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The Gulf Stream: Its History and Links to Coastal Impacts and Climate Change

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Abstract

The Gulf Stream (GS) is possibly the world's most widely recognized oceanic feature—from encounters by Spanish sailors in the 1500s, to Benjamin Franklin's charts in the 1700s, to early observations by Stommel and other in the 1900s. Today, modern undersea observations, satellite data, and computer models have revealed the GS's complex nature, though some challenges remain. This review provides an overview of past and recent studies of the GS, with a focus on links between the GS, extreme weather events, climate change, and coastal impacts. Examples of those links include a potential slowdown of the Atlantic Meridional Overturning Circulation (AMOC) and the GS that could increase coastal flooding, and hurricanes that disrupt the flow of the GS and cause posthurricane coastal sea level rise. A better understanding of the role of the GS in the Earth's system will help in the prediction of future climate change.

1. HISTORICAL BACKGROUND

From the early days of maritime exploration, the Gulf Stream (GS) captured the attention of sailors on the Atlantic Ocean, starting with Spanish explorers such as Ponce de León, who encountered it off the Florida coast in 1513 (De Vorsey 1976). In 1769, Benjamin Franklin famously charted the GS to speed up mail carriers from the Americas to Europe (**Figure 1*a***; for discussions of this chart and early GS observations, see also Marmer 1929, De Vorsey 1976, and Richardson 1980). Today, satellite observations and high-resolution computer models have shown that the GS is much more complex and dynamic than was initially imagined (**Figure 1*b***).

Early observations in the Atlantic Ocean, which included studies of the GS, were conducted by Maury (1874), Pillsbury (1891), Iselin & Fuglister (1948), Stommel (1950, 1959), Worthington (1954), Fuglister (1963), Fofonoff (1981), Brown et al. (1985), Maul et al. (1985), Richardson (1985), Auer (1987), and others. Observational efforts that focused specifically on the GS have included, for example, the Synoptic Ocean Prediction (SYNOP) campaign in the late 1980s and early 1990s, which aimed to provide a better understanding of the physical characteristics of the GS's mesoscale eddies and recirculation gyres (Hogg et al. 1986, Cornillon & Watts 1987, Watts et al. 1995). More recently, underwater gliders have been used to observe the GS (Todd 2021), and programs such as Processes Driving Exchange at Cape Hatteras (PEACH), which use numerous data sources and models, have focused on detailed observations of the GS near the coast and the exchanges between the continental shelf and the open ocean near Cape Hatteras, North Carolina (Seim et al. 2022).

Studies have shown that the GS is part of a western boundary current that starts as the North Brazil Current, then enters the Caribbean Sea to form the Caribbean Current, which flows into the Gulf of Mexico through the Yucatán Channel (Sheinbaum et al. 2002, Oey et al. 2005) to form the Loop Current. The current then exits through the Florida Straits to form the Florida Current, and finally separates from the coast at Cape Hatteras, creating the GS. The contrast between the warm GS waters from the south and the cold slope current waters from the north creates a sharp temperature front that is clearly visible in sea surface temperature images (**Figure 1*b***). The GS system includes warm and cold core eddies shed from the meandering GS, as well as recirculation gyres, including the large subtropical gyre of the Atlantic Ocean in the south and smaller recirculation gyres between the GS and the coast (Mellor et al. 1982, Hogg et al. 1986, Andres et al. 2020). The transport of the GS increases from ∼30 sverdrups (Sv, where $1\ \mathrm{Sv} = 10^6\ \mathrm{m^3/s}$) in the Florida Straits (Baringer & Larsen 2001) to ∼90 Sv off Cape Hatteras at 73°W (Andres 2021) and up to ∼150 Sv at 60°W (Hogg 1992).

The availability of high-resolution global satellite altimetry data since the early 1990s (Fu et al. 1994) revolutionized our view of the oceans from the early concept of the general ocean circulation (e.g., Stommel 1950) to a dynamic feature full of mesoscale and submesoscale eddies (in particular, near western boundary currents like the GS). It is thus challenging to study small-scale features like GS eddies with either observations or models. These findings motivated efforts to develop more realistic ocean models as tools to study and predict the ocean. Improved computational capabilities led to intense efforts to develop ocean circulation models of the GS, starting with simple diagnostic models in the 1980s (Mellor et al. 1982, Blumberg & Mellor 1983) and continuing with prognostic regional numerical models of the GS and the continental shelf with increased realism over time (Robinson et al. 1988, Malanotte-Rizzoli et al. 1989, Thompson & Schmitz 1989, Mellor & Ezer 1991, Kang & Curchister 2013, Chen et al. 2014, Mao et al. 2023).

