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Robust Weakening of the Gulf Stream During the Past Four Decades Observed in the Florida Straits

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Key Points:

- Gulf Stream volume transport through Florida Straits declined by 1.2 ± 1.0 Sv during the past 40 years (95% credible interval)
- We find a weakening trend in the Gulf Stream by applying Bayesian methods to synthesize cable, in situ, and satellite data sets congruently

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

The Gulf Stream is a vital limb of the North Atlantic circulation that influences regional climate, sea level, and hurricane activity. Given the Gulf Stream's relevance to weather and climate, many studies have attempted to estimate trends in its volumetric transport from various data sets, but results have been inconclusive, and no consensus has emerged whether it is weakening with climate change. Here we use Bayesian analysis to jointly assimilate multiple observational data sets from the Florida Straits to quantify uncertainty and change in Gulf Stream volume transport since 1982. We find with virtual certainty (probability $P > 99\%$) that Gulf Stream volume transport through the Florida Straits declined by 1.2 ± 1.0 Sv in the past 40 years (95% credible interval). This significant trend has emerged from the data set only over the past ten years, the first unequivocal evidence for a recent multidecadal decline in this climate-relevant component of ocean circulation.

Plain Language Summary

The Gulf Stream is a major ocean current located off the East Coast of the United States. It carries a tremendous amount of seawater and along with it heat, carbon, and other ocean constituents. Because of this, the Gulf Stream plays an important role in weather and climate, influencing phenomena as seemingly unrelated as sea level along coastal Florida and temperature and precipitation over continental Europe. Given how important this ocean current is to science and society, scientists have tried to determine whether the Gulf Stream has undergone significant changes under global warming, but so far, they have not reached a firm conclusion. Here we report our effort to synthesize available Gulf Stream observations from the Florida Straits near Miami, and to assess whether and how the Gulf Stream transport there has changed since 1982. We conclude with a high degree of confidence that Gulf Stream transport has indeed slowed by about 4% in the past 40 years, the first conclusive, unambiguous observational evidence that this ocean current has undergone significant change in the recent past. Future studies should try to identify the cause of this change.

1. Introduction

The Gulf Stream is the western boundary current of the subtropical North Atlantic Ocean (Stommel, 1965). It flows north through the Florida Straits off Miami and along the continental slope of the South Atlantic Bight before detaching from the coast at Cape Hatteras and meandering freely into the open ocean (Heiderich & Todd, 2020). By virtue of its volume and heat transports, the Gulf Stream affects regional weather, climate, and coastal conditions, including European surface air temperature and precipitation, coastal sea level along the Southeastern United States, and North Atlantic hurricane activity (Donnelly et al., 2015; Little et al., 2019; Palter, 2015). Understanding past Gulf Stream changes is thus important for interpreting observed changes and predicting future trends in extreme events including droughts, floods, heatwaves, and storms (Seneviratne et al., 2021).

Determining trends in Gulf Stream transport is also relevant for clarifying whether elements of the large-scale North Atlantic circulation have changed, and determining how the ocean is feeding back on climate (Jackson et al., 2022). The difference between the northward transport by the Gulf Stream and southward transport due to winds over the ocean interior defines the strength of the Atlantic meridional overturning circulation at 26°N (McCarthy et al., 2015). The overturning circulation is the primary means by which the ocean moves heat across latitudes, cooling tropical regions and warming the poles (Lumpkin & Speer, 2007). Climate models simulate that the subtropical North Atlantic meridional overturning circulation weakened in the recent past. Weijer et al. (2020) found that the maximum of the overturning streamfunction at 26°N weakened by 1.2 ± 0.2 Sv from 1980 to 2010

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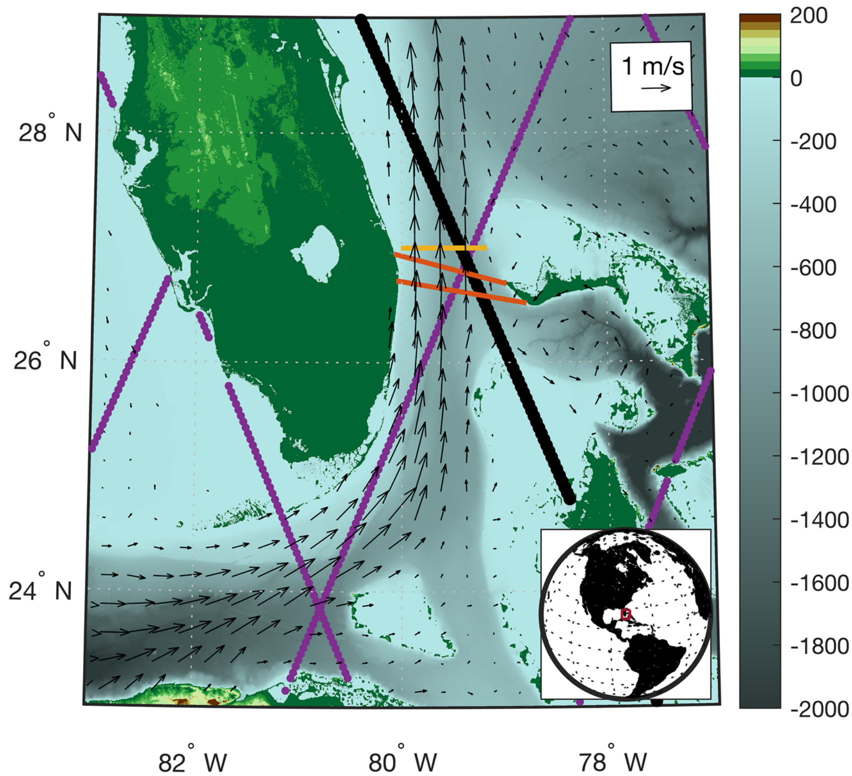

