Has the Gulf Stream Slowed or Shifted in the Altimetry Era?

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Key Points:

- Trends in Gulf Stream latitude, speed, transport, and width estimated for 1993–2018 from altimetry are small compared to their variability.
- The magnitude and sign of trends in Gulf Stream properties are sensitive to the length of the observational record.
- Trends in latitude (speed), if continued, would require nearly doubling (tripling) the altimetric record to be statistically significant.

Abstract

The Gulf Stream is expected to slow and shift poleward over the next century due to climate change. We investigate whether such changes are already observable in the altimetric record (1993–2018) using along-track altimetry. Trends in latitude, speed, transport, and width are calculated in stream-following coordinates to avoid aliasing possible increases in variability into changes in the Stream's intrinsic structure. Statistically significant trends are few and apparently randomly distributed. Further, small changes to the length of the record lead to large changes in the trends and their significance. These results indicate that the probability there have been systematic change in the properties considered is low. Assuming that there may be physical reasons for the trends, we estimate that 22–23 additional years of observations are required detect trends in latitude and transport, and 54 additional years for trends in speed for at least half of the altimetry tracks.

Plain Language Summary

The Gulf Stream transports warm water into the high latitudes of the North Atlantic and is partially responsible for Europe's mild climate. It is expected to slow down and shift northward over the next century in response to climate change. This study investigates whether these changes are already detectable using satellite measurements of sea surface height. Trends in the latitude, speed, width, and transport are calculated in a frame that moves north and south with the Gulf Stream to avoid confusing changes in the strength and frequency of meanders with changes in the Gulf Stream's intrinsic properties. Few observed changes are statistically different from zero and small changes to the length of the record lead to large differences in the size of the changes. This means that Gulf Stream has too much short-term variability to reliably detect changes over the length of the satellite record (1993–2018). Additional observations may make it possible to detect changes. Assuming the Gulf Stream's future variability is consistent with that over the observed record, we estimate that an additional 22–23 years of observations would be required to detect changes in latitude and transport, while detecting changes in speed would require 54 additional years.

1 Introduction

As part of the surface limb of the Atlantic meridional overturning circulation (AMOC), the Gulf Stream (GS) is an important oceanic path for poleward heat and salt transport, and variations of the GS affect local and European climate (Kwon and Joyce, 2013; O'Reilly et al., 2017; Palter, 2015; Siqueira and Kirtman, 2016; Zhang et al. 2019). Several studies have suggested that climate change will lead to a weakening of the AMOC (Cheng et al., 2013; Gregory et al., 2005; Meehl et al., 2007; Schmittner et al. 2005; Schneider et al., 2007) and a concomitant slowdown (Chen et al., 2019; Meehl et al., 2007; Yang et al., 2016; Yin et al. 2010) and northward shift (Yang 2016; Zhang and Vallis, 2007) of the GS. Since the GS is in geostrophic balance with a large (~1 m) sea surface height (SSH) gradient, such changes have the potential to produce enhanced sea level rise on the US East Coast (Bingham and Hughes, 2009; Brunnabend et al., 2014; Little et al., 2019; Yin et al., 2009, Yin et al., 2010).