One of the drawbacks of early numerical models of the GS was the difficulty of free running models (without data assimilation correction) to accurately simulate the separation of the GS from the coast at Cape Hatteras (**Figure 1*b***), which required high-resolution grids to resolve the mesoscale features of the GS and fine oceanic and coastal topography. As a result, numerous

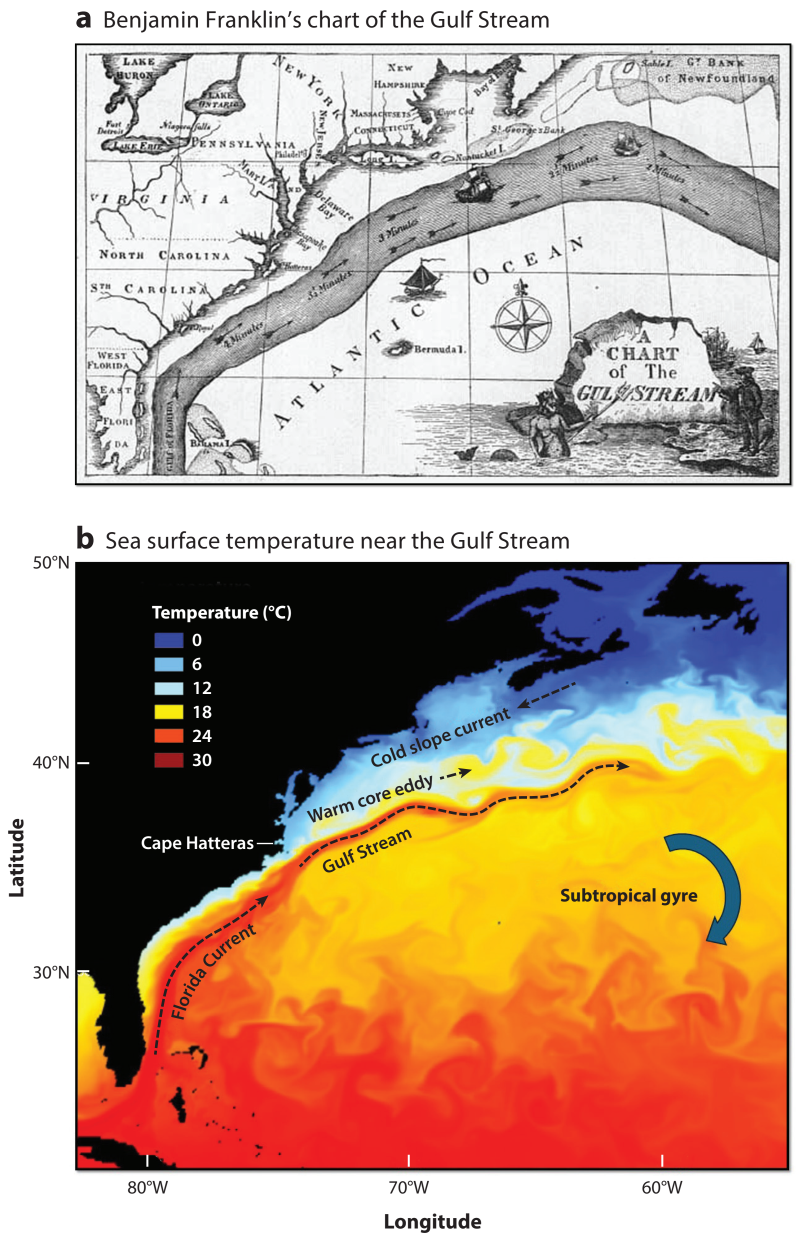

Figure 1

(*a*) Chart of the GS prepared by Benjamin Franklin in 1769 and published in 1786 by the American Philosophical Society (see also De Vorsey 1976, Richardson 1980). Panel reproduced from Marmer (1929) (public domain). (*b*) An example of sea surface temperature over the GS region, showing a portion of the March 8, 2021, forecast from the Copernicus Marine Environment Monitoring Service with additional features discussed in the text added on top. Base image adapted from Copernicus Marine Environment Monitoring Service (2021). Abbreviation: GS, Gulf Stream.

studies investigated the issue of the GS separation from theoretical, observational, and modeling perspectives (Ezer & Mellor 1992, Gangopadhyay et al. 1992, Dengg 1993, Chassignet & Marshall 2008, Ezer 2016b, Gifford et al. 2024). These modeling studies could not find a single factor affecting the GS separation issue and instead indicated contributions from a combination of factors, such as model resolution, coastal and bottom topography, surface heat fluxes and wind stress, and model boundary condition in regional models.

Since the 1990s, intense efforts have also been invested in the development of oceanic data assimilation methods, with projects such as the Data Assimilation and Model Evaluation Experiments in the Gulf Stream Region (DAMEE-GSR) (Willems et al. 1994) and in the North Atlantic Basin (DAMEE-NAB) (Chassignet et al. 2000). These efforts led the way for the development of ocean forecast systems for the GS and beyond (for details, see Pinardi & Woods 2002, Chassignet et al. 2018). One of the earliest real-time ocean forecast systems operated by NOAA was the US East Coast prediction system using a regional ocean circulation model of the GS with altimeter data assimilation (Aikman et al. 1996), emphasizing the potential impact that the GS may have on the coast. In comparison, with today's advanced computation capabilities, we have high-resolution real-time global prediction systems that include ocean–atmosphere–sea ice coupling and advanced data assimilation (e.g., Barton et al. 2021).

