RESEARCH ARTICLE

Uncoupled seasonal variability of transparent exopolymer and Coomassie stainable particles in coastal Mediterranean waters: Insights into sources and driving mechanisms

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Transparent exopolymer particles (TEP) and Coomassie stainable particles (CSP) are gel-like particles, ubiquitous in the ocean, that affect important biogeochemical processes including organic carbon cycling by planktonic food webs. Despite much research on both groups of particles (especially TEP) over many years, whether they exist as distinctly stainable fractions of the same particles or as independent particles, each with different driving factors, remains unclear. To address this question, we examined the temporal dynamics of TEP and CSP over 2 complete seasonal cycles at 2 coastal sites in the Northwestern Mediterranean Sea, the Blanes Bay Microbial Observatory (BBMO) and the L’Estartit Oceanographic Station (EOS), as well as their spatial distribution along a coast-to-offshore transect. Biological, chemical, and physical variables were measured in parallel. Surface concentrations (mean ± standard deviation [SD]) of TEP were 36.7 ± 21.5 µg Xanthan Gum (XG) eq L⁻¹ at BBMO and 36.6 ± 28.3 µg XG eq L⁻¹ at EOS; for CSP, they were 11.9 ± 6.1 µg BSA eq L⁻¹ at BBMO and 13.0 ± 5.9 µg BSA eq L⁻¹ at EOS. Seasonal variability was more evident at EOS, where surface TEP and CSP concentrations peaked in summer and spring, respectively, and less predictable at the shore-most station, BBMO. Vertical distributions between surface and 80 m, monitored at EOS, showed highest TEP concentrations within the surface mixed layer during the stratification period, whereas CSP concentrations were highest before the onset of summer stratification. Phytoplankton were the main drivers of TEP and CSP distributions, although nutrient limitation and saturating irradiance also appeared to play important roles. The dynamics and distribution of TEP and CSP were uncoupled both in the coastal sites and along the transect, suggesting that they are different types of particles produced and consumed differently in response to environmental variability.

Keywords: Transparent exopolymer particles, Coomassie stainable particles, Mediterranean Sea, Time series, Phytoplankton

1. Introduction

The ocean, which currently absorbs ca. 30% of the anthropogenic CO₂, contains a vast amount of carbon in the form of dissolved organic matter (approximately 660 Gt; Hedges, 2002). Understanding the mechanisms that produce and recycle organic matter in the ocean is essential to predicting further changes in CO₂ capture. Marine gel-like organic particles, such as transparent exopolymer particles (TEP) and Coomassie stainable particles (CSP), have gained considerable attention in oceanography over the past years due to their involvement in biological, chemical, and physical processes such as carbon cycling, air–sea interactions, and microbial growth (Engel et al., 2020). TEP are relevant players in the carbon cycle as their production rate is estimated to represent 5%–10% of primary production in the ocean (Mari et al., 2017), and they favor the aggregation and sinking of suspended particles (Engel et al., 2004; Burd and Jackson, 2009), thus impacting the efficiency of the biological carbon pump. In addition, due to their low density (Azetsu-Scott and Passow, 2004), TEP...
can ascend through the upper water column, accumulate in the sea surface microlayer (SML), and influence air–sea gas exchanges (Calleja et al., 2009; Wurl et al., 2016; Jenkins et al., 2018). They can also be released to the atmosphere, contributing to organic aerosols (Aller et al., 2005) and impacting the Earth’s radiative budget (Brooks and Thornton, 2018). Regarding CSP, there is little evidence showing a significant impact on aggregation processes (Priede et al., 2002; Cisternas-Novoa et al., 2015), but CSP also accumulate in the SML (Wurl et al., 2011; Engel and Galgani, 2016; Zancker et al., 2017; Sun et al., 2018) and have been observed in sea spray aerosols (Kuznetsova et al., 2005; Aller et al., 2017).

Phytoplankton are the main source of TEP and presumably also of CSP in the ocean (Passow, 2002b; Thornton and Chen, 2017), although prokaryotic heterotrophs can also produce them (Stoderegger and Herndl, 1999; Radic et al., 2006). Diatoms and cyanobacteria have been shown to produce both CSP and TEP (Passow and Allsredge, 1994; Grossart et al., 1998; Grossart et al., 2006; Endres et al., 2013). Although CSP production by other phytoplankton groups has not yet been examined (reviewed in Thornton, 2018), dissolved organic nitrogen, including protein (stained by the dye Coomassie brilliant blue [CBB]), is known to be released by phytoplankton into the surrounding medium (Hu and Smith, 1998; Suratman et al., 2008; Sarmento et al., 2013). Similarly, TEP precursors, which generally are acidic polysaccharides, are released mostly by phytoplankton (Decho, 1990) and then assembled abiotically into TEP through ionic bonding (Allsredge et al., 1993; Thornton, 2004). Such assembly is presumably also the case for CSP (Cisternas-Novoa et al., 2015), but this process has not yet been tested directly. Zooplankton (Ling and Allsredge, 2003) and prokaryotic heterotrophs (Passow, 2002a; Grossart et al., 2006; Azam and Malfatti, 2007) can use TEP, which is probably also the case for CSP (Radic et al., 2006; Endres et al., 2013; Cisternas-Novoa et al., 2015; Engel et al., 2015). Environmental and biological variables, other than the taxonomic composition of phytoplankton and prokaryotic heterotrophs, impact the production of TEP in the ocean. Phytoplankton physiological state (Passow, 2002a), temperature (Claquin et al., 2008), light intensity (Trabelsi et al., 2008), and nutrient availability (Radic et al., 2006) may alter the production of TEP, while losses can occur through UV-induced photolysis (Ortega-Revuerta et al., 2009). Owing to the lack of similar studies with CSP, only nutrient availability is known to affect CSP production (Radic et al., 2006), while physiological stress did not enhance CSP production by diatoms and cyanobacteria in culture (Thornton and Chen, 2017).

TEP and CSP are defined by the specific dyes that stain them: TEP by Alcian Blue, which stains acidic polysaccharides (Allsredge et al., 1993; Passow and Allsredge, 1995), and CSP by CBB, which stains proteins (Long and Azam, 1996; Engel, 2009). CSP are thought to contain 5–7 times more nitrogen than TEP (Engel and Passow, 2001; Mari et al., 2001), although their content has not been measured directly. TEP have been thoroughly studied in the ocean (reviewed by Passow, 2002b, Bar-Zeev et al., 2015, and Mari et al., 2017). Conversely, CSP were rarely described until the recent development of a spectrophotometric method (reviewed by Thornton, 2018), which is less time-consuming and labor-intensive than the classical microscopic quantitation (Cisternas-Novoa et al., 2014).

Our knowledge of the temporal dynamics of CSP remains limited to a handful of studies at sites where TEP and CSP were measured in parallel. One of these studies was conducted in a low-salinity temperate coastal site in the Baltic Sea, where CSP concentration, measured in both the SML and the subsurface water (SSW), increased in summer and was generally similar to that of TEP (Dreshchinski and Engel, 2017). In studies in the Sargasso Sea (Cisternas-Novoa et al., 2015) and the Fram Strait (von Jackowski et al., 2020), TEP and CSP presented different temporal and vertical distributions. The 2 particle types were also temporally uncoupled during the course of a phytoplankton bloom in a mesocosm study (Cisternas-Novoa et al., 2015).