Figure 1. Study area. Color shading is topography/bathymetry (m) from the GEBCO 2021 grid. Orange lines mark nominal locations of submarine telecommunications cables between Jupiter Inlet (Florida) and Settlement Point (The Bahamas), and between West Palm Beach (Florida) and Eight Mile Rock (The Bahamas). Yellow line at 27°N marks nominal location of in situ sections. Purple dots mark altimeter ground tracks and the thicker black dots mark descending track 178, which was used by Volkov et al. (2020) to estimate Gulf Stream transport through Florida Straits. Black arrows identify the relative magnitude and sense of the surface circulation from drifter data (Laurindo et al., 2017). Inset shows the study area in global context.

due to external forcing, and Menary et al. (2020) reported that the overturning streamfunction at 1,000-m depth at 35°N decreased by 2.3 Sv over 1985–2014. Yet reconstructions derived from sparse hydrographic data available since the 1980s find no significant weakening (Caínzos et al., 2022; Fu et al., 2020; Worthington et al., 2021). It is unclear if the discrepancies reflect issues with the models (inability to resolve fronts, jets, eddies, etc.) or the data (e.g., aliasing of the sparse hydrographic observations), or whether the signal of externally forced change is simply below the detection threshold set by natural variability (Jackson et al., 2022). While continuous direct observations of the overturning circulation are, as yet, too short to corroborate the weakening simulated by models (Lobelle et al., 2020; McCarthy et al., 2020), continuous measurements of Gulf Stream transport are available from as long as forty years ago.

There is a long history of Gulf Stream observations from remote sensing and in situ data along the current's path (Broida, 1969; Iselin, 1936; Pillsbury, 1890; Stommel, 1965). The longest, most continuous record of Gulf Stream transport is from Florida Straits at 27°N (Figure 1; Baringer & Larsen, 2001; Larsen & Sanford, 1985; Meinen et al., 2010; Volkov et al., 2020). Quasi-daily estimates from submarine telecommunications cables calibrated with dropsondes and shipboard surveys extend from 1982. Satellite altimetry provides additional data constraints every 10 days since 1992 (Figures 1 and 2a). Despite this extraordinary density of data, there is, as yet, no consensus that Gulf Stream transport is weakening with climate change. Meinen et al. (2010) gathered the dropsonde and cable data up to 2009, along with earlier upstream float measurements from south of Northwest Providence Channel near 26°N. They argued that the data did not support a change in Gulf Stream transport over 1964–2009, but they did not quantify the longterm rate of change or provide error estimates. In contrast, Park and Sweet (2015) reported a trend equivalent to 1.1 ± 0.1 Sv of weakening from cable data over 1982–2014. However, their calculation did not account for serial correlation of residual transports or the large, time-variable errors on the cable data (Bos et al., 2014; Garcia & Meinen, 2014; Meinen et al., 2010; Volkov et al., 2020), and