As described above, over decades and centuries, studies tried to better understand the physical mechanisms and characteristics of the GS system using observations and models. However, two aspects of the GS received new attention in recent years: the impact of the GS on the western North Atlantic coasts and the links between the GS and climate change. One of the emerging issues of research is that a decline in the Atlantic Meridional Overturning Circulation (AMOC) (Bryden et al. 2005; Smeed et al. 2014, 2018; Volkov et al. 2023) may affect the GS and increase sea level along the coast (the physical mechanism is discussed in detail in Section 2). Ongoing research is thus focusing on links between large-scale open ocean dynamics and the coast (Piecuch et al. 2019, Volkov et al. 2019, Dangendorf et al. 2021, Ezer & Updyke 2024). Notably, in the past, coastal oceanographers and coastal engineers conducted research that was often separated from research by open ocean oceanographers and modelers of the global ocean, but today, these topics are closely linked and thus require more collaborations between different disciplines of oceanography. These links are important, for example, for coastal communities suffering from increased flooding (Ezer & Corlett 2012, Sallenger et al. 2012, Ezer & Atkinson 2014, Sweet & Park 2014, Park & Sweet 2015, Valle-Levinson et al. 2017, Domingues et al. 2018, Sweet et al. 2018, Ezer 2022). Therefore, we need a better understanding of how remote influence from the open ocean is affecting the coast, a process that is difficult to predict. Even the earliest studies, which left unanswered questions about GS characteristics and forcing, had already suggested links between the GS and the climate over Europe and the North American coast (Marmer 1929). Past studies also suggested that variations in the GS may cause variations in coastal sea level (CSL). For example, such links were found by Maul et al. (1985) from observations of the Florida Current transport, by Hong et al. (2000) from a simple Rossby wave model, and by Ezer (2001) from a three-dimensional numerical model of the North Atlantic Ocean. These early findings led to more recent research on the links between open ocean processes and the coast, which are reviewed in the following sections.

2. THE LINKS BETWEEN THE GULF STREAM AND COASTAL SEA LEVEL

The idea that links the GS and CSL is based on a simple physical oceanography concept. The GS flow is mostly a geostrophic current (Johns et al. 1989), implying that the intensity of the surface current is proportional to the sea level slope across the current (a geostrophic current results from a balance between a pressure gradient and Earth's rotation, i.e., the Coriolis effect). A GS current with a speed of 1.5 m/s (Johns et al. 1989) will have a sea level difference of ∼1.5 m over an ∼100-km distance when crossing the GS. Therefore, if one sails from the US East Coast southeastward to, say, Bermuda and crosses the GS on the way, one goes uphill by ∼1.5 m. In other words, the existence of the GS may be viewed as a force that pulls water away from the coast and keeps the CSL lower by ∼1–1.5 m than what it would have been without this current. The GS itself is part of the AMOC. The GS transports warm surface waters northward, where they cool down, sink, and form the dense water masses of the deep ocean (see **Figure 2**).

The real GS and AMOC are much more complex, of course (e.g., see Lozier 2010). There are, for example, considerable variations in the subsurface GS flow, and variations in the total GS transport are related to the surface current (Kelly & Gille 1990). Other complications involve the existence of recirculation gyres that can change the transport along the GS path (Andres et al. 2020) and the separation of the GS from the coast, which can cause different sea level responses to variations in the GS in the Mid-Atlantic Bight north of Cape Hatteras and in the South Atlantic Bight south of Cape Hatteras (Ezer 2019b). The main links between the AMOC, the GS, and CSL result from the fact that a slowdown of ocean circulation that weakens the AMOC and the GS would cause a reduced slope across the GS and an increased sea level along the coast (**Figure 2**). The AMOC may slow down if waters in high latitudes become warmer, fresher (from ice melt), and less dense, an idea that is being examined by numerous studies using models and modern observations. However, it is interesting that even the limited observations in early studies had

