CMEMS OSR5 – Chapter 3

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Section 3.1. The chlorophyll-a gradient as primary Earth observation index of marine ecosystem feeding capacity

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Statement of main outcome: An efficient ocean management for fisheries requires accurate data over large spatial scales. The horizontal gradient of chlorophyll-a (and the derived mesozooplankton habitat) exemplifies a plankton-to-fish index in support of a sustainable ocean management that targets fisheries and ecosystem productivity. The gradient of chlorophyll-a, which expresses the productivity of fronts, showed to sustain the development of mesozooplankton and to attract predators (primarily fish) when the activity period is longer than three to four weeks (Druon et al. 2019). Only productivity features active from weeks to months, such as within eddies or semi-permanent currents, can contribute to the 10–20% of the total phytoplankton productivity that is transferred along marine food chains in the global ocean. Our results highlight that the level of chlorophyll-a gradient occurrence at global scale (area-averaged), which is associated to the mesozooplankton feeding habitat and fish productivity, is maintained over the period 2003–2019 despite the warming of the surface ocean. This suggests that the surface ocean mixing – likely of atmospheric origin – globally tends to compensate for the stabilising effect of thermal stratification. Regional variabilities, however, are highly contrasted with positive and negative trends.

Daily values of chlorophyll-a gradient can be computed at global scale for the last two decades up to near real-time. This is critical to improve our understanding of the plankton-to-fish dynamics, especially under the current effects of climate change, and to build observation-based operational products that will inform the future spatial and dynamic ocean management. The computation of such gradient requires a specific expertise in ocean colour, making them difficult to obtain for non-specialists. Their operational availability could therefore offer a critical benefit to marine biologists and ecosystem modellers and, in turn, to regional fisheries management and Authorities facing overexploitation and the effects of climate change. International marine policies will ultimately be efficiently supported by the use of chlorophyll-a gradient as a direct, observation-based, biological variable monitoring the marine ecosystem productivity across a wide range of spatial and temporal scales.

Products used:

Ref. No.	Product name and type	Documentation
3.1.1	OCEANCOLOUR_MED_CHL_L3_NRT_OBSERVATIONS_009_040 Single sensor MED CHL L3 1 km Sentinel 3 - OLCI	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-OC-PUM-009-ALL.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-038to045-071-073-078-079-095-096.pdf
3.1.2	OCEANCOLOUR_BS_CHL_L4_NRT_OBSERVATIONS_009_045 Single sensor BLACK SEA CHL L3 1 km Sentinel 3 - OLCI	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-OC-PUM-009-ALL.pdf

(*Continued*)

Supplemental data for this article can be accessed https://doi.org/10.1080/1755876X.2021.1946240

Continued.

Ref. No.	Product name and type	Documentation
		QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-038to045-071-073-078-079-095-096.pdf
3.1.3	OCEANCOLOUR GLOBAL CHL L3 4 km NASA MODIS-Aqua and 9 km SeaWiFS	https://oceancolor.gsfc.nasa.gov/l3/
3.1.4	Favourable feeding habitat of Mesozooplankton in the North Atlantic Ocean – monthly 2003–2018 (frequency of occurence, %)	https://data.jrc.ec.europa.eu/dataset/ac456798-24d1-4d76-aeca-fcb3eb0c7e73

3.1.1. Introduction

Sea surface chlorophyll-a is the only marine biological variable that is quantified from space. Ocean colour sensors allow for frequent observations of this variable and thus offer a unique proxy of phytoplankton dynamics (Dutkiewicz et al. 2019). While satellite-derived chlorophyll-a renders possible to monitor the surface ocean primary productivity (chapter 3.2. in OSR4; von Schuckmann et al. 2020), it remains a comparatively weak proxy of the productivity transferred along marine foodwebs, which starts with zooplankton, since about 80% (upwelling) to 90% (oceanic waters) of the primary production is remineralised (Raymont 1980; Libralato et al. 2008).

High levels of horizontal gradient of chlorophyll-a, or productivity fronts, result from the resurgence of sub-surface nutrient-rich waters such as in upwellings, at the edge or in the core part of eddies or along a semi-permanent current (e.g. Brandini et al. 2000; Kouketsu et al. 2016). Productivity fronts were shown to attract fish and top predators (Polovina et al. 2001; Valavanis et al. 2004; Druon et al. 2012, 2015, 2016, 2017; Briscoe et al. 2017; Panigada et al. 2017) as being active long enough (from weeks to months) to allow the development of mesozooplankton populations (Druon et al. 2019). These productivity fronts, mostly efficient at mesoscale for zooplankton production, represent a spatial proxy of food availability for fish populations and feeding hotspot for the pelagic ecosystem when associated to the active aggregation of highly mobile predators (e.g. for bluefin tuna in Druon et al. 2016; of fin whale in Panigada et al. 2017). Productivity frontal features exist at smaller scales when their resilience allows phytoplankton development (few days), but are generally inefficient to transfer the energy to medium-size zooplankton (mesozooplankton, 0.2–20 mm) that requires several weeks of continuous primary production to develop (Figure 3.1.1).

