Atlantic meridional overturning circulation increases flood risk along the United States southeast coast

D.L. Volkov[1,2] , K. Zhang[3], W.E. Johns[4], J. Willis[5], W. Hobbs[6,7], M. Goes[1,2], H. Zhang[5], D. Menemenlis[5]

[1]Cooperative Institute for Marine and Atmospheric Studies, University of Miami; [2]NOAA Atlantic Oceanographic and Meteorological Laboratory; [3]University of California Los Angeles, [4]Rosenstiel School of Marine, Atmospheric, and Earth Sciences, University of Miami; [5]Jet propulsion Laboratory, California Institute of Technology; [6]Australian Research Council Centre of Excellence for Climate Extremes; [7]Australian Antarctic Program Partnership, Institute for Marine and Antarctic Studies, University of Tasmania

Overview

The system of oceanic flows constituting the Atlantic Meridional Overturning Circulation (AMOC) moves heat and other properties to the subpolar North Atlantic, controlling regional climate, weather, sea levels, and ecosystems. Climate models suggest a potential AMOC slowdown towards the end of this century due to anthropogenic forcing, accelerating coastal sea level rise along the western boundary and dramatically increasing flood risk. While direct observations of the AMOC are still too short to infer long-term trends, we show here that the AMOC-induced changes in gyre-scale heat content, superimposed on the global mean sea level (GMSL) rise, are already influencing the frequency of floods along the United States southeastern seaboard. The leading mode of the interannual dynamic sea surface height (SSH) and ocean heat content (OHC) variability in the North Atlantic exhibits a tripole pattern (known as the North Atlantic SSH tripole), with the subpolar gyre varying out-of-phase with both the subpolar gyre and the tropics (Fig. 1). To establish a robust dynamic relationship between the tripole and AMOC, we employed the Estimating the Circulation and Climate of the Ocean Version 4 Release 4 (ECCO) model, which realistically reproduces the observed meridional heat transports in the subtropical gyre (Fig. 2 a,b). We find that oceanic heat convergence, being the primary driver for interannual SSH variability in the subtropical North Atlantic (Fig. 2 c,d), has led to an accelerated gyre-scale warming and associated dynamic sea level rise since 2010, accounting for 30-50% of flood days in 2015-2020 (Figs. 3-5).

1. North Atlantic SSH Tripole

The tripole is defined as the leading Empirical Orthogonal Function (EOF1) of the low-pass filtered dynamic SSH with a cutoff period of 1.5 years. The first Principal Component (PC1; tripole index) depicts the time evolution of the tripole, characterized by an overall SSH decrease in the subtropical gyre in 1993–2010 and a rapid SSH rise in 2010–2015.

