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# 1 Discerning dominant temporal patterns of bio-optical properties in 2 the northwestern Mediterranean Sea (BOUSSOLE site)

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13  
14 **Keywords:** phenology, bio-optical properties, time-series analysis, wavelet analysis

## 15 16 **Highlights:**

- 17
- 18 • The Chl-Fluo variability has driven mostly by annual cycle.
- 19 • The  $c_p$  and  $b_{bp}$  coefficients have driven mostly by 6-months cycle.
- 20 • During winter, mid-term cycles (greater than 10 days) dominate the intra-seasonal signal for all  
21 parameters.
- 22 • During summer, diel cycle has a strong impact on the intra-seasonal variability for all parameters.

## 23 24 **Abstract**

25  
26 A wavelet analysis has been applied, for the first time, to 3-year high-frequency field observations  
27 of bio-optical properties (*i.e.* chlorophyll-fluorescence, beam attenuation and backscattering  
28 coefficients) in the northwestern Mediterranean Sea (BOUSSOLE site), in order to identify their  
29 dominant temporal patterns and evolution. A cross-wavelet and coherence analysis has also been  
30 applied to paired bio-optical coefficients time-series at the BOUSSOLE site, which allows  
31 identifying the temporal relationship between the cycles of the bio-optical properties. Annual, six-  
32 and four- month, intra-seasonal (*i.e.*, mid- and short-terms) cycles are identified from the time-  
33 series analysis. The periodicities of chlorophyll-fluorescence, beam attenuation and particulate  
34 backscattering coefficients correlate well at different temporal scales and specific seasons. At  
35 annual, six- and four- month scales, different bio-optical properties follow rather similar patterns,  
36 likely driven by physical forcing. Intra-seasonal variability consists in both mid- and short-term  
37 variations. The former dominates during the winter and are related to episodic bloom events, while  
38 the latter variations (*i.e.*, diel) prevail during summer, in a stratified water column.



## 39 1. Introduction

40 Phenology is the study of the timing of periodic life events (*Morren*, 1849a; *Winder et al.*, 2010). It  
41 was first investigated on terrestrial plants, which are sensitive to climate variability (*Cleland et al.*,  
42 2007; *Winder et al.*, 2010). Phenology of marine ecosystems has been studied for a few decades,  
43 especially by use of bio-optical proxies that are accessible through satellite ocean color remote  
44 sensing. In the ocean, phytoplankton are considered as a sentinel of changes in the ecosystems,  
45 because they respond rapidly to environmental perturbations (*Bode et al.*, 2015). In such a context,  
46 several studies on phytoplankton phenology (*i.e.* seasonal and annual cycles) have been conducted  
47 in marine ecosystems, from inland to open ocean waters, using chlorophyll-*a* data (*Behrenfeld et al.*  
48 2010, 2016; *Winder et al.* 2010; *Carey et al.* 2016; *Mignot et al.*, 2018). Other cycles (*e.g.* lowest  
49 temporal cycles) are less well-known.

50 In the ocean, changes in nutrients and light conditions have an impact on the phytoplankton  
51 standing stock and on the intracellular chlorophyll concentration (Chl), which is widely used as a  
52 proxy for phytoplankton biomass (*Volpe et al.*, 2012; *Siegel et al.*, 2013). In the Mediterranean Sea,  
53 under high nutrients and low light, phytoplankton growth rate shows the maximum concentration  
54 values. When light intensity increases, there is no longer a need for the cells to produce and sustain  
55 large amounts of the energetically expensive chlorophyll pigment. Under these conditions,  
56 phytoplankton exploit the nutrients still present in the upper layer. This, together with the light  
57 conditions provided by the increased stratification, allows phytoplankton to grow, despite  
58 phytoplankton chlorophyll concentration decreases. The condition of the strong increase in light  
59 determines the decline of phytoplankton pigment demand, while low nutrient concentrations limit  
60 phytoplankton population growth and division rates. Under low nutrients (generally the period of  
61 highest stratification of water column) and high light conditions, phytoplankton shows the minima  
62 of abundance. When light starts to decrease and mixing occurs again, phytoplankton assign the  
63 energy from the newly available nutrients into the production of chlorophyll, however, limiting  
64 their growth rate (*Lavigne et al.*, 2013; *Bellacicco et al.* 2016; *Barbieux et al.*, 2018).

65 In temperate seas like the Mediterranean Sea, a major feature of the annual cycle is the spring  
66 bloom, as it occurs, for instance, in the Gulf of Lion (*D'Ortenzio et al.*, 2014; *Mayot et al.*, 2017).  
67 This bloom typically persists for a few weeks to months. The variability of phytoplankton annual  
68 and seasonal patterns has thus been well studied (*Behrenfeld et al.* 2010; *Volpe et al.*, 2012;  
69 *Lavigne et al.*, 2013, *Mignot et al.*, 2014), while no systematic analyses at shorter time scales have  
70 been conducted to identify the characteristic periods of biomass variability and recurrence along  
71 years at these scales. *Winder et al.* (2010) defined the mid- and low-term phytoplankton fluctuations  
72 as irregular blooms that are often responses to short-term weather events which affect sea  
73 temperature and vertical mixing dynamics. However, several works have shown that Chl can be  
74 complemented with other parameters to describe the ocean ecosystem complexity and  
75 phytoplankton dynamics (*Behrenfeld et al.* 2005, 2006; *Ji et al.*, 2010). These works demonstrated  
76 that the physiological processes affect the carbon to chlorophyll ratio (*Halsey and Jones*, 2015),  
77 especially during intermediate periods of light and nutrients variations, as it occurs in the  
78 Mediterranean Sea (*Bellacicco et al.*, 2016). Furthermore, biological processes such as  
79 phytoplankton photosynthesis and cellular growth and division can be associated with short-term  
80 temporal variations like the daily light-dark cycle (*Neveux et al.*, 2003; *Poulin et al.*, 2018). Diel  
81 variability is often not taken into account in the current ocean colour algorithms, but many  
82 laboratory experiments and studies have demonstrated that, in seawater, there is a diurnal variation

83 of optical properties, from midday to night, that have implications on biomass measurements  
84 (Poulin *et al.*, 2018). Thus, the use of other proxies, such as optical coefficients, may be helpful to  
85 investigate the different temporal scales of phytoplankton avoiding to take into account the effect of  
86 physiological processes on Chl content. In such a context, bio-optical relationships have been  
87 widely established between inherent optical properties (IOPs) and the main biogeochemical  
88 parameters, such as the Chl concentration or fluorescence (Huot *et al.*, 2007, 2008; Dall'Olmo *et*  
89 *al.*, 2009, 2012; Brewin *et al.*, 2012; Antoine *et al.* 2011; Martinez-Vicente *et al.*, 2013; Barbieux *et*  
90 *al.*, 2018; Bellacicco *et al.*, 2018).

91 One of the most studied IOPs is the particulate beam attenuation coefficient,  $c_p$ , used as a proxy for  
92 particle concentration and sensitive to a size range that includes phytoplankton cells (Claustre *et al.*,  
93 1999; Behrenfeld and Boss, 2003).  $c_p$  is the sum of particulate scattering and absorption  
94 coefficients. Its diel variation is primarily due to planktonic adaptation to the daily light cycle, the  
95 dynamics of the upper mixed layer and the variations of particles mass (Siegel *et al.*, 1989; Walsh *et*  
96 *al.*, 1995; Stramski and Reynolds, 1993; Durand and Olson, 1998). The interpretation of diel  
97 variability of  $c_p$  is difficult because it depends on several factors, such as: i) phytoplankton  
98 concentration and composition, ii) physiological status (*i.e.* photoacclimation), and iii)  
99 concentrations of detritus and small heterotrophs (*e.g.* heterotrophic bacteria). The compound effect  
100 of variations of these factors on  $c_p$  remains poorly known (Kheireddine *et al.*, 2014). Recently,  
101 Gernez *et al.* (2011) and Kheireddine *et al.* (2014) have shown that the amplitude and phasing of  $c_p$   
102 diel cycles vary seasonally, which may result from seasonal changes in nutrient concentrations,  
103 phytoplankton abundance, size distribution, and composition. Unfortunately,  $c_p$  is not directly  
104 derivable from satellite observations, thus limiting its applications. The IOP that is directly  
105 proportional to the ocean reflectance and can be retrieved from space is the particulate  
106 backscattering coefficient,  $b_{bp}$  (Lee *et al.*, 2002). Similarly to  $c_p$ ,  $b_{bp}$  is related to particle  
107 concentration to the first order, whereas it also contains information on the particle size distribution,  
108 refractive index, shape and structure of particles (Twardowski *et al.*, 2001, Neukermans *et al.*, 2012,  
109 Slade and Boss, 2015).  $b_{bp}$  is more influenced than  $c_p$  by submicron non-algal particles (Morel and  
110 Ahn, 1991; Stramski and Kiefer, 1991, Stramski *et al.*, 2004), yet their magnitude both covary with  
111 phytoplankton concentration, allowing relationships between  $b_{bp}$  and Chl to be observed (Bellacicco  
112 *et al.*, 2016, 2018; Barbieux *et al.*, 2018). Organelli *et al.*, (2018) suggest that most of  $b_{bp}$  signal is  
113 due to particles with equivalent diameters between 1 and 10  $\mu\text{m}$ , and thus may be significantly  
114 influenced by phytoplankton. Several studies have shown good relationships between both the  
115 optical coefficients and phytoplankton in terms of Chl, carbon or fluorescence, on both global and  
116 regional scales (Behrenfeld and Boss, 2003; Behrenfeld *et al.*, 2005; Dall'Olmo *et al.*, 2009, 2012;  
117 Antoine *et al.*, 2011; Brewin *et al.*, 2012; Martinez-Vicente *et al.*, 2013; Barbieux *et al.*, 2018;  
118 Bellacicco *et al.*, 2018). The complexity of temporal relationships between  $c_p$ ,  $b_{bp}$ , and  
119 phytoplankton biomass proxies should be, thus, studied and observed at a range from diel to annual  
120 cycles.

121 The objectives of this study are to determine the intra-annual dominant temporal patterns (from the  
122 lowest up to annual cycles) of the above-mentioned bio-optical parameters, the changes of these  
123 cycles over time, the characteristics and recurrence strength at those periods and to define the  
124 temporal relationship between the cycles of the bio-optical properties. To this aim a Wavelet  
125 Analysis (WA) was applied, for the first time, to a 3-year time-series (2011–2013) of surface Chl-  
126 fluorescence,  $b_{bp}$  and  $c_p$  at the BOUSSOLE site in the northwestern (NW) Mediterranean Sea

127 (*Antoine et al.*, 2006; Figure 1), enabling the detection of all the intra-annual dominant temporal  
128 patterns.

129

## 130 2. Area of study, data and methods

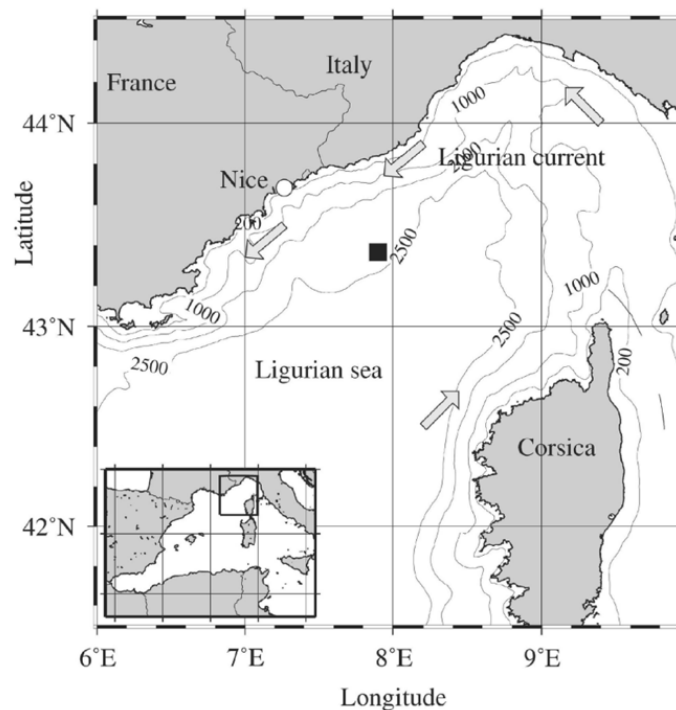
131

### 132 2.1 BOUSSOLE site

133 The BOUSSOLE (*BOU*ee pour l'*acqui*Sition d'*une Série Optique a Long termE*) project started in  
134 1999, and its activities are developed on a site located in the northwestern Mediterranean Sea, at  
135 about 32 nautical miles from the French coast (Figure 1). Essential information about the site  
136 characteristics, the measurement platform, and the instrumentation are also provided in *Antoine et*  
137 *al.* (2006, 2008a,b). The site is protected from coastal inputs by the Ligurian Current, which flows  
138 along the coast toward the southwest (*Millot*, 1999). The physical conditions of the area show  
139 strong seasonality (*D'Ortenzio et al.*, 2014), with deep (~400 m) mixed layers in winter, and a  
140 marked stratification in summer (~20 m; *Antoine et al.*, 2011; *Mayot et al.*, 2017). Hydrodynamics  
141 drive seasonal changes in phytoplankton abundance, which shows a typical mid-latitude temporal  
142 pattern. Oligotrophic conditions prevail in summer where Chl is about 0.1 mg m<sup>-3</sup> (minima ~0.05  
143 mg m<sup>-3</sup>), and concentrations increase up to 3–5 mg m<sup>-3</sup> during the spring bloom, and stay between  
144 0.1–0.3 mg m<sup>-3</sup> the rest of the year (*Gernez et al.*, 2011, *Kheireddine et al.*, 2014). There is,  
145 accordingly, a large range of optical properties (*Antoine et al.*, 2006; *Gernez et al.*, 2011), as  
146 observed over the entire northwestern Mediterranean Sea (*Bosc et al.*, 2004).

147 A moored buoy has been permanently deployed at the BOUSSOLE site since September 2003 and  
148 operates in a quasi-continuous mode, with data acquisition for one minute every 15 min both night  
149 and day. Adequate measures have to be taken to minimize or eliminate bio-fouling, which is  
150 unavoidable with moored instrument. All instruments installed on the BOUSSOLE buoy are  
151 cleaned by divers about every 2 weeks.

152



153

154 Figure 1: The area of the north-western Mediterranean Sea showing the main current branches (grey arrows),  
155 and the location of the BOUSSOLE site in the Ligurian Sea (black square) (*Antoine et al.*, 2011).

## 156 2.2 Optical measurements

157 The volume scattering function at  $140^\circ$ ,  $\beta(140)$ , is measured using in alternation two HOBI Labs  
158 Hydroscat-4 backscattering meters installed at the lower measurements depth of the buoy (*ca.* 9 m).  
159 Instruments are calibrated before deployments (which last about 6 to 12 months) and are equipped  
160 with filters at 442, 488, 550, and 620 nm, here only the green band is used. The instruments operate  
161 at 1 Hz, so that about 60 measurements are recorded during 1 minute, from which the median is  
162 taken as representative for  $\beta(140)$ . Dark current measurements are performed on site with a  
163 neoprene cap covering the instrument windows, average dark readings are subtracted to the time-  
164 series for each deployment. The  $\beta(140)$  values are also corrected for attenuation along the  
165 measurement path (the  $\sigma(\lambda)$  correction of *Maffione and Dana*, 1997) using  $c_p$  (see below) and the  
166 total absorption coefficient derived from inversion of the diffuse attenuation coefficient for  
167 downward irradiance ( $K_d$ ) and the irradiance reflectance (R).  $K_d$  and R are retrieved from parallel  
168 measurements performed with a set of Satlantic OCR-200 series radiometers.  $b_{bp}$  is derived from  
169 the corrected  $\beta(140)$  as follows (*Maffione and Dana* 1997; *Boss and Pegau*, 2001):

$$170 \quad b_{bp}(550) = 2\pi\chi_p(\beta(140,550) - \beta_w(140,550)) \quad (m^{-1}) \quad [1]$$

171 where  $\chi_p=1.13$  (*D. R. Dana and R. A. Maffione*, unpublished manuscript, 2014) and  $\beta_w(140)$ , the  
172 pure seawater scattering at  $140^\circ$ , is computed following *Zhang et al.*, (2009); *Zhang and Hu* (2009)  
173 using the temperature and salinity measured at the same depth with a Sea-Bird Scientific SBE-37SI  
174 CTD sensor.

175 The particulate transmittance ( $Tr_p$ , %) at 650 nm is measured at 4 and 9 m with 25 cm path length  
176 WETLabs C-Star transmissometers (acceptance angle is  $1.2^\circ$ ). Instruments are factory calibrated  
177 with deionized, ultra-filtered, UV-screened water. The corresponding particulate beam attenuation  
178 coefficient,  $c_p$ , is then calculated as:

$$180 \quad c_p(650) = -\frac{1}{0.25} \ln \left( \frac{Tr_p(650)}{100} \right) \quad (m^{-1}) \quad [2]$$

181 This assumes that absorption by colored dissolved organic matter (CDOM) is negligible at 650 nm  
182 (*Bricaud et al.*, 1981).

