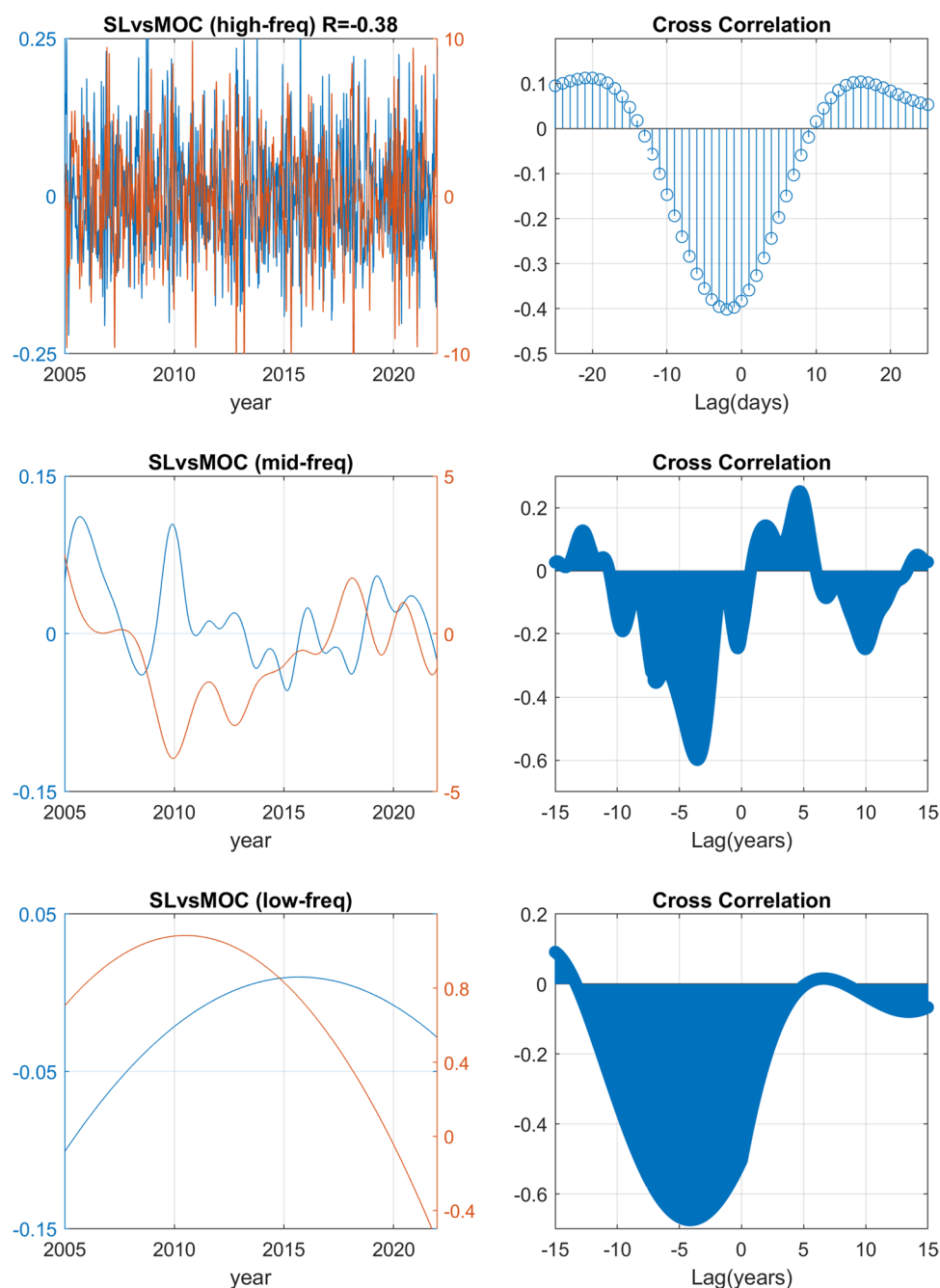
Fig. 6 Comparison between EMD modes of AMOC and sea level in Baltimore; left panels are time series and right panels are cross correlations. Modes were grouped according to mean frequency, top to bottom: high-frequency modes (periods ~ 20 days to ~ 6 months), mid-frequency modes (typical periods ~ 2–5 years), and low-frequency modes (typical periods of 10 years and longer nonlinear trends). The mode near the annual cycle was skipped (mode 6 in Fig. 5)

local conditions than sea level. While sea level variability is dominated by an 8-year cycle, temperature variability is dominated by a 5-year cycle. Correlations of sea level and temperature with AMOC components (R ~ 0.3–0.45) are only significant at the 90%-95% level. A much longer record than the 17-year record here is needed for obtaining higher significance; nevertheless, the pattern of correlation sign and amplitude can help us understand the potential processes involved. First, AMOC is negatively correlated with sea level (especially with the Gulf Stream and Ekman transports, as mentioned before) while positively correlated with temperatures (in particular, with the mid-ocean

transport). This result implies a transport-driven sea level versus a heat flux driven temperature. Second, sea level correlations with AMOC are higher in Norfolk, but temperature correlations are higher in Baltimore, suggesting that sea level in the bay is largely driven by transports from the Atlantic Ocean while temperature in the upper bay is driven more by local atmospheric conditions. A particular period of interest is 2009–2010 when AMOC and NAO were extremely low and sea level anomalously high along the U.S. East Coast (Ezer 2015; Goddard et al. 2015). At the same time, water temperatures were colder than normal across the bay when sea level was raising in Norfolk,

