Remote Sensing Assessment of Ocean Acidification Stressors on Mesoamerican Reef Coral Ecosystems

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Abstract: Anthropogenic CO_2 uptake is driving ocean acidification, with profound implications for the carbonate chemistry of coral reefs and their resilience. This study leverages Copernicus Level-4 satellite datasets of carbon flux variables, including fugacity of CO_2 ($fgCO_2$), partial pressure of CO_2 ($spCO_2$), surface pH, and total alkalinity (TA), to assess the spatial and seasonal variability of acidification stress across the Mesoamerican Reef (89.5–85.5°W, 15.5–22°N). Our analysis reveals distinct seasonal peaks, with elevated $fgCO_2$ and $spCO_2$ and reduced pH and Ω_{ar} concentrated in southern reefs (16–18°N) during February–June. From July to September, Ω_{ar} values rise reef-wide, though southern reefs remain comparatively lower, while October–January represents the least acidified season. These spatiotemporal stress windows underscore the role of hydrography and biogeochemical cycling in modulating carbonate chemistry, providing insights critical for anticipating bleaching, guiding ecosystem-based management, and supporting SDG 14 (Life Below Water).

Keywords: Ocean Acidification; Remote Sensing; Coral Reefs; Carbonate Chemistry; Mesoamerican Reef

1. Introduction

Rising atmospheric CO_2 from fossil fuel combustion reduces ocean pH and alters carbonate chemistry, leading to lower saturation states of calcium carbonate minerals (Doney et al., 2009). These changes threaten marine biodiversity, with coral reefs among the most vulnerable ecosystems due to their reliance on high aragonite saturation states for calcification (Zayed, 2025). Ocean acidification also compounds other stressors such as warming, amplifying risks to reef resilience, biodiversity, and ecosystem services. While global-scale OA assessments exist, fewer studies have systematically examined carbonate chemistry dynamics across the Mesoamerican Reef (MAR). This study applies a remote sensing approach to evaluate seasonal and spatial variability in carbonate chemistry across the MAR, with emphasis on pH, Ω_{ar}, Ω^{a}_{c}, $spCO_2$, $fgCO_2$, and TA, aiming to identify stress windows and vulnerable reef sites.

2. Methodology

The study area spans 15.5–22°N and 85.5–89.5°W, encompassing the MAR. We used Copernicus Marine Environment Monitoring Service (CMEMS) Level-4 biogeochemical products (1985–2024) including surface pH, $spCO_2$, $fgCO_2$, and TA, from which Ω_{ar} and Ω^{a}_{c} were derived. Five representative reef sites (A–E) were selected to capture spatial variability. Monthly and seasonal averages were computed using MATLAB. Seasons were defined as FMAMJ (Feb–Jun), JAS (Jul–Sep), ONDJ (Oct–Jan). Both climatological seasonal cycles and year-by-year seasonal means were analyzed to detect trends. Spatial maps were generated to highlight shifting hotspots of OA stress across latitudes.

3. Results/Findings

The spatial and temporal analysis revealed a persistent **south–north gradient** in acidification stress across the MAR. Seasonal climatologies indicated that during February–June (FMAMJ), the region experienced the lowest Ω_{ar}, with the strongest reductions concentrated in southern reefs (16–18°N). During July–September (JAS), Ω_{ar} values increased across the domain, reflecting the seasonal maximum, but the southern reefs remained relatively lower compared to the north. By October–January (ONDJ), Ω_{ar} values reached their highest reef-wide, representing the least acidified conditions, yet the south again remained slightly lower than northern sites. These results highlight seasonal modulation in magnitude rather than geographic displacement, underscoring the importance of regional hydrography and biogeochemical drivers in shaping carbonate chemistry stress (Doney et al., 2009).