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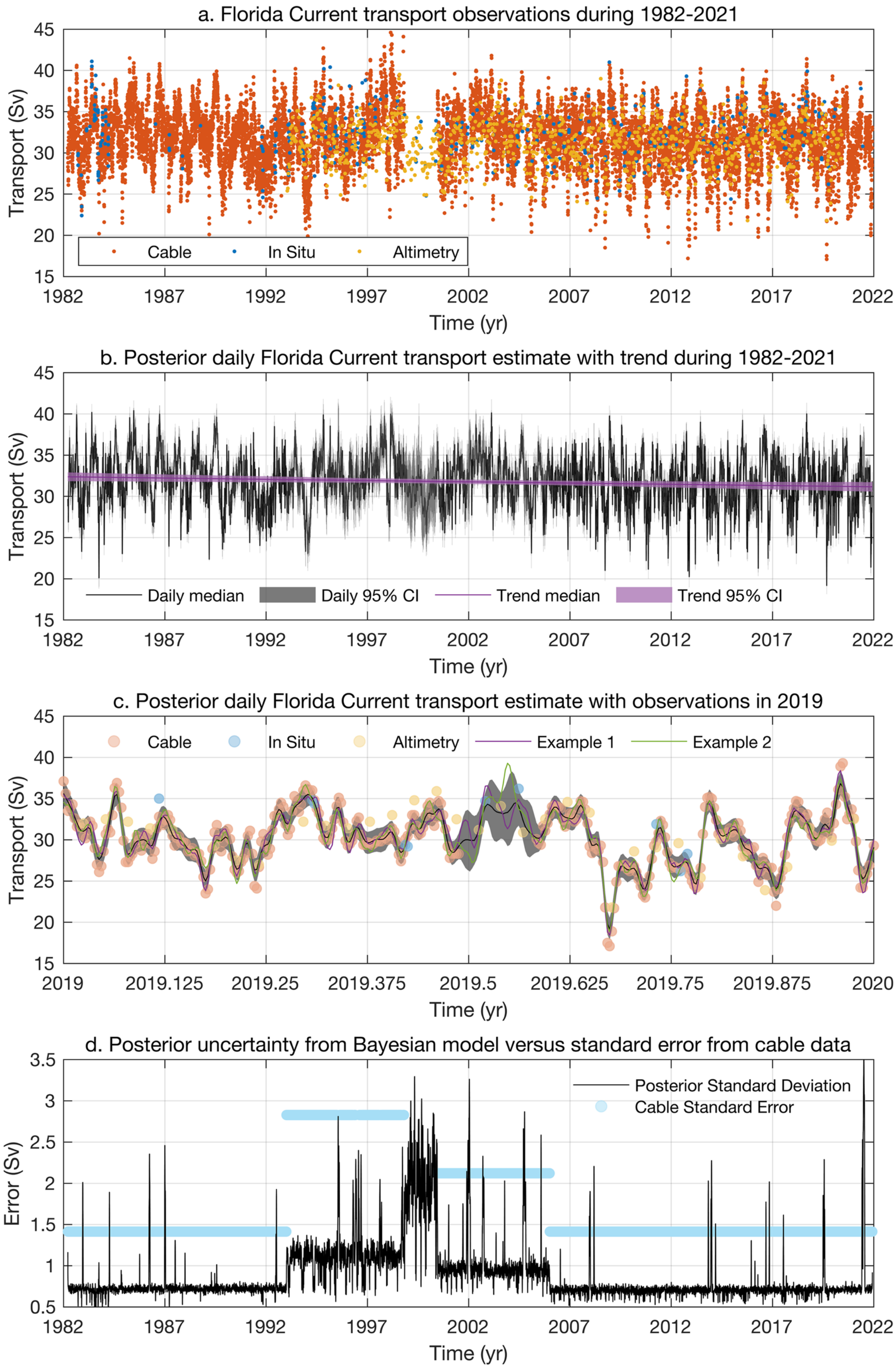

Figure 2.

so their formal errors are perceived to be too small and their results have been disputed. Similar shortfalls apply to the recent paper by Pietrafesa et al. (2022). Evidence for a recent trend farther downstream in the Gulf Stream is also equivocal. Dong et al. (2019) used satellite altimetry to infer a weakening of the Gulf Stream east of 65°W over 1993–2016, but found no change west of 70°W, while Chi et al. (2021) argued that the altimeter record is too short to identify significant Gulf Stream trends, and Rossby et al. (2014) found no evidence for a decrease in Gulf Stream transport from 1993 to 2012 in 20 years of acoustic Doppler current profiler velocity data.

In summary, there have been many attempts to estimate recent Gulf Stream trends from a variety of data sets at different locations, but a definitive answer has remained elusive. We argue that, to make a robust estimate of longterm change with meaningful error bars, the available data should be jointly assimilated in a way that accounts for the time series properties of the transport and uncertainties characterizing the different data streams. Here we apply hierarchical Bayesian modeling (Cressie & Wikle, 2011) to formally combine cable, in situ, and altimetric data at 27°N, and form a new estimate, with uncertainty, of the transport through Florida Straits since 1982.

2. Data

We use Gulf Stream transport data from Florida Straits as provided by the National Oceanic and Atmospheric Administration Western Boundary Time Series (NOAA WBTS) project (Figure 1). Data were downloaded on 10 December 2021.

2.1. Cable Data

We use 13,105 daily Florida Current transport estimates from voltages measured by abandoned submarine telecommunications cables between Florida and The Bahamas. The principle is based on electromagnetic theory: ocean transports of charged particles in the presence of Earth's geomagnetic field result in variable voltages across the cable (Larsen, 1992; Stommel, 1948). Data from 18 March 1982 to 22 October 1998 are from a cable between Jupiter Inlet and Settlement Point, while the data from 9 June 2000 to the present are from a cable from West Palm Beach to Eight Mile Rock. There were no measurements made between October 1998 and June 2000. While observations are given at daily resolution, the effective sampling rate is every three days, since the data are low-pass filtered to suppress geomagnetic effects and other noise. Cable estimates are calibrated against independent transport estimates from free-falling dropsonde floats and lowered acoustic doppler current profiler (LADCP) during cruises by the *R/V Walton Smith* across the Straits (Garcia & Meinen, 2014). Volkov et al. (2020) compared the cable data to dropsonde sections and found standard errors on the cable data of 2.8 Sv for 1993–1998, 2.0 Sv for 2000–2005, and 1.3 Sv for 2006 onward. Larger errors during 1993–1998 and 2000–2005 result from the cables being in active telecommunications use and problems with the recording system, respectively (Meinen et al., 2010; Volkov et al., 2020).

