Coupled Salinity–Temperature Extremes and Upper Ocean Stratification During Marine Heatwaves in the Northwest Atlantic

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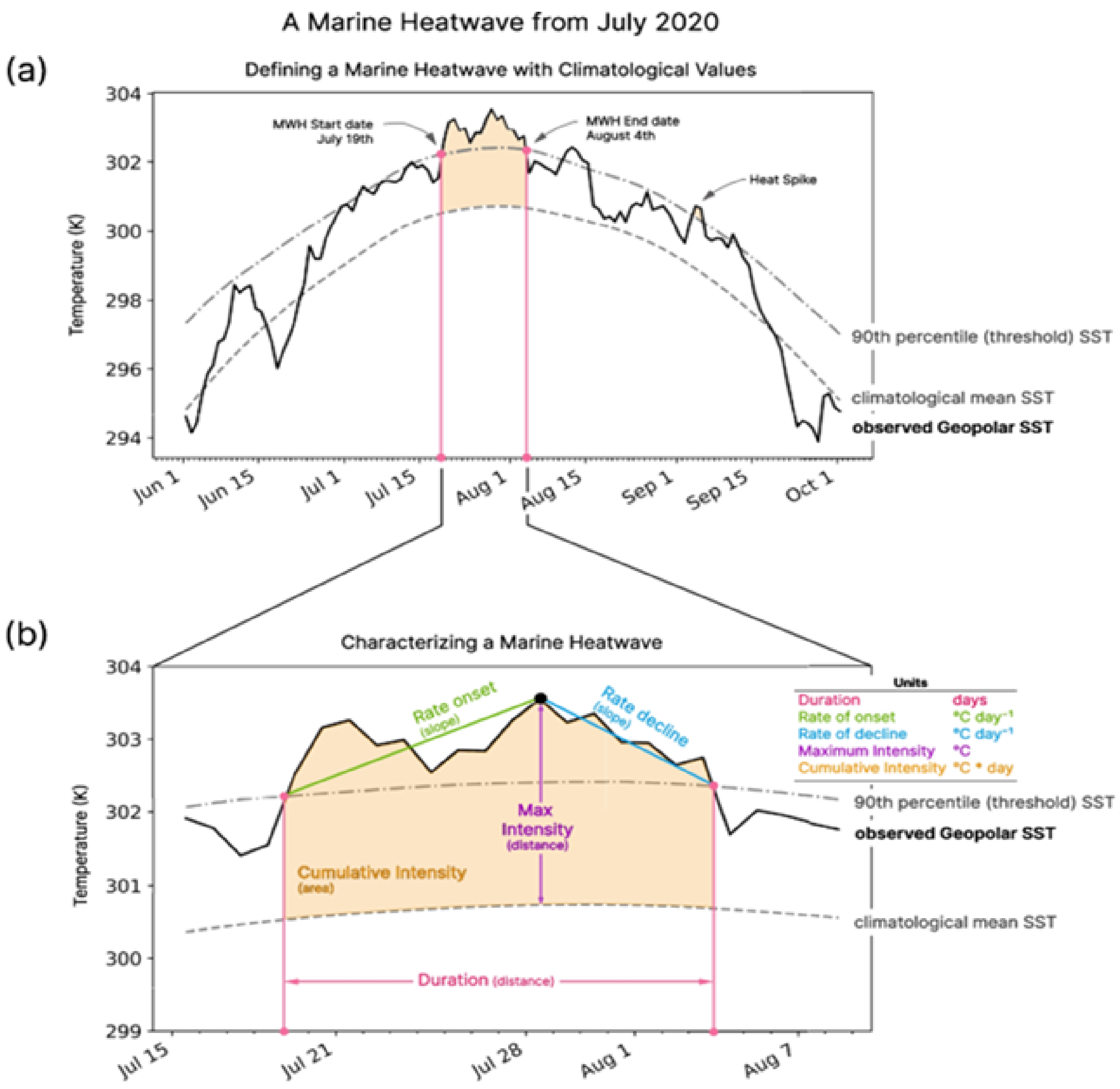
Background – Marine Heatwaves

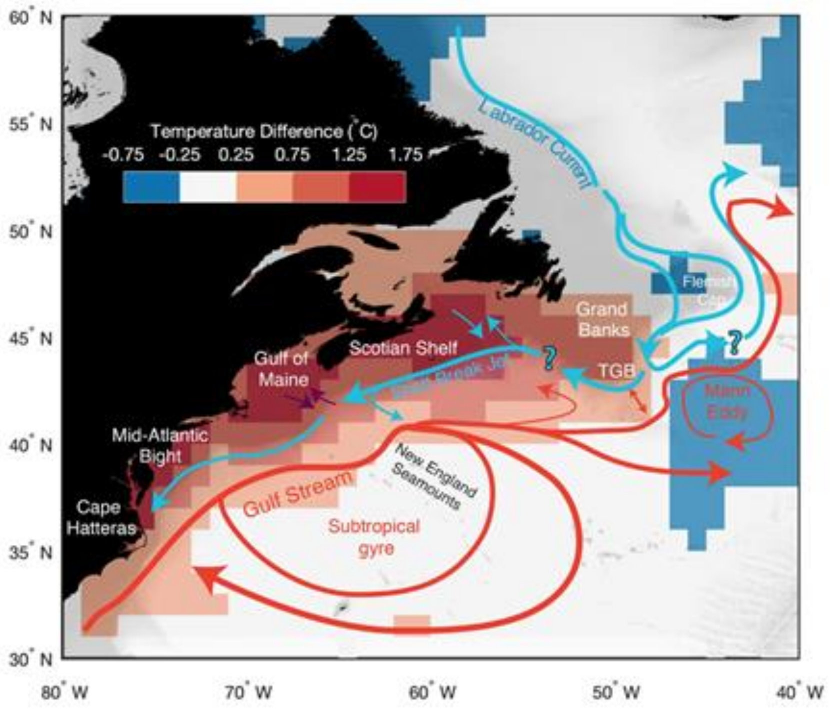
- **SST exceeds 90th-percentile climatology** (mean baseline of 30+ years) for a minimum of **5 days** (*Hobday et. al, 2016*).
- Common MHW metrics:
  - Frequency
  - Maximum intensity
  - Surface coverage
- **Extreme salinity events** follow the same methodology.
  - High-SSS extreme: SSS exceeds 90th-percentile
  - Low-SSS extreme: SSS falls below the 10th percentile



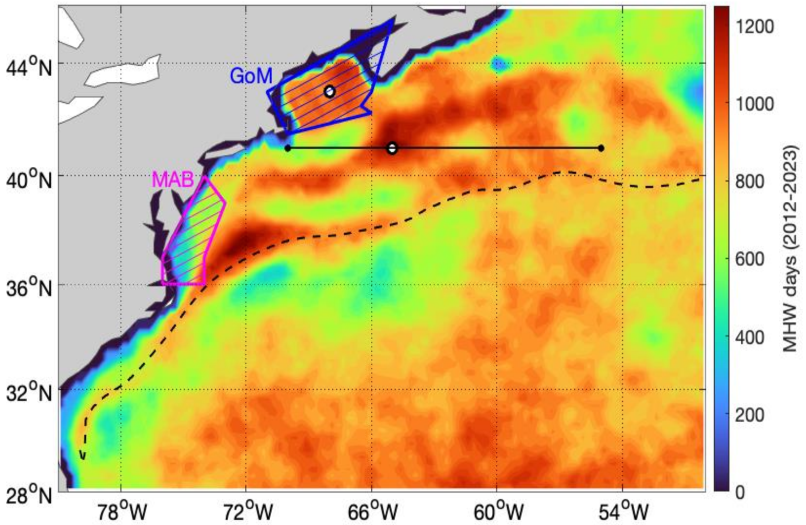
[Wegener et al. 2025]

Background – Northwest Atlantic

- The NW Atlantic is among the fastest-warming ocean regions.
- Two highly vulnerable shelf subregions: Gulf of Maine and Mid-Atlantic Bight.
- MHWs are rising in frequency and intensity.
- Regional dynamics are strongly driven by the Gulf Stream (GS).
- GS brings unusually warm, salty water onto the shelf, boosting MHW likelihood.
- Recent increase in anticyclonic eddy shedding, with AEs moving north of the GS toward the NW Atlantic coast.



