**A suboxic chlorophyll-a maximum persists within the Pacific Oxygen Minimum
Zone off Mexico**

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ABSTRACT

The tropical Oxygen Minimum Zones (OMZ) are known to shelter a chlorophyll-a maximum (CM) within suboxic waters ($< 20 \mu\text{mol kg}^{-1}$), below other chlorophyll-a maxima and with an unknown temporal variability in the Pacific OMZ off Mexico. Here, 1161 chlorophyll-a fluorescence and oxygen profiles collected between 2003 and 2016 were used to describe statistically the physical situation in which the suboxic-CM was found. Results indicate that the suboxic-CM was a persistent feature at seasonal scale at depths between 40-190 m at an average density potential anomaly of $26 \pm 0.2 \text{ kg m}^{-3}$, related to the Subtropical Subsurface Water, which is nearly unaffected by mixing with other water masses. The suboxic-CM south of 21°N was generally associated with the upper limit of the suboxic waters of the OMZ. In this region, the distance between the suboxic waters and the euphotic zone (1% of surface irradiance) was $> - 25 \text{ m}$ year-round, which suggests that persistent low-light levels allow development of the suboxic-CM. The persistence of the suboxic-CM is consistent with its association with a stable microbial community. The effects on the ecosystem and biogeochemical cycles remain to be investigated.

Keywords: Chlorophyll maxima, Suboxia, Persistence, Euphotic zone, Mexican Pacific

1. Introduction

The Oxygen Minimum Zones (OMZ) are found in productive regions of sluggish circulation, where significant microbial respiration rates lead to the formation of steady-state low-oxygen layers at intermediate depths (Gilly et al., 2013). They are characterized by strong oxygen gradients and can be found in the northeast subarctic Pacific, the northern Indian Ocean and the Eastern Tropical Pacific (Paulmier and Ruiz-Pino, 2009). The OMZs of the Arabian Sea and the Eastern Tropical Pacific have suboxic waters ($< 20 \mu\text{mol kg}^{-1}$) at depths shallower than 150 m (Gilly et al., 2013). Under these particular conditions the presence of a subsurface Chlorophyll-a Maximum has been recorded in the upper limit of the suboxic waters, and beneath the one commonly occurring in more oxygenated waters near the nutricline (Goericke et al., 2000; Lavin et al., 2010; Ulloa et al., 2012).

Here, the maximum found under suboxic waters of the OMZ will be called the suboxic-Chlorophyll-a Maximum (suboxic-CM). The presence of the suboxic-CM has been attributed to increased cell numbers of the Cyanobacterium *Prochlorococcus* (Goericke et al., 2000), belonging to genetically distinct lineages (Lavin et al., 2010). The occurrence of this suboxic-CM has important implications for the ecosystem and biogeochemical cycles because it is photosynthetically active, supplying oxygen for the aerobic respiration process or nitrite oxidation, and at the same time able to provide organic matter for remineralization processes (Garcia-Robledo et al., 2017).

In the Tropical OMZ off Mexico, the suboxic-CM has been recorded at depths ranging from 85-115 m where irradiance is between $2\text{-}5 \mu\text{mol Q m}^{-2} \text{ s}^{-1}$ (Garcia-Robledo

et al., 2017). According to laboratory experiments this irradiance is enough to allow growth of *Prochlorococcus* low-light adapted strains (Moore and Chisholm, 1999). In this regard, Cepeda-Morales et al. (2009) used the distance between the euphotic zone depth (1% of surface irradiance; $Z_{1\%}$ hereinafter) and the upper limit of the suboxic waters as a predictor of the presence of the suboxic-CM during the boreal summer. They found, during June of 2006, that the main controlling factor of this distance is the depth of the upper limit of the suboxic waters of the OMZ, because the $Z_{1\%}$ showed limited spatial variability during their study (Cepeda-Morales et al., 2009). However, the temporal variability of $Z_{1\%}$ has not been assessed previously.

As part of the OMZ, the tropical Pacific off Central Mexico has been considered as a distinguishable transitional region, extending from the Mexican coast to 110°W and from 17 to 23°N (Fig. 1), in which different water masses converge (Portela et al., 2016). The circulation and water mass distribution of this region is associated with gradients of dissolved oxygen in the water column. Cepeda-Morales et al. (2013) showed that the depth of suboxic waters undergoes considerable seasonal changes north of 20°N due to the influence of the oxygenated California Current Water (CCW). South of 20°N the variability was less pronounced because of a lower CCW contribution, and the northward advection of suboxic Subsurface Subtropical Water (SsStW) by the Mexican Coastal Current (Fig. 1).