The northwestern (NW) Mediterranean Sea is a temperate oligotrophic sea, characterized by the enhancement of water stratification in late spring and summer due to the increase in solar radiation, which leads to low nutrient concentrations in surface waters (Sala et al., 2002; Duarte et al., 2004; Lucea et al., 2005) and minimum chlorophyll a (Chla) concentrations, and by vertical mixing in fall through winter. Chla concentration in the NW Mediterranean Sea is usually highest in late winter or early spring, triggered by the onset of thermal stratification after winter mixing, coinciding with nutrient availability and high solar radiation (Marty et al., 2002; Gasol et al., 2016). However, the specific conditions that prompt the onset of the bloom in the Mediterranean Sea and other regions are still under debate (Smetacek and Cloern, 2008; Behrenfeld, 2010; Taylor and Ferrari, 2011).

Previous studies of the temporal dynamics of TEP in the Mediterranean Sea, other than those conducted in eutrophic coastal areas or zones heavily influenced by the presence of seagrass meadows (Radic et al., 2005; Scoullos et al., 2006; Iuculano et al., 2017a), showed maximum TEP concentrations in summer, both at coastal and offshore sites (Beauvais et al., 2003; Ortega-Reutua et al., 2018), with a temporal mismatch between TEP and Chla (Ortega-Reutua et al., 2018). In contrast, there are no published studies of CSP distributions in the Mediterranean Sea.

This study was motivated by the paucity of empirical studies on the distribution and seasonality of CSP and their relationship with those of TEP (Cisternas-Novoa et al., 2015; Thornton et al., 2016; Thornton and Chen, 2017; Thornton, 2018). Our main objective was to elucidate whether or not these 2 pools of organic particles follow similar trends over the year and across horizontal and vertical scales. Based on a previous study (Cisternas-Novoa et al., 2015), we hypothesized that CSP distributions and their temporal dynamics would be closely related to those of phytoplankton biomass, while TEP distribution and dynamics would be related to the combination of phytoplankton biomass and taxonomic composition, solar radiation, and nutrient limitation. To test these hypotheses, we assessed the temporal dynamics
of TEP and CSP simultaneously over 2 complete seasonal cycles at 2 coastal sites of the NW Mediterranean Sea characterized by strong seasonality. At the shore-most site, the Blanes Bay Microbial Observatory (BBMO), we followed TEP and CSP concentrations near the surface; at the offshore site, the L’Estartit Oceanographic Station (EOS), which presents a conspicuous deep chlorophyll maximum (DCM) between 20 and 80 m, we examined the seasonal variations in the vertical distribution of TEP and CSP. Horizontal variations of TEP and CSP were also analyzed at 2 depths in a nearby coast-to-offshore transect.

2. Material and methods

2.1. Study sites and sampling

Samples were collected within the Catalan Sea of the NW Mediterranean at (1) the BBMO site at 41.40°N, 2.48°E (http://bbmo.icm.csic.es); (2) the EOS site, 70 km further north at 42.05°N, 3.25°E, and (3) stations along a transect between the Catalan Coast near BBMO and Mallorca Island, on board the RV García del Cid for a cruise designated MIFASOL II (Figure 1). The BBMO is located around 800 m offshore, in an open bay with shallow waters (sandy bottom at 20 m depth) that only weakly stratifies in summer and where most terrestrial inputs arrive as runoff from the surrounding coastal area (details in Guadayol et al., 2009a, and Gasol et al., 2012). The EOS is located 3.2 km off the main coast and 2 km off the Medes Islands, over a water column approximately 92 m deep (Figure 1) that strongly stratifies in summer and is heavily influenced by wind dynamics (Aparicio et al., 2017).

The BBMO and EOS samplings were performed at least once per month, from June solstice 2015 to October 2017, except during adverse weather conditions. At BBMO, water samples were taken with an acid-cleaned bucket from the surface, prefilted through an acid-cleaned 200-μm mesh net to remove large plankton and kept in 20-L acid-cleaned polycarbonate carboys. Carboys were maintained under dim light, covered with black plastic bags to avoid light interference. Further processing of samples was done within 1.5 h at the laboratory. At EOS, 4 depths (surface, 20, 50, and 80 m) were sampled using 5-L Niskin bottles and then filtered through an acid-cleaned 200-μm nylon mesh. Water for TEP and CSP analyses was collected in 1-L acid-cleaned polycarbonate bottles, while those for the rest of variables were kept in 8-L acid-cleaned polyethylene carboys, all of them covered with black plastic bags. Polycarbonate bottles were transported in a cooler box with pack ice. Sample processing was done at the home laboratory within 4 h.

The coast-to-offshore transect was conducted during the MIFASOL II cruise, from October 22, 2015, to October 24, 2015, reaching 145 km from shore, and including stations on the shelf (station 1, closest to the shore), continental slope (stations 2–4), and deep basin (stations 5–7). Seawater was collected at 2 depths: the surface (5 m) and, when present, the DCM, using Niskin bottles (12 L) on a 12-bottle rosette with conductivity–temperature–depth (CTD) casts. Surface variables measured during the transect were TEP, CSP, Chla, inorganic nutrients, prokaryotic heterotroph abundance, and picophytoplankton abundance (flow cytometry). At the DCM, only TEP, CSP, and Chla were measured.

2.2. Physical variables

A calibrated SAIVA/S SD204 sensor was used to measure vertical profiles of temperature and salinity at BBMO and EOS. In August 2016, at BBMO and from May to June 2016 at EOS, the sensor was inoperative. We calculated the mixed layer depth (MLD) as the depth where temperature changed more than 0.15°C with respect to a reference depth of 1 m. At BBMO, we calculated a stratification index that we defined as the temperature difference between the surface and near the sea bottom (20 m). At EOS, the stratification index was defined as the temperature difference between the surface and just below the thermocline. Water transparency (in meters) was measured.
with a Secchi disk at the BBMO and with white-faced Niskin bottles (used as analogous to a Secchi disk) at the EOS. The light extinction coefficient \( K_d \) was calculated as 1.7/water transparency (Kirk, 1994). Total irradiance at 2 m was recorded hourly by a pyranometer at the Malgrat de Mar station, situated at 41° 38' 57"N, 2° 45' 8"E, 520 m from the coast (approximately 5 km southwest of BBMO) and the Sant Pere Pescador station (approximately 25 km north of EOS; Catalan Meteorological Service, www.meteo.cat). We measured the average solar radiation of the 24 h previous to the sampling and calculated the daily-averaged solar radiation dose as:

\[
\text{Solar radiation dose} = \frac{I}{K_d \times \text{MLD}} \times (1 - e^{(-K_d \times \text{MLD})}),
\]

where \( I \) is the average surface irradiance \( (\text{W m}^{-2}) \) in the 24 h previous to sampling, \( K_d \) is the light extinction coefficient \( (\text{m}^{-1}) \), and MLD is the mixed layer depth \( (\text{m}) \).

During the MIFASOL II cruise, a SBE21 Sea Cat Thermo-salinograph was used to obtain surface temperature and salinity and a CTD SBE911 plus to record vertical profiles down to 400 m.

### 2.3. Chemical and biological variables

#### 2.3.1. Particulate organic matter (TEP, CSP, particulate organic carbon [POC], and particulate organic nitrogen [PON])

TEP were analyzed following the spectrophotometric method proposed by Passow and Alldredge (1995). Samples (150–500 ml) were filtered in duplicate under constant low pressure (approximately 150 mm Hg) onto 25-mm diameter 0.4-μm pore size polycarbonate filters (DHI Lab, Denmark). Immediately, the filters were stained with an Alcian Blue solution (500 mL, 0.02%, pH 2.5) for 5 s and rinsed with Milli-Q water. All sampling material was prewashed with HCl (10%) and rinsed with Milli-Q water, and the first milliliters of sample were discarded. All filters remained frozen until further processing. Filters were soaked in 5 mL of 80% sulphuric acid for 3 h, shaking them intermittently, and absorbance of the solution was measured with the spectrophotometer at 787 nm (Varian Cary 100 Bio). The absorption of every batch of Alcian Blue was reported as the average of analytical duplicates in units of %.