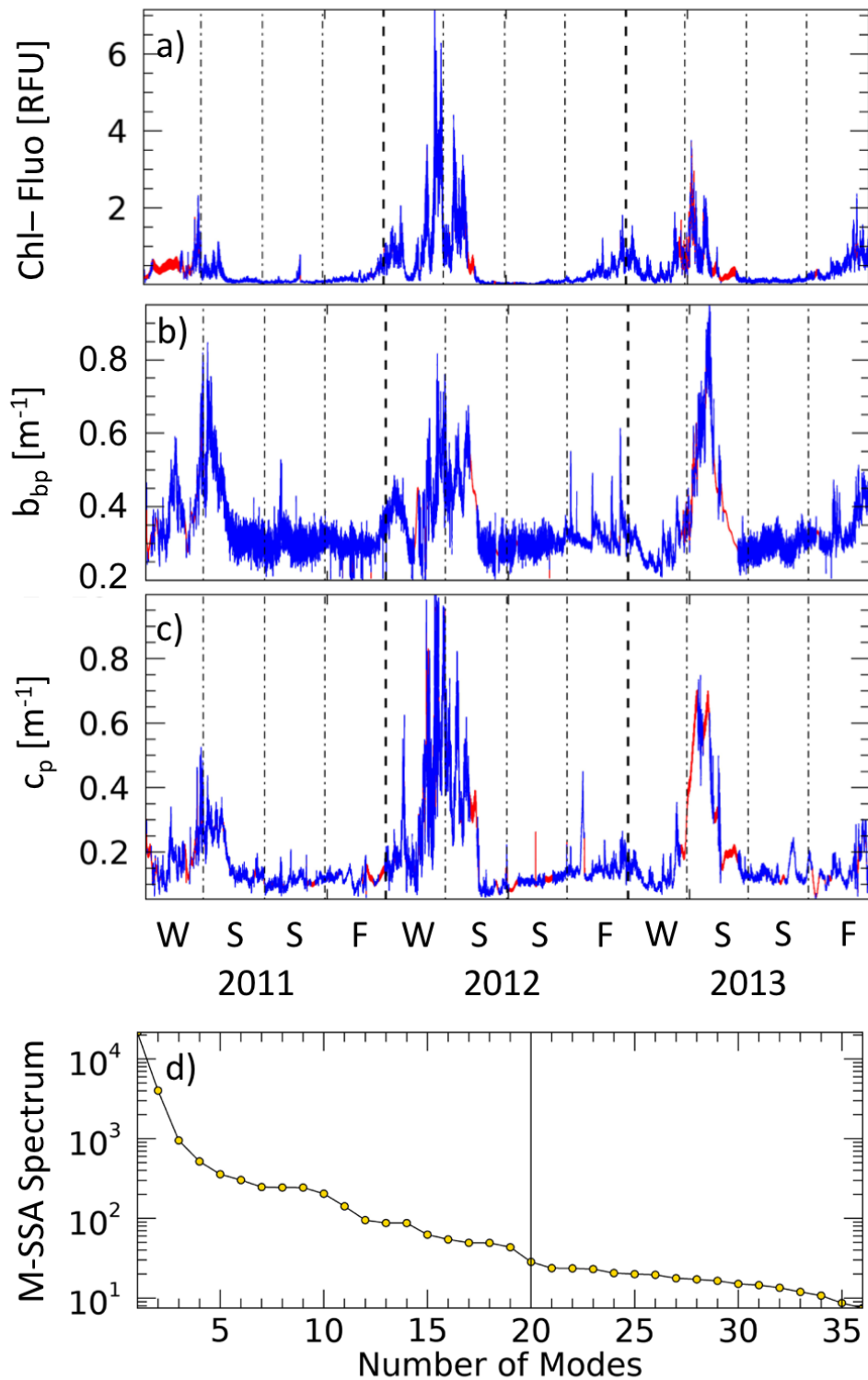
184 Chlorophyll-a fluorescence (Chl-Fluo) is measured in RFU with an ECOFLNTUs WET Labs (now  
185 Sea-Bird Scientific) fluorimeter (470 nm EX/695 nm EM; see  
186 <https://www.seabird.com/combination-sensors/eco-flntu/family?productCategoryId=54758054352>)  
187 at 4 m and 9 m depth.

188 In this study, we selected  $b_{bp}$ ,  $c_p$  and Chl Fluo at the depth of 9 m in order to compare them together.  
189 Here,  $b_{bp}$  is referred to  $b_{bp}$  at 550 nm ( $m^{-1}$ ),  $c_p$  to  $c_p$  at 650 nm ( $m^{-1}$ ).

## 190 2.3 Multi-Channel Spectral Analysis (M-SSA)

191 For each parameter, the period from 2011 to 2013 was used for a total of 105216 measurements  
192 after quality control (Figure 2). It consists in removing outliers using three standard deviations ( $\pm\sigma$ )  
193 confidence limit.

194 An important prerequisite for applying WA is that the time-series has to be continuous at the  
195 minimum considered frequency. Missing data, including those not passing quality control,  
196 represented 19.57%, 13.40% and 22.38% of Chl-Fluo,  $b_{bp}$  and  $c_p$  time-series, respectively. Gaps  
197 were filled using a Multi-Channel Singular Spectral Analysis (M-SSA) technique which is a non-  
198 parametric spectral estimation method relying on data only (Ghil *et al.*, 2002; Kondrashov *et al.*  
199 2006, 2010). This technique is not based on *a priori* parametrized family of probability distribution.  
200 The method uses temporal correlation to fill in the missing data and represents a generalization of  
201 the Beckers *et al.*, (2003) spatial empirical orthogonal functions-(EOFs) based reconstruction.  
202 Kondrashov and Ghil (2006) demonstrated that an increased number of gaps yields the same effect  
203 as an increase of the noise in the measurements. Two different inputs are required to apply M-SSA  
204 for field reconstruction: window-length ( $W$ ) and components ( $M$ ). Both depend on the  
205 characteristics of the time-series, and need to be accurately defined to avoid any bias in the  
206 reconstructed fields. The  $W$  represents the length of the sliding window (expressed in number of  
207 observation) used in the M-SSA in order to identify the leading components of the time-series (Ghil  
208 *et al.*, 2002; Kondrashov *et al.* 2006, 2010). Diversely,  $M$  is the number of eigen-functions used for  
209 signal reconstruction. Here, we applied the M-SSA to the three time-series using specific  $W$   
210 ( $W=5000$ ) and  $M$  components (*i.e.*,  $M = 1$  up to 20) following the recommendations listed in Ghil *et*  
211 *al.*, (2002) and Kondrashov *et al.* (2005, 2006, 2010). These settings are compatible with the  
212 properties of the time-series hereby analyzed, taking into account long, mid- and short-term  
213 variations. Figure 2 (a, b, c) shows the time series of each parameter with missing data  
214 reconstructed after application of M-SSA technique. Figure 2d is the M-SSA spectrum of filled  
215 time-series with  $W=5000$ . The optimum number  $M=20$  corresponds to the number of modes that  
216 explain more than 95% of the variance the M-SSA spectrum.



217

218 Figure 2: Time-series of Chl-Fluo (a),  $b_{bp}$  (b),  $c_p$  (c) for 2011 – 2013 at the BOUSSOLE site. Original data  
 219 are displayed with blue lines, while the gaps-filled by the M-SSA technique are highlighted with red lines.  
 220 The letters W stands for winter, S for spring, S for summer and F for fall. Panel d is the M-SSA spectrum of  
 221 filled time-series with the break of the slope spectrum at 20.

222

223

## 224 2.4 Wavelet analysis

225 Since it was first introduced by *Morlet* (1982; Part I and II), WA has been widely applied to  
226 different fields of science. The main characteristic of the WA lays on the decomposition time-  
227 series, and its time-scale localization and amplitude. Usually, a signal of the series can be  
228 decomposed into different harmonic components using, for example, the Fourier method. This can  
229 be defined as a partition of the variance of the series into its different oscillating components with  
230 different frequencies (*i.e.* the periods). The spectral frequency analysis based on the widely-used  
231 Fourier method makes the assumption that the statistical properties of the time-series do not vary  
232 with time, being stationary and constant. In such a context, the oceanographic processes do not  
233 respect the stationary assumption, and there are evidences of the non-stationary nature of bio-  
234 optical properties (*e.g.*  $b_{bp}$  or  $c_p$ ) along a single year (*Antoine et al.*, 2011; *Gernez et al.*, 2011;  
235 *Dall’Olmo et al.*, 2012; *Barnes et al.*, 2014; *Kheireddine et al.*, 2014). But, the WA overcomes this  
236 problem of non-stationary conditions by performing a local time-scale decomposition of the signal.  
237 Thus, WA provides time-dependent spectra (*Lau and Weng* 1995; *Torrence and Campo*, 1998,  
238 *Percival and Walden*, 2000; *Ampe et al.*, 2014). This approach helps to track how the different  
239 scales are related to the periodic components of the signal. WA is applicable to stationary or non-  
240 stationary time-series and quantifies correlation between two signals (*Daubechies*, 1992; *Lau and*  
241 *Weng* 1995; *Cazalles et al.*, 2008; *Garcia-Reyes et al.*, 2013). Figure 3 gives an example of  
242 application of WA to a stationary synthetic signal and provides elements to interpret the results  
243 obtained by this analysis as well as definition of the main WA indexes.

244 Additionally, in order to understand which are the main dominant cycles that explain the variability  
245 on a three-year’s time-series, the coefficient AWP\* is computed as follows:

246

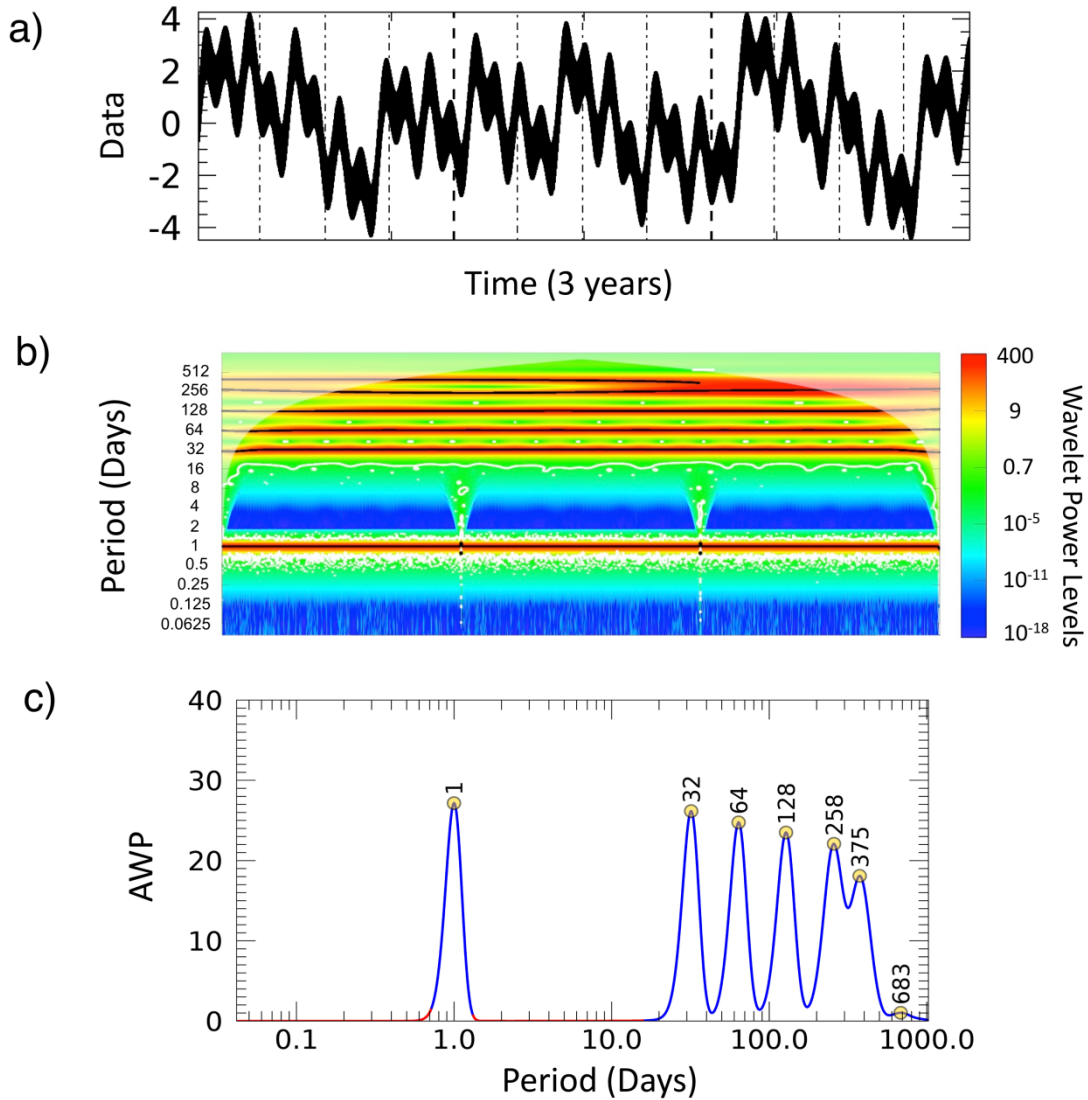
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$$AWP_k^* = \frac{AWP_{period}}{AWP_{maximum}}$$

248

249  $AWP_k^*$  is, thus, the ratio between the average wavelet power ( $AWP_{period}$ ; Table 1) of each local  
250 maximum with respect to the absolute AWP maximum for each parameter  $k$  ( $AWP_{maximum}$ ; Table  
251 1). The ratios allow the rank of cycles for each parameter evaluating which cycles are the most  
252 important (values approximately 1) and which are not (values close to 0).

253 A cross-wavelet analysis (CWA) has also been applied to paired bio-optical coefficients time-series  
254 at BOUSSOLE site, which allows identification of the temporal relationship between the cycles of  
255 the bio-optical properties. The CWA is fundamentally a comparison between the spectra of two  
256 time-series,  $x(t)$  and  $y(t)$  (*Chatfield*, 1989), sampled with the same time step. It results in a quantity,  
257 the cross-wavelet coherence, which can assume values between 0 and 1, indicating the cross-  
258 correlation between the spectra of two time-series, as a function of the period. The most important  
259 information obtained by CWA is the identification of the portions of  $x(t)$  that covaries with  $y(t)$  at  
260 specific periods. An output from CWA, coupled to the wavelet coherence spectra (WCS), is its  
261 time-average (the average coherence; AC). The AC is equal to 1 when there is a perfect linear  
262 relationship at particular periods between the two time-series spectra. In this work, the CWA has  
263 been used to investigate the strength of the relationship between bio-optical properties at different  
264 temporal scales (*e.g.* Figs. 6, 9, 10, 11) and to understand the relative phases between the time-  
265 series. For more information about the theoretical background and applications of WA and CWA  
266 see *Torrence and Combo*, (1998) and *Cazalles et al.*, (2008).



267  
 268 Figure 3: Theoretical example of a three-year time-series of data at 15 minutes' interval, built by overlapping  
 269 6 continuous sinusoids at 1, 32, 64, 128, 256 and a two-year 365 days' cycles (a). The wavelet power  
 270 spectrum (WPS) resulting from the WA is shown in (b) as a function of time. The y axis is the period and  
 271 colors indicate the power levels of the time-series (high levels in red and low levels in blue). The time-series  
 272 has a strong (cyclical) signal for the periods and duration of time in correspondence of the black lines in the  
 273 WPS. The shaded area has not to be considered as it might provide false periodic events (*Torrence and*  
 274 *Compo, 1998*). The thin white contours surrounding regions of stronger variance in the spectra indicate  
 275 coherent time-frequency regions that are significant (*i.e.* > 95% significance). Panel c shows the average of  
 276 WPS which is the average of the power levels for each period over the whole time-series. Local maxima in  
 277 the AWP (yellow dots) indicate periods contributing significantly to the variance of the time-series,  
 278 providing an efficient method to detect and identify periodicities, if present. In red are highlighted periods,  
 279 and correspondent AWP, with low statistical significance (less than 95%; *Roesch and Schmidbauer, 2014*).

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 287



<i>Acronym</i>	<i>Definition</i>
Chl	Chlorophyll Concentration ( $\text{mg m}^{-3}$ )
$b_{\text{bp}}(\lambda)$	Particulate backscattering coefficient ( $\text{m}^{-1}$ )
$c_{\text{p}}(\lambda)$	Beam attenuation coefficient ( $\text{m}^{-1}$ )
Chl-Fluo	Chlorophyll-Fluorescence (RFU)
M-SSA	Multi-Channel Singular Spectral Analysis
W	Window Length ( $N^{\circ}$ of observations)
M	Components
WA	Wavelet Analysis
CWA	Cross-Wavelet Analysis
WPS	Wavelet Power Spectra
AWP	Average Wavelet Power
AWP*	Average Wavelet Power Ratio
WCS	Wavelet Coherence Spectra
AC	Average Coherence

Table 1: Symbol and acronym definitions.

288

289

### 290 3. Results

291 This section starts from the description of each time-series, throughout the detection of the intra-  
 292 annual dominant temporal patterns, and ends with the description of the changes of the main cycles  
 293 over time and the definition of the temporal relationships between the different cycles of the bio-  
 294 optical properties here studied.

#### 295 3.1 Description of the time-series

296 The time-series of each parameter whose gaps are filled by using the M-SSA technique are shown  
 297 in Figure 2. The  $b_{\text{bp}}$  and  $c_{\text{p}}$  range of variation is respectively between  $10^{-4} \text{ m}^{-1}$  and  $10^{-3} \text{ m}^{-1}$  and  
 298 between  $0.1 \text{ m}^{-1}$  and  $1.0 \text{ m}^{-1}$  with minima occurring in the summer/fall (*i.e.* oligotrophic season) and  
 299 maxima occurring in the winter/spring (*i.e.* mesotrophic season), respectively (Figure 2). The Chl-  
 300 Fluo annual signal ranges between 0.012 RFU, in summer/fall, up to 7.5 RFU in winter/spring.

#### 301 3.2 Dominant temporal patterns

302 Figure 4 and Table 2 display the AWP after the wavelet analysis on the three time-series, and the  
 303 correspondent AWP\*. For the Chl-Fluo nine relative maxima (yellow circles in Figure 4a) emerge  
 304 at periods of approximately 351, 200, 124, 46, 31, 21, 10, 3 and 1 days, indicating nine major  
 305 patterns of the Chl-Fluo variability. The AWP spectrum for  $b_{\text{bp}}$  shows seven relative maxima at  
 306 370, 193, 126, 58, 16, 11, 2 days. Finally, for the  $c_{\text{p}}$  relative maxima at 372, 192, 130, 57, 27, 15,  
 307 11, 4, 2, 1 days are detected. In both cases of  $b_{\text{bp}}$  and  $c_{\text{p}}$ , two additional maxima are found at 979  
 308 and 911 days, respectively. These relative maxima have low AWP ( $<1$ ) and are related to periods  
 309 exceeding the upper limit that can be significantly retrieved in this study (*i.e.* 1 year).

310 For brevity, periods close to 365 days are interchanged with the term “annual”, close to 180-days  
 311 with “6-months”, close to 128-days with “4-months”.

#### 312 3.3 Wavelet Power Spectra

313 The WPS of Chl-Fluo (Figure 5a) reveals a persistent annual periodicity, thereby explaining the  
 314 greatest amount of variability. Accordingly, the AWP value shows its maximum (30.8) at this

315 period (Table 2) with two secondary maxima at 4-months and at 6-months, both accounting for half  
316 of the variability with respect to the annual periodicity (14.6 and 15.6 respectively; Table 2).

