Changes in the Gulf Stream preceded rapid warming of the Northwest Atlantic Shelf

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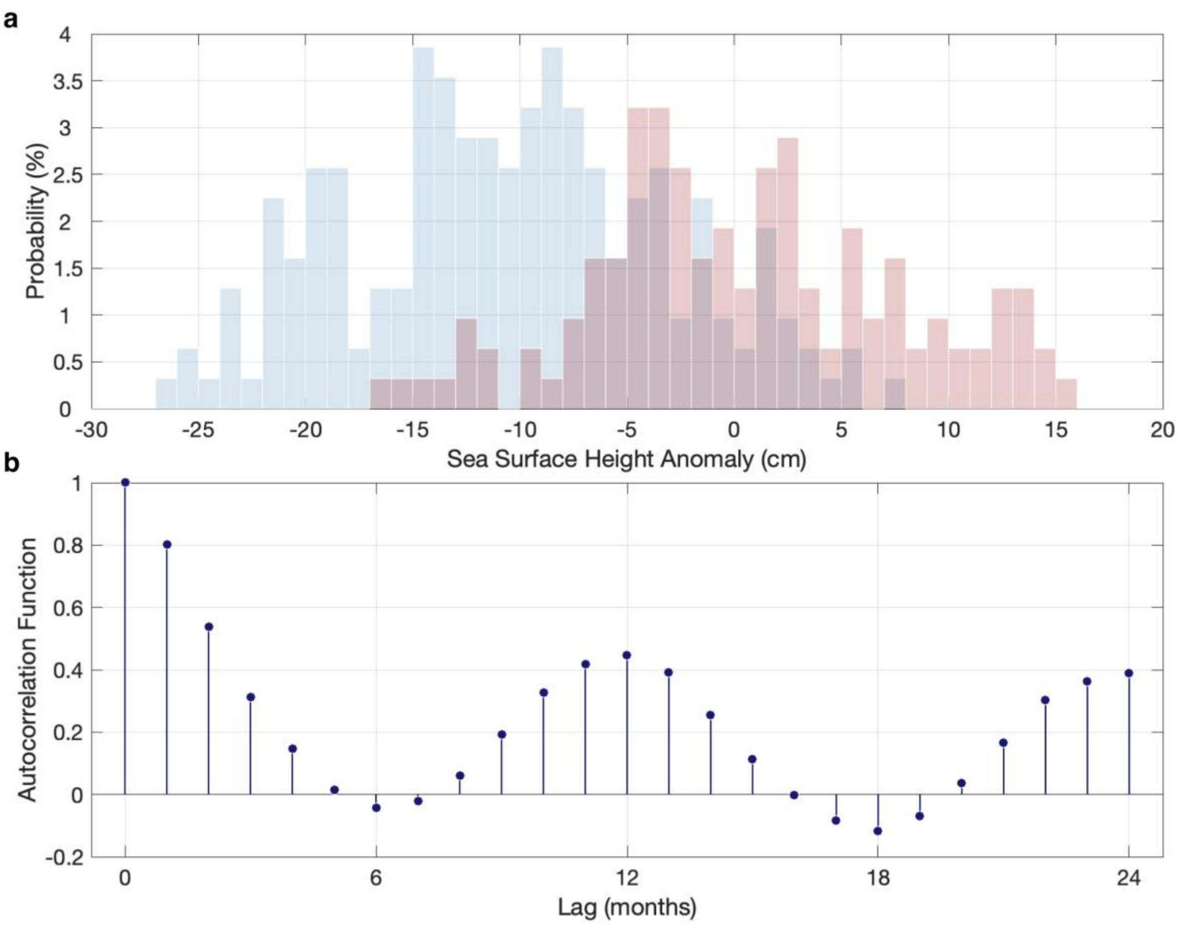
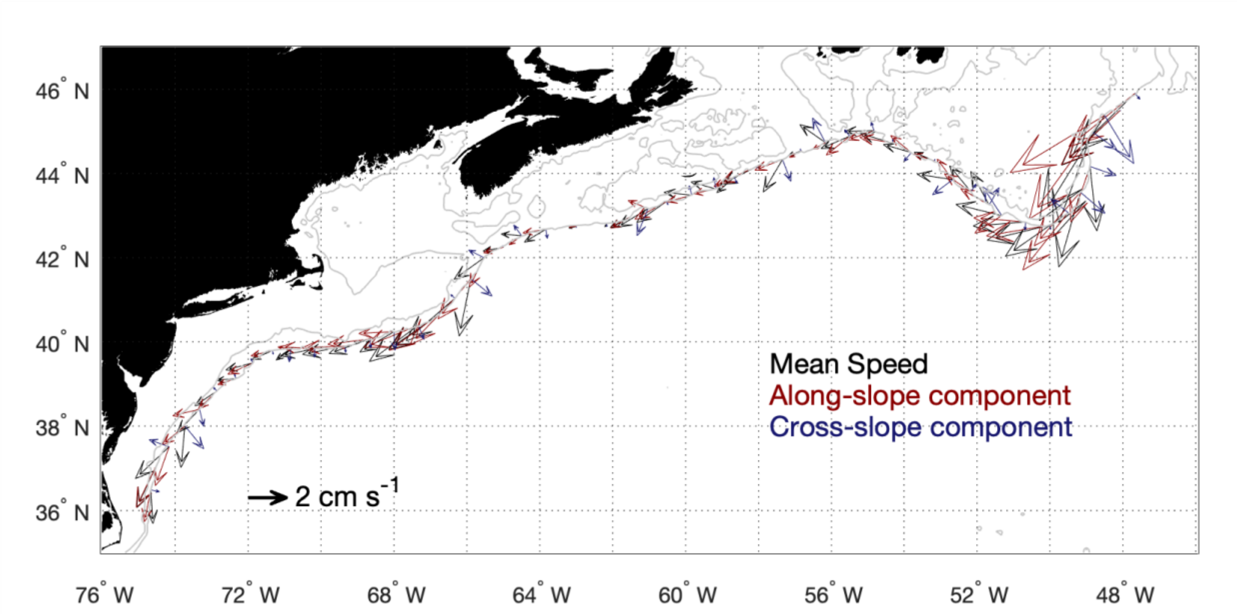
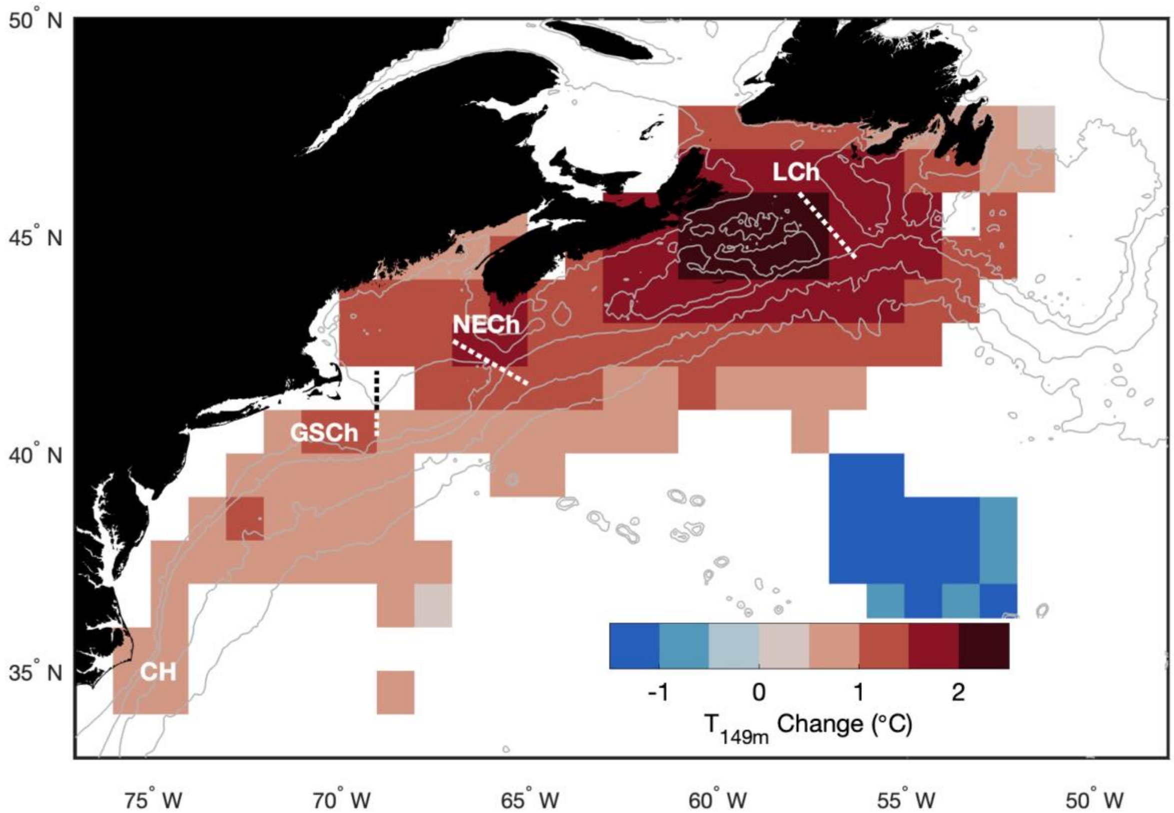
Supplementary Information



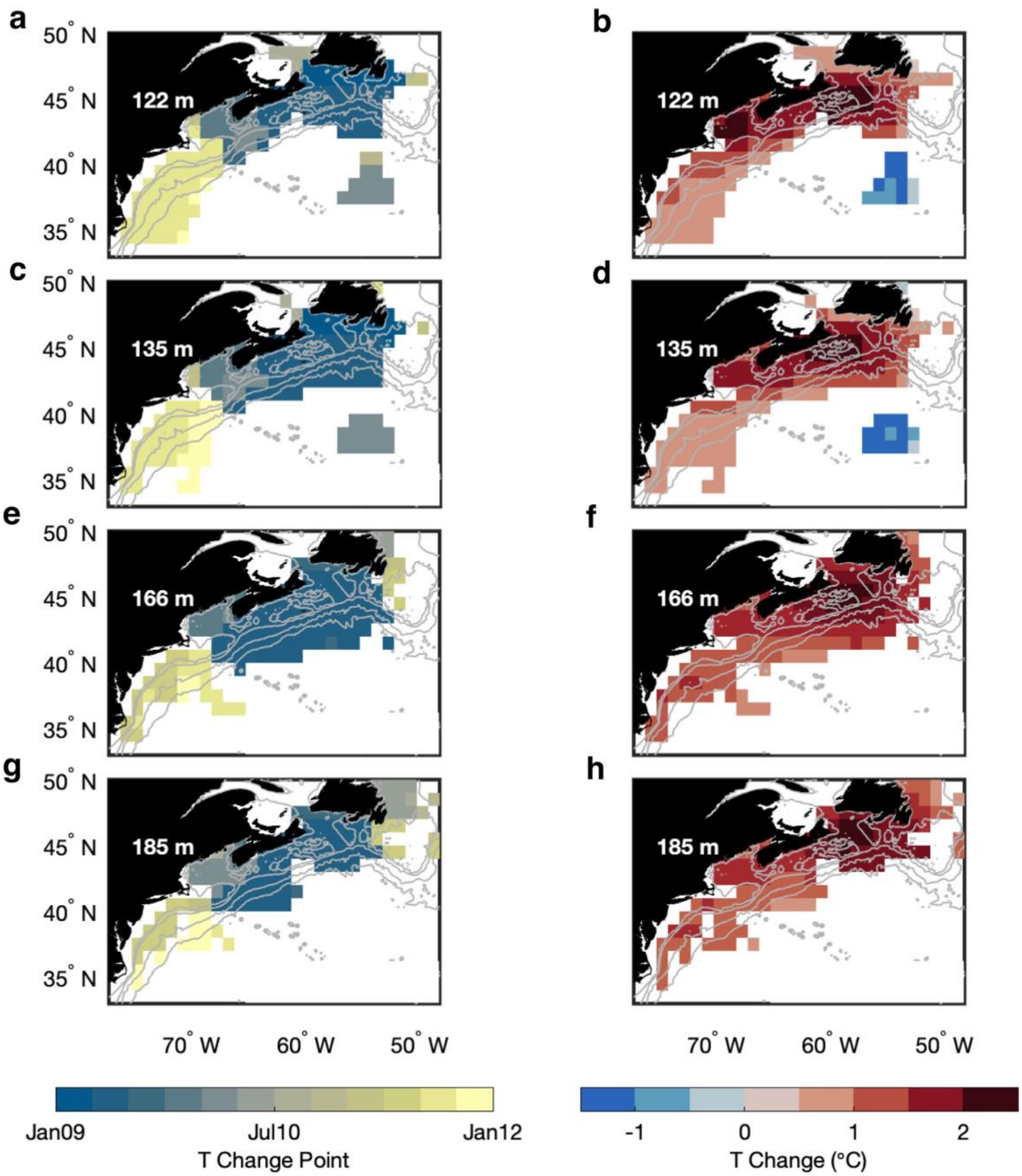
Supplementary Fig. 1. Sample probability distribution and autocorrelation of the sea surface height time series at the Tail of the Grand Banks shown in Fig. 2c. (a) Sample probability distribution histogram of the pre-shift months (January, 1993 – July, 2008; blue bars) and postshift months (August, 2008 – December, 2018, red bars). The transition in 2008 represented a 10.5 cm increase in the mean Sea Surface Height and explains 24.1% of the variability in the time series. **(b)** Autocorrelation function, showing the highest values at 1-, 2-, 12- and 24-month lags, which indicates the strong month-to-month and seasonal signals. The temporal autocorrelation structure explains 45.8% of the variability in the time series.