### CSP concentration was determined by spectrophotometry following Cisternas-Novoa et al. (2014). Duplicate samples (200–350 ml) were filtered onto 25-mm diameter 0.4-μm pore size polycarbonate filters (Whatman and DH) using a constant low filtration pressure (approximately 150 mmHg). The samples were stained immediately with 1 mL of CBB-G 250 solution (0.04%, pH 7.4) for 30 s, always prepared with the same filtered (0.2 μm) seawater from Medes, 80 m depth, and rinsed with Milli-Q water 3 times. The filters were stored frozen in 15-mL polypropylene tubes until further processing in the laboratory (within 4 months). Duplicate blanks (stained empty filters) were prepared with every batch of filtered samples. Both the sample and blank filters were soaked in 4 mL of extraction solution (3% sodium dodecyl sulfate in 50% isopropyl alcohol), and the tubes were incubated in a water bath for 2 h at 37°C. The filters were shaken every 30 min during this period. Optimal water bath temperature and shaking conditions were determined prior to analyzing the samples. We avoided sonication as DH filters do not withstand sonication. We used Whatman Nucleopore filters (apt for sonication) to test that the water bath and shaking were enough to remove the stain from the filters. We measured the absorbance after extraction in the water bath for 2 h and then sonicated the same filters for 2 h and measured the absorbance again. More than 90% of absorbance was recovered without sonication in our samples. The samples were then measured spectrophotometrically at 615 nm (Varian Cary 100 Bio and Shimadzu UV–Vis spectrophotometer UV120). Concentrations of CSP, reported as averages of duplicate measurements, were determined relative to a bovine serum albumin standard and expressed in units of μg BSA eq L⁻¹ after Cisternas-Novoa et al. (2014). A total of 3 calibrations of different CBB solutions were carried out during the temporal series, with calibration factors ranging from 51 to 111 μg BSA eq A⁻¹ (average of 73 ± 33 μg BSA eq A⁻¹), and detection limits ranged from 0.0440 to 0.0609 absorbance units.

In 4 of the BBMO samplings (November 2016 and April, August, and October 2017), TEP and CSP were also measured following the microscopy method (Alldredge et al., 1993; Passow and Alldredge, 1995). Duplicate samples of 50 mL were filtered onto 25-mm diameter 0.4-μm pore size polycarbonate filters (DHI), stained, and the excess dye removed. Blanks were prepared as stained empty filters. The filters were placed on the white side of a semi-transparent glass slide (CytoClear, Poretics Corp., Livermore, US) and stored frozen (–20°C) until microscopic analysis. Following Engel (2009), abundance, area, and size–frequency distribution of TEP and CSP in the size range of 1–760 μm were determined using a light microscope (Olympus BX61) connected to a camera (Olympus DP72). Filters were screened at 200× magnification. Thirty pictures were taken randomly from each filter along 2 perpendicular cross sections (15 pictures each; resolution 1,360 x 1,024 pixel, 8-bit color depth). ImageJ image...
analysis software (version 1.44, public domain, developed at the U.S. National Institutes of Health) was used to semi-
automatically analyze particle numbers and area.

For POC and PON analyses, seawater (1,000 mL) was
filtered through combusted (4 h, 450°C) GF/F glass fiber
filters (Whatman) and filters frozen at −20°C until pro-
cessed. Prior to analysis, the filters were thawed in an
HCl-saturated atmosphere for 24 h to remove inorganic
compounds. The filters were then dried and analyzed with
an elemental analyzer (Perkin-Elmer 2400 CHN). No repli-
cates were collected due to water volume limitations.

2.3.2. Chla

Chla measurements started by filtering 150 mL (BBMO) or
100 mL (EOS) of seawater on GF/F filters (Whatman,
25-mm diameter) and storing filters at −20°C until further
processing. The pigment was extracted in acetone (90% v:
v) at 4°C in the dark for 24 h. Fluorescence was measured
with a calibrated Turner Designs fluorometer, following
Yentsch and Menzel (1963). Analytical duplicates were
taken, with average coefficient of variation between du-
plicates of 3%.

2.3.3. Inorganic nutrients

Dissolved inorganic nutrients (nitrate, phosphate, and sil-
icate) were measured with standard segmented flow analy-
ysis with colorimetric detection (Hansen and Grasshoff,
1983), using a SEAL Auto Analyzer AA3 HR (BBMO) or
Bran + Luebe autoanalyser (EOS).

2.3.4. Phytoplankton identification and biomass

Phytoplankton > 5 μm were identified and counted with an
inverted microscope. Seawater was fixed with hexamine-buffered formaldehyde solution (4% final concen-
tration) and 100 mL were allowed to settle in Uter-
möhl chambers at 4°C until analysis (Utermöhl, 1958). The
samples were stored for a maximum of 6 months, and we
did not observe any signs of cell damage. Phytoplankton
was identified to the species level when possible and
finally classified into 4 groups: diatoms, dinoflagellates,
coccolithophores, and “other microalgae.” We used conver-
sion equations to calculate C content from volume mea-
surements (Menden-Deuer and Lessard, 2000). For
diatoms, we used log pg C cell⁻¹ = log −0.541 (0.099) +
0.811 (0.028) × log V; for the other algae groups, log pg C
cell⁻¹ = log −0.665 (0.132) + 0.939 (0.041) × log V, where
V is cell volume in μm³ and the values inside parentheses
are the 95% confidence intervals.

2.3.5. Picophytoplankton, nanophytoplankton, and
prokaryotic heterotroph abundance and biomass

Picophytoplankton (Prochlorococcus, Synechococcus,
and picoeukaryotes), nanophytoplankton (photosynthetic na-
noeukaryotes), and heterotrophic prokaryotes were enu-
merated by flow cytometry after fixation with 1%
paraformaldehyde plus 0.05% glutaraldehyde (final con-
centrations), following standard methods (Gasol and Mor-
án, 2015). Abundances were converted to biomass (μg L⁻¹)
using average C-to-cell conversion factors gathered in
Simó et al. (2009) of 51 ± 18 fg C cell⁻¹ for

Prochlorococcus (22 source studies), 175 ± 73 fg C cell⁻¹
for Synechococcus (28 source studies), 1,319 ± 813 fg C
for picoeukaryotes (24 source studies), and 1 fg C cell⁻¹
= 220 V (μm³) for photosynthetic nanoeukaryotes (1
source study), where cell volume V was set to 34 μm³
(assuming a spherical model with a radius of 2 μm). The
content carbon of prokaryotic heterotrophs was estimated
empirically from the bead-standardized side scatter of the
relevant populations following Calvo-Díaz and Morán
(2006). Size was converted to C content following Norland
(1993), yielding the estimated average biomass per cell in
our study of 19.0 ± 0.5 fg C (n = 30) at BBMO and 19.3
± 2.7 fg C (n = 19) at EOS.