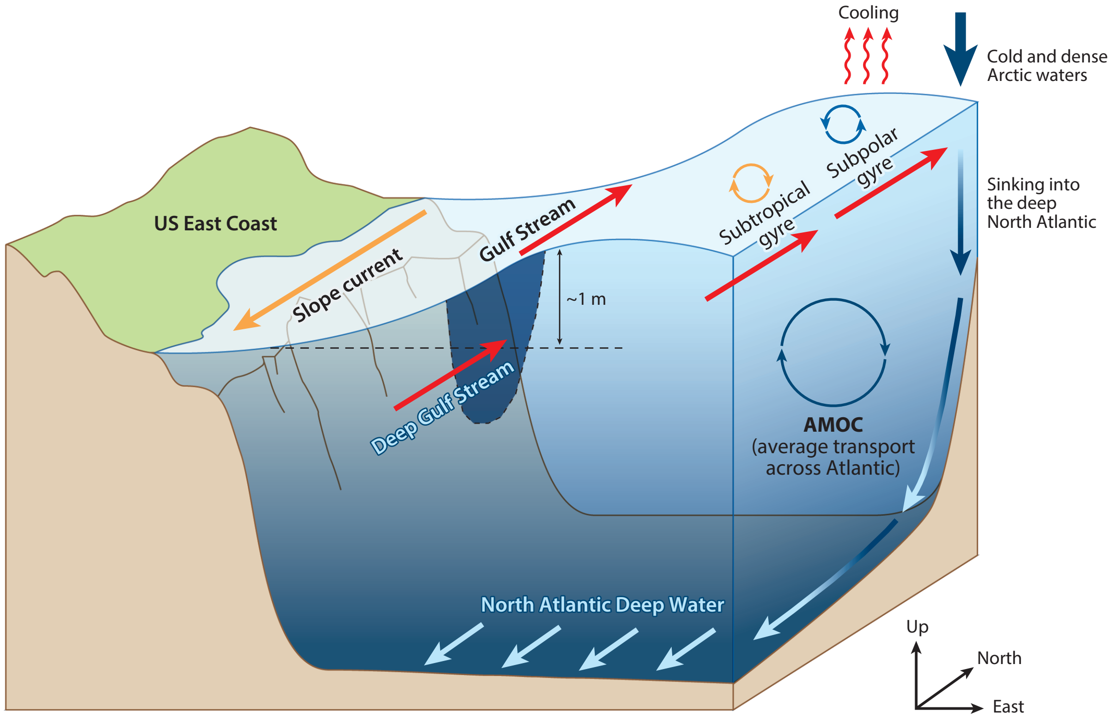

Figure 2

Schematic diagram of the AMOC and the GS. This diagram demonstrates how the existence of the GS keeps the sea level along the US East Coast lower than the offshore sea level, so if the ocean circulation slows down, sea level would rise along the coast. Abbreviations: AMOC, Atlantic Meridional Overturning Circulation; GS, Gulf Stream.

already suggested some links between the GS and CSL (Montgomery 1938, Wunsch et al. 1969, Lee & Brooks 1979, Blaha 1984). As expected from the theory above, many past studies found statistically significant negative correlations between the intensity of the GS flow and CSL—that is, a weakening GS is linked with increased CSL (Ezer et al. 2013; Ezer & Atkinson 2014, 2017; Park & Sweet 2015; Ezer 2016a, 2019b, 2020a,b, 2022; Wdowinski et al. 2016; Pietrafesa et al. 2022). However, it is possible that part of the correlation between the GS and CSL may not indicate a direct link but instead relates to factors like wind, which can influence both the GS and CSL (Lentz 2024). Moreover, the GS–CSL correlation coefficients, while statistically significant at over a 95% confidence level in most studies, are typically ∼0.3–0.6 (Ezer & Atkinson 2017) depending on the timescale involved, the location, and the data source. Therefore, a large part of the CSL variability is clearly driven by factors other than the GS.

Studies may also use different data sources to represent the intensity of the GS; some have used the daily cable observations of the Florida Current transport (Baringer & Larsen 2001, Meinen et al. 2010), as was done by Park & Sweet (2015) and Ezer & Atkinson (2017), while others have used the estimated GS current from satellite altimeter data, as was done, for example, by Ezer et al. (2013). Note, however, that altimeter data provide only sea surface height and surface currents, while the measurements of the Florida Current provide the total transport of the current. After high-frequency variations associated with weather and local dynamics have been filtered out, correlations of low-frequency variations of CSL with the GS can be as high as 0.85 (Ezer et al. 2013), though a higher correlation of CSL is often found with changes in the GS flow rather than with the velocity/transport itself (i.e., sea level is rising the most when the GS is in a significant weakening trend). Correlations are also different between the South Atlantic Bight, where the GS is close to the coast, and the Mid-Atlantic Bight, farther north and downstream, after the GS separates from the coast at Cape Hatteras. In the Mid-Atlantic Bight, the GS is a meandering free jet with mesoscale eddies and recirculation gyres, which makes the GS–CSL links more complicated (Ezer 2019a).

There are, of course, forces other than the GS that contribute to variations in CSL, such as atmospheric pressure and wind (Piecuch et al. 2016), internal Atlantic variabilities and Rossby waves (Dangendorf et al. 2021, 2023), and changes in heat fluxes over the subtropical gyre (Volkov et al. 2019). Because of the complexity of the links between the GS and CSL, it is often difficult to separate different factors that can influence sea level variability based on observations alone. However, experiments with numerical ocean models can test the idea of a direct impact of the GS on CSL. This kind of test was done by Ezer (2016a), who conducted controlled simulations forced only by imposed oscillations in the Florida Current transport while holding winds fixed. The results demonstrate that variations in the GS can result in quite coherent CSL variations along the US East Coast, like those found in tide gauge observations. The mechanism involves fast-moving barotropic waves propagating from the Florida Straits northward along the GS path, which excite southward-propagating coastal trapped waves (Huthnance 1978, Hughes & Meredith 2006) that spread the signal along the coast. The simulations also show that wind-driven sea level variability is notably different in character than GS-driven sea level variability.

