Exploring the Influence of Bottom Oxygen Gradients on Marine Heatwave Severity in the Gulf of Mexico (1992-2023)

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PROJECT TIMELINE–

Tracking changes over time → Comparing long-term patterns of oxygen and marine heatwave severity

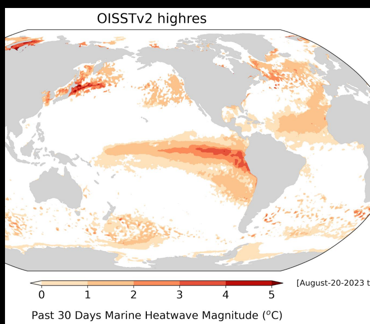
Initial Plan	• Are changes in ocean circulation patterns influencing the formation and movement of oxygen-depleted dead zones in major ocean basins?
Revised Plan	• Is the severity of marine heatwaves (MWHs) in the Gulf of Mexico associated with the expansion of oxygen-depleted dead zones in the coastal area?
→ First Setback:	• NOAA Gulf Hypoxia data inconsistent across years and locations • OISSTv2.1 high-res daily satellite v.s. sparse ship-collected points
Final Research	• **Does the natural spatial gradient of baseline bottom-oxygen concentrations in the Gulf of Mexico correspond to patterns of marine heatwave severity?**

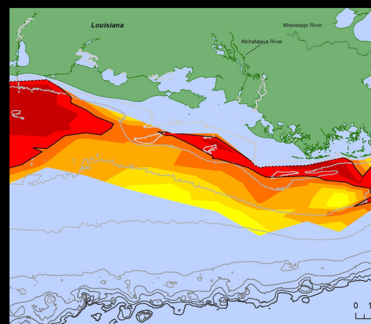
I initially planned to track how dead zones or areas of low oxygen in the ocean might shift over time with ocean currents, then decided to narrow the scope of my question to specifically analyze whether or not low-oxygen dead zones in coastal areas of the Gulf of Mexico are associated with the severity of marine heatwaves.

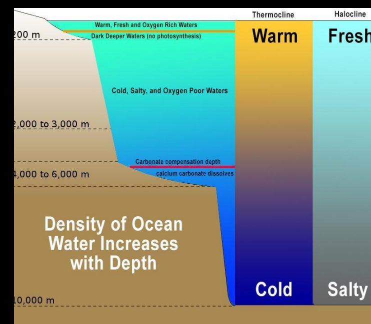
Unfortunately, I realized pretty quickly that the NOAA Gulf Hypoxia Watch data I planned to use was not standardized at all across years or locations, so I couldn't treat it as a clean comparable time series with the SST data because some years they sample more places than others, in different patterns, at different times.

Therefore in my given timeframe, instead of studying temporal changes in dead zones, I focused on whether the existing natural spatial gradient of bottom oxygen in the Gulf of Mexico corresponds to patterns of marine heatwave severity over the last 30 years.

Definitions–







Marine Heatwaves

Detection algorithm based on Hobday et al. (2016): "periods when SST exceeds the local 90th percentile threshold for at least 5 consecutive days."

Bottom-Oxygen Levels

The concentration of oxygen dissolved in seawater near the seafloor, measured in micromoles per kilogram (μmol/kg).
Project Target Depth: ~50m

Stratification

Layers of the ocean form because warmer water is lighter, floating on top of colder, denser water which prevents mixing between surface and deep sea layers.

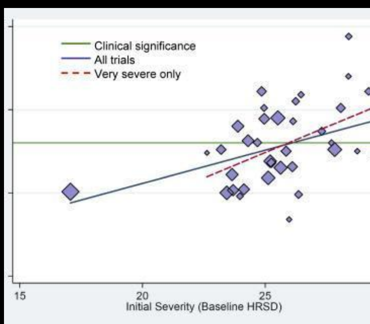
Now that I've given a brief overview I want to define some key terms.