[Gonclaves Neto et al. 2021]



Total MHW days for the analysis period of 2012–2023

Motivation

- MHWs are becoming more frequent and intense globally, with disproportionate impacts in dynamic regions like the Gulf Stream—**yet key drivers of their variability remain insufficiently understood.**

- Most studies focus on temperature alone, **overlooking salinity as a co-evolving and potentially controlling factor** in upper-ocean stratification and heat retention.

- The NW Atlantic is a hotspot where mesoscale processes (e.g., eddies, warm-core and cool-core rings) strongly modulate ocean structure, **demanding a coupled temperature–salinity perspective**.

- Understanding **how salinity-driven stratification enhances or suppresses vertical mixing** is critical to explaining why some MHWs persist near the surface while others extend deeper.

- **Adding salinity to the Marine Heat Wave toolbox** alongside temperature to better capture how marine heatwaves form, evolve, and persist.

- We examine **temperature–salinity co-evolution** during MHWs in the NW Atlantic using satellite observations and ocean reanalysis for the period 2012–2023.

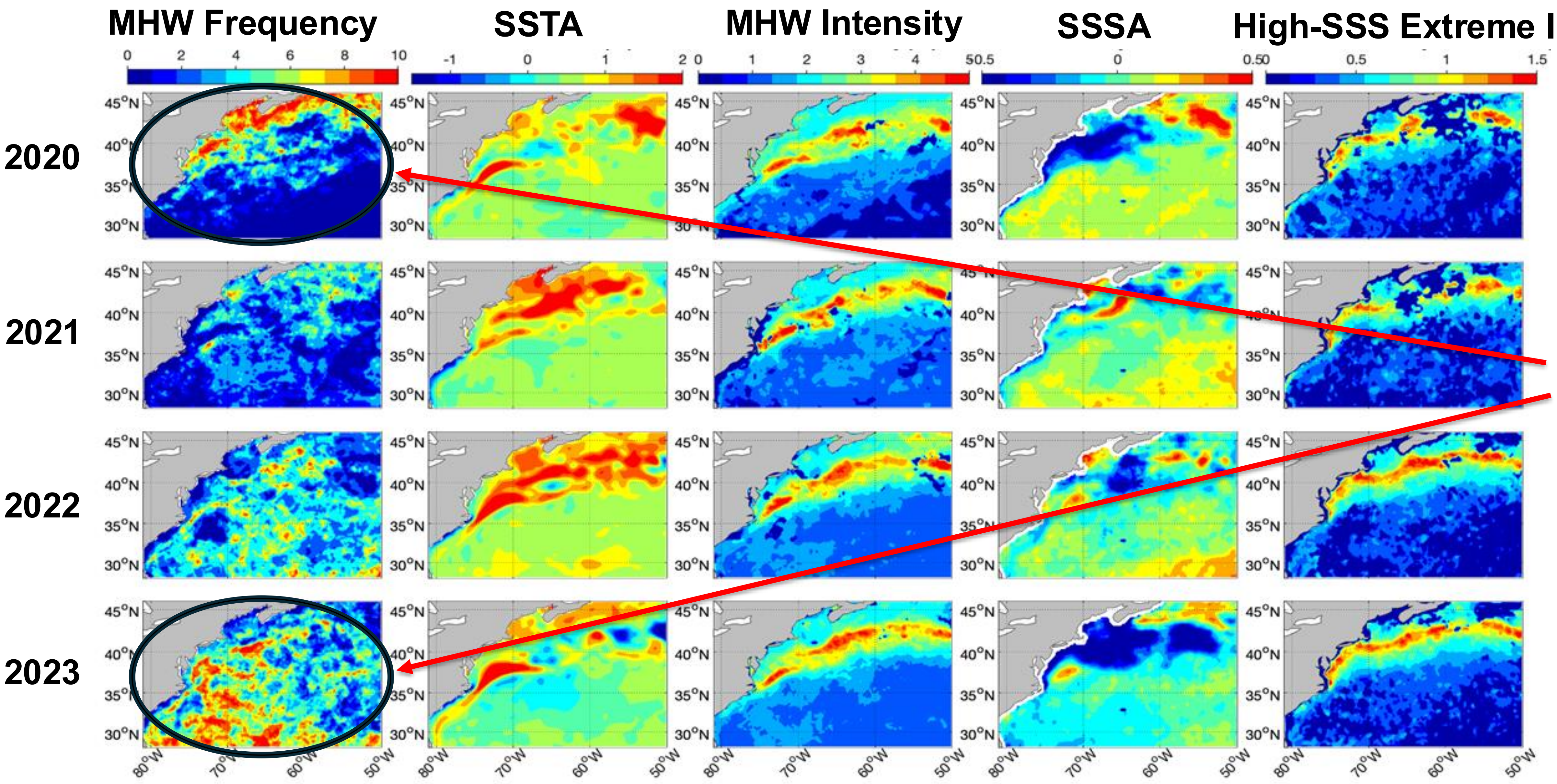
Why is Sea Surface Salinity important for MHW studies?

- Surface freshening **strengthens near-surface stratification** and can **reduce vertical mixing**, **limit entrainment of cooler subsurface water** and favor surface-intensified and persistent MHW.

- In contrast, **high-salinity conditions** linked to GS-influenced waters may result in warm, saline, denser water masses with **deeper mixed layers** that promote surface and subsurface-intensified MHW.

- These two mechanisms can therefore produce contrasting extreme salinity-MHW relationships:
  - ➢ Low SSS on the continental shelf waters can support surface-trapped warming through increased stratification.
  - ➢ High SSS due to advection of GS and/or warm-core ring warm and saline waters can support both surface and subsurface warming due to reduced stratification.