As mentioned above, the mechanisms involved in the links between variations in the GS and CSL depend on the timescale involved. I first discuss short-term variability (days to seasonal timescales) here, then address long-term variability (interannual to multidecadal timescales) in Section 3, in the context of the GS's role in climate change. Short-term variations in the GS flow can be the result of several different mechanisms, such as natural daily and seasonal variability in the Florida Current (Meinen et al. 2010), GS meanders and mesoscale eddy activities (Kang & Curchister 2013, Todd 2021), or interaction with extreme events, like tropical storms and hurricanes. While storm surges due to hurricanes have been well-known and simulated by models for many years, a relatively new finding is that storms can also disrupt the flow of the GS and cause a posthurricane sea level rise for weeks after the storm disappeared. This indirect impact of hurricanes on CSL through alteration of the GS has been simulated by models (Ezer et al. 2017; Ezer 2018, 2019a, 2020b; Park et al. 2022, 2024) and shown by direct observations (Todd et al. 2018). The phenomenon is as follows: When a hurricane or tropical storm is moving close to the GS (within hundreds of miles; Ezer 2019a), it cools the GS warm waters through intense mixing and heat loss to the atmosphere, which in turn reduces thermal and density gradients across the GS front and weakens the baroclinic geostrophic flow; the weaker GS raises CSL for days or weeks after the storm has disappeared, causing increased flooding along the coast during posthurricane days. While the destruction of the GS front by the storm is a fast process (hours to days), the recovery of the GS is a slow advective process—new warm, tropical waters need to reach the GS from the south. At a 1-m/s flow speed, it would take ∼1 month for water to propagate along the GS path from the Florida Straits 3,000 km downstream to the northeast, say, off the Newfoundland coast. An example of the indirect impact of hurricanes on CSL and flooding is shown in **Figure 3**.

Flooding in Norfolk, Virginia (in the southern Chesapeake Bay, hundreds of kilometers away from the Florida coast), can often be predicted when the observed Florida Current off Miami suddenly declines (**Figure 3**). During the period August–October 2019, a major hurricane (Dorian) (Ezer 2020b), a minor hurricane (Humberto), and a tropical storm (Melissa) passed offshore, and each time, the GS transport declined, sea level rose, and flooding in Norfolk (as well as other coastal locations) occurred. Similar long-term poststorm flooding occurred during other offshore storms that did not make landfall, such as during Hurricane Matthew in 2016 (Ezer et al. 2017; Ezer 2018, 2019a; Park et al. 2022, 2024). These types of so-called sunny-day floods or

