Author Comments 2 on "The effect of seasonally and spatially varying chlorophyll on Bay of Bengal surface ocean properties and the South Asian Monsoon"

We would like to thank Reviewer 2 who provided constructive and insightful comments that have greatly improved the revised manuscript. We have incorporated all their suggestions where possible. Reviewer 2 comments have been reproduced in black with authors response in blue and excerpts from the revised manuscript in italics. The revised and renumbered figure is included at the end of the document.

Response to Reviewer 2

1. It would be good to quantify the impact of chlorophyll on the changes in SST. Maybe the Abstract or the Conclusion could capture this important aspect.
We have now provided the change in SST due to biological warming in the Abstract as suggested.

> *"The largest SST response of 0.5℃ to chlorophyll forcing occurs in coastal regions, where chlorophyll concentrations are high (> 1 mg m^{-3}), and when climatological mixed layer depths shoal during the intermonsoon periods."*

2. Could the authors clarify the errors in their estimates of impact, given that the horizontal resolution of the effective coupled model is actually governed by the 90 km grid spacing of the MetUM-GOML3.0? I understand that the 4km satellite observations have been re-gridded to the 90km model grid. If this is not correct, could the authors specify the horizontal resolution of the ocean model (which is really okay for the vertical – with 100 levels in the upper 1000 m, of which 70 levels are in the top 300m)?
Regridding the 4 km satellite observations to the coarser 90 km model grid has implications on the representation and impact of biological warming in the BoB, which has been discussed in comment 8 below. Running the ocean model at a finer resolution than the atmosphere (90 km) would have little value, because the ocean properties (e.g., SST) must be averaged to the atmospheric grid before they are passed back to the atmosphere. Similarly, the ocean receives surface heat, moisture and momentum fluxes on the 90 km atmospheric grid, so these fluxes would be identical across the atmospheric gridbox even if the ocean were run at higher resolution. The only value from a higher-resolution ocean would come from non-linear effects of sub-90 km spatial variability in chlorophyll on the ocean properties (i.e., if the SST averaged across a 90 km x 90 km of finer-resolution ocean columns with higher-resolution chlorophyll differed from the SST of single 90 km x 90 km gridbox with averaged chlorophyll concentrations). We are unable to speculate about the errors in using a coarser-resolution model with unresolved mesoscale chlorophyll distributions. A separate study using a high-resolution fully-coupled model is needed to further investigate the mesoscale impact of chlorophyll on ocean properties.

Reviewer 2 is correct about the 4 km satellite observations that were re-gridded to the ~90 km oceanic and atmospheric model grid. We have now added more detail about the horizontal resolution of MC-KPP and MetUM in Section 2.1.

> *"The atmospheric and oceanic horizontal resolution is N216 (0.83° longitude* x *0.56° latitude), which corresponds to a horizontal grid spacing of approximately 90 km."*

> *"MC-KPP consists of a grid of independent one-dimensional columns, with one column positioned under each atmospheric grid point at the same horizontal grid spacing as MetUM GA7.0."*

3. Given the 90 km horizontal resolution of the ocean model, how reliable are the inferences for the "coastal chlorophyll impacting the SST" results? Is there really a coast in the ocean model? Should we interpret them as near-coastal? The whole BOB would be a 25 x 25 grid ocean at 90 km resolution. Most of the coastal regions are resolved by such a grid with less than 2 grid points. Maybe the authors could clarify this with care, so that future studies can build upon this limitation.
We have shown that coastal chlorophyll influencing SST is a robust result. However, a higher-resolution model would likely focus this response in a narrower region close to the coast. Future study using a high-resolution model is needed to further investigate the impact of coastal chlorophyll. See comment 8 below about the limitations of the horizontal resolution of MC-KPP presented as a new paragraph.

To clarify to Reviewer 2, there is no immediate transition from land to sea in MC-KPP. Instead, the coastal region in MC-KPP is represented over multiple grid points with points that are partially ocean and partially land. At these points, surface properties (e.g., fluxes, temperatures) are computed separately for the land and sea portions of the points. At these points, MC-KPP receives the "ocean part" of the fluxes from the atmospheric model; the atmospheric model combines the SST from MC-KPP with the surface temperature from the land model to construct a gridpoint-mean temperature. We have provided a clearer definition of the coastal region in MC-KPP in Section 2.1.

