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Key Points:

- Trends in Gulf Stream (GS) latitude, speed, transport, and width estimated for 1993–2018 from altimetry are small compared to their variability
- The magnitude and sign of trends in GS metrics 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

Supporting Information:

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

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

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Abstract The Gulf Stream (GS) 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. Decadal trends in latitude, speed, transport, and width are calculated in stream-following coordinates to avoid spurious signals due to changes in higher-frequency GS variability. 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 suggest that the current observations are insufficient to detect significant trends in these metrics. If the trends continue at the current rate, detection of trends at more than half of the altimetry tracks would require 22–23 additional years of observations for latitude and transport and 44 additional years for speed.

Plain Language Summary The Gulf Stream (GS) 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 trends are already detectable using satellite measurements of sea surface height. GS speed, width, and transport are calculated in coordinates which are always centered on the GS axis to avoid potential false trends from changes in the variability of the GS position. Few observed trends are statistically different from zero and small changes to the length of the record lead to large differences in the magnitude of the trends. This means that GS has too much short-term variability to reliably detect trends over the length of the satellite record (1993–2018). Additional observations may make it possible to detect trends. Assuming the GS'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 trends in latitude and transport, while detecting trends in speed would require 44 additional years.

1. Introduction

As part of the surface limb of the Atlantic meridional overturning circulation (AMOC), the Gulf Stream (GS) is an important path for poleward heat and salt transport, and variations of the GS affect local and European climate (Kwon & Joyce, 2013; O'Reilly et al., 2017; Palter, 2015; Siqueira & Kirtman, 2016; Zhang et al., 2019). Several studies 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) and northward shift (Caesar et al., 2018; Smeed et al., 2018; Yang et al., 2016; Zhang & 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 & Hughes, 2009; Brunnabend et al., 2014; Little et al., 2019; Yin et al., 2009, 2010).

There appears to be general agreement that climate change will eventually cause the GS to slow and shift with the slowdown of the AMOC. For example, climate simulations by Hu and Bates (2018) suggest that the AMOC will weaken over the next few decades, leading to reduced GS transport and increased sea level rise northwest of the GS, and those by Hand et al. (2019) predict a northward shift of the GS by the last half of the 21st Century. However, evidence that these charges have 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 (Dong et al., 2019; Rossby et al., 2014; Sanchez-Franks, 2015; W. Z. Zhang et al., 2020) 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

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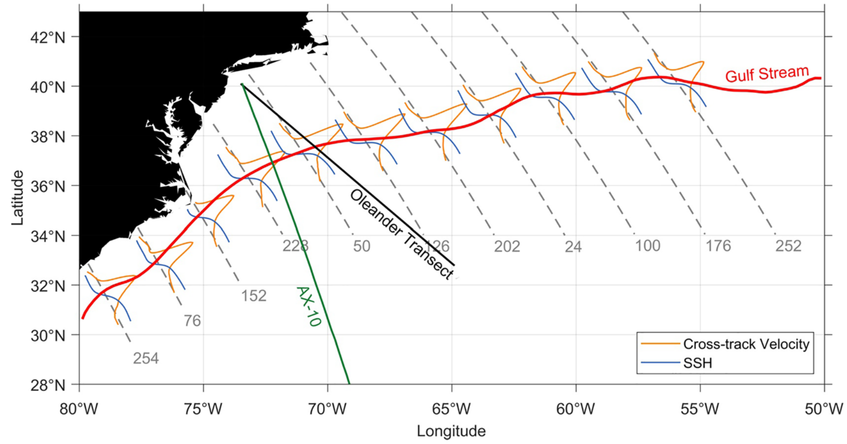

Figure 1. Locations of the altimeter tracks used in this study (dashed lines) labeled by track number. The blue and orange curves give the 1993–2018 mean absolute dynamic topography (ADT) and cross-track velocity at each line; the mean is taken in stream-following coordinates. The Oleander Transect,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

been inferred from changes in coastal sea level (Ezer, 2015; Ezer et al., 2013), sea surface temperature (SST; Caesar et al., 2018; Smeed et al., 2018), reanalyzes (Yang et al., 2016), and gridded hydrography (Smeed et al., 2018). Evidence for a poleward shift of the GS is more mixed, with some studies reporting a northward shift (Caesar et al., 2018; Smeed et al., 2018; Yang et al., 2016) while Bisagni et al. (2017) find that it has moved southward.