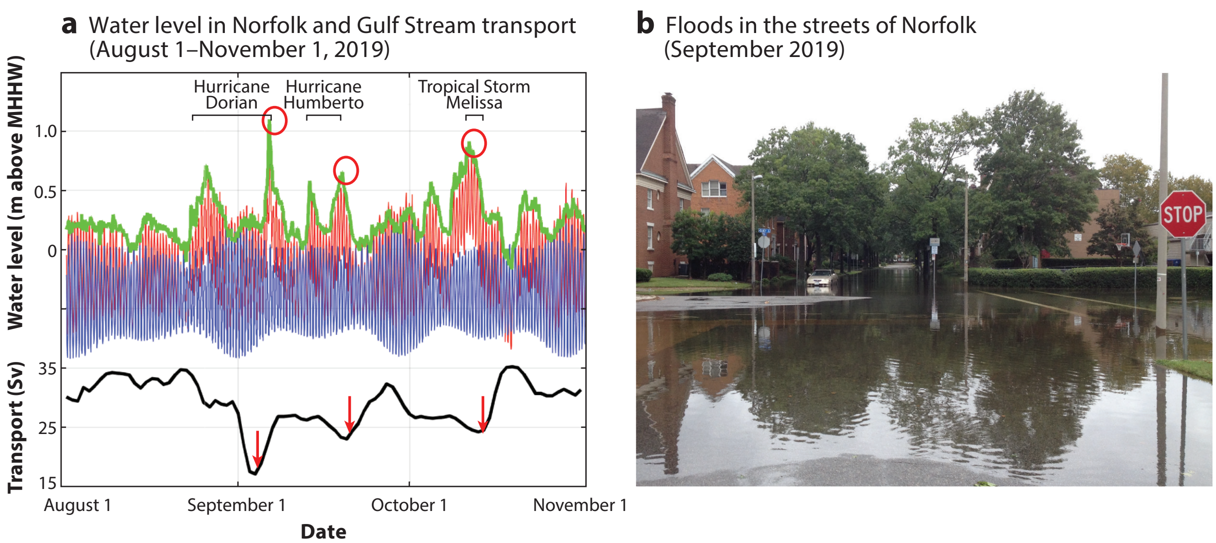

Figure 3

(*a*) Hourly water levels from NOAA's Sewells Point tide gauge near Norfolk, Virginia (*colored lines*), and daily GS transport from cable measurements of the Florida Current transport near Miami (*black line*). The blue, red, and green lines are predicted tides, observed water level, and subtidal anomaly, respectively. Two hurricanes (Dorian and Humberto) and a tropical storm (Melissa) passed offshore during the period August–October 2019, and each time, the GS slowed down (*red arrows*) and the water level rose (*red circles*), causing minor street flooding for several days. The correlation coefficient between the GS transport and water level anomaly was −0.5 (with >95% confidence level). (*b*) Street flooding in Norfolk in September 2019 when Hurricane Dorian was offshore in the Atlantic Ocean. Photo by T. Ezer. Abbreviations: GS, Gulf Stream; MHHW, mean higher high water; Sv, sverdrup (10^6 m^3/s).

nuisance floods are different than direct storm surge flooding—they last longer (over several tidal cycles), and their frequency has increased significantly in recent years due to sea level rise and increased storm intensity (Ezer & Atkinson 2014, Sweet & Park 2014, Park & Sweet 2015, Wdowinski et al. 2016, Ezer 2022). In the past, only major hurricane storm surges caused flooding, but because of the additional sea level rise, even weak storms can now cause minor to moderate flooding. The same is true for the floods induced by the GS—in the past, they may not have been noticeable, but the additional sea level rise means that the GS impact can raise the CSL over the threshold for flooding. The seasonal variations in CSL are also linked to the GS. For example, the highest seasonal sea level in the Chesapeake Bay occurs in the fall during the period of the largest decline in the GS transport. Additional contributions to high sea level during the fall come from the hurricanes that are active during this period and the annual and semiannual tides (Ezer 2020a, 2023).

3. THE GULF STREAM AND CLIMATE CHANGE

The GS flow is an important part of the AMOC (**Figure 2**). It is the upper branch of the AMOC, which transports warm and salty tropical waters northward, where they cool down and sink to form the southward-flowing deep circulation branch. The AMOC is part of the great ocean conveyer belt (Broeker 1991), a simple schematic description of a global circulation pattern. Despite recent observations that show much more complex and variable deep circulation patterns than the simple conveyer belt picture (Lozier 2010), the main idea of pathways connecting climatic changes in high latitudes with deep water mass formation and changing weather and climate worldwide remains. Basic physics implies that if waters in high latitudes become warmer and fresher due to global warming and melting ice, they become less dense, do not sink as fast, and thus weaken the AMOC. Observations suggest, for example, that when the AMOC is weak, the GS may shift northward (Joyce & Zhang 2010). However, in another study, non-eddy-resolving general ocean circulation models showed different results, with a stronger AMOC that is linked with a northward shift of the GS path (De Coetlogon et al. 2006). These contradictory results emphasize the difficulty of fully understanding the GS's behavior, given its spatial and temporal variability. Temporal or climate-related shifts in the GS can have significant implications for coastal ecosystems, like the extreme warming of the New England coasts in 2011 that may have affected the lobster population (Gawarkiewicz et al. 2012). Coupled climate models show that weakening of the thermohaline circulation can lead to regional dynamic sea level change and modification of circulation patterns, including the GS (Levermann et al. 2005). The GS can thus be the link between the AMOC, climate change, and coastal impacts—if the GS slows down with a weakening AMOC, then CSL along the North American coast rises (see the GS–CSL links discussed above). The question is, Do we have evidence for climatic changes in the GS and AMOC from data or models?

The problem of identifying a long-term trend in the AMOC is that direct observations of it across the entire Atlantic Ocean exist for only ∼20 years (Moat et al. 2023), and these observations are dominated by interannual and decadal variability, so a much longer record is needed to separate natural variability from long-term trends. On the other hand, the record of cable observations of the Florida Current transport extends over 40 years (albeit with considerable gaps). In fact, a recent study using sophisticated analysis of multiple observations found strong statistical evidence that the GS flow near the Florida Straits has been in decline over the past 40 years (Piecuch & Beal 2023). Other studies of the Florida Current show different trends at different timescales, with indications of potential long-term decline (Pietrafesa et al. 2022). Some studies were not as conclusive about GS trends, such as the 20-year direct observations of Rossby et al. (2014) and those of Andres et al. (2020); the latter study showed a GS decline in one section but not in another section nearby due to local recirculation gyres. Using altimeter data, Dong et al. (2019) and Zhang et al. (2020) also found spatial differences in trends with a weakening flow and shifting path in the eastern portion of the GS, while the western portion, closer to Cape Hatteras, did not show a significant trend. Finding trends in the GS mean flow is especially difficult downstream of Cape Hatteras, where GS meanders, eddy shedding, and recirculation gyres dominate the dynamics.