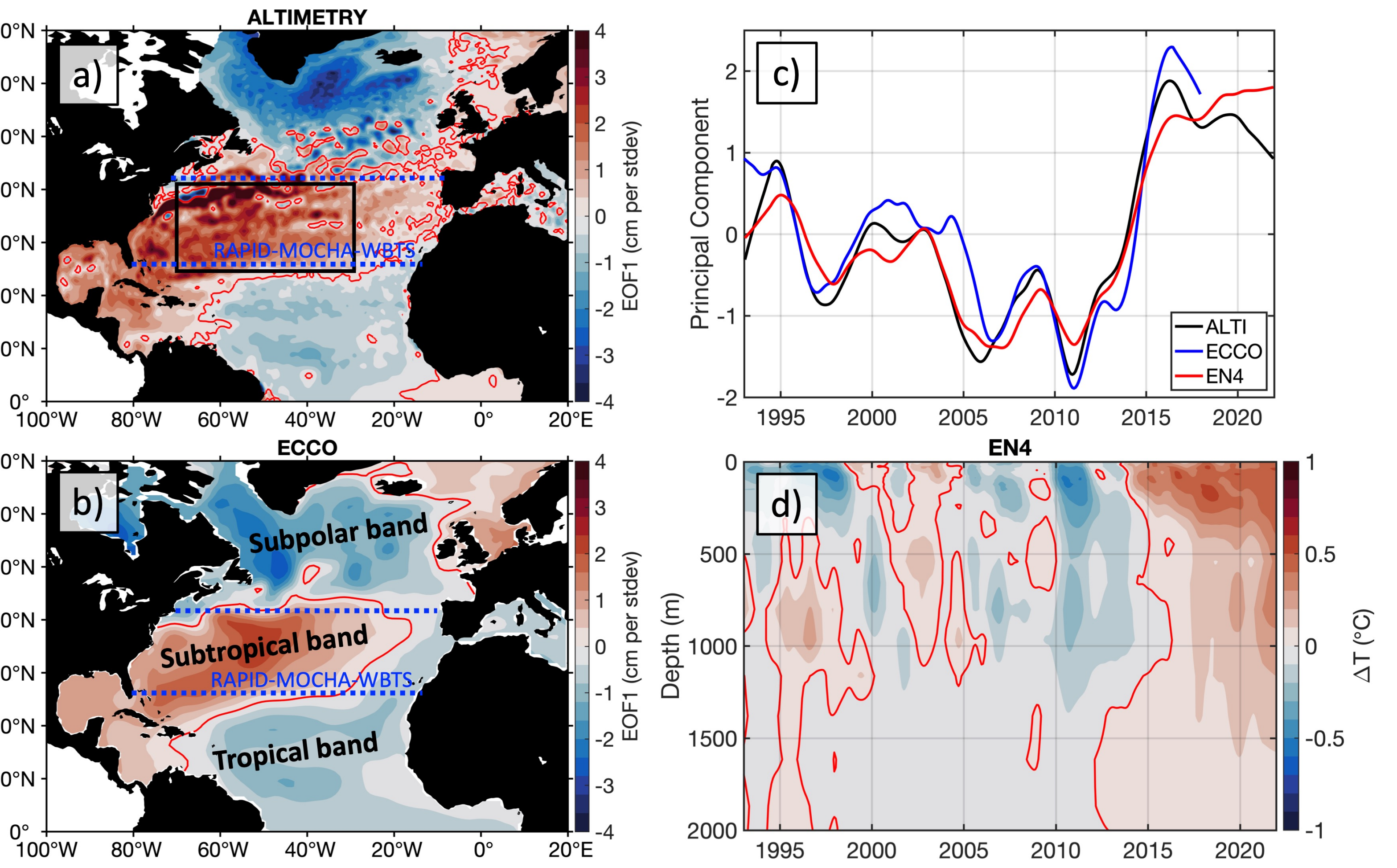
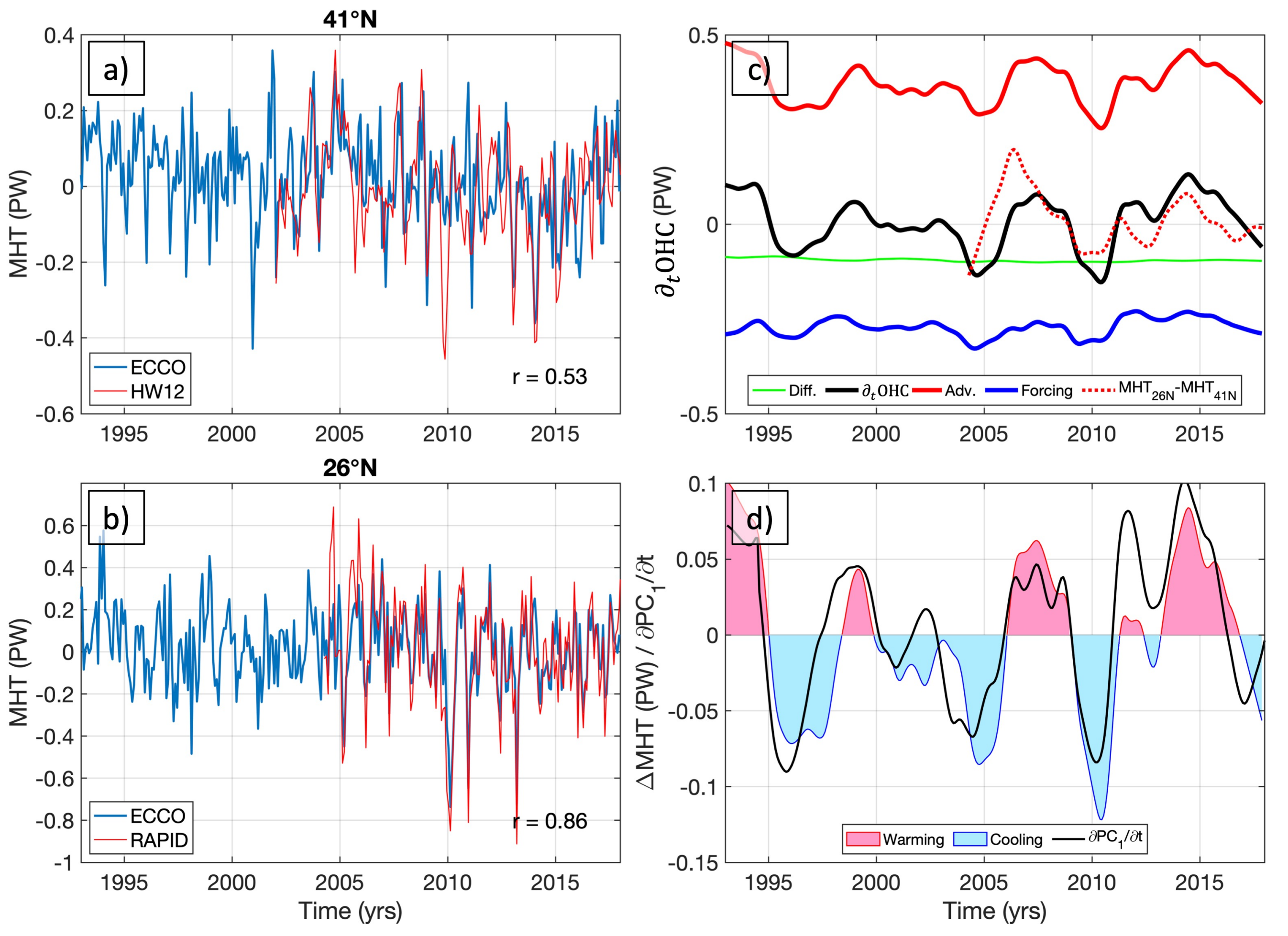