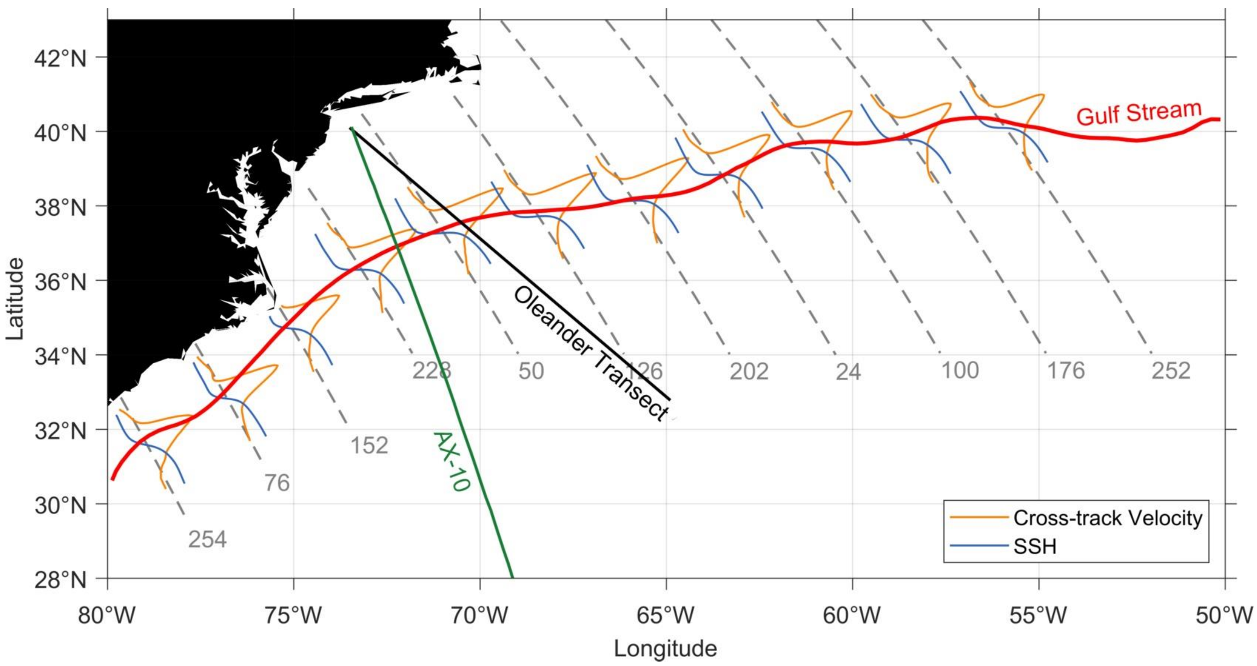

Figure 1 Locations of the altimeter tracks used in this study (dashed lines) labeled by track number. The blue and orange curves give the 1993–2018 mean ADT and cross-track velocity at each line; the mean is taken in stream-following coordinates. The Oleander Transect, the AX-10 XBT Line, and mean Gulf Stream axis (i.e., the 25-cm ADT contour) are also shown for reference.

While there appears to be general agreement that climate change will eventually cause the GS to slow and shift, evidence that this has already happened is mixed. On the one hand, in-situ observations have detected no long-term change in its transport or position at the Oleander transect (Rossby et al., 2014; Sanchez-Franks et al., 2014; Dong et al., 2019) and the AX10 transect (Dong et al., 2019); both transects are shown in Figure 1. On the other hand, a slowing of the GS has been inferred from changes in coastal sea level (Ezer et al., 2013; Ezer, 2015), sea surface temperature (SST; Caeser et al., 2018; Smeed et al., 2018), reanalyses (Yang et al., 2016), and gridded hydrography (Smeed et al., 2018) or altimetry (Dong et al., 2019, Smeed et al., 2018). Evidence for poleward shift of the GS is more mixed, with some studies reporting a northward shift (Yang et al., 2016, Caesar et al., 2018; Smeed et al., 2018) while others find that it has moved southward (Bisagni et al., 2017; Dong et al., 2019).

Some of this disagreement may stem from the use of temporally averaged gridded products, which may alias increased meander frequency or amplitude into an apparent broadening and slowing of the GS. Indeed, McCarthy et al. (2018) argued that the apparent slowing along the main axis of the GS and acceleration along the flanks visible in gridded altimetry was consistent with a recent destabilization of the GS (Andres, 2016). In an effort to avoid these aliasing problems, Dong et al. (2019) considered changes in GS properties (latitude, speed, width, etc.) in a stream-following coordinate centered on its main axis. They found statistically significant trends in GS position (southward) and speed (slowing) east of ~65ºW, but no such trends further west from altimetry or from the Oleander and AX10 transects (Figure 1). However, the result of no significant trends west of ~65ºW was sensitive to the time interval considered—significant southward and widening trends west of 65ºW were found for the period 1993–2011 but not for 1993–2016. Such sensitivity to the length of observations suggests that the trends are not robust. Further, the production of gridded altimetry requires significant interpolation in time and space which may introduce distortions which are difficult to quantify (see, e.g., Ballarotta et al., 2019). In this study, we pursue a strategy similar to Dong et al. (2019) and consider changes in GS-following coordinates but make use of along-track altimetry at its native spatial and temporal resolution, avoiding artifacts due to interpolation and temporal smoothing.