2.2. In Situ Data

We also use Gulf Stream transport sections from a variety of in situ platforms across Florida Straits. Of these, 247 sections are from free-falling dropsonde floats, 85 are from LADCP, 60 are from acoustically-tracked Pegasus floats, and 9 from Pegasus floats in dropsonde mode. Pegasus float measurements were made from 1982 to 1984 as part of the Subtropical Atlantic Climate Studies program (Molinari et al., 1985), while the observations from Pegasus floats in dropsonde mode were obtained during later campaigns between 1986 and 1988. Dropsonde and LADCP measurements began later in 1991 and 2001, respectively. All WBTS in situ observations are on hiatus since 2021 due to permitting issues with The Bahamas. Meinen et al. (2010) and Garcia and Meinen (2014) gave detailed discussions of these observations and their uncertainties.

2.3. Altimetry Data

Finally, we use 979 Florida Current transport estimates from satellite altimetry. Satellite altimeters observe the global sea-surface height field every 10 days. By virtue of geostrophy, gradients in sea-surface height are coupled

Figure 2. (a) Observed Gulf Stream transport from undersea cable (orange), in situ (blue), and satellite altimetry (yellow). Pearson correlation coefficients between cable and in situ, cable and altimetry, and in situ and altimetry at their common time points are 0.76, 0.63, and 0.58, respectively. (b) Posterior medians (black line) and 95% pointwise credible intervals (gray shading) of daily transport from the Bayesian model along with the estimated median trend and 95% pointwise credible interval (purple line and shading). (c) Detail of observed (orange, blue, and yellow dots) and modeled (black line and gray shading) transport during 2019. Two randomly drawn posterior ensemble members are shown for comparison (purple and green lines). (d) Standard errors on cable data (blue dots) and standard deviations on posterior solutions (black line).

to surface geostrophic currents. Motivated by this relationship, Volkov et al. (2020) used along-track altimetric data from descending track 178 (black dots in Figure 1) to compute sea-surface height differences across Florida Straits, resulting in the 10-daily Florida Current transport estimates from January 1993 used here. Volkov et al. (2020) compared their altimetry-based transport estimates to data from cables, dropsondes, and LADCP, and derived a standard error on the 10-daily altimetric transports of ∼2 Sv.

3. Model

We develop a hierarchical Bayesian model to synthesize Gulf Stream transports from cable, in situ, and altimetry data. Hierarchical modeling is based on the notion of conditional probabilities, providing a coherent framework for jointly assimilating the available data and modeling the sources of uncertainty. Our model follows the paradigm of Berliner (1996), and consists of three levels: a process level encodes mathematical rules describing the temporal evolution of the process, a data level prescribes the relationships between the true process and the imperfect data, and a prior level imposes constraints on the uncertain model parameters. We evaluate solutions and propagate errors using Bayes' rule and Markov chain Monte Carlo (Cressie & Wikle, 2011; Gelman et al., 2006).

We use autoregressive–moving-average (ARMA) models (Cryer & Chan, 2008) as the basis of our Bayesian algorithm. Our model equations, which are given below, are the result of data exploration and trial and error. We successively applied ARMA(p, q) models with p autoregressive terms and q moving-average terms to the data, increasing the order (p, q) until we achieved white-noise residuals. We interpreted the lowest-order model that produced white-noise residuals as the simplest model that could justifiably be applied to the data. Note that the goal was not to specify equations based on physics, but rather to describe the structure in the data.

3.1. Process Level

We model the Gulf Stream volume transport process $\boldsymbol{T} = [T_1, \ldots, T_K]^\top$ in terms of a third-order autoregressive [AR(3)] process added to a time mean, seasonal cycle, and linear trend

$$T_k - \boldsymbol{w}_k^\top \boldsymbol{\beta} = \sum_{i=1}^{3} \left[\rho_i \left(T_{k-i} - \boldsymbol{w}_{k-i}^\top \boldsymbol{\beta}\right)\right] + s_k, \tag{1}$$

where $s_k \sim \mathcal{N}\left(0, \sigma^2\right)$ is zero-mean, independent and identically distributed white noise with unknown variance σ^2, $k \in [1, K]$ is the index, $\boldsymbol{w}_k$ is the kth column of the $[6 \times K]$ design matrix of predictors

