

Ocean Acidification in the Planetary Boundaries Framework

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Planetary Boundaries Exceedingly Transgressed

The Planetary Boundaries (PB) Framework seeks to identify key Earth system processes that sustain planetary stability and are vulnerable to large-scale perturbations driven by human activities (Richardson et al. 2023). Seven of the nine planetary boundaries are exceeded, including the boundary of ocean acidification (Sakschewski et al. 2025).

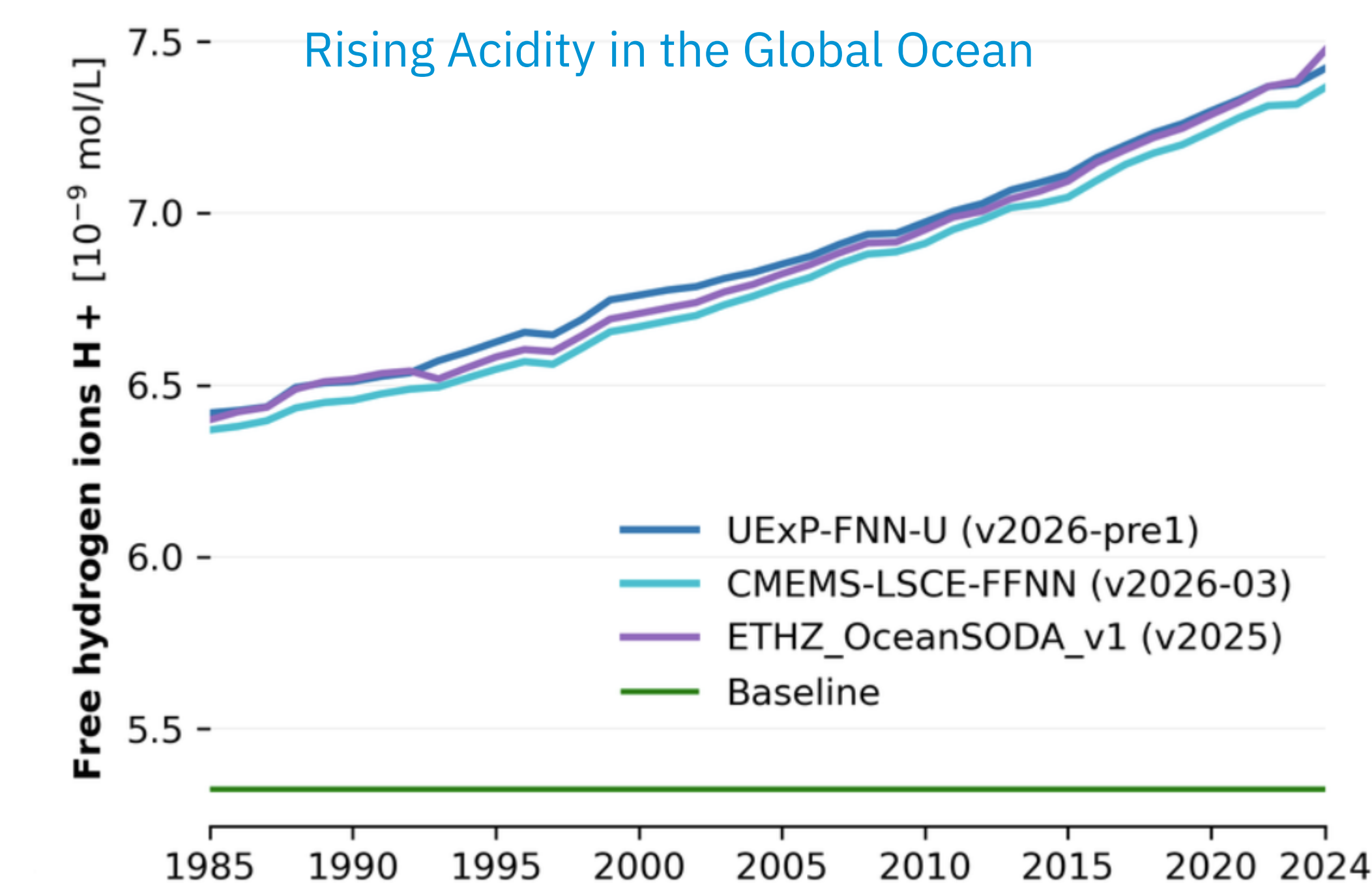


Figure 1. Global annual mean surface hydrogen ion concentration, based on UExP-FNN-U, CMEMS-LSCE-FFNN, and OceanSODA-ETHZ. Global means are calculated on each product's native grid; differences between products largely reflect differences in spatial coverage.

Ocean Acidification: Cause and Consequences

- **Main driver:** Anthropogenic CO₂ dissolves in sea water and forms carbonic acid, releasing hydrogen ions that bind carbonate ions.
- **Ecosystem impacts:** Rapid changes in carbonate chemistry challenge calcifying organisms and threaten ecosystem functioning. Non-calcifying species can also be affected, as changes in seawater chemistry can alter internal physiology, impacting energy budgets, growth, and reproduction.
- **Climate feedback:** Declining buffer capacity (Müller et al. 2023) reduces the efficiency of the ocean sink for anthropogenic CO₂ and thereby weakens the ocean's capacity to mitigate climate change.

