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1 **Physical mechanisms affecting phytoplankton variability along the** 2 **Chilean coast.**

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6 keywords: sea surface temperature, chlorophyll, precipitation, coastal upwelling, background nutrients, Chile, Northern
7 Zone, Central Zone, Southern Zone, SPSA, Ocean colour, rivers, EBUS.

8 Chile has high phytoplankton production due to being a classic example of an Eastern Boundary
9 Upwelling System. Monthly averaged chlorophyll (Chl) and physical parameters (sea surface
10 temperature, precipitation rate, southerly and westerly winds) were studied off the Chilean coast
11 from 2002 to 2018, in order to understand the primary production along this important ocean
12 margin. The coastal margin was split into three zones and ten sub-sections. The Northern Zone had
13 a low phytoplankton production with small seasonal variability, except in its north. This pattern is
14 due to a narrow shelf, weak winds, lack of precipitation and relatively stable weather conditions
15 driven by the Southeast Pacific Subtropical Anticyclone (SPSA). The Central Zone presented a
16 seasonally varying production, with a high Chl concentration in summer and early spring. This is
17 linked to the SPSA movement and sunlight reduction during the winter. A high Chl activity is seen in
18 the Southern Zone despite this Zone being at the limits of the SPSA effect, leading to weak longshore
19 winds only during the warm season. Overall, this study has demonstrated the importance of shelf
20 width and the upwelling driven by the presence or absence of the SPSA for ocean primary
21 production. Thus, the most productive region is from 35°S to 45°S owing to both variables being
22 present.

23 **1. Introduction**

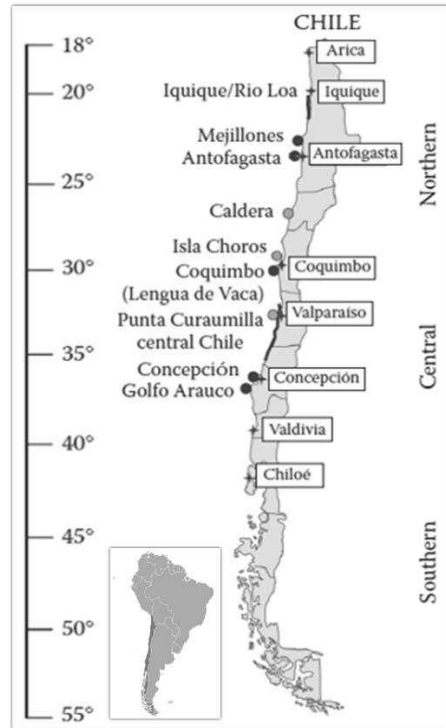
24 Eastern Boundary Upwelling Systems (EBUS) are considered the most productive zones of the
25 world's oceans (García-Reyes et al., 2015). They are dominated by seasonally-regulated upwelling
26 episodes linked to alongshore winds (Mogollón and Calil, 2017; Vergara et al., 2017). These winds
27 force the surface waters offshore to be replaced with nutrient-rich deep water. This phenomenon
28 is known as the Zonal Ekman Transport (ZET; Yuras et al., 2005; Corredor-Acosta et al., 2015; Echevin
29 et al., 2014; Gómez et al., 2012). There are many EBUSs, such as off California, Morocco, and
30 Namibia, but the most productive is in the Peru-Chilean region, owing to the Southeast Pacific
31 Subtropical Anticyclone (SPSA) and Humboldt Current System (HCS). The SPSA creates favourable
32 winds for upwelling, while HCS causes the water to be even colder and transports the nutrients
33 northwards (Ancapichun and Garcés, 2015; Yuras et al., 2005; Gómez et al., 2017). As a result, the
34 annual cycles of phytoplankton and primary production are significant, making the Peru-Chile coast
35 responsible for more than ten percent of the worldwide marine fisheries (Vergara et al., 2017;
36 Mogollón and Calil, 2017; Corredor-Acosta et al., 2015; Gómez et al., 2012; Yuras et al., 2005).

37 In the particular case of Chile, the phytoplankton concentrations display significant spatial variation
38 due to the long latitudinal coastal extension, over which the atmospheric temperatures slowly
39 decrease and the rainfall increases southwards (CONAMA, 2008). These are themselves driven

40 mainly by the SPSA and the HCS, which are intermittently perturbed by the Pacific Decadal
41 Oscillation (PDO), EL Niño Southern Oscillation (ENSO), and Antarctic Oscillation (AAO; Mogollón
42 and Calil, 2017; Ancapichun and Garcés, 2015). The SPSA generates a high-pressure system around
43 the coast that compresses and heats the descending air mass, creating stable atmospheric
44 conditions (Schultz et al., 2012). Another factor is the Andes, whose high elevations of over 5,000 m
45 contain snowpacks in their peaks, which provide a primary freshwater source for fluvial systems
46 draining to the coast (Cordero et al., 2019). Additionally, the Andes constrain the meridional spread
47 of the SPSA, enhancing its effectiveness and leading to dry weather in Chile and wet conditions in
48 the Amazon basin (Barrett et al., 2009; Schultz et al., 2012; Garreaud, 2009).

