Dynamics of a Persistent Gulf Stream Heatwave

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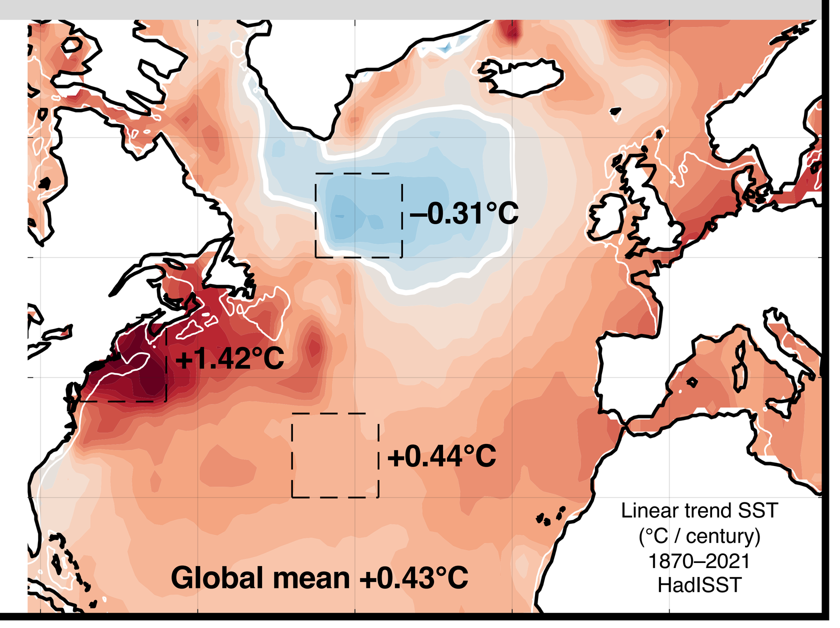
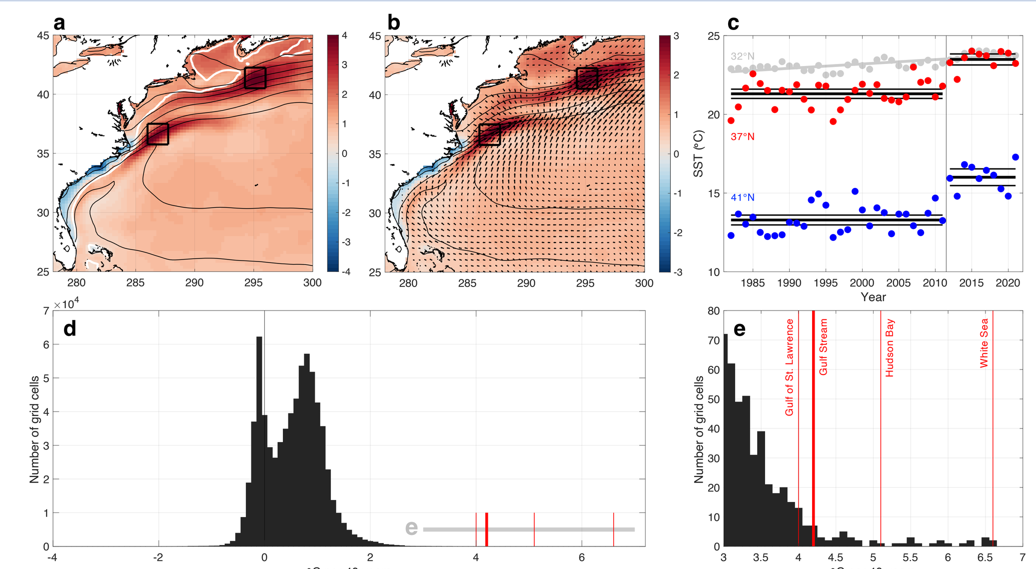
1. Background and Objectives

- The global ocean is absorbing more than 90% of the excess heat accumulating in the climate system due to anthropogenic emissions of greenhouse gases, but the **accumulating heat is not distributed uniformly**.
- The pattern of SST warming is **shaped by the ocean circulation and coupled ocean-atmosphere dynamics**.
- Within the North Atlantic Ocean are broad regions of starkly **contrasting SST trends**.
- SSTs in a 500,000 km^2 area east of New England have warmed by 1.4°C per century since 1870, which is **over 3x the global mean rate** of warming over the same period.
- The objective is to use **observations** to understand the nature of this warming, and to diagnose the role of regional ocean circulation and coupled air-sea interactions.