Some of this disagreement may stem from the use of data temporally averaged at fixed locations, which may alias increased meander frequency or amplitude into an apparent broadening and slowing of the GS (Figure S1). Indeed, McCarthy et al. (2018) argued that the apparent slowing along the GS axis and acceleration along the flanks visible in averaged 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 metrics (latitude, speed, width, and transport) in stream-following coordinates. 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). Similar results were also reported by W. Z. Zhang et al. (2020), which suggested that the significant trends only appeared east of ~61ºW. However, Dong et al. (2019) found the result of no significant trends west of ~65°W was sensitive to the time interval considered—significant southward and widening trends west of 65°W 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. GS Metrics

GS metrics are derived in stream-following coordinates using a combination of along-track and ¼° 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). When the GS crosses a track more than once, the metrics for the two crossings with eastward velocity are 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 S2–S5.

2.1. Latitude

The GS is surrounded by eddies with comparable velocities, which makes it difficult to distinguish the two from the maximum velocity. A common proxy for the GS axis is the 25-cm ADT contour from gridded altimetry (Andres et al., 2013; Lillibridge & 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 seasonal 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 60° 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} ($= 10^3\ m^2 s^{-1}$); this unit is such that if the GS were a 1,000 m deep barotropic jet with surface-layer transport T Sv km^{-1} the total transport would be T Sv. Since the velocity is calculated from ADT using geostrophy, the sea-level drop across the GS is a proxy for the surface-layer transport, with an ADT drop of ∼0.9 cm equivalent to 1 Sv km^{-1} of transport. We do not calculate transport and width 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 ∼0.5° east of track 50 and reports total transport at 55 m rather than geostrophic transport at the surface. Nevertheless, the correlation between annual mean transport at track 50 and that reported by the Oleander is 0.71 over 1995–2004 (a period when the Oleander transport time series is relatively gap-free), which is significant at the 95% level, 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. The width obtained from along-track data is multiplied by the sine of the angle between the track and GS axis (obtained from the 25-cm ADT contour) to correct for the fact that the tracks do not cross the GS at right angles.

