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Abstract:

Nine years after the Deepwater Horizon (DwH) oil spill (April 20, 2010 to July 15, 2010), the recovery of primary productivity at the ocean surface remains to be investigated. Here, we used the normalized fluorescence line height (nFLH) from the Moderate Resolution Imaging Spectroradiometer (MODIS) as an indicator of chlorophyll *a* concentration (Chl *a*). First, from the spatiotemporal variations of nFLH between 2001 and 2017, a reduction of nFLH after the DwH oil spill was observed (for a relatively long period, from 2011 to 2014). Second, a stepwise multiple regression model was used to examine which of the following environmental factors could explain the annual variations in nFLH: river discharge, total nitrogen load, total phosphorus load, photosynthetically available radiation, sea surface temperature, and wind speed. Results show that river discharge, sea surface temperature, and wind speed are the primary factors that regulated the annual nFLH variations in the DwH area during the pre-spill years. In contrast, this same model could not explain the reduction of nFLH for the four years after the DwH oil spill. After 2015, nFLH appears to have resumed to the pre-spill concentrations. Here we suggest that the nFLH reduction between 2011 and 2014 could have originated from the DwH oil spill, although the exact mechanism is yet to be determined.

Keywords: Deepwater Horizon oil spill, phytoplankton, chlorophyll *a*, fluorescence, primary productivity, recovery, remote sensing.

1. Introduction

The Deepwater Horizon (DwH)[1] oil spill, which occurred between April 20, 2010 and July 15, 2010, released over 130 million gallons of crude oil over the course of 87 days into the Gulf of Mexico. It is the largest marine oil spill in US history (Crone and Tolstoy 2010, McNutt *et al* 2012). Numerous studies have investigated the influence of the accident on the region, looking at factors such as: the oil compositions and their toxicity to aquatic organisms (Forth *et al* 2017, Reddy *et al* 2012, White *et al* 2012), the response of the microbial community (King *et al* 2015, Kostka *et al* 2011, Quigg *et al* 2016), and the negative psychological and socio-economic impacts (Gill *et al* 2012, Grattan *et al* 2011, Smith *et al* 2011). With regard to the question about whether the marine ecosystem in the Gulf of Mexico has fully recovered, researchers have published different perspectives on this. For example, Girard and Fisher (2018) demonstrated—using high-definition imagery data—that deep-sea corals were heavily impacted and had not recovered by 2017. Using state-structured models, Girard *et al* (2018) suggested that the complete recovery of corals will take up to three decades (depending on the initial level of impact). As for the food web, the oil spill may have led to a significant decrease of the fishery yield which could take more than 30 years (especially for some slowly-growing populations) to recover fully (Ainsworth *et al* 2018). Tatariw *et al* (2018) found that the salt marsh denitrification capacity (over the moderate and heavy oiling) areas had not yet recovered six years after the DwH oil spill. Long term studies are required—especially given the long life cycles of many of the organisms of interest, and the interannual variability in the meteorological and environmental conditions of the Gulf of Mexico.

The impacts of the DwH spill on phytoplankton population dynamics in the northern Gulf of Mexico have been under debate since the accident occurred (Ozhan *et al* 2014). Hu *et al* (2011) suggested that phytoplankton productivity may have been stimulated by the DwH oil spill in the

[1]A full list of the acronyms used in study is summarized in Table S1

short term (weeks-months). A more recent study, however, found that the Mississippi River discharge may have also accelerated the phytoplankton growth after the spill (O'Connor *et al* 2016), which is consistent with previous observations of primary productivity in the region (Quigg *et al* 2011). Bretherton *et al* (2018a) mimicked the chemical conditions after the DwH oil spill and found that the biological and physiological responses of phytoplankton to crude oil vary with species. Although some members of the phytoplankton community respond positively to the addition of oil, this was found to not be the case when both oil and dispersant were present (Bretherton *et al* 2018b). Moreover, the chemical structure of the crude oil, the concentration level, and various environmental factors (e.g., temperature, light, and nutrient level) also influence the phytoplankton response to oil and/or dispersant (González *et al* 2009, Kamalanathan *et al* 2018, Østgaard *et al* 1984, Ozhan and Bargu 2014, Ozhan *et al* 2014, Vargo *et al* 1982). In general, most studies have focused on short-term responses of chlorophyll *a* (Chl *a*) concentrations to the DwH oil spill (days-weeks-months). An evaluation of the long-term response (multi-year) is still lacking.

Chl *a*, which is used as a proxy for the phytoplankton biomass and primary productivity in the ocean, is generally estimated globally using satellite data (Behrenfeld and Falkowski 1997). Approximately 40% of all carbon fixation on Earth comes from marine phytoplankton (Falkowski, 1994). Compared to the traditional ship surveys and laboratory analysis—both of which are time-consuming, and limited to small spatial and temporal coverage—satellite remote sensing provides large-scale observations of the Chl *a* at near real-time (Behrenfeld and Falkowski 1997). To date, many satellite sensors have been used for monitoring ocean color, such as the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) (O'Reilly *et al* 1998), the Medium Resolution Imaging Spectrometer (MERIS) (Moses *et al* 2009), the Moderate Resolution Imaging Spectroradiometer (MODIS) (Hu *et al* 2012), and the more recent Sentinel-3A Ocean and Land Color Instrument

(OLCI) (Toming *et al* 2017). However, it is challenging to obtain accurate Chl *a* estimates in coastal waters due to the interference caused by colored dissolved organic matter (Eurico J. D'Sa and Miller 2003, Eurico J D'sa *et al* 2006) and by the atmosphere (Le *et al* 2013, Siegel *et al* 2000). Recent studies suggest that the MODIS normalized fluorescence line height (nFLH)—which is determined after an atmospheric correction, and is relatively insensitive to colored dissolved organic matter—serves as a good indicator of Chl *a* concentration (Hu *et al* 2005, Hu *et al* 2011, McKee *et al* 2007).