Distribution of T–S Extremes



MHW toolbox output using OISST and SMOS/SMAP SSS:

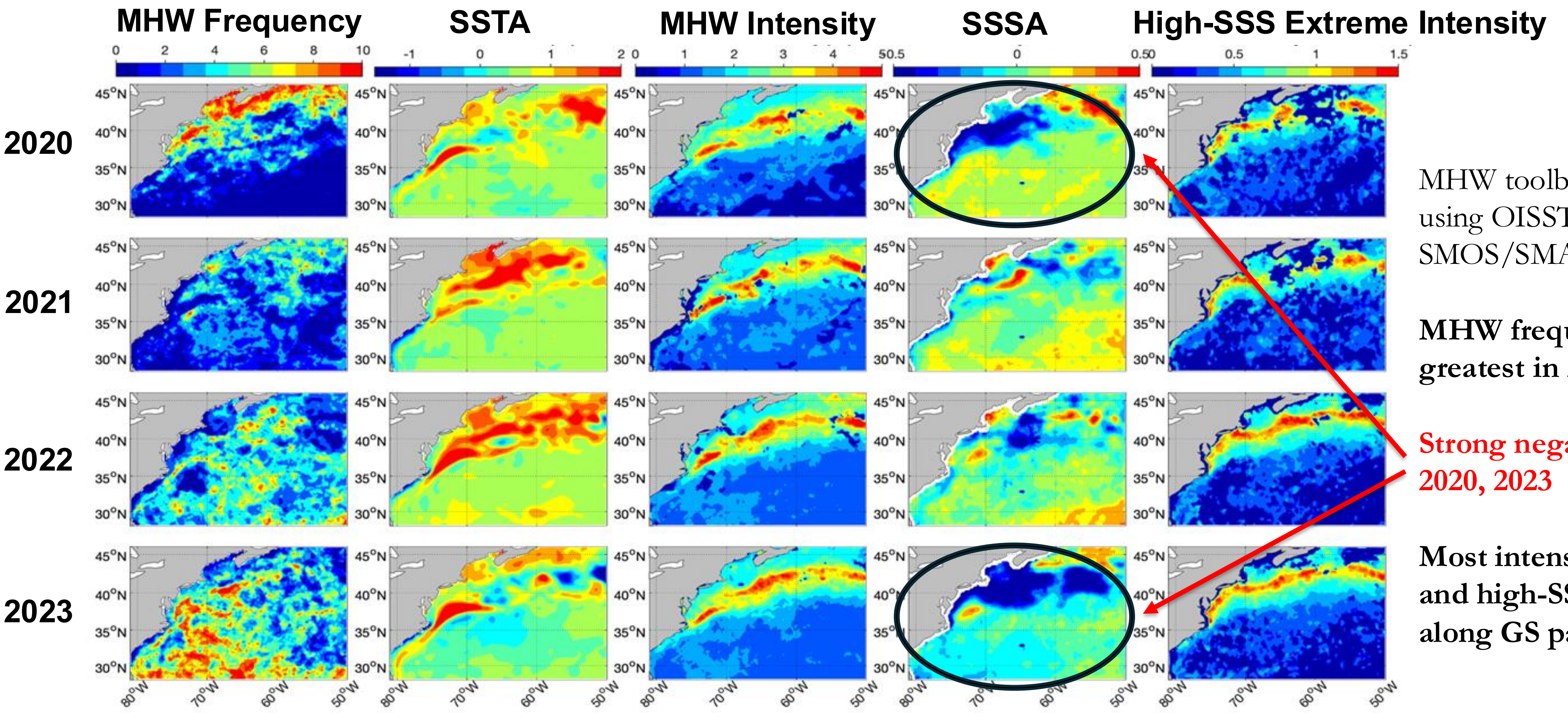
MHW frequency greatest in 2020, 2023

Strong negative SSSA in 2020, 2023

Most intense MHWs and high-SSS extremes along GS path

Map showing the annual number of discrete MHW events, mean SST anomalies, mean MHW intensity, mean SSS anomalies, and mean extreme salinity event intensity.

Distribution of T–S Extremes



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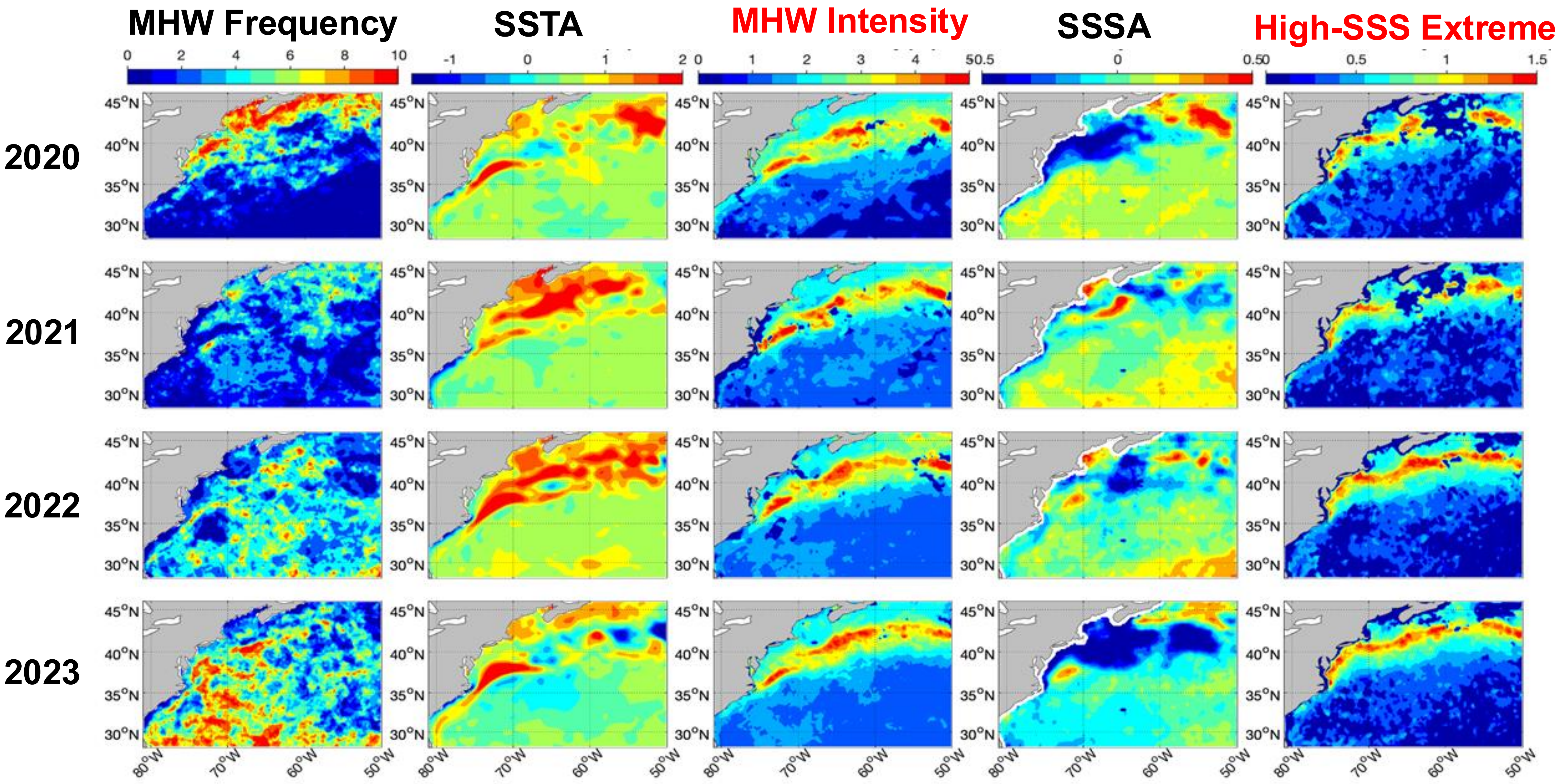