First, marine heatwaves. The standard marine heatwave detection algorithm calculates them as periods when sea surface temperature exceeds the local 90th percentile threshold for at least 5 consecutive days.

Next, stratification refers to layers forming in the ocean because warm water sits on top of colder water due to it being less dense, and this limits vertical mixing which keeps heat trapped near the surface potentially worsening marine heatwaves since deeper water isn't able to rise and cool the surface.

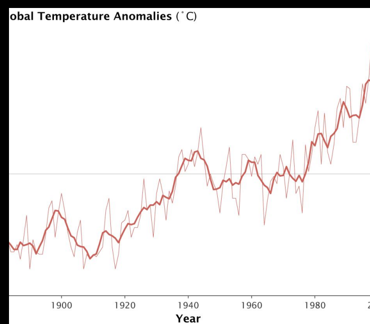
And also, bottom oxygen refers to the concentration of dissolved oxygen near the sea floor.
For my research I chose to focus on a target depth of about 50 meters because it's deep enough to avoid interference from surface mixing, but shallow enough to still be influenced by stratification.

More Definitions–



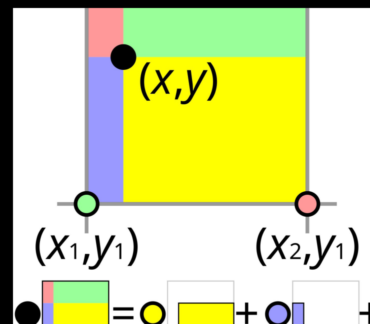
Baseline

The average conditions over a long period of time used for comparative analysis.



Anomaly

Measurement of how much the current condition differs from the baseline.



Interpolation

Method to estimate data at locations where it wasn't directly measured by using surrounding known values. Used to fill in gaps in the oxygen data.

A few more quick definitions.

Baseline refers to the long-term average conditions that we use for comparison. In this case, the average monthly sea surface temperature over my reference period.

An anomaly is how much a given temperature deviates from that baseline so whether the its warmer or cooler than normal on average.

And finally, interpolation is how we estimate missing data between known points. I used interpolation to match the grid of bottom oxygen measurements onto the finer sea surface temperature grid so that the two datasets could be accurately compared point by point.

Data Sources–

OISSTv2p1: NOAA Satellite SST Data
→ Daily sea surface temp 1981-2024

WOA23: World Ocean Atlas 2023
→ Climatological averages of bottom oxygen (~50m depth)

m_mhw Toolbox: MHW Detection
→ MATLAB adapted algorithm

I used two main datasets.

For daily, high-resolution satellite data of sea surface temperatures, I used NOAA's Optimum Interpolation SST Version 2.1 dataset.

I also used the bottom oxygen climatology data from the World Ocean Atlas 2023 dataset which provided average dissolved oxygen levels at different depths globally.

Both datasets were subsetted to the Gulf of Mexico region between 15°N–31°N latitude and 98°W–80°W longitude.

In addition to the raw data, I used the m_mhw MATLAB toolbox, which applies the standardized marine heatwave detection algorithm developed by Hobday et al. This detection method is published and peer-reviewed, and allowed me to automate the detection process across such a big spatial and temporal dataset while ensuring consistency in that every grid point uses exactly the same detection method. I did have to modify one of the functions slightly to stay compatible with my existing workflow operating with 'datenum'.