Considering that the presence of the suboxic-CM has been reported where the upper limit of the suboxic waters of the OMZ reaches the euphotic zone (1% of surface irradiance), it is hypothesized that the suboxic-CM will persist where oceanographic processes keep the upper limit of the OMZ within the euphotic zone at seasonal scales

and within the Pacific OMZ off Mexico. Hence, the aim of this work is to determine if the suboxic-CM is persistent within the Pacific OMZ off Mexico at seasonal scales.

2. Material and methods

In this study, 14 years of data comprising 1161 CTD, chlorophyll-a fluorescence and oxygen profiles, measured with CTD attached sensors, were used to analyze the spatio-temporal variability in the occurrence of the suboxic-CM. CTD measurements were acquired with a Seabird 911 plus with a deck unit and a sampling frequency of 24 Hz. Precision and resolution of temperature were 0.001 and 0.0003°C, respectively, whereas conductivity had precision and resolution of 0.0003 and 0.00004 Siemens m⁻¹. Dissolved oxygen in all cruises was based on the measurements of SBE-43 polarigraphic sensors with an initial accuracy of 2% of saturation. From the records on cruise reports, the fluorimeter used in this study had a resolution of 0.02 mg m⁻³ and sensitivity of 0.03 mg m⁻³.

CTD data were processed according the manufacturer recommendations and all profiles considered were recorded with 1 m vertical resolution, had a maximum depth >100 m and < 45% missing values in fluorescence data. The *in-situ* temperature, practical salinity and the geographical coordinates were used to compute the TEOS-10 properties. Then, conservative temperature and absolute salinity were used in TS diagrams, where the water masses were identified based on Portela et al. (2016) boundaries (Fig. 1).

The upper limit of the suboxic water ($Z_{min_{OMZ}}$) was taken as the depth of the 20 $\mu\text{mol kg}^{-1}$ oxypleth, which has been shown to be a reliable indicator considering uncertainties and detection limits of most methodological approaches (Paulmier and Ruíz-Pino, 2009). In the context of the OMZ, the spatial distribution of profiles with suboxic-CM was investigated.

2.1. Chlorophyll-a fluorescence pre-processing and profile classification

Aberrant data (spikes) due to electronic noise were removed from the fluorescence following a similar approach to those described by Schmechtig et al. (2014). Specifically, in each profile the residuals between a central value ($V3$) and its corresponding median was computed over 5 depths as indicated in equation 1. The 10th and 90th percentiles of all residuals were estimated. All values ($V3$) with residuals greater than twice the 90th percentile and less than twice the 10th percentile, were removed.

$$RES = V3 - median(V1, V2, V3, V4, V5) \quad \text{Eq. 1}$$

After the above procedure, the data were smoothed with a Butterworth filter, as recommended by Roberts and Roberts (1978), using a first degree polynomial and a cut-off frequency of 0.1 Hz. The filtered signal was then normalized according to Sauzede et al. (2015) as in equation 2. This procedure transforms the fluorescence values to a range of 0 to 1 and allows consideration of fluorescence profiles gathered from different instruments, either calibrated or un-calibrated (Sauzede et al., 2015).

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$$Fluo_{norm}(z) = \frac{fluo(z) - \min(fluo)}{\max(fluo) - \min(fluo)} \quad \text{Eq. 2.}$$

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142 $Fluo_{norm}$ is the normalized fluorescence signal at a given depth (z), $fluo$ is the fluorescence
143 value given by the instrument using the factory calibration and min and max($fluo$) are the
144 minimum and maximum values measured in a given profile.

145 Finally, the pre-processed fluorescence profiles were classified into two broad
146 mutually exclusive categories: (i) suboxic-CM profiles when at least one maximum occurs
147 under suboxic conditions of the OMZ (<20 $\mu\text{mol kg}^{-1}$) and (ii) other-CM that encompass
148 profiles without chlorophyll-a fluorescence maximum within suboxic conditions (Fig. 2).
149 The classification is based on the detection of maxima and the concentration of dissolved
150 oxygen associated with them, so a definition of maximum is required. All points that had
151 a maximum value relative to their neighbors and with a value greater than 0.1 normalized
152 units were considered as a local maximum after visual inspection (Fig. 2).

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154 2.2. Environmental conditions in suboxic-CM depths

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156 To describe the environmental conditions in which suboxic-CM was found, the
157 temperature, salinity, oxygen concentration, the depth in which suboxic-CM was recorded
158 and the depth of the 1% of surface irradiance (satellite-derived) were recorded. The depth
159 of suboxic-CM was associated with the $Z_{min_{OMZ}}$ using the Pearson correlation coefficient.