317 In the case of  $b_{bp}$ , the annual cycle has an AWP value of 24.3. The most dominant patterns are  
318 associated to the 6-month cycle with an AWP of 29.7, and 4-month cycle with AWP of 24.3 (Figure  
319 4). A significant cycle is also present with a period of 58 days (AWP value of 11.0). The WPS  
320 (Figure 5b) highlights a range between 11 and 16 days, particularly evident at the winter-to-spring  
321 transitions, with a clear inter-annual variability and the AWP value for this cycle is less than 5  
322 (Figure 4). For cycles between 0.5 and 2 days, the AWP is generally lower, yet not zero, indicating  
323 that some periodicity for  $b_{bp}$  at these scales exists though with limited impact on the overall  
324 variability (Table 2). Cycles less than 2 days also have less statistical significance along the three  
325 years of data.

326 The  $c_p$  cycles at 4-months, 6-months, and 1-year periods are observed in the WPS (Figure 5c),  
327 resulting in AWP values of 20.3, 33.0 and 31.8, respectively (Figure 4 and Table 2). Other relative  
328 maxima have average values less than 6. The WPS (Figure 5c) also highlights 1, 2, 4, 11-15, 27 and  
329 57 day cycles, evident at the transition from winter to spring of 2012. For the period at 1 day, the  
330 AWP is low, though greater than zero, and still statistically significant, indicating that some  $c_p$   
331 variability at this scale exists (Table 2).

332 The signal of the annual cycle covers all seasons for all parameters (Figure 5), which have maxima  
333 at a particular moment of the year: always in winter and spring (Figure 2 and Figure 5). The 6-  
334 month period is the dominant pattern in the case of  $b_{bp}$  and  $c_p$ , and is the second dominant pattern in  
335 the Chl-Fluo time-series. The 4-month cycle shows a considerable magnitude for  $b_{bp}$  and  $c_p$ , but is  
336 limited for Chl-Fluo (Table 2). Moving to the lowest temporal cycles, Figure 5 shows how diel  
337 cycles are detectable for most of the three time-series, confirming the importance of this temporal  
338 scale, especially for Chl-Fluo and  $c_p$  time-series.

339 Summarizing, Chl-Fluo shows a strong annual cycle signal along the entire time-series, but  
340 particularly from spring 2011 to winter 2013 considering only the lightened areas (Figure 5a). The  
341 year 2012 (more specifically from winter 2011 to spring 2013) shows a strong cyclic nature at  
342 periods greater than 1 week.

343 WPS of  $b_{bp}$  shows high power levels from 128 to 365 day periods (Figure 5b). However, for periods  
344 lower than 64-days, the strength of the WPS is high only during spring and winter.

345 Contrarily, WPS of  $c_p$  (Figure 5c), shows evident inter-annual variability yet not all the temporal  
346 footprints (*i.e.* periods) have high values in 2011 and 2013. Dominant cycles are persistent at higher  
347 temporal scales from 2011 to 2013, whereas periods lower than 64 days are dominant only in the  
348 winter and spring in agreement with the other bio-optical properties.

349 The Chl-Fluo AWP is also characterized by two relative maxima in correspondence with 46 and  
350 124 days (Table 2), occurring only in the mesotrophic periods of the year (winter – spring of 2012;  
351 Figure 5a). The AWP of  $b_{bp}$  shows relevant cycles also at the 11-16, 58 and 126 day periods  
352 occurring in the most productive periods of the year of 2011 – 2013 (winter and spring).  
353 Furthermore, the 126-day cycle has a strong influence on the entire time-average spectrum (Figure  
354 4 and 5b). In case of  $c_p$ , there is a relevant cycle at 130 days. All these cycles have strong signals  
355 during the winter and spring seasons (Figure 5). In such a context, Figure 6 illustrates the AC  
356 obtained with the CWA between the different bio-optical coefficients along the entire 3-year time-  
357 series of observations. A high correlation ( $> 0.8$ ) between the periodicities of bio-optical  
358 coefficients greater than 10 days is observed (Figure 6). Periodicity at these scales has been poorly  
359 represented in the literature, and with the use of WA all of these cycles can be retrieved and

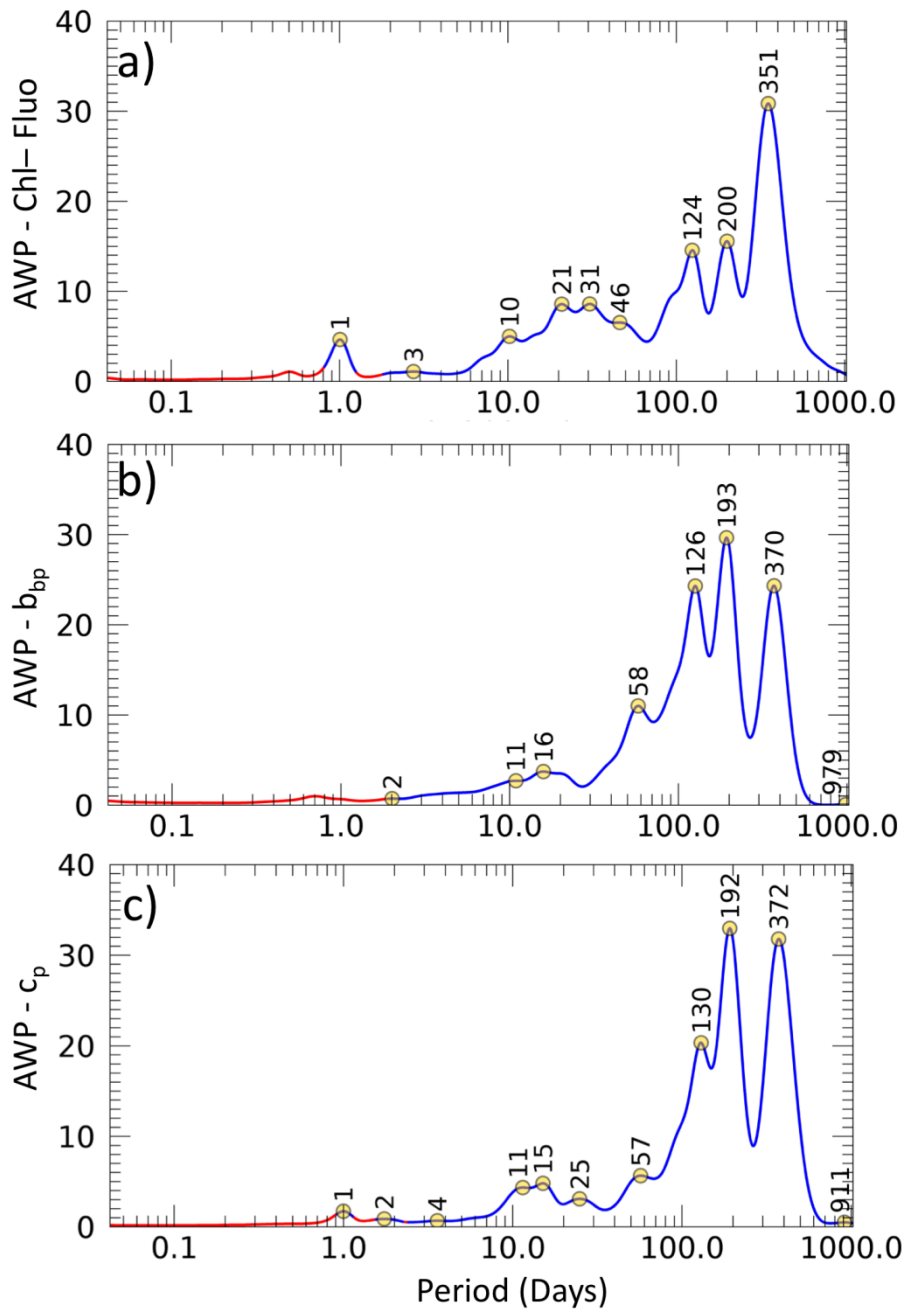
360 described. Figure 5 displays evident cycles in winter 2012 for all parameters (black lines; *i.e.* a  
361 productive period), and, therefore, it is an optimum case of study to highlight those lesser-known  
362 cycles, such as the intra-seasonal cycles (*i.e.* diel, weekly, monthly). In order to complement the  
363 analysis, an opposite case of study has been analyzed by applying a specific WA on summer 2012,  
364 *i.e.* the most oligotrophic period. Moreover, in these seasons, the diurnal variance of parameters is,  
365 in general, the highest in winter and the lowest in summer (*not shown*). Finally, the selected data  
366 sets have a limited number of missing observations (less than 11 % in both winter and summer  
367 seasons), restricting the use of reconstructed measurements.

368 In order to highlight the mid and short-term variability, a specific WA has thus been applied to two  
369 selected seasons of the time-series: winter and summer 2012 (Figures 7 and 8). Figure 7 shows the  
370 AWP obtained by WA on winter 2012 and Table 3 contains the AWP\* values correspondent to the  
371 maxima. For the  $b_{bp}$ , four significant maxima are retrieved (yellow circles in Figure 7a) at periods of  
372 17, 10, 5 and 1 days indicating four major patterns of  $b_{bp}$  variability in this season. There is also a  
373 12 hour cycle that emerges from the analysis, but with reduced statistical significance in respect to  
374 other cycles (less than 95%). The  $c_p$  AWP shows five relative maxima at 29, 12, 3, 2, and 1 days. A  
375 diel cycle is evident and represents the third maximum even if with a low AWP. Ultimately, for the  
376 Chl-Fluo, detected relative maxima are 29, 18, 11, 3 and 1 days. In winter, the dominant temporal  
377 patterns are of cycles greater than 10 days for all three parameters.

378 The opposite season, summer, is the counterpart case of study. This is the period of lowest  
379 productivity along the entire year at BOUSSOLE site. Figure 8 shows a time-series for each  
380 parameter and the corresponding AWP and AWP\* (Table 4). For the  $b_{bp}$  different maxima emerged  
381 (yellow circles in Figure 7a) in correspondence to 18, 10, 7, 4, 2, 1 days and 12 hours indicating  
382 these cycles as the main driven temporal patterns of variability during the season. The diel cycle is  
383 the second important temporal pattern for this coefficient. The  $c_p$  AWP shows five relative maxima  
384 at 23, 10, 4, 3, 1 days. The diel cycle is the most dominant for  $c_p$  in summer (AWP of 22.0). Lastly,  
385 the Chl-Fluo has eight relative maxima at 22, 12, 8, 4, 3, 1 days and 12 hours and the diel cycle is  
386 the most significant local pattern. One could argue that, during summer, the quenching effect can  
387 dominate and drive the diel cycle of Chl-Fluo. Therefore, this has to be taken into account in the  
388 interpretation of the results for the Chl-Fluo diel cycle (*Xing et al., 2017*).

### 389 **3.4 Cross-Wavelet Analysis**

390 The Chl-Fluo vs  $b_{bp}$  time-series have high AC values for periods ranging from 1 day ( $\cong 0.7$ ) to 1  
391 year ( $\cong 1$ ). At lower scales, there is a high correlation only during the winter and spring (Figure 9).  
392 This is also true for the Chl-Fluo vs  $c_p$  and the  $c_p$  vs  $b_{bp}$  time-series which have coherence values 0.7  
393 and 0.8 for the 1 day period, respectively, and up to  $\cong 1$  at the annual scale. At periods lower than 1  
394 day, the correlation between the three bio-optical parameters is low ( $<0.5$ ). The Chl-Fluo to  $c_p$   
395 coherence analysis reveals that the correlation is higher at daily scales ( $> 0.7$ ) with respect to Chl-  
396 Fluo/ $b_{bp}$ . The AC value is higher with respect to Chl-Fluo and  $b_{bp}$ . This is confirmed by what is  
397 expected about the relationship between  $b_{bp}$  and phytoplankton cells (*Loisel et al., 2001; Stramski et*  
398 *al., 2004, Dall'Olmo et al., 2009; 2012*).



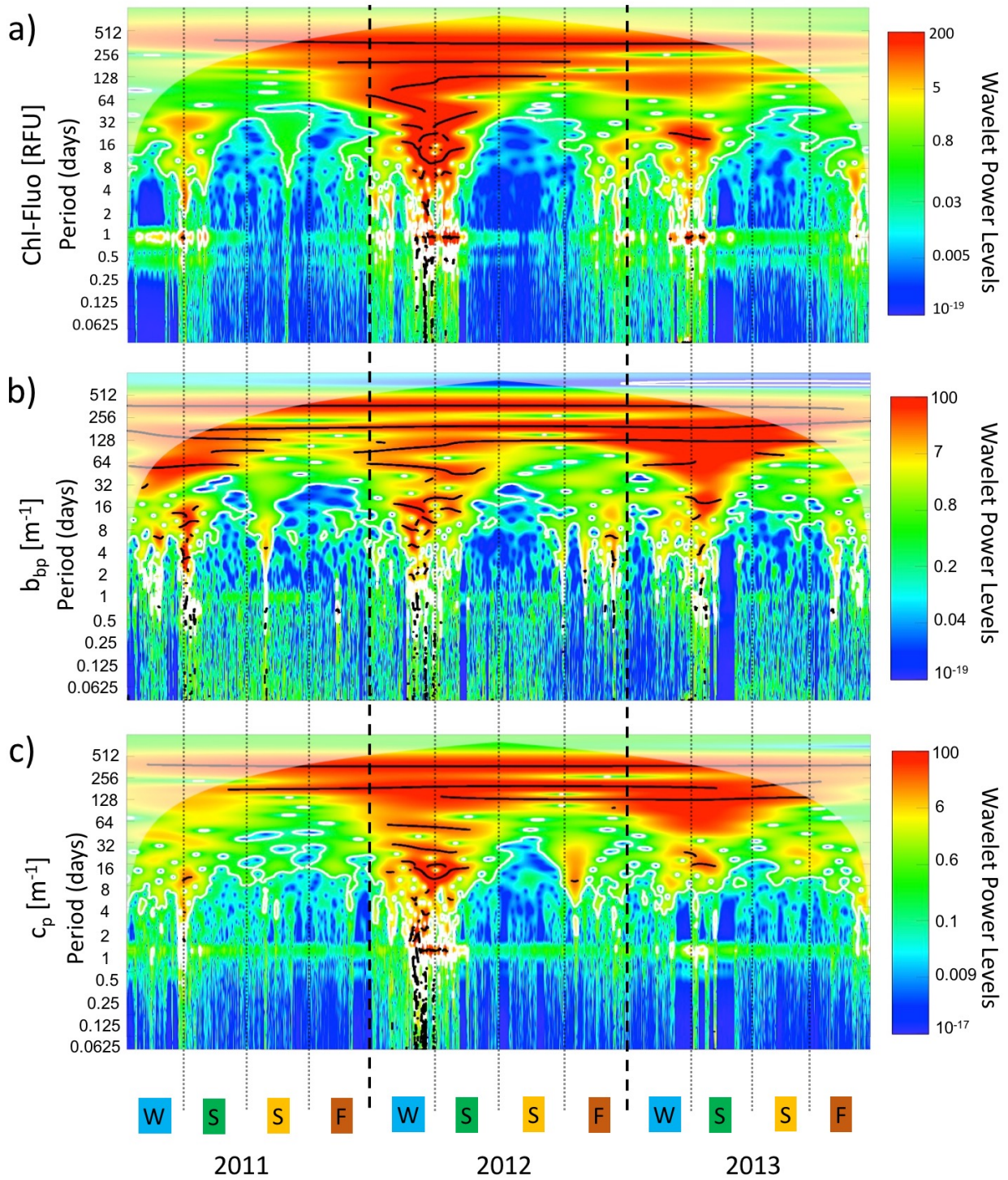
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400 Figure 4: AWP of the Chl-Fluo (a),  $b_{bp}$  (b) and  $c_p$  (c). The statistical significance is 95% in case of the  
 401 highest temporal scales, from day to annual scales, for each parameter (blue line). At the lowest temporal  
 402 scales, the significance is lower than 95% (red line) and the results have to be interpreted with caution. The  
 403 statistical significance is computed following *Roesch and Schmidbauer* (2014). Yellow dots are the relative  
 404 local maxima for the single parameter with also information of the exactly days.

Period (days)	351	200	124	-	46	31	21	-	10	3	-	1
$AWP_{Chl-Fluo}^*$	<b>1.0</b>	0.50	0.47	-	0.21	0.27	0.27	-	0.16	0.05	-	0.15
Period (days)	370	193	126	58	-	-	-	16	11	-	2	-
$AWP_{b_{bp}}^*$	0.82	<b>1.0</b>	0.82	0.37	-	-	-	0.13	0.09	-	0.02	-
Period (days)	372	192	130	57	-	-	25	15	11	4	2	1
$AWP_{c_p}^*$	0.96	<b>1.0</b>	0.62	0.17	-	-	0.09	0.15	0.13	0.02	0.03	0.05

405 Table 2: AWP\* from the AWP of each parameter. Numbers in bold indicate the dominant cycles.

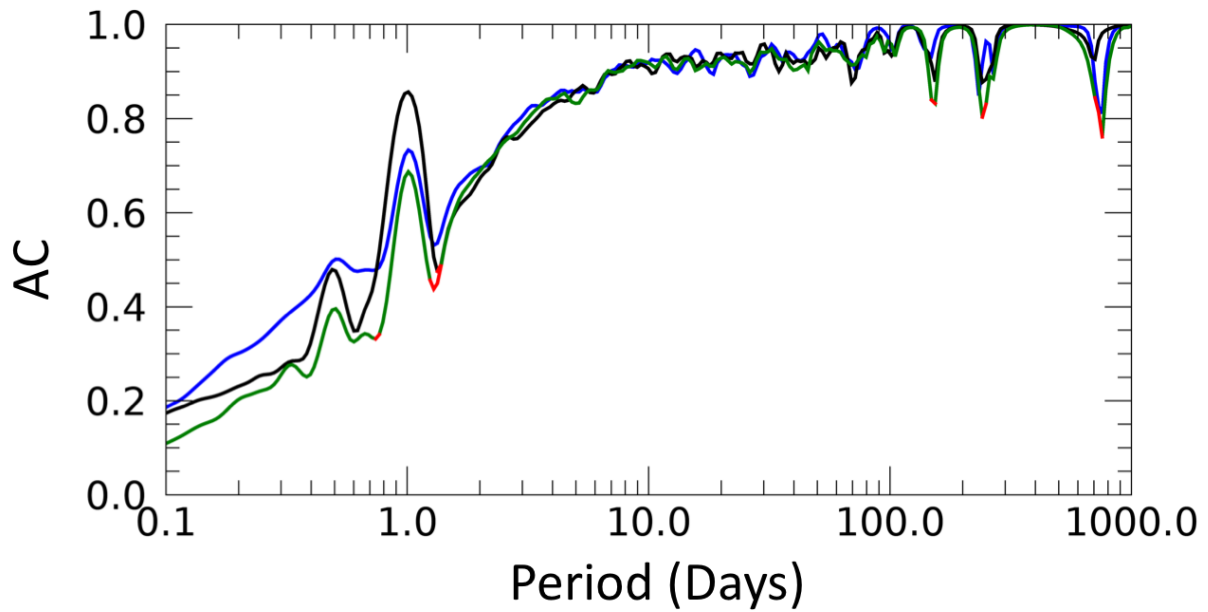




407

408 Figure 5: WPS for Chl-Fluo (a),  $b_{bp}$  (b) and  $c_p$  (c). The letters W stands for winter (in blue), S for spring (in  
 409 green), S for summer (in orange) and F for fall (in brown). The time-series has a strong (cyclical) signal for  
 410 the periods and duration of time in correspondence of the black lines in the WPS. The shaded area has not to  
 411 be considered as it might provide false periodic events (*Torrence and Compo, 1998*). The thin white contours  
 412 surrounding regions of stronger variance in the spectra indicate coherent time-frequency regions that are  
 413 significant (*i.e.* 95% significance). The significance test is computed following *Roesch and Schmidbauer*  
 414 (*2014*).