Assessment of the Planetary Boundary of Ocean Acidification

- **Control variable:** Aragonite saturation state (Ω). It reflects the availability of carbonate in seawater relative to the amount needed for stable aragonite formation, with values below 1 indicating corrosive conditions. Ω is closely tied to CO₂ levels in the atmosphere, making it a useful indicator of the impact of rising CO₂ on both ocean chemistry and marine organisms.
- **Historical range:** Ω varies by region, predominantly ranging from 3.3-4.0 in tropical regions to 1-2 in polar regions.
- **Planetary Boundary:** The boundary for global mean surface Ω is set at 2.86, which is 80% of the pre-industrial value of 3.57 (estimated by Jiang et al. 2023). The 80% threshold was selected with the aim of preventing large-scale aragonite undersaturation in high-latitude waters, while maintaining well-oversaturated conditions in low-latitude regions, thereby limiting harmful impacts on marine calcifiers.

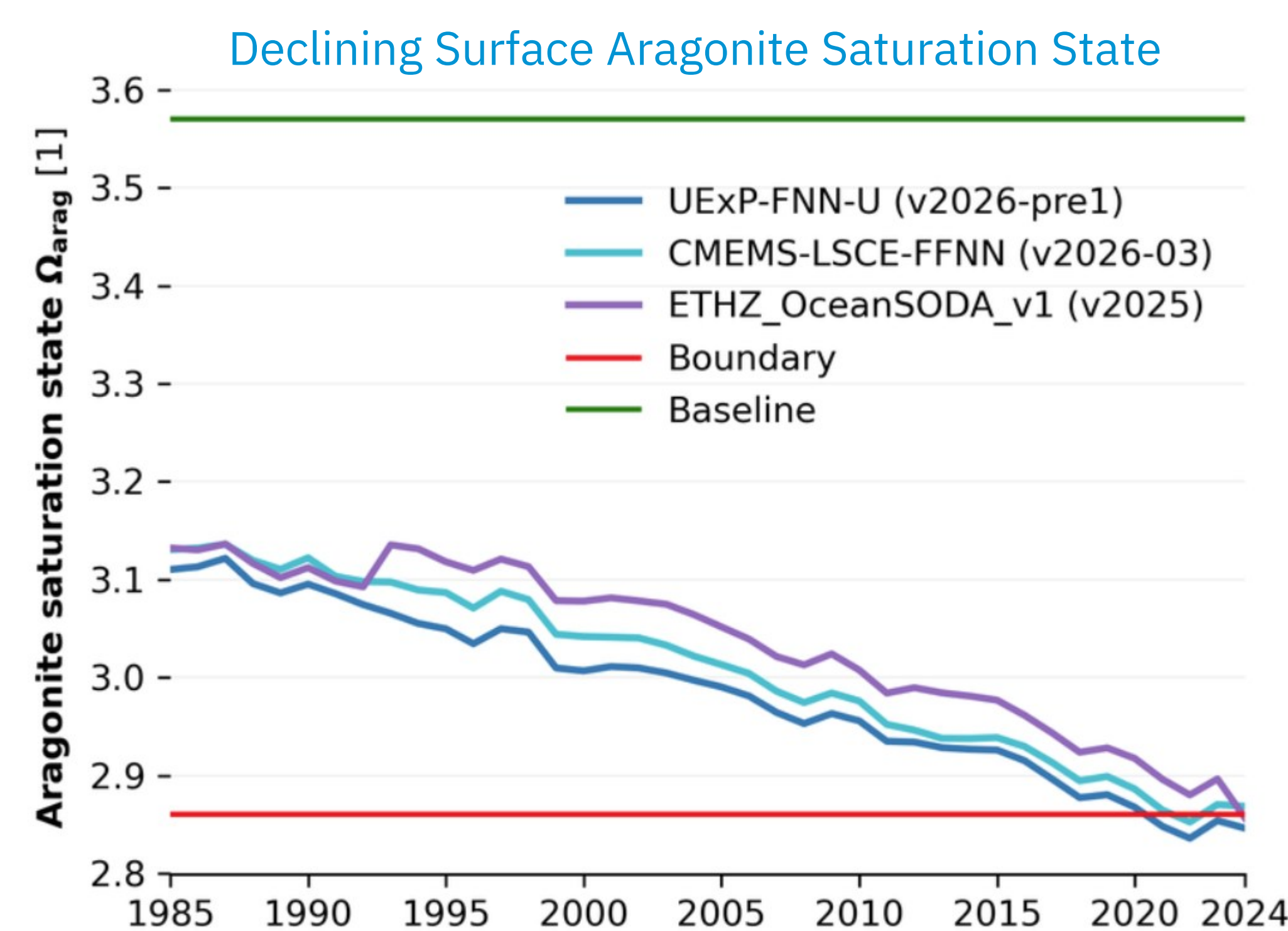


Figure 2. Global annual mean surface aragonite saturation state based on UExP-FNN-U, CMEMS-LSCE-FFNN, and OceanSODA-ETHZ. Global means are calculated on each product's native grid; differences between products largely reflect differences in spatial coverage.