160 Due to lack of *in-situ* data of irradiance and to get a proxy of the illumination
161 conditions, MODIS L1A passes for study area, were downloaded from the ocean color

website using the L1/L2 browser. The data were processed with SeaDAS version 7.5.3, using default options (including atmospheric corrections) to obtain the satellite-derived euphotic zone at 1x1 km spatial resolution. Then the data were temporally binned during the cruise duration (7-16 days). Using the approach of Lee et al. (2007), the depth of the euphotic zone is determined semi-analytically from the Inherent Optical Properties, and is considered reliable in Case-1 and optically complex water (for detailed description see Lee et al., 2007).

It should be noted that Lee et al. (2007) actually determine the depth, which we will call $Z_{1\%}$, at which irradiance becomes 1% of the Photosynthetically Available Radiation just below the sea surface, that is not strictly equal to the euphotic zone depth (for a discussion of the term see Banse, 2004; Cullen, 2015). The above procedure was used to compute the distance between $Z_{1\%}$ and $Z_{min_{OMZ}}$ following Cepeda-Morales et al. (2009) and defined as indicated below:

$$\Delta Z = Z_{1\%} - Z_{min_{OMZ}} \quad \text{Eq. 3.}$$

Defined in this way, negative values of ΔZ occur when $Z_{min_{OMZ}}$ is deeper than $Z_{1\%}$, meaning that <1% of irradiance is found at the upper limit of the suboxic waters of the OMZ. Positive ΔZ occurs when $Z_{min_{OMZ}}$ is shallower than $Z_{1\%}$, implying illumination of the upper limit of the suboxic waters of the OMZ.

A scatter plot of ΔZ and the integrated chlorophyll in the depth interval between the $Z_{min_{OMZ}}$ and 300 m, was used to assess associations and to identify a threshold value in which the suboxic-CM occurs. The integrated chlorophyll was computed using the

fluorimeter output with the factory calibration. For this step, the normalization of the signal (Equation 2) was not applied.

2.3. Spatial analysis

Given that the OMZ is more variable north of 21°N (Cabo Corrientes) and relatively stable to the south, the suboxic-CM occurrence was divided in two geographical regions: (i) north and (ii) south of 21°N. In each region, the profiles were classified as detailed below.

The classification of the profiles in mutually exclusive categories is very important in the context of this work. Distinguishing between suboxic-CM profile or other-CM can be seen as a search for a special feature: the occurrence of suboxic-CM (Fig. 2). In other words, the search of the suboxic-CM is a Bernoulli trial, in which there are only two possible states: to be present (1) or absent (0). It is possible to compute a relative frequency or the percentage of occurrence of the suboxic-CM relative to all profiles as explained below.

Also, it is possible to build a 2 x 2 contingency table by considering as success when the suboxic-CM was present and failure when it was absent. Here a Barnard test was used to investigate if there were statistical differences between suboxic-CM proportions north and south of Cabo Corrientes (~ 21°N), using the data presented in Table 1 and the Barnard package in R 3.4.3 (Barnard, 1947, 1945; R Core Team, 2017). The Barnard test is robust test of independence for contingency table analysis.

To analyze the spatio-temporal variability of the occurrence of the suboxic-CM, data binning was used to deal with the uneven distribution of profiles in space and time. Stations (Fig. S1) were binned over a regular grid of 1° x 1°. The chosen cell size was a compromise between the spatial resolution and the number of stations within each cell. Additionally, the data were grouped by seasonal quarters (Jan-Mar, Apr-Jun, Jul-Sep, Oct-Dec). For each bin and quarter, occurrence of the suboxic-CM was computed as a relative frequency defined as follows:

$$SuboxicCM_{occ} = N_{suboxicCM} / N_{TOTAL} \quad \text{Eq. 4.}$$

where $N_{suboxicCM}$ is the number of profiles in which at least one chlorophyll-a fluorescence maximum within the OMZ (so called suboxic-CM) was detected, and N_{TOTAL} is the total number of valid profiles in each cell.

Only cells with three or more observations were considered in the computation of the suboxic-CM occurrence. In addition, $Z_{min_{OMZ}}$, $Z_{1\%}$, ΔZ and the integrated chlorophyll, were median binned in the same grid as those from the suboxic-CM occurrence. Here the spatial distribution of the integrated chlorophyll-a fluorescence was used to validate the spatial pattern of the suboxic-CM occurrence, because it does not depend on the identification of the maxima, and it does not use normalization of the chlorophyll-a fluorescence values.

To identify the mechanisms controlling the suboxic-CM, the temporal variability of its occurrence, $Z_{min_{OMZ}}$, $Z_{1\%}$ and the solar cycle were compared. Solar cycle was theoretically estimated using the SOLPOS irradiance model developed by the National

Energy Laboratory, as described in Mignot et al. (2018). Briefly, the SOLPOS model estimates the maximum expected irradiance under cloud-free conditions in a given date and geographical location. Also, the amount of nitrates were estimated during each season at the suboxic-CM, using the CANYON algorithm based on a trained neural network (Sauzède et al., 2017).

