Upper Ocean Response on the Passage of Tropical Cyclones in the Azores Region

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Abstract. Tropical Cyclones (TCs) are extreme climate events that are known to strongly interact with the ocean through two mechanisms: dynamically through the associated intense wind stress, and thermodynamically through moist enthalpy exchanges at the ocean surface. These interactions contribute to relevant oceanic responses during and after the passage of a TC, namely the induction of a cold wake and the production of chlorophyll (~~chl~~Chl-a) blooms. This study aimed to understand these interactions in the Azores region, an area with relatively low cyclonic activity for the North Atlantic basin, since the area experiences much less intense events than the rest of the basin. Results for the 1998-2020 period showed that the averaged induced anomalies were on the order of +0.~~026~~050 mg~~/m^3~~ m^{-3} for the ~~chl~~Chl-a and -1.~~554~~615 K for SST. Furthermore, looking at the role played by several TCs characteristics we found that the intensity of the TCs was the most important condition for the development of upper ocean responses. ~~Two other analysed conditions were the TC's translation speeds and the impacted areas, which also showed to be positively affecting the registered induced anomalies.~~Additionally, it was found that bigger TCs induced greater anomalies in both variables, while faster ones created greater Chl-a responses, and TCs that occurred later in the season had greater anomalies. Two case studies (Ophelia, in 2017, and Nadine, in 2012) were conducted to better understand each upper ocean response. Ophelia showed to affect the SST at an earlier stage while the biggest ~~chl~~Chl-a induced anomalies were registered at a later stage, allowing the conclusion that thermodynamic exchanges conditioned the SST more while dynamical mixing might have played a more important role in the later stage. Nadine showed the importance of the TC track geometry, revealing that the TC track observed in each event can impact a specific region for longer, and therefore induce greater anomalies.

Introduction

Tropical Cyclones (TCs) are potentially intense atmospheric disturbances which are characterised by a low-pressure centre (eye) where strong winds curl around. Among other important properties, TCs are thermodynamic dependent phenomena, meaning that intense temperature gradients need to occur in the lower atmosphere to maintain and intensify the storm. Thus, TCs are fed from warm sea water which provide a strong moist enthalpy flux from the oceanic surface to maintain a steep temperature gradient within the lower and middle troposphere and produce massive water vapour convection (Emanuel, 2003; Holton ~~&~~and Hakim, 2012; Pearce, 1987).

The strong wind stress present near the surface and the associated intense curl are also shown to induce vertical mixing and Ekman upwelling in the upper layer of the ocean. In ~~the~~his seminal study~~ by~~, Price (1981) ~~it is shown~~shows, through both observed and numerical modelling data, the evolution of sea surface temperature (SST) on the passage of a hurricane, with the emergence of a cold wake of SST after a TC due to entrainment of water from shallow layers. This effect has since been well studied and documented with many case studies observed, for example, the case of Hurricane Felix, in the vicinity of Bermuda in 1995, that showed decreases in the order of 3.5-4 ºC (Dickey *et al.,* 1998), or the cases of cyclones Nargis (2008) and Laila (2010), in the Bay of Bengal, that caused SSTs to drop by around 1.76 ºC (Maneesha *et al.*, 2012). Additionally, several model-based works ~~have been done~~focused on either ~~according to~~ the ~~effect~~effects caused by the TCs, ~~as well as~~or the interaction of the TC with its own cold wake (e.g., Chen *et al.*, 2017; Zhang *et al.*, 2019).

There are also biological responses to the passage of a TC. Due to the upwelling of colder water, ~~there may also occur the~~ transport of nutrient-rich water from the sub-superficial layer may also occur (Kawai ~~&~~and Wada, 2011). In this case, phytoplankton can quickly increase in the surface layer following the rise in nutrients. This increase can be remotely sensed through satellite observations that capture the chlorophyll-a concentration (Chl-a) increasing after the passage of a TC, since ~~chl~~Chl-a is generally accepted as a proxy for biological activity (Kawai ~~&~~and Wada, 2011; Liu *et al.*, 2009; Subrahmanyam *et al.*, 2002; Walker *et al*., 2005).

The oceanic response, either physical or biological, to the passage of a TC depends on various aspects, most remarkably the TC's intensity and its translation speed but also the oceanic subsurface conditions (Zheng et al., 2008). The magnitude and significance of these aspects on the modulation of the oceanic response varies regionally, although it is generally regarded that the most impactful phenomena to be those of an intense and slow TC (Chacko, 2019; Price, 1981; Price et al., 1994). Recent studies (e.g., Chacko, 2019; Pan et al., 2018; Shropshire et al., 2016) have shown that regional differences do matter when studying the biological response. In the case of the Bay of Bengal, it was shown that the intensity of a TC is less important, and the most meaningful aspects are the TC's translation speed and, to a lesser degree, a pre-existing shallow mixed layer (Chacko 2019). The results from this study are important to stress that relatively weaker TCs can also induce a strong biological response after their passage.

Until now, the Azores region has not been studied regarding its thermodynamic and biological impacts. This section of the North Atlantic basin presents much fewer and weaker cyclones than the tropical band of the basin, with this region being mainly a zone where TCs undergo either cyclosis or post-tropical transition into extra-tropical cyclones or mid-latitude storms (Baatsen et al., 2015; Haarsma et al., 2013). The north-eastern Atlantic (NEA) basin, where the Azores archipelago is located, presents significantly less TCs than the western counterpart, closer to the USA coast (Baatsen et al., 2015; Lima et al., 2021; Haarsma et al., 2013). However, there is growing evidence of a significant increase in the frequency of strong TCs in both western (Kossin et al., 2020) and eastern (Lima et al., 2021) halves of the north Atlantic Ocean. The climatology of the area points to a south-north gradient in both SST and ~~chl~~Chl-a, with a decrease in the former and an increase in the latter (Amorim et al., 2017~~).~~; Caldeira and Reis, 2017). In general, the southern part of the Azores region offers SSTs high enough to maintain TCs, although the necessary atmospheric conditions (e.g., high lapse rates and low wind shear) need to occur for their passage northeast through the Azores (Lima et al., 2021). However, this area is undergoing a transition due to anthropogenic climate change and an increase both in number and intensity of TCs is expected (Baatsen et al., 2015; Haarsma et al., 2013). Therefore, the NEA basin is a challenging study region to assess the impact that lower intensity TCs have on the oceanic surface.

The main aim of this study is to analyse in detail the upper ocean response observed after the passage of a TC in the Azores region, which is characterised by its lower-than-normal cyclonic activity in relation to the rest of the north Atlantic basin. In particular, we aim to evaluate the impacts on ~~sea surface temperature (~~SST~~)~~ and ~~chlorophyll~~Chl-a concentration ~~(Chl-a)~~ produced by ~~three~~ important TC characteristics (averaged maximum wind speed, ~~cumulative impacted area, and~~ average translation speed, overall impacted area, time of occurrence, and geometry of the track). Two practical case studies, relative to Nadine (2012) and Ophelia (2017) are then thoroughly analysed to reflect the drawn conclusions for this area.

Data

~~Data~~The main data used to evaluate the oceanic response in this study is divided into three main parts: Remotely sensed interpolated data used to characterise the ~~chl~~Chl-a and SST, respectively, and TC track data, which provides the necessary additional information on the location and dynamic variables of each TC, that allow to explore the oceanic response in the aforementioned data. Additionally, non-interpolated datasets are used for the case studies to validate the interpolated ones; and wind-stress data is used for the Hurricane Ophelia study case.

Biological oceanic response was evaluated using a multi-sensor daily ~~chl~~Chl-a product available through the Copernicus Marine Environment Monitoring Service (CMEMS) in a 4 km x 4 km resolution from the end of 1997 to the present (CMEMS, 2021b). This product, delivered by the ACRI-ST company, is based on the Copernicus-GlobColour project and obtained by merging different sensors: SeaWiFS, MODIS, MERIS, VIIRS-SNPP&JPSS1, OLCI-S3A&S3B. The final ~~chl~~Chl-a product is a mix of several algorithms that consider different water conditions, such as oligotrophic, mesotrophic, coastal, clear, and complex waters (Garnesson et al., 2019). To produce a "cloud free" product, the resulting data was subjected to daily interpolation to fill any gaps (Krasnopolsky et al., 2016; Saulquin et al., 2019). The lack of gaps in this dataset is particularly relevant in the context of this study since the areas analysed will be concentrated around the TCs; it is then expected that large amounts of the analysed areas would be under cloud coverage and, therefore, some of the analysed data is not real but interpolated values. Nonetheless, CMEMS provides approximate uncertainty levels for this data, which we used to assess the quality of our results. For further validation purposes we used also a non-interpolated Chl-a product generated by the Ocean Colour component of the European Space Agency's Climate Change Initiative project (OC-CCI) (Sathyendranath et al., 2019). This dataset results from a merge of several sensors: SeaWiFS LAC and GAC, MODIS Aqua, MERIS, VIIRS, and OLCI.

ESA’s OCC-CI version 5.0 Chl-a product has 0.042º resolution and a daily temporal resolution (Sathyendranath et al., 2021).

To evaluate the physical oceanic response and to relate this to the biological one, a daily SST dataset from the CMEMS was used, with a 0.05º resolution. This data is available from 1981 up to the near present (CMEMS, 2021a). Similarly, to the previous ~~chl~~CMEMS interpolated Chl-a product the SST field is also a blended gap-free analysis product, with the present one resulting from re-processed (A)ATSR, SLSTR and AVHRR sensor data being applied to the Operational SST and Sea Ice Analysis (OSTIA) system (Donlon et al., 2012). This reprocessed analysis product provides an estimate of the SST at 20 cm depth. The inputs to the system are SSTs at 10:30 am and 10.30 pm local time which means that the analyses roughly correspond to the daily average SST (Good et al., 2020; Lavergne et al., 2019; Merchant et al., 2013). As stated before, approximated error values for SST are also provided by CMEMS. Additionally, AVHRR Pathfinder version 5.3 collated data was used as non-interpolated data for validation. This dataset, similarly to the CMEMS one, is a collection of twice-daily (averaged to daily), 4km spatial resolution, merged SST product, provided by NOAA’s National Centers for Environmental Information (Saha et al., 2018). The merge of this data, however, is only used to spatially collate the data, as it is a single instrument measurement (AVHRR) onboard NOAA-7 through NOAA-19 Polar Operational Environmental Satellites (POES).

Wind stress data to assist in the analysis of the Hurricane Ophelia study case was provided by NOAA’s CoastWatch dataset available at https://coastwatch.pfeg.noaa.gov/erddap/griddap/erdQMstress1day_LonPM180.html. This dataset is derived from wind measurements obtained from the Advanced Scatterometer (ASCAT) instrument on board EUMETSAT’s MetOp satellites (A and B) at a daily 0.25º resolution, from 2013 to the present. ASCAT presents a near all-weather capacity (not affected by clouds), as it operates a frequency in C-band (5.255 GHz), therefore, minimizing the number of missing values in predominately clouded areas such as the case of TC paths.