2.4. Statistical analyses

The nonparametric Wilcoxon–Mann–Whitney test was
used to check for statistical differences in the different
environmental variables among seasons. The seasons were
separated by the winter/summer solstices and the spring/
fall equinoxes. We also used the nonparametric Wilcoxon–
Mann–Whitney test to assess statistical differences of the
variables among regions (BBMO and EOS). We performed
pairwise Spearman correlation analyses to test for covaria-
tions between environmental and biological variables in
the BBMO, EOS, and MIFASOL II data sets. Bivariate anal-
yses (ordinary least squares) between TEP and CSP concen-
trations and several biological, chemical, and physical
variables were performed in EOS profiles. We log-
transformed data to fulfill the requirements of parametric
tests. A harmonic analysis of the annual component
(period, 365 days) of the TEP and CSP time series was
performed using the HarmonicRegression package in the
R software (Lueck et al., 2015). The samplings of December
2016 were not used in the harmonic analysis because
these anomalously high TEP and CSP values were thought
not to be a response to freshwater discharges. Statistical tests,
calculations, and illustrations were performed with Micro-
soft Office Excel 2010, Ocean Data View software version 4
(Schlitzer, 2017), and R (version 3.5.1).

SD (σ) was calculated using the following formula:

$$\sigma = \sqrt{\frac{\sum (x - \bar{x})^2}{(n - 1)}}$$

where $\bar{x}$ is the mean of the sample and n is the sample
number.

Standard error (SE) was calculated as:

$$SE = \frac{\sigma}{\sqrt{n}}$$

3. Results

3.1. Variation of the main physical and chemical
variables in the time series

BBMO and EOS are 2 sites relatively unaffected by human
impacts or river discharges (Guadayol et al., 2009a; Ros
and Gili, 2015), where oceanographic variables present the
typical seasonal cycle of temperate coastal systems. SST
changed from an average + 2 SD of 13.4°C ± 0.4°C (BBMO)
and 13.2°C ± 0.5°C (EOS) in winter to 22.9°C ± 2.2°C

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were low throughout the year at both stations (Table 1, Figures S1 and S2). In summer, high heat fluxes led to higher surface temperatures and the development of a shallow stratified layer (average MLD of 6.5 ± 5.7 m in BBMO and 4.6 ± 4.7 m in EOS; Table 1). Water transparency ranged from 5 to 20 m in BBMO and 5 to 24 m in EOS, with the highest values in summer at both stations. Dissolved nitrate and silicate concentrations in the surface were lowest in summer at both BBMO and EOS (Table 1). However, surface phosphate concentrations (average of 0.04 ± 0.02 μmol L–1 in BBMO and 0.04 ± 0.06 μmol L–1 in EOS) did not exhibit marked seasonal variations but were low throughout the year at both stations (Table 1). Dissolved inorganic nutrients at EOS usually increased with depth in summer months, while they were homogeneously distributed across depth in the other seasons, with a few exceptions (Figure S3).

3.2. Variation of TEP, CSP, POC, and PON over the time series

The ranges and averages of surface TEP concentration were similar at both coastal stations. At BBMO, surface TEP concentrations ranged from 8.4 to 80.9 μg XG eq L–1 (average ± SD of 36.7 ± 21.5 μg XG eq L–1; Figure 2), while at EOS, they ranged from 5.8 to 126 μg XG eq L–1, with an average of 36.6 ± 28.3 μg XG eq L–1 (Table 1, Figure 3). Regarding seasonal patterns in surface waters, higher TEP concentrations were observed recurrently in early summer (Figures 2 and 3), which was confirmed by harmonic analyses for both BBMO (P = 0.03) and EOS (P = 0.04; Figure S4). The exception to this general pattern was the sample from December 2016, when a peak of TEP concentration at the surface coincided with a sharp decrease in salinity at both stations. At BBMO, this salinity drop was accompanied with higher nitrate and Chla concentrations; at EOS, it came along with an increase in phosphate (Figures S1 and S2).

The higher concentration of TEP at EOS was observed between the surface and 20 m in summer, coinciding with shallow mixed layers, while TEP concentration was usually homogeneously distributed during the rest of the year, despite the presence of a mixed layer in certain months (April, May, September, and October 2017).

CSP concentrations in the surface waters were similar at both stations (Table 1). In BBMO, surface CSP concentration varied between 4.7 and 24.8 μg BSA eq L–1 (average ± SD of 11.9 ± 6.1 μg BSA eq L–1; Figure 2), while at EOS, it varied between 4.5 and 22.4 μg BSA eq L–1 (average of 13.0 ± 5.9 μg BSA eq L–1; Figure 3). CSP concentrations only followed a significant seasonal pattern at EOS (harmonic analysis, P = 0.02). Differences in vertical CSP distributions also occurred among seasons at EOS (Figure S3). In summer, CSP concentrations were higher at 20 m, that is, below the mixed layer depth. In spring, concentrations were higher within the mixed layer depth, although in April and May 2017, a peak was also observed at 60 m. In fall and winter, there was no clear pattern of CSP distribution with depth (Figure S3).

POC and PON concentrations were also similar in both coastal stations (Table 1), but no clear seasonal patterns were detected (harmonic analysis, P > 0.05). At BBMO, surface POC ranged from 5.82 to 33.16 μmol L–1 (average ± SD of 12.1 ± 6.0 μmol L–1; Figure 2); at EOS, it ranged from 4.33 to 18.02 μmol L–1 (average of 9.9 ± 4.1 μmol L–1; Figure 3). Surface PON concentrations averaged 1.8 ± 1.0 μmol L–1 at BBMO and 1.5 ± 1.7 μmol L–1 at EOS. At both BBMO and EOS, TEP and POC dynamics were significantly correlated (r = 0.41, P = 0.028, n = 29 at BBMO and r = 0.50, P = 0.029, n = 19 at EOS; Table 2). CSP was significantly correlated to POC (r = 0.58, P = 0.021, n = 16) and PON (r = 0.57, P = 0.020, n = 16) only at EOS. TEP and CSP were not correlated at any of the stations (P > 0.05; Table 2).

3.3. TEP and CSP size distributions

The TEP size distributions, determined by microscopy and image analysis in surface waters of BBMO in 4 different months (November 2016 and April, August and October 2017), followed an exponential distribution, with the smallest particles (<1.25 μm), being the most abundant in 3 of the 4 samples. In April 2017, a unimodal distribution was observed, with particles ranging from 2.5 to 3.5 μm being the most abundant, followed by the smallest ones (Figure 4). The slopes of the linear regressions between average particle diameter and TEP abundance (log-transformed) were –1.53, –1.83, –1.84, and –0.93 for November, April, August, and October, respectively.

The CSP size distributions followed an exponential shape with higher abundances of the smaller particles in the 4 samples analyzed (Figure 4). The slopes of the linear regressions between average particle diameter and TEP abundance (log-transformed) were –1.34, –1.42, –1.52, and –1.34 for November, April, August, and October, respectively.

3.4. Variation of biological variables over the time series

Chla concentrations were similar at both stations (Table 1), varying between 0.13 and 1.52 μg L–1 (average ± SD of 0.49 ± 0.39 μg L–1) in the surface of BBMO (Figure 2), between 0.13 and 0.75 μg L–1 (average of 0.31 ± 0.19 μg L–1) in the surface of EOS (Figure 3), and between 0.05 and 0.84 μg L–1 (average of 0.34 ± 0.19 μg L–1) in the whole water column of EOS (Figure S3). Maximum concentrations occurred in winter at both stations (Table 1). Total phytoplankton biomass (Figure S3) was not correlated with Chla at either of the 2 stations (P > 0.05) and was maximum in late winter in both cases. Prokaryotic heterotroph abundance at the surface ranged from 5 × 105 to 17.26 × 105 cells mL–1 at BBMO (Figure 2) and from 6.69 × 104 to 6.90 × 105 cells mL–1 at EOS (Figure 3).