Ocean colour remote sensing is central to the detection of productivity fronts because not all frontal features detected by satellite-derived temperature do correspond to chlorophyll-a fronts, and vice versa, due to a variable cross-front contrast for sea surface temperature and chlorophyll-a (Kahru et al. 2012). Furthermore, thermal fronts are often masked during the summer due to increased vertical stratification near the surface, whereas chlorophyll-a fronts are less affected (Pegau et al. 2002; Takahashi and Kawamura 2005).

The habitat analyses suggest that the horizontal gradient of chlorophyll-a is a better proxy than chlorophyll-a when seeking the spatial distribution of mesozooplankton and marine predators. We emphasise in this paper that, while this variable requires an advanced knowledge in ocean colour limitations, its availability would greatly help the marine biologist community to produce robust, observation-based, plankton-to-fish indicators from local to global scale in nowcast and hindcast modelling, such as input data to develop more robust full ecosystem models (Hernvann et al. 2020).

3.1.2. Methods

The meso-scale frontal features of productivity identified in the mesozooplankton habitat study (product 3.1.4 for the North Atlantic in the product table) were detected daily by computing the horizontal gradient of chlorophyll-a from ocean colour sensors at 1/24 degree resolution from MODIS-Aqua and 1/12 degree from SeaWiFS sensors (CI-Hu algorithm reprocessed in January 2018, product 3.1.3 in the product table). This algorithm employs the standard *OC4v6* algorithm merged with the colour index (*CI*) of Hu et al. (2012) for the relatively clear water. The empirical relationship of Pitarch et al. (2016) was used in the Baltic Sea to correct from the chlorophyll-a overestimation generated by the high content of dissolved organic matter. Daily chlorophyll-a data are pre-processed (i) to limit the loss of coverage after the horizontal gradient computation due to scattered cloud coverage and associated missing data and (ii) to filter out eventual stripes from the optical sensor. Iterations of a median filter are used to recover missing data on the edge of the valid data, while a Gaussian-smoothing procedure allows for removing potential sensor stripes (Druon et al. 2012). Chlorophyll-a gradient (*gradCHL*) was derived from the daily chlorophyll-a data using a bi-directional gradient norm over a three by three grid-cell window as follows:

$$gradCHL = \sqrt{Dx^2 + Dy^2}$$

with *Dx* and *Dy*, the longitudinal and latitudinal chlorophyll-a horizontal gradient, respectively, corrected by the pixel size in km. Small and large chlorophyll-a fronts refer to variable levels of chlorophyll-a gradient values. Compared to the central front location, the gradient computation allows for quantifying how the front can potentially support high trophic levels since chlorophyll-a gradient values were linked to the mesozooplankton biomass (the higher gradient, the higher biomass; biomass estimated from the Continuous Plankton Recorder based on 131 taxa, Druon et al. 2019).

The chlorophyll-a gradient computation can only be performed using single sensor chlorophyll-a data as merged data from different sensors inevitably lead to gradients generated at the interface between data of different sensors. In the perspective of increasing coverage area, the merging of gradients from various sensors likely presents less difference than the gradient obtained from the merging of chlorophyll-a products as satellite imagery is, by nature, efficient in detecting horizontal contrasts (relative levels) compared to absolute levels. Note, however, that chlorophyll-a gradients are sensitive to the spatial resolution (the lower resolution, the lower chlorophyll-a gradient value) so that the unit is to be expressed in mg chlorophyll-a.m^{-3}.km^{-1}. A resolution of 1/24 degrees showed to capture the main productivity features of importance for the pelagic ecosystem (see habitat studies herein).

The mesozooplankton habitat is a daily value between 0 and 1, directly derived from the log-transformed value of the chlorophyll-a gradients after a close relationship was found with the mesozooplankton biomass (Druon et al. 2019). The habitat formulation is computed on a daily basis in each grid cell using (i) the horizontal gradient of chlorophyll-a (rescaled values from 0 to 1) and (ii) a suitable range of chlorophyll-a content (value of 0 or 1). The range of suitable chlorophyll-a and minimum value of gradient (*gradCHLmin*) suitable for mesozoopankton are derived using the same cluster analysis as in Druon et al. (2019) but applied to the 2018 reprocessed chlorophyll-a data by NASA. The maximum slope of the cumulated distribution of chlorophyll-a gradient at the location of mesozooplankton presence is used to define the gradient where the daily habitat function reaches the maximum value of 1 (intermediate gradient value, *gradCHLint*). The mesozooplankton habitat is therefore bounded, at its lower limit, by the minimum size of influential productivity fronts and, at its upper limit, by a maximum chlorophyll-a content representing a potential limit by eutrophication. Continuous daily values of habitat between 0 and 1 are applied for increasing chlorophyll-a gradient levels (linear increase in log-scale) from *gradCHLmin* to *gradCHLint*.