The TC track data is made available by the *International Best Track Archive for Climate Stewardship Project* version 4 (IBTrACS v4) free access dataset (Knapp *et al.*, 2009). This dataset contains global information regarding TC activity since the 1851 hurricane season up to ~~the most recent full hurricane season, 2020.~~2020. It aggregates variables such as TC geographical location, maximum wind speed, minimum sea level pressure, and storm radius estimation based on wind intensity, measured at 6-hour intervals (original dataset interpolates for increased resolution, at 3-hour rates, however this interpolation only includes the geographical location). For the 1998-2020 period, the Azores region experienced the passage of 62 individual TCs accounting to 642 6-hour observations that are categorised in the following intensities according to the Saffir-Simpson hurricane wind scale (Taylor *et al.*, 2010):

- 148 tropical depression observations.
- 389 tropical storm observations.
- 85 category 1 hurricane observations.
- 18 category 2 hurricane observations.
- 2 category 3 hurricane observations.

The full TC tracks can be better visualised in Fig. 1, with the left panel showing the full track for all these 62 TCs' observed in the NA basin for the 1998-2020 period and the right panel ~~shows~~showing a zoomed view relative to the considered Azores region. Tropical depression observations (dark blue in Fig. 1, right panel) account for 23 % of the total observations and will not be considered in this study, as they present the lower branch of intensities with winds below the 34-kt (18 m/s) threshold. Therefore, a total of 494 TC 6-hour observations were considered for this study.

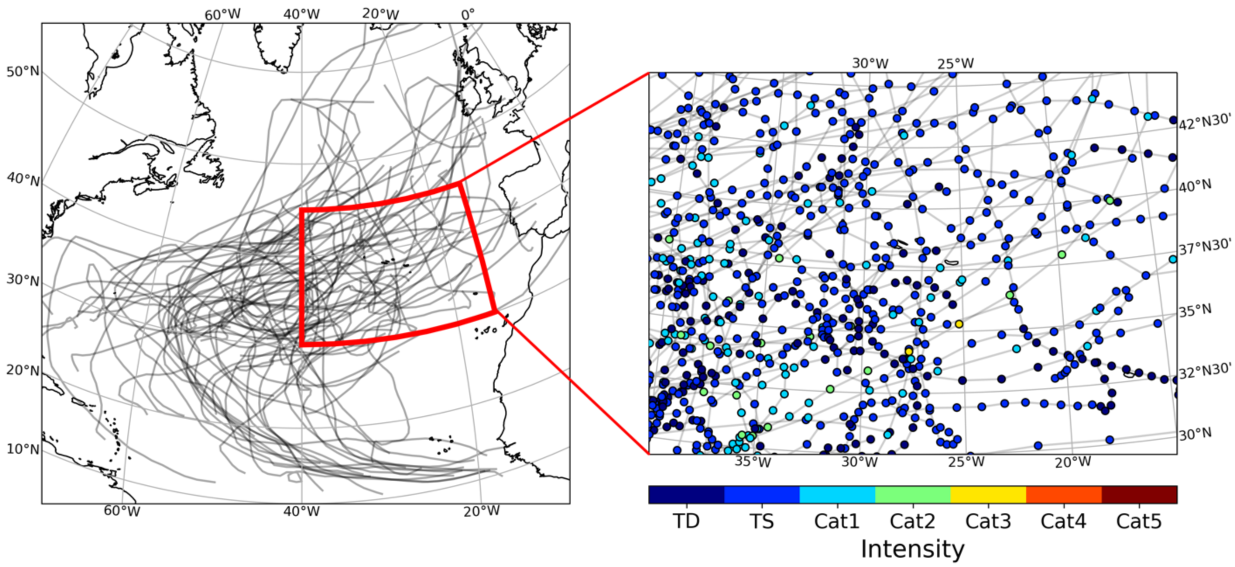


Figure 1 - Left panel: North Atlantic basin and the tracks for all TCs that went through or occurred inside the study region (shown by the red outline). Right panel: Zoom of the previous red outline, with each TC observation marked in different colours for intensity (TD: Tropical Depression; TS: Tropical Storm; Cat1 - Cat5: Hurricane category according to the hurricane Saffir-Simpson wind scale).

Since the interpolated datasets used for most of this study do not share the same time frame and to better encapsulate full years of data, the timeframe of the present study will be from January 1st of 1998 to December 31st of 2020. Moreover, while we have extracted all the data described above covering the entire North Atlantic basin, we will focus on the area around the Azores archipelago, delimited by the 15ºW and 40ºW meridians and between the 30ºN and the 45º parallels~~.~~ (Fig. 1).

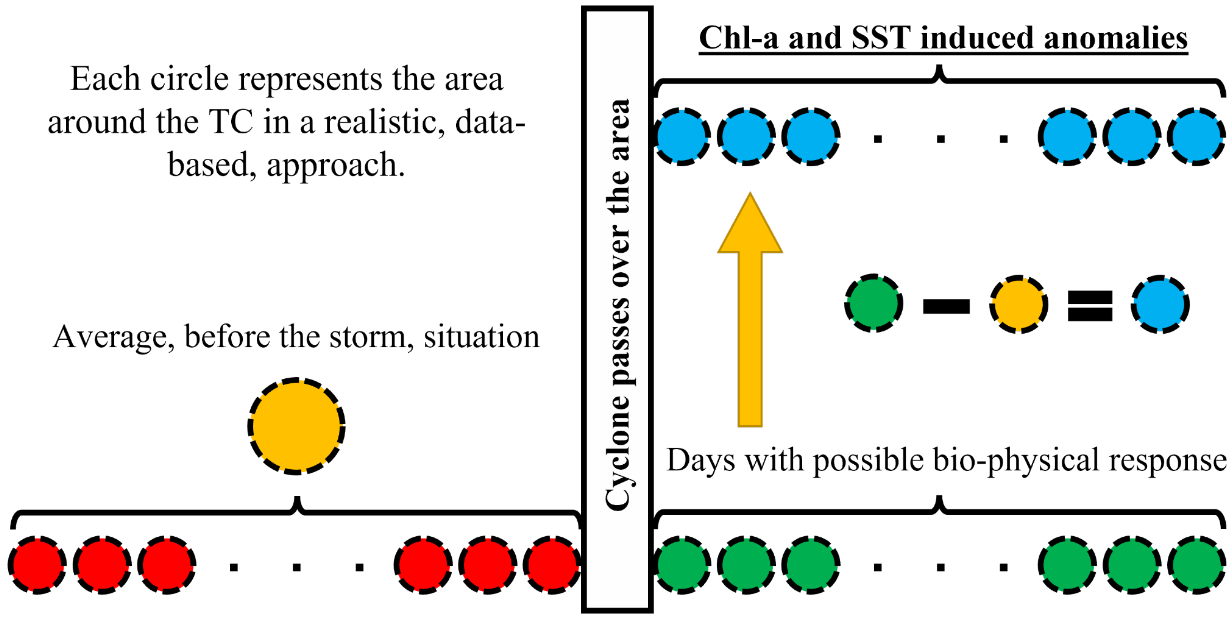
Methodology

The ~~area of focus on this study is centred in the Azores archipelago in the North Atlantic basin, pictured in Fig. 1. The area is longitudinally delimited by the 15ºW and 40ºW meridians and latitudinally between the 30ºN and the 45º parallels. This~~ region of study was chosen due to its nature regarding TCs, since it is an area with fewer and less ~~quantity and intensity of~~intense tropical storms (Hart ~~&~~and Evans, 2001; Lima et al., 2021; Ramsay, 2017). Generally, tropical cyclosis and post-tropical transition ~~occurs~~occur here (Baatsen et al., 2015; Haarsma et al., 2013). Because of these aspects, it corresponds to a much less studied area and is a good region to characterise oceanic ~~bio-~~

~~physical~~biophysical effects after the passage of (generally) weaker TCs at higher-than-tropical latitudes~~,~~ and to compare the obtained results with previous literature.

To cope with large amounts of data, the bio-physical response was evaluated within a small area around individual locations obtained for each TCs' best-track location. For this, we used the approximated quadrant radius given by the IBTrACS v4 dataset. This dataset provides different types of radii depending on the considered isotach, for this study we used the 34-kt isotach as it corresponds to the lower-bound for the Tropical Storm status according to the Saffir-Simpson hurricane wind scale (Taylor et al., 2010). Since the considered area of analysis ~~would be~~falls above the 34-kt isotach, ~~any~~ tropical ~~depression observation was~~depressions were not considered (exact partition of intensities is given at the beginning of the *Results* section). ~~To correct~~There are some missing radii values in the middle of TC tracks~~,~~ and in order to correct a simple linear regression was applied. ~~An example~~To illustrate the application of this methodology ~~can be observed~~we present the study cases in ~~Figs. 6a~~the *results and* ~~7a~~*discussion* section, for hurricanes Ophelia (2017) and Nadine (2012~~), respectively.~~). From inside this area of analysis, we may retrieve the ~~chl~~Chl-a concentration and SST at their respective resolution~~, as well as study their anomalies and post-storm responses.~~. The analysis inside the considered area ~~is made recurring to~~was performed using histograms, in which each pixel inside the 34-kt isotach contributes to that ~~TC's observation~~TCs histogram.