3. Results

All profiles were classified as indicated in Fig. 2 to assess frequency of occurrence of the suboxic-CM in the study area. From the 1161 inspected profiles, 42.8% were classified as suboxic-CM and 57.2% belong to the class other-CM (Table 1). This indicates that suboxic-CM was not dominant but was still a largely significant class in the whole study area. These suboxic-CM show a spatial pattern: north of $\sim 21^{\circ}\text{N}$, other-CM profiles dominated, while to the south, suboxic-CM profile class was prevalent (Table 1). The difference in proportions of suboxic-CM between the two regions was statistically significant (Barnard test score = 19.0, p-value <0.05).

3.1. Suboxic-CM characteristics

The Suboxic-CM present had a mean integrated chlorophyll of $19.63 \pm 9.36 \text{ mg.m}^{-2}$ (Fig. 3a; mean $\pm$ standard deviation) at a mean depth of $107 \pm 21 \text{ m}$ (Fig. 3c). Physically, suboxic-CM were associated with the potential density anomalies values between 25.1-

26.4 kg m⁻³ ($\sigma_0 = 25.94 \pm 0.16$ kg m⁻³; Fig. 3a), which corresponded to a salinity of 34.93 ± 0.03 g kg⁻¹ and temperature of 14.3 ± 0.7 °C (Fig. 3b). Biogeochemically, the suboxic-CM were associated with a depth of the upper limit of OMZ suboxic waters ($Z_{min_{OMZ}}$) located at an average depth of 74.78 ± 17.76 m and a satellite-derived euphotic zone depth ($Z_{1\%}$) of 74.14 ± 20.03 m (Fig. 3c-d), ranging from 7.31 to 150.31 m (Table S1).

Comparing the characteristics of the chlorophyll-a and oxygen profiles, the depth of the suboxic-CM had a positive linear correlation ($r = 0.74$, $n=497$, $p < 0.05$) with $Z_{min_{OMZ}}$ (Fig. 3c). That is, shallower suboxic waters were related to shallower suboxic-CM. Additionally, the dissolved oxygen in which the suboxic-CM was found had a clear mode below 10 $\mu\text{mol kg}^{-1}$, half of the defined upper limit of the suboxic waters of the OMZ (20 $\mu\text{mol kg}^{-1}$; Fig. S4a). The relative position of the suboxic-CM was found 36.6 ± 14.3 m below the $Z_{min_{OMZ}}$ (Fig. S4b). Comparing the OMZ and light characteristics, the suboxic-CM was found when $Z_{min_{OMZ}}$ was near or just above $Z_{1\%}$ (Fig. 3d).

Comparing the chlorophyll-a with both the oxygen and light characteristics, the integrated chlorophyll-a fluorescence increased when the level of 1% of irradiance lay 25 m above the suboxic waters (Fig. 4). Greater distances (> 25 m) between a shallower 1% of surface irradiance and deeper suboxic waters (negative Δz ; cf Equation 3) led to lower integrated chlorophyll-a fluorescence. This important relationship was not linear and high statistical dispersion was observed (Fig. 4).

3.2. Spatial and temporal patterns

Firstly, the patterns of the potential factors controlling Suboxic-CM: $Z_{min_{OMZ}}$, $Z_{1\%}$, and their difference (Δz) were assessed. The $Z_{min_{OMZ}}$ varied between seasons but overall showed a consistent spatial pattern (Fig. 5 a-d). The $Z_{min_{OMZ}}$ was generally deeper north of Cabo Corrientes and in the Gulf of California (>100 m). Farther south, $Z_{min_{OMZ}}$ was shallower (<100 m) and tended to shoal toward the coast. The boundary between deeper and shallower regions appeared to be farthest north in April-June ($\sim 24^\circ N$ inside the Gulf of California) and farthest south in October-December ($\sim 19^\circ N$ offshore of Cabo Corrientes). A similar pattern was observed in the depth of the 1% of surface irradiance. It was shallower near the coast and deeper offshore, with considerable seasonal changes within the Gulf of California (Fig. 5 e-h). The spatial and temporal variability of ΔZ (Equation 3) was related to the above-described changes in $Z_{min_{OMZ}}$ and $Z_{1\%}$. Figure 6a-d shows that the upper limit of the suboxic waters and the euphotic zone were near or overlapped (red colored cells) mainly south of $21^\circ N$. Some isolated cells also indicated overlap further north during spring (Apr-Jun) around $22^\circ N$ at the entrance to the Gulf of California (Fig. 5f).