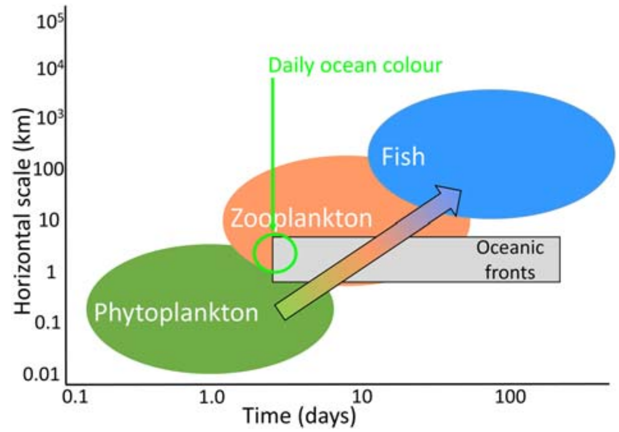

Figure 3.1.1. Schematic representation of time and space scales involved in the development of phytoplankton, zooplankton and fish. Productive fronts, which are areas of continuous primary production for weeks to months, are efficient vectors of energy from phytoplankton to medium-size zooplankton and appropriately tracked by daily ocean colour. This defines a high ecotrophic efficiency, i.e. a high proportion of the net annual production consumed by higher trophic levels.

Even if we only present here the results of chlorophyll-a gradients and mesozooplankton habitat from MODIS-Aqua (4 km, since July 2002), other sensor data are available for various periods and resolutions with an increasing optical quality with time. The available sensors currently are CZCS (9 or 4 km, October 1978–June 1986 – not continuous), OCTS (9 or 4 km, November 1996–June 1997), SeaWiFS (4 or 9 km, 1997–2010), MERIS (4 or 1 km, 2002–2012), VIIRS (since 2012) and Sentinel 3a and 3b since February 2016 and April 2018 respectively (1 km, 300 m). The herein multiannual global product of chlorophyll-a gradient is at 4 km resolution and result from daily estimates (daily to monthly to annual). As mentioned above, and due to the imagery nature of this satellite observation, the merging of chlorophyll-a gradients from different sensors at the same spatial resolution would increase daily spatial coverage. Gradient products derived from high-resolution chlorophyll-a data, starting with 300 m, may interact with human-induced activities such as the track of large ships, the latter being able to mix the upper productive ocean layer over a sufficient spatial scale.

3.1.3. Results and discussion

Figure 3.1.2 describes an example of the two steps of daily chlorophyll-a gradient computation from the original chlorophyll-a data (panel a) with (1) a median filter followed by a Gaussian smoothing (panel b) and (2) a bi-directional gradient norm over a 3 by 3 grid-cell window (panel c) for 18 July 2019 in the western Mediterranean Sea. The median filter and Gaussian smoothing allows for a reasonable interpolation at the edge of existing data with a chlorophyll-a recovery mean relative error below 5% (S.I. of Druon et al. 2012). This process allows for a substantial recovery of the original data (about +11% in the example of Figure 3.1.2) depending on data and the associated cloud distribution. The relative gain in coverage is much higher after the gradient calculation (+22% in the presented example). The use of the median filter and Gaussian smoothing procedure is therefore particularly relevant in habitat coverage in cases of dappled cloud occlusions. This procedure also removes the sensor stripes that may occur in specific optical configurations (zoomed area in panel a, Figure 3.1.2) and are substantially amplified by the gradient computation (panels d and e, Figure 3.1.2). While filtering out extremely low levels of chlorophyll-a gradient, this smoothing procedure however maintains the smallest productivity features of influence to mesozooplankton as attested by the relationship with the mesozooplankton biomass (Figure 3.1.3, pink line on panel a) towards low levels.

Environments where productivity may mostly occur in the subsurface layer, and consequently not seen by satellite optical sensors, are generally considered to be substantially less productive than when occurring near the surface because of the exponential decrease of light with increasing depth. Areas where a deep chlorophyll-a maximum occurs may thus characterise a quantitatively low source for mesozooplankton feeding, albeit locally important.

Another potential limitation of the approach is the presence of suspended inorganic matter and coloured dissolved organic matter (Gohin et al. 2002) which may bias the chlorophyll-a estimation in river-influenced coastal waters. This bias mostly occurs near river plumes and in the Baltic Sea where dissolved organic matter content is high. In these areas, this bias can be overcome by using a mixed chlorophyll-a algorithm (OC5 and CI-Hu) as adopted by the CMEMS GlobColour product (Garnesson et al. 2019). The empirical chlorophyll-a correction presently used in the Baltic Sea (Pitarch et al. 2016) is a first-order correction leading to a symmetric and zero-centred error distribution. High levels of the chlorophyll-a (above 10.0 mg.m^{-3}, see Table 3.1.1) resulting of an overestimation from above-mentioned particulate or dissolved matter or corresponding to potentially eutrophicated areas are set to a zero value for the mesozooplankton habitat.

Table 3.1.1. Habitat parameterisation used to define the environmental envelope of mesozooplankton in the North Atlantic Ocean, where CHL and gradCHL are the sea surface chlorophyll-a content and horizontal gradient from the MODIS-Aqua sensor, respectively (CHL data reprocessed by NASA in 2018).

Parameter values for mesozooplankton suitable habitat	Minimum value	Intermediate value	Maximum value
CHL (mg.m^{-3})	0.089*	N/A	10.0*
gradCHL (mg m^{-3}.km^{-1})	0.0002*	0.00876**	N/A

*Values identified using the same type of cluster analysis as in Druon et al. (2019).