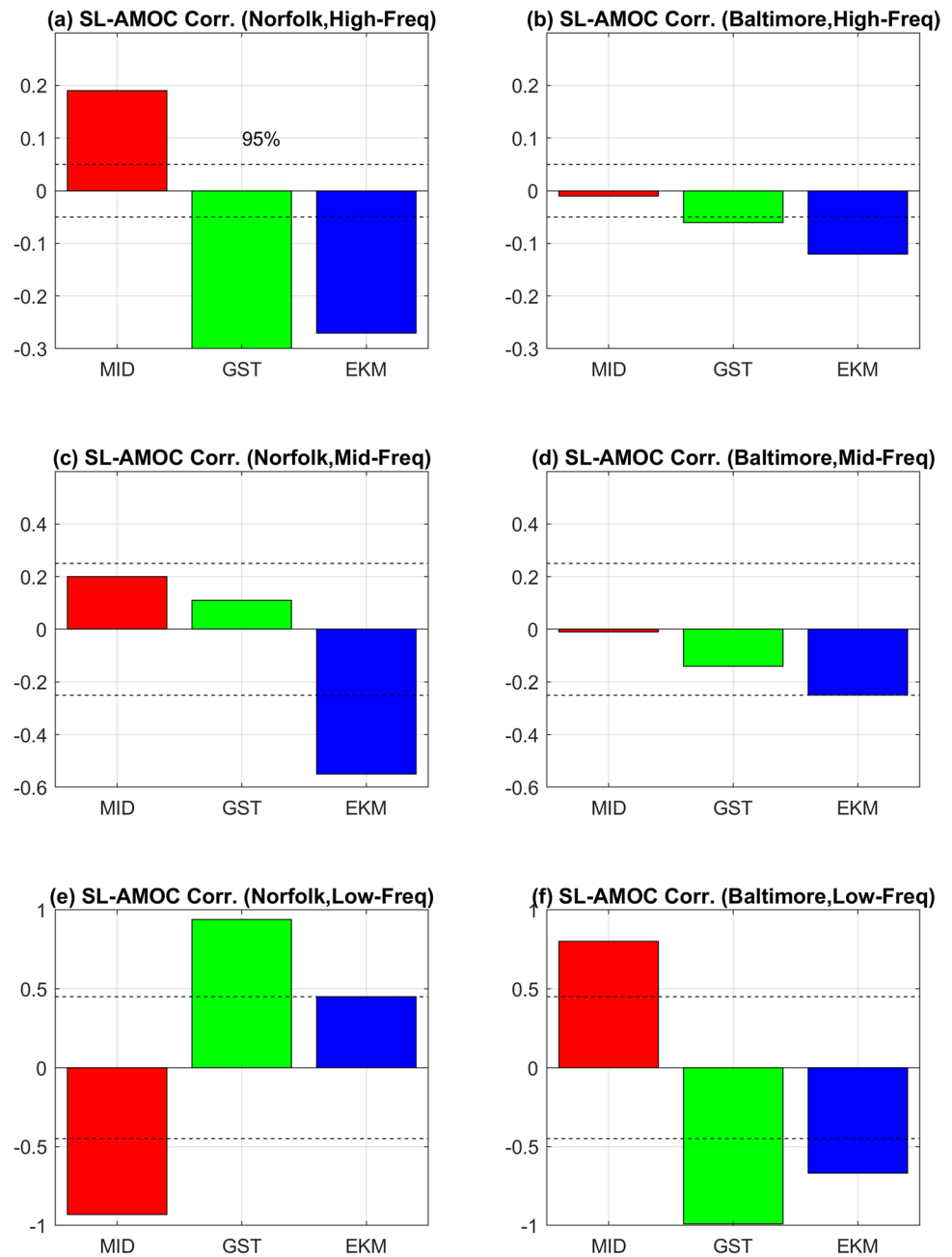**Fig. 7** Same as Fig. 6, but for sea level in Norfolk

so thermosteric effect is not a factor. However, while sea level in Norfolk reached a peak in 2009–2010, sea level in Baltimore peaked only 1–2 years later in 2011, creating phase difference as noted before. In 2019, when AMOC was in another low phase, temperature in Baltimore was low again and sea level was high across the CB. The latter case is somewhat different than the more dramatic AMOC low in 2009–2010, because in 2019 only the Gulf Stream transport was low (Fig. 10a), with no significant change in the wind-driven Ekman component and the density-driven mid-ocean transport.