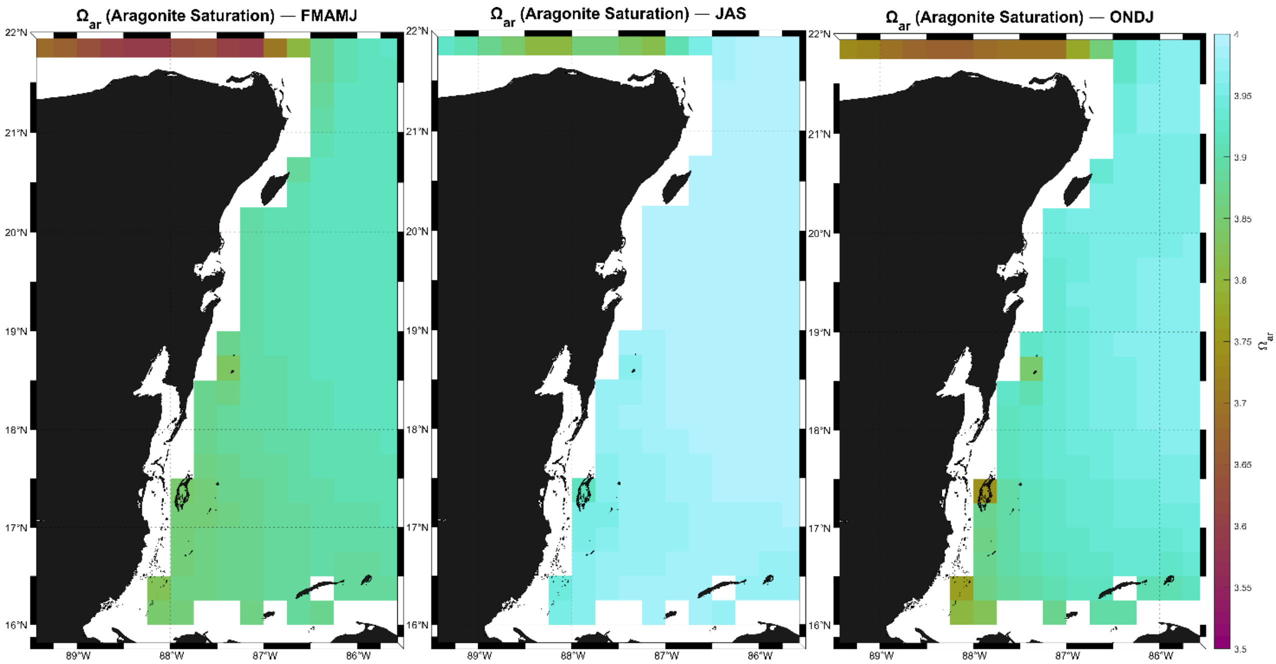

Figure 1: Spatial maps of seasonal OA stress across MAR

At the site level, a clear hierarchy emerged among the five reef locations analyzed. Sites B, E, and A maintained the most favorable carbonate chemistry, with average Ω_{ar} values of ~3.9–4.0, relatively higher pH, and lower $spCO_2$ concentrations. Site C displayed intermediate conditions, while site D consistently exhibited the lowest pH, highest $spCO_2$, unstable alkalinity, and the most pronounced seasonal dips in Ω_{ar}, reaching values near 3.6. The ranking of relative resilience was therefore B ≈ E ≈ A > C > D. The decline toward Ω_{ar} ~3.6 is particularly significant because experimental evidence suggests that values approaching this threshold impose calcification stress on marine organisms, including corals and larval shellfish (Gimenez et al., 2018). Moreover, physiological processes such as calcium ion homeostasis are increasingly recognized as compounding mechanisms that exacerbate coral vulnerability under acidified conditions (Armstrong and Bahr, 2025).

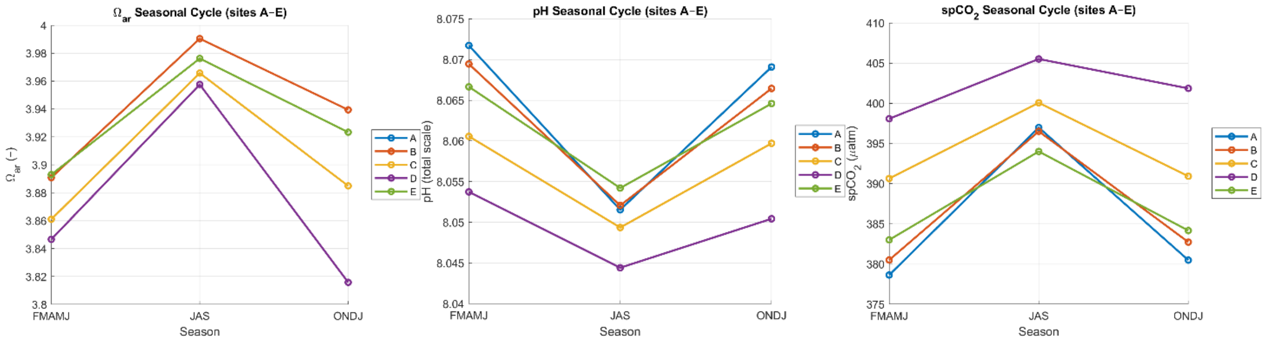

Figure 2. Seasonal cycles of carbonate chemistry parameters at five reef sites (A–E) within the MAR. Plots display (a) aragonite saturation state (Ω_{ar}), (b) pH (total scale), and (c) $spCO_2$ (µatm) averaged by season. Sites B, E, and A maintain more favorable carbonate chemistry, while site D consistently exhibits the lowest Ω_{ar} and pH and the highest $spCO_2$, indicating heightened vulnerability.

Long-term time series analysis from 1985 to 2024 demonstrated a consistent trajectory of acidification across the MAR. Average Ω_{ar} declined from ~4.1 in the late 1980s to ~3.6 in recent years, while pH decreased from ~8.10 to ~8.02. In parallel, $spCO_2$ increased from ~350 to above 420 µatm, mirroring atmospheric CO_2 rise, and $fgCO_2$ uptake weakened, indicating reduced ocean buffering capacity. These findings point to a systemic OA trend, with site D showing the steepest deterioration, suggesting that local biogeochemical and hydrological drivers may amplify regional ocean acidification stress.