2. Hotspots in High-Resolution Satellite Observations

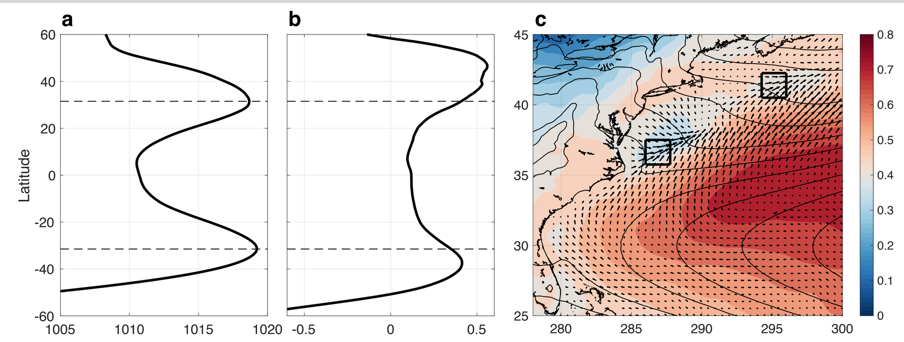
- Two strips, closely following mean SST gradient, warmed by remarkable amount over past 40 years—more than anywhere else in open ocean.
- Most of ~4°C warming in Gulf Stream region since 1982 realized in a stepwise shift in 2012.
- Statistically distinct from center of gyre region.
- Clear response of the wind stress—anticyclone over broader N. Atlantic basin locally accelerated exactly over hotspots, signaling reduced stability in the marine atmospheric boundary layer.



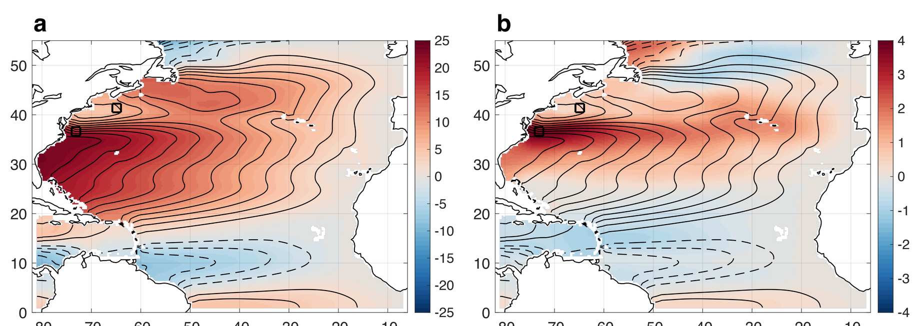
High-resolution satellite observations of the ongoing marine heatwave in the Northwest Atlantic Ocean. **a**, Observed linear trend in sea surface temperature (SST) from 1982–2021 (°C per 40 years, colors), with annual mean SST for context (isotherms contoured every 2°C) and the smoothed 100-m isobath (white contour) to indicate the continental shelf. **b**, Differences in SST (°C, colors) and surface wind stress (arrows), 2012–2021 minus 1982–2011, with annual mean SST. **c**, Time series of annual mean SST averaged within the two boxes marked on **a** and **b**, with the mean and 95% confidence intervals for the two time periods. Also provided in **c** is a time series of annual mean SST in a reference area near the center of the gyre region (30–35°N, 290–295°E) with a linear trend (gray circles and line). **d**, Histogram of global SST trends in 0.1°C bins. **e**, Expanded view of the extreme positive tail of the histogram (range denoted by the gray line in **d**), with red lines marking the peak trends within the four global locations where trends of at least 4°C per 40 years are observed.

