Hotspots and drivers of compound marine heatwave and low net primary production extremes
Response to the second round of reviews by referee 2

Natacha Le Grix, Jakob Zscheischler, Keith B. Rodgers, Ryohei Yamaguchi, and Thomas L. Frölicher

November 10, 2022

The authors did a nice work to account for most of my major concerns in initial evaluation of the paper. There are however two changes that I could like the authors to consider (and some very minor comments) before the paper can be definitely suitable for publication.

We thank the reviewer for their feedback on our previous response and their in-depth reviewing of our Methods.

My first major comments relates again to their decomposition procedure. The authors indeed write (l. 295): $dn_i \sim \Delta n_i$. If I understand it well:

- dn_i refers to mean biomass anomaly between t_0 (climatological value) and t_{max} (maximum absolute anomaly relative to climatology).

There might be a misunderstanding here. We define dn as the mean biomass anomaly over all compound event days. Using the reviewer's notation, t_0 would be the first compound event day in the time series, when both SST and NPP exceed their extreme event thresholds, and t_{max} the last compound event day in the time series.

- Δn_i refers to the integrated biomass change between t_0 and t_{max}.

That is correct. In our manuscript, we had defined Δn_i as the integrated biomass change between t_1 (climatological value) and t_2 (maximum absolute anomaly relative to climatology). We like the reviewer's use of t_0 and t_{max} and replace t_1 by t_0 and t_2 by t_{max} in the revised manuscript:

Δn_i corresponds to the integrated biomass change over the period over which the biomass changes from its climatological mean value (at t_0, $n_i(t_0) = 0$) to its maximum absolute anomaly reached during a compound event (at t_{max}, $n_i(t_{max}) = n_{imax}$).

$$\Delta n_i = \int_{t_0}^{t_{max}} \partial_t n_i dt = n_i(t_{max}) - n_i(t_0) = n_{imax} \quad (1)$$

Given the formula, Δn_i is thus simply the difference in biomass between t_0 and t_{max} (i.e. $\mathrm{n}_i(t_{max}) - n_i(t_0)), [...]$

That is correct (see equation 1).

[...] while dn_i is the biomass anomaly averaged between t0 and tmax (i.e. $\sum dn_i$).

As stated above, this is not correct. We rather define dn_i as the biomass anomaly averaged over all compound event days.

By construction, Δn_i should therefore be systematically larger than dn_i (about twice larger), which indeed appears to be the case on Figure 5.

Δn_i is the mean biomass change between t_0 and t_{max} for all compound events, which is equivalent to the mean largest biomass anomaly $n_i(t_{max})$ during compound events. dn_i is the mean biomass anomaly over all compound event days. We agree that Δn_i is, by construction, expected to be systematically larger than dn_i, which indeed appears to be the case on Figure 5.

By definition,

$dn_i = (dn_i(t_0) + dn_i(t_1) + dn_i(t_2) + ... + dn_i(t_{max}))/N$, N being the number of 5-days output timesteps between t_0 and t_{max}

As explained above, we define dn as the mean biomass anomaly over all compound event days (and not the mean biomass anomaly between t_0 and t_{max}).
$dn = (dn_i(t_{first}) + dn_i(t_{second}) + ... + dn_i(t_{last}))/N^*$, N^* being the number of compound event days in the time series.

Thus:

$$\mathrm{dn}_i = (\partial_t n_i(t_0)\Delta t + (\partial_t n_i(t_0) + \partial_t n_i(t_1))\Delta t + (\partial_t n_i(t_0) + \partial_t n_i(t_1) + \partial_t n_i(t_2))\Delta t + ... + \sum \partial_t n_i(t_0 -> t_{max})\Delta t)/N$$

$$dn_i = ((N * \partial_t n_i(t_0) + (N-1)\partial_t n_i(t_1)) + (N-2)\partial_t n_i(t_2)) + ... + 1 * \partial_t n_i(t_{max}))\Delta t)/N$$

As you can see, this calculation is clearly different from $\sum \partial_t n_i(t_0 -> t_{max})\Delta t$, which corresponds to your definition of dn_i.