2 Intrinsic properties of the GS

Properties of the GS are derived in stream-following coordinates using a combination of along-track and ¼º gridded altimetry available from the Copernicus Marine Service spanning 1993–2018. Specifically, we derived its latitude, downstream velocity, transport, and width from along-track absolute dynamic topography (ADT) at 11 descending altimeter tracks between 80°W and 55°W (Figure 1) as described below. When the GS crosses a track more than once, properties are calculated for the two crossings with eastward velocity and averaged. These variables are first calculated at the native temporal resolution (~10 days), then averaged seasonally. Time series of GS latitude, velocity, transport and width at the 11 tracks are shown in supplemental Figures S1–S4.

2.1 Latitude

A straightforward definition of GS latitude is the location of its maximum downstream velocity. However, the GS is surrounded by eddies with comparable velocities, which makes it difficult to distinguish the two from the maximum velocity definition. A common proxy for the location of the axis of the GS is the 25-cm ADT contour from gridded altimetry (Andres et al., 2013, Lillibridge and Mariano, 2013; Rossby et al., 2014); Chi et al. (2019) have shown that this ADT contour closely follows the GS axis as defined by the maximum velocity. In this study, we use the 25-cm ADT contour as a first guess in the search for the maximum velocity axis. Specifically, the latitude of the GS at each track is first estimated using the 25-cm ADT contour from weekly gridded ADT. We then search within 75 km of this first-guess for the maximum geostrophic velocity normal to the altimeter track. The value of 75 km is chosen because it is about half the GS width. Small changes in this value do not affect any of the conclusions of this study.

The correlation between GS latitude derived from along-track ADT at track 50 and that derived from ADCP measurements at the Oleander transect (Figure 1) is 0.81 for 1993–2017, which is significant at the 99% confidence level. [Significance estimated using the random phase method (Ebisuzaki, 1997) with 20,000 samples.] This gives us confidence that the GS latitude derived from this method is reliable.

2.2 Downstream velocity

Along-track SSH can only be used to estimate geostrophic velocity normal to the track. If the angle between the cross-track velocity and GS direction is non-zero, the estimated velocity profile will be broader and slower than the actual GS. To correct for this, we project velocity derived from altimetry onto the downstream direction by rotation by the angle between the track and the 25-cm ADT contour from weekly gridded altimetry. The median value of this angle is less than 30° at all tracks; cases where this angle exceeds 60º are excluded.

2.3 Transport

Surface-layer GS transport is calculated by integrating the downstream velocity between the first zero velocity points to the north and south of its axis. Transport is reported in Sv km^{-1} ($= 10^3\ \mathrm{m^2 s^{-1}}$); this unit is such that if the GS were a 1000 m deep barotropic jet with depth surface-layer transport T Sv km^{-1} the total transport would be T Sv. Since the velocity is calculated from ADT using geostrophy, the surface-layer transport is a proxy for the sea-level drop across the GS, with 1 Sv km^{-1} of transport equivalent to an ADT drop of approximately 0.9 cm. We do not calculate transport at track 152, which is near Cape Hatteras, because the GS is too close to the coast to determine its northern boundary from altimetry.

The Oleander transect crosses the mean GS axis approximately 0.5º east of track 50 and reports total transport at 55 m rather than geostrophic transport at the surface. Nevertheless, the correlation between transport at track 50 and that reported by the Oleander is 0.71 over 1995–2004 (a period when the Oleander transport timeseries is relatively gap-free), indicating that the along-track transport estimates have some skill.

2.4 Width

A straightforward definition of GS "width" is the distance between zero-velocity points on either side of its axis. However, this definition produces estimates which are sensitive to small fluctuations of velocity around zero. To avoid this, GS width is defined as the distance between the two points where the downstream velocity reaches e^{-1} of its maximum value.