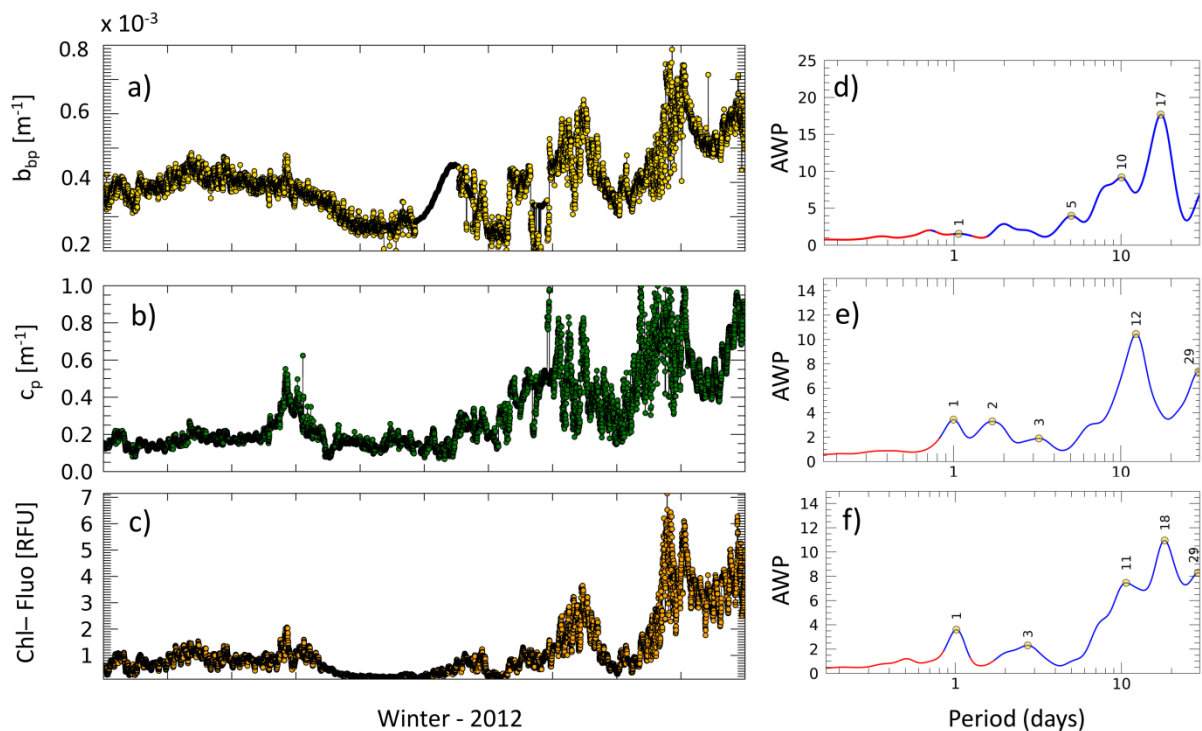
415



416

417 Figure 6: AC obtained from the CWA between paired bio-optical properties: Chl-Fluo vs.  $b_{bp}$  (green line),  
 418 Chl-Fluo vs.  $c_p$  (black line) and  $b_{bp}$  vs.  $c_p$  (blue line). In red are highlighted periods where the AC is with low  
 419 statistical significance (less than 95%).

420



421

422 Figure 7: Time-series of  $b_{bp}$  (a),  $c_p$  (b) and Chl-Fluo (c) in Winter 2012. AWP of  $b_{bp}$ ,  $c_p$ , Chl-Fluo are in  
 423 panels d, e, f. Red lines are located where the statistical significance is less than 95% and the results have to  
 424 be interpreted with caution. The significance test is computed following *Roesch and Schmidbauer (2014)*.

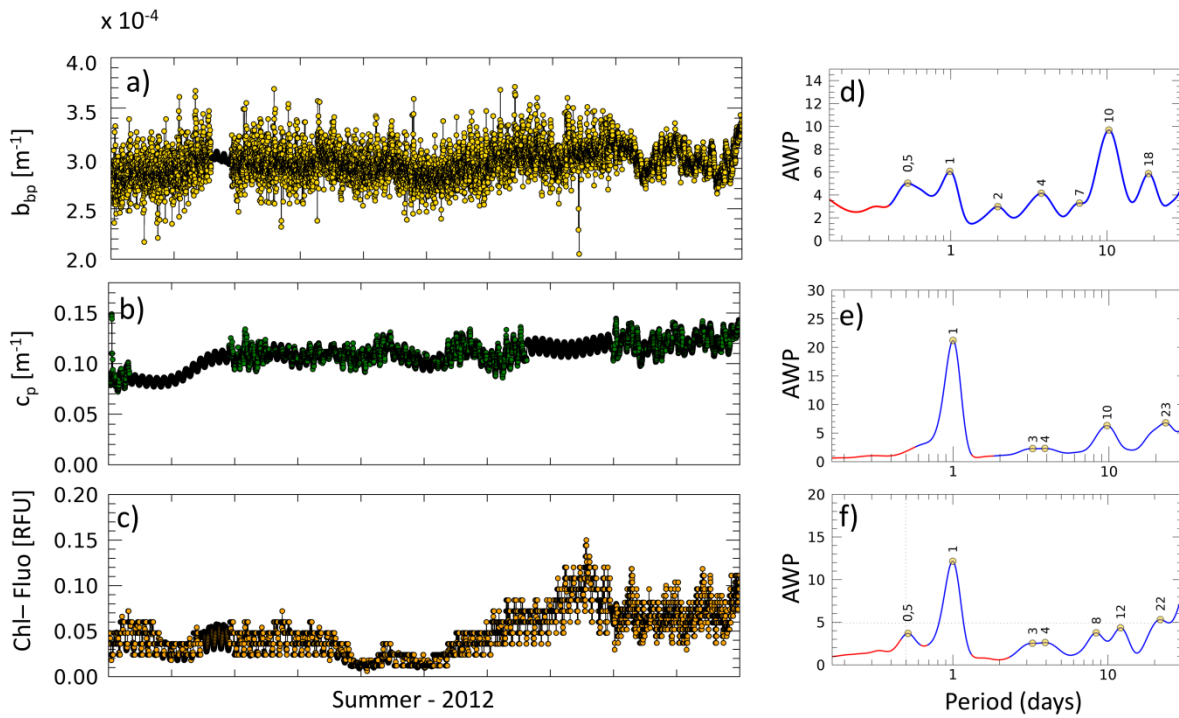
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426

Period (days)	-	17	10	5	-	1
$AWP_{b_{bp}}^*$	-	<b>1.0</b>	0.52	0.23	-	0.09
Period (days)	29	-	12	3	2	1
$AWP_{c_p}^*$	0.70	-	<b>1.0</b>	0.18	0.31	0.33
Period (days)	29	18	11	3	-	1
$AWP_{Chl-Fluo}^*$	0.76	<b>1.0</b>	0.68	0.21	-	0.33

427 Table 3 AWP\* from the AWP of each parameter in Winter 2012. Numbers in bold indicate the dominant  
428 cycles.

429



430 Figure 8: Time-series of  $b_{bp}$  (a),  $c_p$  (b) and Chl-Fluo (c) in Summer 2012. AWP of  $b_{bp}$ ,  $c_p$ , Chl-Fluo are  
431 reported in panels d, e, f. Red lines are located where the statistical significance is less than 95% and the  
432 results have to be interpreted with caution. The significance test is computed following *Roesch and*  
433 *Schmidbauer* (2014).  
434  
435

Period (days)	18	10	7	4	2	1	0.5
$AWP_{b_{bp}}^*$	0.61	<b>1.0</b>	0.34	0.43	0.31	0.63	0.52
Period (days)	23	10	-	4	3	1	-
$AWP_{c_p}^*$	0.32	0.30	-	0.11	0.11	<b>1.0</b>	-
Period (days)	22	12	8	4	3	1	0.5
$AWP_{Chl-Fluo}^*$	0.44	0.36	0.31	0.22	0.21	<b>1.0</b>	0.30

436 Table 4: AWP\* from the AWP of each parameter for Summer 2012. Numbers in bold indicate the dominant  
437 cycles.

438

439

## 440 4. Discussion

### 441 4.1 Annual cycle

442 The most generally observed pattern was a phytoplankton maximum in the winter/spring season,  
443 minimum in summer and a successive increase in fall season, that corresponds to a typical annual  
444 cycle of a temperate ocean, as already reported for the north-western Mediterranean Sea (*Antoine et*  
445 *al.*, 2011; *D'Ortenzio et al.*, 2014).

446 The main pattern revealed by WA applied to BOUSSOLE data is the periodicity of the seasonal  
447 evolution: from late fall to early spring (essentially the winter) where there is always a convergence  
448 of Chl-Fluo,  $b_{bp}$  and  $c_p$  signals (Figures 5 and 9).

449 The spring bloom in the Ligurian Sea is regulated by the increase of light availability after the  
450 winter mixing of the water column that redistributes nutrients from deep to surface waters (*Antoine*  
451 *et al.*, 2011; *D'Ortenzio et al.*, 2014). The phasing, duration and intensity of the annual bloom  
452 varies from year to year, with a stronger bloom in 2012 in respect to 2011 and 2013 (Figure 2;  
453 *Mayot et al.*, 2016). This variability arises from the range of the processes controlling bloom  
454 dynamics, including physical forcing such as meteorological extreme events, and/or interaction  
455 between different species of phytoplankton organisms (*Winder et al.*, 2010).

456 During summer, the increase of light availability causes the decrease of intra-cellular photosynthetic  
457 pigments concentration need and, concurrently, the low nutrient availability limits the  
458 phytoplankton population growth and its abundance stays low (*Bellacicco et al.*, 2016). The  $b_{bp}$  and  
459  $c_p$  are characterized by a similar temporal pattern in summer (Figure 2 and 5). During fall, as light  
460 availability decreases and mixed layer deepens, phytoplankton concentration increases again.

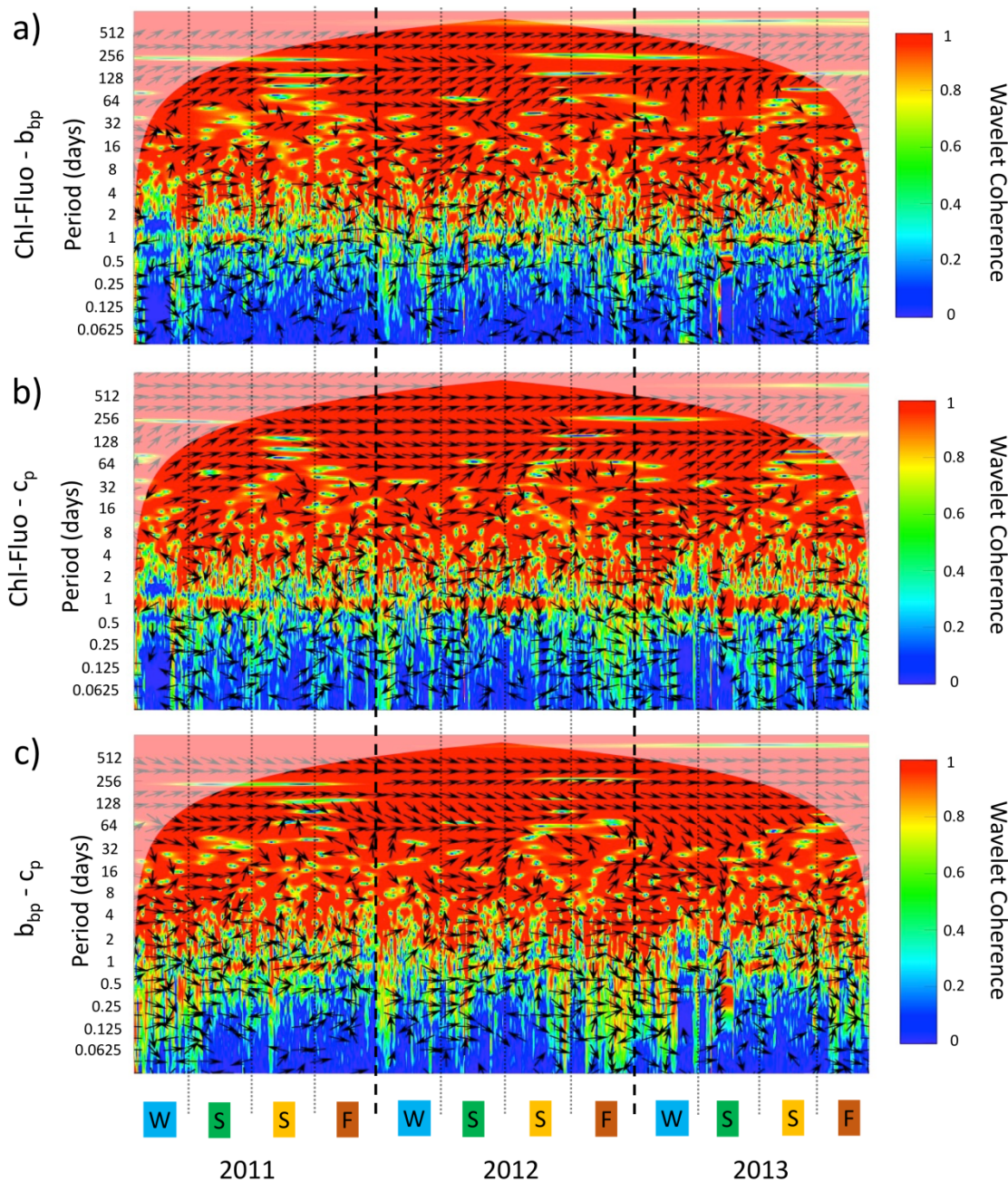
461 The  $b_{bp}$  and  $c_p$  time-series are coherent with the Chl-Fluo time-series at annual scale because both  
462  $b_{bp}$  and  $c_p$  are sensitive to particle size ranges that include phytoplankton (*Stramski et al.*, 2004;  
463 *Sosik et al.*, 2008; *Organelli et al.*, 2018), thus phytoplankton cells abundance strongly impacts the  
464 variability of  $b_{bp}$  and  $c_p$ . Figures 6 and 9 reveal how the bio-optical properties have a WCS and AC  
465 close to 1 at annual scale along the entire time-series. In detail, Chl-Fluo is in advance in respect to  
466 the annual signal of  $b_{bp}$  (Figure 9a), while with  $c_p$  they are in phase (Figure 9b). The  $c_p$  leads in  
467 respect to the  $b_{bp}$  annual signal as highlighted by the arrows in the Figure 9c. In such a context, the  
468 maximum of Chl-Fluo is in shift in advance of approximately 20 days with respect to  $c_p$  and  $b_{bp}$   
469 (Figure 4 and Table 2). This could be attributed to the inter-annual variability (low bloom maxima  
470 in 2011 and two maxima in 2013 for Chl-Fluo) which determined a dephasing in the AWP. Another  
471 reasonable explanation can be that the Chl-Fluo annual maximum (independently of its strength) is  
472 not occurring always at the same time (*i.e.* indeed there are four maxima in the Chl-Fluo time-  
473 series: March in 2011 and 2012, April and December in 2013; Figure 2). Nevertheless, there is a  
474 good coherence between the parameters at annual temporal scales ( $AC \cong 1$ ; Figure 6).

### 475 4.2 Six- and four- month cycles

476 Other fundamental cycles retrieved by WA are at 6 months and 4 months. The 6-month cycle is  
477 unexpectedly the most important cycle in cases of  $b_{bp}$  and  $c_p$ , while for Chl-Fluo it is second in  
478 terms of dominance. The 4-month cycle is the third important cycle for all of the parameters,  
479 especially for  $b_{bp}$  (Table 2). AC shows a strong correlation of the WPS for all combinations of bio-  
480 optical coefficients at these periods ( $\cong 1$ ; Figures 6 and 9). The 6-month cycle is dominant for  $b_{bp}$   
481 and  $c_p$ , whereas it has a lower strength for the Chl-Fluo, a consequence of the inter-annual  
482 variability of its WPS (Figure 5a). The 6- and 4-month cycles are interpreted here as mainly due to



483 the winter-to-spring modification of the mixing intensity (*D'Ortenzio et al., 2005*), nutrient and  
484 light availability, grazing and shift in phytoplankton community structures (*Mignot et al., 2014;*  
485 *Sammartino et al., 2015*). *Bellacicco et al., (2016)* highlight that the use of Chl as a proxy of  
486 phytoplankton biomass, as well as Chl-Fluo, is strictly influenced by intracellular processes,  
487 especially in intermediate seasons, such as late spring and early fall. Alternately,  $b_{bp}$  and  $c_p$  are  
488 sensitive to the abundance of phytoplankton cells and non-algal particles, as well as particle size  
489 distribution, refractive index, and the shape and structure of particles in the seawater. Therefore, in  
490 these intermediate periods, where the Chl-Fluo signal is low while  $c_p$  and  $b_{bp}$  are relatively high, the  
491 6-month cycle signal detection could be reduced impacting total seasonal and annual cycles. For  
492 example, in early fall, there are low nutrients and low light conditions and the result is an increase  
493 of phytoplankton cells, as indicated by the increase of  $c_p$  and  $b_{bp}$ , however phytoplankton does not  
494 have a high concentration of photosynthetic pigment, and consequently a low Chl-Fluo. In late  
495 spring, the photoacclimation process is particularly relevant and impacts on Chl-Fluo due to high  
496 nutrients and high light availability. The  $b_{bp}$  and  $c_p$  proxies are not affected by the phytoplankton  
497 physiological state (*Bellacicco et al., 2016; Barbieux et al., 2018*) and the effect of the carbon  
498 accumulation in phytoplankton cells dominates the  $c_p$  and  $b_{bp}$  WPS (Figures 4 and 5b, c), while the  
499 physiological signal (*i.e.* photoacclimation) has an effect on the strength of the signal in WPS of the  
500 Chl-Fluo signal (Figures 4 and 5a). Figure 9 displays how  $c_p$  signal is in advance with respect to  $b_{bp}$   
501 at 6 month cycles along 2012 and 2013. On the other hand, the  $b_{bp}$  signal is in delay in respect to  
502 Chl-Fluo in 2012, while with  $c_p$  they are in phase from summer 2011 to spring 2012. Figure 9 also  
503 shows the relationship between parameters at the period of 4-months. In this period, Chl-Fluo signal  
504 is delayed in respect to  $c_p$  as in the case of 6-months, while  $c_p$  signal seems to be in advance  
505 compared to the  $b_{bp}$  signal. From the analysis, the intensity of a 4-month cycle differs in cases of  
506 Chl-Fluo in respect to  $b_{bp}$  and  $c_p$  (Table 2).