Fig. 1: The North Atlantic Sea Surface Height (SSH) tripole.
The spatial patterns of EOF1 of the low-pass filtered SSH anomalies in (**a**) satellite altimetry data and (**b**) in the ECCO model; (**c**) the temporal evolutions of EOF1 patterns (PC1) for satellite altimetry SSH anomalies (black), for SSH anomalies in the ECCO model (blue), and for thermosteric SSH anomalies in EN4 data (red). (**d**) The time-depth diagram of the upper 2000-m potential temperature averaged over the area 30°W–70°W and 25°N–40°N outlined by the black rectangle in panel (a). The blue dashed lines in (**a**), (**b**) show the 26.5°N (RAPID-MOCHA-WBTS) and 41°N transects, across which the observational estimates of the meridional heat transports are available.

2. Relationship with the AMOC

The full-depth, basin-wide oceanic heat budget is assessed using the ECCO model between the latitudes of 26°N and 41°N, where observational estimates of the AMOC at 26°N (RAPID array) and at 41°N (combination of satellite altimetry and Argo measurements) are available. The ECCO meridional heat transport (MHT) variability at these latitudes agrees well with observational estimates. Results demonstrate that the interannual variability of OHC in the subtropical band of the tripole is primarily driven by the MHT divergence/convergence, while the contribution of the net surface heat flux is of secondary importance.

Fig. 2: Oceanic heat budget in the subtropical North Atlantic.



(**a**) The time series of the MHT anomalies relative to the common time intervals at 41°N (black) in the ECCO model and (red) from Hobbs and Willis, 2012; (**b**) the time series of the MHT (black) in the ECCO model at 26°N and (red) from RAPID observations at about 26°N (Johns et al., 2023); (c) the full-depth ocean heat budget between 26°N and 41°N: (black) the time-change in OHC, (red) heat advection, (blue) the volume-weighted averaged forcing term that includes surface forcing, penetrated shortwave radiation, and geothermal forcing, (dotted black) the diffusion term; the dotted red curve shows the MHT divergence anomaly from observations (difference between the MHT anomalies at 26.5°N and at 41°N); (**d**) the OHC convergence between 26°N and 41°N in the ECCO model (red and blue shading indicating warming and cooling between the two latitudes, respectively) and the time-derivative of the PC1 of the low-pass filtered SSH from satellite altimetry (∂PC1/∂t; black curve).