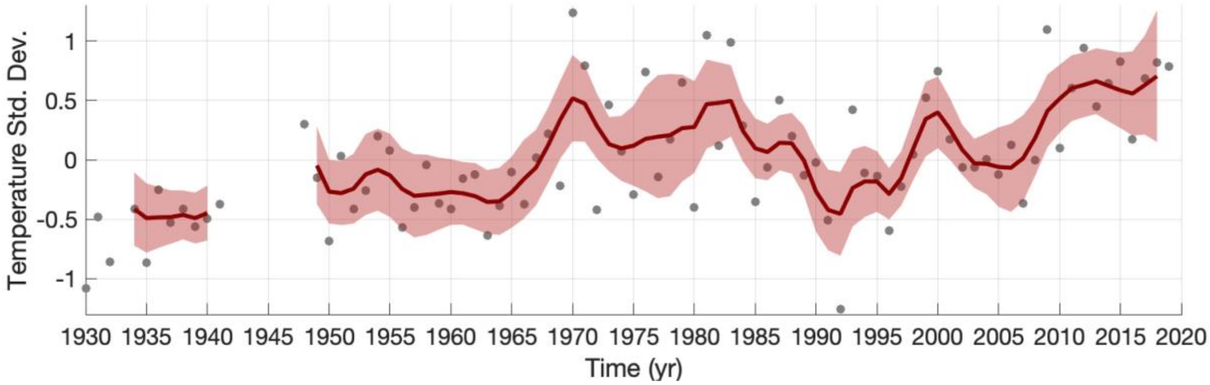
Supplementary Fig. 2: Along-slope velocity between Flemish Pass and Cape Hatteras. Black arrows indicate the 26-year mean surface speed as interpolated onto the 500-m isobath. Red and blue arrows are the along- and across-slope velocity components as calculated from the angle between two consecutive grid points from Flemish Pass. Gray contours are the 100-m and 500-m isobaths. The monthly along-slope velocity is used to calculate the lagged correlations shown in Fig. 3a.



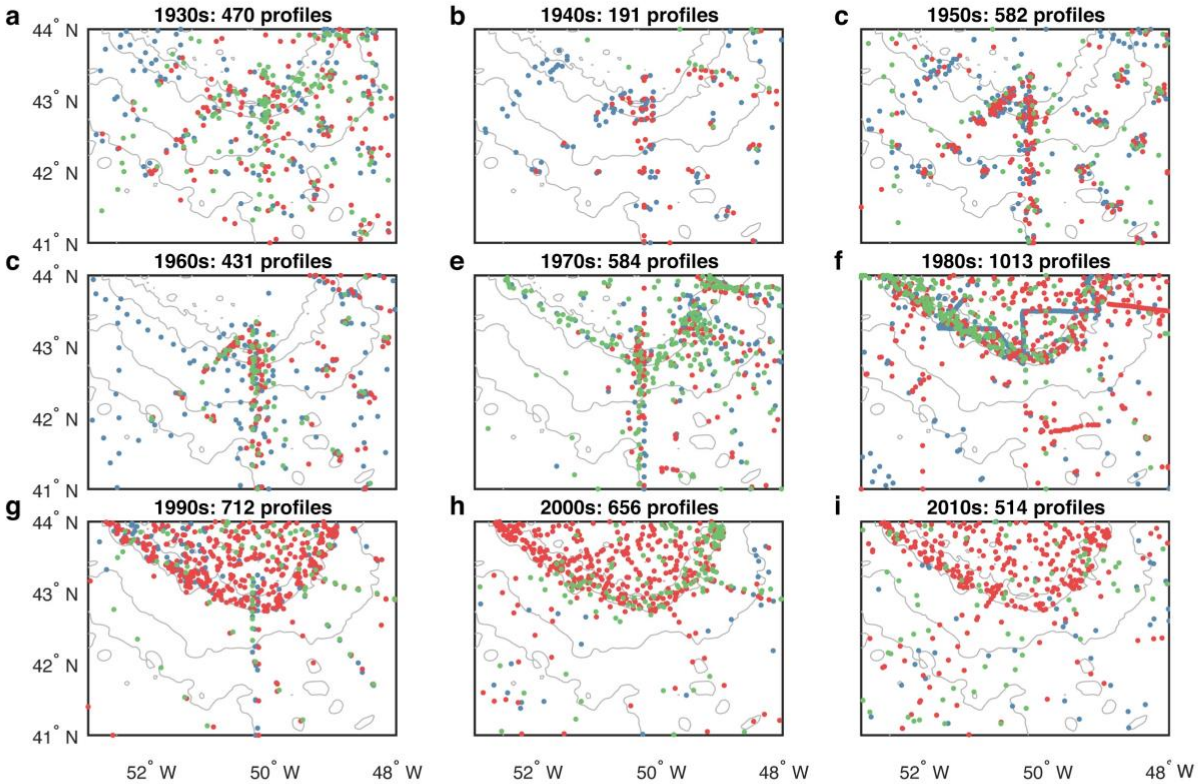
Supplementary Fig. 3: Magnitude of the 149-m temperature shift in the Northwest Atlantic. The temperature shift is calculated at each grid point as the mean temperature after the change-point timing minus the mean temperature before the change-point timing, as shown in Fig. 3b, for 1993–2018. The shades only show grid points whose single change point happened between January 2009 and December 2011. All of the changes on the shelf and slope are positive, i.e., represent a shift towards warmer waters. Colors are displayed in 0.5°C bins. The 100-m, 1,000-m, 3,000-m and 4,000-m isobaths are contoured in gray. The main cross-shelf features are identified. LCh = Laurentian Channel; NECh = Northeast Channel; GSCh = Great South Channel; CH = Cape Hatteras. Colormap from the Cmocean package[1].



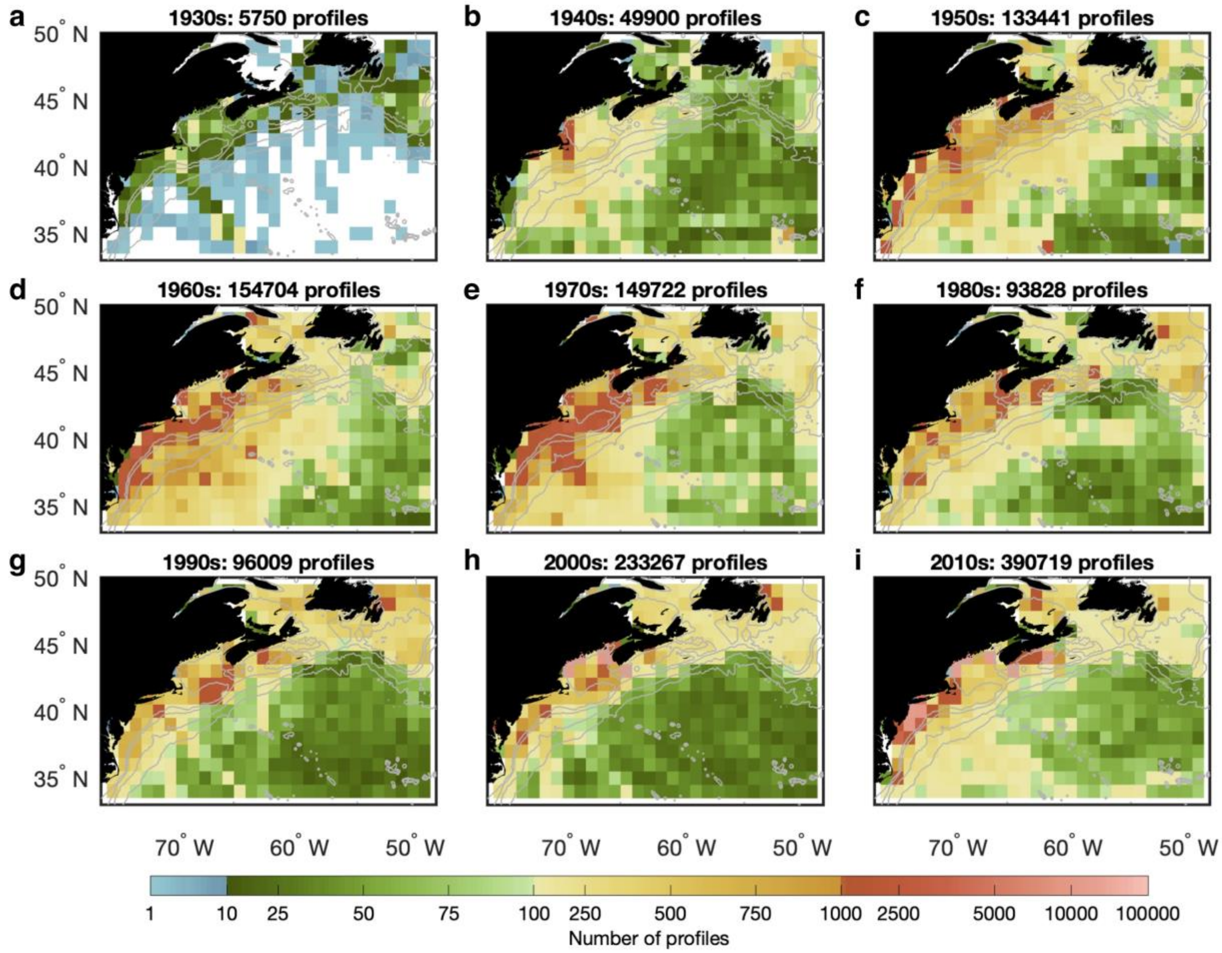
