



EGUsphere, author comment AC1  
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## Reply on RC1

Abigale M. Wyatt et al.

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Author comment on "Ecosystem impacts of marine heat waves in the northeast Pacific" by Abigale M. Wyatt et al., EGU sphere, <https://doi.org/10.5194/egusphere-2022-17-AC1>, 2022

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**We thank the reviewers for the helpful comments to improve our manuscript. We are confident that we can strengthen the manuscript with a discussion of the significance of our results following both reviewers' suggestions. In particular, we propose to add a new figure (inserted below) which shows the magnitude of the biological response to marine heat waves in comparison to interannual variability in both the Alaska gyre and transition zone, and allows to discuss the changes that are significant vs. the one that are relatively mild (i.e. amplitude lower than one standard deviation, see details in comment R2-2 below). This figure demonstrates that while marine heatwaves are classified as extreme events, the response of biological production to these events is relatively mild compared to each region's interannual variability.**

**Please see below for a detailed response to each comment.** Note: Reviewers comments are in plain text, *while manuscript quotes are in italics*. **We hope these proposed changes are satisfactory for us to move forward with the publication in Biogeosciences.**

This paper focuses on quantifying and explaining ecosystem impacts of marine heat waves in the NE Pacific, using a modelling approach supported by observational comparisons. The focus is on anomalies in chlorophyll and phytoplankton and their drivers. The topic is of high interest to the community. Several recent papers and theses look at the impacts of the 2014-15 Blob on productivity rates, ecosystem assemblages, and biogeochemical measurements like trace metals. This study broadens that work to consider a wider spatial area, assess drivers quantitatively, and provide some context for the results of previous work like decreasing nitrate observed by BGC-Argo floats. However, in many places in the paper, I was left wondering about whether the small changes detected were significant. Including statistical tests for significance would strengthen the paper, making the overall message more convincing. In general, the paper is well written, but I do have a few additional comments that I think could further improve it.

This paper reports many anomalies for marine heat waves based mostly on model results. Some of the anomalies are very small relative to the absolute concentrations or rates. Which ones are significantly different from zero? The paper would be strengthened by including a statistical test for significance in each case where a change associated with marine heat waves is reported, providing clarity for which changes are significant and which should be reported as no change within error. Examples include (but are not

limited to):

- 2% lower large phytoplankton population in the AG
- 2% decrease in large:small phytoplankton in both regions
- 05 mg m<sup>-3</sup> decline in chlorophyll in the NPTZ and 0.02 mg m<sup>-3</sup> increase in chlorophyll in the AG – The AG value is especially small compared to mean chlorophyll in this location. Is the mean for MHW years significantly different from the mean for other years, given the fairly high variability in this region?
- Mean-MHW values throughout sections 3.3 and 3.4. With 9 MHW years and many non-MHW years in the model, it should be straightforward to calculate whether the MHW years are significantly different (perhaps a Mann-Whitney test or similar) in different months.
- 13% lower large phytoplankton production
- The location of the 2 μM nitrate contour in Figure 5b. Given the variability in the location of this contour in the 9 MHW events, is the mean significantly different from the all-year average?

**We address the significance of the listed statistics in the new proposed figure (see below) which compares the size of the marine heat wave composite biological anomalies to the interannual variability of each region. This figure shows that chlorophyll and phytoplankton production anomalies tied to marine heatwaves can for some of these events reach relatively high values compared to the interannual variability exhibited in each region (i.e. of the order of 1 to 2 standard deviations). For instance, in year 1965 there are strong negative production anomalies ( $>2.2 \sigma$  for large phytoplankton production;  $>2.1 \sigma$  for small phytoplankton production) in the NPTZ. Yet, on average across the 9 events, and in contrast to prior work using satellite-based chlorophyll (e.g. Whitney 2015), we find that chlorophyll, phytoplankton and zooplankton production respond relatively modestly to marine heatwaves in both regions (variability of the order of 1 standard deviation or lower, new Figure). Notably, however, we find a relatively robust decrease in the ratio of large phytoplankton to small phytoplankton production across all events and in both regions (meets or exceed 1 standard deviation), suggesting that marine heatwaves in the northeast Pacific result in a shift of the phytoplankton assemblage favoring small phytoplankton production.**

**Thus we propose to complement the result section and discussion using this figure and have rewritten the abstract as follows:**

