Interactive comment on "Destruction and reinstatement of coastal hypoxia in the South China Sea off the Pearl River Estuary" *by* Yangyang Zhao et al.

Yangyang Zhao[1,2], Khanittha Uthaipan[1], Zhongming Lu[3], Yan Li[1], Jing Liu[1], Hongbin Liu[4,5], Jianping Gan[3,5,6], Feifei Meng[1], Minhan Dai[1]

[1]State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen, 361102, China
[2]Environmental Physics, Institute of Biogeochemistry and Pollutant Dynamics, ETH Zurich, Zurich, 8092, Switzerland
[3]Division of Environment and Sustainability, Hong Kong University of Science and Technology, Kowloon, Hong Kong SAR, China
[4]Division of Life Science, Hong Kong University of Science and Technology, Kowloon, Hong Kong SAR, China
[5]Department of Ocean Science, Hong Kong University of Science and Technology, Kowloon, Hong Kong SAR, China
[6]Department of Mathematics, Hong Kong University of Science and Technology, Kowloon, Hong Kong SAR, China

Correspondence to: Minhan Dai (mdai@xmu.edu.cn)

Anonymous Referee #2

I found this manuscript to be a useful contribution to our understanding of the spatial and temporal nature of oxygen depletion as a large coastal system responds to large events. The narrative is relatively easy to follow and the results are clearly communicated with figures. I think the analysis could benefit from a small amount of additional computations, but I also think that the results and discussion section needs to be reorganized. There is substantial mixing of results and discussions between the two sections, and I think it would be best and easiest to simply combine the two sections into one "Results and Discussion" section that is reorganized into a clear narrative.

[Response]: We are grateful that the reviewer valued our study. We also appreciate the critical comments and constructive suggestions from the reviewer, which will be fully considered in our revised manuscript. In brief, we will follow the suggestions to reorganize the paper to combine results and discussion into a clear narrative, with an outline as below:

3 Evolution of intermittent hypoxia off the PRE

- 3.1 Extensive hypoxia before typhoon
- 3.2 Destruction of the hypoxia by typhoon
- 3.3 Reinstatement of the hypoxia after typhoon

4 Maintenance, destruction and reinstatement of coastal hypoxia

- 4.1 Water column stability
- 4.2 Oxygen sinks and hypoxia formation timescale
  - 4.2.1 Mixing-induced oxygen sinks
  - 4.2.2 Biochemical-induced oxygen sinks

4.2.3 Hypoxia formation timescale

4.3 Imprint of tropical cyclones on the evolution of coastal hypoxia

We additionally have (1) calculated the vertical diffusion for oxygen using the density-based eddy diffusivity from Cui et al. (2019) with our observed DO concentrations and estimated buoyancy frequency; (2) calculated and plotted the surface-to-bottom salinity and temperature differences to show the spatial distribution of stratification; (3) calculated the potential maximum surface area of the hypoxia associated with tidal fluctuations. The spring-to-neap tidal oscillations lead to variations in the DO concentration off the Lingdingyang sub-estuary with a maximum neighboring oxygen range of 0.5 mg L^{-1} (Cui et al. 2019). Assuming the observed DO concentration in Leg 1 (from a neap tide to a spring tide; Fig. 1e) was overestimated by 0.5 mg L^{-1} (i.e., ~ 15 µmol kg^{-1}), the total area of the hypoxic and oxygen-deficient zone would be at most ~ 990 km^2 and ~ 1930 km^2, respectively, 34-50% larger than our observed areas; and (4) discussed our results and estimates by comparing with previous studies in this study area and other large river-dominated shelf systems. We will address these concerns from the reviewer in our responses as of below.

Below are some specific and more general comments for the authors to consider:

(1) Line 49: "typhoons" should be plural

[Response]: Accepted. We will correct it in our revisions.

(2) Figure 1: It is a little difficult to discern the station locations of the different legs, given the overlapping in the circles. One suggestion could be to use different symbols to present (1) stations visited on all legs, (2) stations visited on legs 1+2, (3) stations visited on legs 2+3, and (4) stations visited on 1+3.

[Response]: We appreciate the suggestion. We have modified Figure 1b to show the stations more clearly: (1) stations visited in all legs, (2) stations visited only in Leg 1 and Leg 2, (3) stations visited only in Leg 1, and (4) stations visited only in Leg 2 (Fig. 1b).