The goal of this study was to evaluate whether the Chl *a* concentration level—a proxy for primary productivity—was affected by the DwH oil spill in the northern Gulf of Mexico over a multi-year time period (and, if so, has it recovered to pre-spill levels—and when)? First, the spatiotemporal variations of the MODIS nFLH were evaluated from 2001 to 2017. Then, a multiple regression model was developed by correlating the nFLH anomaly with the anomalies of six environmental variables. Finally, by comparing the MODIS nFLH anomaly with the estimated nFLH anomaly (using the statistical model), the potential influence of DwH on long-term productivity in the northern Gulf of Mexico was explored.

2. Methods

2.1. Study area

The northern Gulf of Mexico region where the ocean surface was once covered by DwH oil spill was selected as the study area. Figure 1 shows the extent of the domain and the spatial distribution of “oiling days”—that is, the total number of days a surface location was covered by oil (during the period from April 23 to August 11, 2010). This was based on data downloaded from the Gulf of Mexico Environmental Response Management Application (https://erma.noaa.gov/gulfofmexico/erma.html). Specifically, oiling days were calculated based on satellite Synthetic Aperture Radar (SAR) image classifications (Garcia-Pineda *et al* 2013). Here, the footprint of the surface oiling is referred to as the "overall-DwH area", while the portion that suffered the most severe impacts (i.e. which had more than 30 oiling days) is referred to as the "central-DwH area". The overall-DwH area includes the entire study domain of 96,278 km^2, while the central-DwH area accounts for 7.4% (7,121 km^2) of this. By comparing the Chl *a* in these two areas, the oil spill effects could be evaluated across spatial scales.

2.2. MODIS nFLH

Because the standard algorithms used for estimating Chl *a* from MODIS have shown relatively high uncertainties for the northeastern Gulf of Mexico (Eurico J D'sa *et al* 2006, Hu *et al* 2003), we used the better performing MODIS nFLH as the proxy of Chl *a* in this region (Hu *et al* 2005, McKee *et al* 2007). The nFLH is defined as the difference between the water-leaving radiance at 678 nm and a linearly interpolated water-leaving radiance at two surrounding bands (667 nm and 748 nm) (Behrenfeld *et al* 2009). Monthly MODIS nFLH data with a spatial resolution of 4 km (representing the period from January 2001 to December 2017) were obtained from the NASA Ocean Color website (https://oceancolor.gsfc.nasa.gov/) (data accessed in spring 2018), and then delineated for the study area (Gao and Li 2019).

2.3. Environmental factors

In this study, we selected six physical and chemical environmental variables that may influence Chl *a* in the DwH area: river discharge (Q), sea surface temperature (SST), photosynthetically active radiation (PAR), wind speed (WS), total phosphorus load (TP), and total nitrogen load (TN). The daily river discharge data for the Mississippi River at Tarbert Landing (Gage ID: 01100Q) and the Atchafalaya River at Simmesport (Gage ID: 03045Q) from 2001 to 2017 were obtained from the U.S. Army Corps of Engineers (http://rivergages.mvr.usace.army.mil). Monthly discharge values were calculated for these two stations, and the values from the two stations were summed to represent the total monthly river discharge into the Gulf of Mexico. The 4 km monthly SST and PAR data were obtained from the NASA Ocean Color website (https://oceancolor.gsfc.nasa.gov/), and were further processed into monthly time series for the overall-DwH area (Gao and Li 2019). Wind speed data were collected from the NOAA National Data Buoy Center (https://www.ndbc.noaa.gov/). Since the Deepwater Horizon station (Station ID: 42872) was destroyed on April 20, 2010, the wind data were acquired from the nearest station—the Luke offshore test platform (Station ID: 42040). The hourly wind speeds were aggregated to monthly mean values, except in cases where all data were missing for a certain month. In these cases, the climatological mean values for that month were used. The monthly TP and TN loads were obtained from the USGS stations located at the Atchafalaya and Mississippi Rivers (https://nrtwq.usgs.gov/mississippi_loads/#/GULF) (Lee *et al* 2017). The monthly load amount is the product of constituent concentration and discharge integrated over time. The time series of these environmental factors are shown in Figure S1.

