Supplement Text S1. Reported impacts of ecosystem stressors in coastal regions

Warming: Surface warming of the coastal ocean has been reported in regions around the world (Supplement Table S5), which could have the superimposing effect of increasing coastal marine heatwaves (Capotondi et al., 2024; Hu et al., 2021). Surface water warming weakens the CO_2 uptake of waters, but decreases the buffering capacity of the carbonate system, thus enhancing acidification (Doney et al., 2012). It also reduces the ability of marine waters to store oxygen (Takano et al., 2023). Warming of the coastal ocean has been reported to affect the viability of corals (Perry et al., 2025), aerobic marine species (Moree et al., 2023), as well as impact greenhouse gas exchange (Resplandy et al., 2024). Surface warming on continental shelves may reduce exchange with open ocean waters through enhanced stratification (Mathis et al., 2019), thus affecting the ecosystem environment through changes in water sources and residence times (Lacroix et al., 2021).

Acidification: Ocean acidification and its implications are also largely reported in many regions around the globe (Supplement Table S5). Coastal OA increases calcium carbonate solubility, which can be detrimental for the growth and survival of calcifying organisms in coastal regions, such as corals and shellfish (Fabry et al., 2008; Hoegh-Guldberg et al., 2019). OA may also impact non-calcifying fish by impairing their sensory ability to find suitable settlement sites (Dixson et al., 2010) and detect predatory cues, as well as the viability of coastal vegetation (Hall-Spencer et al., 2019). Lower pH reduces the oxygen-binding capacity of respiratory proteins in some fishes and mollusks, which acts against the aerobic scope for activity (Doney et al., 2012).

Primary Productivity and Algae Blooms:

Eutrophication due to river nutrient inflows combined with warming of the climate is known to lead to regional blooms of harmful algae (Heisler et al., 2008). The increased biomass produced by the algae can, however, lead to deoxygenation once it sinks as detritus (Fennel and Testa, 2019), potentially enhancing the size of hypoxia areas, so-called dead zones (Rabalais et al., 2010). Increased subsurface biomass also enhances subsurface acidification due to the degradation of the organic matter (Cai et al., 2011). High algae concentrations can also induce light-shading, which can be detrimental to benthic species, such as corals (Bessell-Browne et al., 2017). Increased primary productivity owing to nutrient supply can, however, also have the positive climate impact of increasing the uptake of carbon from the atmosphere (Dai et al., 2022).

Deoxygenation:

Deoxygenation generally impacts the growth, body size, and habitat of marine species (Moree et al., 2023), and can enhance CH_4 and N_2O, which form under anaerobic conditions (Resplandy et al., 2023; Rosentreter et al., 2023). Declining oxygen levels below a critical threshold, known as hypoxia, have led to mass mortalities of organisms in several areas (Diaz and Rosenberg, 2008). Areas of hypoxia are growing in the ocean, although the expansion of coastal hypoxia zones are uncertain (Breitburg et al., 2018; Schmidtko et al., 2017). Hypoxia strongly affects the physiology and activity levels of marine organisms (Wu 2012).

Supplement Text S2. Extending model runs to 2022 and in the future based on past relationships

We investigated both the model's and observation's past transient response of coastal ocean environmental variables to human-caused climate and eutrophication changes (see Extended Figure 2-a-d, Supplement Table S4). For this purpose, we chose atmospheric CO_2 and riverine nitrogen transports as explanatory metrics since they are partly directly controllable through human actions to increase/reduce greenhouse gas emissions and river pollution, and evaluated their past long-term trend relationships with ecosystem stressors derived from both models and observations (Extended Figure 2). We firstly find a strong correlation of global coastal SST with global atmospheric CO_2 concentrations (R^2=0.97-0.98 for 1980-2022), with the averaged rate of warming of 0.008 ± 0.001°C ppm^{-1} reflecting the strong relationship of coastal warming caused by global anthropogenic CO_2. H^+ changes also show high correlation with atmospheric CO_2 changes in both model and simulations (R^2=0.99), increasing at a rate of per ppm CO_2 (Figure 5-b). Long-term coastal NPP changes show robust correlation with the changes of global river nitrogen exports to the ocean (R^2=0.99) as well as with atmospheric CO_2 (0.92-0.93, (Extended Figure 2)). O_2 is partly correlated with global atmospheric CO_2 concentrations (R^2=0.82-0.96, Extended Figure 2), albeit one of the most uncertain and weakest driver correlations, likely due to the multiple sources of influence of O_2 concentrations, ranging from increased temperature effects on solubility, shelf circulation changes, and the sources/sinks of O_2 from biological processes (Cai et al., 2011).