3.4 Surface currents at the mouth of the Chesapeake Bay

The data analyzed so far show that the lower CB is more closely linked with variability over the Atlantic Ocean than the upper bay, suggesting that the exchange of water and heat through the mouth of the CB may play a role in the dynamics of the bay. Observations of surface currents by CODAR stations have been carried out systematically since ~2007 (for details see Atkinson et al. 2009 and Ezer et al. 2022). These currents are dominated by the semi-diurnal and spring/neap

Fig. 8 Linear correlations between sea level and AMOC components for the 3 frequency bands as in Figs. 6–7 (high to low frequencies from top to bottom); left/right panels are for Norfolk/Baltimore. The AMOC components are mid-ocean transport (red bars), Gulf Stream transport (green) and Ekman transport (blue). Dash lines represent estimated correlation values for 95% confidence level when considering the loss of degrees of freedom for lower frequency modes

tidal cycles, as well as large variability during storms. Therefore, a 30-day low-pass filter was applied to remove high-frequency variability (Fig. 11a), and yearly mean anomalies were calculated and compared with the Gulf Stream transport and with observations in Norfolk (Fig. 11b). There is a persistent increased outflow trend of 0.22 cm/s per year (negative/positive values indicate outflow/inflow direction) that will be discussed later. The interannual variations in currents include a cycle with period of ~ 3–5 years and a strong outflow in 2010, around the time of colder temperatures, weaker Gulf Stream, and higher sea level, that were discussed before. Because the record is relatively short (only

15 years) the correlations between the surface currents and the other observations are only significant at 80%-90% confidence level, though the pattern of variations is interesting. During years of anomalous surface currents, sea level and the Gulf Stream show the following patterns: in 2010 when the outflow was maximum (largest negative anomaly), the Gulf Stream was weak and sea level peaked, but in 2013 and 2017 when the outflow was especially weak (positive anomaly) the Gulf Stream was stronger and sea level lower. This pattern is also consistent with the trend of increased outflow (Fig. 11a) when AMOC and the Gulf Stream are weakening over time due to climate change (Ezer et al. 2013;
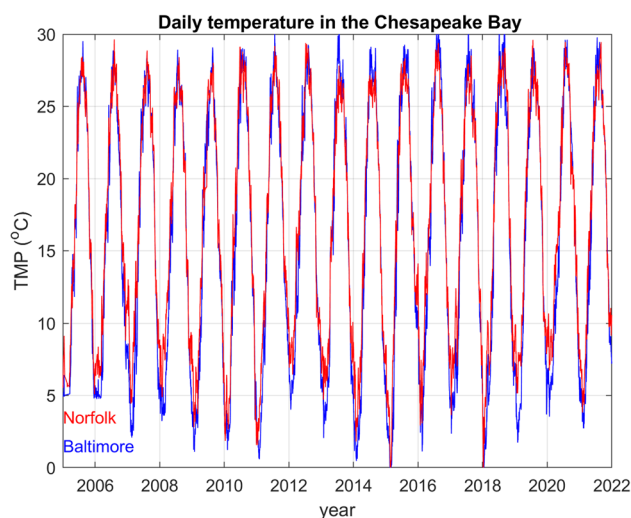
Fig. 9 Daily water temperature in Norfolk (red) and Baltimore (blue) calculated from NOAA 6-min data

Ezer 2015; Piecuch and Beal 2023). The results here show that surface outflow change of 1 cm/s is roughly equivalent to ~2 Sv change in AMOC transport. Reconstruction of AMOC using sea level data estimated recent AMOC decline of ~0.44 Sv per year (Fig. 9 in Ezer 2015), which based on the results here is equivalent to 0.22 cm/s per year change in surface currents, exactly the trend shown in Fig. 11a. The proximity between this estimate and the observational trend in outflow could be a coincidence, and does not imply cause and effect, i.e., it does not necessarily imply that AMOC directly drives surface currents in the CB, but rather that maybe both are affected by climate change.