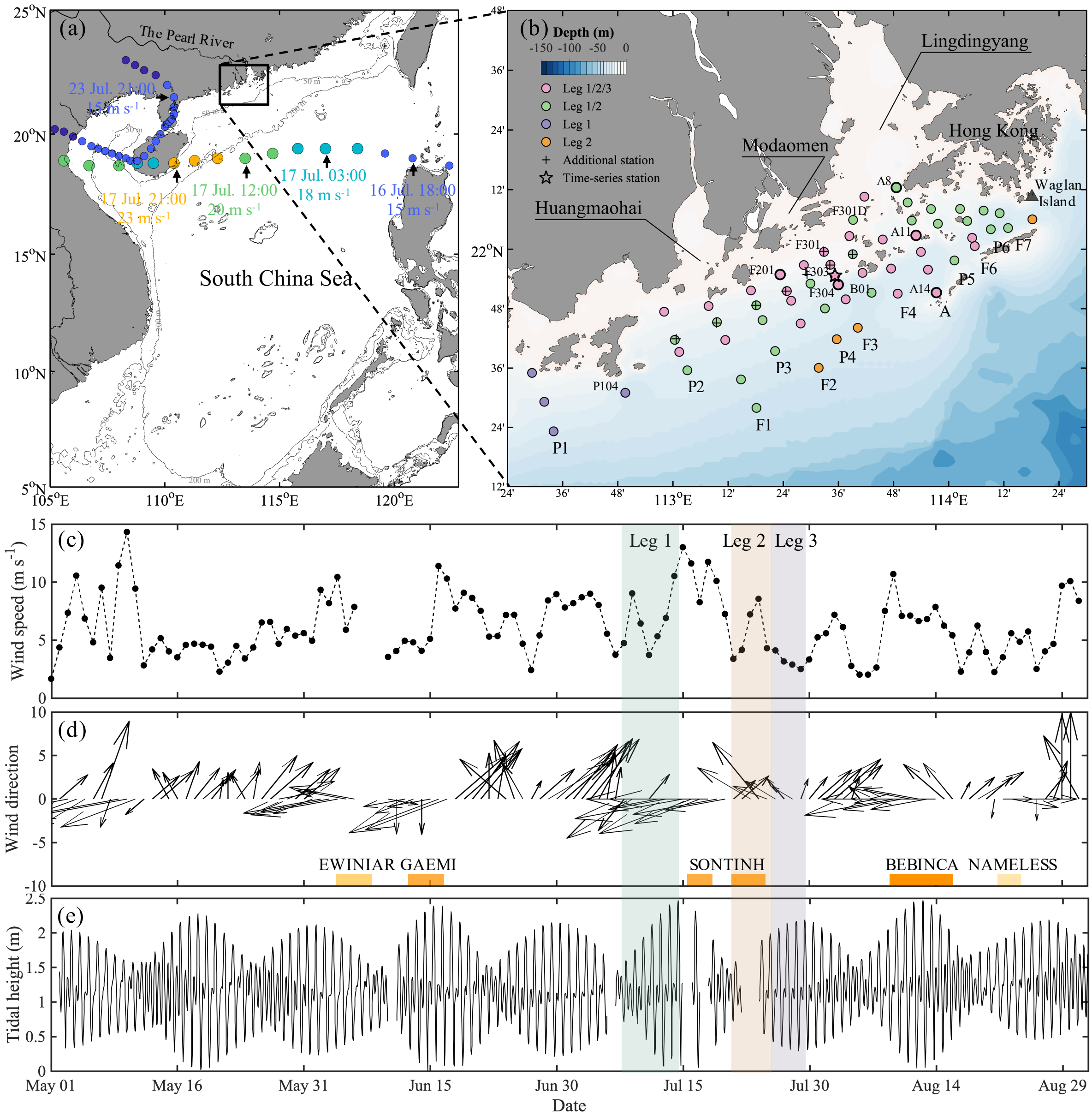

Figure 1: (a) Map of the study area on the northern South China Sea (NSCS) shelf, showing the track of Typhoon SONTIHN (circles) across the NSCS during July 16-24, 2018. The color of the circles represents the magnitude of wind speed. Additionally, the smaller circles denote tropical depression (wind speeds ≤ 17.1 m s^{-1}) and the larger circles denote tropical storm (wind speeds within 17.2-32.6 m s^{-1}). The arrows denote the locations of the typhoon as marked with time and wind speed. The grey lines are the depth contours at 50 and 200 m. (b) Sampling stations on the NSCS shelf off the Pearl River Estuary in summer 2018. The pink, green, purple and orange circles denote stations surveyed in all three legs, only both Leg 1 and Leg 2, only Leg 1 and only Leg 2, respectively. Time-series observations were conducted at Station F303 as marked by the star, and vertically high-resolution samplings were conducted at stations marked with bold circles. (c) The wind speed and (d) wind direction at Waglan Island (triangle in (b)) from May to August, 2018. Bars at the bottom of (d) mark times when tropical cyclones impacted the NSCS. (e) The tidal height at the Dawanshan gauge station near Station F303 from May to August, 2018. The shaded area indicates the cruise periods for Leg 1 (grey), Leg 2 (pink) and Leg 3 (blue), respectively.