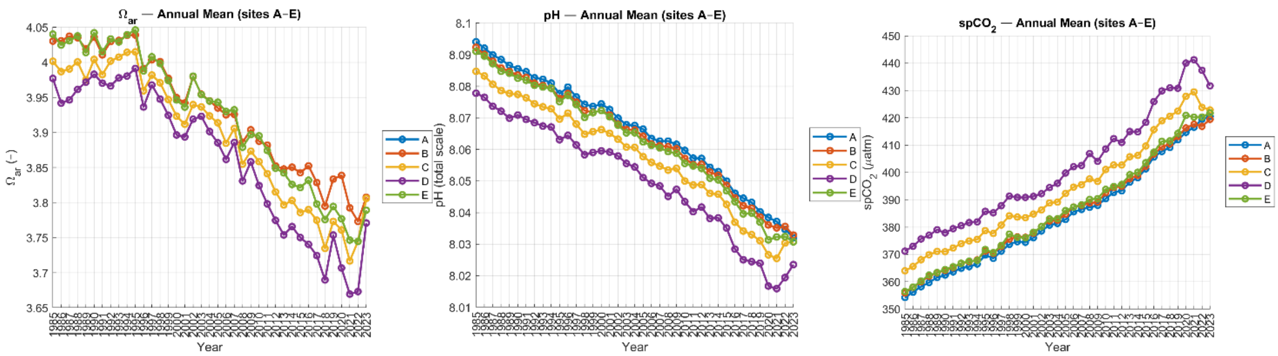

Figure 3: Site-wise time series of Ω_{ar}, pH, and $spCO_2$ (1985–2024)

4. Conclusion

This study demonstrates that the Mesoamerican Reef is undergoing progressive ocean acidification, expressed through both seasonal stress windows and site-specific vulnerabilities. Although Ω_{ar} values remain above undersaturation, their decline toward ~3.6 highlights a measurable reduction in calcification potential for reef-building corals, consistent with biological thresholds reported in experimental work (Gimenez et al., 2018; Armstrong & Bahr, 2025). Sites B, E, and A appear relatively resilient in maintaining higher saturation states, while site D emerges as the most vulnerable, reflecting both external chemical stressors and internal physiological constraints.

The broader implications extend beyond ecological outcomes. Just as Alaskan fisheries were shown to face the highest risks where communities most depend on marine resources (Mathis et al., 2014), reef-dependent societies of the MAR are similarly exposed to the cascading effects of acidification on biodiversity, fisheries, and coastal protection. Ocean acidification therefore represents not only a chemical and ecological threat but also a socio-economic one, reinforcing its role as a critical dimension of climate change (Zayed, 2025). By identifying seasonal hotspots and vulnerable reef sites, this work provides a framework for targeted monitoring and management strategies, aligned with SDG 14 (Life Below Water), and emphasizes the urgency of integrating carbonate chemistry indicators with reef resilience planning at both local and regional scales.

References

Armstrong, D.A. and Bahr, K.D. (2025). Corals in ocean acidification and the role of calcium ion homeostasis to maintain calcification. *ICES Journal of Marine Science*, [online] 82(4). doi:https://doi.org/10.1093/icesjms/fsaf050.

Feely, R.A. and Doney, S.C. (2011). Ocean Acidification: the Other CO2 Problem. *Limnology and Oceanography e-Lectures*, [online] 1(1). doi:https://doi.org/10.4319/lol.2011.rfeely_sdoney.5.

Gimenez, I., Waldbusser, G.G. and Hales, B. (2018). Ocean acidification stress index for shellfish (OASIS): Linking Pacific oyster larval survival and exposure to variable carbonate chemistry regimes. *Elem Sci Anth*, 6(1), p.51. doi:https://doi.org/10.1525/elementa.306.

Mathis, J.T. (2015). Ocean acidification risk assessment for Alaska’s fishery sector. *Progress in Oceanography*, [online] 136, pp.71–91. doi:https://doi.org/10.1016/j.pocean.2014.07.001.

Tuyet, T., Gehlen, M. and Chevallier, F. (2020). Global ocean surface carbon product. *HAL (Le Centre pour la Communication Scientifique Directe)*. [online] doi:https://doi.org/10.48670/moi-00047.

Zayed, A. (2025). CLIMATE CHANGE AND ITS IMPACT ON MARINE BIODIVERSITY: A STUDY OF OCEAN ACIDIFICATION AND CORAL REEF HEALTH. *Modern American Journal of Biological and Environmental Sciences*, [online] 1(1), pp.14–20. Available at: https://usajournals.org/index.php/5/article/view/3 [Accessed 18 May 2025].