2.4. Approach

To evaluate the variations of the nFLH (and its anomaly) before and after the DwH spill at different spatial and temporal scales, the monthly data were further processed into monthly climatology mean values (e.g., the climatology in January is the mean of the nFLH values of all Januaries from 2001 to 2017) and annual mean values. The monthly nFLH anomaly time series values were calculated by subtracting the monthly climatology mean values from the monthly values. To further explore whether the DwH oil spill had impacted the nFLH, a stepwise multiple regression model was developed after Ho (2006). The anomalies of the nFLH and the environmental variables were used in the procedure so that the correlation between MODIS observations and model estimations would not be affected by the seasonal cycles. First, the monthly climatological values for these six environmental factors were derived, and then the anomaly time series were generated. In the stepwise multiple regression model, the monthly nFLH anomaly was set as the dependent variable, while the anomalies of the environmental forcings were the independent variables. For each of the independent variables in the multiple regression model, only those terms that passed the significance test (with p-values < 0.05) were adopted. The nFLH anomaly values estimated by the model were then compared with the MODIS observations. Specifically, the correlation (R), bias, and standard error (SE) were used to evaluate the performance of the regression model.

3. Results

3.1. Spatiotemporal variations of nFLH and anomaly

Figure 2 shows the monthly mean nFLH and corresponding anomaly values from 2001 to 2017 for the overall-DWH area. From the monthly mean time series, it is evident that the nFLH had seasonal patterns with peaks of 0.151-0.227 mW cm^{-2} μm^{-1} sr^{-1} during the winter (December to February) and dips of 0.062-0.095 mW cm^{-2} μm^{-1} sr^{-1} in the late spring to early summer (May to July). Overall, the monthly anomaly values are mostly negative from 2011 to 2015. Furthermore, the annual mean nFLH values within the overall-DwH area and the central-DwH area were compared from 2001 to 2017 (Figure 3). For the overall-DwH area, the nFLH decreased after the DwH oil spill (in 2010) and reached its lowest point in 2012 (0.107 mW cm^{-2} μm^{-1} sr^{-1}), and then resumed to the long term mean value (0.129 mW cm^{-2} μm^{-1} sr^{-1}) in 2015. For the central-DwH area, nFLH had a similar pattern except in 2010. The nFLH peaked in 2010 over the central-DwH area (0.128 mW cm^{-2} μm^{-1} sr^{-1}), which was caused by the short-term stimulation of phytoplankton due to the oil spill (Hu *et al* 2011) and by the contributions of river discharge (O'Connor *et al*

2016). Then, the nFLH plunged in 2011 and remained relatively low until 2013, when it again began to increase (and exceeded the long term mean value of 0.107 mW cm^{-2} μm^{-1} in 2014). It is worth noting that the annual nFLH in the central-DwH area dropped more significantly than in the overall-DwH area in 2011.

Figure 4 shows the spatial patterns of the annual nFLH anomaly from 2001 to 2017. In the central-DwH area, obvious positive anomalies were observed in 2010 and 2015, while negative anomalies prevailed from 2011 to 2013. The positive anomaly in 2010 was clearly stronger than any others that occurred in the previous years. The positive anomaly in 2015 consists of two small isolated clusters—one within and one outside of the central-DwH area—which differs from the pattern in 2010. In the overall-DwH area, the anomaly values were mostly negative from 2011 to 2014, which are consistent with the annual mean nFLH time series in Figure 3. Moreover, large positive anomalies were observed in 2008 and 2009 along the coast, but not in the central-DwH area. These anomalies may be due to the high discharge (Q) in these two years (Figure S2). Regardless, the locations of these anomalies indicate that primary productivity along the coast, which is close to the outlet and is rich in nutrients from freshwater inflows, is more sensitive than that in the central-DwH area.

Moreover, the nFLH anomaly patterns in August were examined from 2001 to 2017 (Figure 5). An apparent positive anomaly can be observed surrounding the central-DwH area in August 2010. This also agrees with the findings by Hu *et al* (2011) which suggested that Chl *a* was stimulated by the DwH oil spill shortly after it occurred. In addition, distinct positive anomalies also occurred within the central-DwH area in August 2008, but there was no apparent positive anomaly that emerged in this area for August in the years after 2010. Since SST is negatively correlated to nFLH, the positive anomalies in 2008 can be explained by the fact that the

190 SST in that year was the lowest for the study period (Figure S3). However, the SST in 2010 was above average, which supports the above point about the oil spill stimulating Chl *a*.

192 In addition, obvious negative anomalies were present from 2011 to 2013 in the central-DwH area (either with regard to the annual anomaly or the August anomaly), indicating that the oil spill may not have stimulated the phytoplankton in the relatively long term. The U.S. drought of 2012 may also have exacerbated the negative anomaly by reducing the nutrient loading into the Gulf of Mexico (Wetz *et al* 2011), but this effect might not have lasted for a very long time (as the annual mean Q in 2013 recovered to the climatological value of the period from 2001 to 2017; see Figure S2).

199 **3.2. The relationship between nFLH and environmental forcing factors**

200 To examine the potential effects of the oil spill on the nFLH over the DwH area, the MODIS observed nFLH anomaly data were compared with their counterpart from the stepwise multiple regression model. Through the regression procedure, three variables—the anomalies of Q, SST, and WS—were identified as the significant predictors for nFLH anomaly. The stepwise regression results are summarized in Table S2, with the coefficients listed in Table S3. The nFLH anomaly is most related to the anomaly of Q, which shows a significant correlation ($R = 0.31$, $p = 0.000$). By incorporating the anomalies of SST and WS in a stepwise manner, the R values increased to 0.42 and 0.46, while the standard errors decreased to 0.0180 and 0.0177 mW cm^{-2} μm^{-1} sr^{-1}, respectively. This selected model (with three independent variables) is thus referred to as Model_3 hereafter.