~~To analyse the TCs' impact on their passage, a different approach was taken than the typical anomaly analysis since the effects caused by a TC may not be visible in simple anomalies computed against climatology. Some authors suggest that an appropriate time window to analyse the maximum bio-physical oceanic response would be approximately circa 10 days after the passage of a TC (Kawai & Wada, 2011). To assess the best temporal window for our region, we analysed the daily anomalies registered between 30 days before and 30 days after the passage of a TC. Afterwards, we chose two time windows to reflect different situations (Fig. 2): (a) An average, before the storm, situation, which is required to assess the oceanic conditions before the TC occurred in the area (i.e., average of red circles in Fig. 2, resulting in yellow circle); (b) And secondly, a time-window after the TC passed over the area, impinging the most significant response (Green circles, Fig. 2). Based on these definitions the induced anomaly can be calculated (blue circles, Fig. 2) by subtracting each daily value of (b) from the average situation before the storm described in (a). In the end, this leaves us with a large pool of observed daily induced anomalies to study, from which we may study the responses according to different TC intensities, translation speeds, or affected area.~~



~~**Figure 2 - Resumed schematic of the applied methodology in each TC observation. Do note that the circles are a mere representation of each affected area. The colour coding follows: Red – Individual daily observations before the TC; Green – Individual daily observation after the TC passes over the region; Yellow - Averaged values before the TC; Blue – Individual daily induced anomalies. A more detailed description of the methodology is presented in the text.**~~

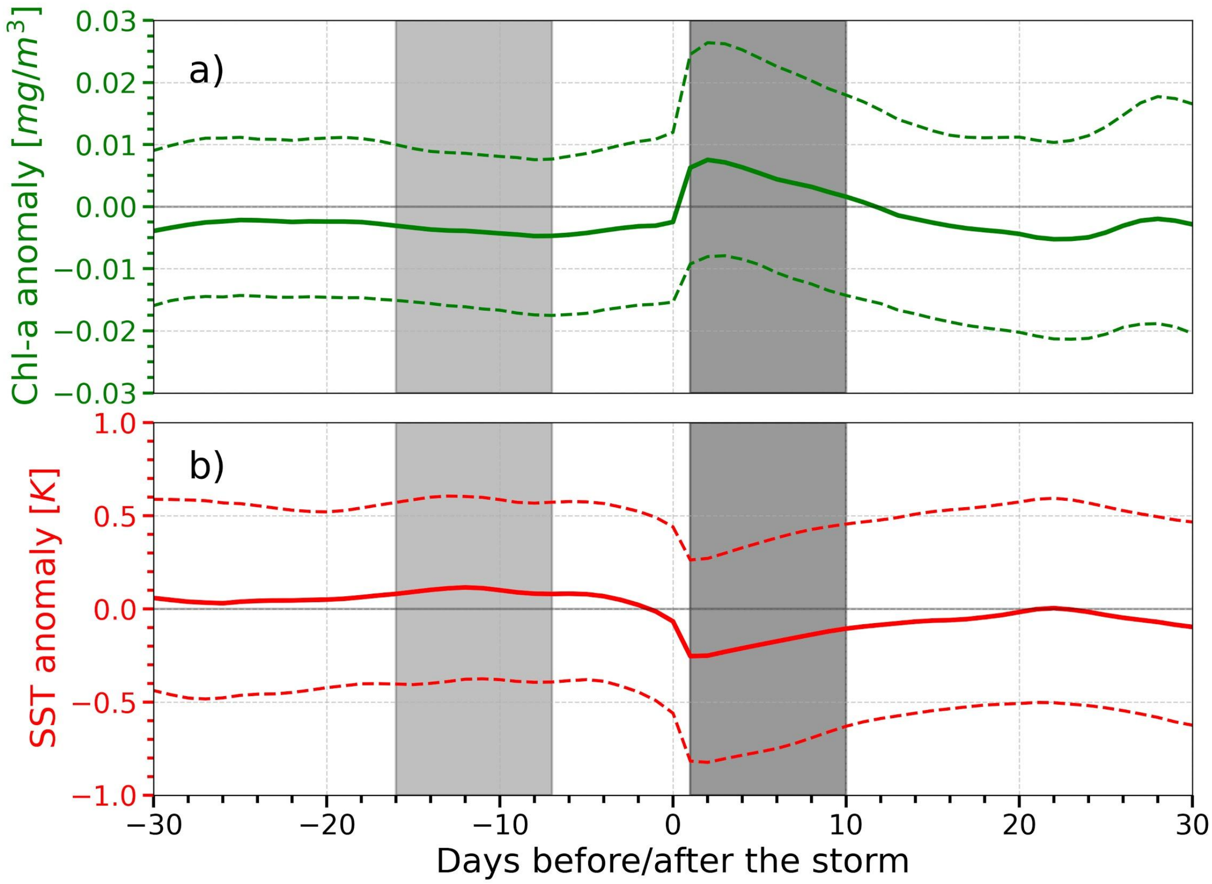
To analyse the TCs' impact on their passage, inspiration was taken from Kawai and Wada (2011), who computed the climatic monthly standard deviation of Chl-a on 0.25º grids over a 5-year study period. Here, we computed for each storm the daily standard deviation of both Chl-a and SST over their respective grids relative to the climatology over the same area (only the area impacted by the TC was considered) for the study's complete time frame; this analysis was performed considering 30 days before and after each TC to allow then the analysis of an ideal window to compute the induced anomalies. To compute this ideal window, we searched for the maximum difference between the number of standard deviations over the climatological value before and after the storm.

To compromise between having the maximum difference and ensuring a time window as close as possible to the storm (to minimize external factors to the TC), we performed a sensibility study on the length and location of the considered time window. First, we analyse the overall maximum difference in the 61-day period (including the day of the storm) and then search for a secondary maximum value that is within 10% of it considering a smaller sample of days, decreasing in groups of 5 days each time this search is made (e.g., the first iteration would be 25 days before and 30 after, the second 30 before and 25 after, the third 25 before and after, etc.), until an optimum maximum difference value is identified. With this window defined, the induced anomalies are simply the difference between the daily values of Chl-a or SST after and before the TC.

As an example of this methodology, Fig. 2 shows the Chl-a standard deviation over the climatological value in the case of Hurricane Nadine. In this case, only 15 days around the TC are shown for clarity. We can see that the maximum difference is obtained between 8 days before and 1 day after the storm (ΔChl-a max). However, when we take into account the compromise of considering windows located as close as possible to the occurrence of the TC over the region, we see that the value found between 4 days before and 1 day after is within 10% of the absolute maximum. This methodology is then applied to all 6-hour observations individually and for each TC, thus resulting in two groups of induced anomalies (per TC and per 6-hour observations) where we can study these with respect to the TCs averaged (per TC) or instantaneous (6-observations) characteristics.

To address the possibility that some pixels are overlaid on top of each other, which would contaminate the analysis, as observed in the case of the slow erratic Hurricane Nadine (~~track seen in Fig. 7a~~presented in the *results and discussion* section as a study case), we did not take into consideration the days in which the TC is over the aforementioned overlaid region. ~~Therefore~~In these cases, the days considered are those ~~after~~when the ~~cyclone~~TC has completely travelled over ~~these areas.~~the area (i.e., that pixel is no longer inside the radius of influence of the TC). However, when we consider independent 6-hour observations, this caveat cannot be accounted for since we have no way of knowing if that area has been influenced or not by the TC before, for how long, or even if a future observation will impact the area.

~~To identify the appropriate time periods in this analysis we used a linear kernel change point detection algorithm that detects changes in the mean of any given signal (Celisse et al., 2018; Truong et al., 2020). Figure 3 shows the daily distribution of the Chl-a (Fig. 3a) and SST (Fig. 3b) anomalies 30 days before and after the TC passed over a given area. Using the change point detection algorithm, we identified 2 main periods associated with this passage: i) 7 to 16 days before the TC, representing an average condition prior to the arrival of the TC; ii) from 1 to 10 days after the period where it is clearly visible the effects on the oceanic variables. It is important to note that more periods were identified in between and after those presented due to the sensitivity of the algorithm but were not considered in the analysis for being too small or not showing relevance in our study (e.g.: from -17 to -30 days, or -4 to +1 days). The main 2 identified periods coincided in both cases (Figs. 3a and 3b), while those extra periods varied both in number and location.~~



~~**Figure 3 - Average daily a) chl-a (green solid line) and b) SST (red solid line) anomalies registered in a month period before/after each TC observation. Dotted lines show the first and third quartiles of each day. Shaded light grey area represents the period (-16 to -7 days) considered for the computation of the average before the storm situation and the darker grey represents the time period (+1 to +10 days) used to compute the induced anomalies.**~~