(3) Although Figure 3 nicely illustrates how stratification returned after the cyclone, it does not capture any patterns over space and it does not capture the entire coverage of the study in

time. Figure 2 provides a nice, qualitative picture of the changes in water properties over time and space, but I think it might be helpful to also generate maps of the stratification changes, perhaps by plotting max N2 over space or the difference in temperature and salinity (or density) between surface and bottom waters. This would have the benefit of showing if stratification was weaker after it was reinstated than before the typhoon, where stratification was strongest, and how it related in space to hypoxia.

[Response]: We agree with the reviewer that changes in the spatial distribution of stratification would help better understand how it is related to hypoxia in space. Following suggestions, we have plotted the difference in temperature and salinity between surface and bottom layers (Fig. 2). We will also revise our discussion on the effect of stratification on the formation and maintenance of hypoxia: "The surface-to-bottom salinity difference showed large values within the surface plume area, which almost covered the bottom hypoxic zones. For exceptions such as the hypoxia zone off the Modaomen sub-estuary with relatively small surface-to-bottom salinity differences, the surface-to-bottom temperature differences were large (i.e., $\Delta T_{b\text{-}s} < -4$ °C) due to the shoreward intrusion of cold offshore subsurface waters. The regions occupied by the surface plume and the shoreward-intruded shelf bottom waters therefore overlapped, resulting in a more stable water column where a patchy hypoxic zone could persist for more than 5 days (Cui et al. 2019)".

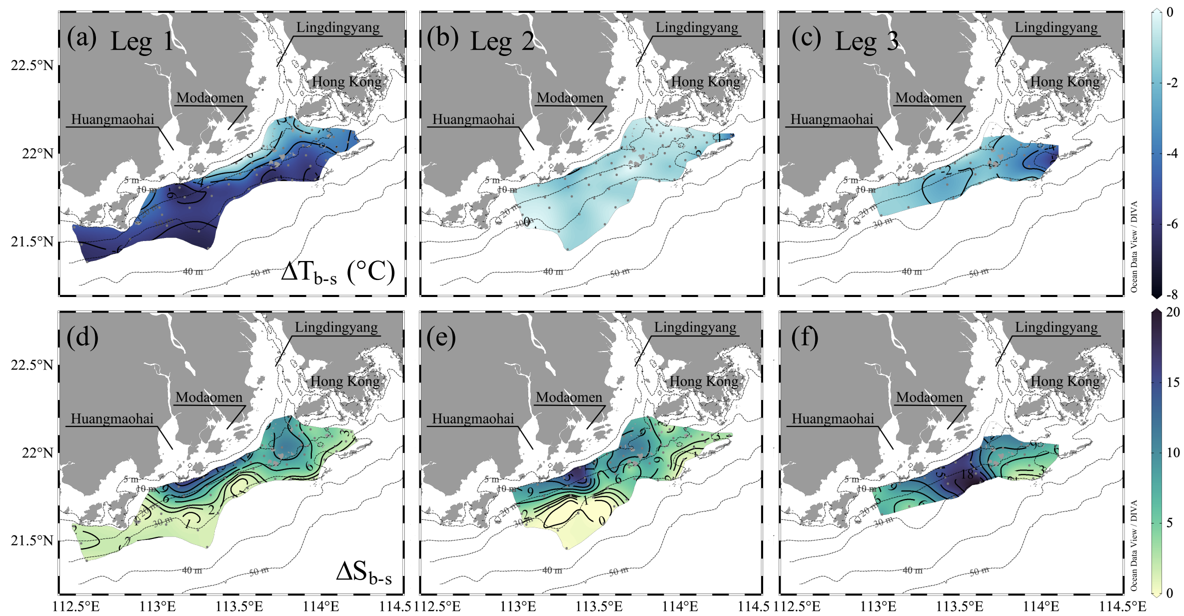

Figure 2: Surface-to-bottom temperature (a-c) and salinity (d-e) distributions off the PRE during Leg 1 pre-typhoon, and during Legs 2 and 3 post-typhoon. $\Delta T_{b\text{-}s}$ and $\Delta S_{b\text{-}s}$ represent the difference in temperature and salinity between the bottom and surface layer, respectively.