Supplementary Fig. 4: Post-2008 temperature shifts on the Northwest Atlantic Shelf. Timing **(left; a,c,e,g)** and magnitude **(right; b,d,f,h)** of the identified temperature shifts at the 122-m **(a,b)**, 135-m **(c,d)**, 166-m **(e,f)** and 185-m **(g,h)** layers from the EN4 objective analysis. The 100-m, 1,000-m, 3,000-m and 4,000-m isobaths are contoured in gray. Based on the results of the 149-m layer, analysis was limited to a polygon defined by the vertices (30^{o}N, 80^{o}W), (36^{o}N, 65^{o}W), (36^{o}N, 52^{o}W), (43^{o}N, 48^{o}W), (48^{o}N, 42^{o}W), (51^{o}N, 47^{o}W), (53^{o}N, 54^{o}W), and (48^{o}N, 80^{o}W). Colormaps in panels **a** and **b** are, respectively, from the Crameri[2] and Cmocean[1] packages.



Supplementary Fig. 5: Ninety-year (1930-2019) time series of the normalized temperature anomalies at the Tail of the Grand Banks at 350 m--the mean depth of the 27.25 kg m^{-3} isopycnal. The red line and shades are the three-year running mean and the standard error envelope, respectively. The gray circles are one-year averages. Plotting temperature at a fixed depth allows us to include the quality-controlled profiles of temperature that do not also have salinity (3,565 profiles that reach a depth of 350 m), and also combines the signal of the deepening thermocline (as in reference 14) as well as water mass changes on density surfaces. The method for making this time series is the same as that described in the methods for the T-S plot, where the bin-average was subtracted from each profile before averaging the anomalies. In this case, the anomaly was also normalized by the standard deviation in the bin, so that the plotted anomalies are the mean number of standard deviations from the mean temperature in the box at the Tail of the Grand Banks.