Phytoplankton communities were similar at both stations (Figures S1 and S2). Highest surface abundances of Prochlorococcus cells generally occurred in fall (except at EOS in 2016, where Prochlorococcus was found in spring), whereas maxima of Synechococcus occurred in spring. Picoeukaryotes and nanoeukaryotes were generally more abundant during the first 4 months of each year. The highest diatom biomasses were found in late fall.
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<th>Variablea</th>
<th>BBMOb</th>
<th>EOSb</th>
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<td>Winter (n = 6)c</td>
<td>Spring (n = 6)</td>
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<td>Temperature (°C)</td>
<td>13.4 ± 0.4A</td>
<td>16.8 ± 3.0B, C</td>
</tr>
<tr>
<td>Salinity</td>
<td>38.2 ± 0.1A</td>
<td>38.1 ± 0.1B, D</td>
</tr>
<tr>
<td>Stratification index (°C)</td>
<td>0.04 ± 0.06A, C</td>
<td>1.24 ± 1.35B, C</td>
</tr>
<tr>
<td>Water transparency (m)</td>
<td>11.0 ± 4.0A</td>
<td>16.5 ± 3.1A, C</td>
</tr>
<tr>
<td>MLD (m)</td>
<td>18.0 ± 3.2A</td>
<td>8.6 ± 6.8B</td>
</tr>
<tr>
<td>Solar radiation dose (Wm⁻²)</td>
<td>40.2 ± 25.7A</td>
<td>179 ± 103B, B</td>
</tr>
<tr>
<td>Nitrate (µmol L⁻¹)</td>
<td>0.89 ± 0.47A</td>
<td>0.34 ± 0.29B, A</td>
</tr>
<tr>
<td>Phosphate (µmol L⁻¹)</td>
<td>0.06 ± 0.04A</td>
<td>0.03 ± 0.01A</td>
</tr>
<tr>
<td>Nitrate:Phosphate</td>
<td>15.7 ± 8.5A</td>
<td>10.9 ± 6.4A, B</td>
</tr>
<tr>
<td>Silicate (µmol L⁻¹)</td>
<td>1.35 ± 0.38A</td>
<td>1.04 ± 0.50B, A</td>
</tr>
<tr>
<td>Chla (µg L⁻¹)</td>
<td>107 ± 0.36A</td>
<td>0.32 ± 0.13B</td>
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<tr>
<td>POCl (µmol L⁻¹)</td>
<td>12.4 ± 4.5A</td>
<td>11.0 ± 3.7A, B, A</td>
</tr>
<tr>
<td>PON (µmol L⁻¹)</td>
<td>1.7 ± 0.7A</td>
<td>1.6 ± 0.6A, B, A</td>
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<tr>
<td>PHA (×10⁹ cells mL⁻¹)</td>
<td>9.04 ± 3.09A</td>
<td>10.21 ± 4.04A, B</td>
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<tr>
<td>TEP (µg XG eq L⁻¹)</td>
<td>32.2 ± 9.9A</td>
<td>34.5 ± 24.0A, B</td>
</tr>
<tr>
<td>CSP (µg BSA eq L⁻¹)</td>
<td>8.8 ± 3.8A, B, A</td>
<td>15.5 ± 6.7A</td>
</tr>
<tr>
<td>TEP: Chla (µg XG eq µg⁻¹)</td>
<td>37.0 ± 26.3A</td>
<td>126 ± 76.9B, A</td>
</tr>
<tr>
<td>CSP: Chla (µg BSA eq µg⁻¹)</td>
<td>9.0 ± 3.8A, B, A</td>
<td>53.2 ± 23.5B</td>
</tr>
<tr>
<td>TEP: C (µg XG eq µg⁻¹)</td>
<td>10.9 ± 0.28A</td>
<td>1.27 ± 0.83A</td>
</tr>
<tr>
<td>CSP: C (µg BSA eq µg⁻¹)</td>
<td>0.39 ± 0.27A, B</td>
<td>0.53 ± 0.22A</td>
</tr>
<tr>
<td>TEP: POC (µg XG eq µg⁻¹)</td>
<td>0.2 ± 0.1A</td>
<td>0.2 ± 0.1A, B, A</td>
</tr>
<tr>
<td>CSP: POC (µg BSA eq µg⁻¹)</td>
<td>0.8 ± 0.4A, B</td>
<td>1.6 ± 1.0A, B</td>
</tr>
</tbody>
</table>

(continued)

Downloaded from http://online.ucpress.edu/elementa/article-pdf/9/1/00165/485853/elementa.2020.00165.pdf by guest on 16 January 2022
Table 1. (continued)

<table>
<thead>
<tr>
<th>Variable</th>
<th>BBMO(^b)</th>
<th>EOS(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter (n = 6)</td>
<td>Spring (n = 6)</td>
</tr>
<tr>
<td>C: Chla (μg μg(^{-1}))</td>
<td>37.5 ± 26.8(^a)</td>
<td>99.6 ± 21.3(^a)</td>
</tr>
<tr>
<td>POC: Chla (μg μg(^{-1}))</td>
<td>154 ± 73(^a, c)</td>
<td>452 ± 231(^b, c) (5)</td>
</tr>
</tbody>
</table>

BBMO = Blanes Bay Microbial Observatory; EOS = L’Estartit Oceanographic Station; XG = Xanthan Gum.

\(^a\)M.L.D indicates mixed layer depth; Chla, chlorophyll \(a\); POC, particulate organic carbon; PON, particulate organic nitrogen; PHA, prokaryotic heterotrophic abundance; TEP, transparent exopolymer particles; CSP, Coomassie stainable particles; C, carbon in phytoplankton biomass; and daily solar radiation dose, average previous 24 h.

\(^b\)Superscripted capital letters denote significantly different \((P < 0.05)\) groups after nonparametric analysis of variance followed by Mann Whitney tests.

\(^c\)In parentheses is the sample number \((n)\) whenever it differed from the one reported in the column heading.
Dinoflagellates had maxima in late spring, but coccolithophores did not present clear seasonal variations at either of the stations (Figures S1 and S2).

Regarding the entire sampled water column at EOS, Prochlorococcus biomass presented high values at 50 m in the summers of 2015 and 2017. Synechococcus showed...
Figure 3. Surface values of chemical and biological variables in L’Estartit Oceanographic Station. Concentrations of (a) transparent exopolymer particles and Coomassie stainable particles, (b) particulate organic carbon and chlorophyll \( a \), and (c) phytoplankton and prokaryotic heterotrophic biomasses. Each tick on the x-axis indicates the monthly sampling date starting in June 2015 (J1 indicates July). Error bars represent standard error of the mean \( (n = 2) \). DOI: https://doi.org/10.1525/elementa.2020.00165.f3
maximum concentrations at 20 m and/or 40 m in spring and summer. Diatom biomass was very high in the upper 50 m in November 2015 (Figure S3).