- *Marine heatwaves (MHWs) are a recurrent phenomenon in the Northeast Pacific that impact regional ecosystems and are expected to intensify in the future. These events, including the 2014–2015 “warm blob,” are associated with widespread surface nutrient declines across the subpolar Alaska Gyre (AG) extending south into the North Pacific Transition Zone (NPTZ) with reduced chlorophyll concentrations confined to the NPTZ only. Here we explain the contrast between these two regions using a coupled global ocean-biogeochemical model (MOM6-COBALT) with Argo float and ship-based observations to investigate how MHWs influence marine productivity. Our study finds that chlorophyll, phytoplankton and zooplankton production respond relatively modestly to MHWs in both regions (variability of the order of 1 standard deviation or lower), with the stronger response in the NPTZ. Differences in the reaction of the two primary phytoplankton size classes (large  $>10 \mu\text{m}$ , small  $<10 \mu\text{m}$ ) to changes in seasonal iron and nitrate limitation explain the differences in ecosystem response to MHWs across the two biomes. The reduced nutrient supply during MHWs strongly influences large phytoplankton in the NPTZ (-13 % annually), whereas it has a limited impact on the usually iron-limited large phytoplankton population in the AG (-2 %). In contrast, we find that MHWs yield a small springtime increase in small phytoplankton population in*

*both regions due to shallow mixed layers and higher mean irradiance. These modest primary production anomalies, however, modify the phytoplankton size distribution, resulting in a significant decrease in the ratio of large to small phytoplankton production that meets or exceeds the time series interannual variability. This shift in the assemblage towards small phytoplankton production is associated with reduced secondary and export production, especially in the NPTZ.*

**And the new figure caption will read:**

- *Fig ##: Composite anomalies during MHWs compared to the standard deviation of the spatially averaged interannual variability (in units of sigma) for a) the AG (red) and b) the NPTZ (black). Chl is shown as a monthly mean while large phytoplankton production, small phytoplankton production, the ratio of large to small phytoplankton production, total zooplankton production and export production are annually integrated. Individual heat wave years shown chronologically from left to right as faded blue rectangles.*

**Note on method for the new figure: To calculate the composite anomalies for the 6 ecosystem variables, we detrended the model time series, calculated at each model grid point. We then used these detrended data to update figures 6, 7 & 8, which also examined composite anomalies. The area averaged composite anomaly was compared to the area averaged standard deviation of the monthly model output (1958 - 2020), which we used as a metric of interannual variability.**

Boundaries of nitrate and iron limitation are discussed, but I'm unsure of how these are defined. Nitrate limitation may be defined by the 2  $\mu\text{M}$  contour line, though this should be explicitly stated. I'm not sure what iron value would be considered limiting here. In general, the iron concentrations in the model (Figure S2) seem very high with modelled values around 100-150 nM iron in winter, whereas typical values for dissolved Fe in the region appear to be < 1 nM (see <https://doi.org/10.1016/j.marchem.2015.04.004> for example). Is the model iron limiting anywhere? I could not discern the hatching in Fig. 6 discussed in Line 222 or the gray and purple lines discussed in Lines 225-226.

**We apologize for the confusion here which was also mentioned by Reviewer 2. This paragraph references a figure showing limitation boundaries that was removed prior to the original submission. This paragraph will be edited to reference the Line P data analysis only.**

- *The Line P data support the model result and show an expansion of the nitrate-depleted region during the 2014–2015 "warm blob" (Fig. 4), leading to a westward shift of the 2  $\mu\text{M}$  boundary to 140° W in 2014 (vs a location of ~130° W in the other years). In the model, this westward shift of the nitrate boundary is overestimated, extending past 140° W. Thus, in both the observations and model this implies that nitrate becomes depleted inside the climatological boundary of the HNLC AG. The HNLC region can therefore be considered to contract while the nitrate-depleted region expands.*

How are the limitation factors shown in Figure 7h defined? This section, along with that around Line 58, also caused me to wonder about the role of light limitation. Is the NPTZ actually iron limited before the spring bloom or is it light limited then? Is there grazing limitation that is important to controlling the size of the spring bloom in the NPTZ?