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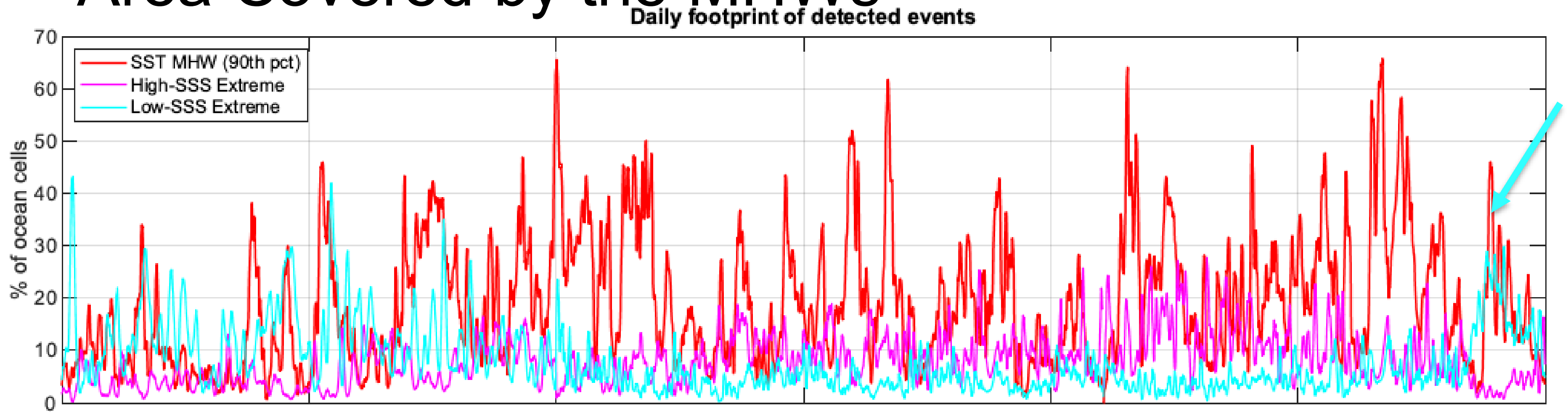
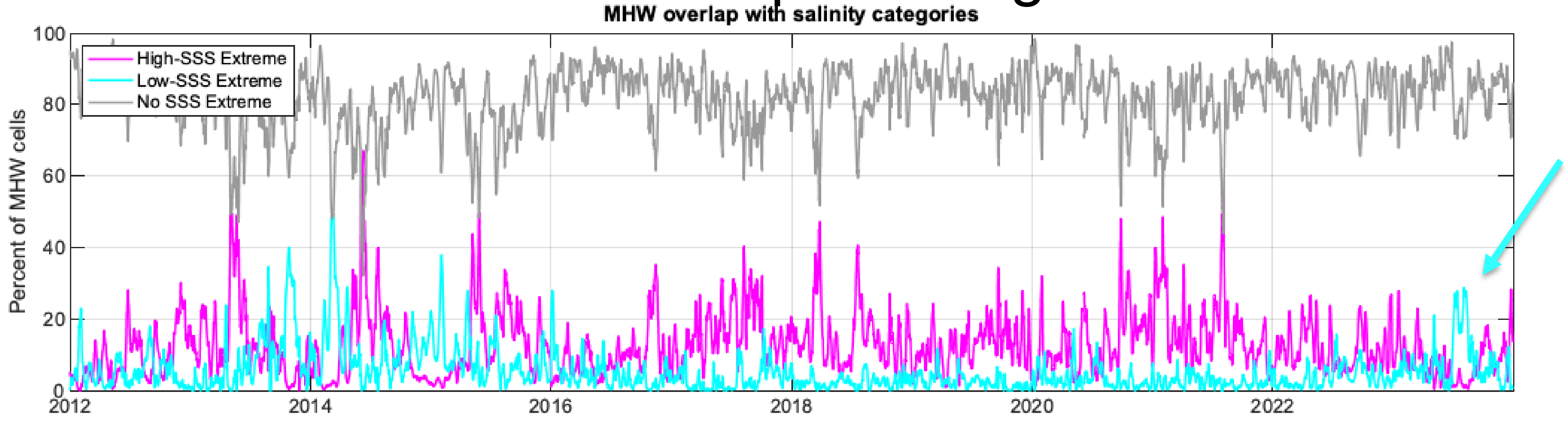
How often do MHWs overlap with Salinity Extremes?

Area Covered by the MHWs



Large **spike in low-SSS extreme** coverage in summer 2023.

MHW Grid Cells Overlap with High/Low SSS Extreams

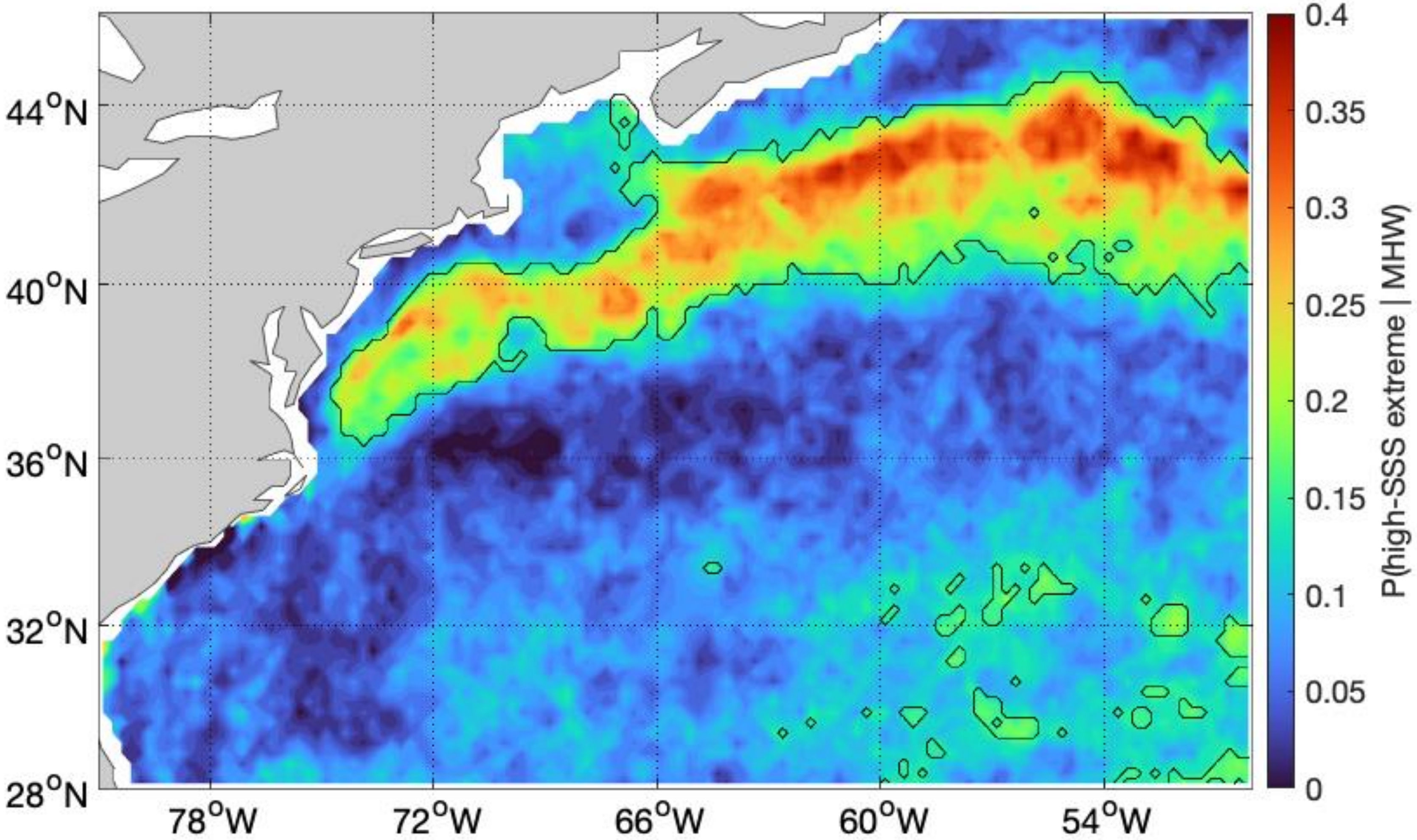


Increase in MHW – low SSS extreme overlap in summer 2023. About **~30% of MHWs overlapped with low-SSS extremes**.