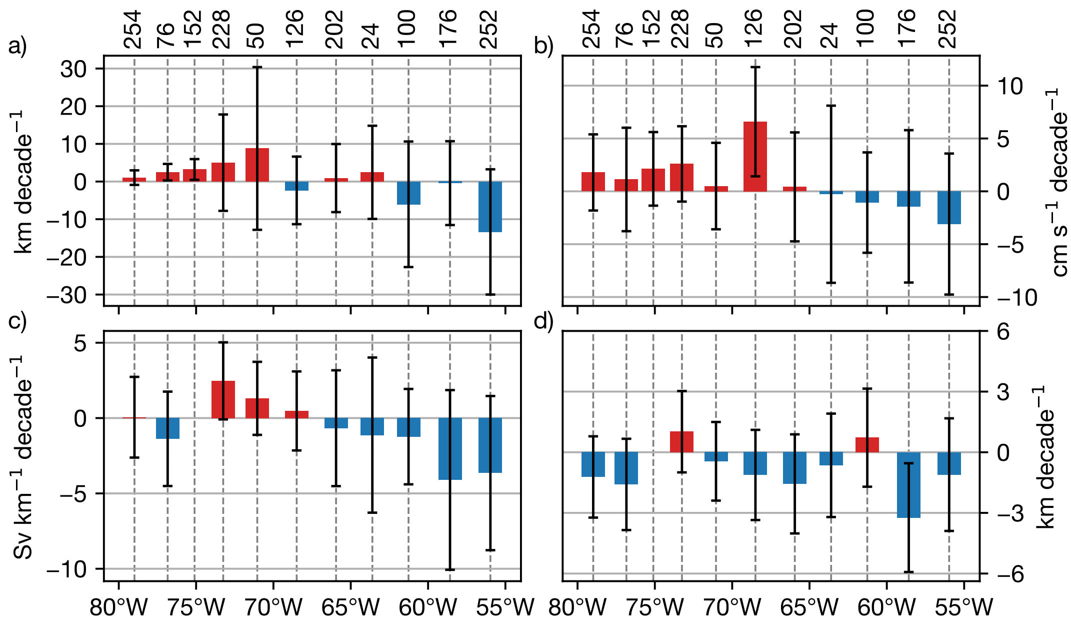

Figure 2. Decadal trends of Gulf Stream (GS) (a) latitude (converted to from degrees to kilometers), (b) downstream velocity, (c) surface-layer transport, and (d) width at 11 altimetry tracks. The most likely value of the trend is indicated by red bars for positive trends and blue bars for negative trends;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

3. Trends in GS Metrics

3.1. Results

The linear trends in GS latitude, maximum downstream velocity, surface-layer transport, and width are shown in Figure 2. The 95% confidence intervals are derived using a t statistic with autocorrelation effects included (Lee & Lund, 2004); see Supplementary Text S1 for details. 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 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 S7).

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 42 hypotheses (four for each of the 11 tracks, except for transport and width 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.