Methods–

1. Load SST data, convert variables, calculate monthly climatology and get daily SST anomalies

2. Use MHW detection algorithm to calculate total MHW days at each grid cell in the Gulf of Mexico from 1992-2023

3. Load Bottom Oxygen data, coarser grid than SST (1° v.s. 0.25°) so interpolate to fill in missing values

4. Align both datasets and run spatial analysis
   - Correlation measurements
   - Coastal v.s. Offshore averages

In terms of my methods, first I processed the SST data:

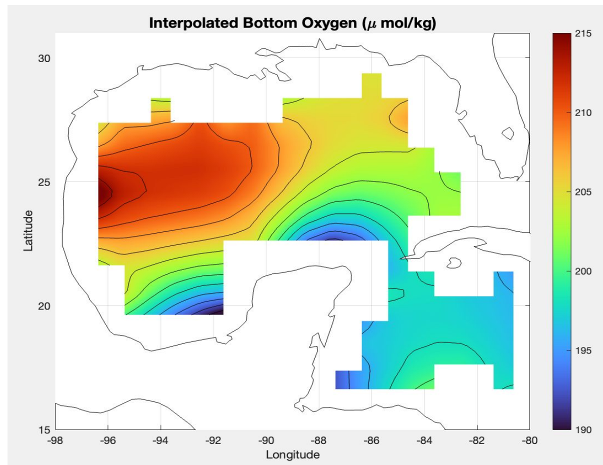
I calculated a monthly baseline climatology, subtracted it from daily SST to get anomalies, and used the marine heatwave detection algorithm to flag events based on the Hobday definition.

Then, I loaded the bottom oxygen data, focusing on the 50-meter depth layer, and used interpolation to match the grid of bottom oxygen measurements onto the finer sea surface temperature grid so that the two datasets could be compared point by point.

And finally, I calculated the total number of marine heatwave days at each grid point from 1992 to 2023, and compared that spatial pattern to bottom oxygen concentrations.

Interpolated Bottom Oxygen (µmol/kg) Map

This map shows bottom oxygen concentrations across the Gulf of Mexico at ~50 m depth, interpolated to match the SST grid. Values appear higher in the western Gulf, and lower in the southeast.



This map shows the estimated bottom oxygen concentrations in the Gulf of Mexico at roughly a 50 meter depth.

Higher oxygen levels tend to occur in the western Gulf, while the southeast near Florida shows lower oxygen values.

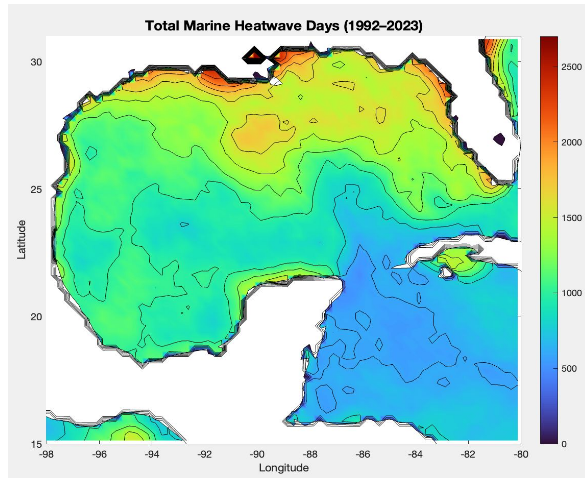
One important thing to note, along the immediate coastline there's a lot of blank or missing data.

That's because the World Ocean Atlas dataset doesn't fully resolve very shallow waters near the shore, focusing more on open ocean conditions.

This is relevant later when we think about how representative the coastal-offshore comparisons are.

Total Marine Heatwave Days (1992-2023) Map

This map shows the total number of marine heatwave days at each location in the Gulf of Mexico from 1992 to 2023. The northwestern Gulf and coastal regions show the highest marine heatwave persistence.