Suggests that low SSS contributed to active MHW year, in addition to low winds.

(Top) Percent area of the domain covered by marine heatwaves (MHW; red), marine cold spells (MCS; cyan), high-salinity extremes (magenta; >90th percentile), and low-salinity extremes (cyan; <10th percentile) during 2012-2023. (Bottom) Percent of MHW cells overlapping with high-salinity extremes (magenta), low-salinity extremes (cyan), and no salinity extreme (grey).

High-SSS Imprint During MHWs

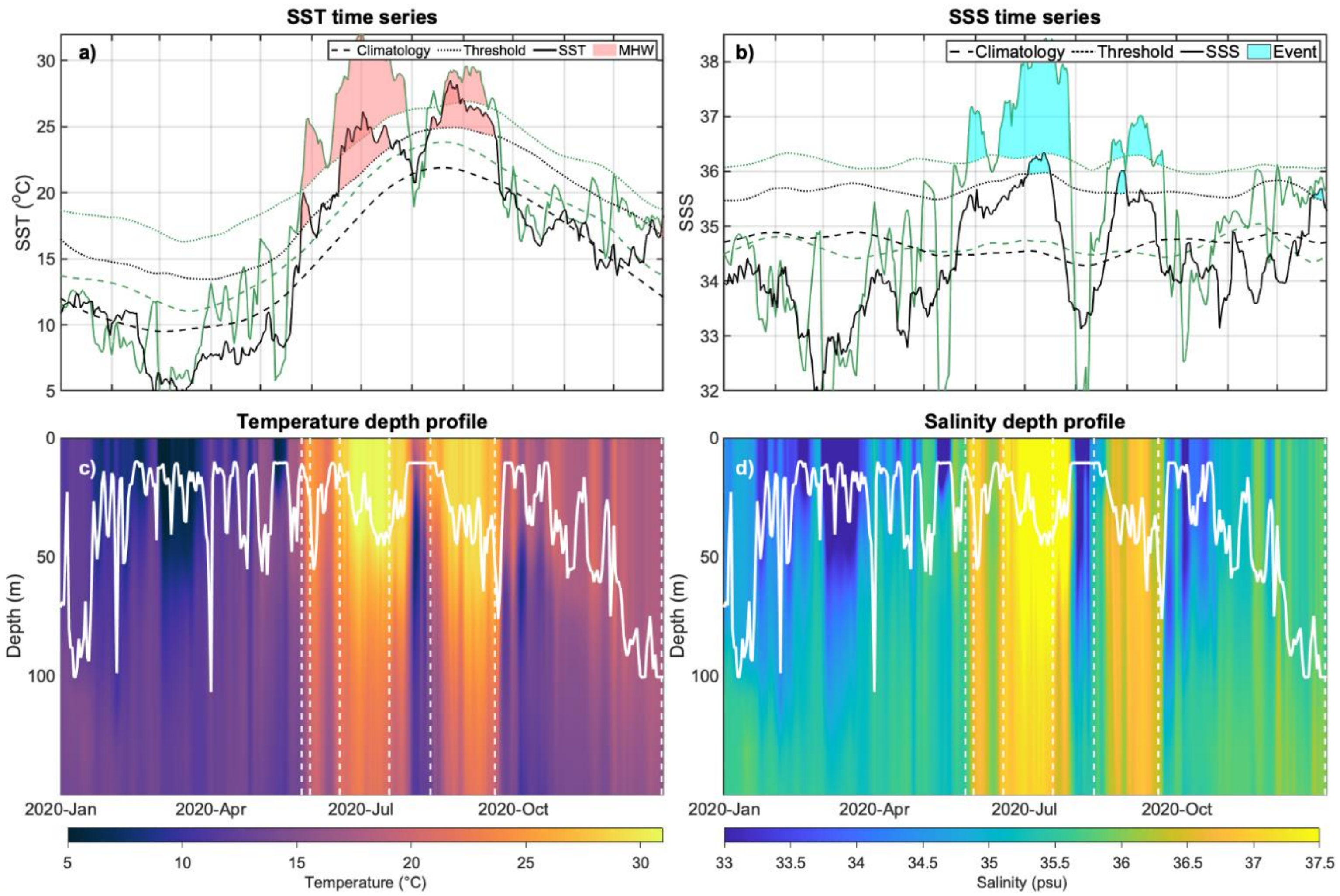


Spatial distribution of **conditional probability** for high-salinity anomalies during MHW conditions across the NW Atlantic for the period 2012–2023. Black contours indicate grid cells where the observed conditional probability exceeds the pointwise 95% confidence threshold (0.21). Larger values indicate regions where MHW days co-occur more frequently with high-salinity anomalies than expected under null hypothesis assumption of mutually independent events.

- A substantial fraction of MHW days coincide with high-SSS extremes
  - indicating that MHWs frequently occur within warm, saline GS-influenced water masses, and both MHW and high-SSS events are mutually dependent.
- High-salinity-MHW co-occurrence depends strongly on regional water masses in the NW Atlantic.

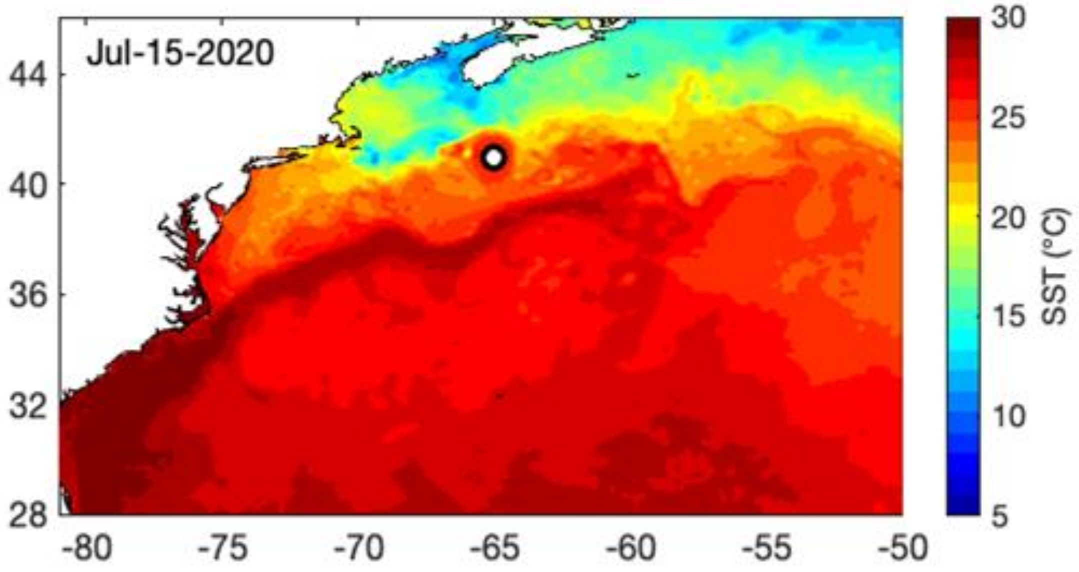
The important point is not that salinity alone causes the MHW. Rather, high SSS acts as a water-mass tracer.
It shows where MHWs occur within warm, saline Gulf Stream-influenced waters, consistent with advective preconditioning and vertically extensive warming.