We thank the reviewer for writing these detailed calculations. However, we define dn as the mean biomass anomaly over all compound event days. Please note that the first compound event day in the time series may follow a day of anomalous biomass, and that compound event days are not necessarily in succession. The above calculations cannot compute dn. They would have worked well, however, to compute the mean biomass anomaly between t_0 and t_{max}.

I would either recommend calculating:

$\Delta n_i = (\partial_t n_i(t_0)\Delta t + (\partial_t n_i(t_0) + \partial_t n_i(t_1))\Delta t + (\partial_t n_i(t_0) + \partial_t n_i(t_1) + \partial_t n_i(t_2))\Delta t + ... + \sum \partial_t n_i(t_0 -> t_{max})\Delta t)/N$ (and the corresponding contributions) and compare it to the dni as defined in the manuscript.

We tried following the suggestion to redefine Δn_i as the mean biomass anomaly between t_0 and t_{max}. We recomputed Δn and its corresponding contributions as the cumulative sum of $\partial_t n_i \Delta t$, of $NPP\Delta t$, and of $Loss\Delta t$, divided by the number of time steps between t_0 and t_{max}. However, the recomputed Δn was not as good an approximation of dn as the Δn we had defined in the manuscript (see Fig. 1a-h compared to Fig. 5a-h in the manuscript). The recomputed Δn underestimates dn (Fig. 1e-h compared to Fig. 1a-d). Therefore, we stick to our previous definition: Δn remains the integrated biomass change between t_0 and t_{max}.

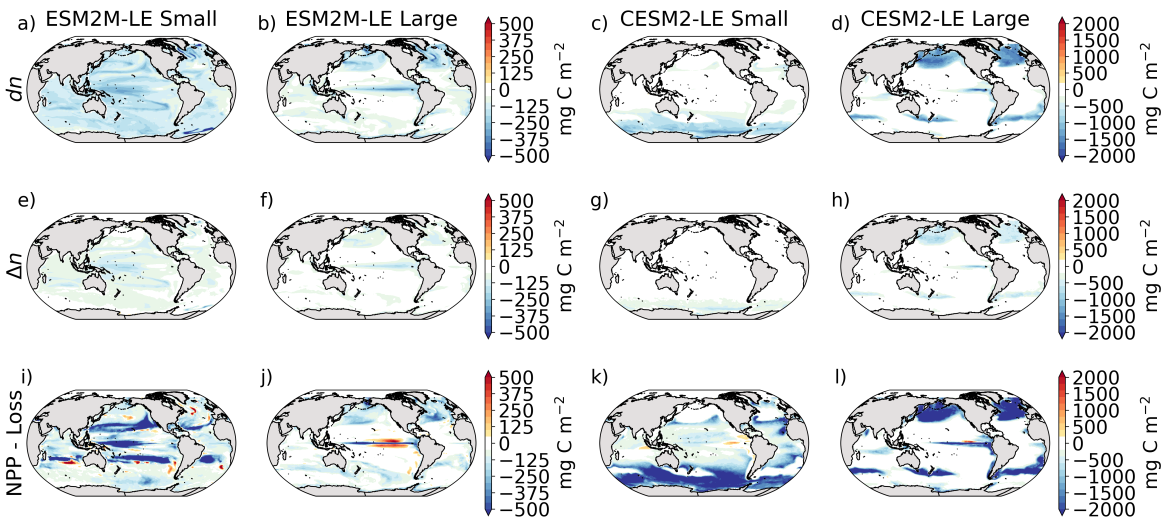

Figure 1: Biomass anomaly dn (mg C m^{-2}) of small and large phytoplankton during compound MHW-NPPX events in ESM2M-LE (a,b) and in CESM2-LE (c,d). Mean biomass anomaly Δn (mg C m^{-2}) over the period over which biomass changes from its climatological mean value up to its maximum anomaly reached during a compound MHW-NPPX event (e-h). Contribution of biological processes ($NPP - Loss$, i-l) to Δn.