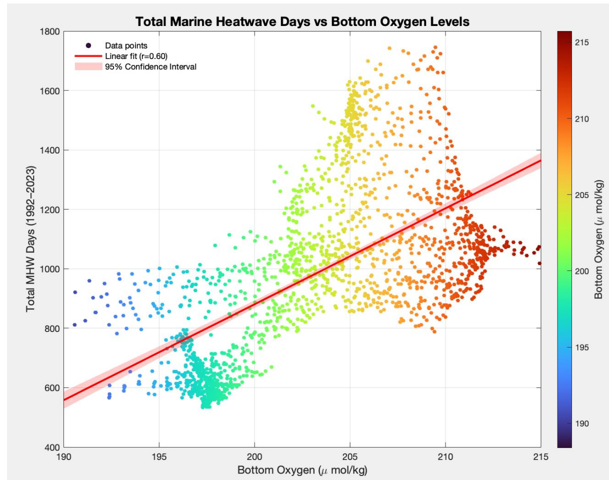
This map shows the total number of marine heatwave days between 1992 and 2023, based on the standardized detection algorithm.

We see that the highest concentration of heatwave days happened along the northwestern Gulf coast — especially around Texas and Louisiana.

Offshore areas especially the southeastern Gulf had fewer total marine heatwave days.

Relationship between Bottom Oxygen Levels and MHW Days

This scatterplot shows each grid cells' bottom oxygen concentration compared to its total marine heatwave days. The positive trend suggests areas with higher bottom oxygen have more marine heatwave days overall.



Here, each dot is a grid point where I compared bottom oxygen to total marine heatwave days.

I found a statistically significant positive correlation: areas with higher bottom oxygen levels tended to experience more total marine heatwave days.

The correlation coefficient was about 0.60, and the p-value was extremely small, meaning this relationship is not likely due to random chance.

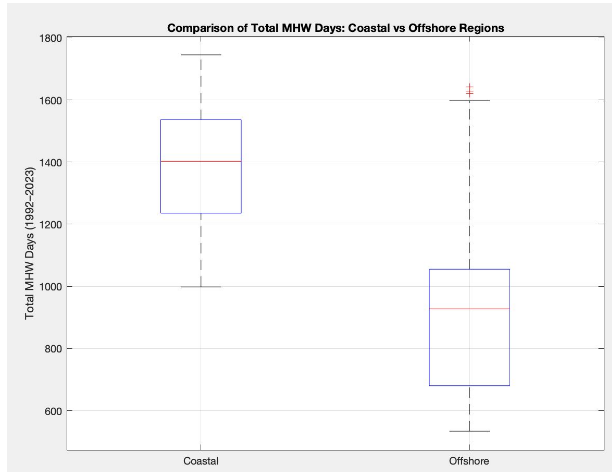
However, correlation does not mean causation. So I cannot definitively say that higher bottom oxygen levels causes more marine heatwaves or vice versa because there are very likely hidden variables at work.

My work shows that they are positively associated, meaning when one is higher, the other tends to also be higher in the same area during the time period. This however does not prove that one causes the other.

One possible hypothesis I came up with is that regions with better-oxygenated bottom waters may also be more strongly stratified — meaning heat gets trapped near the surface longer as less oxygen is being stirred up or used by organisms, which could lead to more frequent or longer marine heatwaves.

Coastal vs. Offshore Comparison – MHW Days

This boxplot compares the number of marine heatwave days between coastal and offshore regions. Coastal areas very clearly had more marine heatwave days on average.



To dig deeper, I split the Gulf into coastal and offshore regions.

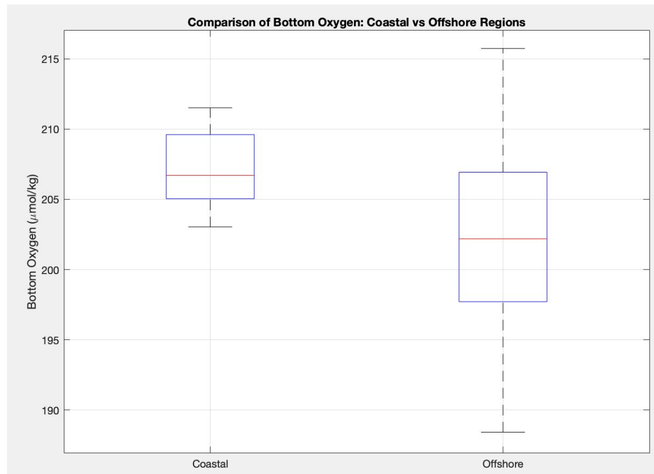
The coastal area was defined as north of 26 degrees latitude and between 95 and 86 degrees west longitude, I essentially wanted to focus on the northwest Gulf where I expected to see stronger influences based off the other maps.