210 The biases of the Model_3 estimated monthly nFLH anomaly values from the MODIS nFLH anomaly during the study period are shown in Figure S4. The nFLH anomaly is clearly overestimated from 2011 to 2014 (positive bias), which may have been caused by the DwH oil

spill. To evaluate the performance of Model_3 on an annual basis, we calculated the annual mean bias (Figure 6) based on the monthly bias values within each year. The annual mean bias values from 2001 to 2010 were mostly negative with a mean of -0.00464 mW cm^{-2} μm^{-1} sr^{-1}. However, they became positive in 2011 and peaked in 2012. The annual mean bias suggests a considerable overestimation from 2011 to 2014, with a mean value of 0.0136 mW cm^{-2} μm^{-1} sr^{-1}. During 2015, the annual mean bias resumed to the pre-oil level, with a mean bias of -0.00261 mW cm^{-2} μm^{-1} sr^{-1} from 2015 to 2017.

4. Discussion

The effects of environmental forcing factors on phytoplankton vary across coastal areas (Green and Gould 2008, Hu *et al* 2011, Le *et al* 2014, Quigg *et al* 2011). Based on the stepwise multiple regression analysis of the anomaly data, Q, SST, and WS were identified as the most significant factors regulating the anomaly of Chl *a* (as indicated by nFLH) in the DwH area. According to the model results, Q is the most important factor—which agrees with the the findings by Le *et al* (2014). Moreover, previous studies have indicated that SST and WS could impact primary productivity in the Gulf of Mexico (Agawin *et al* 2000, Bianchi *et al* 2010, Green and Gould 2008). It has been reported that nitrogen and phosphorous are the two key limiting nutrients for primary productivity in the northern Gulf of Mexico (Dagg and Breed 2003, Steven E. Lohrenz *et al* 1997, Steven E. Lohrenz *et al* 2008, Quigg *et al* 2011). Although total nitrogen and total phosphorous were not included explicitly in the model, their impacts were implicitly included because of their high correlations with Q (Figure S5). The relatively low correlation between the model estimates and the MODIS observations (R = 0.46) can be attributed to two sources of uncertainties. The first are the uncertainties of the input data. The data associated with the model were collected via different approaches (e.g., remote sensing, in situ) and are of various spatio-temporal resolutions.

These inconsistencies unavoidably have impacted the correlation negatively. The second source is related to the environmental variables which were not included in the model. Even though our model included the principal environmental drivers that regulate the nFLH in the DwH area, there are still other factors that influence primary productivity given the complexity of the marine ecosystem (e.g., loop currents, tropical storms, etc.).

The biases between the modeled and observed nFLH anomalies have allowed us to explore the effects of environmental factors beyond those from the regression model (with the assumption that the input data uncertainties only add noise to the biases). Figure 6 clearly shows that the model experienced a significant change point in 2010. A mild underestimation from 2001 to 2010 is contrasted with a strong overestimation (2.9 times larger than the magnitude of the underestimation) from 2011 to 2014. Since the switch from under- to over-estimation began in 2010 and lasted for several years—and the most common environmental drivers have been represented in the model—we propose that this suppression effect might be attributed to the DwH oil spill. This argument also agrees with the study by Parsons *et al* (2015) which found that chlorophyll biomass was 85% lower in 2010 compared to the baseline of the previous 20 years (primarily due to the lower quantity of phytoflagellate, which decreased by 95%). Given that the DwH oil spill may have stimulated some phytoplankton while inhibiting others (Ozhan and Bargu 2014), there was a short-term increase in Chl *a* concentrations observed after the incident (Hu *et al* 2011). While some reports have found that the surface water of the Gulf of Mexico has recovered well from the DwH oil spill (Franz 2017, Ferris 2017), D'Sa *et al* (2016) found fluorescence intensities and dissolved organic carbon concentrations three years after the DwH oil spill suggestive of a potential long-term persistence of oil in the dissolved organic carbon pool in the northern Gulf of Mexico. After 2015, primary productivity appears to have resumed to the pre-spill concentration levels. Thus, collectively the results from these studies offer insights about the responses of the primary producers.

While the surface oil was transported away from the DwH area by surface ocean currents and cleanup efforts, the multi-year reduction of primary productivity may be attributed to spill residue in the underlying sediments. For instance, Duan *et al* (2018) investigated the persistence of residual oil in the sediment at Bay Jimmy five years after the spill. They found that the concentrations of total petroleum hydrocarbons, n-alkanes, and polycyclic aromatic hydrocarbons increased significantly within the sediment after the oil spill. Previous studies have shown that polycyclic aromatic hydrocarbons had depressive effects on the phytoplankton biomass (Kamalanathan *et al* 2018, Marwood *et al* 1999, Pelletier *et al* 2006, Sargian *et al* 2005). Five years after the spill, most of the n-alkanes and polycyclic aromatic hydrocarbons had degraded and recovered to pre-spill levels. Even though the concentrations of total petroleum hydrocarbons were still relatively high, they had decreased by 97% compared to the level at 1.5 years after the spill. These, and the in situ observations reported in Franz (2017) and Ferris (2017), support our finding that primary productivity started to recover around 2015.