Secondly, the spatio-temporal patterns of the $Z_{min_{OMZ}}$, $Z_{1\%}$, and Δz were related to those of the suboxic-CM to analyze the persistence in the enlighten OMZ system. Thus, the frequency of occurrence of the suboxic-CM (Figs. 6e-h, S2 and S3) showed a similar pattern of quarterly variability (Figs. 5 and 6a-d), coinciding with a region in which the $Z_{min_{OMZ}}$ was near (25 m of separation) or intersected with $Z_{1\%}$ year-round (Fig. 6). The region north of $21^\circ N$ was characterized generally by low values of occurrence (9.5 ± 17 4%), while to the south high values (67.1 ± 33 78%;) were found.

This pattern persisted in all seasons despite some heterogeneity in localized cells (Fig. 6e-h). This general pattern it was also observed in the integrated chlorophyll-a fluorescence (Fig. 6i-l). The persistence of suboxic-CM can be observed more clearly in Fig. 7a, where occurrence was relatively high in all quarters (median > 50 %). Nevertheless, some variations were recorded. Suboxic-CM occurrence was more frequent from January to September than from October to December in the region south of 21°N (Figs. 6 and 7a). Similar persistence of the relatively high integrated chlorophyll values is occurred, despite slightly lower biomass during January-March and October-December (Fig. 6i-l). In addition, there was high statistical variability in the occurrence of the suboxic-CM (note the width of the box in Fig. 7a) due to the spatial heterogeneity (Fig. 6e-l). Quarterly summary statistics of the CANYON-nitrates are presented in Table 2, with the median values varying from 33.98 in January-March to 30.10 $\mu\text{mol kg}^{-1}$ in October-December. The minimum values remained above 25 $\mu\text{mol kg}^{-1}$ in all quarters (Table 2).

4. Discussion

The results showed a persistence of the suboxic-CM in a specific region of the Pacific OMZ off Mexico south of 21°N. Here the possible reasons to explain why it happens in this geographically constrained region within the study area are discussed, including investigating the effect of the physical water mass dynamics, the Z_{minOMZ} variability, nitrates limitation and the changes in light penetration.

The suboxic-CM occurred in a set of specific physical conditions, strongly associated with the 26 kg m^{-3} isopycnal (Fig. 3b). This isopycnal surface corresponds to the relatively stable Subtropical Subsurface Water (StSsW; Fig. 1), which has a high influence at sub-surface levels of 75-400 m depth in the Tropical Pacific off Central Mexico (Portela et al., 2016). The seasonal changes in the horizontal mean circulation mainly impact the less dense water masses such as the fresher California Current Water or the warmer Gulf of California Water, or both fresher and warmer Tropical Surface Water, which lay above the StSsW.

Vertically, upwelling can transport StSsW towards the surface, but within a limited range of 30-50 km from the coast determined by the regional Rossby radius of deformation. It also coincided with the curl of the wind stress presented in figure S5, where the minimum and maximum values occur near the coast with considerable seasonal changes. In contrast, the wind stress curl in the open ocean had low absolute values and tends to be negative all year (Fig S5).

Because of that, it can be concluded that a direct effect of wind does not explain the seasonal variability of the suboxic-CM occurrence observed in figure 7. Indeed, the direct effect of wind will be limited to the coastal regions and, in our database profiles at distances shorter than 50 km, only represent a small fraction of the considered profiles. At smaller meso- and submeso-scales, eddies and filaments can also affect the distribution of the water masses properties introducing local variability. This can be associated with the reported spatial heterogeneity of the suboxic-CM, but are out of the scope of this work.

In this stable StSsW water mass, the results indicate that the dissolved oxygen is a key factor for the development of the suboxic-CM taking into account the significant linear relation between the depth of the suboxic-CM and the $Z_{min_{OMZ}}$ (Fig. 3c), and also because the suboxic-CM was mostly found at dissolved oxygen concentrations $< 10 \mu\text{mol kg}^{-1}$ (Fig. S4). These specific O_2 conditions can be related to the intense recycling of nutrients that takes place within the upper limit of the OMZ intensifying the nutricline (Lam et al., 2009; Paulmier et al., 2011; Kalvelage et al., 2013). Previous studies also support the key role of low dissolved oxygen concentration, for instance regulating the distribution of grazers such as metazoans (Goericke et al., 2000).

In addition to the stability of the water mass and the vicinity of the OMZ, the results suggest that illumination of the suboxic waters is an important factor promoting suboxic-CM (Fig. 4). The integrated chlorophyll-a was higher when the suboxic waters were shallower (positive values) or not separated by more than 25 m from the 1% of irradiance. The 25 m of separation can be considered as a threshold for the occurrence of the suboxic-CM (Fig. 4). Nonetheless, the 25 m threshold based on the 1% of surface irradiance should be interpreted with caution as a proxy of illumination of the OMZ. The suboxic-CM has been reported to occur at irradiances ranging from 0.2-2% of surface values (Goericke et al., 2000). Even in these extremely low-light levels it can be expected that there is photosynthetic activity of *Prochlorococcus* populations, which is potentially associated with the suboxic-CM.