3.2. Detectability of Trends

Figures 3a–3d 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

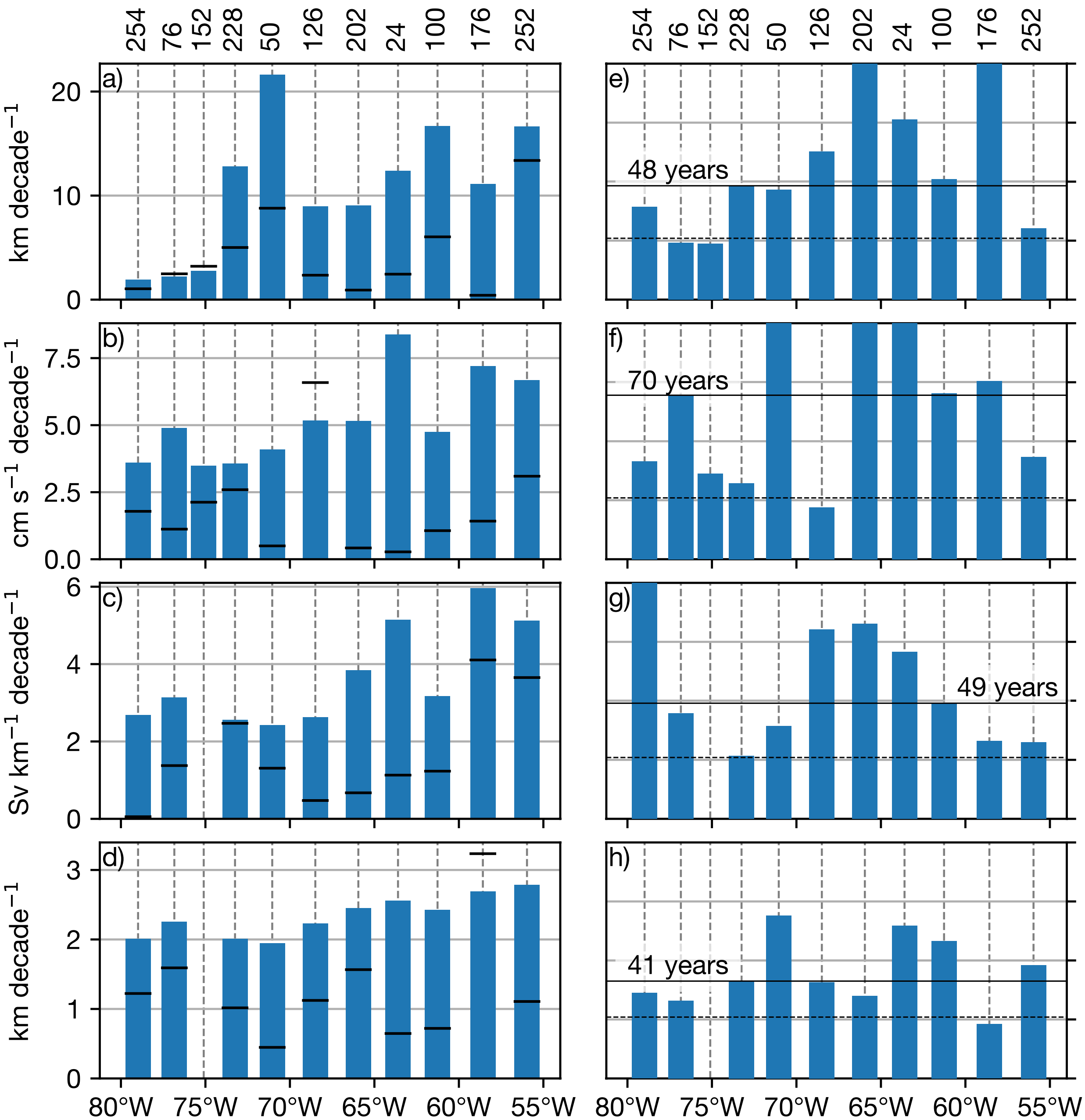

Figure 3. (a–d) The magnitude of decadal trends required for detection at the 95% confidence level and (e–h) the time required for the trends in Figure 2 to be distinguishable from zero at the 95% confidence level (the time of emergence) for Gulf Stream (GS) (a and e) latitude, (b and f) downstream velocity, (c and g) surface-layer transport, and (d and 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 GS axis. Track numbers are indicated at the upper panels.

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 70°W, 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 70°W (~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 traditional 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 time of emergence, 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 Supplementary Text S1.

The resulting emergence times are shown in Figures 3e–3h. Note that trends at some tracks are so weak that it would take more than 100 years 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 more than half of the altimetry tracks (Figures 3e and 3g). 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 (Figure 3h). Finally, downstream velocity is highly variable and detecting trends in velocity for at least half of the tracks would require almost tripling the length of the altimetry record (to 70 years) (Figure 3f).

It should be noted that these emergence 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.

Although longer time series of the GS metrics can be derived from numerical hindcast or future projections, it is hard to evaluate the reliability of the GS trends from those products. Chi et al. (2018) found that even models constrained by observations could not reproduce most GS metrics well. It is reasonable to assume that hindcasts and climate projections without assimilating satellite SST and sea level anomaly would perform even worse. Further, Yang et al. (2016) found conflicting trends of the GS strength between observations and some CMIP5 simulations. We therefore do not address trends from long numerical simulations in this study.

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 68.5°–70°W (Figures 2a and 2b). The northward migration at these tracks is what might be expected from a slowing of the AMOC, since the bottom vortex stretching due to downslope flow in the deep western boundary condition contributes to separation at Cape Hatteras (Zhang & Vallis, 2007). However, this mechanism also predicts that the GS should *de*celerate, which is the opposite of what is observed west of 70°W. The trends are mixed downstream of 70°W, with some hints of a slowdown and southward shift in the extreme east—the slowdown is consistent with the Zhang and Vallis (2007) mechanism, but the southward shift is not. Both transport and width trends have a more complex spatial structure (Figures 2c and 2d). 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 68.5°W (track 126)—where the speed has increased by near 10%—and transport at 58.6°W and 56°W (tracks 176 and 252) and width at 58.6°W (track 176)—which have all decreased by about 10% (see Figure S8).

West of about 70°W, 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 65°W, trends in Dong et al. (2019) are larger (by more than a factor of 2 for latitude and speed) than the (mostly insignificant) trends shown in Figure 2.