> "*The coastal region in MC-KPP is represented with columns that are partially ocean and partially land. The surface properties for ocean and land are computed separately in MC-KPP and the mean grid point temperatures are computed in the atmospheric model by combing the ocean and land surface temperatures from MC-KPP.*"

4. Furthermore, as authors point out in lines 205-212, there are lots of missing values of h2 in coastal regions (not surprisingly) – this again could influence the inferences in lines 384-400. Please also see comment 7 below.
The relatively few missing h_2 values in the coastal region are due to the highly turbid coastal water close to the coast that is excluded in the chlorophyll satellite product. We have added black hatching to Fig. 1 to show missing h_2 grid points in MC-KPP (new figure included at the end of this document). We have added a paragraph discussing the limitations and implications of the interpolated h_2 values. Please see comment 7 below.

5. The first paragraphs of Section 3.1 and 4.1 are hard to follow. This reader was getting very confused with the increase/decrease and high/low ordering of sentences. Maybe talk about changes focusing on regions first and then the months. A minor issue is the frequent usage of the phrase 'in reality' in both paragraphs. This phrase occurs five times in lines (233-239) and another five times in lines (264-271) – almost once in every sentence. Maybe use 'observed', 'satellite' etc.
We have restructured the first paragraph of Section 3.1 and removed unnecessary instances of "in reality", replacing them with 'observed' as suggested.

> *"The BoB surface ocean responds to the imposed annual cycle of h_2 in the perturbation run during the onset of the southwest monsoon. In the central BoB, values of h_2 increase above the global constant of 17 m, as observed surface chlorophyll concentrations are low during southwest monsoon onset (Fig. 4a-c). Along the northern BoB coast, values of h_2 are as low as 5 m, as observed surface chlorophyll concentrations in coastal areas are higher than those in the central BoB (Fig. 4a-c). During May and June, the values of h_2 decrease and mixed-layer solar absorption increases in the northwest BoB, as observed high coastal chlorophyll concentrations extend oceanward across the continental shelf (Fig. 4b-c). In the southwest BoB, the imposed h_2 decreases in May and June to 14 m, as the strengthening SMC advects high chlorophyll concentrations from the south coast of India and Sri Lanka (Fig. 4b-c)."*

We have replaced the months with "spring" and "autumn" intermonsoon, and restructured sentences in the first paragraph of Section 4.1.

> *"During the spring intermonsoon, a peak in surface chlorophyll concentrations and shallow MLDs led to an increase in SST. During the autumn intermonsoon, another peak in surface chlorophyll concentration led to a similar, but weaker increase in SST due to deeper MLDs and stronger turbulent surface fluxes."*

We have also condensed and restructured the first paragraph of Section 3.2 (see author comment from Reviewer 1 on lines 263-272).

6. Lines 245, 257 – the superscripts for units did not come through in my downloaded version. There are other similar occurrences throughout the paper. Please check.
You are right that the superscripts for the units failed to appear in the uploaded manuscript. Apologies for that. We will ensure that the superscripts are shown in the revised manuscript.

7. It is encouraging to note that the authors have used the Satellite-derived chlorophyll concentrations to h2 using a fifth-order polynomial parameterization. They reported the improvement of SST and precipitation in the coastal region. However, the coastal BoB is mostly dominated by river water, where the above algorithm (5th order polynomial to get h2) might not be totally applicable. The authors have actually interpolated and/or extrapolated to fill the data gaps (page 5, 205). This could possibly lead to a positive bias in precipitation in the head BoB in the post-monsoon period (Figure 8). Could the authors please clarify these two aspects or limitations.
It is a good suggestion to discuss the limitations in the chlorophyll satellite product and solar penetration depth parameterisation. Oceanic constituents such as CDOM and suspended sediments are falsely interpreted as a chlorophyll-a concentration, leading to overestimation of chlorophyll-a concentrations in coastal regions. We have now referred to the Ganges river delta as this is a region susceptible to inaccurate and undetermined chlorophyll and h_2 due to the high levels of coastal turbidity. An overestimation in chlorophyll-a concentration could lead to an overestimate in biological warming with repercussions on BoB precipitation rates.

> *"The derivation of the imposed annual cycle of h_2 in coastal regions has limitations. Firstly, the ocean colour algorithms used to determine chlorophyll concentrations from satellite are not completely effective in turbid coastal waters (Morel et al., 2007; Tilstone et al., 2013). Organic and inorganic constituents such as Coloured Dissolved Organic Matter (CDOM) and suspended sediments strongly attenuate blue light and are thus falsely identified as a chlorophyll-a pigment, which typically leads to an*

overestimation in chlorophyll concentration (Morel et al., 2007). Secondly, the Morel and Antione (1994) chlorophyll parameterisation is not applicable for coastal waters, as the parameterisation is based on the absorption by chlorophyll-a pigment and not by the attenuation of other in-water constituents. Missing h_2 values in the Ganges river delta are interpolated from neighbouring h_2 values that are likely associated with satellite product and parameterisation uncertainty. The Ganges coastal region has been found to influence spring intermonsoon SST and precipitation rates in the northern BoB. Possible positive biases in chlorophyll concentration in the Ganges river delta are likely to lead to an overestimation in the coastal biological warming, SST and precipitation rate increase. Ocean colour algorithms to determine proxy coastal chlorophyll concentrations are still an area of active research (Blondeau-Patissier et al., 2014). Future studies should consider the attenuation of solar radiation from other oceanic constituents in turbid coastal regions to better represent radiant heating in the upper ocean."