In the study area, the upper limit of the OMZ remained illuminated all year due to its shallow position and the stability of the StSsW, leading to the persistence of the suboxic-CM south of 21°N year-round (Figs. 1, 5 and 6). This year-round persistence can

be perturbed by mechanisms including changes in water mass distribution, the local circulation and the variability in the light penetration due to the solar cycle, changes in attenuation of light or the presence of clouds.

In this regard, the proportion of different water masses may produce vertical displacements of the $Z_{min_{OMZ}}$ (Cepeda-Morales et al., 2009). However, the results indicated the $Z_{min_{OMZ}}$ is relatively stable south of $21^{\circ}N$ in seasonal scales (Fig. 7b) with no statistical significant differences, as indicated by a Welch's heteroscedastic test at 95% of confidence ($F=1.70$; $p\text{-value}=0.16$). $Z_{min_{OMZ}}$ was less variable than $Z_{1\%}$, which naturally follows the solar cycle (Fig. 7c). The low variability of the $Z_{min_{OMZ}}$ has been observed in previous studies (Cepeda-Morales et al., 2013; Paulmier and Ruiz-Pino, 2009), and highlights the stability of the OMZ in the Pacific off Mexico south of $21^{\circ}N$. North of $21^{\circ}N$ the $Z_{min_{OMZ}}$ was statistically different among quarters ($F=5.70$, $p\text{-value}=0.03$, $\alpha=0.05$), in agreement with the previous description by Cepeda-Morales et al. (2013).

Nitrate variability it is not expected to have profound effects on the suboxic-CM occurrence, because the suboxic-CM is associated with *Prochloroccus* cells (Garcia-Robledo et al., 2017; Goericke et al., 2000; Lavin et al., 2010). These cyanobacteria are adapted to the conditions of oligotrophic environments: they have low nitrogen requirements and they can use several nitrogen sources such as nitrates, nitrites, ammonium and urea (Aldunate et al., 2019; Astorga-Eló et al., 2015; Biller et al., 2014). Another reason to consider that nitrates have a limited effect, can be drawn from the nitrate estimations presented in Table 2. Nitrates at the suboxic-CM position, presented seasonal changes, but they remain above $25 \mu\text{mol kg}^{-1}$ all year, which is greater than the

~16 $\mu\text{mol kg}^{-1}$ used as a proxy of the nitracline (Chavez et al., 1996 and references therein). Thus, the suboxic-CM can use different nitrogen sources such as nitrites or urea, have low requirements, and it is located in a region with plenty of nutrients (Astorga-Eló et al., 2015; Ulloa et al., 2012). Thus, the regulation of its occurrence by nitrates variations is not expected to be significant.

Instead, the suboxic-CM seem to be more limited by light because it is at the base of the euphotic zone, and it can be sensitive to all processes modifying the light availability. Long Rossby waves can be a plausible mechanisms causing vertical displacements of the isopycnals, hence moving the suboxic-CM and changing light conditions. Also, the presence of other chlorophyll maxima can itself affect the light distribution. For example, in the North Pacific subtropical gyre it has been demonstrated that increased chlorophyll concentration at the chlorophyll maximum, can lead to an increase in light attenuation, producing a shadowing effect over deeper levels (Letelier et al., 2004).

Of the above explanations, we can consider the light distribution in the water column as the primary source of variations in the suboxic-CM occurrence while nutrient variability has a secondary role. However, variability in nutrient supply cannot be ruled out completely, as different nutrients may have a different impact on the suboxic-CM. However, the biology of *Prochlorococcus* is beyond the scope of this work and more data are required to investigate how macro and micronutrients can affect the distribution of these populations. Finally, it is possible to state as a conceptual paradigm, that the temporal variability in light penetration has a primary effect on the suboxic-CM south of 21°N and the local influence of wind, and nitrate variability have a limited effect.

5. Conclusions

The median frequency of occurrence of the suboxic-CM was > 60 % in all quarters of the year south of 21°N. In this region, the upper limit of the suboxic waters was shallower, and remains near or overlaps with the euphotic zone year-round. These results support the hypothesis that the suboxic-CM is a persistent trait in the Tropical Pacific off Central Mexico because the conditions that promote it remain stable over seasonal scales. The persistence of the suboxic-CM can be taken as an indication of stability of the ecosystem in which the suboxic-CM arises as a response of phytoplankton communities to the redox conditions of the OMZ suboxic waters.