3 Trends in GS properties

3.1 Methodology

Trends are calculated using ordinary least squares. To estimate confidence intervals for the regression slope, $\hat{\alpha}$, we use the t statistic

$$\mathrm{t} = \hat{\alpha}\left[\frac{\sum_{i=1}^{N}(t_i - \bar{t})^2}{\hat{t}_\star \hat{\sigma}_E^2}\right]^{\frac{1}{2}}, \tag{1}$$

where $\hat{\sigma}_E^2$ and $\hat{t}_\star$ are estimates of the variance and decorrelation times of the residuals after regression and N is the total number of samples. The decorrelation time in units of the sample frequency is defined as the maximum of

$$t_\star = 1 + 2\sum_{j=1}^{N-1} w_j\, \rho_j \tag{2}$$

and one, where ρ_j is the lag-j autocorrelation of the residuals and the weights are

$$w_j = \frac{\sum_{i=1}^{N-j}(t_i - \bar{t})\big(t_i + t_j - \bar{t}\big)}{\sum_{i=1}^{N}(t_i - \bar{t})^2} \tag{3}$$

(e.g., Lee and Lund, 2004). Both $\hat{\sigma}_E^2$ and ρ_j are estimated by fitting AR(p) models to the residuals using conditional maximum likelihood estimation with order penalized using the Bayesian information criterion (e.g., Wei, 2006), as implemented by the Python package *statsmodels*, version 0.12.1. Finally, the confidence intervals are computed by comparing the t statistic to the point value function of a t distribution with $N_e - 2$ degrees of freedom, where $N_e = N/t_\star$ is the effective degrees of freedom.

This procedure is particularly useful in the analysis of latitude at the two tracks immediately downstream of Cape Hatteras, which have long decorrelation times (see supplemental Figure S5). The residuals for majority of the other properties are well-modeled by white noise with $t_\star = 1$ season, in which case the above formula for the confidence intervals reduces to the standard version (e.g., von Storch and Zwiers, 1999).

3.2 Results

The linear trends in GS latitude, maximum downstream velocity, surface-layer transport, and width are shown in Figure 2. The error bars on these trends are quite large and very few trends are distinguishable from zero at the 95% confidence level. The only statistically significant trends are the slight northward shift in latitude at tracks 76 and 152 (2.5 ± 2.2 and 3.2 ± 2.8 kilometers per decade, respectively), the increase in speed at track 126 (7 ± 5 cm s^{-1} per decade), and the decrease in width at track 176 (-3.2 ± 2.7 km per decade). Using monthly, rather than seasonal, means produces the same conclusion. Annually averaged data produce trends with slightly wider confidence intervals, reflecting the fact that the actual decorrelation times are generally less than a year when higher frequency data are used, but cannot be less than a year for