**The nutrient limitation factors are computed in the model based on saturating kinetics. For instance, nitrate limitation is based on a Michaelis Menten formulation. We have updated the methods section 2.3 to clarify how they are**

**computed.**

- *Phytoplankton growth is explicitly modeled as size-dependent functions of light, temperature and nutrient limitations (nitrate, ammonia, phosphate, etc.). Small phytoplankton are simulated to be efficient nutrient and light harvesters (Munk and Riley 1952; Geider et al. 1997) in contrast to large phytoplankton, which are parameterized to grow quickly in response to abundant nutrients. Notably, in the study regions, this results in large phytoplankton being sometimes iron limited while small phytoplankton are not. The limitation factors are output from the model as a number between zero and one, with zero indicating complete limitation, i.e. no phytoplankton growth.*

**And, yes you are right, iron is the main limiting nutrient in spring in the NPTZ, as can be seen in figure 7. However, as we state in section 3.3 light limitation is indeed a significant factor before the spring bloom that we have chosen to discuss in terms of mixed layer depth, (shallower during marine heatwaves) as follows:**

- *The model suggests that marine heat waves promote the growth of small phytoplankton and small to medium-sized zooplankton in early spring before dropping in summer–fall (Fig. 7e,f), due to the shallower mixed layer in winter and early spring (-10 m, Fig. 7b) that relieves light limitation and spurs small phytoplankton production (a positive production anomaly of +2 mmol m<sup>-2</sup> d<sup>-1</sup>, Fig. 7e).*

Minor suggestions:

Line 92: I was very surprised to read that chlorophyll data was not available for 2008-2010 from Line P. I contacted chief scientist, Marie Robert, to ask. She looked into it and has found that the data exists but that there is a problem with some of the summary .csv files. Some individual casts seem to contain the data but the whole cruise files do not. She is working on updating the files. I suggest you contact her directly for updates: Marie.Robert@dfo-mpo.gc.ca

**We have reached out to Maire Robert and Figure 4g will be updated with the new data, which aligns with the model and reinforce our initial conclusions.**

Section 2.5: Suggest BGC-Argo rather than bioArgo. Suggest referencing Appendix A here.

**Changed as suggested. Reference to Appendix A added.**

Line 175: Fig. X

**Corrected to Fig. 4b**

Lines 203-214: Suggest mentioning in this section that the high nutrient regime near the coast is temporally variable and mainly controlled by the timing of upwelling events.

**The text was changed to:**

- *The Line P program's June and August cruises sample three regimes (Fig. 4): the temporally variable, high-nitrate near-shore region (>10 □□M at ~125o W)...*

Figure 1: I'm unclear why the bounding box for the average anomalies shown in panels a and b is different from either box shown on the maps. The targeted area appears to be mainly in the NPTZ. I suggest that it would be more illuminating to show the time series

for the black NPTZ box in panels a and b rather than a different region that is not used in further analysis. Panel b: The region for this anomaly is probably the same as for panel a, but it would be good to state that. I think the location of OSP should be 50oN 145oW, not 50.1oN 149.9oW.

**The authors agree that it was confusing to include the NPTZ and AG boxes in Fig 1. Descriptions of these regions have been moved to Fig 5. We have also removed the time series of chlorophyll anomalies (panel b) to simplify the text. Figure 1 is now clarified to show the time series from which marine heat waves were selected using the box 35o to 46o N and 150o to 135o W. This specifically follows the selection and analysis of Xu et al. as detailed in the methods. The location of OSP was corrected as suggested.**

Figure 2: the colours of the float trajectories in the upper panels should match those in the lower time period panel. In particular, the brown colour in the upper panels is orange in the lower panel. Colour bar label is cutoff for panel b.

**Yes, thank you. This was a mistake and colors have been corrected to match and we have replaced the labels to ensure they are fully visible.**

Figure 3: Suggest adding property labels to the colour bars, i.e. not just units.

**We added labels (PSU, NO3 and Temp) to colorbar labels**

Also for the y-axis of Figure 10.

**We added "NCP" to Figure 10 y axis**

Figure 4: Colour bar labels are cut-off. Figure 5: Colour bar labels and legend are cut-off.

**This has been corrected to make sure full labels are visible on all figures.**

Please also note the supplement to this comment:

<https://egusphere.copernicus.org/preprints/2022/egusphere-2022-17/egusphere-2022-17-AC1-supplement.pdf>