A more direct connection to increase in net outflow is the increase in precipitation in the northeastern U.S. region and increased river discharge into the CB (Rice et al. 2017) – if inflow from rivers increases, outflow from the mouth of the bay should increase as well. The analysis of Rice et al. (2017) indicated about 30–40% increase in discharge from 1927 to 2014, or about 0.4% increase per year, compared with ~2.5% increase in surface outflow per year from 2007 to 2021. Figure 12 shows a comparison between the monthly river inflow into the CB and the surface currents out of the CB—both inflow and outflow show positive trends of increased flow. The 1.4% per year increased river flow into the CB during 2007–2021 is closer to the increased surface outflow during this period (2.5%/y), than the previous estimates of Rice et al. (2017) for 1927–2014. Therefore, it seems that the trend of increased flow in/out of the CB have accelerated in recent years. While correlations between surface currents and AMOC or between currents and river discharge are statistically significant (Fig. 12), the correlation is not very high, indicating potential combination of several
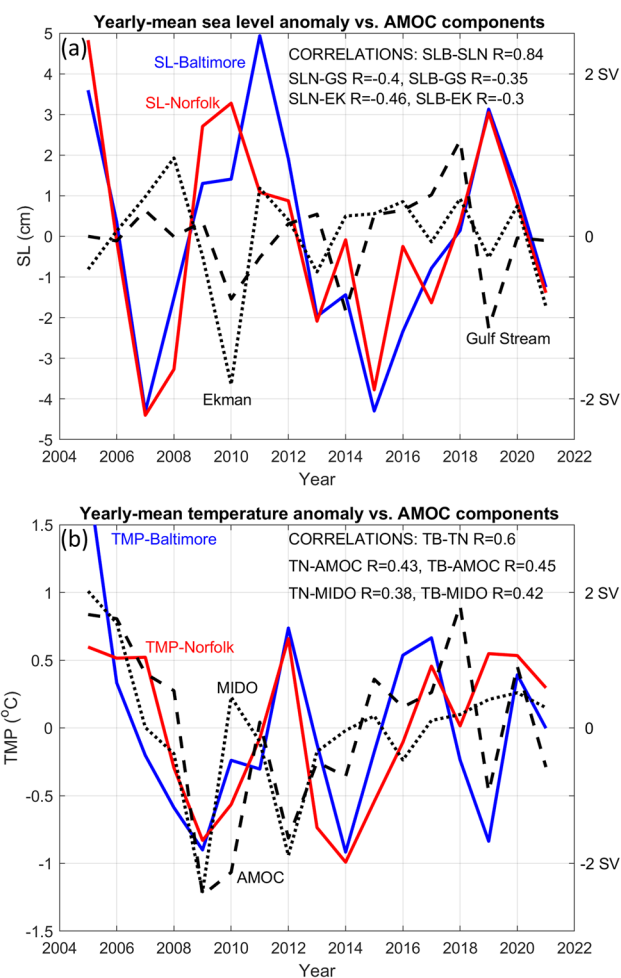

Fig. 10 Yearly mean sea level (**a**) and temperature (**b**) anomalies in Baltimore (blue) and Norfolk (red). AMOC components with significant correlations are Gulf Stream transport (dash black line in **a**), Ekman transport (dotted black line in **a**), total AMOC transport (dash black line in **b**), and mid-ocean transports (dotted black line in **b**). Correlations are also shown

factors. Additional factors that can impact surface velocities and should be further explored in future studies include for example, the decrease in tidal range in the CB (Cheng et al. 2017), impact of sea level rise and inundation on the estuarine dynamics (Ezer 2023), coastal erosion, change in stratification, etc.; all these changes can affect the complex dynamics of the CB as seen in past observations of currents near the mouth of the CB (Valle-Levinson et al. 2003).

4 Summary and discussion

Understanding the impact of potential climate change on the CB's ecosystem and population is important for planning mitigation and adaptation options. The acceleration in flooding due to fast sea level rise has been documented in many
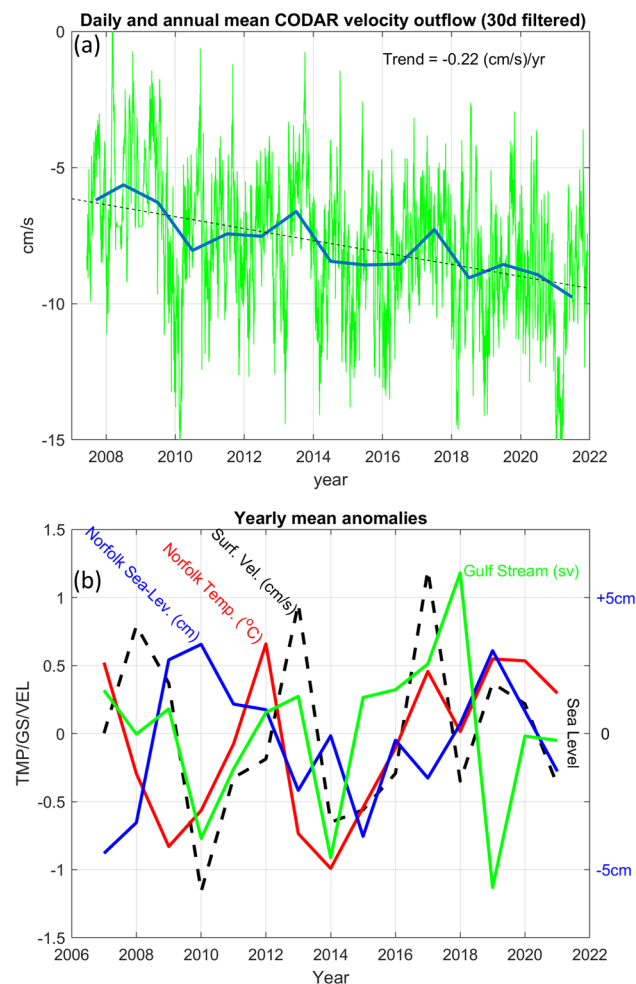
Fig. 12 Monthly streamflow into the CB (blue) and surface outflow out of the CB (red). The monthly outflow is calculated from the daily data (Fig. 11a with reverse sign). Dash heavy lines are the linear trends which are indicated (both positive, 1.4% increase inflow per year and 2.5% increase outflow per year). The correlation between the data and the P-value are also indicated