(4) Figure 4 – I think it would be more interesting to also show vertical oxygen distributions on figure 4, to show where hypoxia exists relative to the vertical structure and stratification.

[Response]: Accepted. We have added oxygen profiles at multiple stations accompanying the vertical distributions of temperature, salinity and buoyancy frequency (Fig. 3). The DO concentrations decreased sharply at the base of the surface plume (salinity ~ 30).

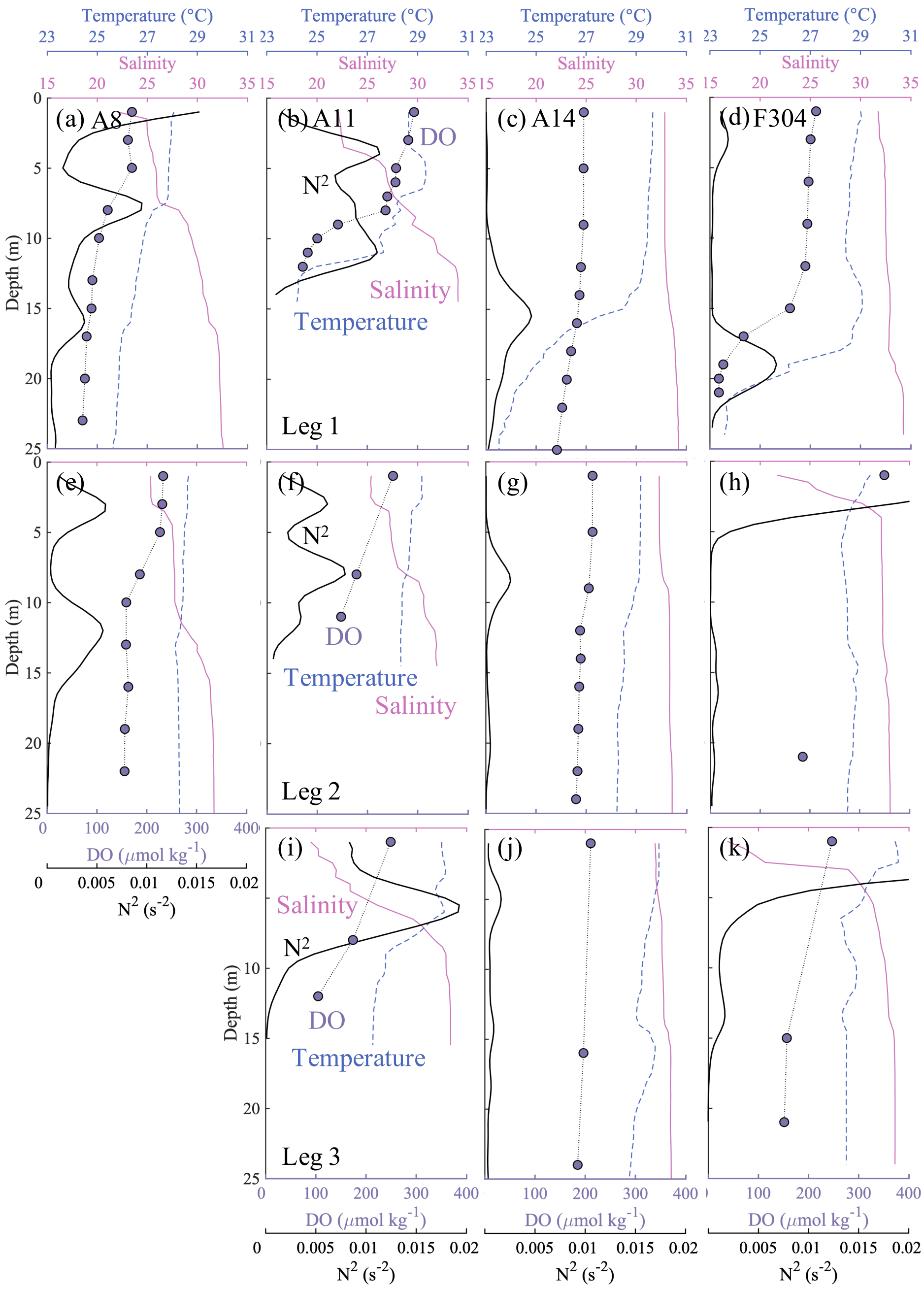

Figure 3: Profiles of temperature (°C) (green dashed lines), salinity (pink solid lines), dissolved oxygen (DO, μmol kg^{-1}) (purple dots) and buoyancy frequency N^2 (s^{-2}) (bold black solid lines) at stations A8, A11, A14 and F304 (see Fig. 1b), with visits both pre-typhoon (Leg 1) and post-typhoon (Legs 2 and 3). The vertical distributions of N^2 have been smoothed by the Gaussian method.