Case Study 1: MHW Co-occurrence with High-SSS Extreme



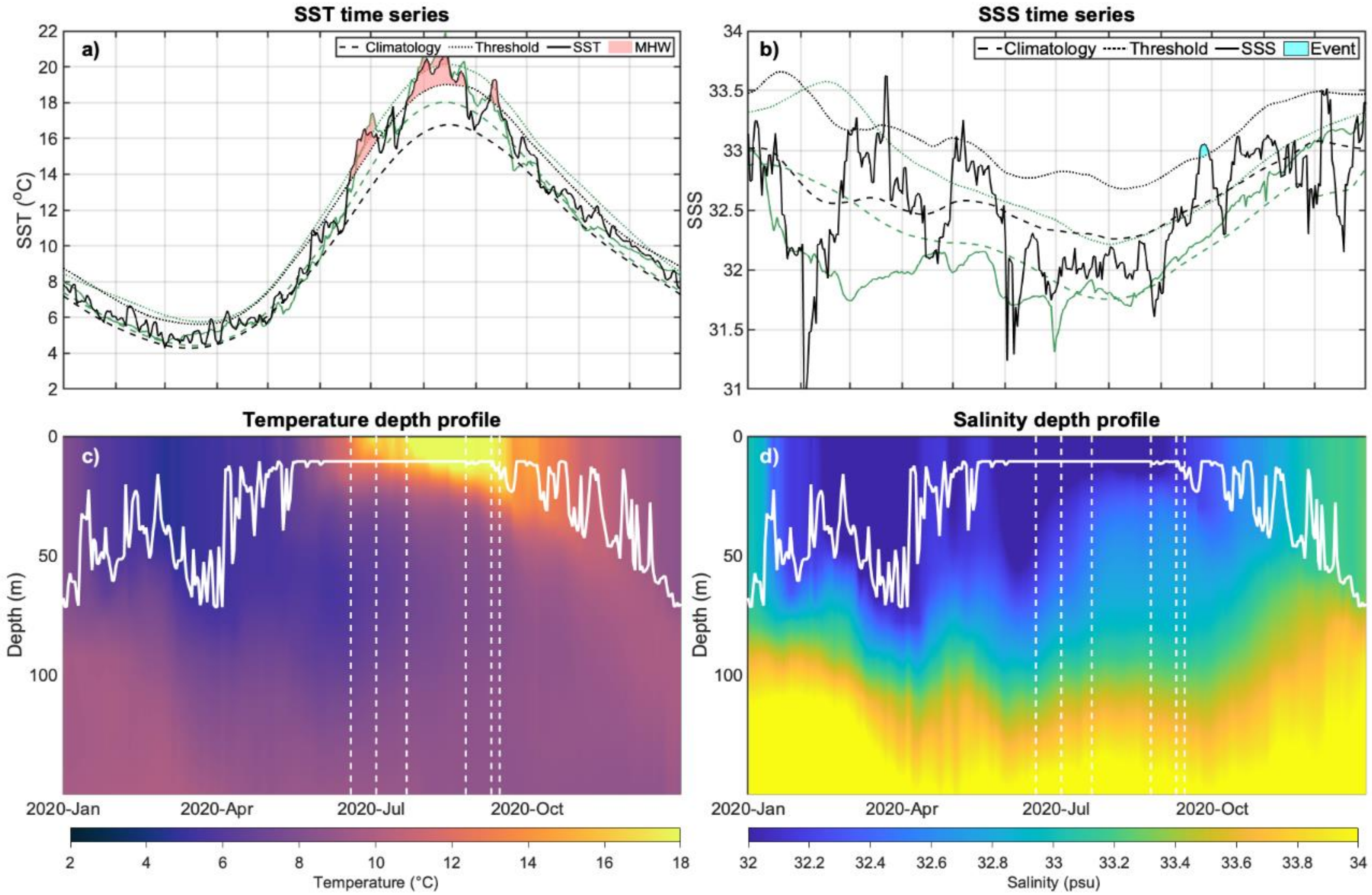
Top panel: Time series of climatology, MHW (left)/extreme salinity events (right) threshold, and SST (°C, left)/SSS (right) using satellite observations (black) and GLORYS12 reanalysis (green). Detected MHW events and extreme salinity events are highlighted (pink/cyan). Bottom panel: GLORYS12 reanalysis temperature (°C, left)/salinity (right) profiles to 150 m depth with MLD (solid white line) and duration of MHWs detected using satellite observations (MHW start/end; dashed white lines).

- Consecutive 2020 MHWs at (41°N, 65°W): **SST anomaly > +4°C**, first event starting in late May and last event ending in mid September.
- Driver: saline advection via **anticyclonic eddy**.
- Warm, saline water deepened MLD and intensified MHW.



SST at peak MHW intensity, marker showing place of time series.

Case Study 2: MHW Co-occurrence with Low-SSS Extreme



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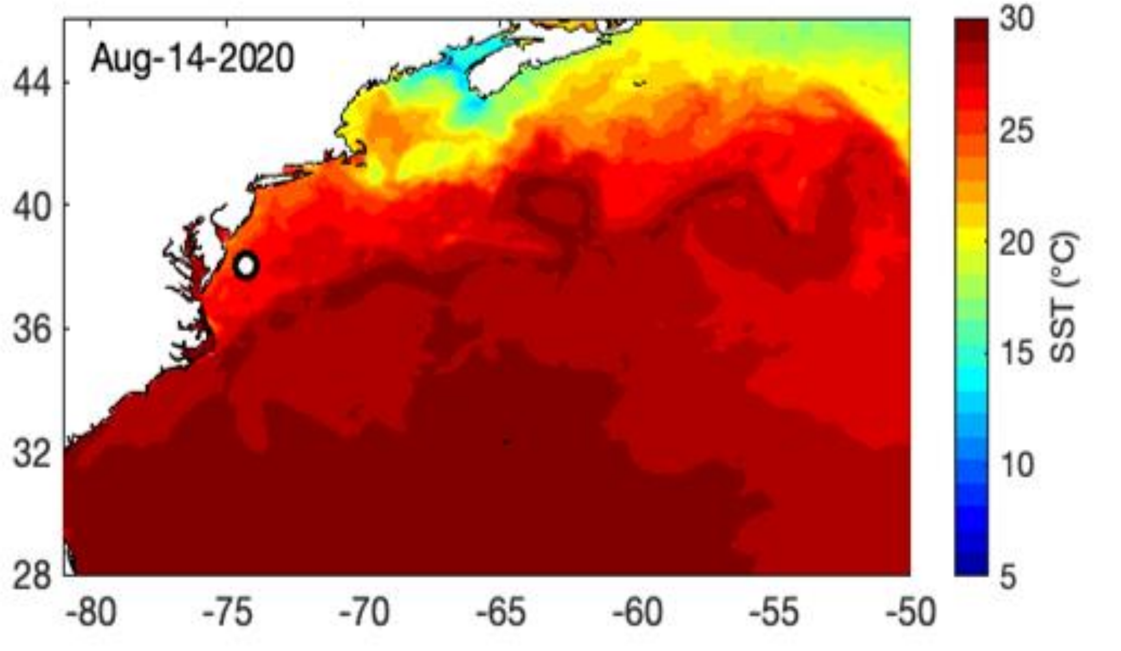
- August 2020 MHW at (43°N, 68°W) : **SST anomaly > +2.5°C**, lasting ~3 weeks.
- Negative SSS anomaly **enhanced stratification**.
- Reduced mixing **prolonged surface warming**.
- Warming constrained to mixed layer.