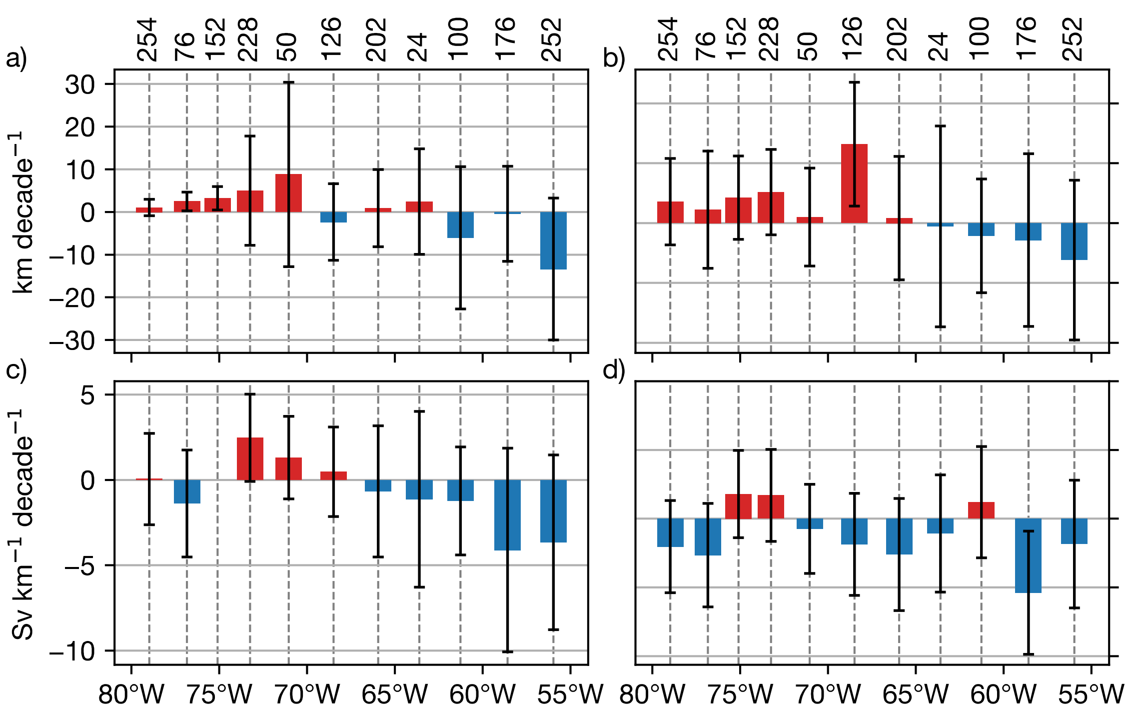

Figure 2. Decadal trends of Gulf Stream (a) latitude (converted to from degrees to kilometers), (b) downstream velocity, (c) surface-layer transport, and (d) width at 11 altimetry tracks. The most likely value of the trend is indicated by red bars for positive trends and blue bars for negative trends; error bars give 95% confidence intervals. The horizontal position of each bar is the longitude at which that track crosses the mean Gulf Stream axis. Track numbers are indicated at the upper panels.

annual data. The few trends based on seasonal data that are significant at the 95% confidence level remain significant in annual data. Adjusting the significance threshold also does not change the results significantly: only two additional trends (latitude at track 252 and transport at track 228) are significant at the 90% confidence level and only a handful of additional trends are significant at the 80% confidence level (Figure S6).

The null hypothesis that there is no trend is likely to be rejected one time in twenty by random chance when using the 95% confidence level. In the present case, we are testing 43 hypotheses (four for each of the eleven tracks, except for transport at track 152) and so should expect 2–3 of the trends to be significant even if there are no real trends. Four trends pass significance test in the present case, which is only slightly more than one would expect from random chance.

3.3 Detectability of trends

Figure 3(a-d) shows how large trends in latitude, speed, transport, and width would need to be in order to be detectable at the 95% confidence level. The GS follows the shelf edge closely upstream of Cape Hatteras, so the variability in latitude is small and correspondingly small trends are detectable. Latitude variability increases rapidly downstream of Cape Hatteras so that the trend at track 50 would need to exceed 22 km per decade to be detectable. East of 70ºW, the detection thresholds for latitude trends are steadier at 10–13 km per decade. The detection thresholds for speed, transport, and width are somewhat smaller west of 70ºW (~4 cm s^{-1} per decade for speed, ~3 Sv km^{-1} per decade for transport, and ~2 km per decade for width) than further east (5–7 cm s^{-1} per decade for speed, 3–6 Sv km^{-1} per decade for transport, and 2–3 km per decade for width).

A tradition perspective (followed thus far) is that trends are not considered real unless they meet a certain confidence threshold. An alternate perspective is that we may have reasons to believe that the trends are real, but the observational record is too short and noisy to detect them. We can then ask how long we must observe the GS for the signal of the trends to rise above the noise of the system. To estimate this “breakout time,” we assume that each quantity can be represented as the linear trend given in Figure 2 plus stationary noise. The noise is estimated from the observed time interval and the number of observations necessary for the trend to be different from zero at the 95% confidence level is calculated by inverting the method used to estimate confidence intervals given in section 3.1.