**See also Figure 3.1.3.

The habitat products using the 2018 reprocessed chlorophyll-a data shows a direct link with the relative biomass of mesozooplankton for relatively low levels of chlorophyll-a gradient (between *gradCHLmin* and *gradCHLint*, Figure 3.1.3, panel a) similarly to Druon et al. (2019). This link suggests that relatively small productivity fronts are less resilient than larger productive features as a minimum of three to four weeks of continuous primary production is needed to reach high mesozooplankton biomass levels (Druon et al. 2019). These small fronts may correspond to productivity features in development that host a growing mesozooplankton population or to dying features with decreasing plankton populations. The relatively lower than expected biomass values of mesozooplankton at high levels of chlorophyll-a gradient (high habitat values near and above *gradCHLint*, Figure 3.1.3, panel a) correspond to large and resilient productivity fronts hosting a well-developed mesozooplankton population although likely impacted by predation from higher trophic level organisms. The highest *gradCHL* levels matching the maximum mesozooplankton biomass may relate to the less frequent highly productive fronts that are uncontrolled by predation. The panel b of Figure 3.1.3 highlights an example of a daily distribution of mesozooplankton habitat (continuity of Figure 3.1.2(c)) resulting of small (habitat value about between 0.15 and 0.75) and large (habitat value above 0.75) productivity fronts. These areas respectively correspond to mostly open waters and either river-influenced coastal areas or the Alboran Sea that is influenced by the Atlantic surface waters.

The panel a of Figure 3.1.4 describes the latitudinal dynamics of mesozooplankton in the North Atlantic, with peaks of biomass from May to June-July (south to north) and seasonal duration of relatively high biomass levels from three (30–40°N) to seven months (40–50°N), and five to four months in the northern areas