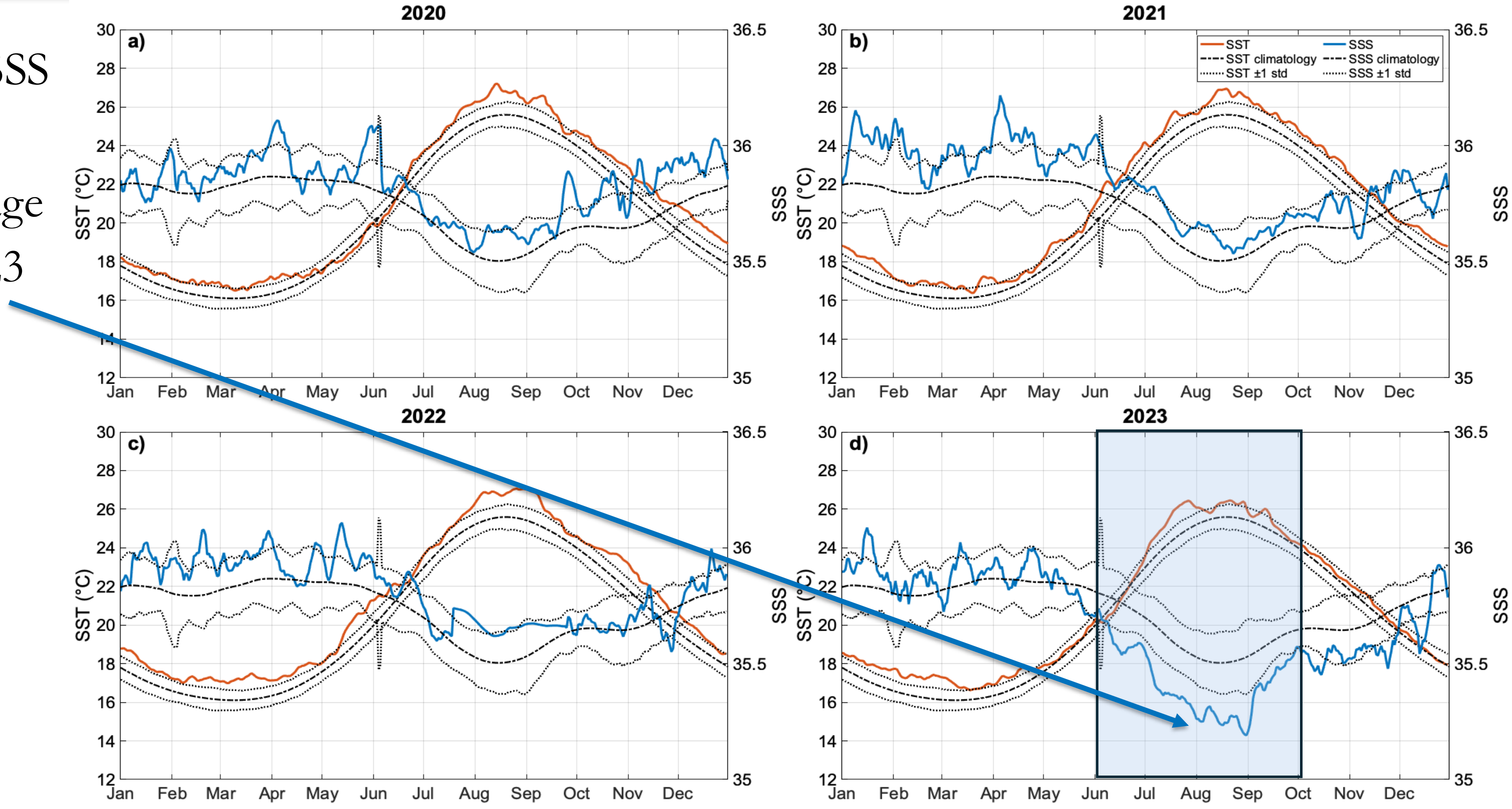


SST at peak MHW intensity, marker showing place of time series.

2023 North Atlantic Shelf Freshening

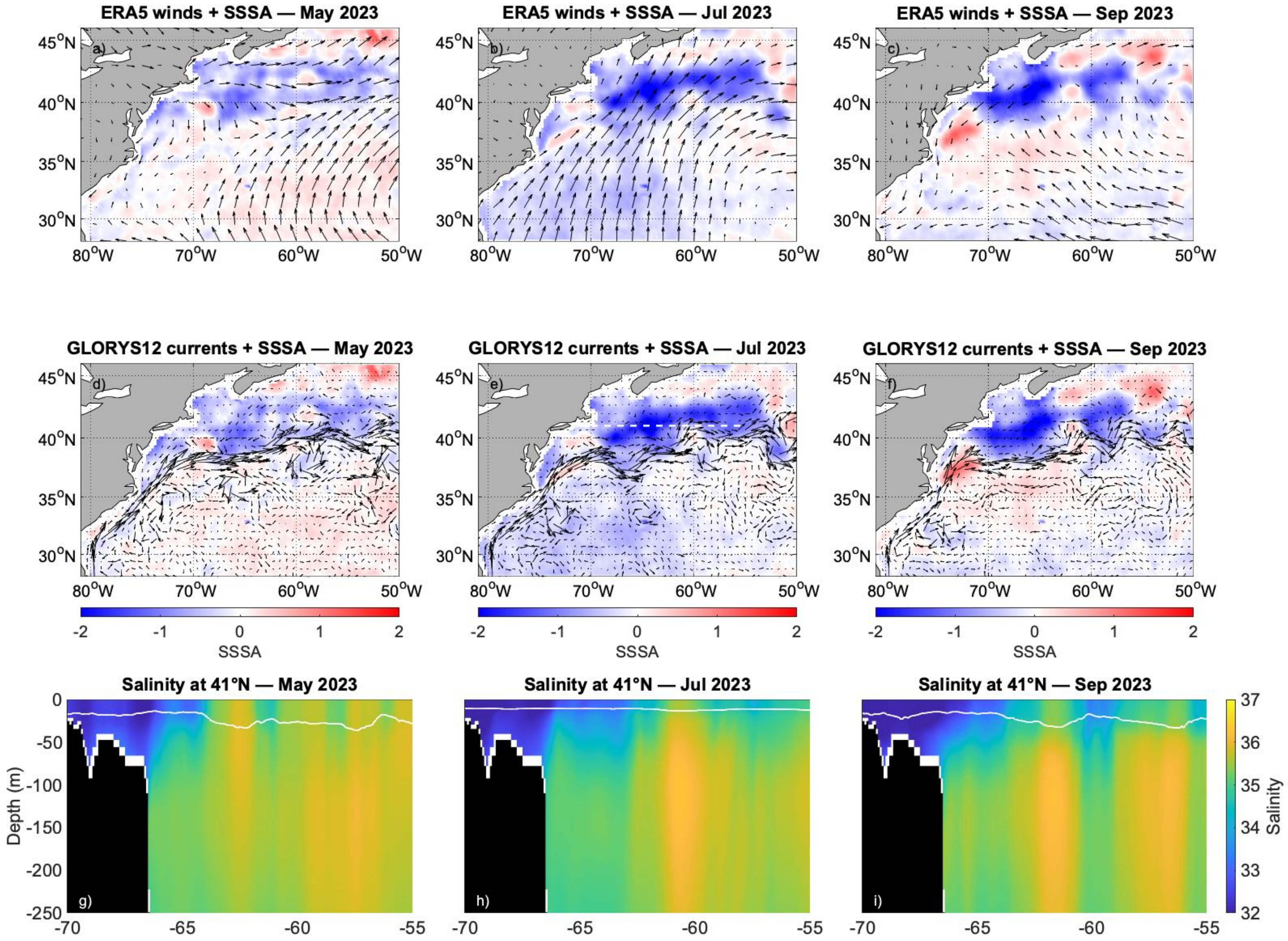
Spatially-averaged SSS falls far below the climatological average during summer 2023 when compared to other years.