(5) You report on the decline in oxygen concentration in the water column after the typhoon passing as a metric of oxygen consumption rate. It would make the paper more compelling, and help the discussion, to compare these rates of oxygen depletion to similar rates published in other systems (e.g., Testa and Kemp 2014, others?)

[Response]: We will add such comparisons in our revisions: "Our estimated OCR is comparable in magnitude to the community/bacterial respiration rate from previous studies in this study area (9.6 μmol O_2 kg^{-1} d^{-1}, Su et al. (2017); 7.9 to 19.0 μmol O_2 kg^{-1} d^{-1}, Cui et al. (2019); 16.8±8.9 μmol O_2 kg^{-1} d^{-1}, Li et al. (2019)) and within the range in other estuaries and coastal systems (Dortch et al. 1994, Robinson 2008)".

(6) Line 315-319: Can you estimate the oxygen diffusivity rate from your data, based on any published estimates of diffusivity for the region, or estimated from your density profiles? This would allow you to be more quantitative in your comparison of OCR and diffusivity as eventually balancing. I think you could also speculate, perhaps with data, why OCR could have possibly declined, either as the post-bloom organic material was exhausted or due to oxygen limitation of respiratory uptake?

[Response]: Accepted. We have estimated the vertical diffusion for oxygen based on the published diffusivity from Cui et al. (2019) along with our observed DO concentrations and estimated buoyant frequency: "Using the density-based eddy diffusivity (K_z) of < 5×10^{-6} m^2 s^{-1} for N^2 larger than 1×10^{-3} (Cui et al., 2019), we estimated the vertical DO diffusivity (VDIF = $K_z\times(\partial DO/\partial z)$) of ~ 0.25 g m^{-2} d^{-1} with a maximum of 0.54 g m^{-2} d^{-1} in the top 10 m at stations A8 and A11, which was comparable to the results from Cui et al. (2019). It therefore acted as a barrier layer, with weak dissipation of oxygen into the subsurface waters". As inhibited by freshwater input-induced stratification, the oxygen supply by the vertical diffusion was much smaller than the biochemical consumption, leading to a relatively strong net oxygen consumption.

The decline in OCR could result from a reduced supply of labile organic matter or oxygen limitation of respiratory uptake. Oxygen enriched incubations of unfiltered water samples revealed that the OCR could be significantly enhanced when the initial *in situ* DO concentration was low (e.g., ~ 30 μmol kg^{-1}), but changed little when the *in situ* DO concentration was higher than ~ 90 μmol kg^{-1} (He et al. 2014). Here, the bottom DO concentrations were ~ 180 μmol kg^{-1} at station F303 in the time-series observations, much higher than the oxygen threshold for respiratory uptake. However, the strong post-storm blooms shifted offshore with the river plume and the Chl *a* concentrations over the hypoxic zone also decreased in Leg 3 as comapred to Leg 2 (Fig. 4), reducing the downward transport of labile organic matter to the hypoxic zone. The decline in the OCR in this study thus very likely owed to a reduced supply of labile organic matter.

