Compound high temperature and low chlorophyll extremes in the ocean over the satellite period Response to referee comments

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0.1 General Comments

This manuscript uses satellite data to identify events in the ocean that occur at extremes of both SST and chlorophyll, "compound" events. This is an emerging field of study, particularly for the ocean and is important for understanding how our planet is changing under global warming. The paper is well written and suitable for publication. I have some suggestions for improving the manuscript.

We thank the reviewer for the positive and encouraging feedback.

0.2 Specific Comments

There has been a lot of work done, dating back to the 1980s, on coral bleaching events, which are largely temperature driven. It might be outside the scope of this paper, but it could be interesting to see if there are any similarities between the global distribution and timing of coral bleaching events and the compound events described in this paper.

We thank the reviewer for this interesting comment. Whereas a full assessment of the similarities between coral bleaching events and compound events is outside the scope of this paper, we added to the Discussion section (l. 315 to 317):
"These correspond to regions where the sea surface temperature and chlorophyll anomalies are predominantly negatively correlated, and also to regions where most of the warm-water corals are located and where coral bleaching events often occurred in the recent past Hughes et al., 2018."

Concerning the timing of coral bleaching events, El Niño became a predominant trigger of mass bleaching in the 1980s, when global warming increased the thermal stress of strong El Niño events (Hughes et al. 2018). Our study shows that El Niño is also associated with increased frequency of compound events in the eastern equatorial Pacific and in the Arabian Sea. Therefore, coral bleaching events may often co-occur with compound events in these regions during the positive phase of ENSO. The 2015-2016 El Niño event was indeed associated with both a compound event and a coral bleaching event in the equatorial Pacific (Fig. 1 of this paper and Fig. 3 of Hughes et al. 2018). However, in the past two decades, many additional regional-scale bleaching events have occurred outside of El Niño conditions (Hughes et al. 2018), since temperature thresholds for bleaching are increasingly exceeded throughout all ENSO phases due to global warming. Thus, similarities in the timing of coral bleaching events and of compound events may change over time with global warming.

Avoid the use of terms like "high-resolution", "high quality" and "high temporal-spatial coverage" as they are not quantitative terms (section 2.1). For example, they say the SST dataset they use is "high-resolution" but also state that it has a resolution of 0.25 $\circ$, which these days is not considered a high-spatial resolution for a SST dataset, just the opposite, it would be considered a rather coarse resolution, given that there are products available at $<$ 1 km spatial resolution. However, I realize that "high resolution" is part of the AVHRR acronym, so clearly the term needs to be used in that context. Similarly, they frequently refer to the 1998-2018 time period as being "short" (i.e., line 103, 299). Obviously, this is the longest record of satellite chl we have ever had. When these statements are made they need to clarify exactly how the 20 years of data is not sufficient, if that is indeed the case.

We agree and have applied the suggested changes to the manuscript. We have changed "NOAA's daily high-resolution Optimum Interpolation SST (OISST) analysis product" to "NOAA's daily Optimum Interpolation SST (OISST) analysis product"; ".. provides a high quality daily.. " to ".. provides a daily.. "; ".. with high temporal-spatial.." to "..with temporal-spatial.."; "relatively short data record" to "21-year data record".

How do the chlorophyll results of the NASA Ocean Biogeochemical Model compare to the ESA OC-CCI product? I am more familiar with that product being used when there is a need for a dataset spanning across all OC sensors.

The ESA chlorophyll product combines the existing satellite ocean color sensors (SeaWIFS, MODIS and VIIRS) and corrects for differences between sensors such as band location differences, the fact that each of the satellites observes parts of the Earth at different times, or that each sensor has its own signal to noise ratio. In our manuscript, we use a product that assimilates ocean color satellite data from SeaWIFS, MODIS and VIIRS into the NASA Ocean Biogeochemical Model (NOBM). We added the following sentences to the Methods section where we describe the chlorophyll dataset:
"NOBM takes care of differences between sensors and also provides complete coverage at a daily resolution, without the gaps that are intrinsic to satellite data due to clouds and high solar zenith angles. Its chlorophyll outputs have been validated against the NASA satellite products (Gregg and Rousseaux 2014)."
Indeed, even though the chlorophyll outputs of the NASA Ocean Biogeochemical Model have not yet been compared to the ESA OC-CCI product, they have been validated

against the NASA satellite products (Gregg and Rousseaux 2014) as we further explain: "The annual median chlorophyll is similar when computed using the satellite products or the NOBM products, although in the high latitudes, areas of high chlorophyll in the satellite products are reduced in the assimilation data. According to Gregg and Rousseaux 2014, these are artifacts of satellites sampling only the warmer, more sunlit months while the assimilation model produces information for all days of the year. In the North Indian Ocean, high chlorophyll due to seasonal aerosol obscuration in the satellite product is also reduced when assimilated. Trends in global mean chlorophyll are similar from 1998 to 2012 in both the satellite and assimilation products."

0.3 Technical Comments

Section 2.2.3 It is difficult to keep track of all of these climate indices as written here – it might be easier to digest if this information was presented in a table.

We added a table in section 2.2.3 that summarizes the climate modes used in our study, their indices, and their associated acronyms. We also moved the exact definition of these climate indices into the Appendix to facilitate the reading of section 2.2.3.

Figure 2. Why is just the time period 2013-2015 shown? And why this location?

We extract a short time period at one grid cell to facilitate the visualization of MHWs, LChl events and compound events on a single graph. We chose a grid cell in the equatorial Pacific and a time period between 2013 to 2015 because we knew from Fig. 1 that during the Blob, a long MHW co-occurred with extremely low chlorophyll in this region.

Figure 4 and 5. Since the data shown in Figure 5 is very relevant to that shown in Figure 4, I wanted to be able to look at them side by side, which is difficult since they are on separate pages. Consider merging these together into one plot.

We like this suggestion and merged the two figures. Thank you.

All Figures. Label the color bars with the variable shown and the units.

Variable and units were added to each figure.

Section 3.3.1 The discussion in the first paragraph about the global scale distribution is hard to follow, especially since the data is not shown. My first thought was that there must be a difference in behavior between hemispheres, and I was wondering if they took that into account, and then that is brought up in the next paragraph with the discussion of Figure 7. I suggest removing the first paragraph entirely, and just focusing on the behavior as a function of latitude and day of year, which clearly shows that the MHWs are more

prevalent in the winter (northern and southern).

We agree and have removed that short paragraph.

Figure 10. It is impossible to distinguish between the four different colors of green, and the two different yellows. Is there even much difference in the distribution between the negative and positive phases? If there is, it is impossible to tell on this figure. I suggest redoing with just 5 colors, one per index.

We have changed the colors of this figure so as to better highlight the differences between climate phases. We kept the 10 indices (and added those suggested by the second reviewer), since the positive and negative phases of a climate mode are associated with a different distribution of compound events (Fig. 8 and 9 in the revised manuscript).

Be consistent in the use of acronyms. Acronyms are used for the climate modes in Figure 10, but in the text acronyms are not used. Same for LMF, acronym is defined but not always used.

We carefully checked the manuscript and now use acronyms consistently throughout the text.

References

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