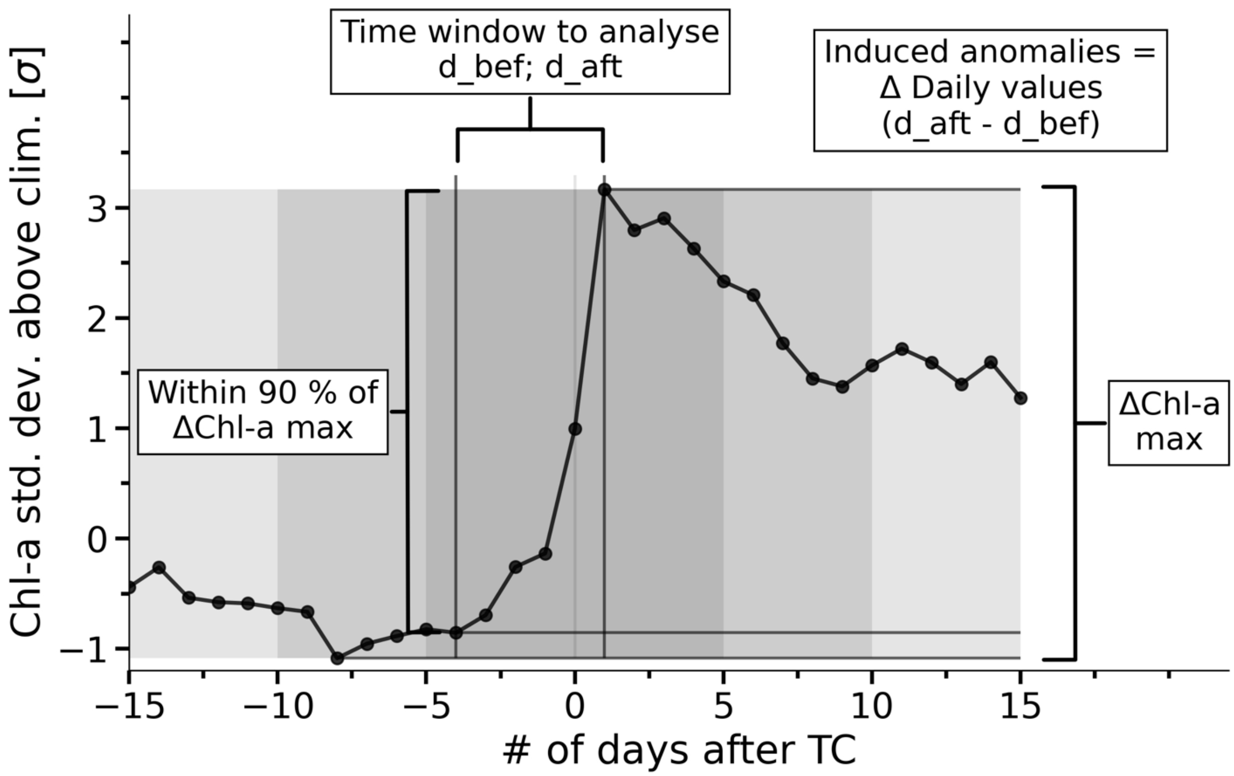


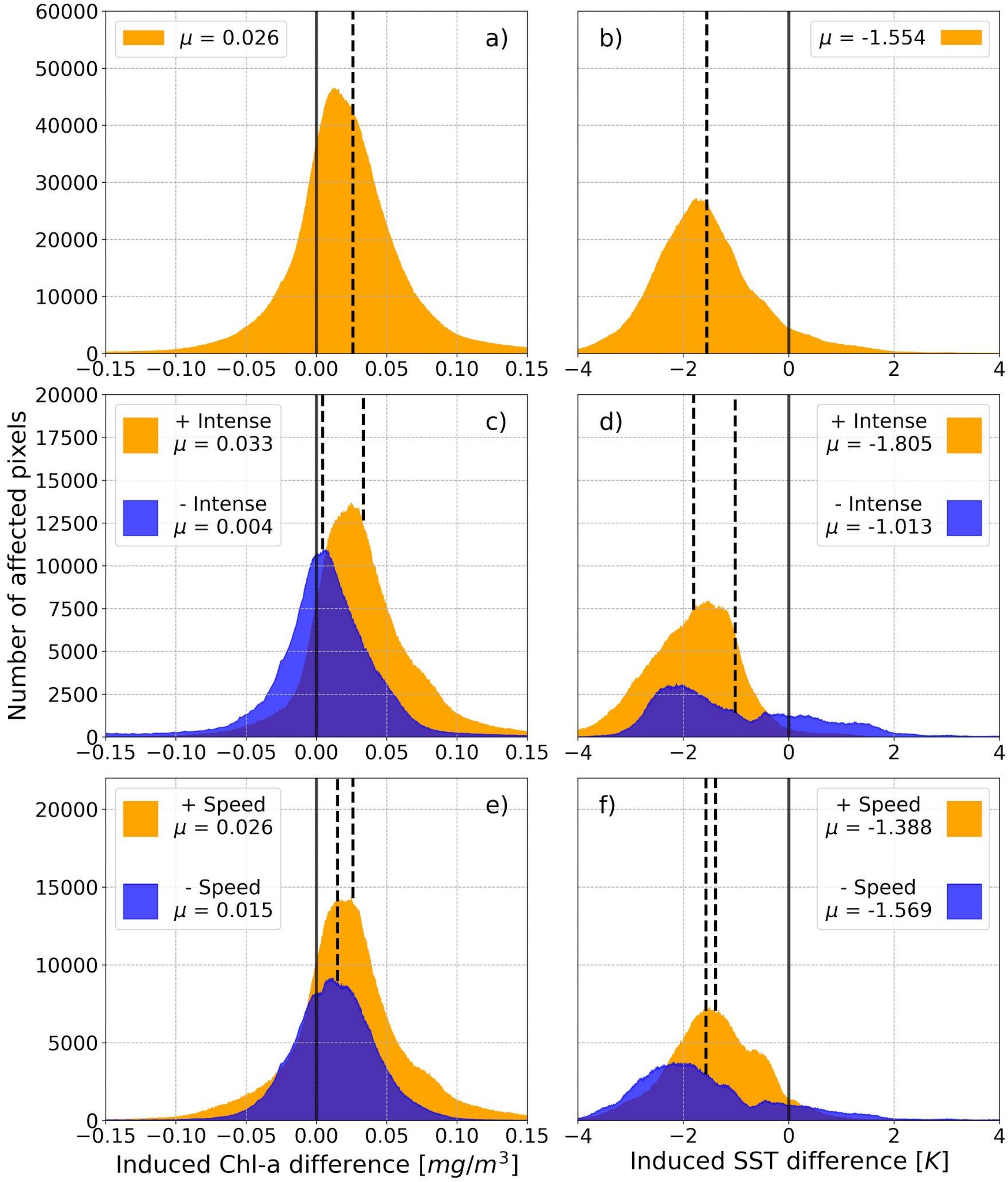
Figure 2 - Schematic of the applied methodology for each TC. Black line shows the number of standard deviations from the climatological values for the area surrounding Hurricane Nadine. A detailed description of this methodology can be found in the text.

As previously mentioned in the *Data* section, the interpolated data used for this study is expected to encounter some regions where clouds are to be expected due to the presence of the TCs. To account for this potential caveat, we looked at the uncertainties associated with the data before and after the TCs, as well as during the TC (e.g., day 0 in Fig. 2), to evaluate if there were clear increases in uncertainty for cloud covered situations.

Two case studies were looked at in greater detail: Hurricane Ophelia (2017) and Hurricane Nadine (2012). The former was performed to assess the different impacts along the lifecycle of the storm, and different histograms were produced for smaller portions of the TC. The latter was made to analyse the possible increasing impacts the storm geometry could cause. Additionally, these study cases were used as validation for the interpolated “cloud-free” data, where a comparison was made between the non-interpolated and the interpolated “cloud-free” data described in the *Data* section.

Results and Discussion

Applying the mentioned methodology leaves us with a large pool of induced anomalies, from which we can now evaluate the distribution of anomalies for both the ~~chl~~Chl-a and SST as shown in Figs. ~~4a~~3a and ~~4b~~3b in the form of histograms of induced ~~chl~~Chl-a and SST anomalies, respectively. Both variables ~~suffered~~present a large impact after the passage of TCs, with the ~~chl~~Chl-a presenting a mean response of positive 0.~~026~~050 mg~~/m^3~~ m^{-3} and the SST showing a mean response of negative 1.~~554~~615 K. Figs. ~~4c~~3c-f show the corresponding distributions as a function of the cyclone's intensities (Figs. ~~4c~~3c and ~~4d~~3d) and translation speeds (Figs. ~~4e~~3e and ~~4f~~3f). To make these distinctions, we chose only the high values (either regarding intensity or translation speed) to be those above the third quartile and the lower values to be those below the second quartile.



~~**Figure 4 - Histograms for the: a) Total chl-a and b) SST induced anomalies; c) Chl-a and d) SST induced anomalies after weaker (blue) and powerful TCs (orange); e) Chl-a and f) SST induced anomalies after slow TCs (blue) and fast TCs (orange). Each subplot histogram presents the respective population mean value (μ) in a dashed black line, and the zero value on a grey line.**~~

Firstly, regarding intensity (Figs. ~~4c~~3c and ~~4d~~3d), we have the induced response of the most powerful intensities in orange and the weaker ones in blue. Regarding the impact as a function of intensity it is possible to observe that more powerful TCs tend to induce a stronger biological response than weaker ones, which have a mean response ~~much~~ closer to zero. It is also important to note that the more powerful TCs have a response that is much more skewed towards extreme positive values of ~~chl~~Chl-a. Fig. ~~4d,~~3d also shows a ~~much larger~~great impact regarding different intensities in SST, in which even weaker TCs show a substantial mean response of -1.~~013~~517 K and nearly all the analysed pixels showing negative induced anomalies. Important to note the nearly bimodal nature of this distribution, which can be attributed to both the earlier phase of TCs (more energy being drawn from the ocean) resulting in more negative SST values, and the less negative corresponding to the ~~latter~~later part of TCs since baroclinic instabilities are more prevalent than the action of moist enthalpy flux from the ocean at this phase (Baatsen et al., 2015; Emanuel, 2003). Powerful TCs induced a more varied distribution of anomalies, with a mean response of -1.~~805 K. Do note that these different distributions do not represent the same geographical areas, since they are analysing different observations associated with the location of each TC as it moves along its storm-track~~694 K.

Regarding the different translation speeds, Fig. ~~4e~~3e shows that, for biological responses, ~~this categorization~~faster TCs show a greater mean value of +0.060 mg m^{-3}. This difference is not as ~~important since they present similar mean responses, close to~~ expressive as the ~~general~~ one ~~seen~~ in Fig. ~~4a, with faster TCs showing a slightly larger mean value.~~3c. On the other hand, the SST response (Fig. ~~4f~~3f) seems to be weakly impacted by the TC's translation speed, with slower TCs ~~having~~have a slightly stronger impact than faster ones~~. Even though~~, while the mean response values do not differ as much as the ones in Fig. ~~4d, these distributions show relatively greater deviations~~3d. Additionally, even if faster TCs do not affect the SST response as much as slower ones, the mean value is still close to what is seen in the general case in Fig. ~~4b~~3b, and most of the impact is towards negative SSTs.