It is also worth noting that this study is focused on surface water (i.e., the first few meters) because of the strong light attenuation in the wavelengths used to calculate MODIS nFLH (i.e., 667, 678, and 748 nm). Moreover, our findings are based on a statistical model, which does not represent physical mechanisms. Additionally, although earlier analysis by NASA showed sensor degradation after 2011, the degradation was corrected through improved time-dependent sensor calibration and vicarious calibration in NASA's data reprocessing version 2014.0 (Hu *et al* 2015). Therefore, the temporal patterns of MODIS nFLH are unlikely affected by sensor calibration changes.

To date, continuous long-term field observations before and after the spill are still lacking, which hamper the understanding of the variability within this large area. In the absence of such long-term field data, this study shows an alternative way to evaluate the long-term changes of primary productivity (via Chl *a*) in the DwH area, which may be adapted for other oil spill events.

5. Conclusions

The most significant finding from this study is that—although annual changes in MODIS nFLH (used as a proxy for Chl *a*, an indicator for primary productivity) before 2010 can be explained by environmental forcing factors (river discharge, sea surface temperature, and wind speed)—the same explanation does not hold between 2011 – 2014. The behavior between 2011 and 2014 is speculated to be a result of the long-term, chronic impact of the DwH oil spill. Although it is impossible to verify this hypothesis due to a lack of continuous field measurements, this study represents the first attempt to use long-term satellite data to evaluate the potential chronical effects of the DwH oil spill on primary productivity. This also suggests the importance of continuous field measurements to help pinpoint the reasons behind the changes of phytoplankton productivity in future oil spills.

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Data availability statement

The data that support the findings of this study are openly available at the Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC) at https://data.gulfresearchinitiative.org/data/E2.x842.000:0001 (doi: 10.7266/n7-xsm6-wx65).

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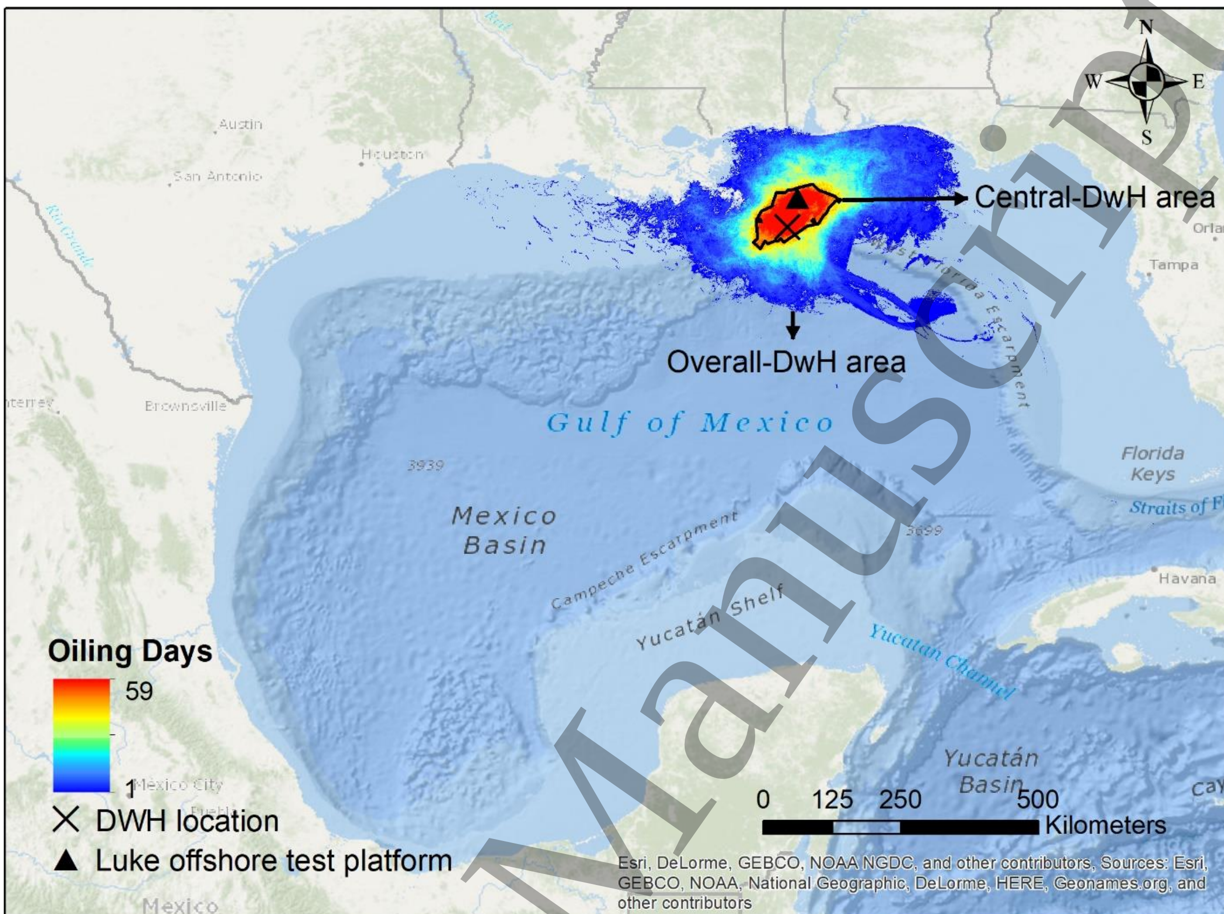


Figure 1. The footprint of the Deepwater Horizon (DwH) oil spill, with the locations of the DwH oil rig (28.7381° N, 88.3658° W) and the Luke offshore test platform (29.2083° N, 88.2258° W) indicated. The entire footprint of the surface oiling is referred to as the "overall-DwH area", while the portion that suffered the most severe impacts (which had more than 30 oiling days) is referred to as the "central-DwH area" (delineated by the black line). The oiling data were downloaded from the Gulf of Mexico Environmental Response Management Application website (https://erma.noaa.gov/gulfofmexico/erma.html).