When I compared the two, coastal areas had significantly more marine heatwave days, on average, about 473 more over the 30-year period.

This difference was statistically significant, confirming that coastal regions have experienced more persistent extreme warming events.

Coastal vs. Offshore Comparison – Bottom Oxygen

This boxplot compares bottom oxygen levels between coastal and offshore regions. Coastal values were slightly higher, but the difference was much smaller than for marine heatwave days.



I also compared bottom oxygen concentrations between coastal and offshore regions using the same boundaries.

Coastal areas had only slightly higher bottom oxygen on average, about 4.6 micromoles per kilogram more, but this difference was still statistically significant due to the large number of data points.

The small magnitude of difference suggests that even though marine heatwaves were more severe along the coast, bottom oxygen alone does not fully explain that pattern despite the trend being statistically significant.

My best assumption is other factors like stratification strength, water depth, and local circulation probably also play key roles

* Coastal Region outlined:
(lat > 26°, -95° < lon < -86°)

Key Statistical Findings–

Correlations between bottom oxygen levels & marine heatwave days

r = 0.60157
→ positive correlation
→ moderate to strong
→ as bottom oxygen levels rise, the number of marine heatwave days also tends to rise

p-value = 2.7767e-175
→ p < 0.001, statistically significant trend

Average bottom oxygen levels at 50 m by region

Coastal: 207.2388

Offshore: 202.6267

→ Bottom oxygen levels were slightly higher (~4.6) on average near the coast than offshore

2-sample t-test p-value: 5.408e-43
→ p < 0.001, statistically significant trend

Average marine heatwave days at 50 m by region

Coastal: 1384.3928

Offshore: 911.6643

→ On average, coastal locations had 473 more MHW days over 30 years than offshore areas.

2-sample t-test p-value: 1.4499e-179
→ p < 0.001, statistically significant trend

Here I detailed my main numerical findings.

I calculated the correlation between bottom oxygen levels and total marine heatwave days across the grid. The result was r = 0.60, which is a moderate to strong positive correlation. That means that, overall, areas with higher oxygen near the seafloor tended to have more marine heatwave days. The p-value is incredibly low so statistically, this would be considered a very significant trend.

Coastal bottom oxygen was only slightly higher on average, but still in a statistically significant way due to the large number of data points even though the magnitude of the difference is small.

On the other side of the scale, Coastal areas had way more marine heatwave days, about 473 more over 30 years, than offshore areas and that difference was also significant with a t-test p-value < 0.001. So from this, we can assume that oxygen is not the only driving factor in this dynamic, it seems there’s something about coastal zones that must make them especially vulnerable to marine heatwaves. This could be due to factors like nutrient runoff, shallower mixed layers, or possibly stronger land-sea temperature gradients that make them more prone to persistent surface warming.

Conclusion–

- Areas with higher bottom oxygen in the western Gulf of Mexico had more total marine heatwave days from 1992 to 2023.
- There is a moderate positive correlation ($r = 0.60$) between bottom oxygen concentration and MHW days.
- Coastal areas had significantly more MHW days than offshore areas, but only slightly higher bottom oxygen.
- Bottom oxygen gradients seem to be related to patterns of marine heatwave severity, but that does not certify causality.
  - Other factors like stratification, currents, nutrient runoff, etc.
- TO NOTE: Coastal hypoxia could still be underestimated due to gaps in oxygen data right along the coast.

→ **SO WHAT NOW?**

So what do we take away from this? First, In the western Gulf—where bottom oxygen levels are relatively high—we also see the most MHW days. The spatial patterns in bottom oxygen seem to align with patterns of marine heatwave persistence.