We extracted past linear relationships of SST to estimate first-order projection estimates based on future CO_2 emissions and river N transports (Extended Figure e-h). While these estimates only give a rough indication of future change with continuing emissions and riverine transports, they are limited due to non-linear change that may occur at the large scale, as well as the crossing of possible critical thresholds. Modelled and observed SST, H^+, and O_2 were correlated with past atmospheric CO_2, while model and observed NPP correlated with past river N transports (Supplement Text S2, Supplement Table S4). The future 2100 levels of atmospheric CO_2 were taken from Meinshausen et al. (2019)**Error! Reference source not found.**, and 2100 riverine N transports were derived from Beusen et al. (2022)**Error! Reference source not found.**, based on extending the data that only covers the period to 2070, to 2100.

Supplement Text S3. Description of Ecosystem Stressor Change in Regional Classes

Polar: Due to Arctic amplification, sea-ice free waters are warmed rapidly. Cold Arctic waters also generally allow for stronger CO_2 uptake and acidification. Sea ice decline ongoing decline increases CO_2 dissolution, and thus acidification as well. Sea ice melting due to atmospheric warming and additional river heat fluxes however also decreases the amount of O_2 dissolved within the surface ocean. NPP increases due to climate-driven effects and potential increase in terrestrially-derived nutrient sources.

Subpolar: Often large cold shelves with disproportionate increase in SST due to high latitude atmospheric warming, but moderate increases in H^+ and NPP. Changes are majorly driven by both climate-driven and riverine effects. Atlantification and warming of the Barents Sea plays a strong weight for regional average, while Patagonian shelf undergoes low rates of change.

Marginal: Large marginal shelves with widespread shallow areas, high shelf water residence times and diminished exchange with the open ocean are areas of disproportionate warming, acidification, and high river influence. Deoxygenation effects are however limited in the water column likely due to the shallowness of the waters.

Western Boundary: Generally around average coastal ocean warming and acidification. While some regions (Gulf of Maine) are strongly affected by changes in shelf circulation, others (East China Sea, Chesa) are strongly affected by changes in riverine inputs, reflecting in NPP increases. Deoxygenation is estimated at around the average global coastal rate.

Eastern Boundary: Changes in eastern boundary upwelling systems are uncertain due to the uncertain response of coastal wind. Our analysis tends to suggest more upwelling averaged over all regions, reflected in slower than average warming rates, averaged acidification, higher NPP, and increased deoxygenation.

Monsoonal: Strong increase in SST due to potentially stronger stratification with precipitation increases. NPP is declining on most shelves due to enhanced stratification, but large river nutrient increases on certain monsoonal shelves (e.g. the Bay of Bengal) can overall enhance primary productivity.

Tropical: Strong stratification at the shelf break of tropical shelves to a degree enhances effects of warming, acidification, and increasing nutrient supply, which efficiently translates into larger primary productivity increases.

River-driven: Areas of stronger stratification and river inputs, act as areas of stronger primary productivity, which can reflect in stronger acidification and deoxygenation rates, especially in the subsurface. Higher surface warming than average.

Open ocean-driven: Subject to trends occurring in open ocean subbasins and the degree of exchange between shelf and open ocean.

Supplement Text S4. Advantages and limitations of individual models and observational products applied to the coastal ocean

Model approaches: The models applied here represent strong advancements in terms of coastal representation compared to global ocean biochemical models used in current global assessments (e.g. Canadell et al., 2022; De Vries et al., 2023; Friedlingstein et al., 2024). They are run at a very high resolution for the global coastal ocean domain (around 0.1-0.4 °), they represent sedimentary processes and they account for river inputs to the ocean and their changes (Lacroix et al., 2021-b; Mathis et al., 2022). ICON-COAST also features a number of important coastal-specific biogeochemical processes, such as tidal wave resuspension, particulate aggregation, and temperature-dependent organic matter remineralization. They still, however, likely misrepresent physical processes in the coastal ocean due to relatively low horizontal and vertical resolution for fine-scale bathymetry and circulation (e.g. Ward et al., 2020), as well as omit many potentially important biogeochemical processes. These could, for instance, mean either positive or negative bias in mixing of coastal waters with the open ocean (Liu et al., 2019; Lacroix et al., 2021), which impacts the biogeochemical composition of the coastal waters.