3. Relationship with Coastal Sea Level

The North Atlantic SSH tripole exerts its influence on sea level along the U.S. southeast and Gulf of Mexico coasts. The amplitudes of the tripole-related coastal sea level changes, obtained by regressing tide gauge records on the PC1 of the altimetric SSH (tripole index), exceed 10 cm at the tide gauges located to the south of Cape Hatteras and in the Gulf of Mexico (Fig. 3a). These relatively large amplitudes are comparable to the absolute GMSL rise since 1993 (see insert in Fig. 3a). Due to the GMSL rise, the mean values of the probability density functions of sea level have been shifting towards higher water levels, thus increasing the probability of water levels breaking the minor flood thresholds (Fig. 3b).

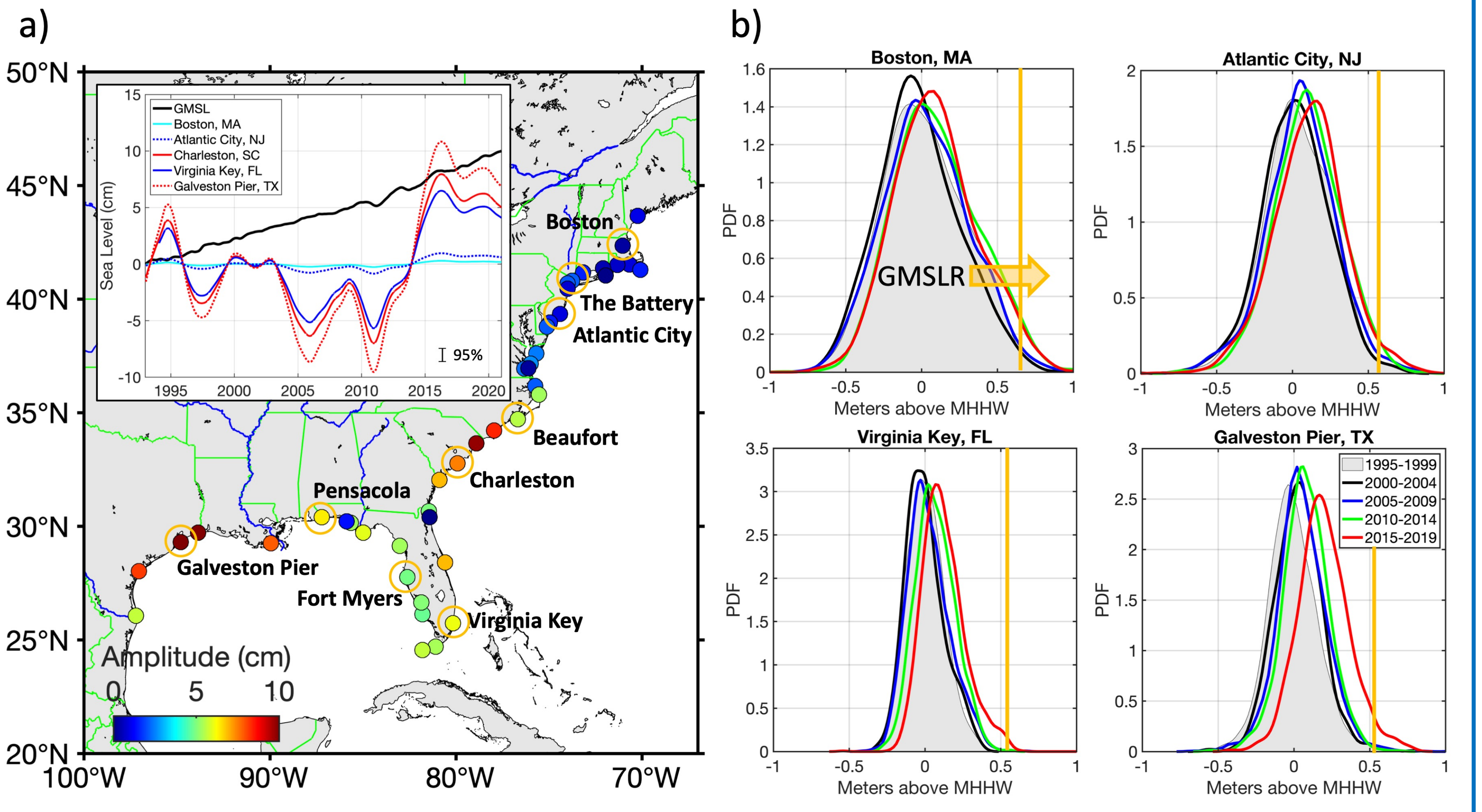


Fig. 3: The North Atlantic Sea Surface Height (SSH) tripole and coastal sea level.
(**a**) The locations of tide gauges and the amplitude of the tripole-related SSH changes at these tide gauges (colored circles). An insert shows (black) the Global Mean Sea Level (GMSL) change and (other color curves) the tripole-related SSH time series at several tide gauges. The vertical error bar in the insert shows the 95% confidence interval for regression. (**b**) Probability density functions (PDF) for daily highest water levels relative to 1983–2001 mean higher high water (MHHW) tidal datum at Boston (MA), Atlantic City (NJ), Virginia Key (FL), and Galveston Pier (TX) tide gauges over the following time intervals: (gray shading) 1995-1999, (black) 2000–2004, (blue) 2005-2009, (purple) 2010–2014, (red) 2015–2019. The vertical orange lines indicate the NOAA minor flood thresholds published in a NOAA Technical Report (Sweet et al., 2022). The orange arrow points in the direction of the shift of probability density functions due to the GMSL rise (GMSLR).

4. Coastal flood risk

The annual expected exceedances for daily highest water levels in 2015–2019 at several tide gauges along the U.S. east and Gulf coasts show the impact of vertical land motions, the GMSL rise, and the tripole on the frequency of floods (Fig. 4). A flood day occurs when the water level exceeds the minor flood threshold (vertical orange lines in Fig. 4) for at least an hour. The removal of the tripole-related changes from tide gauge records to the south of Cape Hatteras would reduce the annual number of flood days in 2015–2019 by 30–50% (compare black and red curves in the middle and lower panels of Fig. 4; Fig. 5).

Fig. 4: Annual expected exceedances for daily highest water levels in 2015–2019 relative to 1983–2001 mean higher high water (MHHW) tidal datum at several tide gauges along the U.S. East and the Gulf of Mexico coasts.
(Black) Expected exceedances for the actual (Observed) sea level records, (red) for the records with the tripole-related sea level subtracted (No Tripole), (blue) for the records with the Global Mean Sea Level subtracted (No GMSL), and (dotted magenta) for the records corrected for vertical land motion (No VLM). The vertical orange lines indicate the NOAA Minor flood thresholds. The annual expected exceedances are shown for tide gauges highlighted by circles in Fig. 3a.