Declining Surface Aragonite Saturation State

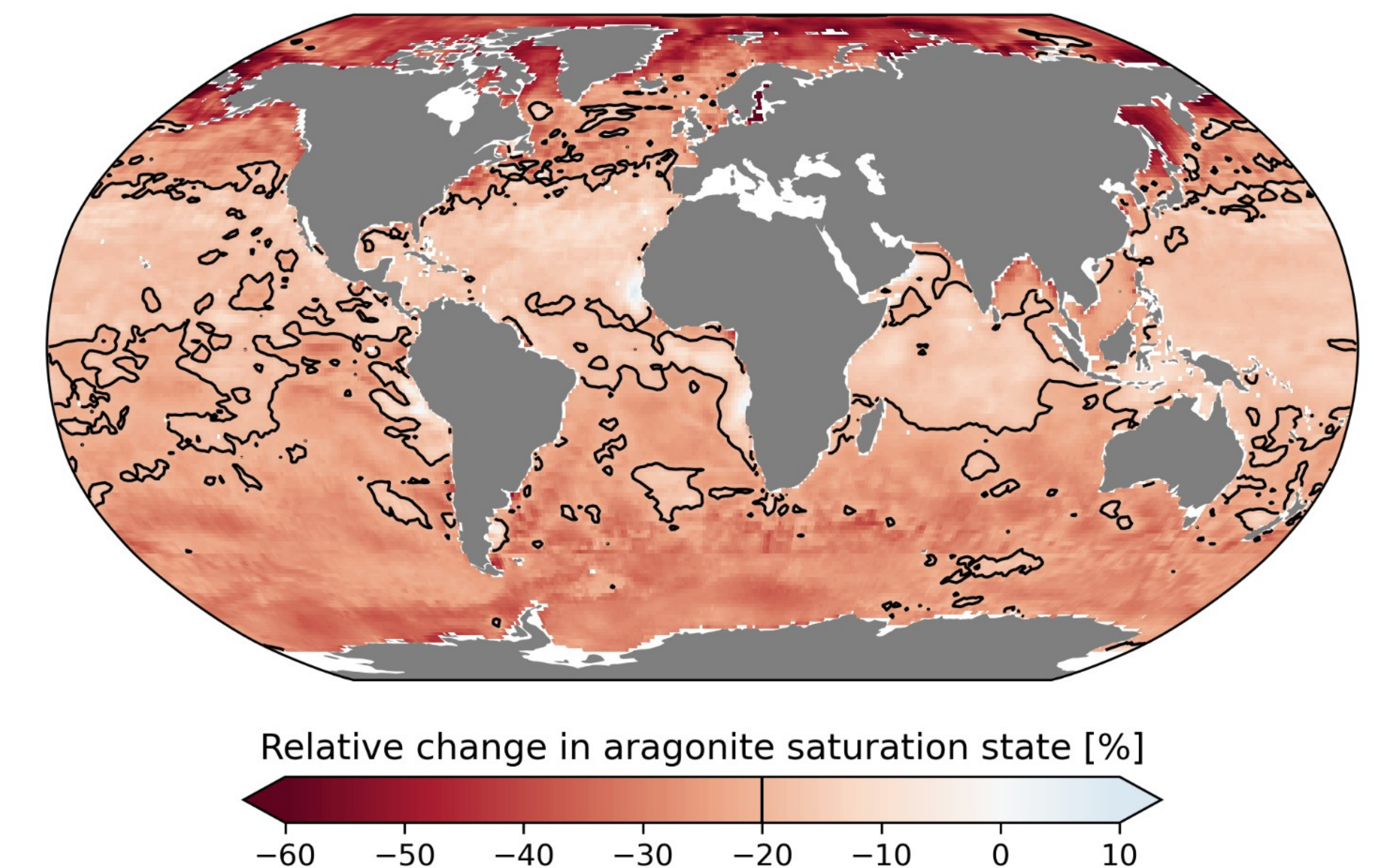


Figure 3. This map shows relative anomalies in surface aragonite saturation state for the year 2024 (based on UExP-FNN-U) with respect to year 1750 (based on observationally-adjusted CMIP6 model results, Jiang et al. 2023). The contour line marks a decline of 20%.

Potential Improvements for Future Assessments

- **Re-evaluate boundary value:** Research of the past years demonstrates that the biological impacts of ocean acidification set in earlier than previously thought (e.g., Bednaršek et al. 2019).
- **Ocean interior acidification:** Acidification of subsurface waters can be more severe than acidification at the surface and is highly relevant for marine life, yet so far excluded from our PB analyses.
- **Regional variability:** Changes in regional variability are of greater relevance for biological impacts than changes in the global mean.

We are currently exploring approaches to further strengthen the scientific robustness of analyses of ocean acidification within the Planetary Boundaries framework and welcome further scientific input and expert feedback.

References

- Richardson et al., "Earth beyond six of nine planetary boundaries.", *Science advances* 9.37 (2023).
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