Fig. 11 **a** daily (green) and annual (blue) mean surface velocity measured by CODAR stations near the mouth of the CB; downward linear trend (dash line) indicates increased outflow from the CB toward the Atlantic Ocean. **b** Yearly mean data for CODAR surface velocity (dash black line), Norfolk sea-level (blue) and water temperature (red), and the Gulf Stream transport (green). Y-axis for sea-level in on the right and for all other variables on the left

studies (Ezer and Corlett 2012; Ezer and Atkinson 2014; Boesch et al. 2018; Sweet and Park 2014; Park and Sweet 2015; Ezer 2022, 2023). While global sea level continues to rise, local variations in sea level are more difficult to predict – Ezer (2023), for example, shows large differences withing the CB between SLR prediction based on climate models and SLR based on local statistics of past data. A particular difficulty in SLR prediction is the impact of remote, large-scale oceanic variations such as changes in ocean currents, impact of Rossby Waves on coastal sea level (Dangendorf et al. 2021, 2023) and changes of heat flux divergence over the subtropical gyre (Volkov et al. 2019). Potential slow-down of AMOC and the Gulf Stream (Ezer et al. 2013; Ezer 2015; Piecuch and Beal 2023) already showed their impact on increased SLR and coastal flooding, but the impact may
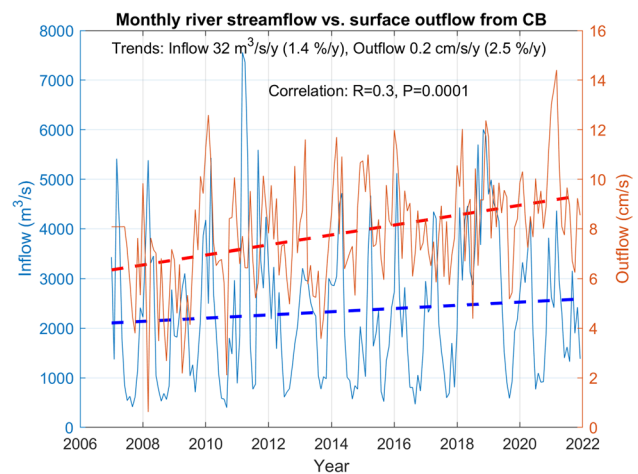
be very different along different sections of the U.S. East Coast (Ezer 2013; Little et al. 2019; Volkov et al. 2023). Moreover, most previous studies of the links between remote Atlantic variability and the coast include only coasts that are directly in contact with the open ocean, while the remote impact inside estuaries like the CB is more complicated due to local dynamics (e.g., tides, rivers, and estuarine circulation). The exchange of water, heat, and salt through the mouth of a bay is of particular interest as it provides a link between a bay and the open ocean.

In the CB, for example, a recent study (Ezer 2023) found some unexplained long-term sea level variability that has opposite phases in stations in the upper bay compared with stations in the lower bay. Such long-term variability is likely linked to large-scale climate variability such as variations in AMOC (Ezer 2015) and NAO (Ezer and Atkinson 2014), though observations of AMOC are quite short (about two decades) so studying decadal variations is challenging. To examine these variations, daily, monthly and annual data of various observations were analyzed – they include sea level, surface temperature, river discharge, surface currents near the mouth of CB bay, and the RAPID/AMOC transport (which also includes the Gulf Stream transport). The results suggest that part of the observed long-term variabilities in the CB originated in the Atlantic Ocean and impacted the CB by creating variations in the exchange of flow at the mouth of the bay. Several results support this hypothesis:

1. EMD analysis shows more energetic low-frequency variability in the lower CB (at similar periods as seen in the AMOC variability) than in the upper CB. The upper bay

seems to be more affected by local dynamics and the seasonal cycle than by flow exchange with the Atlantic Ocean.

2. When comparing sea level in the upper and lower CB, the lowest frequency modes and trends are out of phase, indicating different forcing, while variabilities in all other modes from periods of days to few years are positively correlated.

3. Correlation between sea level and the 3 components of AMOC are more significant in Norfolk than Baltimore and the sign of correlations of the low frequency modes are exactly opposite between the two locations. The mechanism is still not completely understood. For example, *negative* correlation between sea level variability in Norfolk and the Gulf Stream transport has been found before for high-frequency variability such as following hurricanes (Ezer and Atkinson 2014; Ezer 2020b; Park et al. 2022, 2024), due to weakening of the Gulf Stream post hurricanes and reduced sea level gradients across the Gulf Stream. However, why is there a *positive* correlation between the Gulf Stream transport and Norfolk's sea-level (and negative correlation in Baltimore) for the low-frequency modes?

4. Analysis of yearly mean temperatures and their comparison with AMOC shows *positive* correlations that are larger in Baltimore than Norfolk – This contrasts with sea level-AMOC correlations that are *negative*, with higher values in Norfolk. This may suggest that sea level variations are driven by transports coming from the south, when temperature variations are driven by local air-sea interactions, which are stronger in the more isolated northern bay.