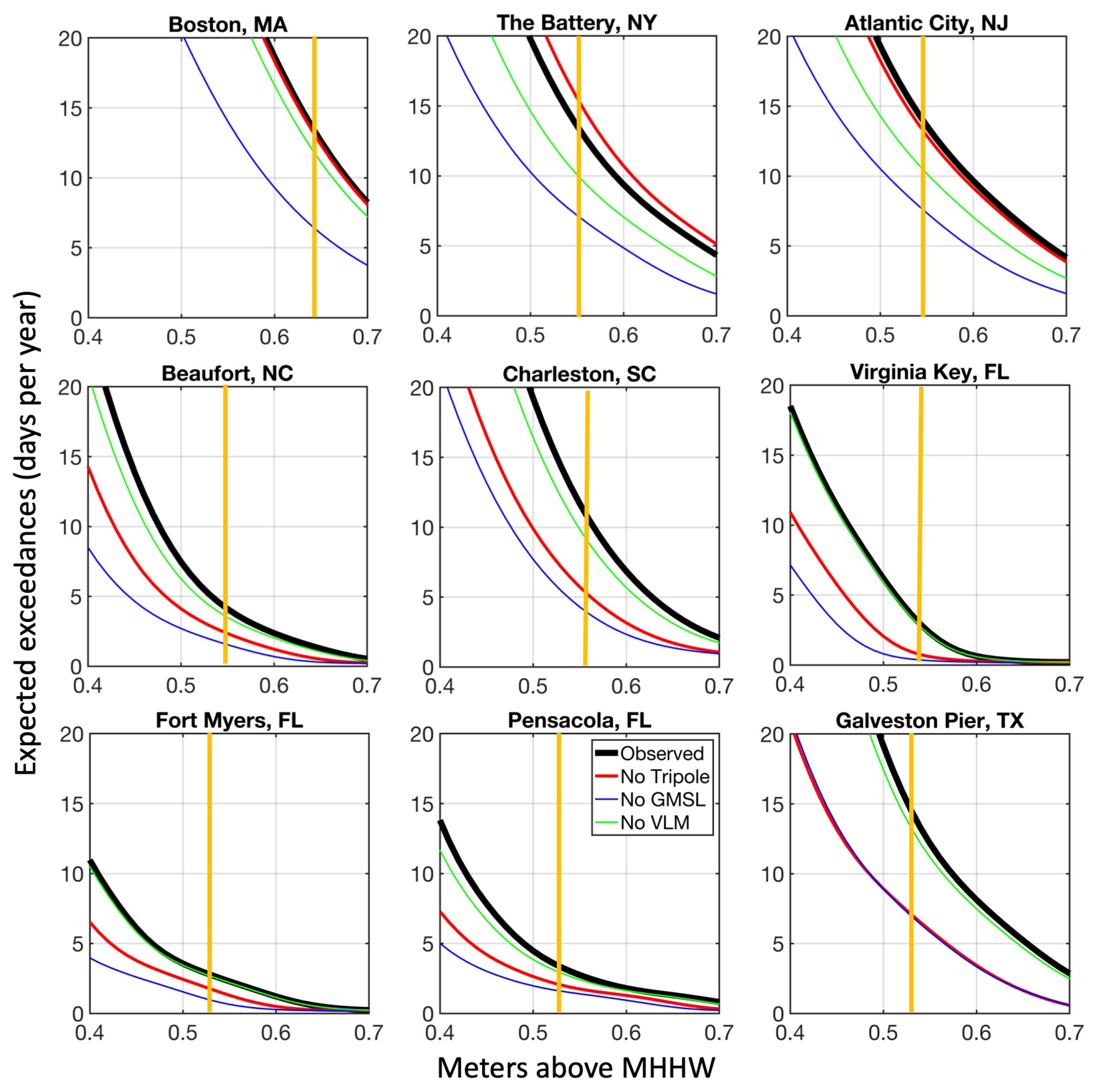