$$\mathsf{w} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ t_1 & t_2 & \cdots & t_K \\ \cos(2\pi t_1/\tau_\mathrm{A}) & \cos(2\pi t_2/\tau_\mathrm{A}) & \cdots & \cos(2\pi t_K/\tau_\mathrm{A}) \\ \sin(2\pi t_1/\tau_\mathrm{A}) & \sin(2\pi t_2/\tau_\mathrm{A}) & \cdots & \sin(2\pi t_K/\tau_\mathrm{A}) \\ \cos(2\pi t_1/\tau_\mathrm{Sa}) & \cos(2\pi t_2/\tau_\mathrm{Sa}) & \cdots & \cos(2\pi t_K/\tau_\mathrm{Sa}) \\ \sin(2\pi t_1/\tau_\mathrm{Sa}) & \sin(2\pi t_2/\tau_\mathrm{Sa}) & \cdots & \sin(2\pi t_K/\tau_\mathrm{Sa}) \end{bmatrix}, \tag{2}$$

where t_k is the kth time and τ_A and τ_Sa are annual and semiannual periods, respectively, $\boldsymbol{\beta} = [\beta_1\ \beta_2\ \ldots\ \beta_6]^\top$ are unknown regression coefficients, and $\{\rho_1, \rho_2, \rho_3\}$ are unknown AR coefficients. We scale and center time such that $t_1 = -1$ and $t_K = 1$. Note that the ∼ symbol is read "is distributed as" and $\mathcal{N}\left(a, b^2\right)$ is the normal distribution with mean a and variance b^2.

3.2. Data Level

The data-level equations express our assumption that data are noisy, unbiased versions of the true underlying process.

3.2.1. In Situ Data

We assume that the in situ section data $\boldsymbol{x} = [x_1, \ldots, x_K]^\top$ correspond to the transport process $\boldsymbol{T}$ according to

$$x_k = T_k + d_k, \tag{3}$$

where $d_k \sim \mathcal{N}(0, \delta_k^2)$ is random noise with zero mean and δ_k^2 is the data error variance. Similar to Volkov et al. (2020) and Garcia and Meinen (2014), we set $\delta_k^2 = (1.0\ \text{Sv})^2$ if the data value was taken by dropsonde, $\delta_k^2 = (1.5\ \text{Sv})^2$ if it was taken by LADCP, $\delta_k^2 = (1.0\ \text{Sv})^2$ if it was taken from Pegasus profiling float, and $\delta_k^2 = (1.0\ \text{Sv})^2$ if it was taken by Pegasus float in dropsonde mode.

3.2.2. Cable Data

We model differences between the cable data $\boldsymbol{y} = [y_1, \ldots, y_K]^\top$ and the transport process $\boldsymbol{T}$ using a second-order moving-average [MA(2)] equation

$$y_k = T_k + \sum_{i=1}^{2} (\theta_i e_{k-i}) + e_k, \tag{4}$$

where $e_k \sim \mathcal{N}(0, \epsilon_k^2)$ is random noise with zero mean, ϵ_k^2 is the data error variance, and $\{\theta_1, \theta_2\}$ are unknown MA coefficients. This model captures the fact that errors on the cable data are not independent from one another because three-day averaging is applied to the data. To obtain similar errors to Volkov et al. (2020) and given the form of Equation 4, we set $\epsilon_k^2 = (0.9\ \text{Sv})^2$ for data before 1993, $\epsilon_k^2 = (2.0\ \text{Sv})^2$ for data over 1993–1998, $\epsilon_k^2 = (1.4\ \text{Sv})^2$ for data over 2000–2005, and $\epsilon_k^2 = (0.9\ \text{Sv})^2$ for data since 2006.

3.2.3. Altimetry Data

The altimetry-based transport estimates are based on the dynamical notion that sea-surface height gradients are proportional to geostrophic currents, but sea-surface height can also be affected by other Earth-system processes, such as coastal-trapped waves and gravitational attraction and loading (Ponte et al., 2018). To capture this in our model, we imagine that the altimetric data $\boldsymbol{z} = [z_1, \ldots, z_K]^\top$ observe a process $\boldsymbol{U} = [U_1, \ldots, U_K]^\top$ that represents a combination of effects related and unrelated to transport $\boldsymbol{T}$. We model the relationship between $\boldsymbol{U}$ and $\boldsymbol{T}$ as

$$U_k - T_k = \phi(U_{k-1} - T_{k-1}) + g_k, \tag{5}$$

where $g_k \sim \mathcal{N}(0, \tau^2)$ is zero-mean, independent and identically distributed white noise with unknown variance τ^2 and unknown AR coefficient ϕ. In other words, we assume the effects unrelated to transport behave as a first-order autoregressive [AR(1)] process. We represent the relationship between the data and the process as

$$z_k = U_k + f_k, \tag{6}$$

where $f_k \sim \mathcal{N}(0, \omega_k^2)$ is random white noise with zero mean and ω_k^2 is the data error variance. We set $\omega_k^2 = (2.0\ \text{Sv})^2$ following Volkov et al. (2020).