While numerous studies have shown links between climatic changes and variability in the open Atlantic Ocean and CSL (Yin et al. 2009; Ezer & Corlett 2012; Sallenger et al. 2012; Ezer et al. 2013; Ezer & Atkinson 2014, 2017; Ezer 2015, 2019b, 2020a; Goddard et al. 2015; Little et al. 2019; Volkov et al. 2019, 2023; Dangendorf et al. 2021, 2023), they often suggested different linkage mechanisms. Mechanisms mentioned as links between the open ocean and the coast (besides the GS variability mentioned above) include, for example, Rossby waves, changes in wind patterns associated with the North Atlantic Oscillation, and changes in heat fluxes over the subtropical gyre. It is thus likely that these links involve combinations of factors. A few studies have tried to find direct links between the observed CSL and the AMOC. For example, Piecuch et al. (2019) looked for links between CSL in New England and the AMOC and suggested that a large-scale atmospheric teleconnection through the wind pattern is involved, though direct links to the GS were not clear for this location farther downstream along the GS path. More recently, observations of currents and sea level near the mouth of the Chesapeake Bay showed links to variations in the AMOC, and variations in the GS strength seemed to affect the flow exchange between the bay and the Atlantic Ocean (Ezer & Updyke 2024).

Is there evidence that the long-term AMOC has been in decline? Since the record of direct continuous observations of the AMOC is relatively short (the RAPID program's observations of the AMOC started in 2004; Moat et al. 2023), studies must rely on other means, such as models or proxies. Past observations, before the recent AMOC monitoring started, do point to an AMOC decline but do not provide a complete picture of the changes (Bryden et al. 2005). Using different proxies, such as the relation between the AMOC and surface temperature, a reconstruction of the AMOC from temperature indeed shows a significant AMOC slowdown during the twentieth century (Rahmstorf et al. 2015, Caesar et al. 2018). Since CSL observations from tide gauges span a much longer period than AMOC observations, another way to study past AMOC variations is to use the correlation (discussed above) between sea level and the GS and the relation between the GS and the AMOC to reconstruct the past AMOC before direct observations of it existed. **Figure 4** shows an example of such a reconstruction of the AMOC since 1935, using the correlation of the AMOC with the sea level difference between Bermuda and the US East Coast (for details, see Ezer 2015). This reconstruction agrees quite well with the RAPID observations of the AMOC (Smeed et al. 2014) and with early observations (Bryden et al. 2005), while showing a general decline of the AMOC since 1935.

The reconstruction shows past periods of significantly larger AMOC slowdown that resemble the recent climate change. Of particular interest was the period between the 1950s and 1970s, when diagnostic models and data analysis suggested decadal changes in the thermohaline structure of the Atlantic Ocean (Levitus 1989), a significant weakening in the GS transport (Greatbatch et al. 1991), and sea level rise along the coast of North America (Ezer et al. 1995). These decadal changes between the 1950s and the 1970s not only resemble the recent climatic changes since around 2000 but also show a very similar weakening trend of ∼4.5 Sv/decade (**Figure 4**). However, when the early observations were made in the 1950s and 1970s, linking an anomalously weak GS and sea level rise to decadal variations in the AMOC was not possible with the available data. A recent reconstruction of century-long global sea level further confirmed links between the AMOC, the GS, and CSL and revealed an unprecedented long recent weakening in the GS flow (Ezer & Dangendorf 2020). The long-term (approximately seven decades) AMOC weakening trend in **Figure 4** is ∼0.22 Sv/decade (Ezer 2015). In comparison, the recent analysis