Or redefine dn_i as $n_i(t_{max}) - n_i(t_0)$ and compare it to Δn_i as defined in the manuscript.

We decided not to follow the suggestion to recompute dn_i as $n_i(t_2) - n_i(t_1)$. dn remains computed as the mean biomass anomaly during compound event days, so as to stay consistent with the rest of the manuscript, where we decompose $dNPP$ into the contributions of the growth rate anomaly $d\mu$ and of the biomass anomaly dn. Note that Δn_i, the integrated biomass change between t_1 and t_2, is itself equal to $n_i(t_2) - n_i(t_1)$ (equation 1).

There will otherwise by a mathematical inconsistency and I suspect that proceeding either ways will end up in a closer match between Δn_i and dn_i in the paper.

We explain above that our definition of Δn_i yields a better estimate of dn_i, and that we do not change the definition of dn_i.

We agree that dn and Δn are, by definition, different and removed "$dn_i \sim \Delta n_i$" in equations 7 and 8. Still, one can apprehend the sign of dn by the build up of a compound event's maximum absolute biomass anomaly, i.e., by Δn. On Figure 5 of the manuscript, panels a-b and e-h are similar, which supports our method of using Δn to gain a first understanding of dn.

We clarified the difference between dn and Δn in section 2.5 where we write: "Over time, biomass changes build up a biomass anomaly dn that might be sufficient to drive or contribute to driving extremely low $dNPP$. In this study, we intend to explain the contribution of dn to $dNPP$ during compound MHW-NPPX events using equation 6. A positive or negative biomass anomaly during a compound event may be explained by an overall increase or decrease in biomass over time, until the largest biomass anomaly reached during the compound event. Therefore, we integrate $\partial_t n$, NPP and $Loss$ over all periods over which dn builds up, i.e., over which n changes from its climatological mean value (at t_0, $n_i(t_0) = 0$) to its maximum absolute anomaly relative to the climatology reached during a compound event (at t_{max}, $n_i(t_{max}) = n_{imax}$). Δn refers to the integrated biomass change between t_0 and t_{max}, which corresponds to the largest biomass anomaly reached during a compound event. Note that Δn is not exactly equivalent to dn. Δn is a tool to understand the build-up of the largest biomass anomaly reached during a compound event, whereas dn is the mean biomass anomaly over all compound event days." (l. 287-294)

Lastly, we replaced "this method would enable us to quantify the contribution of biological processes to dn." by "this method would enable us to apprehend the contribution of biological processes to dn." (l. 299)

My second comment relates to the fact that the authors do not discuss anywhere the fact that their biological contribution systematically exceeds the integrated biomass changes, i.e. that the residual systematically opposes the biological contribution. I would recommend the authors adding a small paragraph in the discussion section where they could provide hypotheses to explain this behaviour (that I still don't understand).

We added to Section 6: "Note that integrated NPP - $Loss$ generally exceeds the integrated biomass changes (Fig. 5e-l), with some exceptions, e.g., in the high latitudes for small phytoplankton in ESM2M-LE. Δn, NPP and $Loss$ terms include an error term when computed from 5-day mean, 10-meter vertically integrated biomass. Further studies at higher temporal and vertical resolution are needed to remove errors in all terms in equation 8, so as to quantify the exact NPP - $Loss$ contribution to Δn." (l. 462-465). As we do not not know these error terms, we do not want to speculate reasons for the $NPP - Loss$ contribution usually exceeding the integrated biomass changes.

Minor Comments:

L553: “(see section 2.5,”: a closing parathensis is missing.

We added a closing parenthesis.

L553: “resulting in in”: remove one “in”

We removed an extra "in".