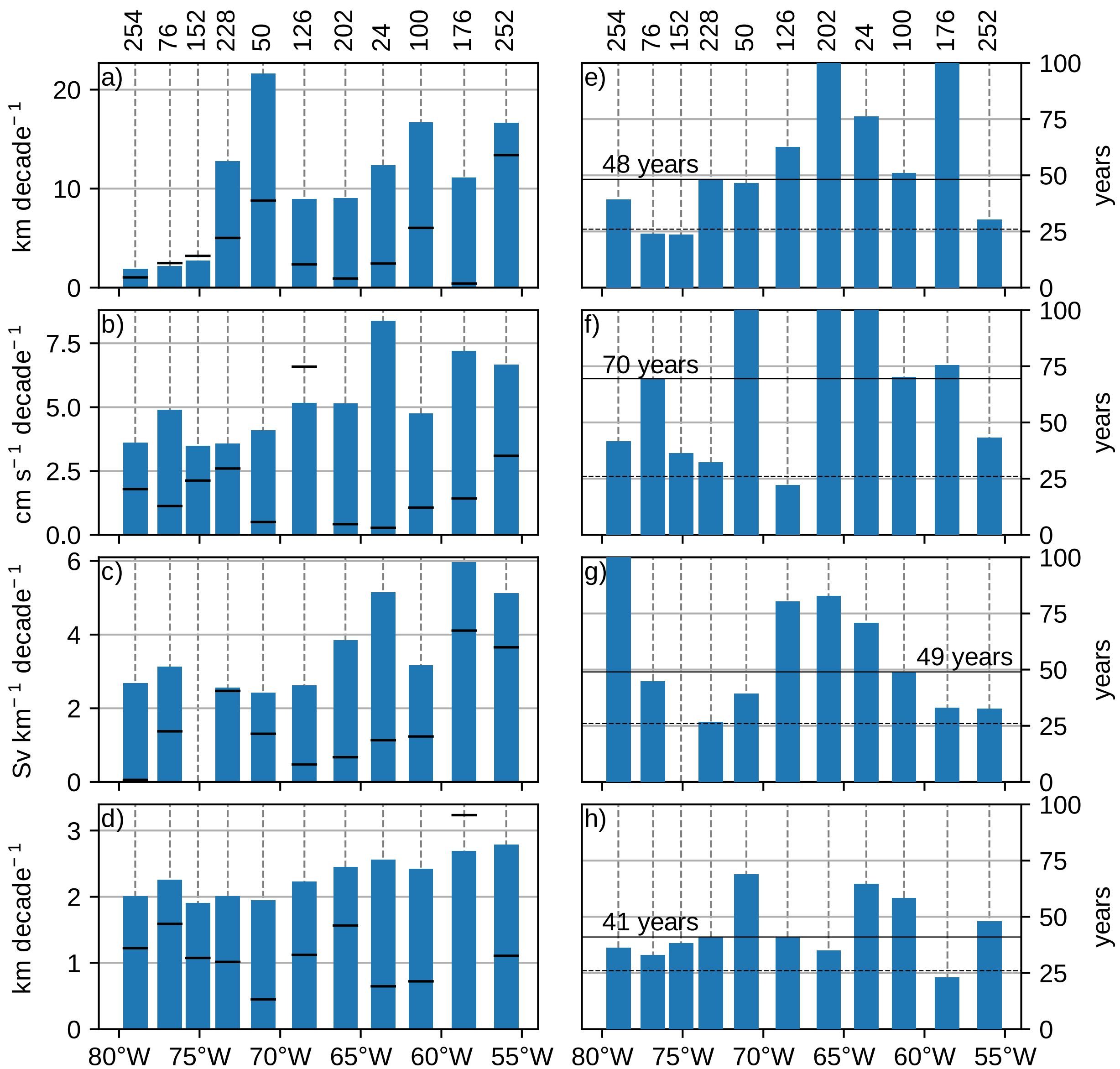

Figure 3. (a–d) The magnitude of decadal trends required for detection at the 95% confidence level and (e–h) the time required for the trends in figure 2 to be distinguishable from zero at the 95% confidence level (the "breakout time") for Gulf Stream (a, e) latitude, (b, f) downstream velocity, (c, g) surface-layer transport, and (d, h) width at 11 altimetry tracks. Black lines give the magnitude of the actual trend estimated at each track. The horizontal position of each bar is the longitude at which that track crosses the mean Gulf Stream axis. Track numbers are indicated at the upper panels.

The resulting breakout times are shown in Figure 3(e-h). Note that trends at some tracks are so weak that it would take more than 100 years of data for the trends to become significantly different from zero; at these tracks the calculation was cut off after 100 years. For latitude and transport, it would take nearly doubling the altimetry record (from 26 years to 48–49 years) for trends to become significant for at least 50% of the altimetry tracks (Figs. 3e & g). The trends are larger relative to the confidence intervals for width, so it would only take an additional 15 years of observations for at least half of these trends to be distinguishable from zero (Fig. 3h). Finally, downstream velocity is highly variable and detecting trends in velocity for at least half of the tracks would almost tripling the length of the altimetry record (to 70 years) (Fig. 3f).