Coastal ecosystem effects caused by coastal vegetation, coral reefs, and benthic carbonate shell producers are also not taken into account in either model configuration. Coastal vegetation may play a role in regulating the effects of eutrophication, acidification, and deoxygenation, while the dissolution of coral reefs, to a degree, acts against acidification. Certain biological effects, such as variable stoichiometry of biomass and acclimation of phytoplankton to climate and other environmental changes, are not represented, which could have implications for biological productivity changes facing increasing nutrient loadings. Increasing riverine loads of terrestrial carbon since preindustrial (Regnier et al., 2013; 2022) are not explicitly accounted for in the models presented here, and could either contribute to higher H^+ ion production and deoxygenation through enhanced organic matter decomposition, or increased alkalinity inputs to the ocean through increasing weathering sources of bicarbonate (e.g. Guo et al., 2015).

Observational products: Satellite-based retrievals of surface temperature are a state-of-the-art methodology to retrieve surface temperature, but they may comprise a certain degree of uncertainty at the coastal local level. Low-resolution products, for instance, may not resolve coastal bathymetry to an extensive enough degree to resolve coastal features and or even certain narrow coastal regions. Coastal zones are particularly challenging to study from space due to different land versus sea characteristics and shallow-water response to observed signals as opposed to the pelagic (open ocean) zones. Consequently, algorithms tuned for the latter may at times be suboptimal for coastal zones of individual regions (Smit et al. 2013). Natural processes, such as weather systems, currents, upwellings and downwellings, and bathymetry, exacerbate retrieval challenges.

For individual regions, it has been reported that local trends derived from highly-resolved SST products may have a bias of up to 0.1 °C per decade in either positive or negative direction compared to local in-situ data (e.g., Massud-Ul-Alam et al., 2022), which would likely also partly affect SST trends computed here. As the SST products are also used as inputs for the H^+ O_2 and NPP products presented here, the uncertainties in SST could propagate to these variables. We note however that we investigate the trends at the coarse regional scale in our study, and such local bias may be compensated at larger aggregations.

H^+ products shown here rely on spatially resolved carbonate system data products, which provide state-of-the-art coverage of the global ocean based on machine-learning algorithms trained on in-situ measurements. Since these rely on available measurements for gap filling, the availability of data in the heterogeneous coastal ocean may not always be sufficient to weigh specific important coastal processes. The availability of data is especially potentially lacking in terms of time series, which means that trends can be limitedly evaluated. Differing dominant coastal processes in the coastal ocean compared to the open ocean may also, to a degree, limit the robustness of the products in certain regions.

VGPMs are currently using satellite-derived products that estimate spatial NPP based on chlorophyll retrieval, using assumed relationships with SST, produced biomass carbon ratio, and light use efficiency. The chlorophyll product is close to a direct retrieval from satellite data through reflected greenness. The VGPM standard product shown here has the limitation that it ignores photo-acclimation and simply equates chlorophyll-*a* concentration to phytoplankton biomass (Taboada et al., 2019), which would, however, require further assumptions to model. Another recognized limitation is that it estimates the maximum rates of productivity through a simple relationship with available light and SST rather than factoring in the effects of nutrients or variable community composition (Behrenfeld and Falkowski, 1997). This could be especially important in ecologically diverse areas of the ocean, especially since the coastal regions are known to be particularly ecologically diverse. The VGPMs do not account for subsurface productivity, through for instance benthic species and submerged vegetation (macroalgae, seagrasses). This limitation could mean an underestimation of biological productivity trends shown in our study.

Global temporal oxygen datasets resolve global ocean deoxygenation by interpolating from available measurements, as well as through the application of machine learning algorithms. While the products cover the coastal ocean, the quality of the data in these regions may, however, be limited to a degree (A. Ito, personal communication). In terms of oxygen data, the large heterogeneity of the coastal ocean requires greater amounts of in-situ data points, especially in terms of subsurface data. A lack of data, especially to construct temporal relationships, may have important limitations for interpolation products, such as in Ito 2022, as well as the machine learning algorithm of Ito et al., 2024, which would require large amounts of data to train accurately. Areas of hypoxia may also be found at a local scale, for instance, close to river deltas and estuaries (Breitburg et al., 2018), which would require datasets of very high resolution (Ward et al., 2020), currently unavailable. Ongoing efforts such as GO_2DAT (Gregoire et al., 2021) may, however, lead to a future improvement of both coastal and open ocean databases of deoxygenation.

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