### 3.5. Variations of TEP and CSP in relation to Chla, biomass, and POC

The average surface TEP: Chla ratio was highest in summer at both stations, as was the ratio of TEP to phytoplankton carbon biomass (TEP: C; Table 1, Figure 5). The average surface CSP: Chla ratio was higher in spring and summer, whereas the CSP: C ratio was higher in summer at BBMO and in spring at EOS (Table 1). The minimum values of TEP: Chla and CSP: Chla occurred in winter at both sites (Table 1). The ratio of carbon biomass to Chla (C: Chla) showed a clear seasonal cycle, with the lowest values in winter and fall (generally below 50) and the highest in spring and summer (generally above 50; Figure 5, Table 1). The POC: Chla ratios were also higher in summer and lower in winter at both stations (Table 1). The TEP: POC ratios peaked in summer, while the CSP: POC ratios peaked in spring (Table 1).

The estimated contribution of TEP-C to the POC pool at BBMO and EOS (surface) ranged between 4% and 44% (average ± SD of 14% ± 9%) and between 3% and 37% (average of 16% ± 9%), respectively. TEP-C was within the ranges of phytoplankton and prokaryotic heterotrophic biomass, and TEP-C contributed the most to the nondetrital particulate carbon pool in summer at EOS (Figure 6).

### 3.6. Environmental and biological variables as potential predictors of seasonal TEP and CSP dynamics

At BBMO, the variable that best correlated to TEP variability was dinoflagellate abundance \( r = 0.50, P = 0.005, \)
n = 30), followed by diatoms and nanoeukaryotes (Table 2). However, there was no significant relationship between TEP and Chla or total phytoplankton biomass. On the other hand, *Prochlorococcus* showed a significant negative correlation with TEP (Table 2). CSP were not significantly correlated with any of the studied biological and environmental variables.

At EOS, TEP correlated positively only with the daily solar radiation dose ($r = 0.58$, $P = 0.020$, $n = 16$) and negatively with Chla ($r = -0.47$, $P = 0.047$, $n = 18$), *Prochlorococcus* ($r = -0.61$, $P = 0.008$, $n = 18$), and silicate ($r = -0.47$, $P = 0.036$, $n = 18$). CSP, among all studied variables, was only correlated, positively, with total phytoplankton biomass ($r = 0.53$, $P < 0.044$, $n = 15$).

Unlike TEP concentrations, the ratios of TEP to Chla and phytoplankton biomass correlated positively with solar radiation dose at both stations and negatively with nitrate, except for TEP: C at BBMO (Table 3). Similarly, CSP
to Chl a ratios correlated positively with solar radiation dose ($r = 0.75$, $P < 0.001$, $n = 23$ at BBMO and $r = 0.83$, $P = 0.003$, $n = 13$ at EOS) and negatively with nitrate ($r = -0.62$, $P = 0.001$, $n = 23$ at BBMO and $r = -0.78$, $P < 0.001$, $n = 13$), but CSP to phytoplankton biomass ratios correlated only with nitrate at EOS ($r = -0.59$, $P = 0.024$, $n = 13$).

The vertical distribution of TEP coincided with that of dinoflagellate abundance, whereas CSP peaks coincided with relatively high *Synechococcus* abundance (Figure S3).

### 3.7. TEP and CSP distribution along the coast-to-open sea transect

Surface TEP concentrations ranged from 21.5 to 36.5 μg XG eq L$^{-1}$ (average $\pm$ SD of 30.7 $\pm$ 5.4 μg XG eq L$^{-1}$) and increased from the coast to the open ocean (Figure 7). Surface CSP concentrations, which varied between 2.3 and 8.7 μg BSA eq L$^{-1}$ (average of 5.2 $\pm$ 2.1 μg BSA eq L$^{-1}$), decreased from the coast to the slope and beyond (Figure 7), that is, opposite to TEP. Among the variables measured at surface, TEP concentrations were not correlated with any, whereas CSP correlated significantly and positively

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**Figure 5. Ratios of TEP: C, TEP: Chla, and C: Chla over the BBMO (top) and EOS (bottom) time series.** TEP indicates transparent exopolymer particles ($n = 2$); C, carbon in phytoplankton biomass ($n = 1$); Chla, chlorophyll a ($n = 2$); BBMO, Blanes Bay Microbial Observatory; and EOS, L’Estartit Oceanographic Station. Each tick on the x-axis indicates the monthly sampling date starting in June 2015 (Jl indicates July). Error bars represent standard error of the mean. DOI: [https://doi.org/10.1525/elementa.2020.00165.f5](https://doi.org/10.1525/elementa.2020.00165.f5)
with Chl a (r = 0.93, P = 0.003, n = 7) and nanoeukaryotes (r = 0.86, P = 0.024, n = 7).

4. Discussion

We present the first simultaneous measurements of the distribution of TEP and CSP concentrations over 2 seasonal cycles in the Mediterranean Sea. The methods used to quantify these particles are based on the capability of different dyes to stain acidic polysaccharides and proteins (Passow and Alldredge, 1995; Cisternas-Novoa et al., 2014). However, the actual composition of the organic particles is unknown and depends on their sources and degradation processes (Passow, 2012). Particles probably consist of a mixture of TEP and CSP, along with other organic substances, inorganic molecules, and microbes. For instance, differential activities of extracellular enzymes or exoenzymes (e.g., protease or aminopeptidase vs. glucosidase activities) on marine aggregates (Smith et al., 1992; Piontek et al., 2009) could lead to changes in the relative proportion of TEP and CSP in recent years. In fact, these results have suggested that the actual composition of the particles is different from what has been previously reported by Van Dijken and Chen (2015). Our findings also support that TEP and CSP represent different particles, and the results have been compared with different particles.
correspond to different types of particles, as they presented uncorrelated temporal dynamics over seasonal cycles at the 2 studied coastal sites (Figures 2 and 3, Table 2) and also different vertical distributions (Figure S3). These differences also suggest that they are likely produced by different organisms and/or subject to different aggregation and degradation processes, as suggested in previous studies (Cisternas-Novoa et al., 2015; Thornton et al., 2016; Thornton and Chen, 2017). The absence of parallel temporal patterns of TEP and CSP, however, does not totally preclude that both particles are the same, at least in some cases. In fact, marine organic particles have heterogeneous chemical compositions, and both carbohydrate-rich and proteinaceous regions can coexist in the same aggregate (Busch et al., 2017). For instance, Dreschkinski and Engel (2017) observed that TEP and CSP dynamics were coupled during 2 seasonal cycles in the Baltic Sea, both in the SML and in SSW, which contrasts with our results. However, visual examination of the particles with a FlowCAM (Cisternas-Novoa et al. 2015) or through microscopic examination (Thornton et al., 2016) led to the conclusion that Alcian Blue and CBB generally stain different particle types. In our case, we can conclude that, if both types of particles coexisted in the same aggregates, their TEP and the CSP contents in those aggregates varied independently: A large proportion of the pelagic aggregates we sampled contained Alcian-Blue stainable substances but no CBB stainable substances, as well as the reverse.

4.1. Dynamics of TEP and CSP over the seasonal cycle in the NW Mediterranean Sea

The peak of TEP found in December 2016 at both stations was likely related to freshwater discharges, as it coincided with a sharp decrease of salinity and an increase of nitrate at BBMO and phosphate at EOS. The BBMO is known to receive inputs of nutrients and terrestrial carbon sporadically during storm periods (Guadayol et al., 2009b). Aside from this exceptional sampling time, the maximum TEP concentrations found in early summer at both stations (Figures 2, 3, and S4) are in accordance with previous studies in the Mediterranean Sea (Beauvais et al., 2003; Ortega-Retuerta et al., 2018). Ortega-Retuerta et al. (2018) suggested that TEP maxima in summer could be due to the increase of TEP production under nutrient limitation, the presence of specific phytoplankton groups, and/or the accumulation of TEP due to positive buoyancy during water stratification. This study expands the previous temporal study conducted at the BBMO (Ortega-Retuerta et al., 2018) by incorporating information about phytoplankton biomass and solar radiation dose, which appear to be relevant factors.