Supplementary Fig. 6: Hydrographic and float profiles at the Tail of the Grand Banks from the EN4 database. (a-i) Each panel shows the locations of all profiles taken between April and June in each decade since the 1930s with pairs of temperature and salinity. Months are indicated by colors: blue for April, red for May and green for June. The 100-m, 1,000-m, 3,000-m and 4,000-m isobaths are contoured in gray.



Supplementary Fig. 7: Hydrographic and float profiles from the EN4 database in the Northwest Atlantic. (a-i) The shades show the number of profiles by decade between the 1930s and the 2010s in 1° x 1° bins. Over 1.3 million profiles were used to build the objective analysis in this region, of which 57% were collected in the shelf regions that are used to construct Figs. 3b, 4b, Table 1 and Supplementary Fig. 3. The 100-m, 1,000-m, 3,000-m and 4,000-m isobaths are contoured in gray. Colormaps are from the SciVisColor database[3].

Supplementary References

1. Thyng, K., Greene, C., Hetland, R., Zimmerle, H. & DiMarco, S. True Colors of Oceanography: Guidelines for Effective and Accurate Colormap Selection. *Oceanog* **29**, 9–13 (2016).
2. Crameri, F. *Scientific Colour-Maps: Perceptually uniform and colour-blind friendly*. (2018).
3. Zeller, S. & Rogers, D. Visualizing Science: How Color Determines What We See. *EOS* **101**, (2020).