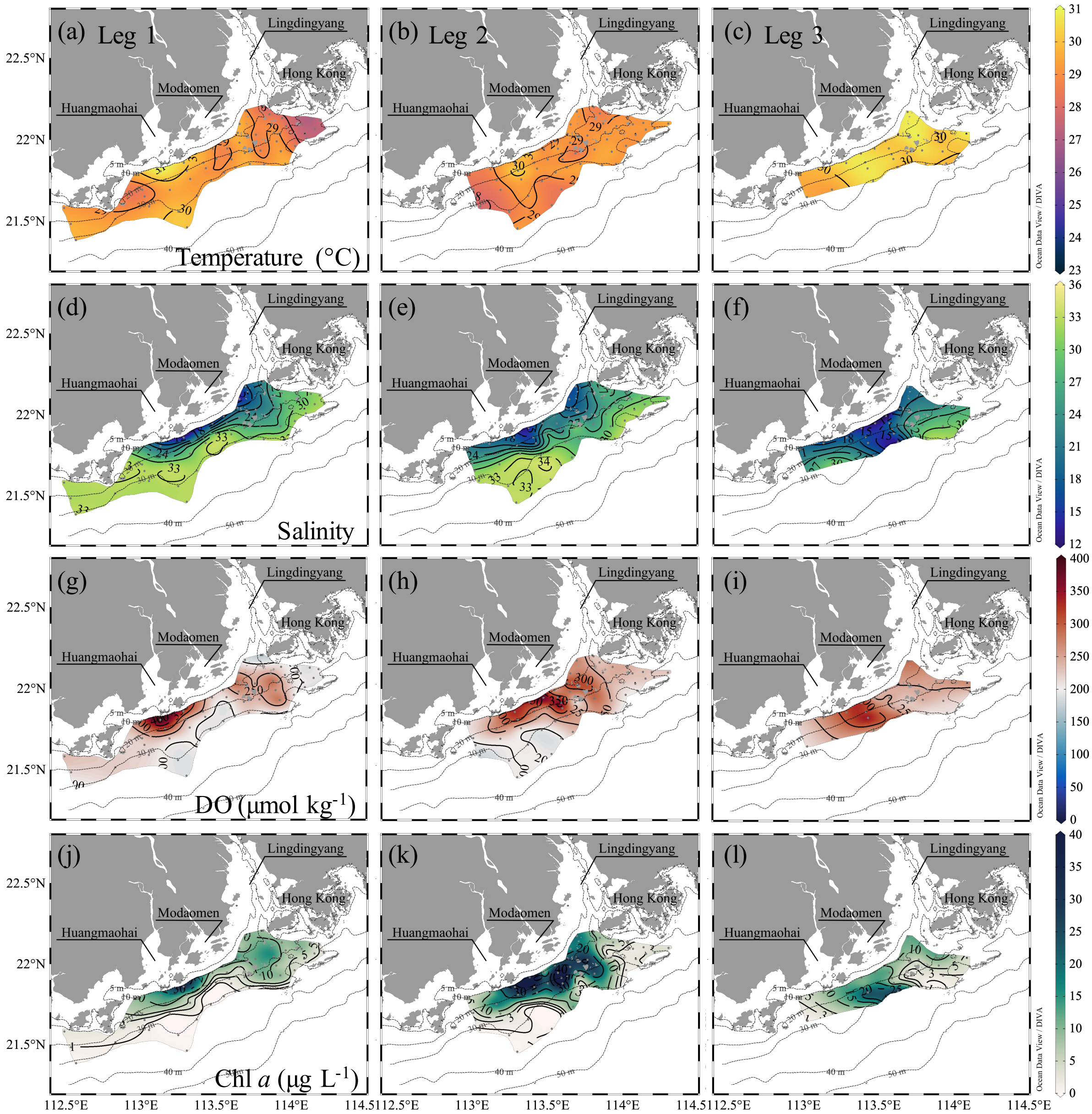

Figure 4: Distribution of temperature (°C), salinity, DO (μmol kg^{-1}) and Chl *a* concentrations (μg L^{-1}) at the surface water layer off the PRE during Leg 1 pre-typhoon, and during Legs 2 and 3 post-typhoon. The white and magenta contours in (g) and (w) show the hypoxic (DO < 63 μmol kg^{-1}) and oxygen-deficit (DO < 94 μmol kg^{-1}) zones. Figures were produced using Ocean Data View v. 5.3.0 (http://odv.awi.de, last access: 08 June 2020)

(7) Paragraph on Line 389: This paragraph reads more like an essay on the factors driving hypoxia and vulnerable to climate change, and does not really discuss the specific details of this study. I suggest deleting it, perhaps keeping the cyclone points for the prior paragraph on cyclone effects.

[Response]: Accepted. We will remove the discussion on the exacerbation of hypoxia under a changing climate, but keep discussions on the response of coastal hypoxia to changes in the frequency and intensity of tropical cyclone activities based on statistics of the maximum wind speed and wind direction of tropical cyclones and the time interval between two successive tropical cyclones using the historical dataset of tropical cyclones that impacted the northern South China Sea from May to September during the period of 1975-2019 (Table 1; Fig. 5).

Table 1: Summary of annual mean numbers of tropical cyclones in each decade from 1950-2019. TD, TS, STS, TY and STY represent tropical depressions (the maximum wind speed near the centre is between 10.8-17.1 m s^{-1} over its lifetime), tropical storms (17.2-24.4 m s^{-1}), strong tropical storms (24.5-32.6 m s^{-1}), typhoons (32.7-41.4 m s^{-1}) and strong typhoons (41.5-50.9 m s^{-1}), respectively.