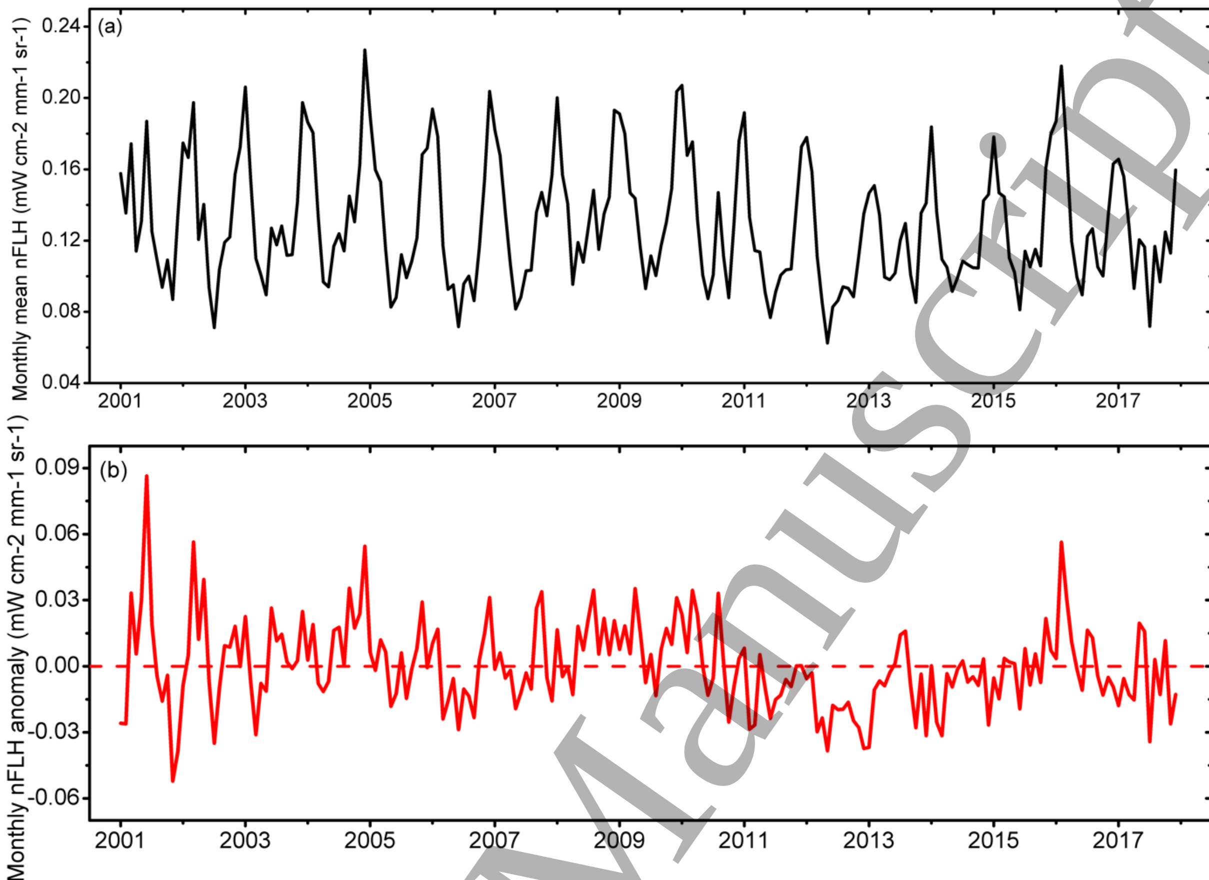
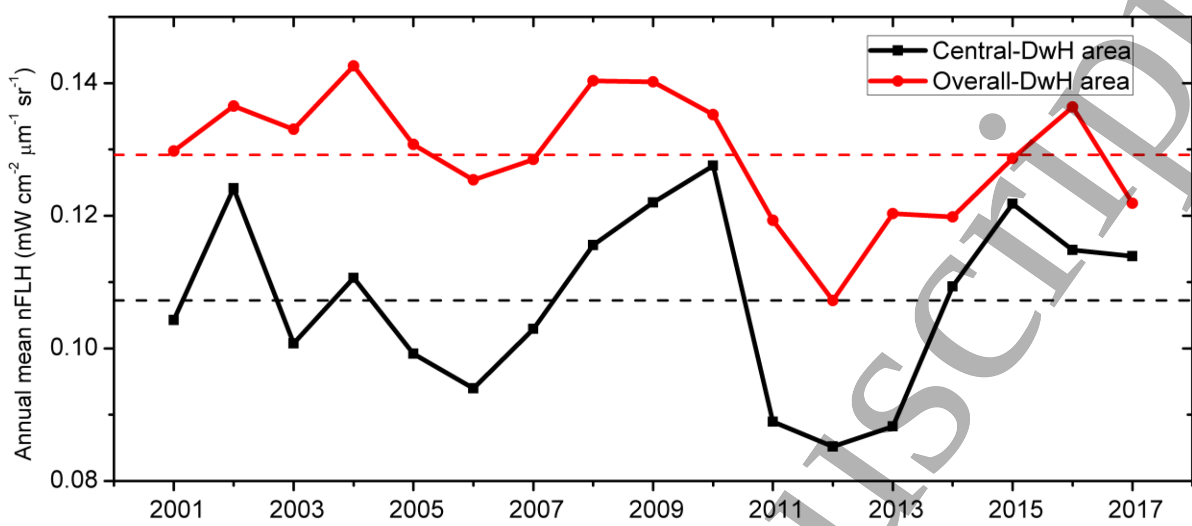


