Bourgeois et al. – Pathways for avoiding ocean biogeochemical damage: Mitigation limits, mitigation options, and projections.

Summary

Bourgeois and colleagues investigate the date when "safe operating limits" are crossed with regard to ocean properties under 3 different climate change scenarios over the next century. They predefine 4 limits for each of 14 properties, from safest (least change) to the least safe (most change) based on their review of the literature. Of their 14 properties, they consider 5 physical properties, 5 chemical properties, and 4 ecosystem properties. They assess time at which limits are crossed using a multi-model ensemble, and in doing so, they are able to provide a a measure of mean ± range in the date, plus a measure of confidence based on how many models agree. High confidence is afforded to those limits that are passed by > 80% of models, and low confidence when < 50% of models show an exceedance of the limit.

The authors present their analysis in 8 Figures and discuss, in simple terms, when exceedances of the limits are passed for each of the 14 properties. They also assess the global warming levels at which point some of the limits are passed, which is a nice addition to their study.

I have some recommendations that I hope the authors can take into account to improve the manuscript.

Main recommendations:

1. After reading the paper, I came away with little clarity in what I had learned. That might seem harsh, but what I am asking for is greater focus in the communication of the main results. There is a lot of data, and given that there are 14 properties with 4 limits, a lot of information to condense. This expansive thinking and data analysis is admirable. However, I think it is important to focus in on some key properties, one at a time, or perhaps separate them into groups (physical, chemical, biological) and address when safe limits are passed in a more systematic manner. This way, a biologist can come along to your paper and immediately seek out the "biology" section and get a sense of when some limits might be passed that are relevant to their work.

2. Another suggestion I have is to place your "safe operating limits" within an ecological, socio-economic or geopolitical context. Everything depends on this. You start with this in your definition of them, but I ask that you then circle back to this at the end within a discussion section (currently not existent). So that I try to be constructive with this suggestion, I will try an example: The collapse of the AMOC or at least its weakening would have socio-economic and geopolitical ramifications, as well as ecological as AMOC transports a lot of heat and nutrients to the subpolar North Atlantic. Passing of AMOC limits might interact with the passing of NPP and biomass limits in the North Atlantic, affecting fisheries as well as temperature and thereby affecting food supply and energy demands of the region. It would also cause heating in the Southern Hemisphere that may cause more extremes in places like Australia, Southern Africa, ect. These sorts of considerations are essential to make your results concrete and tangible for the reader. Everything depends on context setting. Without

this, I finish the paper and think very little of it, not knowing what I've learned and what happens if we cross limit 2. And, it will also help improve your citation of the literature, which at the moment seems inadequate to me when finishing the paper.

3. I also feel that the presentation of the results needs some extra thinking. The statement starting on line 315 that "For the less ambitious mitigation limits, exceedance time estimates generally move towards later times and higher warming levels", doesn't seem to be the case. Looking at Figures 1 and 2 shows that for most properties, the exceedance time is generally *earlier* for the SSP1-2.6 scenario than the SSP5-8.5 scenario. This is the case specifically for:
    - MHW duration
    - Metabolic index
    - Change in biomass
    - Change in AMOC
    - Change in SSL
    - Change in POM flux
    - Global change in dissolved oxygen

    From my reading of Figures 1 and 2 it seems to be rarely the case that "estimates generally move towards later times". Only global change in oxygen at limit 3, and the area of $\Omega_A > 3$ at limit 1 seem to satisfy this statement. I understand and agree with the fact that less models under SSP1-2.6 are exceeding the limits, so the dates that are presented in Figures 1 and 2 are those built from a smaller subset of models that are almost certainly more sensitive. Meanwhile, later exceedances under SSP5-8.5 are the cause of including the less sensitive models. This makes me wonder if this is the right way to present the data… I think the authors should go away and reconsider how to present this information so that they more appropriately present the times of exceedance, because without a careful reading of the paper as it currently stands, the reader will come away confused about the fact that SSP1-2.6 appears more extreme in its effects on the ocean than SSP5-8.5. Perhaps the models themselves need to be compared individually, or grouped into sensitive and un-sensitive models?

4. Another criticism I have with the paper is the use of an 1850-1900 baseline to assess marine heatwave duration. As the authors report, this results in a near-permanent heatwave by the end of the 21st century under the high-emissions scenario. But, ecologically, this is not so interesting. What is more ecologically interesting is to move the baseline incrementally at a rate that captures some degree of physiological adaptation or evolution. For microscopic organisms, this rate might be fast, while for mammals and other top predators, this baseline might be very slow, if not static like the authors consider here. With a rapidly shifting baseline, the authors would be able to comment on the prevalence of anomalous heating events that marine ecosystems, given an ability to adapt, would still not be physiologically prepared for. The authors could assume two extreme cases: they keep their static baseline of 1850-1900 to reflect on the effects to top predators where adaptation is slow, and consider a moving baseline that is always positioned a few years earlier (e.g., 20-year climatology of 1991-2010 when assessing extremes in 2011.) to reflect a rapidly adapting

group of microscopic organisms (e.g., Jin and Agustí, 2018). This also opens the door to extreme cooling phases in the overshoot scenario, which would offer a unique perspective.

5. I also think the description of the EMICs was lost on me. What is the importance of these models and why did you use them? Why do we need to know the specifics about their ensembles and the optimisation of the UVic? Why was this optimisation important for your work? What is the skill of the emulator? What does it tell us if the EMICs and CMIP6 models disagree? I think you have to demonstrate that the use of the EMICs was qualitatively essential to your conclusions, and I do not understand that from the writing as it currently stands.

Specific comments (note that I have held back on specifics until the main comments are addressed):

- Figures 1 & 2: Can you put the x-axis labels (years or global warming level) on the top of the panels as well? It is hard to see the year at which MHW limits are exceeded, for instance.
- Figures 1 & 2: Can you arrange your y-axis categories in order of introduction in your methods? First do the 5 physical properties, then the 5 chemical, then the 4 biological?
- Figure 6 legend needs to say why it doesn't include SAT, even though it's obvious. Just to help the reader out a bit.
- I think it would be better to spell out the properties, rather than use the short hand symbols. For example, use Southern Ocean $\Omega_A < 1$ rather than A_{SO}.
- Line 293: The findings of which were what?
- Line 294: Why were substantial uncertainties in O2 found?
- Line 315: What does "less ambitious mitigation limits" mean?

Thank you for considering my input to your research,

Pearse J. Buchanan.