5. Finally, the most convincing argument for remote influence on the CB comes from the surface currents near the mouth of CB, which show low-frequency variability resembling the AMOC variability. Periods of increased outflow from the CB coincide with periods of colder water temperatures in the CB, higher sea level in Norfolk, and a weaker Gulf Stream transport. The relation between the observations is complicated and does not necessarily indicate cause and effect. For example, the interannual variability is dominated by a 5-year cycle in temperature, surface currents and the Gulf Stream, and an 8-year cycle in sea level. On the other hand, the wind-driven Ekman transport component of AMOC shows more energy at higher frequencies. Past studies identified 6–8 years cycle in the Gulf Stream transport (Ezer et al. 2013) that influence sea level in the Mid-Atlantic coast, but inside the CB it appears that sometimes there is a delayed response in the upper bay, which can explain the observed anticorrelation between sea level in the upper and lower bay.

Another interesting finding is the continuous increase in surface outflow from the CB since observations started in 2007 (Fig. 11a). It can be assumed that this trend represents increased net outflow transport, though there are no continuous observations of the entire water column and the flow there is quite complicated (Valle-Levinson et al. 2003). This trend is consistent with the increase in precipitation and river discharge into the CB as previously reported by Rice et al. (2017) and seen in recent streamflow data (Fig. 12). The net outflow from any bay is generally $\Delta V = R + P\text{-}E$ (R, P and E are river discharge, precipitation, and evaporation rates, respectively); assuming no significant change in evaporation, outflow should increase with increased $R + P$. However, one cannot eliminate the possibility that other climate variability factors may also contribute to this trend, such as the decline in tidal amplitude (Cheng et al. 2017) and impact of sea level rise on the estuarine dynamics. A link was found here between variations in the Gulf Stream transport and variations in surface currents near the mouth of the bay. There are now evidences that there has been a climate-related decline in the observed Florida Straits transport over the last four decades (Piecuch and Beal 2023) and a weakening of the Gulf Stream in the Mid-Atlantic Bight since the 1990s (Ezer and Dangendorf 2020). While the surface current record of 15 years was too short to establish undisputed significant statistical confidence about its relation to AMOC, the trends and variability do point to climate related influence on the environment in CB from remote variations in the Atlantic Ocean, and these variations seem to enter the bay at its mouth, affecting the lower bay. The forcing of the CB is complicated though with different forcing acting on the northern and southern CB at different time scales which result in spatial variations within the bay. The study provides further support to the notion that the lower bay is affected by large-scale, long-term Atlantic variability. The study also found another potential detector for climate change: changes in the outflow from estuaries and bays, and suggests that future projections of climate change in bays and estuaries must consider local dynamics.

Data availability The sea level and the water temperature data are available from NOAA (https://tidesandcurrents.noaa.gov/ and https://opendap.co-ops.nos.noaa.gov/axis/webservices), the AMOC data are available from the RAPID-AMOC site (https://rapid.ac.uk/), and the CODAR surface current data are available from CCPO (http://www.ccpo.odu.edu/currentmapping/). Monthly river streamflow data are available from USGS (https://www.usgs.gov/media/images/estimated-monthly-mean-streamflow-entering-chesapeake-bay).

References

Atkinson LP, Garner T, Blanco J, Paternostro C, Burke P (2009) HFR surface currents observing system in lower Chesapeake Bay and Virginia coast. OCEANS 2009, IEEE Xplore. https://ieeexplore.ieee.org/document/5422254

Bekaert DPS, Hamlington BD, Buzzanga B, Jones CE (2017) Spaceborne synthetic aperture radar survey of subsidence in Hampton Roads, Virginia (USA). Scientific Rep 7:14752. https://doi.org/10.1038/s41598-017-15309-5

Boesch DF, Boicourt WC, Cullather RI, Ezer T, Galloway GE, Johnson ZP, Kilbourne KH, Kirwan ML, Kopp RE, Land S, Li M, Nardin W, Sommerfield CK, Sweet WV (2018) Sea-level rise projections for Maryland, University of Maryland Center for Environmental Science, Cambridge, MD, pp 28. https://www.umces.edu/sea-level-rise-projections

Boon JD, Brubaker JM, Forrest DR (2010) Chesapeake Bay land subsidence and sea level change: an evaluation of past and present trends and future outlook. Special report in applied marine science and ocean engineering, 425. Virgin Ins Mar Sci. https://doi.org/10.21220/V58X4P

Buzzanga B, Bekaert DPS, Hamlington BD, Sangha SS (2020) Toward sustained monitoring of subsidence at the coast using InSAR and GPS: An application in Hampton Roads, Virginia. Geophys Res Lett 47(18): e2020GL090013. https://doi.org/10.1029/2020GL090013

Cheng Y, Ezer T, Atkinson LP (2017) Analysis of tidal amplitude changes using the EMD method. Cont Shelf Res 148:44–52. https://doi.org/10.1016/j.csr.2017.09.009

Dangendorf S, Hay C, Calafat FM, Marcos M, Piecuch CG, Berk K, Jensen J (2019) Persistent acceleration in global sea-level rise since the 1960s. Nat Clim Chan 9:705–710. https://doi.org/10.1038/s41558-019-0531-8