Figure 2. (a) Monthly mean nFLH and (b) the corresponding anomaly values from 2001 to 2017 for the overall-DWH area.



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487 **Figure 3.** Annual mean nFLH values for the overall-DWH area (red line) and the central-DwH
488 area (black line) from 2001 to 2017. The dashed lines represent the climatological annual mean
489 nFLH value for each of these two areas.

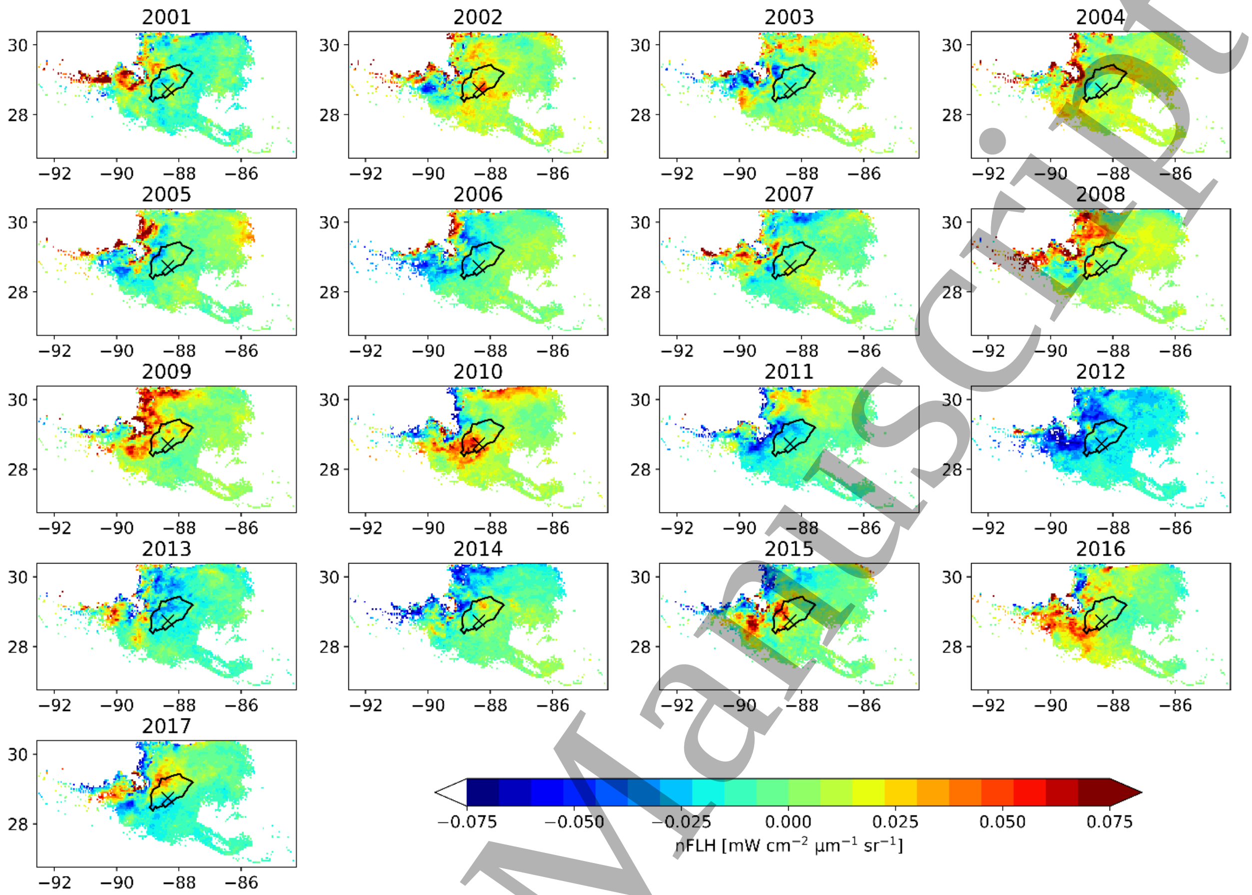


Figure 4. Annual mean nFLH (mW cm^{-2} μm^{-1} sr^{-1}) anomaly from 2001 to 2017. The location of the DwH is marked by "X", and the central-DwH area is delineated by a black line.