8. The BoB is a highly eddy-active region, which has a significant impact on the chlorophyll distribution and on the air-sea interaction (page 13, 570). The authors could expand on how finer resolution ocean models might be helpful in the future for resolving both eddy activities in the open region and mesoscale to sub-mesoscale features in coastal BOB.
We have now mentioned the use of high-resolution, fully dynamical models to improve the representation of mesoscale chlorophyll distributions and eddy activity that influences biological productivity.

"The mesoscale and sub-mesoscale spatial variability of h_2 and associated oceanic processes is inadequately represented in MC-KPP due to its coarse horizontal resolution. The coastal region in MC-KPP is represented by multiple grid points that are partially ocean and partially land at an approximate 90 km horizontal resolution. Such a resolution means that at the coastlines, the mesoscale coastal chlorophyll concentration features and the corresponding solar penetration depths are poorly resolved. Future studies should consider using a high-resolution, fully dynamical model to accurately resolve the coastline and associated solar penetration depths. The simulated dynamics would improve the representation of mesoscale eddy activity along the coast and open ocean, which increases biological productivity (Kumar et al., 2007) that in turn increases local solar radiation absorption."

9. In the BoB (like in other oceans), Chlorophyll maxima is generally not at the surface level. It varies from 10 m to 80 m (Pramanik et al., 2020). The impact of the deep chlorophyll maxima and its relationship with the surface chlorophyll and SST variations may be explored in a separate future work, but worth a mention.
This is an interesting point that we agree should be mentioned close to the end of the Discussion and Conclusions.

"The chlorophyll concentration in the BoB upper ocean is not homogeneous with depth. In situ observations show that the vertical depth of chlorophyll maxima varies between 10 and 80 m (Thushara et al., 2019; Pramanik et al., 2020), often occurring at depths undetected by satellite radiometer sensors (Huisman et al., 2006). Variations in the vertical depth of the chlorophyll maxima would vary the vertical depth of enhanced radiant heating. However, if the depth of the chlorophyll maxima occurs at a depth where solar radiation is significantly reduced (e.g., at the euphotic depth where solar radiation is ~1% of its surface value), then the change in local radiant heating at that

depth would be negligible (Morel and Antione, 1994). Indeed, observations show the occurrence of intense deep chlorophyll maxima in the BoB at depths of 20 to 40 m (Thushara et al., 2019), which might have a strong influence on local mixed layer radiant heating and vertical heat distributions. Hence, the effect of nonuniform chlorophyll concentration profiles on upper ocean radiant heating and SST requires further investigation."

New References

Blondeau-Patissier, D., Gower, J. F., Dekker, A. G., Phinn, S. R., and Brando, V. E.: A review of ocean color remote sensing methods and statistical techniques for the detection, mapping and analysis of phytoplankton blooms in coastal and open oceans, Progress in Oceanography, 123, 123-144, https://linkinghub.elsevier.com/retrieve/pii/S0079661114000020, 2014.

Huisman, J., Pham Thi, N. N., Karl, D. M., and Sommeijer, B.: Reduced mixing generates oscillations and chaos in the oceanic deep chlorophyll maximum, Nature, 439, 322–325, http://www.nature.com/articles/nature04245, 2006.

Pramanik, S., Sil, S., Gangopadhyay, A., Singh, M. K., and Behera, N.: Interannual variability of the chlorophyll-a concentration over Sri Lankan Dome in the Bay of Bengal, International Journal of Remote Sensing, 41, 1-18, https://www.tandfonline.com/doi/full/10.1080/01431161.2020.1727057, 2020.

Tilstone, G. H., Lotliker, A. A., Miller, P. I., Ashraf, P. M., Kumar, T. S., Suresh, T., Ragavan, B. R., and Menon, H. B.: Assessment of MODIS-Aqua chlorophyll-a algorithms in coastal and shelf waters of the eastern Arabian Sea, Cont. Shelf Res., 65, 14-26, https://linkinghub.elsevier.com/retrieve/pii/S0278434313002045, 2013.