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) made a similar point when discussing the differences between their results

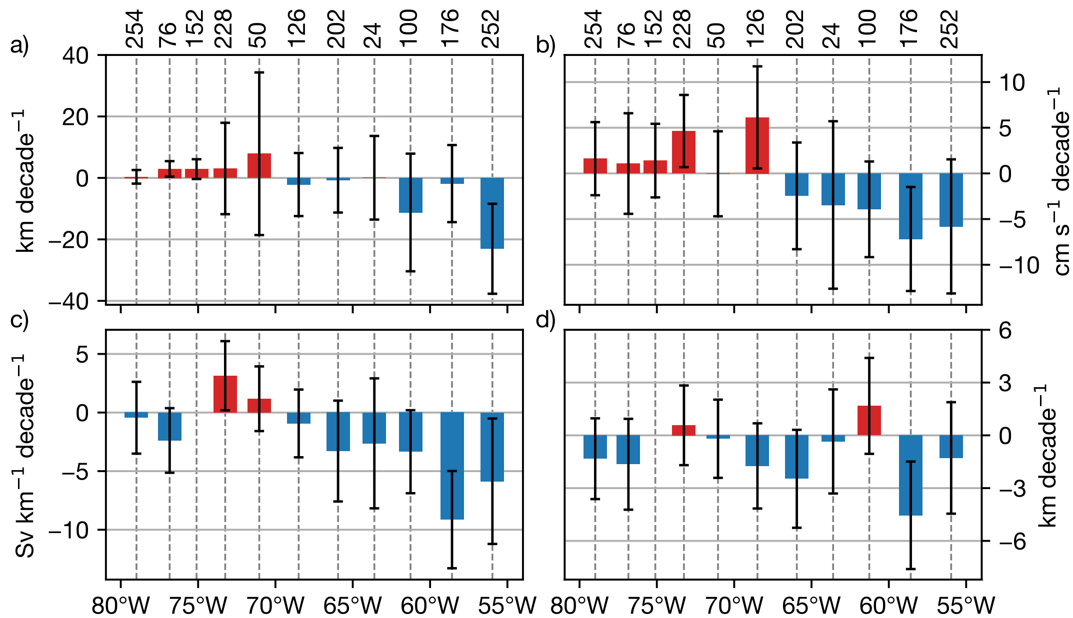

Figure 4. As with Figure 2, but for the period 1993–2016.

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 (Figure 4). Further, several trends east of 65°W are distinguishable from zero at 95% confidence that were not when using the longer time record.

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 metrics at most tracks using seasonally averaged data—the t statistic (Text S1) 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 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 2 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 S8) may be more informative. However, because small changes in the time interval cause large changes in trends indicates that noise in GS metrics is so large that the estimation of statistically significant trends is not stable given the present length of observation data. The emergence times estimated in Figure 3 should therefore be viewed with caution.

The results of this study are consistent with Rossby et al. (2014), who found no statistically significant trend in GS transport from ADCP measurements at the Oleander transect. The discrepancy between our results and some others suggesting a slowdown of the GS may rise from the destabilization of the GS path. Even if the mean latitude and cross-stream structure of the GS are unchanged, the destabilization of its path (Andres, 2016) would still lead to increased (decreased) mean sea level and SST north (south) of its mean path in the Eulerian mean (Figure S1). Studies which average in stream-following coordinates (Dong et al., 2019; Rossby et al., 2014; W. Z. Zhang et al., 2020 and this study) do not find significant changes of the GS transport at the Oleander transect. Thus, the "slowdown" of the GS reported by some previous studies (Caesar et al., 2018; Ezer & Dangendorf, 2020; Smeed et al., 2018; Yang et al., 2016) may not be due to a weakened GS but the destabilization of the GS path.

5. Summary and Conclusions

Taking advantage of 26 years of continuous SSH observations from satellite altimetry, we have examined whether the linear trends in the GS metrics at the satellite tracks are significant over the altimetry era. When calculated at fixed positions, trends in SSH and surface velocity suggest that the GS has slowed and broadened over this period (McCarthy et al., 2018; Smeed et al., 2018). 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 metrics 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 sub-decadal 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, 2015; Ezer et al., 2013) 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.

Data Availability Statement

Along-track and ¼° gridded altimetry products are distributed by the Copernicus Marine Service (https://marine.copernicus.eu) and ADCP measurements from the *MV Oleander* are available from the Oleander project (http://po.msrc.sunysb.edu/Oleander).

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