507  
 508 Figure 9: Cross-wavelet coherence spectra between (a) Chl-Fluo and  $b_{bp}$ , (b) Chl-Fluo and  $c_p$ , and (c)  $b_{bp}$  and  
 509  $c_p$  at BOUSSOLE site. Color indicates the level of covariability between the time-series (values between 0  
 510 and 1); arrows denote the relative phase between the time-series (right: in phase; left: antiphase; up or down:  
 511 one series leads the other by  $90^\circ$ ) with significance covariability ( $> 95\%$ ). Shaded area has not to be  
 512 considered as it might provide false periodic events (*Torrence and Compo, 1998*). The letters W stands for  
 513 winter (in blue), S for spring (in green), S for summer (in orange) and F for fall (in brown), as for Figure 5.

514  
 515 **4.3 Intra-seasonal variability: mid- and short-term cycles**

516 WA detected relevant cycles at scales other than annual, 6- and 4-months are interpreted here as  
 517 caused by intra-seasonal (*i.e.* from diel to monthly) variability of the examined bio-optical  
 518 parameters: the highest cycles are defined as mid-term cycles, while the lowest as short-term  
 519 counterparts. In such a context, the specific WA applied to these particular periods of winter and

520 summer 2012 enables the detection and power of these additional sources of variability (from 12  
521 hours to 29 days; Tables 3 and 4).

522 At the beginning of winter and over the 16 day period,  $c_p$  and Chl-Fluo signals are in phase and then  
523  $c_p$  is in advance compared to the Chl-Fluo footprint. Contrarily,  $b_{bp}$  and Chl-Fluo indicators are in  
524 phase along the entire season. From 2 day up to 16 day periods, Chl-Fluo is partially in phase with  
525  $b_{bp}$  and  $c_p$ , however, some hotspots occur in which both  $b_{bp}$  and  $c_p$  have phase differences in respect  
526 to the Chl-Fluo signal. In cases of  $b_{bp}$  to  $c_p$ , at these highest periods,  $c_p$  leads the  $b_{bp}$  mark (Figure  
527 10).

528 In summer, at the range of 8-16 days, Chl-Fluo is in advance in respect to the  $b_{bp}$  signal, while on  
529 the reverse, the Chl-Fluo indicator at this period is delayed with respect to the  $c_p$ . Regarding the  $b_{bp}$   
530 to  $c_p$  relationship, the former is in advance with respect to the latter at the beginning of summer,  
531 while at the end of summer, there is an opposite situation of delay. Between 2 and 8 days, Chl-Fluo  
532 is not in phase with both  $c_p$  and  $b_{bp}$  signals (*e.g.* start of summer), while the optical parameters are in  
533 phase (Figure 11).

534 A possible explanation of these mid-term cycles could also be given by episodic phytoplankton  
535 biomass increases in response to stochastic events that potentially impact the mixed layer dynamics  
536 which are typical of the winter period at the BOUSSOLE site. For instance, as highlighted by  
537 *Winder et al.*, (2010), extreme wind events could generate biomass oscillations by temporarily  
538 reducing the phytoplankton bloom. In addition, *Nezlin et al.* (2002) showed, using WA, that short-  
539 period variations (less than 100 days) of remotely-sensed chlorophyll during spring seasons  
540 correlated with surface water, air temperatures and wind stress, that have rapidly varied (*i.e.* at the  
541 intermediate scales that we analyze here). The mechanism of these variations was an intensification  
542 of phytoplankton growth resulting from mixing of the water column by wind stress and entrainment  
543 of cold, rich in nutrients, water into the euphotic layer. *Monteiro et al.* (2015) demonstrated the  
544 presence of an intra-seasonal variability that is always driven by wind stress and has a temporal  
545 scale from daily up to 14 - 20 days. These orders of magnitude are consistent with the maxima  
546 reported in the AWP plots, for both winter and summer 2012 (Figures 7, 8; Table 3 and 4).

547 The general Chl-Fluo and  $c_p$  WPS also show a clear diel cycle footprint, particularly evident during  
548 high biomass periods (winter and spring in Figure 5a and c). On the other hand, the diel signal is  
549 less evident for  $b_{bp}$  (Figures 4 and 5b and Table 2). The correlation between  $c_p$  and Chl-Fluo at diel  
550 scale (AC greater than 0.7 in Figure 6) is well known during winter and spring, when the particles  
551 abundance is dominated by phytoplankton cells (*Kheireddine et al.* 2014; *Bellacicco et al.*, 2016).  
552 The diel changes are generally considered to be driven by specific forcings (*Oubelkheir et al.*, 2005;  
553 *Oubelkheir and Sciandra* 2008; *Gernez et al.*, 2011, *Loisel et al.*, 2011; *Barnes et al.*, 2014;  
554 *Kheireddine et al.*, 2014). At diel cycle, the correlation between Chl-Fluo and  $b_{bp}$  periodicities is  
555 lower ( $\cong 0.6$ ) than to Chl-Fluo vs.  $c_p$  ( $>0.7$ ). A good correlation is found in the  $b_{bp}$  vs  $c_p$  ( $>0.7$ ).

556 By applying the specific WA over a three-month period both in winter and summer seasons, more  
557 information can be gathered about short-term variability, especially on the diel cycle.

558 During the winter, Chl-Fluo signal is in advance to  $c_p$  without any phases between parameters  
559 despite AC showing high values (Figure 10). Reversely, the AC between Chl-Fluo and  $b_{bp}$  is lower  
560 (less than 0.5) below diel cycle. The AC between  $b_{bp}$  and  $c_p$  is always lower than 0.6 (Figure 10).

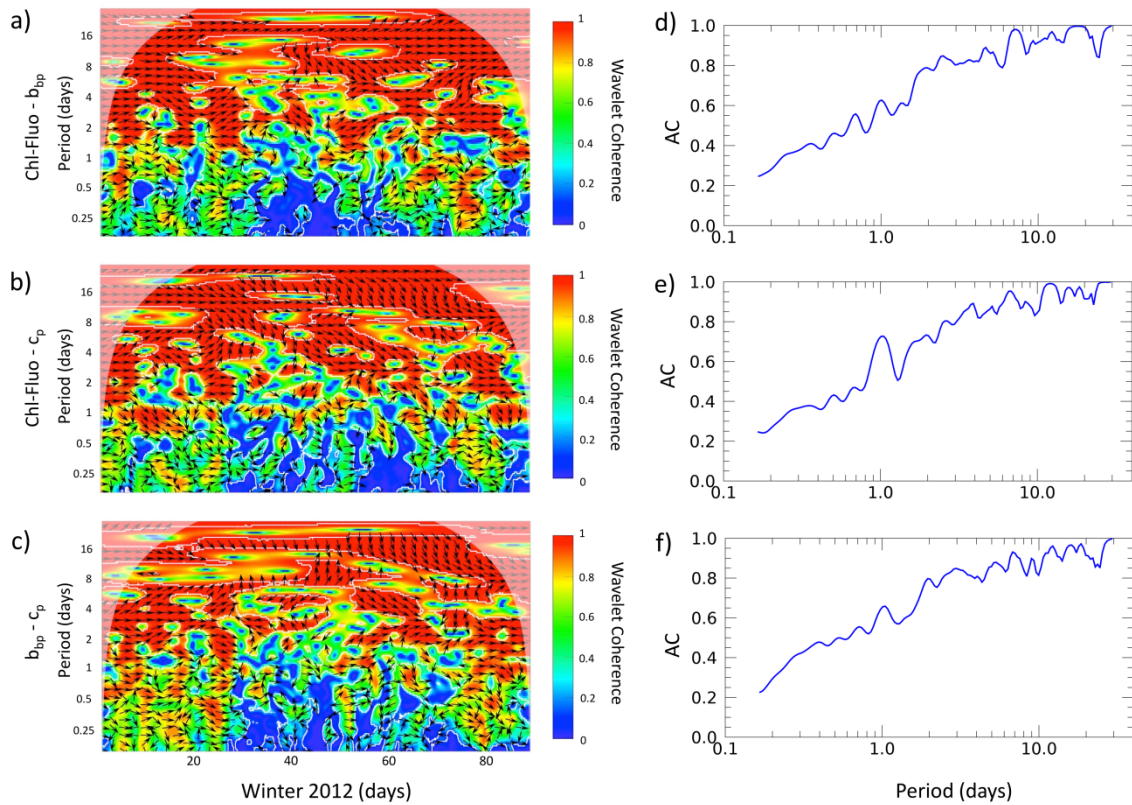
561 In the winter, the period of strong mixing and start of the bloom (*Barnes et al.*, 2014, *Kheireddine*  
562 *et al.* 2014; *Bellacicco et al.*, 2016),  $c_p$  can be increasingly influenced by diel variations of  
563 abundance of phytoplankton cells (*Oubelkheir et al.*, 2005, *Oubelkheir and Sciandra*, 2008), even if  
564 with a marginal impact on total variability (Table 3). In contrast to  $c_p$ ,  $b_{bp}$  diel cycle is not marked

565 by a significant seasonal variability. This would confirm that phytoplankton makes a lower  
566 contribution to  $b_{bp}$  than to  $c_p$ , so their seasonal changes are poorly reflected in overall seasonal  
567 changes.  $b_{bp}$  is influenced more by the presence of sub-micrometer particles such as detrital  
568 particles or heterotrophic bacteria (*Morel and Ahn, 1991; Stramski and Kiefer, 1991, Stramski et*  
569 *al., 2004*), that do not have a periodical diel cycle. Recently, *Organelli et al., (2018)* found that  
570 another main source of variability on  $b_{bp}$  is due to particles with equivalent diameters between 1 and  
571 10  $\mu\text{m}$  giving thus new insight into the  $b_{bp}$  coefficient and particles in seawater.

572 In summer, Chl-Fluo and  $b_{bp}$  have an AC of 0.8 but  $b_{bp}$  is largely in anti-phase with Chl-Fluo, as  
573 expected for this period of year of low productivity. Inversely,  $c_p$  and Chl-Fluo diurnal signals have  
574 an AC value of approximately 1. During this season of absence of high abundance of phytoplankton  
575 (*Kheireddine et al. 2014; Bellacicco et al., 2016*),  $c_p$  can be due to the daily variations of coupled  
576 heterotrophic bacteria and particles pool (*i.e.* phytoplankton cells) which remain within the upper  
577 layer caused by the strong stratification of the water column. However, Chl-Fluo diel signal can be  
578 determined due to the quenching effect (*Xing et al., 2017*). In addition, at periods of 0.5 (*i.e.* 12  
579 hours),  $c_p$  and  $b_{bp}$  signals are in anti-phase with Chl-Fluo. Due to this limited productivity, cycles  
580 greater than 1 day are not the most impactful of the intra-seasonal variability, while conversely the  
581 diurnal signal is well pronounced. *Oubelkheir and Sciandra (2008)* argued that the diel cycle of  $c_p$ ,  
582 and the particles pool, is strictly influenced by changes in the properties of particles (*e.g.* size,  
583 refractive index, shape and internal structure) and also by external environmental and biological  
584 agents, as reported by *Binder and Durand (2002)*. During daytime, phytoplankton cells fix external  
585 inorganic carbon into organic molecules determining an increase of their diameter and refractive  
586 index (*Siegel et al., 1989; Stramski and Reynolds, 1993; Walsh et al., 1995*), and as a consequence  
587 an increase of scattering and attenuation cross section. This was also confirmed by laboratory  
588 experiments on a few phytoplankton species (*Stramski et al., 1995; Durand and Olson, 1998;*  
589 *Claustre et al. 2002; Poulin et al., 2018*). During night-time, phytoplankton cells divide into  
590 smaller cells with lower intra-cellular carbon content, as a result of an uptake of water during  
591 division or of a loss due to respiration (*Durand and Olson, 1998*). Another element to consider on  
592 the  $c_p$  diel variation is the relative dynamics of algal and non-algal stocks (*i.e.* heterotrophs, viruses  
593 and detritus) that could vary in relation to the season and trophic regimes. *Oubelkheir and Sciandra*  
594 *(2008)* showed that the  $c_p$  is strictly related to heterotrophic particles abundance coupled with  
595 phytoplankton cells and associated detritus.

596 To summarize, through the specific three-month WA, more information about detection and power  
597 of these additional sources of variability can be obtained. The mid-term cycles ( $> 10$  days)  
598 dominate intra-seasonal variability during the winter (period of mixing and bloom), while they are  
599 of limited impact in the case of summer which is the period of low biological production and  
600 absence of extreme meteorological events (*Gernez et al., 2011, Kheireddine et al., 2014*) indicating  
601 where the diel cycle is the most recurrent and important source of signal.





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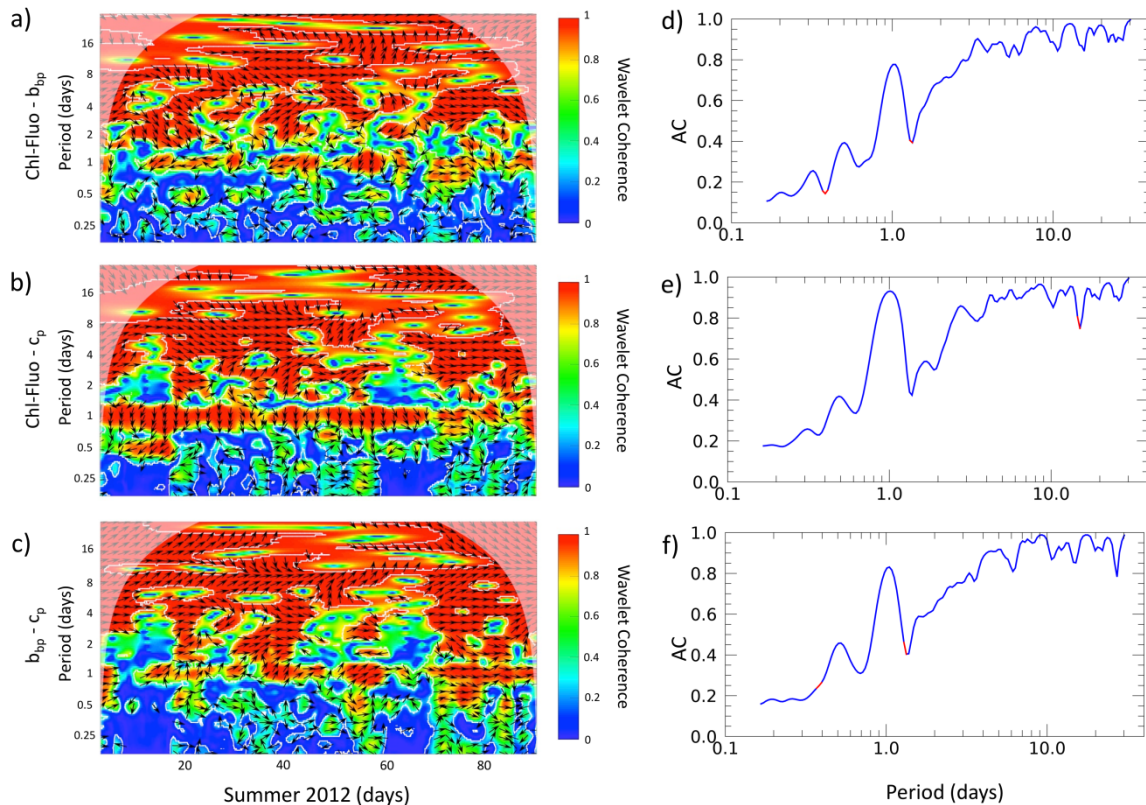
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Figure 10: Cross-wavelet coherence spectra between Chl-Fluo and  $b_{bp}$  (a), Chl-Fluo and  $c_p$  (b), and  $b_{bp}$  and  $c_p$  (c) at BOUSSOLE site for the Winter 2012. Color indicates the level of covariability between the time-series (values between 0 and 1); arrows denote the relative phase between the time-series (right: in phase; left: antiphase; up or down: one series leads the other by  $90^\circ$ ) and significance covariability ( $> 95\%$  and thin white contours). Shaded area has not to be considered as it might provide false periodic events (Torrence and Compo, 1998). AC of each parameter are in Panel d-f. In red are highlighted periods where the AC is with low statistical significance (less than 95%). The significance test is computed following Roesch and Schmidbauer (2014).



611

612 Figure 11: Cross-wavelet coherence spectra between Chl-Fluo and  $b_{bp}$  (a), Chl-Fluo and  $c_p$  (b), and  $b_{bp}$  and  $c_p$   
 613 (c) at BOUSSOLE site for the Summer 2012. Color indicates the level of covariability between the time-  
 614 series (values between 0 and 1); arrows denote the relative phase between the time-series (right: in phase;  
 615 left: antiphase; up or down: one series leads the other by  $90^\circ$ ) and significance covariability ( $> 95\%$  and the  
 616 thin white contours). Shaded area has not to be considered as it might provide false periodic events  
 617 (*Torrence and Compo, 1998*). AC for each parameter are in Panel d-f. In red are highlighted periods where  
 618 the AC is with low statistical significance (less than 95%). The significance test is computed following  
 619 *Roesch and Schmidbauer (2014)*.