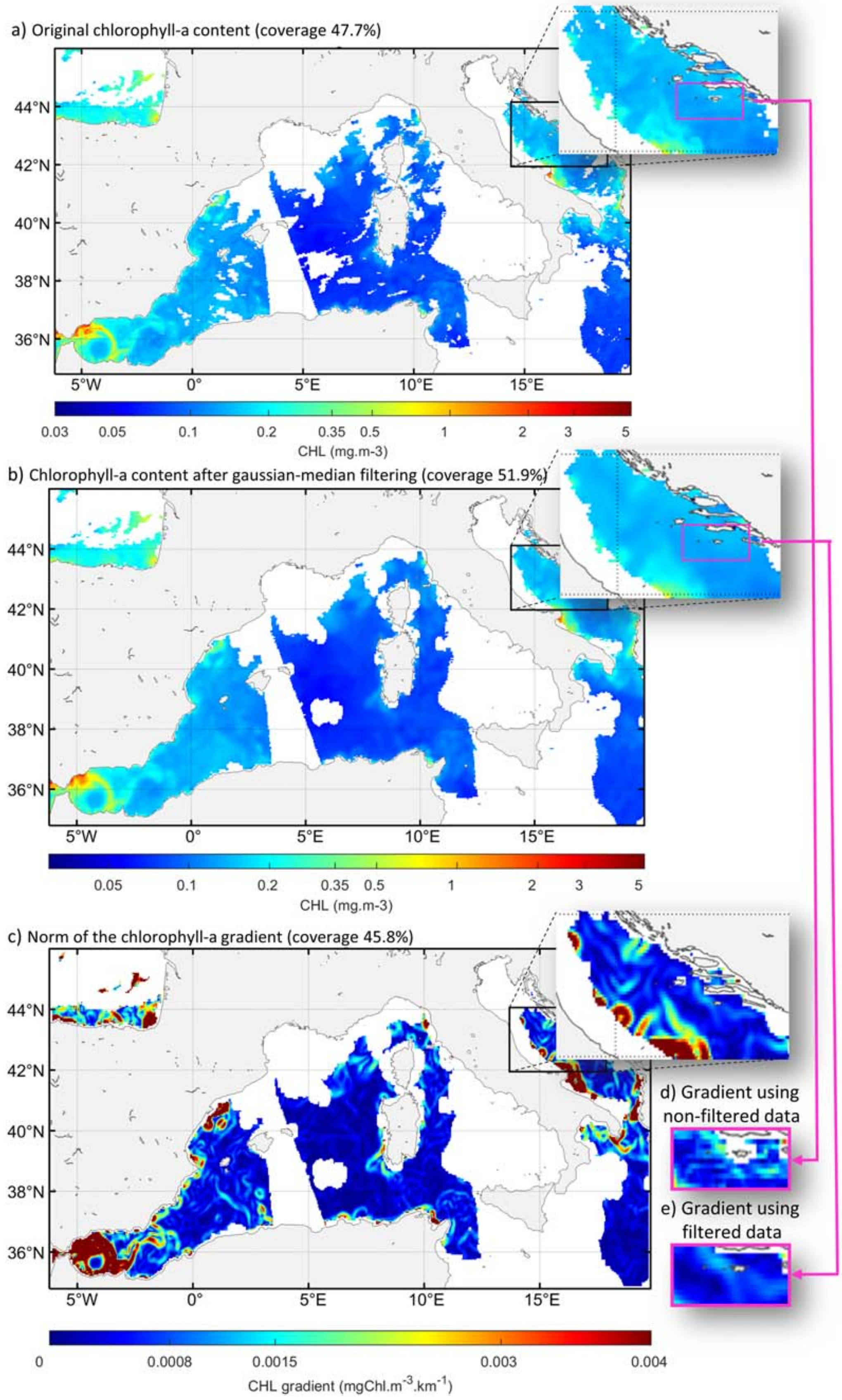

Figure 3.1.2. Example of daily chlorophyll-a processing from MODIS-Aqua sensor (product 3.1.3 in the product table) on 18 July 2019 in the western Mediterranean Sea: (a) original data, (b) data after median filter and Gaussian smoothing, (c) norm of horizontal gradient of chlorophyll-a, (d) zoomed area of the gradient norm using non-filtered data and (e) zoomed area of the gradient norm using filtered data. Note the reduced loss of coverage after the gradient computation (c, 45.8%) compared to the original data (a, 47.7%) due to the median interpolation at the edge (b, 51.9%). Slight sensor stripes on the original data (zoomed area in a) are removed after the Gaussian smoothing (zoomed area in b and e) and would be kept otherwise (d).

(50–60°N and 60–70°N respectively). Peak levels of biomass in the northern latitudes are however about three-fold higher (0.17 vs 0.06 in relative units). This simple, algorithm-type, habitat model generally predicts accurately the suitable conditions for the development of mesozooplankton as shown by the distribution of habitat at the location and time of observed biomass (Figure 3.1.4). The lower habitat level in August and September in the latitude range of 40–50°N may result of the presence of a relatively shallow subsurface chlorophyll-a maximum, which is not sensed by ocean colour sensors. Higher habitat levels, such as in August and September in the latitude range of 60–70°N and in winter in the latitude range of 30–40°N, are likely caused by both the important reduction of day length (see habitat weighted by day length in relative values, dashed line) and predation, which are not accounted for in the habitat estimate. The habitat weighted by day length refers to a notion of daily productivity (daily identification of a chlorophyll-a front multiplied by the relative time of daily activity). While the habitat weighted by day length slightly better correlates with the mesozooplankton biomass (Spearman's r of 0.935, $p \approx 0$, and 0.89, $p \approx 0$, respectively), we decided to keep the notion of daily habitat for mesozooplankton and to develop in parallel a more generic index of Ocean Productivity available to Fish (OPFish, first description in Druon 2017). The OPFish index, based on chlorophyll-a gradient preferences for different trophic levels and on day length, is being successfully compared to spatial fisheries data in the European Seas (Druon et al., 2021). Both the mesozooplankton habitat and OPFish index are different notions (habitat and production, respectively) which can be useful metrics depending on the application.

The global distribution of mesozooplankton habitat from 2003 to 2019 is an extrapolation from the North Atlantic analysis, which covered mesozooplankton taxa from tropical to subpolar latitudes (Druon et al. 2019). This global distribution shows large spatial variability, especially between maximum levels in upwelling areas and minimum levels in the centre of tropical gyres (Figure 3.1.5, panel a). The map of absolute trend informs on contrasting regional variations under the current effects of climate change (e.g. negative trend globally in the tropical Pacific and positive trend in the North Atlantic, Figure 3.1.5, panel b). The maximum levels of mean regional trend over the period 2003–2019 can reach up to about ±1%/year in mesozooplankton habitat frequency unit (% of time occurrence). Therefore, these maximum trend levels represents about ±17% difference in absolute unit over this 17-year period in the global mean map (Figure 3.1.5, panel a). The short time-series of global annual means (Figure 3.1.5, panel c) displays relatively limited oscillations (between 40 and 42.7% in absolute units), which appears to be periodic (6–8 years).

However, the most striking result is the absence of global mean trend observed from the regional trend map (and slightly positive trend from the global annual means, Figure 3.1.5(c)) of chlorophyll-a gradient occurrence despite the surface ocean warming (OSR3; von Schuckmann et al. 2019). This reveals that the turbulent-driven hydrodynamics – likely of atmospheric origin – tends to compensate for the effect of thermal stratification (see discussion in Druon et al. 2019). In turn, this means that the current global marine productivity useful for the upper trophic levels is likely to be maintained. This does not preclude from a negative trend in the future as the warming continues (Allen et al. 2019) considering the complex feedbacks at the ocean-atmosphere interface. Regionally, however, spatial contrasts of changes in mesozooplankton habitat and fish potential feeding do occur and, if decreasing, it will constrain the available resource and force local populations to adapt.

3.1.4. Conclusions

The daily horizontal gradient of chlorophyll-a, and the associated mesozooplankton habitat, is a prevailing proxy of primary productivity available to zooplankton and upper trophic levels because productivity fronts are active long enough to sustain zooplankton development (at least three to four weeks). The chlorophyll-a gradient and associated mesozooplankton feeding habitat provides appropriate information on the useful fraction (10–20%) of the primary productivity transferred along marine food chains and primarily in the pelagic ecosystems. The distribution of the mesozooplankton habitat over the period 2003–2019 highlights (1) a stable global productivity available to high trophic levels despite the surface ocean warming and (2) substantial positive and negative regional trends. This is critical information for regional fisheries management and food security of coastal communities as regards to their adaptation to climate change. Similarly, this information is essential for adapting the effort of industrial fisheries to local fish production and evolving towards sustainable fishing.