3.3. Prior Level

To complete the model, we place prior constraints on the set of model parameters $\{\boldsymbol{\beta}, \rho_1, \rho_2, \rho_3, \theta_1, \theta_2, \phi, \sigma^2, \tau^2, T_{-2}, T_{-1}, T_0, e_{-1}, e_0, U_0\}$. Our approach is to use agnostic, uninformative prior distributions, which have little effect on the posterior solutions, but initialize the sampling algorithm on roughly the right order of magnitude in solution space. All priors and hyperparameter values are listed in Table S1 in Supporting Information S1.

3.4. The Posterior and Evaluating Solutions

Given the model equations and Bayes' theorem, the posterior distribution is

$$\begin{aligned} & p(\boldsymbol{T}, \boldsymbol{U}, \boldsymbol{e}, \boldsymbol{\beta}, \rho_1, \rho_2, \rho_3, \theta_1, \theta_2, \phi, \sigma^2, \tau^2 | \boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}) \propto p(\boldsymbol{\beta}) p(\sigma^2) p(\tau^2) p(\rho_1) p(\rho_2) p(\rho_3) \\ \times \quad & p(\theta_1) p(\theta_2) p(\phi) p(T_0) p(T_{-1}) p(T_{-2}) p(e_0) p(e_{-1}) p(U_0) \\ \times \quad & \prod_{k=1}^{K} \big[p(x_k | T_k) p(y_k | T_k, \theta_1, \theta_2, e_{k-1}, e_{k-2}) p(z_k | U_k) p(U_k | T_k, U_{k-1}, T_{k-1}, \phi, \tau^2) \\ \times \quad & p(T_k | \sigma^2, \rho_1, \rho_2, \rho_3, \boldsymbol{\beta}, T_{k-1}, T_{k-2}, T_{k-3}) \big], \end{aligned} \tag{7}$$

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where p is probability density function, | is conditionality, and ∝ is proportionality.

We evaluate solutions using Markov chain Monte Carlo methods. We sample from the full conditional distributions using a Gibbs sampler (Gelman et al., 2006). We run 20,000 iterations of the sampler, where initial process values are set to zero, and initial parameter values are drawn from their respective prior distributions. To eliminate startup transients, we discard the first 10,000 "burn-in" draws. To reduce serial correlation of the remaining samples, we thin the chains by only keeping one out of every 50 samples. Our final results are based on five separate 200-member chains run to convergence and then concatenated together. More technical details on the model, including convergence, residual, and cross-validation analyses, are provided in Supporting Information S1.

4. Results

The three independent data sets—from cable, in situ, and altimetric observations—clearly capture similar Gulf Stream transports (Figure 2a), yet the amplitude and phasing of the transport variability varies due to the different resolutions and qualities of each data set. For example, the peak-to-peak variability of the daily cable data is greater than from the ten-day altimetry and the seasonal in situ data. Our Bayesian model produces an ensemble of posterior solutions that provide a fully congruent, probabilistic time-series of Gulf Stream transport through Florida Straits based on these very different data sets (Figure 2b).

We obtain daily Gulf Stream transports from 18 March 1982 to 06 December 2021 and find a mean transport of 31.8 ± 0.27 Sv. The ± range is the 95% credible interval, which is the Bayesian analog of the more familiar 95% confidence interval from frequentist statistics. Our estimate of mean transport is somewhat more tightly constrained than the value of 32.1 ± 0.4 Sv reported by Meinen et al. (2010), and lower than the value of 32.2 Sv from Baringer and Larsen (2001) based on a shorter cable record (1982–1998). Daily transport uncertainties (posterior standard deviations) are ∼0.9 Sv on average, which is smaller than the standard errors on the daily cable data, but errors vary in time depending on data quality and availability (Figures 2c and 2d). For example, daily transport uncertainties are relatively larger in July 2019 compared to the rest of that year due to a month-long gap in the cable data then (Figure 2c).

The Bayesian model solution gives clear evidence of significant longterm change. We find that Gulf Stream transport in Florida Straits declined by 1.2 ± 1.0 Sv over the past 40 years (Figures 2b and 3), which is equivalent to a change of 4.0 ± 3.2% relative to the mean transport. This means that the probability P that the Gulf Stream transport weakened more than expected from random chance is $P > 99\%$. This weakening is consistent with our mean transport from the entire record being less than that estimated up to 1998 by Baringer and Larsen (2001).

Further analysis shows that this trend only recently emerged from the data. We performed a set of sensitivity experiments where the model was only given the data through 2005, 2009, 2013, and 2017, and these experiments yielded respective transport-weakening probabilities of $P = 51\%$, $P = 79\%$, $P = 96\%$, and $P = 97\%$ (Figure 3a). This demonstrates that a significant decline in Gulf Stream transport has only become detectable during the past decade, but also that the inference of a significant weakening is insensitive to the end point of the analysis period, so long as it falls within the past decade. The Gulf Stream transport decline from the Bayesian model is also robust to the choice of data analyzed by the algorithm. We performed another set of sensitivity experiments omitting either the cable, in situ, or altimetric data from the analysis, and we found weakenings from the respective experiments of 0.8 ± 1.0, 1.1 ± 1.0, and 1.2 ± 0.9 Sv (Figure 3b). This shows that a very likely ($P > 94\%$) transport weakening is a common signal and not dependent on any one data set.