## 620 5. Conclusions

621 In the last decades, the development of fixed observation sites, such as the BOUSSOLE buoy, as  
 622 well as remote sensing advancement has helped to study the phenology of phytoplankton and  
 623 optical properties. Several works have studied temporal variability of bio-optical properties in  
 624 various oceanic regimes using both field and satellite data (*Behrenfeld et al., 2009, Antoine et al.,*  
 625 *2011; Gernez et al., 2011; Barnes et al., 2014; Kheireddine et al., 2014; Behrenfeld et al. 2015;*  
 626 *Sammartino et al., 2015; Di Cicco et al., 2017*). However, most of these phenological studies focus  
 627 on the annual and seasonal cycles (*i.e.* long-term cycles), while there is limited literature on the  
 628 mid- and short-term cycles, and their recurrence, which characterizes the temporal variability of  
 629 bio-optical properties.

630 In this study, we have focused on bio-optical properties using, for the first time, a statistical *a priori*  
 631 method, as the wavelet analysis (WA) is, on three-year high frequency observations. The main  
 632 goals are to determine the intra-annual dominant temporal patterns of the bio-optical parameters,  
 633 the changes of these cycles over time, the characteristics and recurring strength at those periods and  
 634 to define the temporal relationship between the cycles of the bio-optical properties.

635 The WA applied here reveals a persistent annual cycle for Chl-Fluo which explains the largest  
 636 amount of its variability. On the other hand, and unexpectedly, the 6-month cycle is the most

637 important and dominant temporal pattern of the  $b_{bp}$  and  $c_p$  time-series, with respect to Chl-Fluo,  
638 which accounts for half of the variability in respect to the annual cycle. Together with 6-month, the  
639 4-month cycle is the third source of variability for all the parameters with different strengths. It has  
640 a particular recurrence and magnitude in the case of  $b_{bp}$ , with respect to Chl-Fluo and  $c_p$  and intra-  
641 seasonal variability is driven by mid- and short-terms cycles. During the winter (season of mixing),  
642 the mid-term cycles ( $> 10$  days) are the most important. Episodic bloom events can determine these  
643 cycles, as viewed in the case of bio-optical coefficients, and as also found by *Winder et al.* (2010).  
644 During summer, the diel cycle is the most important and the main source of variability, especially  
645 for  $c_p$  and Chl-Fluo. Considering the entire time-series, at diel scale, the coherence between spectra  
646 of bio-optical coefficients diminishes in respect to annual and seasonal cycles although remaining  
647 high. Chl-Fluo -  $c_p$  and  $b_{bp}$  -  $c_p$  periodicities have a strong temporal correlation in respect to Chl-  
648 Fluo-  $b_{bp}$ . At diurnal scale, Chl-Fluo depends specifically on intra-cellular and physiological  
649 processes in relation to physical forcing, and on phytoplankton cells abundance. The  $c_p$  at the same  
650 scale has its own temporal pattern: in summer,  $c_p$  is driven mostly by heterotrophic bacteria coupled  
651 with low phytoplankton abundances, while in winter,  $c_p$  is more associated with phytoplankton  
652 particles (*Oubelkheir et al.* 2005, *Oubelkheir and Sciandra*, 2008). In the case of  $b_{bp}$ , the correlation  
653 between the periodicities of Chl-Fluo is lower with respect to  $c_p$  because the  $b_{bp}$  is influenced more  
654 by small particles (*Stramski et al.*, 2004; *Kheireddine et al.*, 2014). In such a context, the recent  
655 findings of *Organelli et al.* (2018) open challenges in understanding the complexity of marine  
656 particles structure as sources of variability of the open-ocean  $b_{bp}$  signal that have to be addressed in  
657 the next future in order to better constraint the use of  $b_{bp}$  observations for investigating the  
658 biological carbon pump and phytoplankton phenology studies.  
659 This work thus highlights the need to develop *in situ* technologies as well as new satellite sensors at  
660 higher temporal resolutions (*e.g.* geostationary satellite) for biogeochemical/bio-optical  
661 measurements that have been widely recognized as a priority in the optical and oceanographic  
662 community. Indeed, high frequency observations could help to study, both in space and time, these  
663 mid- and low-term cycles, poorly known, that currently are not taken into account in the ocean  
664 color algorithms despite dominating the bio-optical variability at reduced time-series length (*i.e.*  
665 within the season). Lastly, as it is demonstrated here, the importance of the use of WA as a  
666 powerful instrument for studying both long or short time-series of bio-optical parameters and their  
667 relationships in oceanography (*Winder et al.*, 2010, *Damarcq et al.* 2012, *Ampe et al.*, 2014,  
668 *Corredor-Acosta et al.*, 2015, *Carey et al.* 2016, *Sala et al.*, 2018).

669

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677 vlfr.fr/Boussole/html/project/introduction.php](http://www.obs-<br/>677 vlfr.fr/Boussole/html/project/introduction.php)