The community of marine sciences can highly benefit from the availability of chlorophyll-a gradient to derive advanced analysis in ecosystem functioning and fisheries, including hindcast in the past two decades and nowcast for dynamic ocean management of utmost

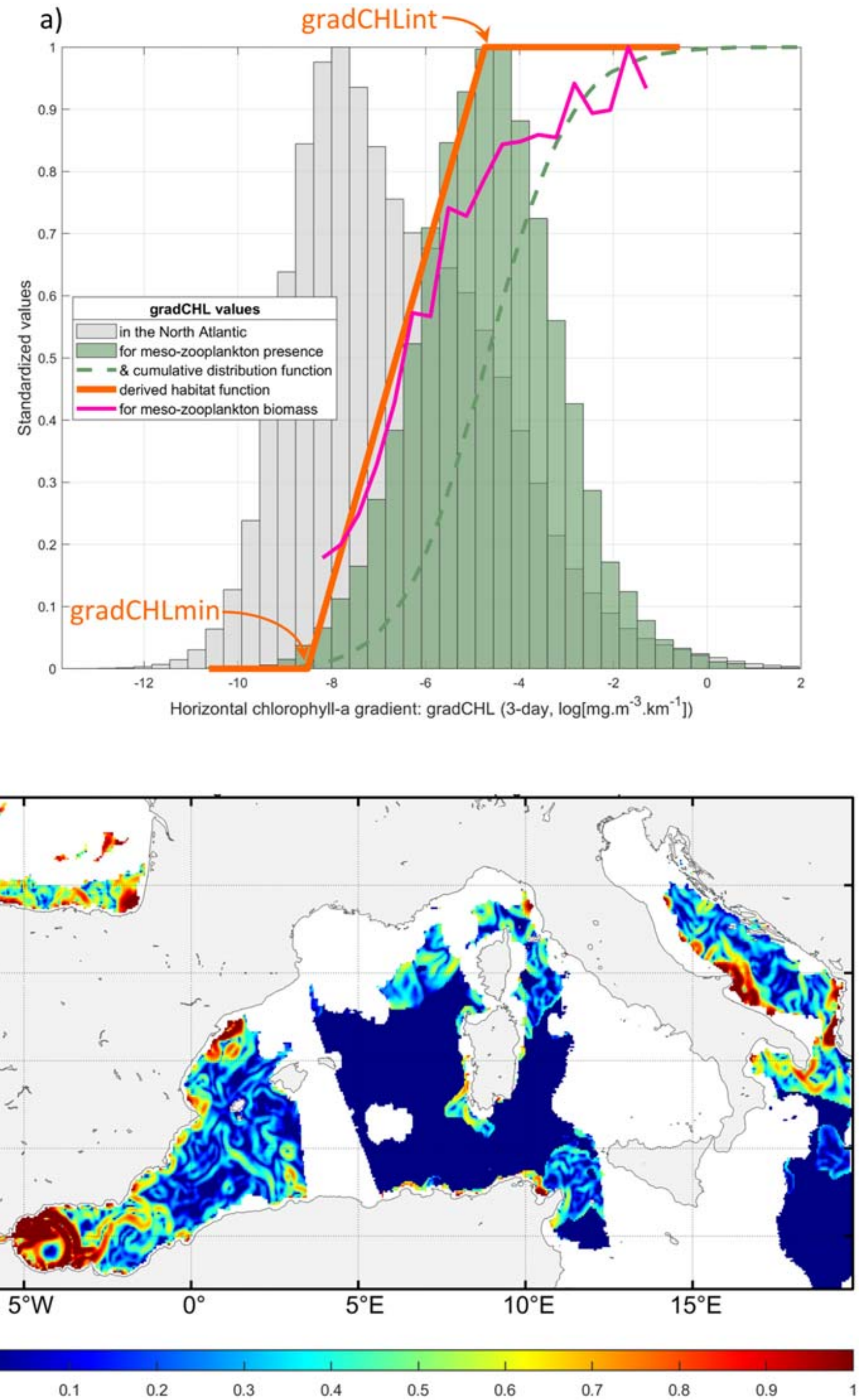

Figure 3.1.3. (a) Standardised frequencies of relative units of chlorophyll-a horizontal gradient (gradCHL; log-transformed) for the whole North Atlantic (background grey histogram) and only for locations where mesozooplankton are present (green histogram, 3-day mean values around the observation day were chosen to increase the number of matching points). The maximum slope of the cumulative distribution of mesozooplankton presence (green dashed line) was used to define the daily habitat linear function (orange line). The mean mesozooplankton biomass (pink line, relative unit) is superimposed. Compared to Druon et al. (2019), this plot represents the latest calibration using the chlorophyll-a data reprocessed by NASA in 2018 (gradCHLmin = 0.0002 mg m^{-3} km^{-1}, gradCHLint = 0.00876 mg m^{-3} km^{-1}). (b) Example of daily mesozooplankton habitat for 18 July 2019 in the western Mediterranean Sea derived from the chlorophyll-a gradient (continuity of Figure 3.1.2c) (also including 0.089 < CHL < 10.0 mg.m^{-3}). See also Table 3.1.1.