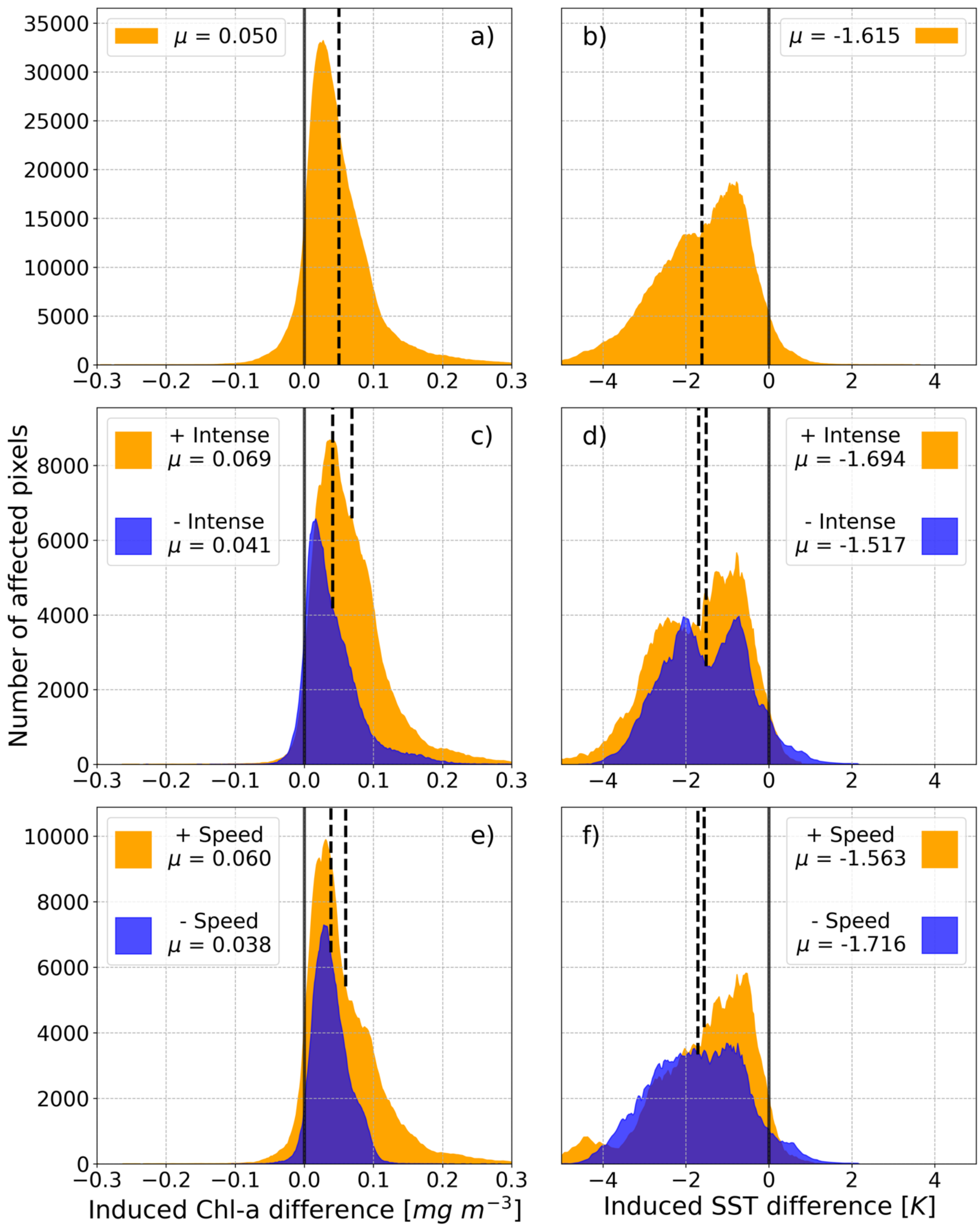
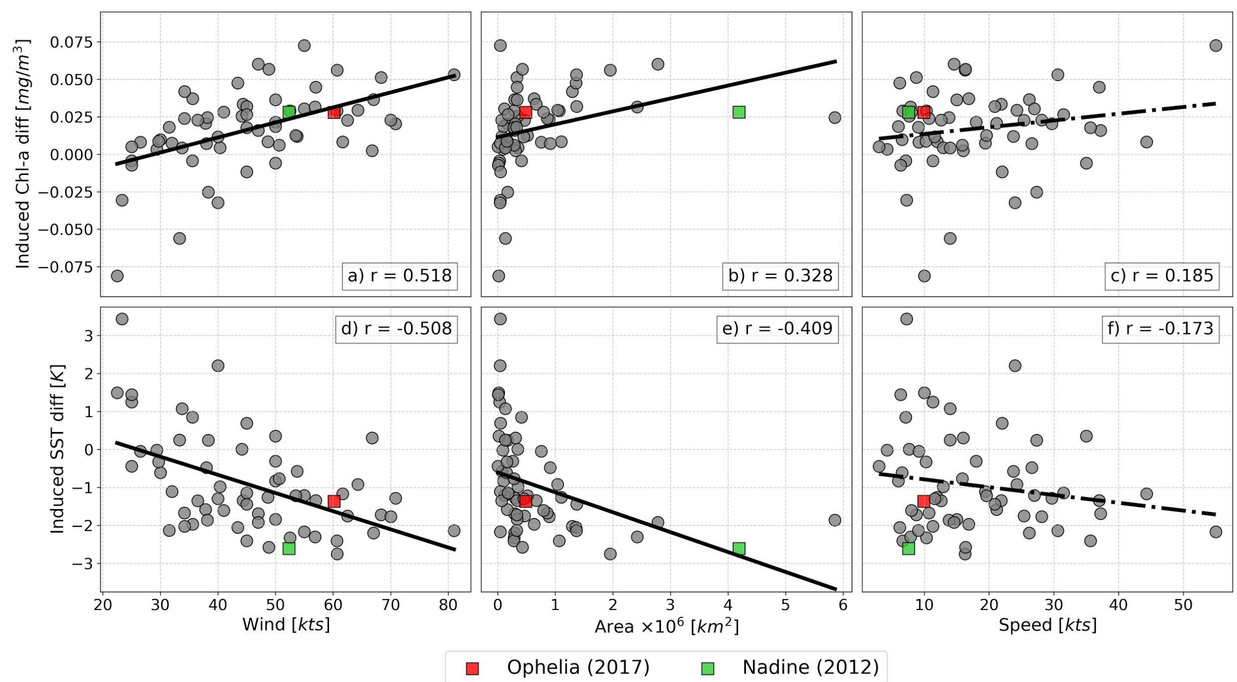


Figure 3 - Histograms for the: a) Total Chl-a and b) SST induced anomalies; c) Chl-a and d) SST induced anomalies after weak (blue) and powerful TCs (orange); e) Chl-a and f) SST induced anomalies after slow TCs (blue) and fast TCs (orange).

Each subplot histogram presents the respective population mean value (μ) in a dashed black line, and the zero value on a grey line.

To quantify these relations, Fig. ~~5~~4 shows the storm-averaged induced anomalies compared to the averaged maximum wind~~, cumulative impacted area,~~ and average translation speed. The linear regression is also shown for each of the comparisons, with nearly all results significant at the 95 % statistical level~~ except for those in the last column (regression line dashed).~~. According to these plots, only the translation speed in relation to the SST induced anomalies (Figs. ~~5c and 5f~~4d) did not show a significant relation ~~with the chl-a and SST induced anomalies,~~ at the 95 % statistical confidence level~~.~~ (marked by the dashed regression line). Regarding the mean wind (Figs. ~~5a~~4a and ~~5d~~4c), and therefore the TC's average intensity within the Azores region, the linear regression showed significantly high values, upwards of 0.5~~.~~ for Chl-a and -0.3 for SST induced anomalies. In the case of ~~chl~~Chl-a, like observed in Fig. ~~4~~3, the relation is positive while with SST this relation is negative. ~~The cumulative area (Figs. 5b and 5e) also presents a significant relation, although less intense than that observed with~~Considering the ~~mean winds. However, it should be noted that this variable is somewhat connected with the mean winds, since more intense cyclones tend to be larger than less powerful ones, but also with the storm phase, since storms nearing their post-tropical transition tend to grow larger (Knaff et al., 2014). It is then relatively straightforward that, in the Azores region, the variable that better relates the bio-physical oceanic response to the passage of a TC is its intensity (Figs. 4 and 5), and to a lesser degree its~~ translation speed~~ (Fig. 4~~, the relation is equally positive and significant for biological responses (r = 0.416).



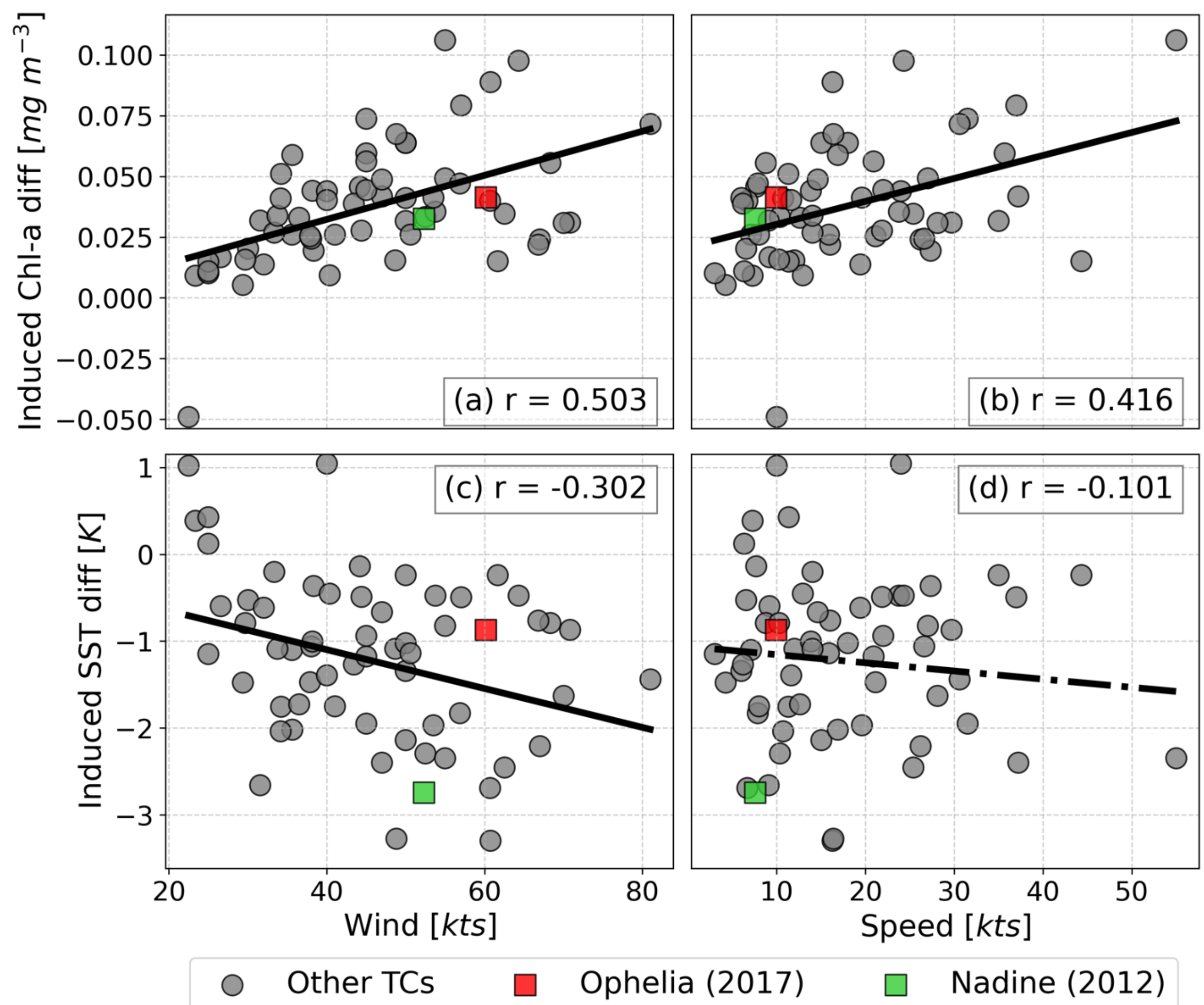


Figure ~~5~~4 - Linear regression of ~~chl~~Chl-a (top panel) and SST (bottom panel) induced anomalies for each TC, respectively, when compared with~~:~~ average winds in knots (left~~ column); cumulative impacted area in km^2 (middle~~ column); and average TC translation speed in knots (right column). In each plot the Pearson R is presented, and the regression's significance is marked by the type of line used in the regression, with a dashed line representing non-significant at a 95 % confidence level~~.~~, and a solid line representing a regression significant at the 95 % confidence level.

Further analysis of other TC characteristics requires a different approach, Fig. 5 shows similar relations to Fig. 4, but considering 6-hour observations instead of total TC mean values. This is made to account for the possible error that averaging a whole TC may create since the cyclone's characteristics may change substantially along its lifetime. This analysis, however, does not consider the possibility of superposition in pixels from observation to observation – i.e., from a TC that either moves slowly or whose track is more erratic, ending up covering the same area for several hours/days. This caveat was not present in Fig. 4 since we considered the TC lifetime as a whole and could then disregard the days of superposition. Using 6-hour observations, we can study several types of characteristics that change between observations, such as the impact area or the time of season when it occurred, adding to the already seen maximum wind speed and translation speed.