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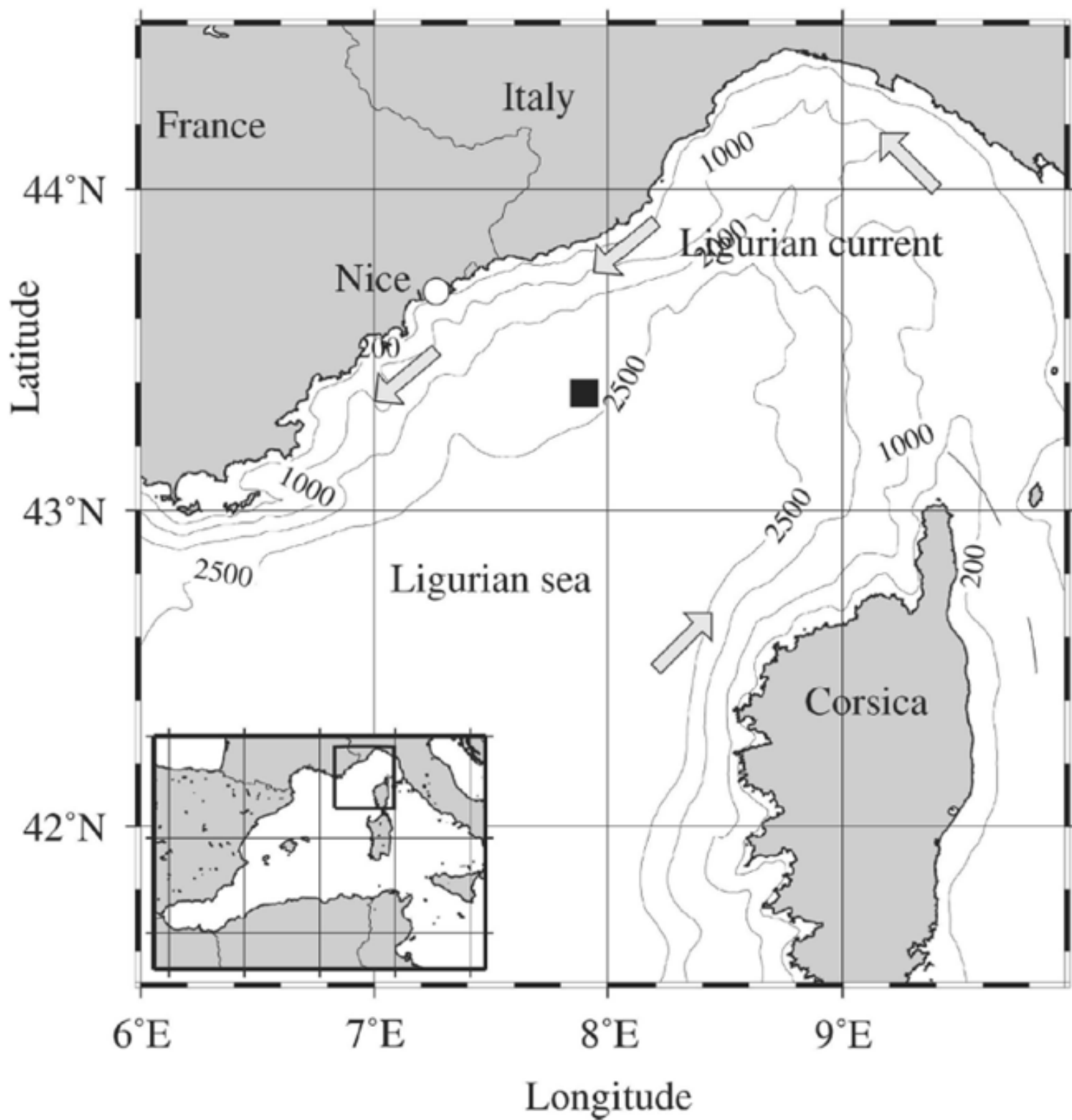
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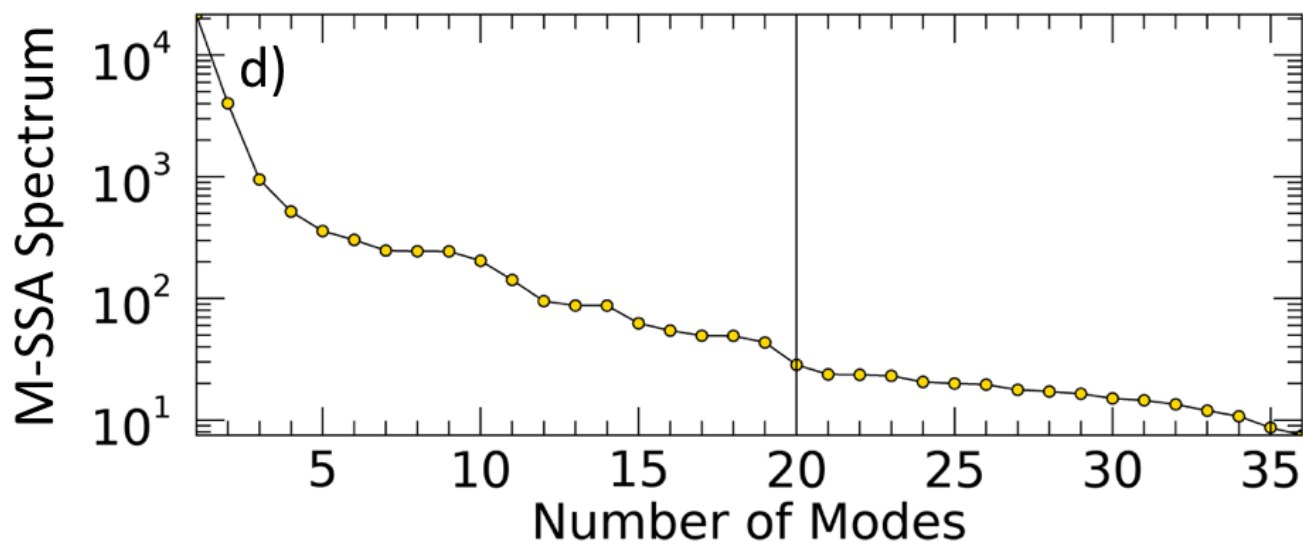
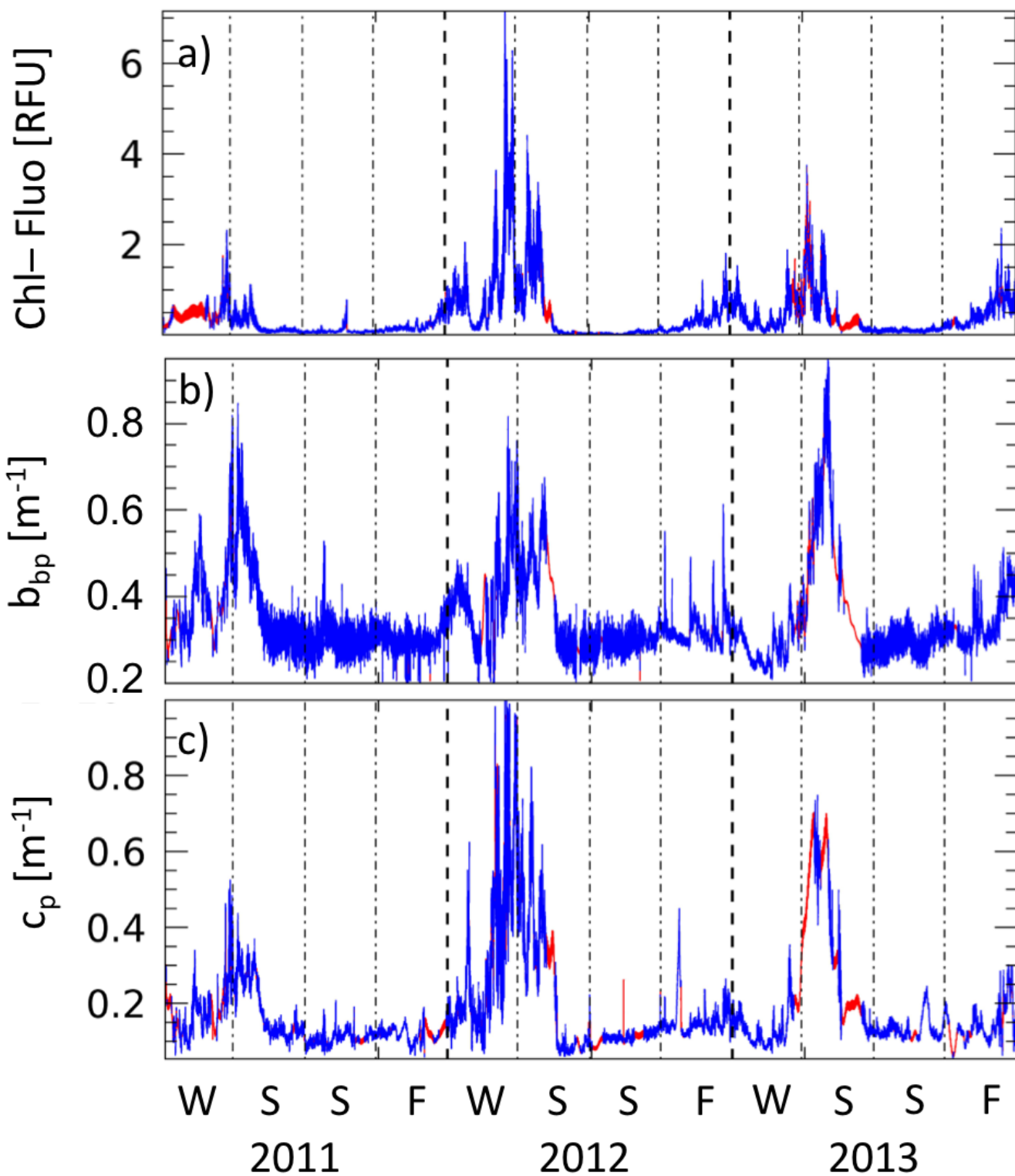
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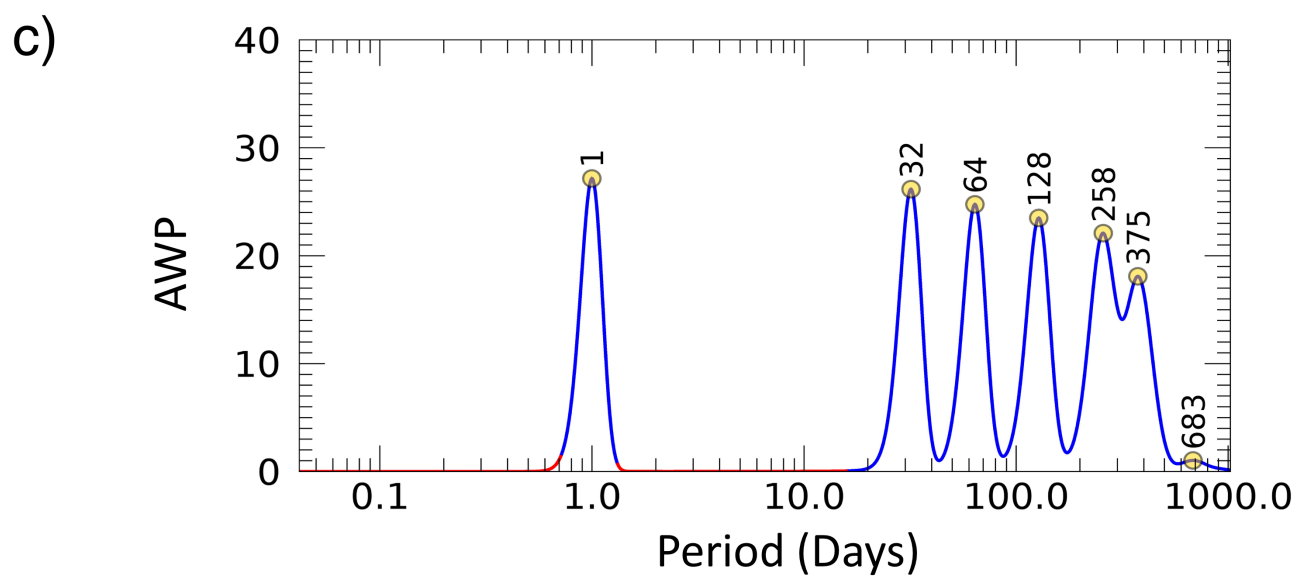
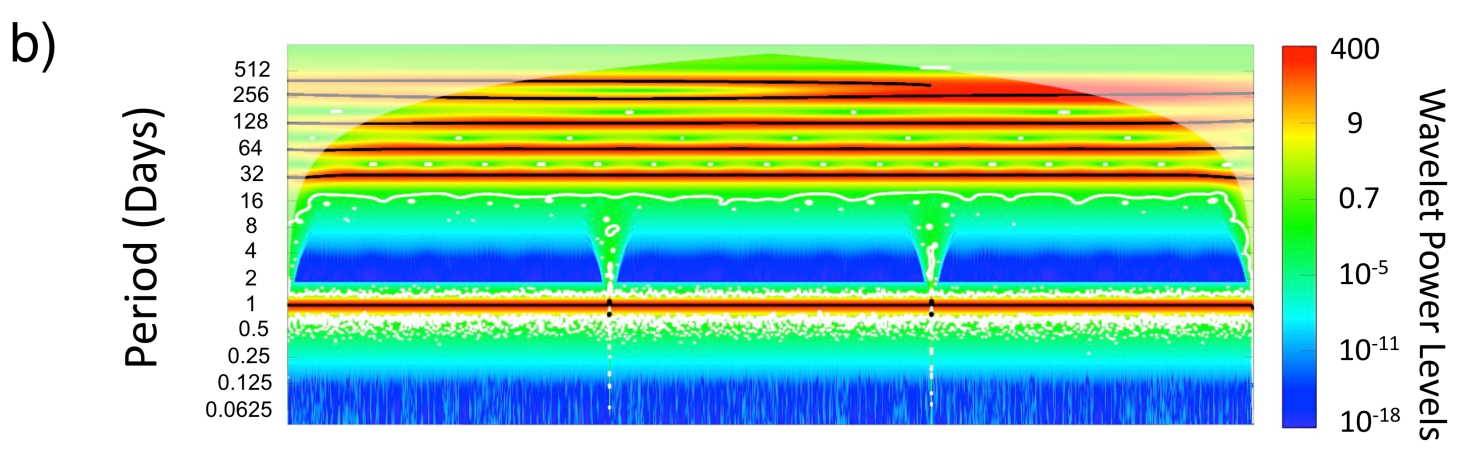
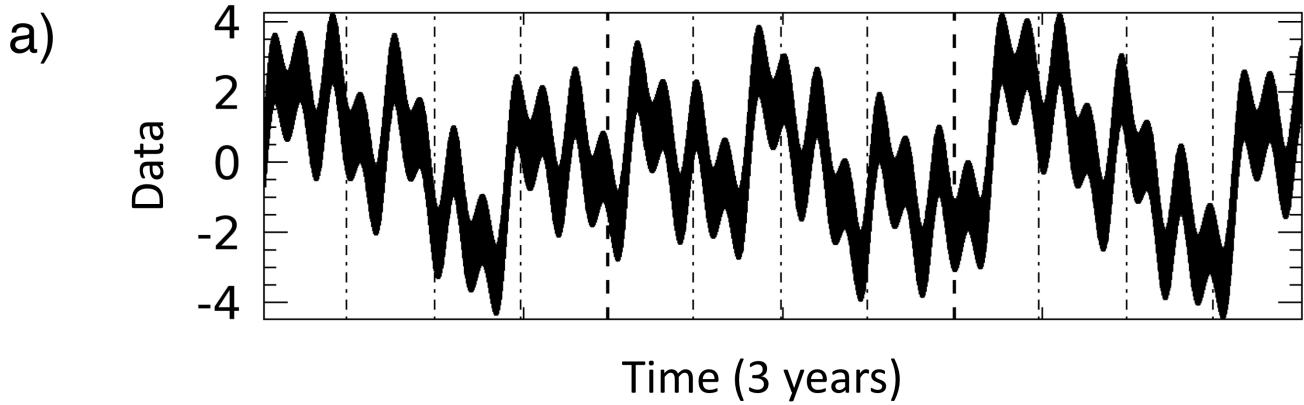
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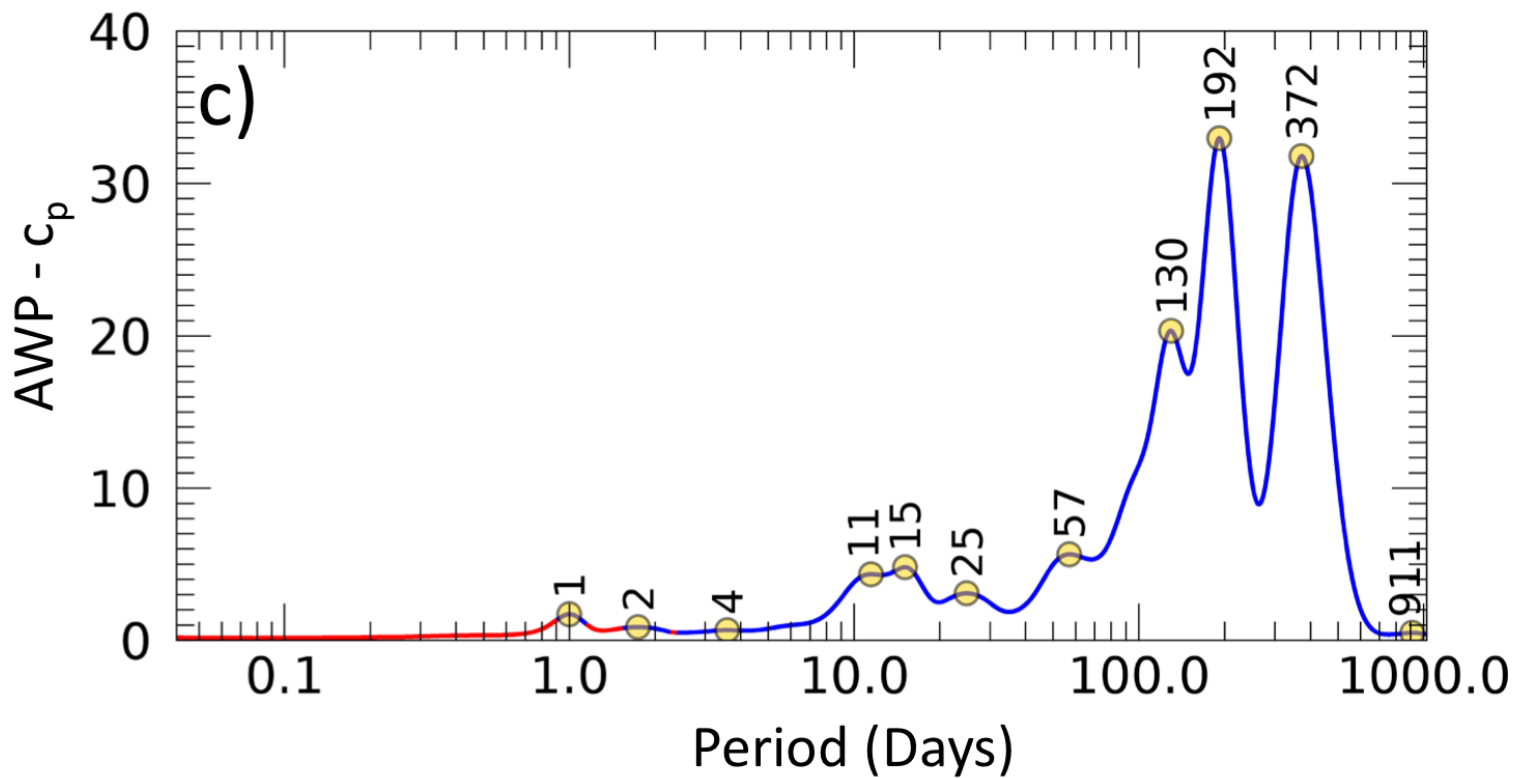
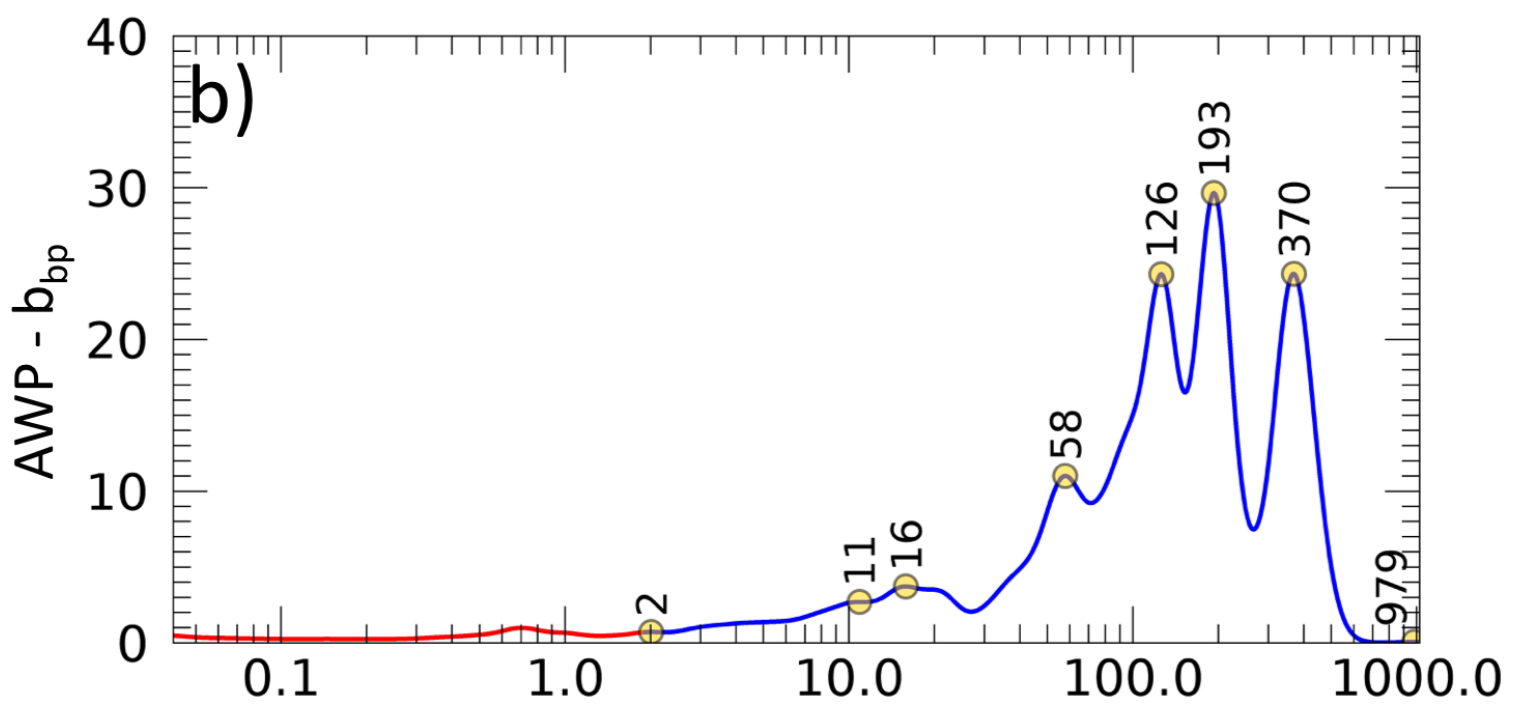
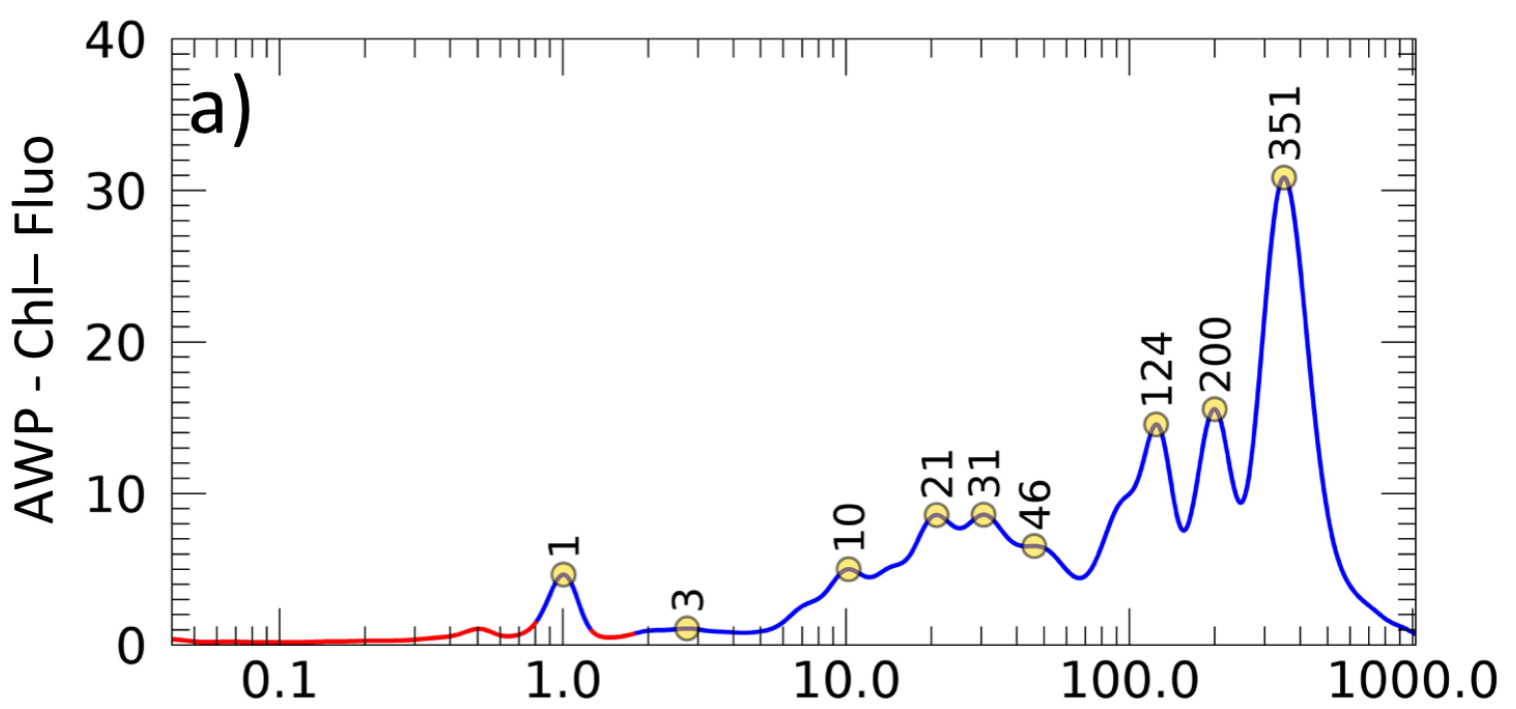
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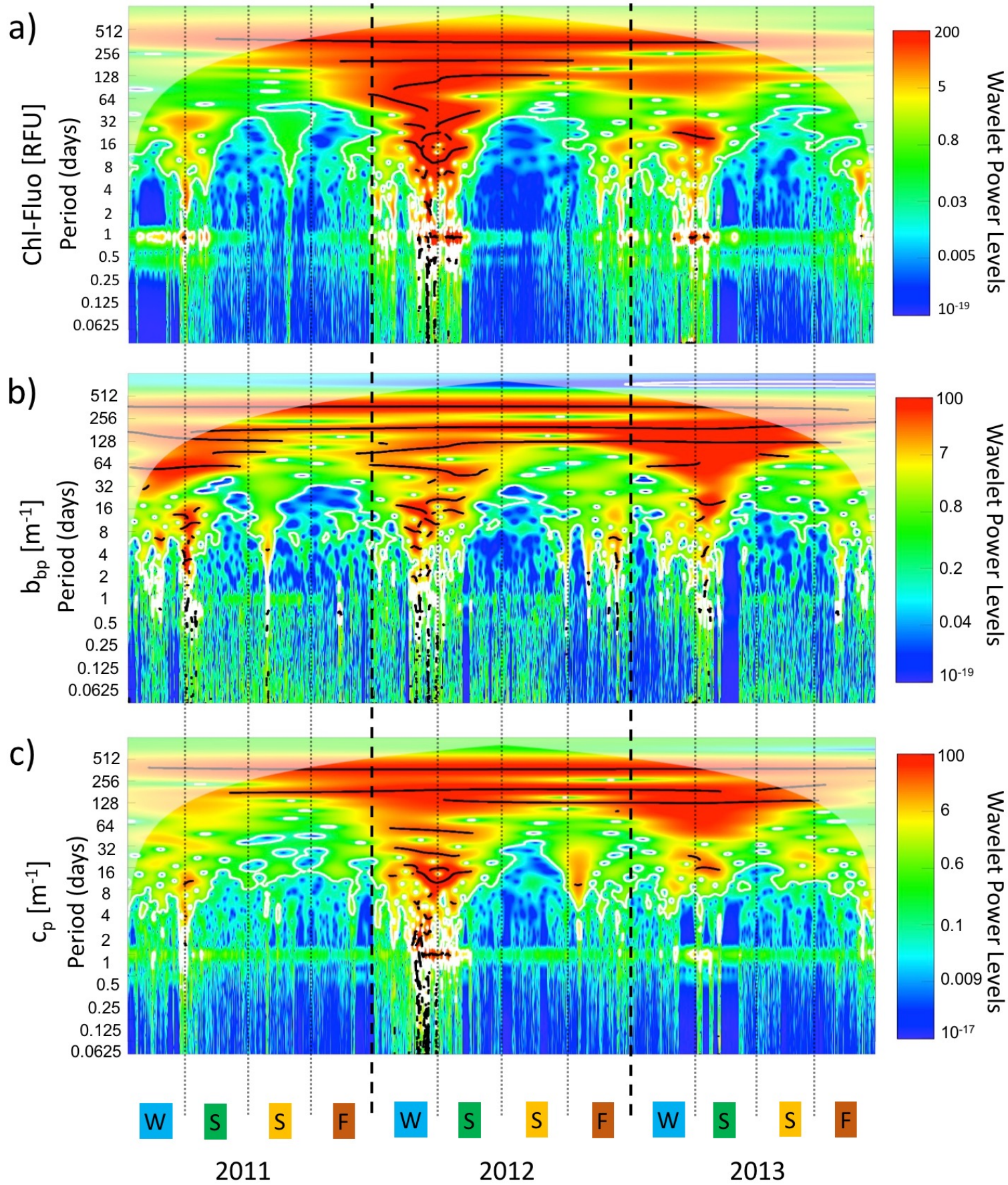