importance in times of climate change. The products resulting of the use of the chlorophyll-a gradient and mesozooplankton habitat will provide great support to policies such as the EU Common Fisheries Policy (European Commission 2013) (e.g. spatial fishing capacities), the Marine Strategy Framework Directive

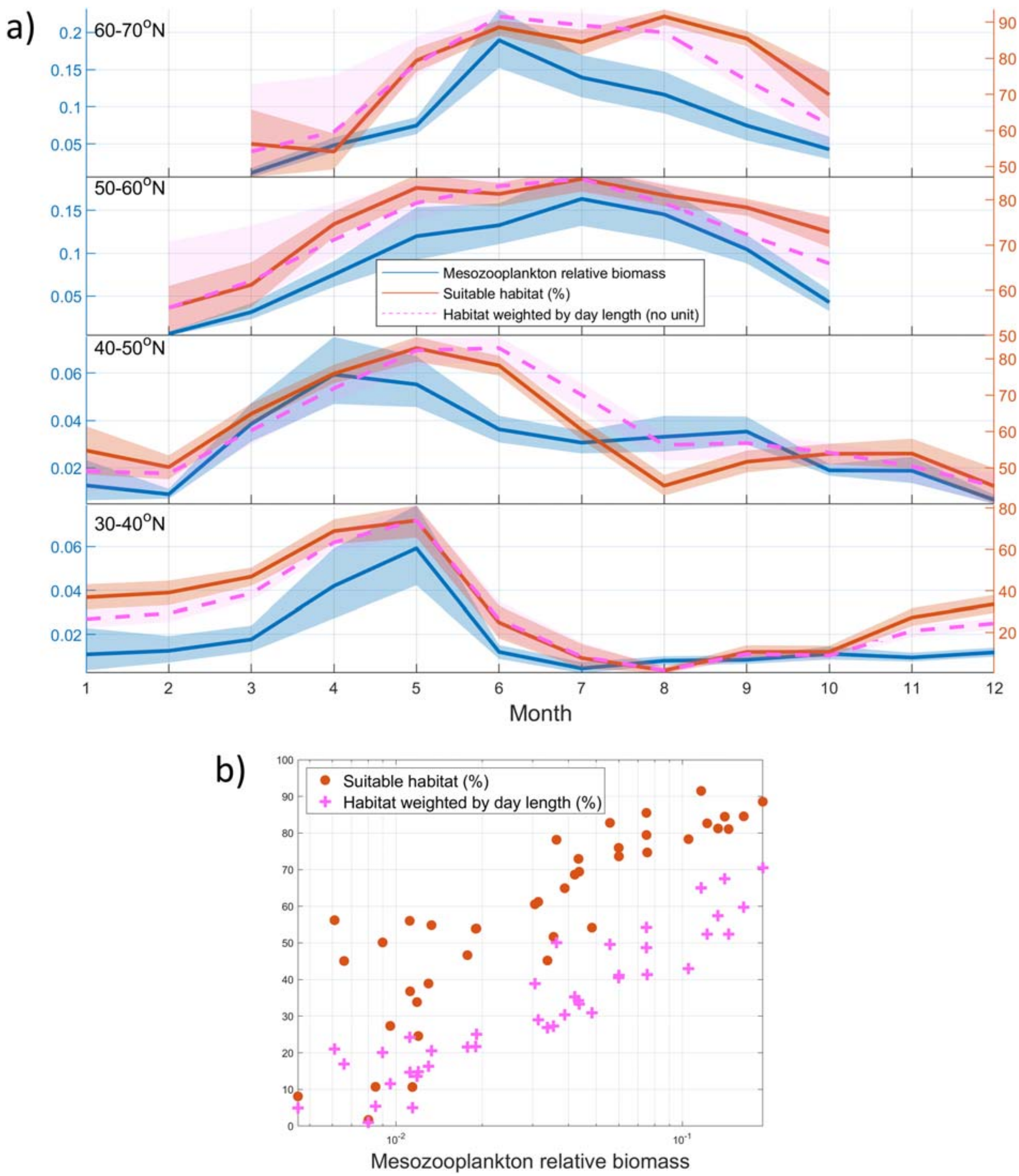

Figure 3.1.4. (a) Monthly mean mesozooplankton relative biomass (blue line), corresponding mean suitable habitat (red line) and mean habitat weighted by day length (dashed pink line) from 2003 to 2016 by 10° latitude range from 30°N to 70°N and for longitudes from 50°W to 10°W in the North Atlantic (see box in Figure 3.1.5(a) and Druon et al. 2019 for details on the data). The 5th and 95th percentile are also represented in respective light colours (the number of matching points by latitude range from south to north are 452, 1929, 1203, 672). (b) Same data presented as mesozooplankton relative biomass versus habitat (red dots) and habitat weighted by day length in relative value (pink plus signs). The Spearman's rank coefficient correlation between the 4256 pairs of mesozooplankton biomass and habitat is 0.89 ($p \approx 0$), and 0.935 ($p \approx 0$) for the habitat weighted by day length.