Acknowledgments

The data used in this work were obtained in the oceanographic campaigns supported by the *Consejo Nacional de Ciencia y Tecnología* (CONACyT) through the projects CONACyT-2015-02-100 and CONACyT-2014-236864-t. The main author is a fellow from CONACyT in the doctoral program at *Centro Interdisciplinario de Ciencias Marinas* (CICIMAR). Additionally, the main author received financial support of the *Laboratoire d'Etudes en Géophysique et Océanographie Spatiales* (LEGOS) and from *the Institut de Recherche pour le Développement* for an internship in Toulouse, France.

The authors are grateful for the filtering and pre-processing of CTD data done by Dr. Víctor M. Godínez. Also, the data for the analysis of the Euphotic Zone Depth were

invaluable and were gathered from the Ocean Biology Processing Group data centers. The authors are profoundly grateful to the reviewers, whose comments and criticism helped to improve substantially the quality of this manuscript. There is no conflict of interest of disclosure regarding this research and the hydrographic data used in this work are available by request from the corresponding author.

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TABLES

Table 1. Number of profiles belonging to the suboxic-CM and other-CM classes. The number of profiles classified considering all profiles, profiles north of Cabo Corrientes ($> 21^{\circ}\text{N}$) and south of this location ($\leq 21^{\circ}\text{N}$) are shown. The percentages of the total are indicated in parentheses.

Profile Class	All	North	South
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Suboxic-FM	497 (42.8)	49 (10.1)	448 (66.2)
Other-FM	664 (57.2)	435 (89.9)	229 (33.8)

Table 2. Quarterly summary statistics of the nitrate concentration at the suboxic-CM and estimated empirically using CANYON algorithm (Sauzede et al. 2017). Nitrate concentration are expressed in $\mu\text{mol kg}^{-1}$.

	JFM	AMJ	JAS	OND
Min.	28.55	27.20	26.94	28.82
Max.	35.13	33.25	31.09	31.67
Median.	33.98	32.13	30.95	30.10
Std. Dev.	0.65	0.89	0.83	0.67

Figure Captions

Fig. 1. Schematic seasonal surface circulation and water mass distribution in the study area. Left (a-d), indicates the Tropical Pacific off Central Mexico (TPCM), the region

delimited by dashed lines and the Gulf of California (GoCA). Currents are indicated by arrows. MCC is the Mexican Coastal Current, which is part of a cyclonic circulation (dotted line). Currents were drawn based on Kurczyn et al. (2012). Right (e-h), are depicted Θ -SA diagrams and the oxygen concentration (colors) for the TPCM. Water mass boundaries delimited the Tropical Surface Water (TSW), California Current Water (CCW), Subtropical Subsurface Water (StSsW), the Gulf of California Water (GSW) and Pacific Intermediated Water (PIW). Water mass boundaries are according to Portela et al. (2016). Cabo Corrientes is indicated as CC in (a).

Fig. 2. Examples of chlorophyll-a fluorescence (Green line) and oxygen (blue lines) profiles found in the study area. Selected profiles illustrate examples of the profile classes: suboxic-CM when at least a chlorophyll -a maximum was found in the suboxic waters of the OMZ (a, c) and other-CM when chlorophyll-a maxima occurred in more oxygenated waters (b, d). The gray shade indicates the layer with suboxic waters of the OMZ ($< 20 \mu\text{mol kg}^{-1}$) and its upper limit is indicated by a horizontal black line. Profiles were obtained during the surveys of March 2016 (a, d), March 2007 (b) and June 2003 (c).

Fig. 3. Bi-variate histograms depicting the characteristics of the suboxic-CM. Blue shaded colors represent kernel density estimates; the darker the color, the greater the frequency density of observations. (a) Shows the distribution of integrated chlorophyll in the depth range from Z_{minOMZ} to 300 m, and related to the density of sea water. (b) Represents the physical properties at which the suboxic-CM was found. (c) Shows the relation between the depth of the suboxic-CM ($Z_{\text{suboxic-CM}}$) and the depth of the upper

limit of the OMZ (Z_{minOMZ}). The best fit line, its equation and the Pearson's correlation coefficient are indicated. In (c), it shows the frequency density considering the depth at which irradiance becomes 1% of the surface value ($Z_{1\%}$) and Z_{minOMZ} . The identity line (1:1) is represented as a diagonal line.

Fig. 4. Scatter plot of ΔZ and the integrated chlorophyll-a in the depth interval from Z_{minOMZ} to 300 m. Note that most of the points with integrated chlorophyll above 10 mg m^{-2} occur when ΔZ is greater than -25 m (vertical line). The negative numbers mean that the two depths are separated by a given distance. Positive values indicated intersection or illumination of suboxic waters (equation 3).