It should be noted that these estimates of breakout times are likely underestimates since we have assumed that the noise is stationary with variance equal to that in the existing data. In reality, most turbulent oceanic processes are “red”, with noise that increases with the length of the record as progressively lower frequency variability influences the observations.

4 Discussion

Although very few of the trends discussed in section 3 are statistically significant, a description of them is worthwhile for comparison to previous studies. Overall, the GS appears to be accelerating and migrating northward west of 68.5º–70ºW (Figs. 2a & b). The trends are mixed downstream of this point, with some hints of a slowdown and southward shift in the extreme east. Both transport and width trends have a more complex spatial structure (Figs. 2c & d). At the two tracks upstream of Cape Hatteras (tracks 254 and 76), transport is steady or decreasing and the Stream is narrowing. The trends in transport and width are positive immediately downstream of Cape Hatteras, then become progressively weaker and more negative to the east. The implied changes in each of these quantities are generally small compared to their mean values. The exceptions are downstream velocity at 68.5ºW (track 126)—where the speed has increased by near 10%—and transport at 58.6ºW and 56ºW (tracks 176 and 252) and width at 58.6ºW (track 176)—which have all decreased by about 10% (see Figure S5).

West of about 70ºW, these trends are largely consistent with Dong et al. (2019), including the small, but significant, northward shift near tracks 76 and 152. However, east of 70ºW, Dong et al. (2019) report a significant southward shift of about 22 km per decade, a significant slowing of more than 5 cm s^{-1} per decade, and a significant reduction in transport of more than 5 Sv km^{-1}

per decade. These trends are larger (by more than a factor of two for latitude and speed) than the (mostly insignificant) trends shown in Figure 3.

The most likely reason for the above discrepancies is the difference in time intervals between the two studies. The trends shown in Figure 2 are for 1993–2018 while Dong et al. (2019) considered the interval 1993–2016. Indeed, Dong et al. (2019) make a similar point when discussing the differences between their results and previous studies, showing that changing the time interval to 1993–2011 produces large changes in the estimated trends. When our analysis is repeated for the same time interval used by Dong et al. (2019), the results become much more consistent with that study (Fig. 4). Further, several trends east of 70ºW are distinguishable from zero at 95% confidence that were not when using the longer time record.