Years	TD	TS	STS	TY	STY	SUM
1950-1959	3.5	1.1	1.2	1.1	1.5	8.4
1960-1969	1.7	0.6	1.5	2.1	2.7	8.6
1970-1979	1.8	0.7	2.1	2.1	1.2	7.9
1980-1989	1.5	0.7	2.5	1.3	1.3	7.3
1990-1999	0.7	1.2	1.8	2	1.1	6.8
2000-2009	0.9	1.4	1.5	1.5	0.8	6.1
2010-2019	0.6	1.8	1.4	0.4	1.5	5.7

(8) I think you should combine the Results and Discussion Sections into one, well-organized narrative. As it stands, there are multiple places where results are reported in the discussion, or there are even methods in the discussion. This would allow you to more clearly and sequentially tell the story of your study. Below are some specific examples to guide this effort: (a) Line 225-239 is largely results and even methods, but is included in the discussion without substantial discussion of the results in the context of the study. (b) Line 285-290. Here, you are describing the method you already described. Move to methods and remove redundancy. (c) Paragraphs beginning on lines 332 and 343 can be combined

[Response]: Following sueesgions, we will move all methods to the section of Materials and methods and reorganize the paper to combine results and discussion into a clear narrative, with an outline as listed above in our response to the general comment.

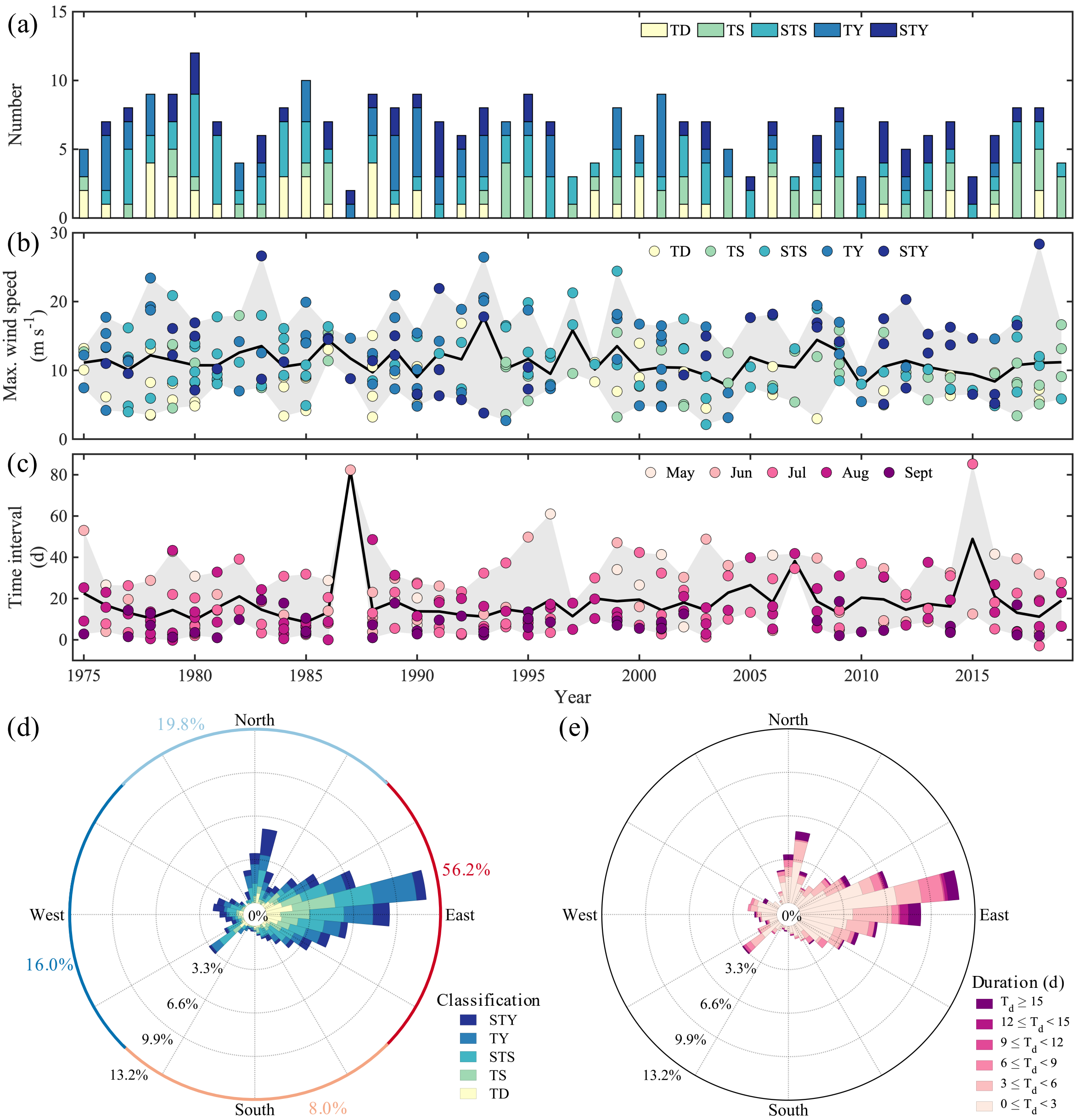

Figure 5: Statistics of tropical cyclones in the northern South China Sea (NSCS) from May to September over 1975-2019. (a) The number of tropical cyclones. TD, TS, STS, TY and STY represent tropical depressions (the maximum wind speed near the centre is between 10.8-17.1 m s^{-1} over its lifetime), tropical storms (17.2-24.4 m s^{-1}), strong tropical storms (24.5-32.6 m s^{-1}), typhoons (32.7-41.4 m s^{-1}) and strong typhoons (41.5-50.9 m s^{-1}), respectively. (b) The maximum wind speed of each tropical cyclone. The black line and grey shadow denote the annual average and range of the maximum wind speeds. (c) The time interval between two successive tropical cyclones. The black line and grey shadow denote the annual average and range of the time intervals. (d) The wind rose of the intensity of tropical cyclones. (e) The wind rose of the duration of tropical cyclones. The wind speed in (b) and wind direction in (d, e) were recorded at the Waglan Island station (Figure 1b).