3. Basin-Scale Footprint of Expanding Global Tropics

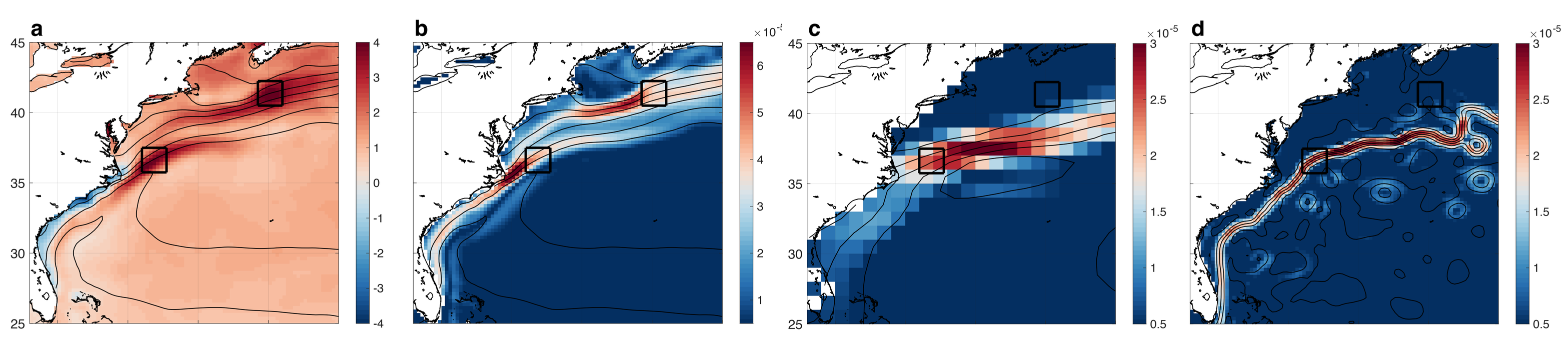
- Global zonal mean SLP maxima trending poleward, associated with the Hadley circulation.
- Accompanying change in meridional structure of zonal wind stress forces changes in subtropical gyre.
- Gyre exhibited poleward shift.
- Strongest streamfunction anomaly near strongest gradients of mean SSH & SST, which, by definition, enables strong local anomalies of either to emerge with even subtle horizontal translations of mean fields.



Footprint of expanding tropics. **a**, Global zonal mean, annual mean SLP (mb) and **b**, diff. in SLP (mb), 2012–2021 minus 1982–2011. Dashed lines denote subtropical maxima in annual mean SLP from **a**. **c**, Diff. in SLP (mb, colors) and wind stress (arrows), 2012–2021 minus 1982–2011, with annual mean SLP (every 0.5 mb).