Fig. 5. Quarterly variability of the upper limit of the suboxic waters of the OMZ (Z_{minOMZ} ; a-d) and the depth at which irradiance becomes the 1% of the value just below the surface ($Z_{1\%}$; e-h). White colors (ND) represent cells with less than three observations or without valid data.

Fig. 6. Quarterly variability of the distance between the 1% of irradiance and the upper limit of suboxic waters (ΔZ ; a-d), the suboxic-CM occurrence (e-h) and the integrated chlorophyll (Int.CHLA; i-l). In (a-d) the red colors indicate where ΔZ is greater or equal to the -25 m threshold. White colors (ND) represent cells with less than three observations or without valid data.

Fig. 7. Quarterly seasonal variability in the suboxic-CM occurrence, the upper limit of suboxic waters of the OMZ ($Z_{min_{OMZ}}$), the depth of 1% of surface irradiance ($Z_{1\%}$) and the daily integrated irradiance for the Photosynthetically Active Radiation (grey line; PAR). In (a) the data were spatially segregated north (white box) and south (grey box) of 21°N. Lower and upper limits of the box correspond to the first and third quartiles. The horizontal line in each box plot represents the median and the whiskers indicate the maximum and minimum values that were not considered as outliers. Points represent grid cells whose value was beyond 2 times the interquartile range (outliers). In (b and c) the mean (point) plus/minus standard deviation (whiskers) are plotted and only represent the variability south of 21°N. The daily integrated irradiance for 2009 (midpoint of all years) was taken as a representative of the seasonal variability.

Supplementary material

Table S1. Quarter summary statistics of the depth at which irradiance became 1% of the value just below the surface ($Z_{1\%}$), and upper-limit of the suboxic water of the OMZ ($Z_{min_{OMZ}}$), for the whole study area.

$Z_{1\%}$ [m]				$Z_{min_{OMZ}}$ [m]		
Quarter	Mean ($\pm$ Std. Dev.)	Min	Max	Mean ($\pm$ Std. Dev.)	Min	Max
Jan-Mar	63.73 $\pm$ 19.31	15.53	103.01	100.02 $\pm$ 32.81	40.23	167.91

Apr-Jun	78.55 ± 21.71	7.31	150.31	120.83 ± 70.74	49.72	334.44
Jul-Sep	83.26 ± 13.87	33.61	113.41	110.11 ± 54.38	64.35	115.00
Oct-Dec	65.65 ± 13.18	34.66	92.11	108.46 ± 37.61	44.17	121.00

Fig. S1. Spatial distribution of CTD profiles in the study area is shown by dots in the grid cells used for the analysis. The colors of the grid cells distinguish the oceanographic areas defined by Portela et al. (2016). CalC: California Current, GoCa: Gulf of California, TPCM: Tropical Pacific off the coast of Central Mexico, TrAr: Transitional Area and TrPa: Tropical Pacific. Cabo San Lucas (CSL) and Cabo Corrientes are also labelled. (CC).

Fig. S2. Number of profiles per cell by quarter. The number in each cell represents the value N_{total} used for the computation of the suboxic-CM occurrence (see equation 4 in the main text). Blue numbers indicated cells with three or more observations, while red numbers highlight cells with less than three profiles, which are not considered in the analysis. Cells without numbers contain no profile.

Fig. S3. Number of profiles belonging to the class suboxic-CM in each cell by quarter. The number in each cell represents the value $N_{suboxicCM}$ used for the suboxic-CM occurrence computation (see equation 4 in the main text). Green numbers indicated cells with three or more observations, while red numbers highlight cells with less than three profiles, which are not considered in the analysis. Cells without numbers contain no profile.

Fig. S4. Univariate histograms of the characteristics of the suboxic-CM (a) show the frequency density of the oxygen concentrations at which the suboxic-CM was found. (b) The distance between the depth of the suboxic-CM ($Z_{\text{Suboxic-CM}}$) from the upper limit of the suboxic waters of the OMZ (Z_{minOMZ}), indicating its relative position. The black line in the histogram represents the density function obtained from a kernel density estimate.

Fig. S5. Quarterly variability of the curl of the wind stress (colors). Vectors represent the wind stress. Data were from CCMP version 2 from Remote Sensing Systems.

116°W 112°W 108°W 104°W 116°W 112°W 108°W 104°W

Wind field seasonal climatologies

(CCMP version 2 RSS)

October 10, 2019

Dear Editor

Deep Sea Research

Special issue Pacific transitional area

In reference to the manuscript DSR2_2018_124

I declare that there is not exit conflicts of interest

Sincerely

Laura Sanchez Velasco

Corresponding author