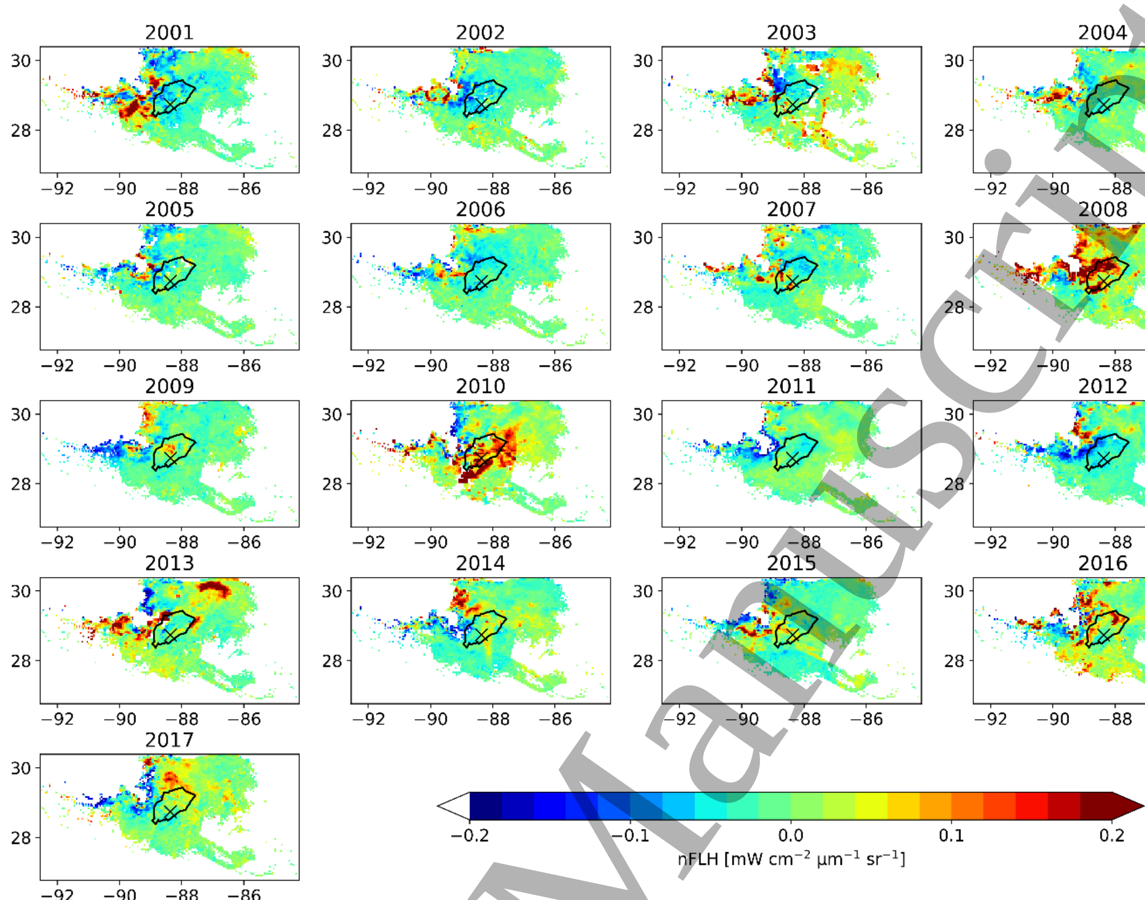
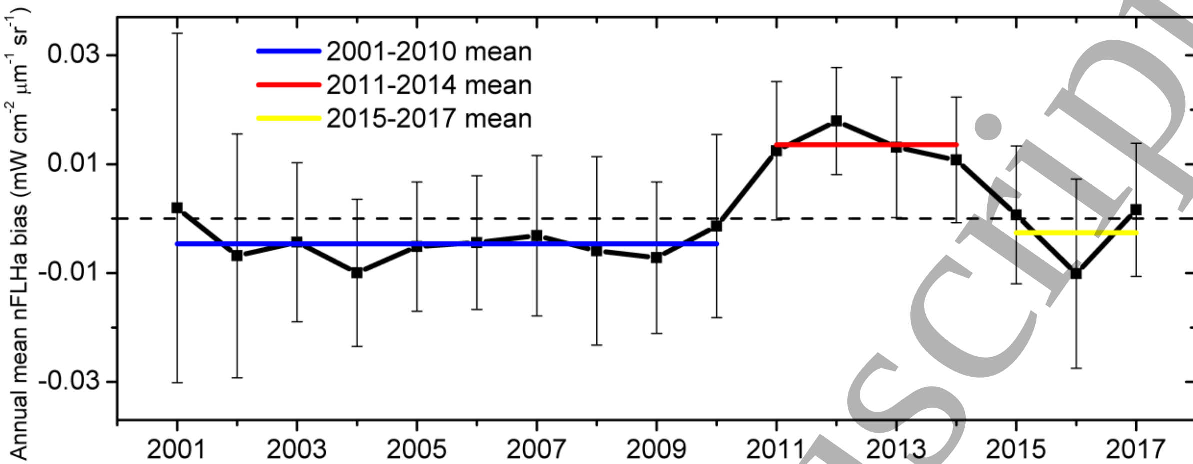


Figure 5. nFLH anomaly during the month of August from 2001 to 2017. The location of DwH is marked by “X”, and the central-DwH area is delineated by a black line.



496

497 **Figure 6.** Annual mean bias between the estimated nFLH anomaly (nFLHa) from the Model_3
498 and MODIS nFLH anomaly from 2001 to 2017. The error bars represent the standard deviations
499 of the biases for each year.