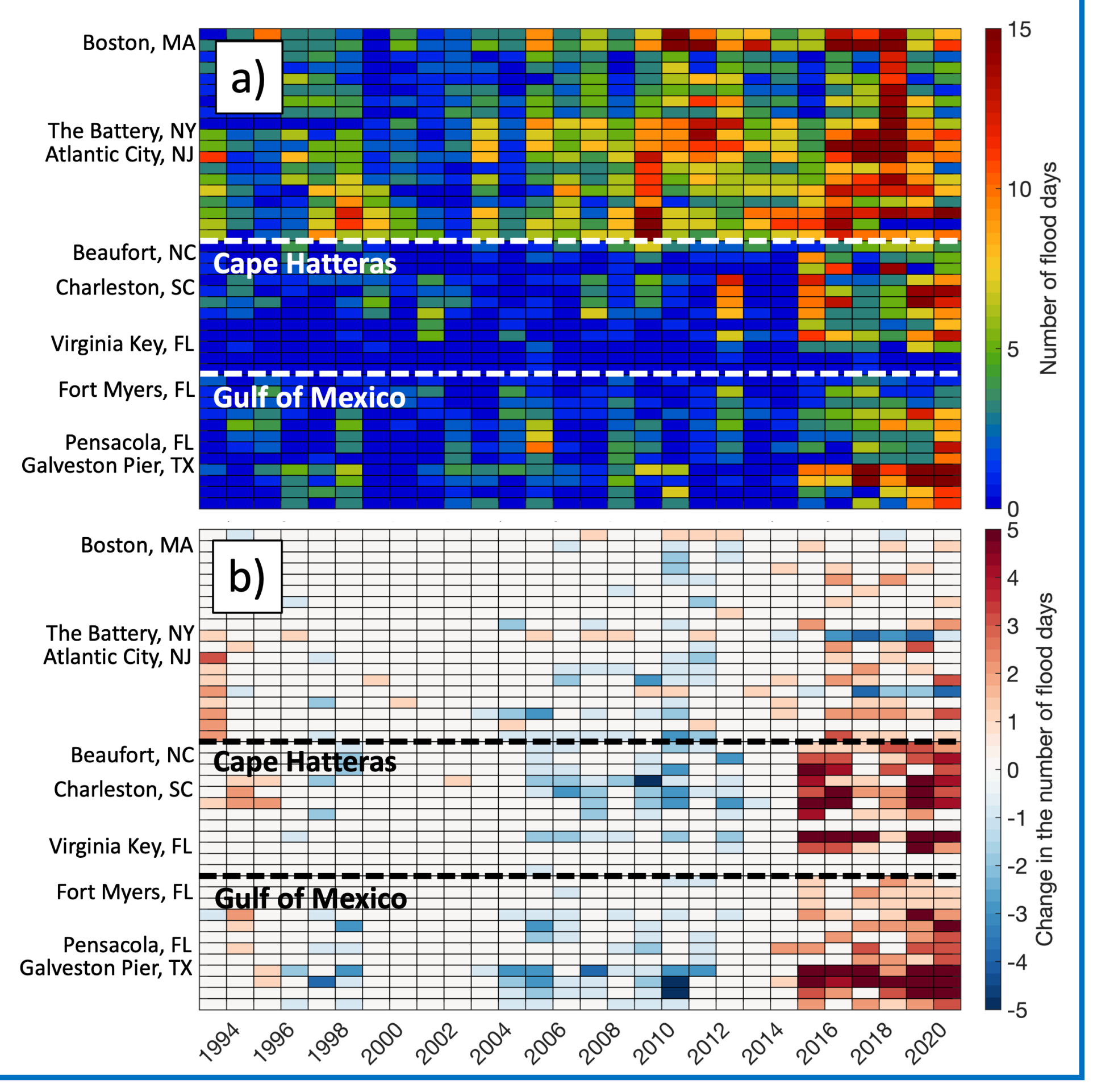