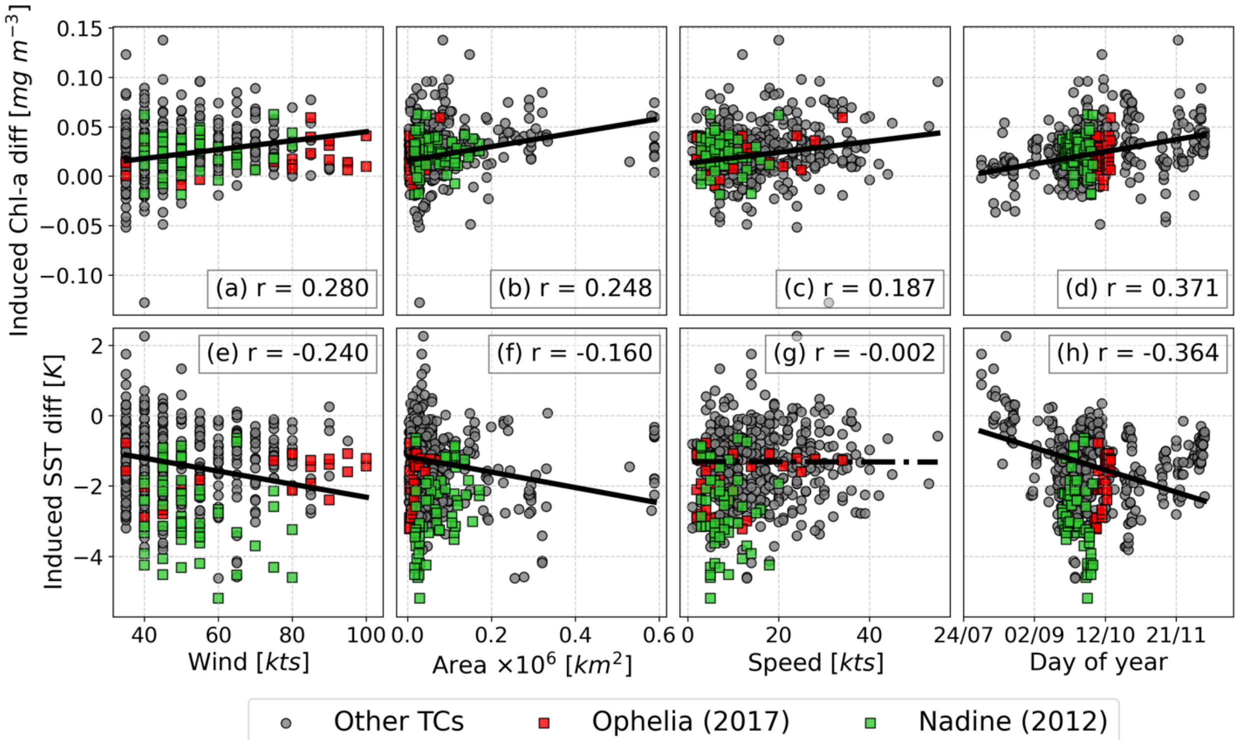
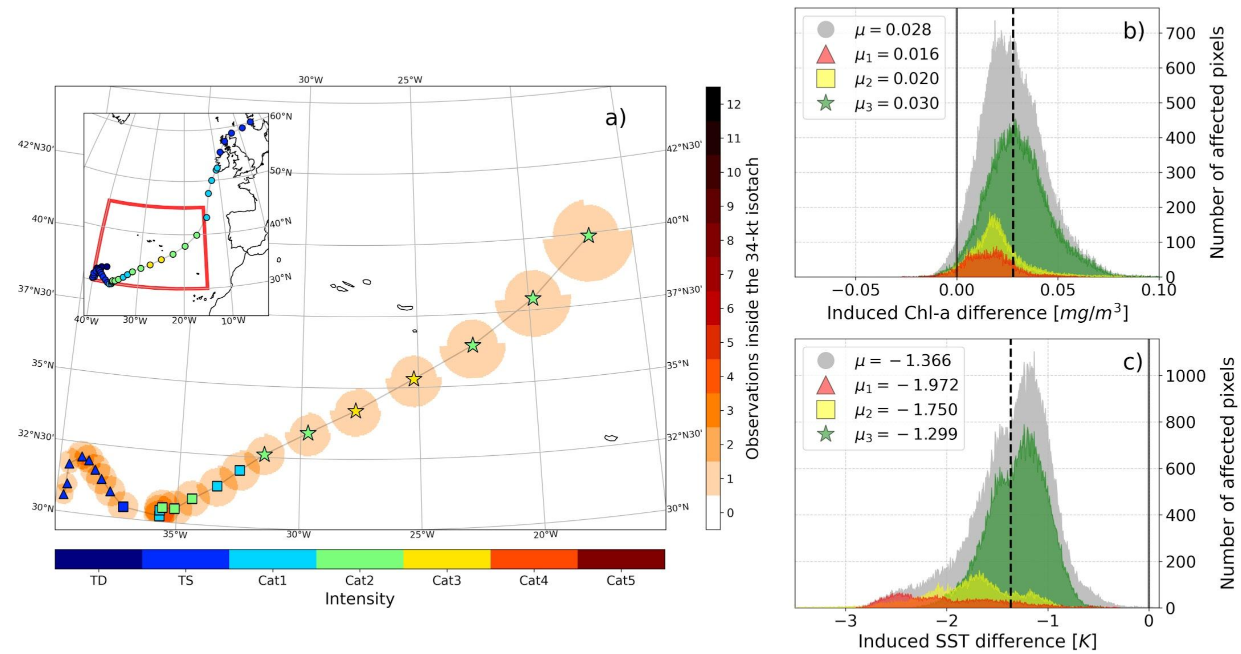


Figure 5 – Same as in Fig. 5 but considering individual 6-hour observations. Two columns are added: (b) and (f) with respect to the area affected by that observation; and (d) and (h) with respect to the time of the season when that observation occurred.

Considering then the maximum wind speed per observation (Fig. 5a and 5e), both variables are significantly related to this characteristic, which is expected considering the analysis made in Figs. 3 and 4. As previously noted in the form of histograms in Fig. 3, most observations show a positive impact regarding Chl-a and, especially for SST as most fall below zero, a negative change after a TC. The affected area (Figs. 5b and 5f) also presents a significant relation, although less intense than that observed with the maximum winds. However, it should be noted that this variable is linked to the mean winds, since more intense cyclones tend to be larger than less powerful ones, but also to the storm phase, since storms nearing their post-tropical transition tend to grow larger (Knaff et al., 2014). ~~Still in Fig. 5, two case studies are marked: Hurricane Ophelia in 2017 (red square) and Hurricane Nadine in 2012 (green square).~~Translation speed is the less correlated variable from those studied (Fig. 5c and 5g), with only the biological response seeing a positive relation to this characteristic, agreeing with the previous results from Figs. 3 and 4. The time period in the season in which the TC occurs seems to also be important for the magnitude of the average induced anomaly seen in both variables (Figs. 5d and 5h) with late occurrences in the season showing greater responses respective to the signal of induced anomalies seen in Figs. 3a and 3b. Lastly, a geographical correlation was concluded not to be relevant for this study (not shown), as both variables were correlated with both latitude and longitude, and only negligible and non-significant relations were found.

The results presented so far in this study result from interpolated “cloud-free” data and should be quality assured to guarantee the integrity of the conclusions made previously. As mentioned in the *Data* section, CMEMS provides measures of uncertainty for the used Chl-a and SST datasets, thus, we have explored these values at different periods as a first step in validating the quality of the data. Figure S1 shows the associated uncertainty with respect to the absolute observed values both for Chl-a (top panels) and SST (bottom panels) for three different periods surrounding a TC event (before, during, and after), and a randomly drawn sample of the same size as the data analysed in the other subplots. It becomes immediately clear from these plots the considerably different magnitude of uncertainty for this data, with Chl-a (Figs. S1a-d) ranging from 25 % to 45 % considering all moments, while SST (Fig. S1e-h) does not commonly surpass 0.4 % with a mean error around the 0.25 %. The randomly drawn sample of data gives a rough idea of the average uncertainty we can find in this dataset, with Chl-a (Fig. S1a) presenting values around 35 % and SST (Fig. S1e) around 0.25 %. Additionally, we should consider three distinct moments of analysis, namely before and after the TC passage, which corresponds to the data used to compute the induced anomalies, and during the TCs, which should be the moment with most cloud-cover over the studied regions. Looking first at Chl-a (Figs. S1b-d) we see the progression from near normal uncertainty before the TC (Fig. S1b) to an increase during TCs (Figs. S1c), maybe due to the higher cloud-covered area in this situation, after the storm (Fig. S1d) however, the uncertainty substantially decreases reaching values below the randomly drawn sample (around 30 % compared to 35 %). For the SST (Figs. S1f-h), the associated uncertainty does not fluctuate substantially, constantly being below the 0.3 % mark. Additionally, it is noticeable in both variables the variation that has been identified before, with Chl-a increasing and the SST decreasing.

Visible in Figs. 4 and 5 are two case studies are marked: Hurricane Ophelia in 2017 (red squares) and Hurricane Nadine in 2012 (green squares). These case studies were chosen based on the presented characteristics, coupled with the amount of sampling data within the region. Hurricane Ophelia (2017) was chosen due to its large intensity in the region (Red ~~square in~~squares, Fig. 4 and 5), reaching a category 3 intensity in the Saffir-Simpson hurricane wind scale, something abnormal for the region (Lima *et al.*, 2021). The complete TC track can be seen in Fig. 6a inset. Besides the large intensity, Ophelia’s genesis took place inside our ~~sector~~study region which enabled us to study different phases of the storm and its impacts on the ocean surface in the region. Even though hurricane Ophelia was so intense, this storm impacted a very small area (Figs. 5b and ~~5e~~5f) particularly when compared with the other case study, Hurricane Nadine (2012). Hurricane Nadine (Fig. 7a) was chosen due to its large sampling, relatively high intensity (maximum category 1) and ~~massive~~great impact area (second ~~largest~~highest in this study~~).~~, considering cumulative area of impact). The large~~,~~ impacted area was amplified by the geometry of the storm's track (i.e., many overlaid observations). Only the final stage of Hurricane Nadine was caught within the study region, producing an ideal case study to analyse the impact of a less intense storm that heavily impacted a particular region due to its geometry.