The correlation shows that bottom oxygen could be playing some role in shaping these patterns. But of course, correlation doesn't mean causation. There are other processes likely at play—like ocean stratification, currents, even nutrient runoff that fuels surface warming.

One important note: due to data gaps near the coast, I may be underestimating true hypoxia in those regions. Especially since coastal hypoxia is episodic, and we're working with long-term climatology from WOA, not high-res temporal data.

Since the WOA dataset smooths across years and has fewer measurements near the coast, it may underestimate how bad coastal hypoxia can get during certain seasons. So while my spatial analysis shows bottom oxygen patterns across the Gulf, the coastal regions may be missing some extreme low-oxygen events that occur episodically.

Future Directions–

- Fill coastal data gaps
- Explore temporal trends between bottom oxygen and MHWs: is the relationship consistent over time as well as space?
- Test how oxygen at other depths interacts with stratification and heatwave persistence
- Investigate other factors

In terms of where this could lead next,

First, I think it's essential to fill in the missing coastal oxygen data, whether from more ship surveys or other sources.

I would also want to look at how this relationship between bottom oxygen and MHWs holds up over time, year to year or decade to decade. Unfortunately this project ended up being limited to spatial data rather than temporal data due to the datasets I was able to access and properly load as I explained. Spatial patterns tell us how something varies from place to place — across the Gulf of Mexico, for example. Temporal patterns tell us how something changes over time — like year to year or month to month. So as it stands this reflects more of a static snapshot rather than a dynamic relationship like I first intended.

I'd also want to test different depths—not just 50 m—and bring in more vertical structure to see how stratification plays in. I played around with this a little bit testing with 20m and 100m, but the most reliable results at least for my purposes resulted from the target depth of 50 m.

And finally, expanding to include other variables like ocean currents or salinity could reveal new mechanisms linking bottom conditions to surface heat events.

Why Does This Matter?

Marine heatwaves threaten fisheries, ecosystems, and coastal economies. This correlation between bottom and surface conditions could inform resilience strategies.

Even without proven causality, this strong correlation raises new questions about coastal dynamics, oxygen cycling, and climate extremes.

Understanding the role of bottom oxygen can help us better predict which regions are more vulnerable to prolonged marine heatwaves.

If areas with higher bottom oxygen are really more prone to prolonged MHWs, this could reflect deeper physical processes like stratification.

Ultimately, this project matters because marine heatwaves are a growing threat to coastal economies, fisheries, coral reefs, and ecosystems. Understanding which regions are more prone to persistent marine heatwaves can help guide adaptation and resilience planning.

This analysis found that spatial patterns of bottom oxygen align with patterns of marine heatwave persistence in the Gulf of Mexico. Coastal areas experienced more MHW days and had slightly higher bottom oxygen levels, suggesting a potential link worth exploring.

This spatial relationship suggests that bottom water conditions possibly linked to stratification or other ocean processes could play a role in influencing how surface warming develops that we're not paying attention to.

- How fast does oxygen get replenished or used up in coastal areas?
- Are regions with certain oxygen patterns more vulnerable to not just heatwaves, but *other* climate extremes (like hurricanes or ecosystem collapses)?
- Could changing oxygen levels due to climate change make marine heatwaves worse in the future?

This project successfully identified a statistically strong spatial relationship between bottom oxygen levels and marine heatwave persistence, while acknowledging data limitations and a need for further research.

Questions?

Thank you for listening!

This project was designed to be exploratory. What I was able to show was a strong spatial relationship, but explaining the exact mechanisms would require more detailed datasets and more targeted analysis. That’s exactly where future research could build off of this.

References–

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https://www.ncei.noaa.gov/products/optimum-interpolation-sst

https://github.com/ZijieZhaoMMHW/m_mhw1.0?tab=readme-ov-file