Dangendorf S, Frederikse T, Chafik L, Klinck J, Ezer T, Hamlington B (2021) Data-driven reconstruction reveals large-scale ocean circulation control on coastal sea level. Nat Clim Change 11:514–520. https://doi.org/10.1038/s41558-021-01046-1

Dangendorf S, Hendricks N, Sun Q, Klinck J, Ezer T, Frederikse T, Calafat FM, Wahl T, Törnqvist TE (2023) Acceleration of U.S. Southeast and Gulf coast sea-level rise amplified by internal climate variability. Nat Commun 14:1935. https://doi.org/10.1038/s41467-023-37649-9

Domingues R, Goni G, Baringer M, Volkov D (2018) What caused the accelerated sea level changes along the U.S. East Coast during 2010–2015? Geophy Res Lett 45(24):13367–13376. https://doi.org/10.1029/2018GL081183

Eggleston J, Pope J (2013) Land subsidence and relative sea-level rise in the southern Chesapeake Bay region. U.S. Geological Survey Circular 1392. https://doi.org/10.3133/cir1392

Ezer T (2013) Sea level rise, spatially uneven and temporally unsteady: Why the U.S. East Coast, the global tide gauge record and the global altimeter data show different trends. Geophys Res Lett 40(20):5439–5444. https://doi.org/10.1002/2013GL057952

Ezer T (2015) Detecting changes in the transport of the Gulf Stream and the Atlantic overturning circulation from coastal sea level data: The extreme decline in 2009–2010 and estimated variations for 1935–2012. Glob Planet Change 129:23–36. https://doi.org/10.1016/j.gloplacha.2015.03.002

Ezer T (2020) Analysis of the changing patterns of seasonal flooding along the U.S. East Coast. Ocean Dyn 70(2):241–255. https://doi.org/10.1007/s10236-019-01326-7

Ezer T (2020) The long-term and far-reaching impact of hurricane Dorian (2019) on the Gulf Stream and the coast. J Mar Sys 208:103370. https://doi.org/10.1016/j.jmarsys.2020.103370

Ezer T (2023) Sea level acceleration and variability in the Chesapeake Bay: past trends, future projections, and spatial variations within the Bay. Ocean Dyn 73(1):23–34. https://doi.org/10.1007/s10236-022-01536-6

Ezer T, Atkinson LP (2014) Accelerated flooding along the US East Coast: On the impact of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic Oscillations. Earth's Future 2(8):362–382. https://doi.org/10.1002/2014EF000252

Ezer T, Corlett WB (2012) Is sea level rise accelerating in the Chesapeake Bay? A demonstration of a novel new approach for analyzing sea level data. Geophys Res Lett 39(19):L19605. https://doi.org/10.1029/2012GL053435

Ezer T, Dangendorf S (2020) Global sea level reconstruction for 1900–2015 reveals regional variability in ocean dynamics and an unprecedented long weakening in the Gulf Stream flow since the 1990s. Ocean Sci 16(4):997–1016. https://doi.org/10.5194/os-16-997-2020

Ezer T, Atkinson LP, Corlett WB, Blanco JL (2013) Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast. J Geophys Res 118(2):685–697. https://doi.org/10.1002/jgrc.20091

Ezer T, Atkinson LP, Tuleya R (2017) Observations and operational model simulations reveal the impact of Hurricane Matthew (2016) on the Gulf Stream and coastal sea level. Dyn Atmos and Oceans 80:124–138. https://doi.org/10.1016/j.dynatmoce.2017.10.006

Ezer T, Henderson-Griswold S, Updyke T (2022) Dynamic observations in the Hampton Roads region: how surface currents at the mouth of Chesapeake Bay may be linked with winds, water level, river discharge and remote forcing from the Gulf Stream. Oceans 2022. IEEE Xplore. https://doi.org/10.1109/OCEANS47191.2022.9977092

Ezer T (2022) A demonstration of a simple methodology of flood prediction for a coastal city under threat of sea level rise: the case of Norfolk, VA, USA. Earth's Future 10(9). https://doi.org/10.1029/2022EF002786

Goddard PB, Yin J, Griffies SM, Zhang S (2015) An extreme event of sea-level rise along the Northeast coast of North America in 2009–2010. Nat Commun. https://doi.org/10.1038/ncomms7346

Huang NE, Shen Z, Long SR, Wu MC, Shih EH, Zheng Q, Tung CC, Liu HH (1998) The empirical mode decomposition and the Hilbert spectrum for non stationary time series analysis. Proc R Soc London Ser A 45:903–995. https://doi.org/10.1098/rspa.1998.0193

Karegar MA, Dixon TH, Engelhart SE (2016) Subsidence along the Atlantic Coast of North America: Insights from GPS and late

Holocene relative sea level data. Geophys Res Lett 43:3126–3133. https://doi.org/10.1002/2016GL068015

Kopp RE, Horton RM, Little CM, Mitrovica JX, Oppenheimer M, Rasmussen DJ, Strauss BH, Tebaldi C (2014) Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. Earth's Future 2:383–406. https://doi.org/10.1002/2014EF000239