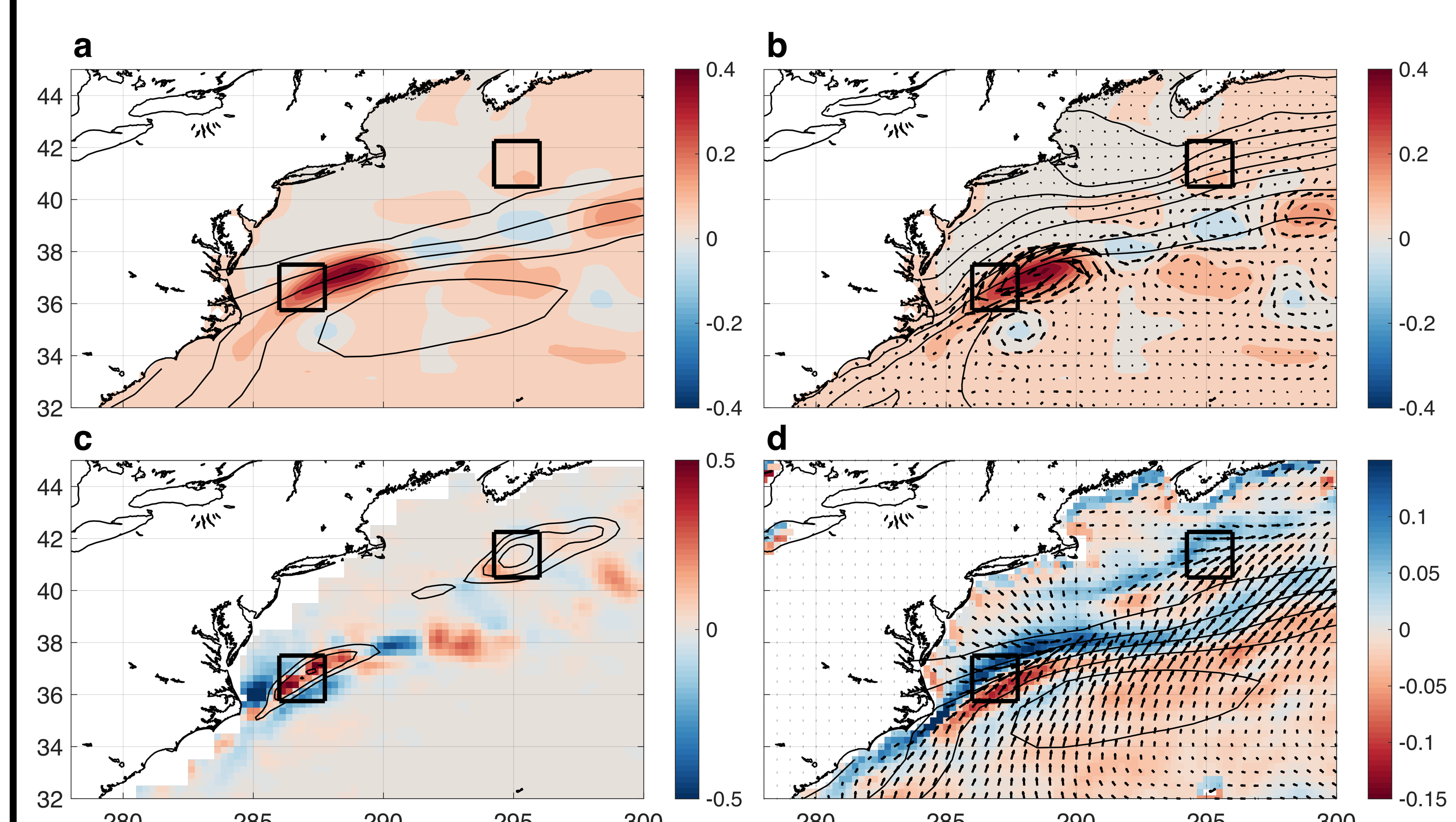


Poleward shifting gyre. **a**, Sverdrup streamfunction calculated from annual mean wind stress, 1982–2021 (10^6 m^3/s, positive clockwise). **b**, Diff. in Sv transport streamfunction (10^6 m^3/s or Sv, colors), 2012–2021 minus 1982–2011, with the field in **a** contoured for context.