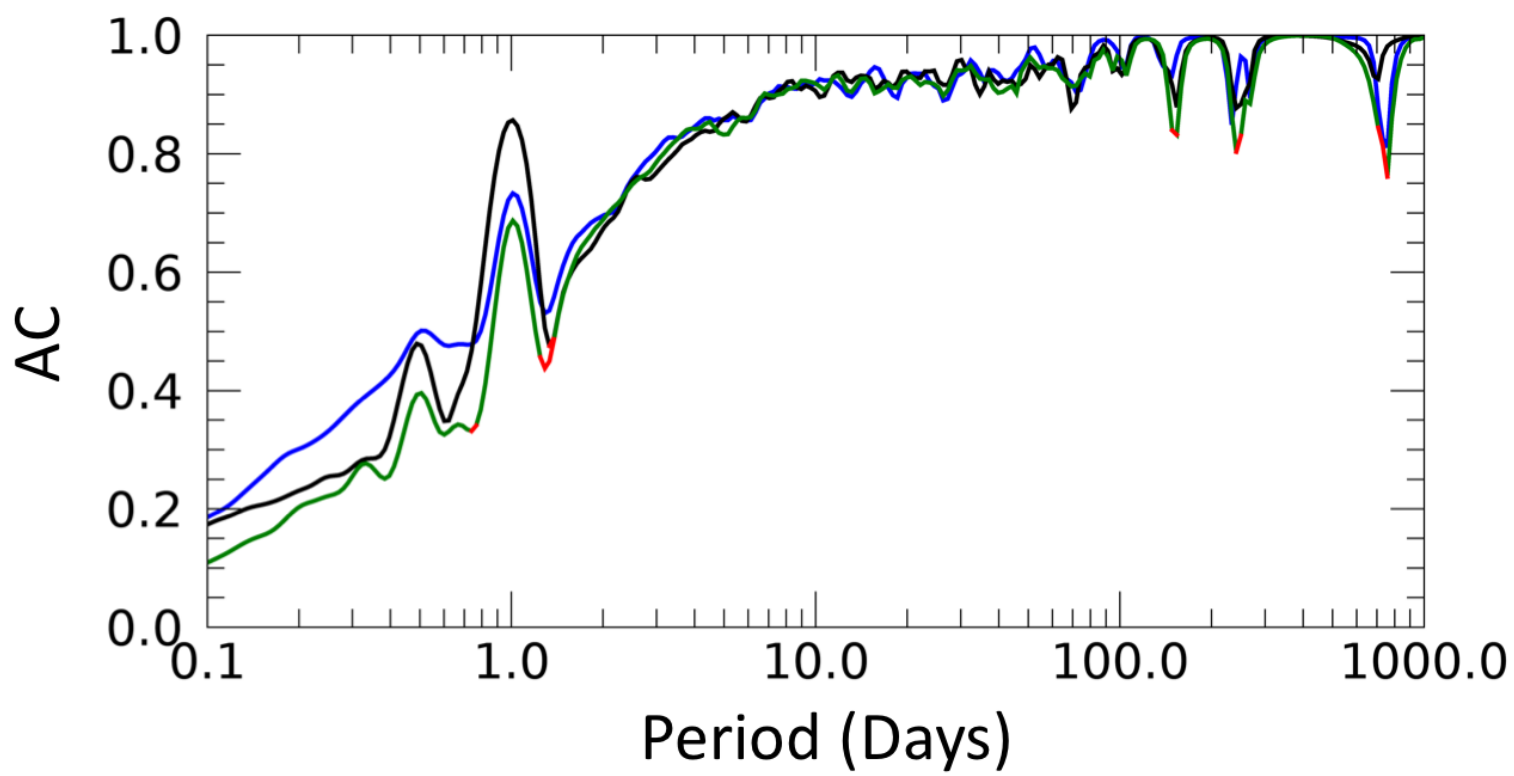


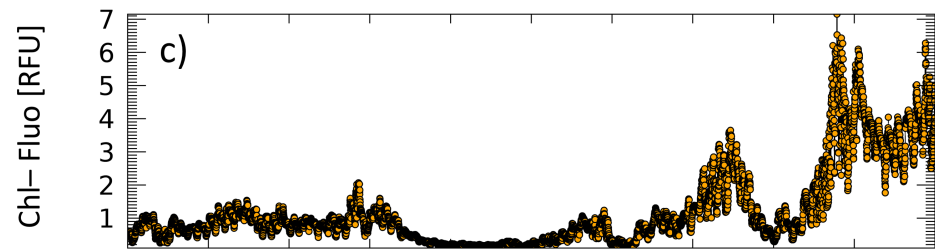
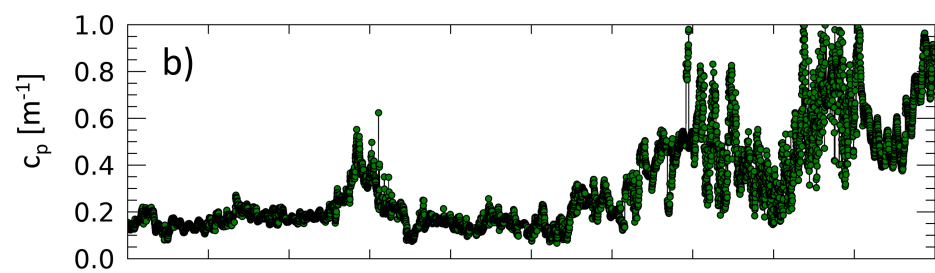
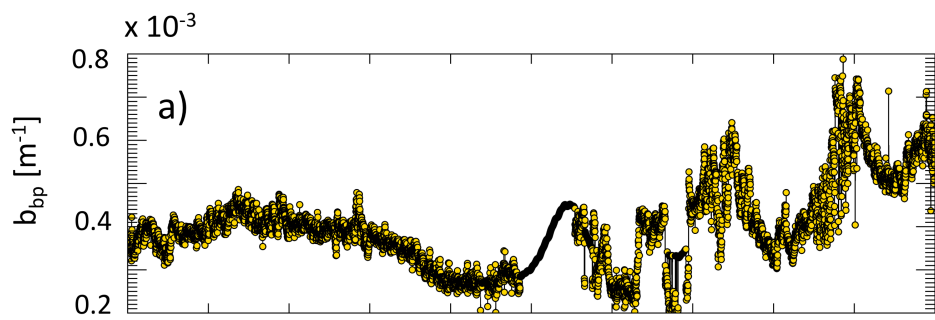




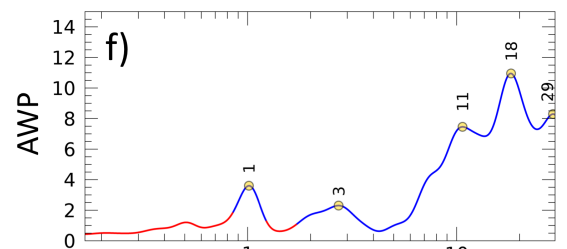
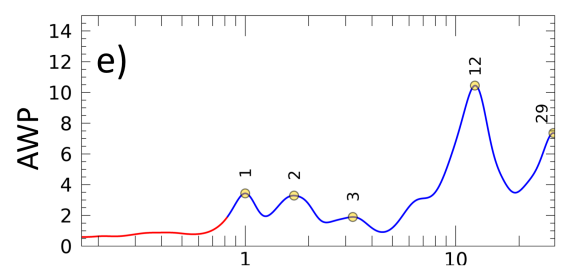
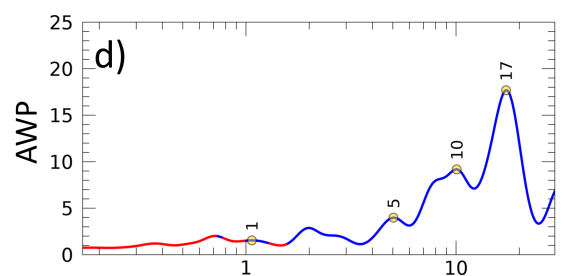






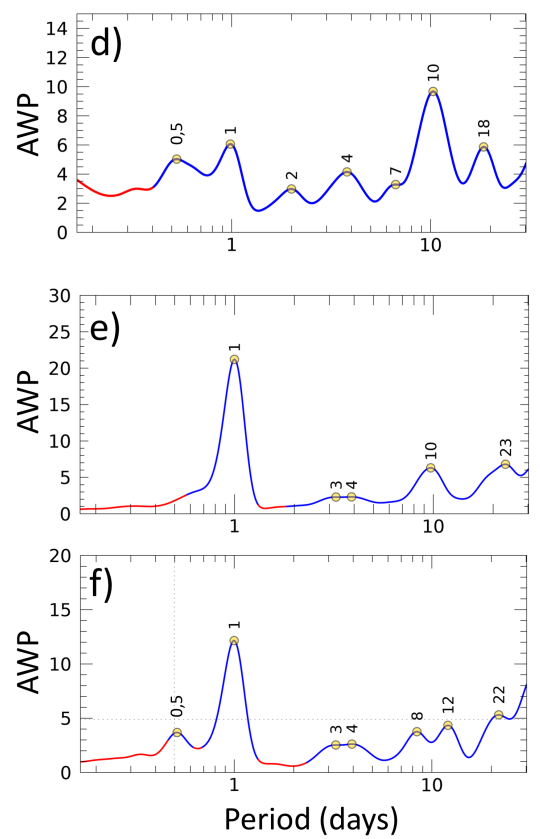
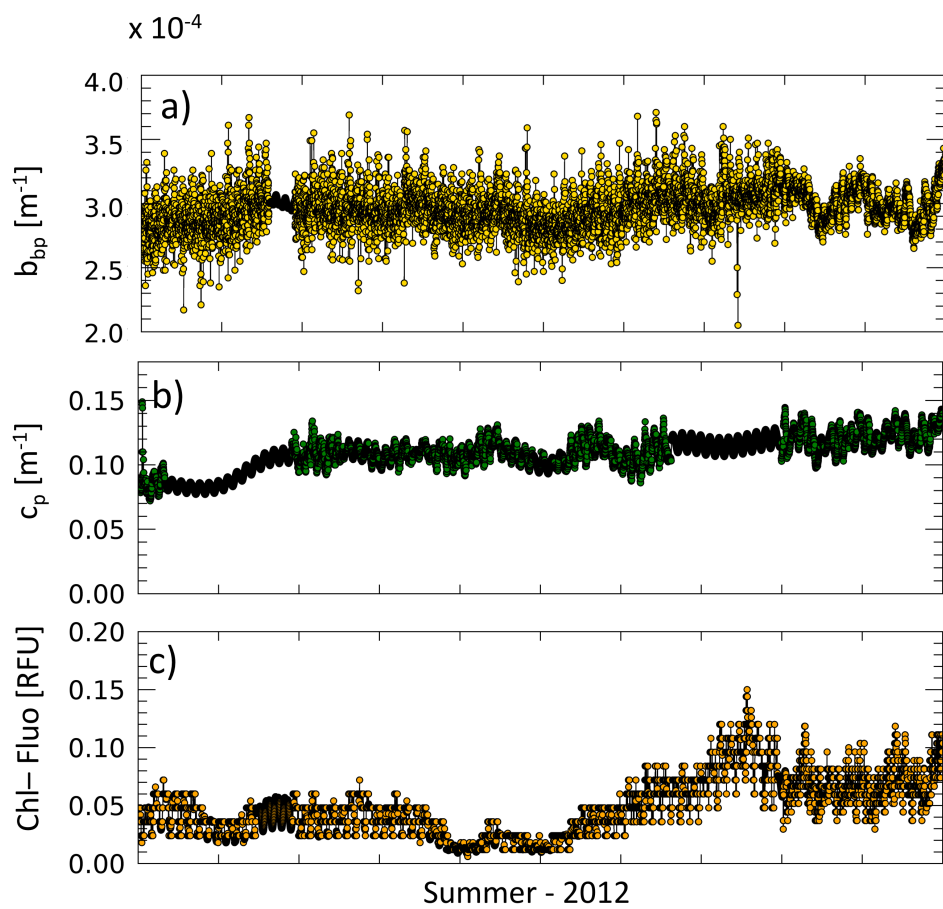


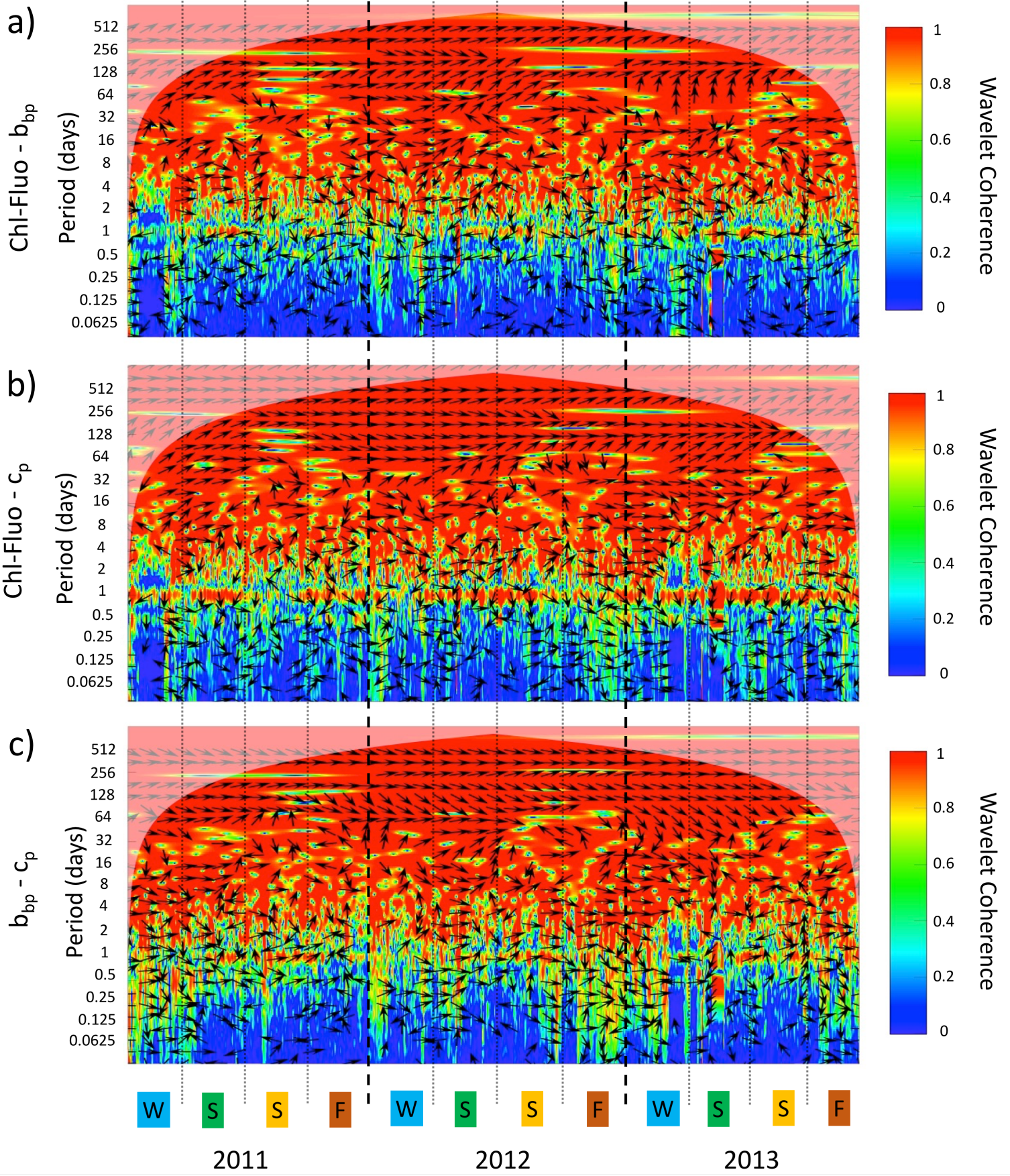
Winter - 2012



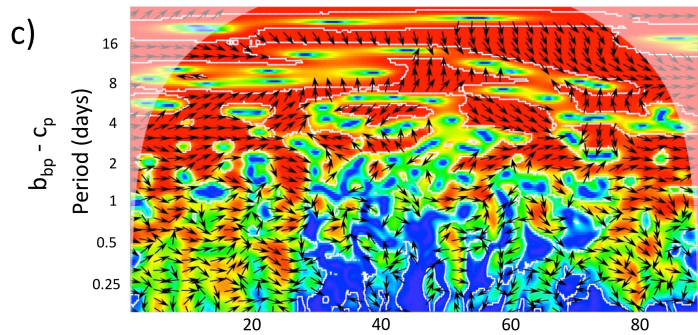
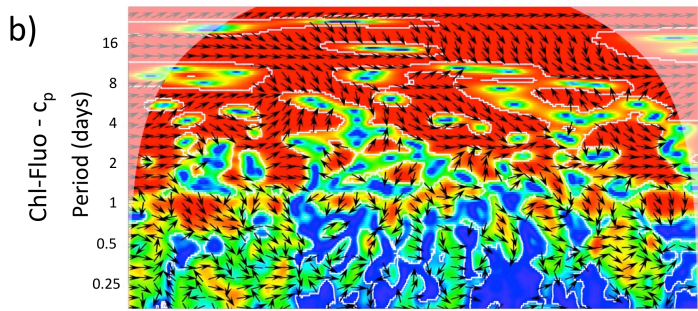
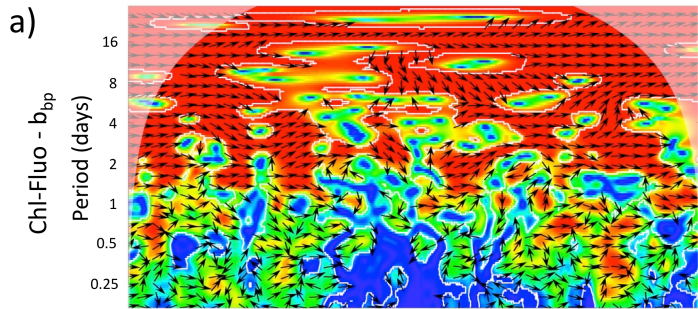
Period (days)



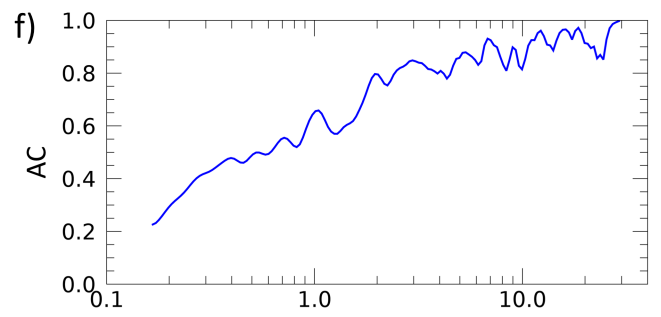
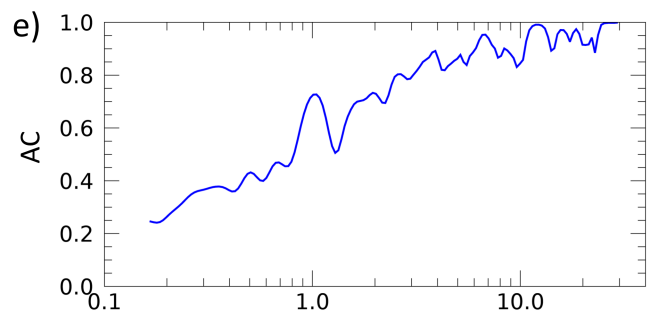
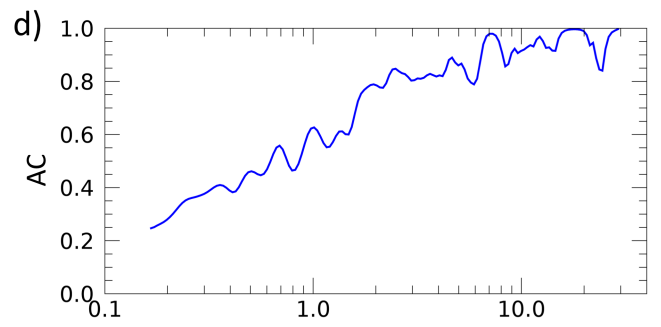








Winter 2012 (days)



Period (days)