Little CM, Hu A, Hughes CW, McCarthy GD, Piecuch CG, Ponte RM, Thomas MD (2019) The relationship between U.S. east coast sea level and the atlantic meridional overturning circulation: a review. J Geophys Res 124(9):6435–6458. https://doi.org/10.1029/2019JC015152

Moat BI, Smeed DA, Rayner D, Johns WE, Smith R, Volkov D, Baringer MO, Collins J (2023) Atlantic meridional overturning circulation observed by the RAPID-MOCHA-WBTS (RAPID-Meridional Overturning Circulation and Heatflux Array-Western Boundary Time Series) array at 26N from 2004 to 2022 (v20221). British Oceanographic Data Centre - Natural Environment Research Council, UK. https://doi.org/10.5285/04c79ece-3186-349a-e063-6c86abc0158c

Park J, Sweet W (2015) Accelerated sea level rise and Florida current transport. Ocean Sci 11:607–615. https://doi.org/10.5194/os-11-607-2015

Park K, Federico I, Di Lorenzo E, Ezer T, Cobb KM, Pinardi N, Coppini G (2022) The contribution of hurricane remote ocean forcing to storm surge along the Southeastern US coast. Coastal Eng 173:104098. https://doi.org/10.1016/j.coastaleng.2022.104098

Park K, Di Lorenzo E, Zhang YJ, Wang H, Ezer T, Ye F (2024) Delayed coastal inundation caused by ocean dynamics post-hurricane Matthew. NPJ Clim Atmos Sci 7:5. https://doi.org/10.1038/s41612-023-00549-2

Piecuch CG, Beal LM (2023) Robust weakening of the Gulf Stream during the past four decades observed in the Florida Straits. Geophys Res Lett 50(18):2023GL105170. https://doi.org/10.1029/2023GL105170

Piecuch CG, Dangendorf S, Gawarkiewicz GG, Little CM, Ponte RM, Yang J (2019) How is New England coastal sea level related to the Atlantic meridional overturning circulation at 26°N? Geophys Res Lett 46:5351–5360. https://doi.org/10.1029/2019GL083073

Rice KC, Moyer DL, Mills AL (2017) Riverine discharges to Chesapeake Bay: Analysis of long-term (1927–2014) records and implications for future flows in the Chesapeake Bay basin. J Env Mng 204(1):246–254. https://doi.org/10.1016/j.jenvman.2017.08.057

Robson J, Hodson D, Hawkins E, Sutton R (2014) Atlantic overturning in decline? Nature Geosci 7:2–3. https://doi.org/10.1038/ngeo2050

Smeed DA, McCarthy GD, Cunningham SA, Frajka-Williams E, Rayner D, Johns WE, Meinen CS, Baringer MO, Moat B, Duchez A, Bryden HL (2014) Observed decline of the Atlantic meridional overturning circulation 2004–2012. Ocean Sci 10:29–38. https://doi.org/10.5194/os-10-29-2014

Sweet W, Park J (2014) From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise. Earth's Future 2(12):579–600. https://doi.org/10.1002/2014EF000272

Thiebaux HJ, Zwiers FW (1984) The interpretation and estimation of effective sample size. J Clim Appl Meteor 23:800–811

Valle-Levinson A, Li C, Royer TC, Atkinson LP (1998) Flow patterns at the Chesapeake Bay entrance. Cont Shelf Res 18(10):1157–1177. https://doi.org/10.1016/S0278-4343(98)00036-3

Valle-Levinson A, Boicourt WC, Roman MR (2003) On the linkages among density, flow, and bathymetry gradients at the entrance to the Chesapeake Bay. Estuaries 26:1437–1449. https://doi.org/10.1007/BF02803652

Valle-Levinson A, Dutton A, Martin JB (2017) Spatial and temporal variability of sea level rise hot spots over the eastern United States. Geophys Res Lett 44:7876–7882. https://doi.org/10.1002/2017GL073926

Volkov DL, Lee S-K, Domingues R, Zhang H, Goes M (2019) Interannual sea level variability along the southeastern seaboard of the United States in relation to the gyre-scale heat divergence in the North Atlantic. Geophys Res Lett. https://doi.org/10.1029/2019GL083596

Volkov D, Zhang K, Johns W, Willis J, Hobbs W, Goes M, Zhang H, Menemenlis D (2023) Atlantic meridional overturning circulation increases flood risk along the United States southeast coast. Nature Comm 14:5095. https://doi.org/10.1038/s41467-023-40848-z

Wang O, Lee T, Frederikse T, Ponte RM, Fenty I, Fukumori I, Hamlington BD (2024) What forcing mechanisms affect the interannual sea level co-variability between the Northeast and Southeast Coasts of the United States? J Geophys Res 129:e2023JC019873. https://doi.org/10.1029/2023JC019873

Wu Z, Huang NE (2009) Ensemble empirical mode decomposition: a noise-assisted data analysis method. Adv Adapt Data Anal 1(1):1–41. https://doi.org/10.1142/S1793536909000047

Wu Z, Huang NE, Long SR, Peng C-K (2007) On the trend, detrending and variability of nonlinear and non-stationary time series. Proc Nat Acad Sci 104:14889–14894. https://doi.org/10.1073/pnas.0701020104