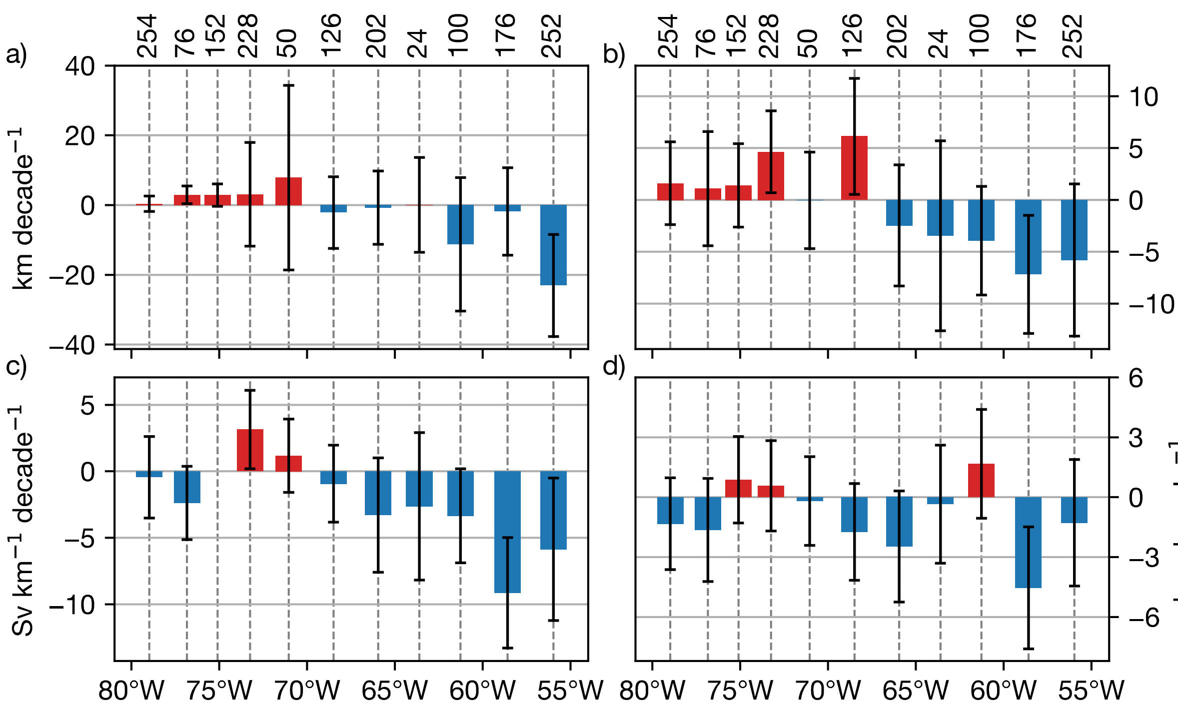

Figure 4. As with Figure 2, but for the period 1993–2016.

Our confidence intervals are still wider than those given by Dong et al. (2019), even after adjusting the time interval. When the decorrelation time is equal to the sampling frequency—as is the case for most properties at most tracks using seasonally averaged data—the t statistic (1) reduces to the standard version given in textbooks and reported by most regression software, which gives the same result reported here. We can only speculate that either the use of gridded altimetry or the temporal smoothing employed by Dong et al. (2019) either suppresses variability or artificially increases the degrees of freedom, leading to narrow confidence intervals.

That changing the analysis window by two years produces such changes in the magnitudes of the trends suggests that even the conservative confidence intervals given in Figures 2 and 4 are misleadingly narrow. Whether statistically significant trends are meaningful depends on the question being asked. If the goal is to describe what has happened, the trends shown in Figures 2 and 4 may be useful as summaries—although reporting the total change implied by the trend (as in Figure S7) may be more informative. However, the fact that a trend is a rate suggests it be interpreted as a prediction of future behavior. This is the perspective implicit in the breakout times reported in Figure 3. However, because small changes in the time interval cause large changes in trends indicates that noise in GS properties is so large that the estimation of statistically significant trends is not stable given the present length of observation data. This is another reason to view the breakout times estimated in Figure 3 should be viewed with caution.

5 Summary and conclusions

Taking advantage of 26 years of continuous sea surface height observations from satellite altimetry, we have examined whether the Gulf Stream (GS) has changed significantly over the altimetry era. When calculated at fixed positions, trends in sea surface height and surface velocity suggest that the GS has slowed and broadened over this period. However, trends in GS transport, latitude, width, and maximum downstream velocity calculated in stream-following coordinates tell a different story. The results in section 3 indicate that any changes in the intrinsic structure of the GS are small compared to their variability. Our confidence that the GS has shifted, slowed, or widened over the nearly three decades of altimetric observations is poor. In fact, the few locations where we have confidence that there is a trend indicate that the GS has accelerated and narrowed rather than slowed and broadened. The answer to the question posed in the title is therefore “we cannot tell,” at least not from the current altimetric record.

Given the strength of subdecadal GS variability, it would take nearly doubling the length of the altimetry record to have 95% confidence that there are nonzero trends in latitude and transport for at least half of the GS-crossing tracks. Unambiguous detection of trends in GS speed at the majority of the tracks would require nearly tripling the record. However, these estimates are predicated on the assumption that the trends are stable in time. The discussion in section 4 indicates that this is unlikely to be the case.

Several studies (Ezer, 2013; Ezer et al., 2013; Ezer 2015) have argued that a hot spot for accelerating sea level rise in the Mid-Atlantic Bight can be explained by a long-term slowing trend in the GS. The results of this study suggest that this explanation is unlikely, since there are no unambiguous trends in GS surface-layer transport and the only unambiguous trend in velocity is *positive*. This suggests that explanation for the Mid-Atlantic sea-level-rise hot spot should be sought elsewhere. For example, Piecuch et al. (2018) have argued that majority of large-scale spatial variation in sea-level rise on the U.S. East Coast is due to geological processes evolving on multi-centennial timescales.

Acknowledgments and Data

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