5. Discussion

Our work builds on many previous studies that have sought to quantify long-term change in Gulf Stream transport using cable data and other measurements from Florida Straits. The weakening we find since 1982 is consistent with many of these studies (e.g., Park & Sweet, 2015; Pietrafesa et al., 2022) and is distinguished by the multiple data sets we use, as well as the rigorous uncertainty quantification and time-series modeling we applied that lend confidence to our results.

Putting our work into the broader context, the recent weakening in transport through Florida Straits is likely part of a century-long decline and may be associated with weakening farther downstream in the Gulf Stream

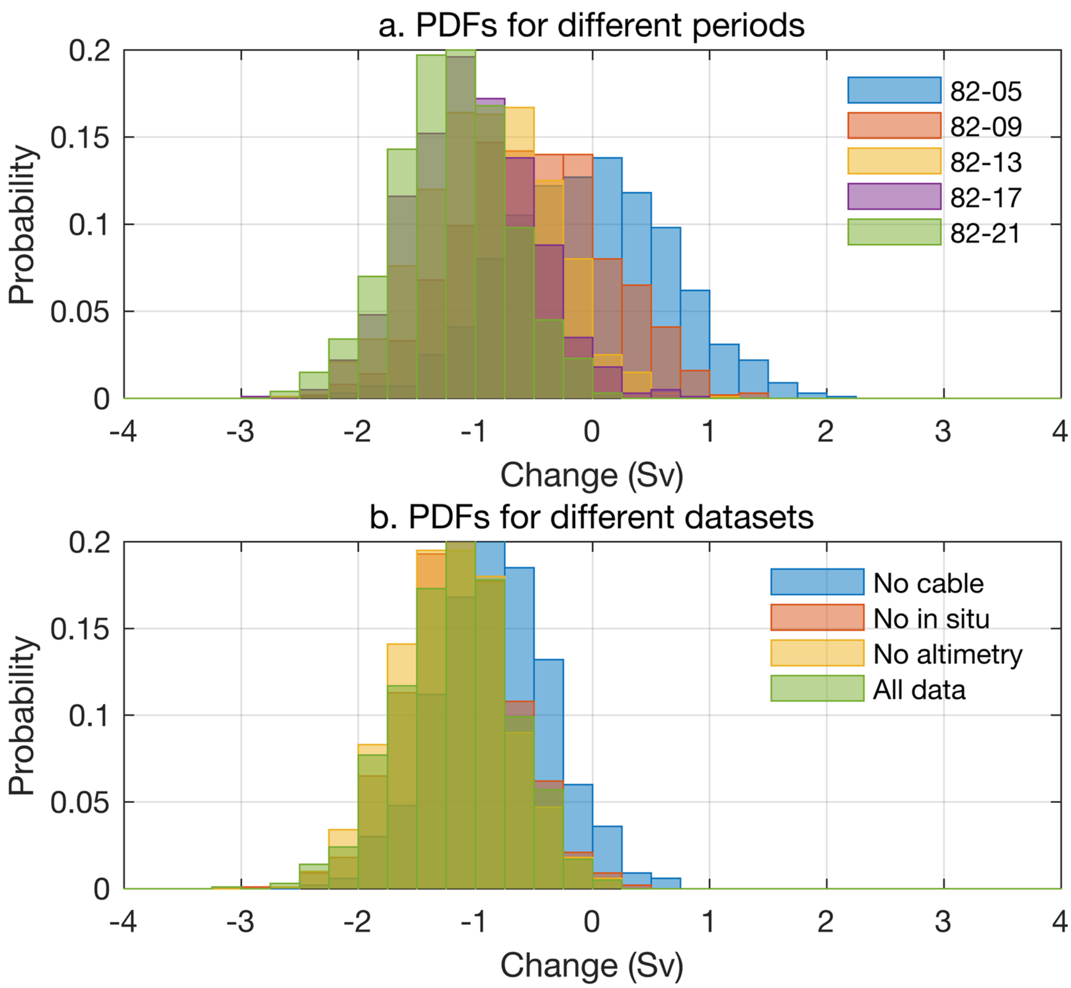

Figure 3. (a) Histograms of modeled transport change estimated over different time periods all starting in 1982. (b) Histograms of modeled transport change over 1982–2021 estimated from experiments excluding each data set from the analysis.

(Piecuch, 2020; Rossby et al., 2022). It is not yet clear whether there is an associated weakening of the Atlantic overturning circulation that carries heat poleward (Moat et al., 2020).

Piecuch (2020) used tide-gauge records from either side of Florida Straits, together with annually-averaged cable data, to conclude that transport through Florida Straits has likely declined steadily since 1909. The weakening we find here is independent of tide gauge records, since these records contain signals from multiple coastal and open ocean processes, in addition to transport, that add noise to the Bayesian model. Piecuch's analysis, using similar Bayesian methods, had to account for these extraneous dynamics.