References

Cui, Y. S., Wu, J. X., Ren, J. and Xu, J.: Physical dynamics structures and oxygen budget of summer hypoxia in the Pearl River Estuary, Limnol Oceanogr, 64, 131-148, doi:10.1002/lno.11025, 2019.

Dortch, Q., Rabalais, N. N., Turner, R. E. and Rowe, G. T.: Respiration rates and hypoxia on the Louisiana shelf, Estuaries, 17, 862-872, doi:10.2307/1352754, 1994.

Fennel, K. and Testa, J. M.: Biogeochemical Controls on Coastal Hypoxia, Annual Review of Marine Science, 11, 105-130, doi:10.1146/annurev-marine-010318-095138, 2019.

He, B. Y., Dai, M. H., Zhai, W. D., Guo, X. H. and Wang, L. F.: Hypoxia in the upper reaches of the Pearl River Estuary and its maintenance mechanisms: A synthesis based on multiple year observations during 2000-2008, Mar Chem, 167, 13-24, doi:10.1016/j.marchem.2014.07.003, 2014.

Kemp, W. M., Sampou, P. A., Garber, J., Tuttle, J. and Boynton, W. R.: Seasonal depletion of oxygen from bottom waters of Chesapeake Bay: roles of benthic and planktonic respiration and physical exchange processes, Mar Ecol Prog Ser, 85, 137-152, 1992.

Li, X. F., Xu, J., Shi, Z. and Li, R. H.: Response of Bacterial Metabolic Activity to the River Discharge in the Pearl River Estuary: Implication for CO2 Degassing Fluxes, Front Microbiol, 10, 1026, doi:10.3389/fmicb.2019.01026, 2019.

Robinson, C.: Heterotrophic Bacterial Respiration, in: Microbial Ecology of the Oceans, edited by: Kirchman, D. L., 299-334, doi:10.1002/9780470281840.ch9, 2008.

Su, J. Z., Dai, M. H., He, B. Y., Wang, L. F., Gan, J. P., Guo, X. H., Zhao, H. D. and Yu, F. L.: Tracing the origin of the oxygen-consuming organic matter in the hypoxic zone in a large eutrophic estuary: the lower reach of the Pearl River Estuary, China, Biogeosciences, 14, 4085-4099, doi:10.5194/bg-14-4085-2017, 2017.

Testa, J. M. and Kemp, W. M.: Spatial and Temporal Patterns of Winter–Spring Oxygen Depletion in Chesapeake Bay Bottom Water, Estuar Coast, 37, 1432-1448, doi:10.1007/s12237-014-9775-8, 2014.