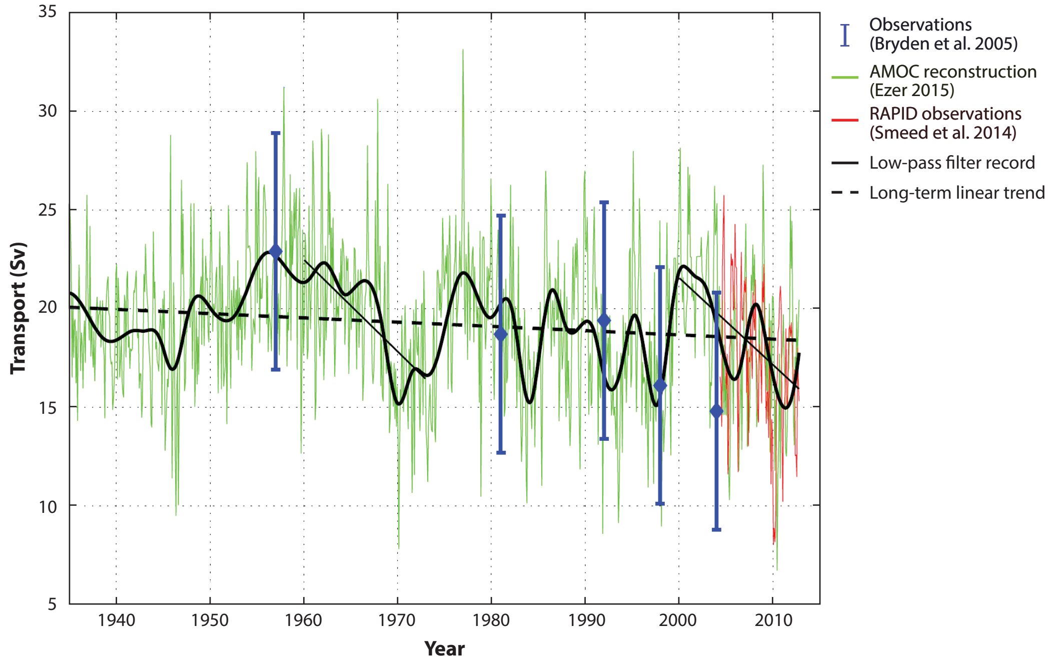

Figure 4

Reconstruction of monthly AMOC transport since 1935 (*green line*) (Ezer 2015), using the correlation between tide gauge sea level differences between Atlantic City and Bermuda and the observed AMOC after 2004 (*red line*) (Smeed et al. 2014). Estimated AMOC transport and error bars from section data across 25°N are shown in blue (Bryden et al. 2005). A low-pass-filtered record (*thick black line*) and long-term linear trend line (-0.22 Sv/decade for 1935–2012; *dashed black line*) are also shown, along with trend lines for two periods with especially large declines (-4.6 Sv/decade for 1960–1972 and -4.4 Sv/decade for 2000–2012; *thin black lines*). Abbreviations: AMOC, Atlantic Meridional Overturning Circulation; Sv, sverdrup (10^6 m^3/s). Figure adapted from Ezer (2015) with permission from Elsevier.

of Piecuch & Beal (2023), using different data and methods, found that the weakening of the GS over the past four decades was ~0.3 Sv/decade, surprisingly close to the results of Ezer (2015).

While determining the long-term trend will require longer records of direct AMOC observations than are currently available, even the current observations over approximately two decades have already shed new light on the AMOC's variability and downward trends (Smeed et al. 2014, 2018). Using a long record of reanalysis data, one can put the short AMOC observations in the context of past decadal variability and show, for example, that the recent AMOC weakening followed a period of increased flow (Jackson et al. 2016). Analysis of observations and climate models can show that the measured decline is not merely a short-term change but is part of a longer-term reduction in meridional overturning circulation over decadal timescales (Robson et al. (2014).

4. SUMMARY

This review has described the history of GS research and the evolution of our understanding of oceanic and atmospheric processes linked to the GS. Early explorers and sailors encountered this strong current and recognized its uniqueness in not following the local wind direction, as was previously assumed for ocean currents (for historical background, see De Vorsey 1976), but they did not recognize many of the GS sources, characteristics, and forcings that we know today. Ship observations since the late 1800s and early 1900s aimed to describe the basic mean flow pattern of the GS system and its role in the Atlantic Ocean circulation. Starting in the early 1990s, with the availability of global satellite altimeter data and the development of eddy-resolving computer ocean models, it became clear that the GS current is part of a dynamic system with much more complex patterns than were previously envisioned, including meanders, eddies, recirculation gyres, and deep western boundary currents underneath. Observations and models also found a wide range of variability in the GS system, from daily oscillations and seasonal changes to interannual and decadal variability.

For years, most studies looked at the GS in the context of an open ocean circulation pattern separated from coastal processes. For example, early ocean circulation models ignored any area with a water depth of less than, say, 100 m. In recent years, with increased awareness of the impacts of climate change, such as the risks to coastal populations from sea level rise, studies began to focus on the role that the GS plays in linking basin-scale climatic changes with impacts on the coast. The overview above examined numerous studies that found GS–CSL links, where a slowdown of the GS is correlated with sea level rise, from daily and seasonal variations to interannual and decadal variations. Past data suggest that the AMOC has started to slow down in recent decades, and some (but not all) studies show a slowdown of the GS as well. Climate models predict further weakening of the AMOC in the future (and some even predict a potential collapse of the AMOC in the coming decades; Smolders et al. 2024).

It is clear today that climatic changes and shifts in ocean currents, including the AMOC and GS, may affect vulnerable coastal communities. Further research using new observing technologies such as autonomous underwater vehicles (Freire et al. 2018), new tools such as artificial intelligence and machine learning (Lou et al. 2023), and new generations of Earth system models (Flato 2011) will help us to better understand and predict future climatic changes. The complex nature of the GS and its interactions with the atmosphere and with local and remote factors makes this a challenging modeling task (Zhang et al. 2016). Can we develop, for example, global climate models that simulate decades and centuries into the future but also resolve the smallest mesoscale and submesoscale features of the GS as well as detailed coastal and estuarine dynamics?

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Old Dominion University's Center for Coastal Physical Oceanography provides facility and computer resources. The Institute for Coastal Adaptation and Resilience provides scientific collaborations and discussions.

LITERATURE CITED

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