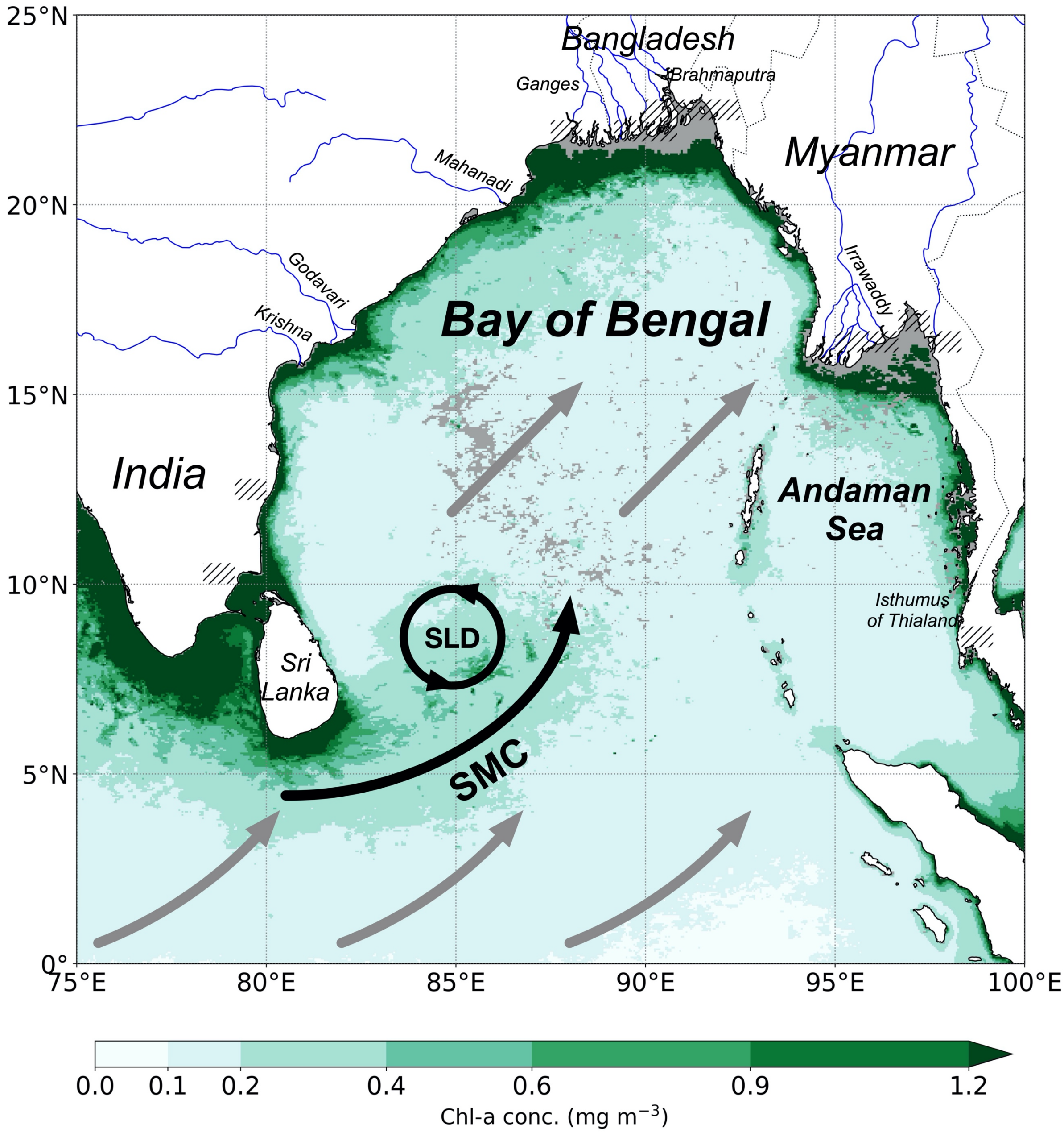

Figure 1: The Bay of Bengal (BoB) and surrounding region of interest. Average JJAS chlorophyll-*a* concentration climatology measured from MODIS-Aqua at 4 km horizontal resolution is shown. The locations of major rivers are represented as blue lines. The Sri Lanka Dome (SLD) is shown as a cyclonic (anticlockwise) black circle and the Southwest Monsoon Current (SMC) is shown as the solid black arrow. South westerly monsoon winds are shown as the solid grey arrows. Missing chlorophyll concentration data is shown in grey. Location of missing h2 grid points in MC-KPP are shown by the black hatching.