The range of our TEP concentrations across the 2 stations (5.8–127 μg XG eq L⁻¹) was similar to that found by Ortega-Retuerta et al. (2018) at the BBMO during the 3 previous years (11.3–289 μg XG eq L⁻¹) and by Iuculano et al. (2017a) in a rocky shore site of the Balearic Sea (4.6–90.6 μg XG eq L⁻¹), while it was generally lower than the range found in a coastal site accumulating Posidonia oceanica leaf litter in the Balearic Sea (26.8–1,880 μg XG eq L⁻¹; Iuculano et al., 2017a).

CSP concentrations at both stations (4.5–24.8 μg BSA eq L⁻¹) were within the range of the few previous published studies (Table 4). The highest CSP concentrations were found in spring; however, according to the harmonic analysis, the seasonal pattern was only significant at EOS (Figures 2, 3, and S4). Cisternas-Novoa et al. (2015) found steady CSP concentrations throughout the

Table 3. Spearman correlations between selected ratios (along with chlorophyll a concentration) and the daily solar radiation dose (Wm⁻²) and nitrate concentration (μmol L⁻¹). DOI: https://doi.org/10.1525/elementa.2020.00165.t3

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Independent Variable</th>
<th>BBMO¹</th>
<th>EOS¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEP: Chla</td>
<td>Daily solar radiation dose</td>
<td>0.74</td>
<td>0.96</td>
</tr>
<tr>
<td>TEP: C</td>
<td>Daily solar radiation dose</td>
<td>0.41</td>
<td>0.78</td>
</tr>
<tr>
<td>CSP: Chla</td>
<td>Daily solar radiation dose</td>
<td>0.75</td>
<td>0.83</td>
</tr>
<tr>
<td>CSP: C</td>
<td>Daily solar radiation dose</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Chla</td>
<td>Daily solar radiation dose</td>
<td>-0.72</td>
<td>-0.80</td>
</tr>
<tr>
<td>C: Chla</td>
<td>Daily solar radiation dose</td>
<td>0.66</td>
<td>0.87</td>
</tr>
<tr>
<td>TEP: Chla</td>
<td>Nitrate</td>
<td>-0.62</td>
<td>-0.80</td>
</tr>
<tr>
<td>TEP: C</td>
<td>Nitrate</td>
<td>ns</td>
<td>-0.63</td>
</tr>
<tr>
<td>CSP: Chla</td>
<td>Nitrate</td>
<td>-0.62</td>
<td>-0.78</td>
</tr>
<tr>
<td>CSP: C</td>
<td>Nitrate</td>
<td>ns</td>
<td>-0.59</td>
</tr>
</tbody>
</table>

¹TEP indicates transparent exopolymer particles; Chla, chlorophyll a; C, carbon in phytoplankton biomass; and CSP, Coomassie stainable particles. 
²r is Spearman’s correlation coefficient, where bold font indicates significance at P < 0.05; p, level of significance; n, sample size.
³Not significant.
year in the upper 100 m of the Sargasso Sea, while Dreshchinskii and Engel (2017) observed the highest CSP abundance during the winter and summer periods in the Baltic Sea, with frequent oscillations in the total area of CSP.

4.2. Main drivers of TEP and CSP dynamics

We first examined Chl$_a$, typically used as an indicator of phytoplankton biomass, as a potential driver of TEP and CSP dynamics, but Chl$_a$ did not correlate positively with TEP or CSP at either of our sampling sites, and correlated

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**Figure 7. Concentrations of transparent exopolymer particles (TEP) and Coomassie stainable particles (CSP) along a coastal–offshore transect.** Concentrations of TEP (circles), CSP (triangles), and chlorophyll a (squares) at 5 m (closed symbols) and the deep chlorophyll maximum (DCM, open symbols) as a function of distance to the shore. Note that DCM was only present at the deeper (farther offshore) stations. Error bars represent standard error of the mean ($n = 2$). DOI: https://doi.org/10.1525/elementa.2020.00165.f7
negatively with TEP at EOS. Ortega-Retuerta et al. (2018) also found a negative correlation of TEP with Chla (at BBMO). Some time-series studies have reported covariation between TEP and Chla (Beauvais et al., 2003; Scoullos et al., 2006; Engel et al., 2017; Parinos et al., 2017), while this covariation was not found by others (Bhaskar and Bhosle, 2006; Taylor et al., 2014) or was only observed during certain periods of the year (Dreshchinskii and Engel, 2017). In our study, the Chla ratio of phytoplankton changed throughout the year at both BBMO and EOS, in accordance with Gasol et al. (2016) and Gutiérrez-Rodríguez et al. (2010) for BBMO. Earlier work has shown that the ratio was usually higher in spring and summer driven by the high irradiance and low nutrients in these seasons (Geider et al., 1998). Consequently, Chla cannot be considered a good indicator of phytoplankton biomass across seasons, and instead we used biomass estimates based on cell abundances, size or species-specific biovolumes, and volume-to-carbon conversion factors.

The findings that CSP correlated positively with total phytoplankton biomass at EOS, while TEP did not show this correlation at either of our sampling sites, support our initial hypothesis that CSP temporal variations, at least at the sea surface, are more closely related to phytoplankton biomass than those of TEP. Although primary production data are not available for our study years, the highest CSP concentrations of the time series (from late winter to early summer) coincide with the period of maximum primary production recorded in a 12-year study (2003–2014) at BBMO (Gasol et al., 2016). Gasol et al. (2016) also reported that Chla-specific primary production (C production per unit of Chla), measured with the 14C method, was highest in summer and lowest in winter, likely due to higher photosynthetic efficiency of summer phytoplankton. Based on our observations, the higher Chla-specific primary production in summer could be partially explained by enhanced production of TEP and CSP, as a portion of these particles would be retained on the filters used for the 14C-PP measurements and thus taken as phytoplankton biomass produced de novo. Along these same lines, Alonso-Sáez et al. (2008) found that DOC release accounted for up to 45% of total primary production at BBMO, with a lower proportion in winter. Because DOC can self-assemble to form TEP, this release of primary production as DOC could have further contributed to higher TEP concentrations in spring and summer.

While CSP did not correlate with measured variables other than phytoplankton biomass (except for POC and PON at EOS), TEP correlated positively with the daily solar radiation dose at EOS (Table 2), and TEP: C correlated positively with the solar radiation dose at both stations, and negatively with nitrate at EOS (Table 2). These correlations could be indicative of either the stimulation of microbial TEP release by light stress, as suggested by Iculano et al. (2017), Gasot and Llabrés (2007), and Zamanillo et al. (2019a), or the enhancement of abiotic self-assembly of dissolved exopolymers into TEP (Shammi et al., 2017). The negative relationship of TEP: C with nitrate (Table 2) could be due to the stimulation of phytoplankton TEP production under nutrient limitation in summer, as suggested by Ortega-Retuerta et al. (2018). CSP: C was also negatively related with nitrate at EOS, but more research is needed to determine whether nutrient limitation stimulates CSP production.

Gasol et al. (2016) found relatively high saturating irradiances (high values for the light saturation parameter) all year round at BBMO, which is a phytoplankton feature typical of regions receiving relatively high light intensities. In winter, the observed light saturation values were close to the surface irradiance at the time of sampling, whereas in summer, they were close to the irradiance values observed at 5-m depth. This depth differential indicates that in summer, phytoplankton cells living above 5 m receive irradiances in excess of their saturating values, which may favor the production of TEP (Gasot and Llabrés, 2007).