This freshening coincided with heightened MHW frequency.



SST (red line), SST climatology, ± one standard deviation from SST climatology, SSS (blue line), SSS climatology, and ± one standard deviation from SSS climatology for 2020, 2021, 2022, and 2023 averaged over the Northwest Atlantic region (28–46°N, 81–50°W).

MHW and Anomalous Freshening in 2023

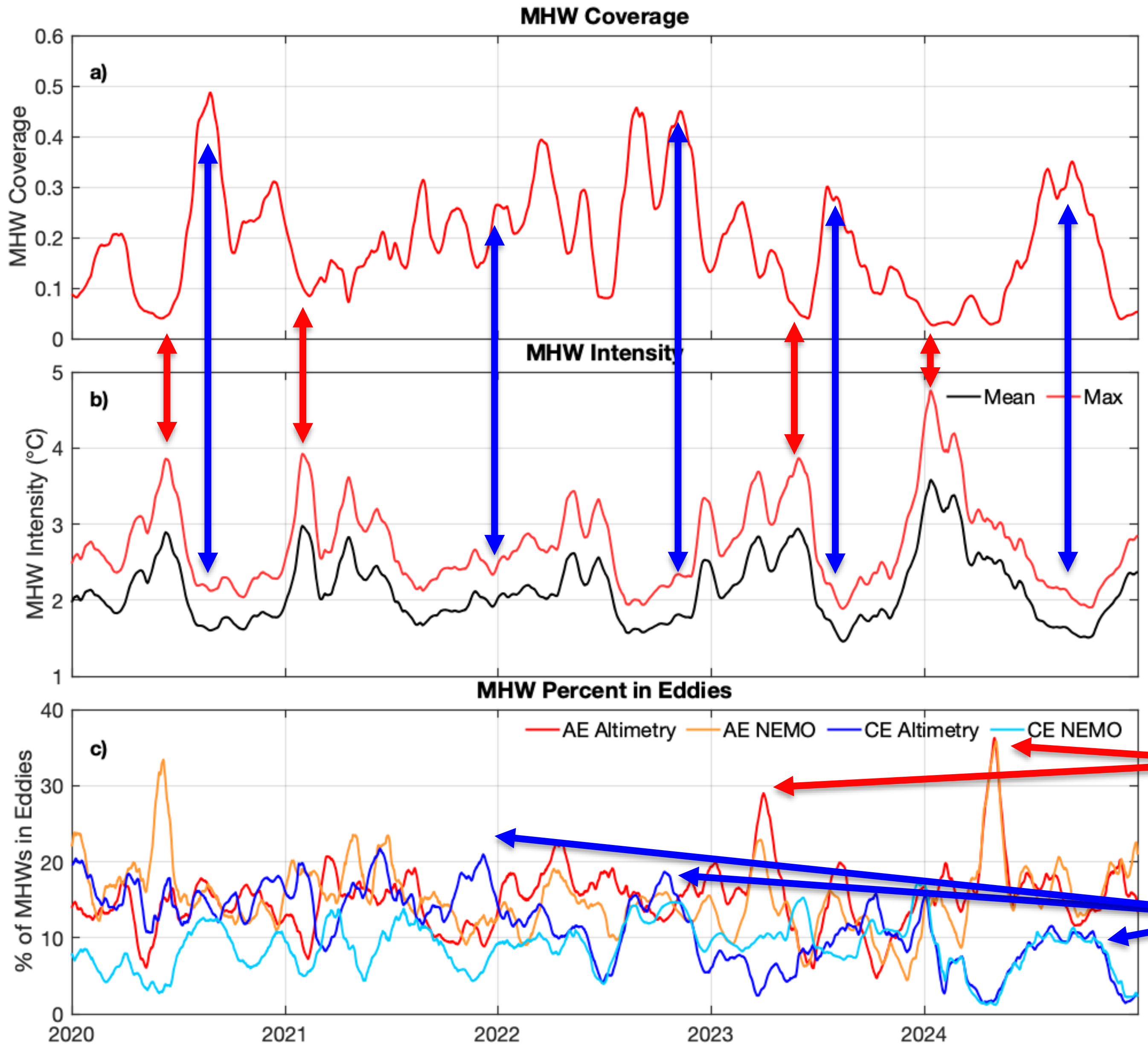


Monthly-averaged SSS anomalies with overlaid ERA5 wind vectors (a-c) and GLORYS12 surface current vectors (d-f). Latitudinal cross-section of monthly-averaged salinity fields from GLORYS12 reanalysis along 41° N overlaid with MLD (white line). Columns correspond to months May, July, and September 2023.

- During this period, pronounced and spatially extensive negative SSS anomalies developed across the continental shelf in early spring, got intensified through summer, and persisted into autumn

- These negative SSS anomalies coincided with widespread MHW activity and weak wind forcing providing conditions favorable for shallow mixed layers and surface-intensified warming.

How Do Gulf Stream Eddies Modulate Marine Heatwave Coverage and Intensity?



Time series of (a) MHW coverage, (b) mean (black) and maximum (red) MHW intensity, and (c) percent of MHWs in eddies.

Looking at the entire domain, MHW coverage and intensity have an **inverse relationship** over time.

Eddies help shape whether a MHW spreads out or intensifies.

Red Arrow: Low coverage & High Intensity
Blue Arrow: High coverage & Low Intensity

Peaks in **MHW intensity** correspond to peaks of MHWs occurring within **AEs.**

Peaks in **MHW coverage** correspond to peaks of MHWs occurring within **CEs.**

	Altimetry	NEMO
AE vs intensity	**r = 0.177, p = 1.9e-17**	**r = 0.151, p = 3.8e-18**
CE vs coverage	**r = 0.337, p = 7.1e-88**	**r = 0.554, p = 4.2e-264**

MHW coverage is more strongly associated with cyclonic or cold-core eddies, while MHW intensity is more associated with anticyclonic or warm-core eddies.

Summary

- Salinity does not set the timing of MHWs but modulates their **vertical structure, intensity,** and **persistence**.

- **Surface-intensified MHWs** are linked to freshening, shallow mixed layers, and enhanced stratification, with an association to **CEs**.

- **Deep-penetrating MHWs** emerge under saline conditions with deeper mixed layers and reduced stratification, frequently overlapping to **AEs**.

- The summer of 2023 featured widespread surface freshening concurrent with elevated MHW coverage, increased overlap between low-salinity extremes and MHWs, and a **higher occurrence of events within CEs relative to AEs**.

- An **inverse relationship between MHW spatial extent and peak intensity** across the domain reflects the governing role of mesoscale eddies, which modulate stratification and differentiate MHW expression between CE- and AE-dominated regimes.