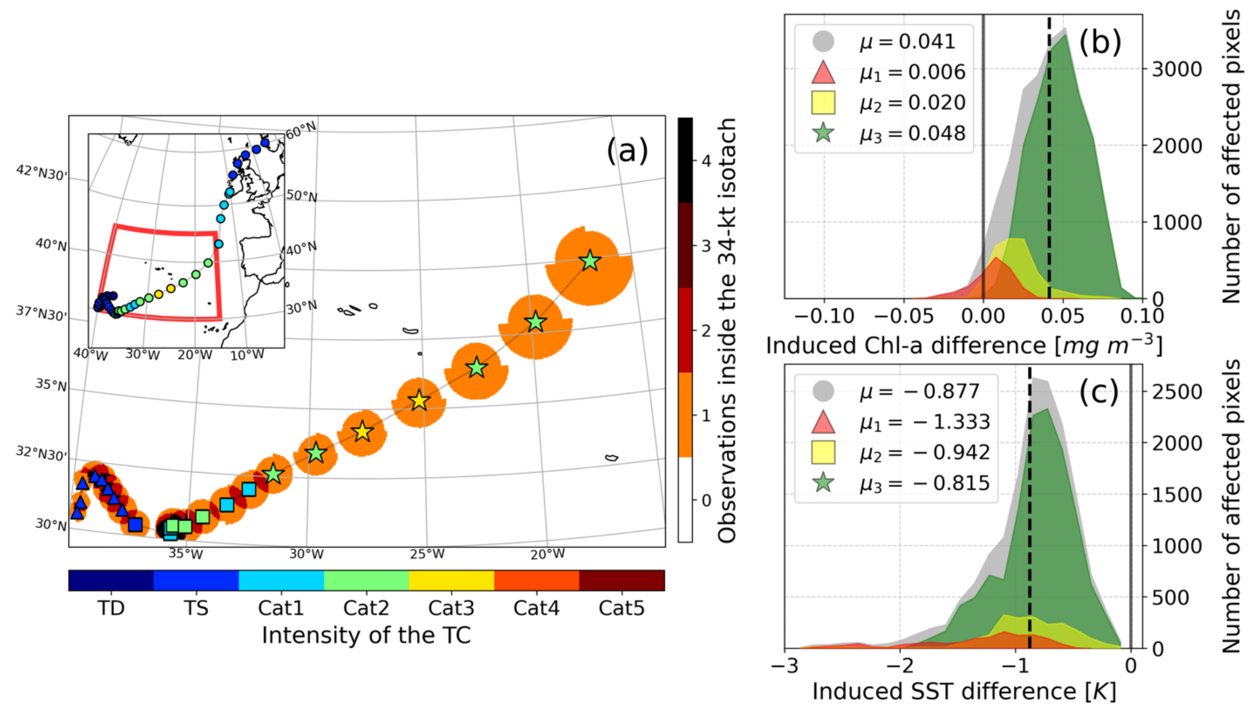
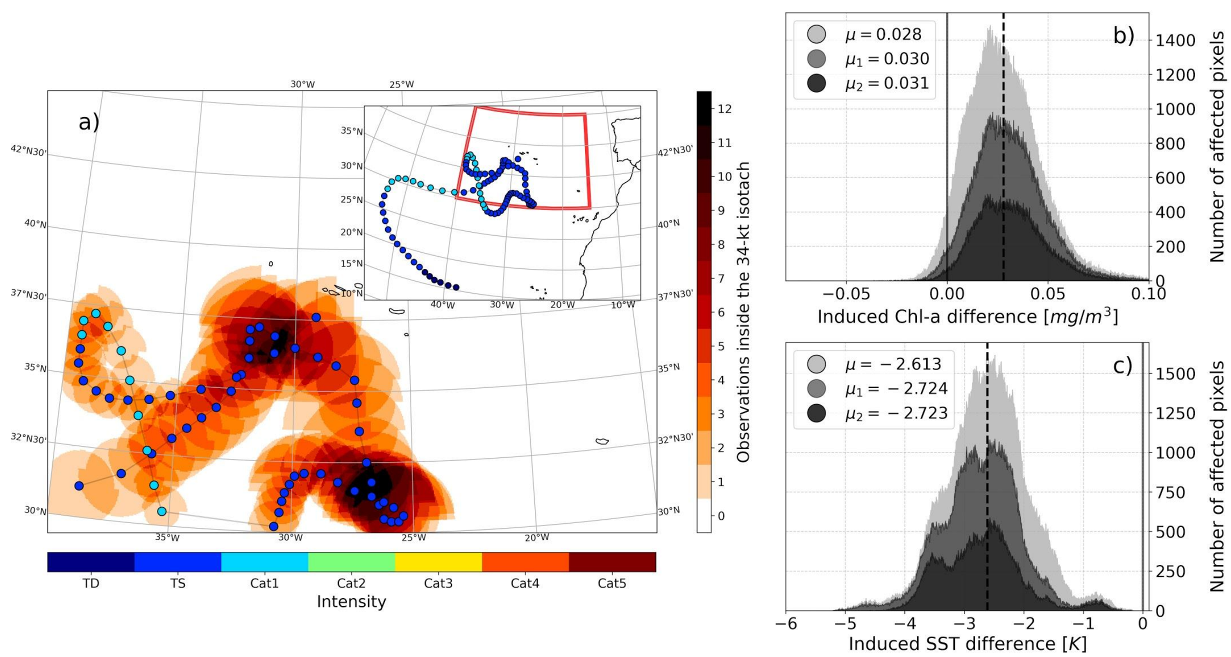


Figure 6 - Case study for Hurricane Ophelia, in 2017, with its track on the left panel (~~intensity~~ scatter marker colour scheme represents intensity as in Fig. ~~2~~1), as well as the affected area around the cyclone (marked as the 34-kt isotach) with shading according to the number of pixels overlapping. Inside, there is an inset with the full track and the region of study marked with a red box. Ophelia track is divided in three phases: ~~Genesis (triangles), maturing (squares) and mature (stars).~~ Histograms show induced ~~chl~~Chl-a (b) and SST anomalies (c), by phase of the storm (colours) and ~~general~~in total (grey). The phase of the storm is marked in (a) as triangles (genesis), squares (maturing), and stars (mature) and correspond to the aforementioned colours in (b) and (c).

For the case study of Hurricane Ophelia (2017), three different phases of the storm were studied, corresponding approximately to: cyclogenesis (Fig. 6a, triangles), maturing (Fig. 6a, squares), and mature hurricane (Fig. 6a, stars). There are 23 total observations; the first two phases encompass 8 observations and the last one 7. Each of these phases has its own histogram in Figs. 6b and 6c (shown in colours), for the induced ~~chl~~Chl-a and SST anomalies, respectively. The histograms are inserted in a larger one (in grey), representing the total induced anomalies caused by Ophelia and therefore, the sum of all three phases will result in the bigger ~~one~~histogram. Regarding the ~~chl~~Chl-a induced anomalies (Fig. 6b), Ophelia seemed to have a higher impact towards the end of its track in the region of study, when the storm had the highest intensity and the mean values of the induced anomalies increased along the track. Even at the storm's genesis, the induced anomalies were mostly positive with a mean value of +0.~~016~~006 mg~~/m^3~~ m^{-3} reaching +0.~~030~~048 mg~~/m^3~~ m^{-3} in the most intense phase. In contrast, the SST induced anomalies (Fig. 6c) present the highest mean response (-1.~~972~~333 K) at the initial phase. The SST induced anomaly is then seen decreasing as the storm goes on, with the last phase weighing the most in the general distribution (as was seen for the ~~chl~~Chl-a). The highest SST impact of the storm during the initial phases may reflect that this is the phase of the storm with highest interaction with the ocean, regarding thermodynamic exchanges (Emanuel, 2003).



As a further insight to Ophelia's interaction with the ocean surface, Fig. S3 shows the mean modulus of wind stress on the surface, by day of analysis (Fig. S2a) and by Ophelia's 6-hour observations (Fig. S2b). Marked in both these plots are the analysed periods in corresponding colours and marker type to Fig. 6, these plots exceed the original study region, in order to fully encompass the TCs entire lifetime. There is a significant relation between the increased mean modulus of the wind stress and the evolution of the TC in time. This increase may be related to the increase in the storm's intensity, as Ophelia reaches its maximum intensity, so does the observed interaction with the ocean, decreasing afterwards as the storm moves north-eastward and undergoes post-tropical transition. This observed interaction with the ocean might be the reason for the maximum induced anomaly of Chl-a being observed at the end of Ophelia's passage over the study region, inducing the mixing of the superficial layer.

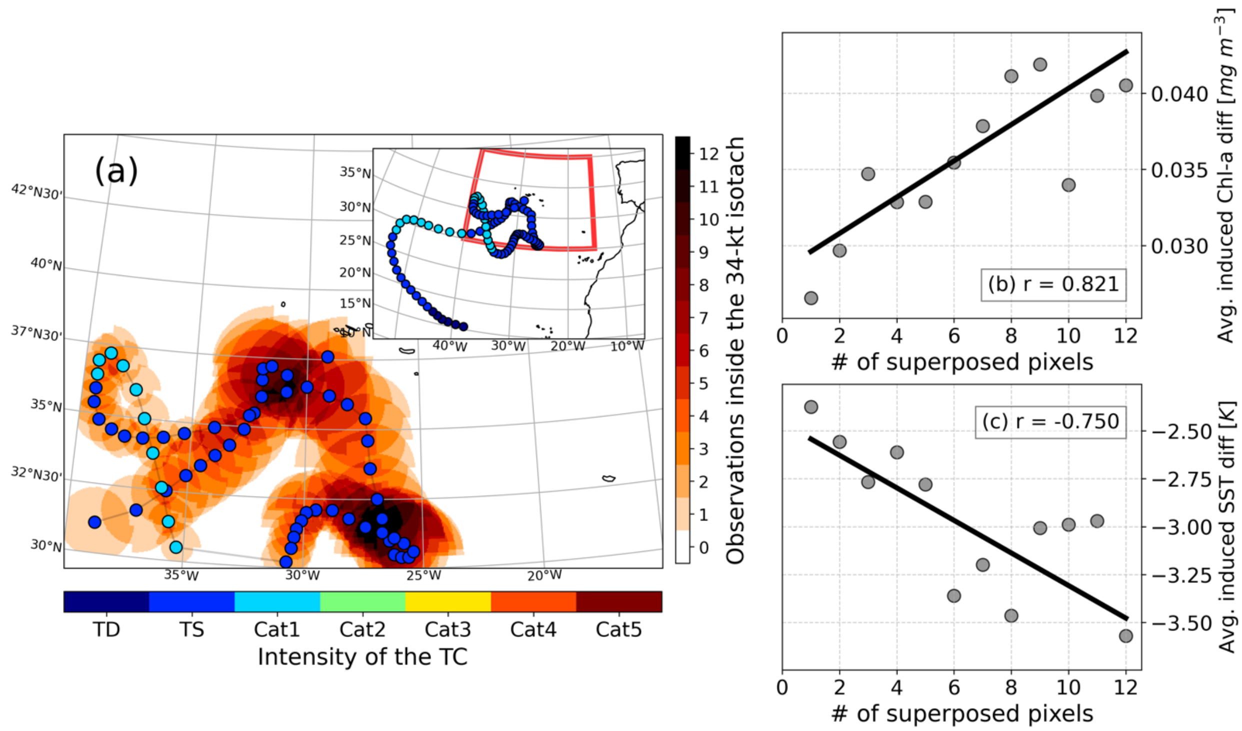


Figure 7 - Case study for Hurricane Nadine, in 2012, with the ~~right~~left panel the same as in Fig. 6. For Nadine, ~~histograms~~ plots (b) and (c) pertain to the average induced ~~chl~~Chl-a and SST anomalies, respectively, based on the amount of ~~overlap~~superposition verified in each pixel~~: soft grey – No overlap; Dark grey – 3-pixel overlap; Black – 5-pixel overlap~~.