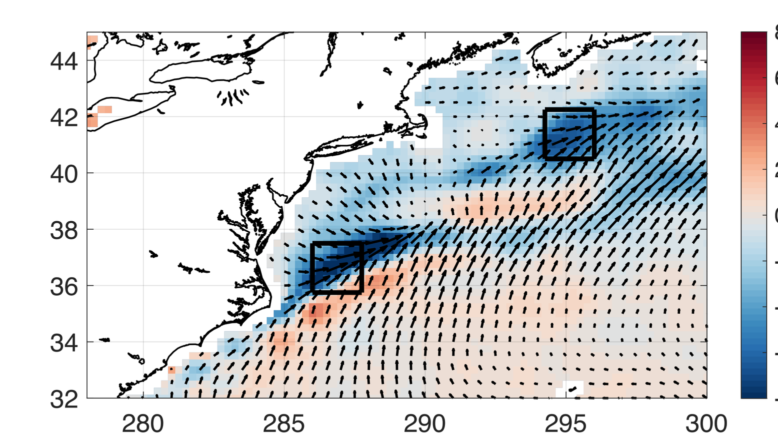
Horizontal SST & SSH gradients. **a**, Reproduction of Fig. 1a. **b**, Horizontal gradient of SST (°C/m) with mean SST (every 2°C). **c**, Horizontal gradient of 1° ADT field (m/m) with mean ADT (every 0.2 m). **d**, Horizontal gradient of 0.25°ADT field (m/m) with mean ADT (every 0.2 m).

4. Regional Coupled Dynamics Sustain SST Anomaly



- Local SSH anomaly (~0.4 m) along mean SSH gradient (gyre edge).
- Clockwise geostrophic current anomalies emerged, with substantial cross-isotherm component that initiates warming through advection.
- Both V' **T** and **V** T' contribute to further spreading SST anomaly.
- Local wind acceleration along major axis of hotspot drives strips of Ekman pumping and suction that amplifies anomalous SSH gradient and geostrophic SST advection (*positive feedback*).

- Wind acceleration also leads to greater net surface heat flux—primarily latent (*negative feedback*).
- Balancing advective and LHF anomalies yields a net warming tendency such that 4 months is required to reach the observed warming.