Prokaryotic heterotrophs can influence TEP and CSP dynamics in the ocean not only through particle colonization and enzymatic degradation (Passow and Allredge, 1994; Long and Azam, 1996) but also by producing TEP

### Table 4. Compilation of published Coomassie stainable particle (CSP) concentrations (mean ± SD, range), chlorophyll a (Chla) concentrations (mean ± SE, range; μg L−1), and CSP: Chla ratios (mean ± SE ranges) and CSP: Chla ratios (mean ± SE, ranges). DOI: https://doi.org/10.1525/elementa.2020.00165.t4

<table>
<thead>
<tr>
<th>Location</th>
<th>Time Frame</th>
<th>Depth (m)</th>
<th>CSP (μg BSA eq L−1)</th>
<th>Chla (μg L−1)</th>
<th>CSP: Chla</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sargasso Sea</td>
<td>February, May, August, and November 2012; May 2013</td>
<td>0–100</td>
<td>3.2 ± 0.7 to 22.4 ± 0.4</td>
<td>0.25–0.75a</td>
<td>—b</td>
<td>Cisternas-Novoa et al. (2015)</td>
</tr>
<tr>
<td>Baltic Sea</td>
<td>June 3–19, 2015</td>
<td>1 and 10</td>
<td>15–56 a</td>
<td>1.2 to 1.7</td>
<td>—</td>
<td>Cisternas-Novoa et al. (2019)</td>
</tr>
<tr>
<td>Northwestern Mediterranean Sea (BBMO and EOS)</td>
<td>October 2015–October 2017 (time-series study)</td>
<td>Surface</td>
<td>12.4 ± 6.0, 4.5–24.8</td>
<td>0.4 ± 0.3, 0.13–1.52</td>
<td>45.6 ± 35.7, 4.8–163</td>
<td>This study</td>
</tr>
</tbody>
</table>

aExtracted from graphs.
bNo reported values.
4.3. Contribution of TEP, phytoplankton, and prokaryotic heterotrophs to POC

TEP contributed remarkably to the POC pool (overall range of 3%–44%), in similar proportions to those measured in the northeastern Atlantic Ocean (1.5%–68%; Harlay et al., 2009, 2010), but lower than many of the percentages reported across the Atlantic Ocean (28%–110% by Zamanillo et al., 2019b), the Mediterranean Sea (60% to >100% by Bar-Zeev et al., 2011; 14% to >100% by Parinos et al., 2017; 4% to >100% by Ortega-Retuerta et al., 2019) and the western Arctic Ocean (135%–179% by Yamada et al., 2015). This disparity across studies, where unrealistic TEP contributions higher than 100% abound, points to the uncertainty in the TEP-to-C conversion factor across systems and seasons. In alignment with Bar-Zeev et al. (2011), Parinos et al. (2017), and Zamanillo et al. (2019b), we used a conservative value (0.51 µg TEP-C µg XG eq⁻¹) from a range of conversion factors determined experimentally with cultured and natural marine diatoms (Engel and Passow, 2001). Other authors (Harlay et al., 2010; Yamada et al., 2015; Ortega-Retuerta et al., 2019) used higher values from the same seminal study (0.63–0.75 µg TEP-C µg XG eq⁻¹). In any case, the C content of TEP is expected to vary with their monomeric composition, which in turn depends on TEP origin (Engel and Passow, 2001); with this information lacking, comparisons of TEP carbon between oceanic studies is problematic. Another reason for the frequent oversizing of the TEP contribution to POC is merely methodological: TEP are measured on 0.4-µm pore-size filters because they are not retained quantitatively on the GF/F filters used for POC (Passow and Allerdge, 1995; Engel and Passow, 2001) and, therefore, an unknown fraction of TEP may be lost in the measured POC pool.

Despite these uncertainties and the use of a conservative conversion factor, in summer the estimated carbon in the form of TEP was higher than that of phytoplankton and prokaryotic heterotrophs, at least at EOS (Figure 6). TEP: POC also tended to be higher in summer in this site (Table 1), suggesting a higher TEP contribution to the POC pool in this season. A higher contribution might affect particle density: Particles with relatively higher TEP would be of lower density (Engel and Schartau, 1999) and, consequently, would present a lower sinking velocity or could even ascend (Azetsu-Scott and Passow, 2004; Mari et al., 2007) and accumulate at or near the surface. We hypothesize that the lower density of TEP-rich particles in summer would have also contributed to their observed accumulation in the sea surface (i.e., above 20 m at EOS), in conjunction with higher production rates under high light and nutrient limitation.

4.4. TEP and CSP size distribution

The microscopic examination provided evidence that, even though TEP were generally dominated by small particles as in previous studies (Passow and Allerdge, 1994; Mari and Burd, 1998; Harlay et al., 2009), their size distribution changed over time (Figure 4). The modal distribution of the April sample could be indicative of freshly produced TEP from a particular source, maybe a specific phytoplankton population, or to aggregation processes. The steeper TEP size distribution slope in August with respect to October could be related to solar radiation, which could either inhibit TEP aggregation into larger sizes or break up larger aggregates into small TEP, or both. By contrast, CSP size distributions were similar throughout the year, which we suggest hints at a lower aggregation potential of CSP compared to TEP.

4.5. Distribution of TEP and CSP in the coast-to-offshore transect

The different distribution patterns of TEP and CSP along the coast-to-offshore transect (Figure 7) indicate that the 2 particle types are also uncoupled on the spatial scale. Like the observations over the temporal scale, the positive correlation of CSP with Chl a illustrates that CSP variations are more directly linked to those of phytoplankton than TEP variations. Supporting that hypothesis, Arin et al. (1999) found higher concentrations of particulate protein and higher percentages of detrital protein in surface waters of the shore-most station than in the open sea along a coast-to-offshore transect in the NW Mediterranean Sea.

5. Conclusions

According to our results, TEP and CSP are most likely independent particle types as they presented uncoupled temporal dynamics at 2 coastal sites and uncoupled spatial distributions along a coast-to-offshore transect in the NW Mediterranean Sea. Taxonomy-segregated phytoplankton biomass was the main driver of both TEP and CSP concentrations: diatoms, dinoflagellates, and nanoeukaryotes each explained 40%–50% of TEP distribution at surface, with dinoflagellates covarying best with TEP over depth and Synechococcus abundances best matching CSP vertical profiles. While CSP are best explained by phytoplankton biomass, nutrient limitation and the release of phytoplankton carbon under saturating irradiance are suggested as additional drivers of the distribution and
temporal dynamics of TEP. The finding that 2 geographically close coastal sites exhibit similar temporal patterns of TEP concentration suggests that TEP variability indeed reflects a response to the environmental seasonality characteristic of this temperate oligotrophic region.

Data accessibility statement
The data are deposited at https://doi.org/10.5281/zenodo.5633941.

Supplemental files
The supplemental files for this article can be found as follows:
  Figures S1–S4. PDF

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Competing interests
The authors declare that they have no conflict of interest.

Author contributions
Analyzed samples in the context of the Blanes Bay Microbial Observatory and L’Estartit Oceanographic Station time series, with the help of EOR and CCN: MZ.

Provided accompanying physical, chemical, and biological data: CM, JMG, JP, CP.

Helped with data contextualization: AE, CCN.

Wrote this article with the help of all coauthors: MZ, EOR, RS.

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