(European Commission 2008, 2017) (descriptor D1 pelagic habitats, D3 commercially exploited fish, D4 food webs), the EU Biodiversity strategy for 2030 and the United Nations Sustainable Development Goal 14 ('to conserve and sustainably use the oceans, seas and marine resources for sustainable development').

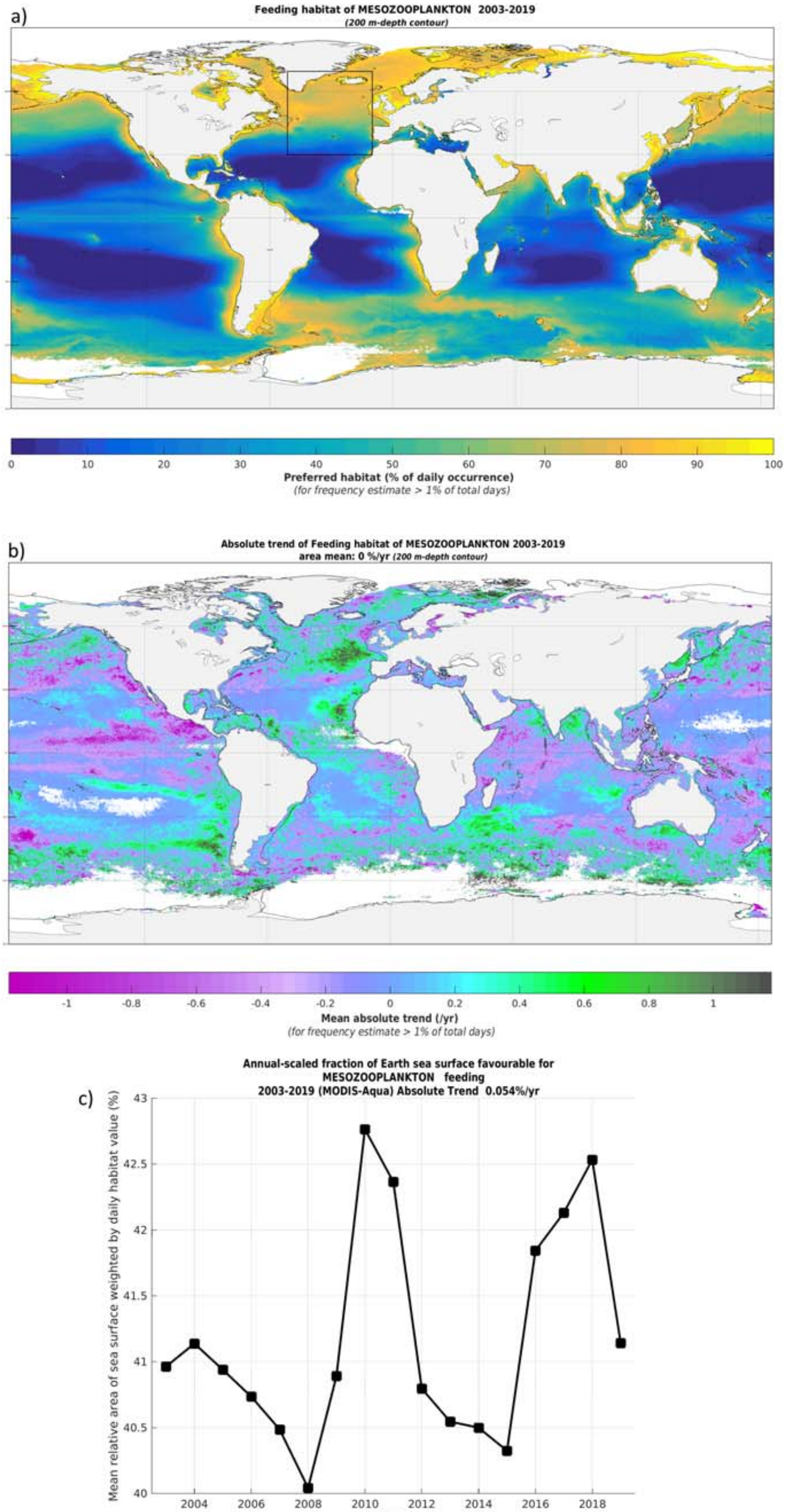

Figure 3.1.5. (a) Suitable feeding habitat for mesozooplankton in the global ocean as a mean value for 2003–2019 (the box refers to area used in Figure 3.1.4, 200 m-depth contour is shown), (b) regional trends in absolute value (computed from the local annual means) and (c) global annual variability (expressed in absolute habitat value of the global surface ocean). The mesozooplankton feeding habitat is defined by the presence of large productivity fronts and is expressed as the frequency of occurrence weighted by the front gradient value. Positive regional trends represent an increase in frequency of occurrence of productivity fronts. Blank areas correspond to cloud or sea ice cover, or to habitat suitability with chlorophyll-a detection below 5% of the total number of days in the considered period.