Hurricane Nadine's (2012) case study shows very different behaviour and impact during its lifetime to that of Hurricane Ophelia. In this case, ~~histograms represent differently impacted areas, with~~we present scatter plots of the ~~darker histograms~~ averaged induced anomalies for the areas (Figs. 7b and 7c) corresponding to the ~~areas with more overlaid~~superposition of pixels, i.e., the number of repeated observations inside the 34-kt isotach due to storms track geometry (as seen in Fig. 7a). ~~The threshold chosen for analysis were 3 overlaid observations for the middle shade and 5 for the darkest one, with the biggest histogram showing the general induced anomalies for Hurricane Nadine.~~ The conclusions drawn regarding the ~~chl~~Chl-a and SST induced anomalies are similar and significant in this case study: The more time the TC spent over a certain area the more this area became affected by its passage, with large anomalies registered in both variables (over 0.~~031~~040 mg~~/m^3~~ m^{-3} and -~~2.723~~3.500 K for ~~chl~~Chl-a and SST, respectively~~). This shows that the TC intensity is somewhat irrelevant given that the geometry of its track is ideal to stay longer over~~), and all cases being positive (negative), for Chl-a ~~region. With this in mind, it~~(SST). It is possible to hypothesise that the translation speed also had a relevant role in these results, with a slower TC (Nadine was one of the slowest TCs in this study, as seen by the closer observations in Fig. 7a and by Figs. ~~5c~~4 and ~~5f~~5) spending more time over a region and therefore producing larger anomalies.

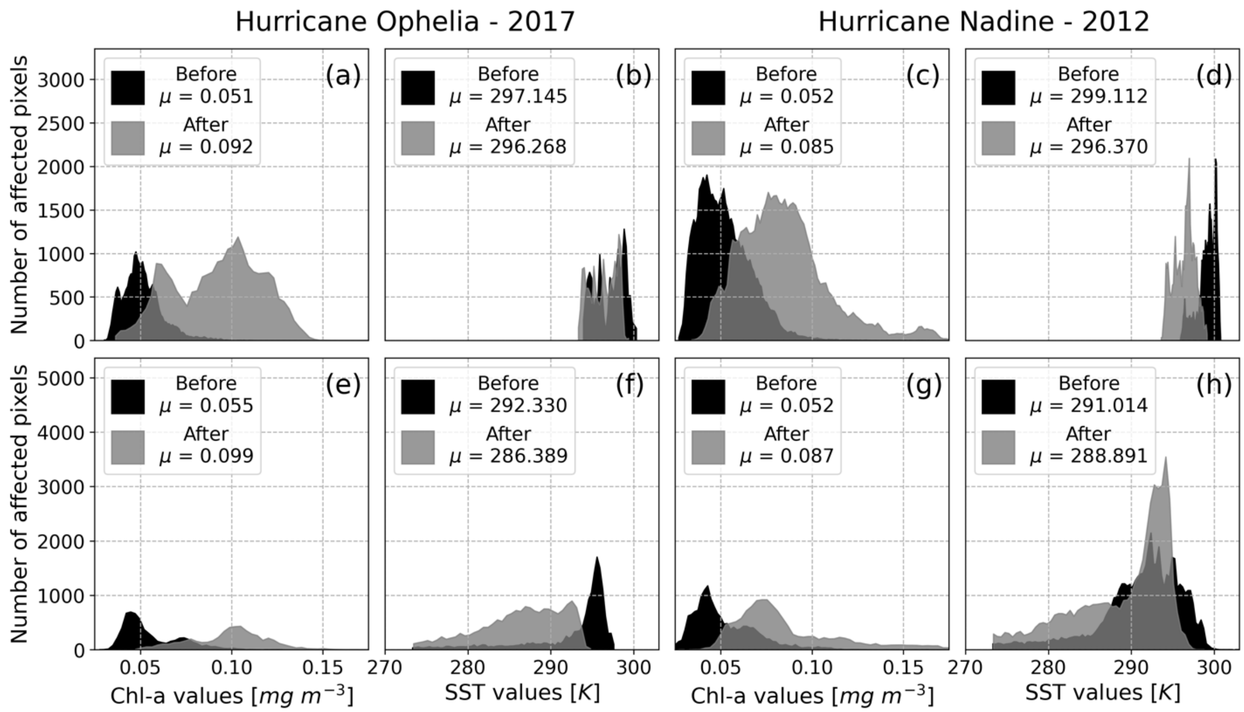


Figure 8 – Comparison between interpolated "cloud-free" data (top row), and non-interpolated data (bottom row), for Hurricanes Ophelia (2017) and Nadine (2012). Values for non-interpolated data were obtained with the same methodology as the ones presented before and represent the exact same days of analysis. Mean values for each histogram are presented, with black histograms representing the situation before the TC and the grey ones the situation after.

For these two case studies, we considered an additional quality assessment exercise, by comparing the interpolated "cloud-free" data to similar non-interpolated datasets. Figure 8 shows the histograms obtained for Ophelia and Nadine for the situations before and after the TC, independently, since non-interpolated data cannot be correctly subtracted as corresponding pixels may not be available. Overall, and despite the different number of observations considered, the Chl-a presents the same average response between the different types of data for both TCs, with non-interpolated data having an observed mean increase of 0.044 mg m^{-3} for Ophelia (Fig. 8e) compared to 0.041 mg m^{-3} for interpolated data (Fig. 8a), with these values representing the difference in the mean values shown in Fig. 8. Likewise, non-interpolated data reveals an increase of 0.035 mg m^{-3} for Nadine (Fig. 8g), compared to 0.033 mg m^{-3} for interpolated data (Fig. 8c). Looking at the histograms, the shape of the data itself does not differ too much between the different types, with peaks more or less located over the same values and distributions ranging the same values. However, for the SST variable, despite both TC's present relatively similar decreases between both types of data, the non-interpolated data has a wider range of values, and the peaks do not correspond so closely. This, however, may be due to the process of data collation. In this process, some pixels are averaged with incorrect ones, resulting in unrealistic values in some areas. This can be identified by the unrealistic SST seen in Figs. 8f and 8h, with values that do not support TC development around 18-19ºC and, so far as reaching 0ºC. Nonetheless, interpolated SST data does show the less uncertainty as verified before as the process of interpolating the data fixes this issue (Fig. S1).

Final remarks

The current study provides the first general assessment of the bio-physical oceanic response to the passage of TCs in a relatively low cyclonic activity area such as the region near the Azores archipelago. It is important to stress the efficiency of identifying the precise timing and associated spatial impacts of all TCs using remotely sensed products that rely on interpolated areas to fill existing gaps due to cloud coverage or lack of satellite imagery.

Over the Azores region, it was generally identified the existence of a bio-physical response after the passage of a TC was identified from the analysis of ~~chl~~Chl-a and SST datasets, which produced signatures of positive ~~(chl~~Chl-a~~)~~ and negative ~~(~~SST~~)~~ induced anomalies~~, for a period of about two weeks after the passage of a TC.~~. This signature is ~~considerably~~ more intense for the SST analysis, in which the passage of a TC results in nearly all observed pixels to have a negative (i.e., cooling) induced anomaly. On average, TCs produced positive anomalies in the order of 0.~~026~~050 mg~~/m^3~~ m^{-3} regarding ~~chl~~Chl-a and a mean SST cooling of 1.~~554~~615 K.

The more powerful TCs tend to produce more intense bio-physical oceanic responses, which agree with previous literature on the topic (Chacko, 2019; Price, 1981; Price et al., 1994). ~~The TCs~~TC translation speed was also ~~confirmed~~found to be ~~relevant in inducing~~associated with the induced anomalies~~ in both variables~~, although ~~in this instance the direct relation was not confirmed since results were not~~the relationship was found to be positive and significant in the case of Chl-a while it was not significant at the 95 % statistical confidence level for SST. The impacted area was also found to be significantly linked to the oceanic response. However, the sensitivity to the impacted area can rise due to several other factors: slower TCs impact larger areas (due to track geometry); more intense TCs impact larger areas (Knaff et al., 2014); and TCs nearing post-tropical transition are generally larger (Knaff et al., 2014). These effects, either individually or combined, can affect the induced anomalies at different levels. Additionally, the oceanic response was found to be increased later in the season, with significant relation in both variables, this may be due to the seasonal variability of the variables themselves, as the normal climatological values for that time of the year is exceeded in exceptional TC conditions (Amorim et al., 2017; Lima et al., 2021) and the oceanic response may help the impacted area return to expected values in both variables, in respect to that time of the year.

Two particular case studies were evaluated in further detail concerning hurricanes Ophelia (2017) and Nadine (2012). Hurricane Ophelia was a particular case as it corresponds to the only major hurricane in this study region and had almost its entire track inside this area. Ophelia showed strong induced anomalies for both ~~chl~~Chl-a and SST variables. Regarding ~~chl~~Chl-a, Ophelia had a stronger impact towards the end of its track within the region, revealing that its intensity played a key role in inducing ~~chl-a anomalies.~~Chl-a anomalies, with the mean modulus of wind stress revealing a positive and significative relation to the evolution of the storm and therefore its intensity. On the other hand, Ophelia had a stronger impact on the SST in its cyclogenesis, probably related to ocean-atmosphere thermodynamic exchanges during its maturing. Hurricane Nadine, one of the slowest TCs in this study, showed more prominent anomalies, especially regarding SST. In this case, considering the low translational speed of Nadine, the objective was to study the impact that consecutive overlaid observations had on the induced anomalies. It is evident through this analysis that the impact increases with the number of ~~overlaid~~superposed observations, implying that Nadine's slow translation speed and particular track geometry played a key role in creating such anomalies.

This study allowed for both the quality control of the remotely sensed "cloud-free" ~~chl~~Chl-a and SST multi-sensor products~~,~~ by comparing them to similar non-interpolated products, and in the sense that it identified expected changes in the variables in areas covered by TC clouds and established crucial relations with some principal TC aspects. Future studies should aim to understand the inherent physical mechanisms that affect the ocean during and after the passage of a TC to better comprehend the associated induced anomalies.

Code and Data availability

All code and raw data used to support the conclusion of this article will be made available by the authors, without undue reservation.

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Author Contribution

Miguel M. Lima: Conceptualization, methodology, software, validation, formal analysis, investigation, writing – original draft, review ~~&~~and editing. Célia M. Gouveia: Validation, supervision, writing – review ~~&~~and editing. Ricardo M. Trigo: Validation, supervision, writing – review ~~&~~and editing, funding acquisition.

Declaration of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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