Ocean and climate models consistently simulate that Gulf Stream transport is strongly coherent with the strength of Atlantic overturning on decadal and longer timescales (Beadling et al., 2018; Gu et al., 2020; Moreno-Chamarro et al., 2017; Thomas et al., 2012). But climate models have a hard time simulating narrow western boundary currents. There are common biases in strength, depth, variability, and separation latitudes of simulated western boundary currents when compared to observations. Moreover, variability and trends in western boundary currents can be different upstream than downstream, because the ocean eddy climate (frequency and growth) changes with latitude and topography. From observations and theory we know that most of the flow in the Gulf Stream is part of the gyre circulation of the subtropical North Atlantic with only a fraction associated with overturning. How can we be sure whether the decline in Florida Straits is related to a decline in the overturning circulation?

Validating the models requires long-term observations. Farther upstream and offshore of Florida Straits available observations are still equivocal on Gulf Stream and overturning circulation decline. For instance, Rossby et al. (2014) used 25 years of shipboard acoustic Doppler current profiler data from the Oleander program to conclude that Gulf Stream transport has been stable at 36°N, with no decline. At the same time, Rossby et al. (2022) later combined their Oleander data with hydrographic profiles from 1930 to 2020 to estimate a long-term 2.0 ± 0.8-Sv weakening of upper-ocean transport between the New England Slope and Bermuda, a region that includes the Gulf Stream and its recirculations. Ezer (2015) use tide-gauge data from Atlantic City, New Jersey and Bermuda to infer a similar weakening of the ocean circulation. Rossby et al. (2022) attribute 0.4 Sv of their weakening to the overturning circulation, but with low confidence.

The RAPID monitoring array has been measuring basin-wide Atlantic overturning at 26°N since 2004. Indeed, the Florida Straits cable data used here form part of this monitoring array. These extraordinary data inform our understanding of overturning circulation variability on sub-decadal timescales (Bryden, 2021; Frajka-Williams et al., 2016; Moat et al., 2020), but the record is, as yet, too short to shed light on long-term change.

As for gyre strength, Frajka-Williams (2015) extended the upper-mid-ocean transport from RAPID back in time using satellite altimetry to estimate that the subtropical Atlantic gyre circulation has been holding steady over 1993–2014. On the other hand, ocean reanalyses show a marginally significant weakening of the gyre during 1993–2016 (Jackson et al., 2019). This trend, however, is reliant on which observed wind product is used to drive the model. Different products drive opposing trends in wind curl and therefore gyre transport at 26°N since 1980 (Piecuch, 2020). Resolving these differences and achieving consistency between different wind-stress-curl estimates is necessary for determining longterm trends in gyre transports. There is also debate surrounding whether proxy reconstructions based on natural archives support a decline in the North Atlantic circulation since the Industrial Revolution (Caesar et al., 2022; Keil et al., 2020; Kilbourne et al., 2022; Little et al., 2020).

More generally, the relationship between western boundary current transport, gyre transport, and the overturning circulation is dependent on timescale and forcing (Gu et al., 2020; Moreno-Chamarro et al., 2017). For example, RAPID data show that, while Gulf Stream and gyre transports compensate one another on sub-annual timescales, decadal changes in the deep overturning circulation are largely balanced by equal and opposite changes in gyre transports of upper mid-ocean waters (Frajka-Williams et al., 2016; Moat et al., 2020; Smeed et al., 2018). The relationship between them could very well be changing over the long-term as well, as the thermohaline properties of the ocean adjust in a warming world. Ultimately, it is not clear whether the decline in Florida Current transport we find here portends a weakening overturning circulation.

This open question underscores the value of strategically placed observations and sustained long-term monitoring of the ocean, as well as the urgency of finding better ways of assimilating all existent observations into a congruent framework, like the Bayesian model we develop here, that can rigorously quantify uncertainty and change.

Moving forward, we have begun a multiyear program—FOCUS—funded by the National Science Program to monitor sea level and water mass properties within Florida Straits that should help determine whether the weakening of the current is related to a weakening of the overturning. Waters that are part of the overturning circulation, originating from across the equator in the South Atlantic, have distinct properties within the Straits. If the flux of these South Atlantic waters is found to vary in tandem with Florida Current transport this is another clue that the Florida Current and overturning circulation may be linked. In addition, similar Bayesian methods to those we use here could be applied to other existent data sets to paint a fuller picture of past and projected changes in North Atlantic circulation. For example, the overturning circulation time series from RAPID could be assimilated with the thousands of temperature and salinity observations from hydrographic cruises and Argo floats close to 26°N, including within Florida Straits, to further explore how circulation changes are related to water mass properties (Caínzos et al., 2022; Fu et al., 2020; McCarthy et al., 2020; Worthington et al., 2021).

Data Availability Statement

The data used here were downloaded from the NOAA WBTS project website on 10 December 2021 (https://www.aoml.noaa.gov/phod/wbts/). The Bayesian model code can be found at CGP's GitHub website (https://github.com/christopherpiecuch).

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