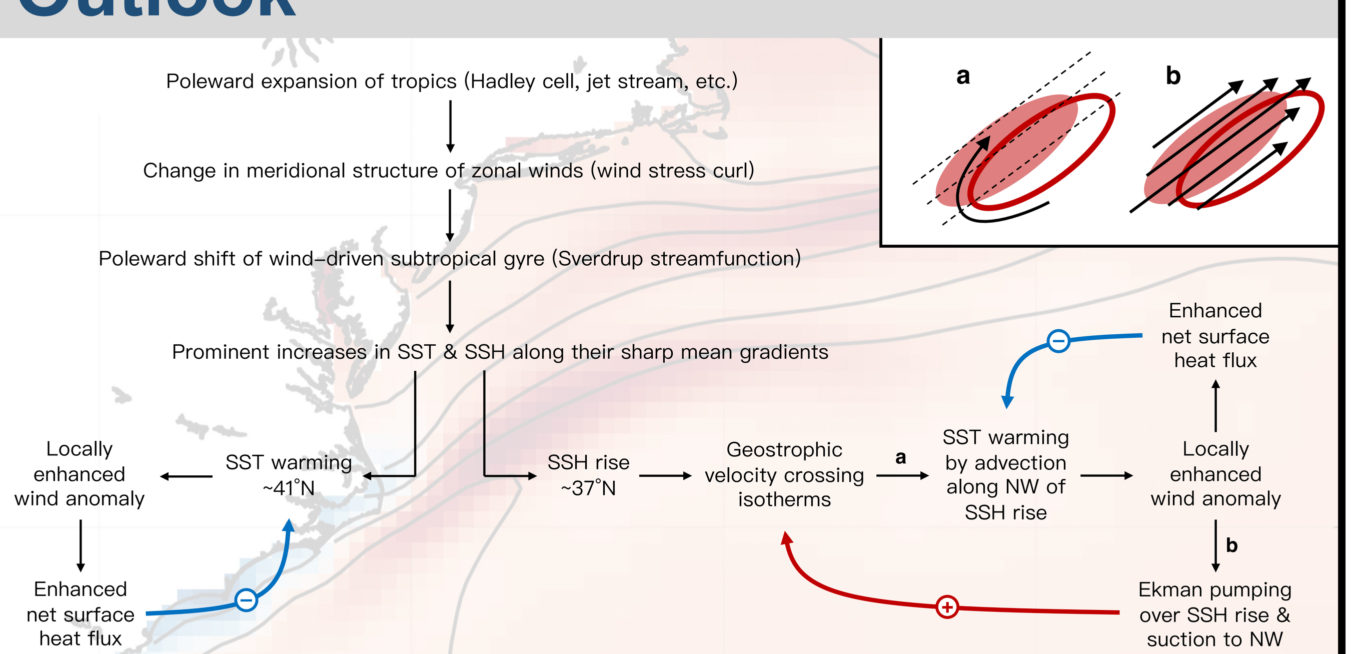


Coupled feedback sustaining marine heatwave. **a**, SSH diff. (m, colors), 2012–2020 minus 1993–2011, with annual mean ADT for context (contoured every 0.2 m). **b**, Diff. in SSH (m, colors) and surface geostrophic velocity (arrows), with annual mean SST for context (isotherms contoured every 2°C). **c**, Diff. in horizontal temperature advection due to the changes in geostrophic velocity and SST (°C/day), with the SST difference for context (contoured every 0.5°C, starting at ± 1.5°C). **d**, Diff. in Ekman pumping velocity (m/day, colors) and surface wind stress (arrows), with annual mean ADT.

Negative feedback by net surface heat flux. Diff. in net surface heat flux (W m^{-2}, colors) and surface wind stress (arrows), 2012–2021 minus 1982–2011. Negative. net surface heat flux indicates heat loss by the ocean.

5. Summary and Outlook

- In 2012, the Gulf Stream ~130 km off the U.S. Mid-Atlantic coast warmed by nearly 3°C, in excellent agreement with high-resolution global climate model simulations subject to a doubling of atmospheric carbon dioxide.
- Concurrent sea level and wind observations reveal a positive feedback mechanism whereby the induced changes in ocean currents advect warm SSTs, inducing a surface wind acceleration that maintains the initially amplified sea level gradient.
- Is this phenomenon merely a decadal marine heatwave that will retreat to the (smaller) background SST trend, or a robust feature of the ocean's response to climate change that we may expect to continue or even intensify in coming decades?



6. Datasets and References

- **Sea surface temperature**: NOAA OIv2 (Reynolds *et al.* 2002) and HadISST1 (Rayner *et al.* 2003)
  Reynolds, R. W., Rayner, N. A., Smith, T. M., Stokes, D. C., & Wang, W. (2002). An Improved In Situ and Satellite SST Analysis for Climate. *Journal of Climate*, *15*(13), 1609–1625.
  Rayner, N. A. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research*, *108*(D14), 4407.
- **Wind stress, sea level pressure**, and **surface heat flux**: ERA5 (Hersbach *et al.* 2020)
  Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049.
- **Ocean mixed layer depth**: GLORYS 12v1 (Lellouche *et al.* 2018)
  Lellouche, J.-M., Greiner, E., Le Galloudec, O., Garric, G., Regnier, C., Drevillon, M., et al. (2018). Recent updates to the Copernicus Marine Service global ocean monitoring and forecasting real-time 1/12° high-resolution system. *Ocean Science*, *14*(5), 1093–1126.
- **Sea surface height anomaly**: CMEMS (CMEMS 2022)
  European Union-Copernicus Marine Service. (2021). GLOBAL OCEAN GRIDDED L4 SEA SURFACE HEIGHTS AND DERIVED VARIABLES REPROCESSED (1993-ONGOING) [Data set]. Mercator Ocean International.
- **Absolute dynamic topography**: AVISO L4 (NASA 2011)
  AVISO. (2011). AVISO Level 4 Absolute Dynamic Topography for Climate Model Comparison [Data set]. NASA Physical Oceanography DAAC.
- **Bathymetry**: ETOPO1 (Amante and Eakins, 2009)
  Amante, C. (2009). ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis [Data set]. National Geophysical Data Center, NOAA.