Fig. 5: Impact of the North Atlantic SSH tripole on coastal-flood risk.
(**a**) The number of flood days per year between 1993 and 2020 at each tide gauge used in this study (indicated on the vertical axis). A flood day is defined as the day when the water level exceeds the Minor flood threshold for 1 h or more. (**b**) The difference between the actual number of flood days and the number of flood days after subtracting the tripole-related sea level from tide gauge records. The positive/negative values indicate years and tide gauges, when and where the North Atlantic SSH tripole was increasing/decreasing the frequency of floods. The horizontal dashed lines show the approximate locations of Cape Hatteras and the boundary between the U.S. Atlantic and Gulf coasts.



5. Conclusions

- The impact of the North Atlantic SSH tripole on coastal-flood risk along the U.S. southeast and Gulf coasts since 2015 is comparable to the impact of the GMSL rise since 1993.
- If the tripole variability were absent, the frequency of floods in the region since 2015 would be 30–50% less than present.
- The role of tripole-related changes has increased over time as the GMSL is steadily rising.

References

Johns, W.E., et al. (2023). Towards two decades of Atlantic Ocean mass and heat transports at 26.5N, Philos. Trans. R. Soc. A., 381:20220188, https://doi.org/10.1098/rsta.2022.0188.
Hobbs, W. R. & Willis, J. K. (2012). Midlatitude North Atlantic heat transport: a time series based on satellite and drifter data. J. Geophys. Res. 117, C01008.
Sweet, W. V. et al.(2022). NOAA Technical Report., https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html.

Acknowledgements

This research was carried out in part under the auspices of the Cooperative Institute for Marine and Atmospheric Studies, a cooperative institute of the University of Miami and NOAA (NA20OAR4320472), and at the Jet Propulsion Laboratory, California Institute of Technology under a contract from NASA. D.L.V., K.Z., and M.G. were supported by the NOAA Climate Variability and Predictability program (grant number NA20OAR4310407) and by the NOAA Atlantic Oceanographic and Meteorological Laboratory. H.Z. and D.M. were supported by NASA Modeling, Analysis, and Prediction and Physical Oceanography programs.