49 The Chilean coast is generally grouped into three Zones with very distinctive properties: the
50 Northern (18°-30°S), Central (30°-40°S) and Southern Zones (40°-56°S; Thiel et al., 2007; CONAMA,
51 2008; Figure 1). The Northern Zone has a climate that is extremely arid, with almost no precipitation
52 (Schultz et al., 2012). The Central Zone exhibits a Mediterranean-like climate, where most of the
53 precipitation occurs during a few winter storms (Garreaud et al., 2020). Finally, the Southern Zone
54 is considered to have a hyper-humid climate (Aguayo et al., 2021). The cycles mentioned in the
55 northern and Central Zones are driven by SPSA movement to the north during the winter, allowing
56 more stable weather conditions in the north and precipitation events during the winter (Aguirre et
57 al., 2021). By contrast, the Southern Zone is only affected by the SPSA in the summer south to
58 around 42°S (Ancapichun and Garcés, 2015).

59 The Northern and Central Zone coastlines are relatively straight (N-S; Figure 1). However, the coastal
60 topography produces current variations that are hard to predict (Thiel et al., 2007). This leads to the
61 formation of complex bay circulation systems, with counter-rotating gyres, which could affect the
62 plankton dynamics. This is more marked in the Southern Zone due to its intricate geography; with
63 many archipelagos and fjords mainly located south of Chiloe Island (Iriarte et al., 2007). At the same
64 time, along the Chilean coast there exist areas with strong upwelling due to their topographic capes
65 generating eddies and filaments. These are in Mejillones-Antofagasta (23.1°-23.6°S), Coquimbo
66 (30°S), Valparaiso (33°S) and Concepción (36.8°S; Figure 1; Thiel et al., 2007; Gómez et al., 2012).



67

68 FIGURE 1. STUDY AREA WITH THE PRINCIPAL UPWELLING REGIONS LOCATED, THE GREY POINTS ARE ZONE WITH FREQUENT UPWELLING, WHILE THE BLACK
 69 DOTS ARE THE MAIN UPWELLING FILAMENTS ZONES. FINALLY, THE BLACK LINES SHOW THE COASTAL SECTIONS WITH OCCASIONAL UPWELLING (THIEL ET
 70 AL., 2007).

71 Another significant difference between Zones is the ocean shelf width, which is a key factor in the
 72 ocean remineralisation process (Thiel et al., 2007). The Northern Zone has a narrow continental
 73 shelf, in places of less than 10 km width (Ancapichun and Garcés, 2015; Marchant et al., 2007; Jacob
 74 et al., 2011). However, the region near Peru has a broad shelf that continues north until Arica
 75 (Echevin et al., 2014; Thiel et al., 2007; Cortés et al., 2017). This shelf below 10 km width continues
 76 south until 35°S (Marchant et al., 2007). Then, its width southwards until 40°S varies from 40 to 70
 77 km, except near the Arauco Peninsula (37-38°S), where it reduces to 12 km (Thiel et al., 2007;
 78 Marchant et al., 2007). Finally, the Southern Zone along with its intricate geography, has a shelf over
 79 70 km wide and reaching more than 100 km at 46°S (Strub et al., 2019; Marchant et al., 2007). The
 80 shelf edge has a depth of 150-200 m (Marchant et al., 2007; Cortés et al., 2017).

81 Previous studies have mainly covered specific zones of Chile; specifically, the Central-Southern Zone
 82 (e.g. Vergara et al., 2017; Corredor-Acosta et al., 2015; Gómez et al., 2017; Ferreira et al., 2020).
 83 This leaves much of the long and varied Chilean coast unstudied. This is very important because the
 84 Chilean coastline has an evident multi-zone character, from experiencing the southern end of the
 85 Peruvian high productivity through a region with less production and less extensive production to a
 86 higher production region in the Southern Zone. Therefore, this overall study covers the whole
 87 territory and will help to understand which regions are more productive. This information is also
 88 valuable as a first stage for developing better fisheries strategies.

89 This study aims to understand and quantify the physical mechanism that controls alongshore
 90 phytoplankton production along the entire Chilean coastline [18.3°S to 53.5°S]. The objectives are
 91 (i) to estimate the trends in seasonal, interannual and spatial variability for parameters that are

92 known to affect phytoplankton production and (ii) to compute an order of magnitude analysis of
93 the main nutrient sources.

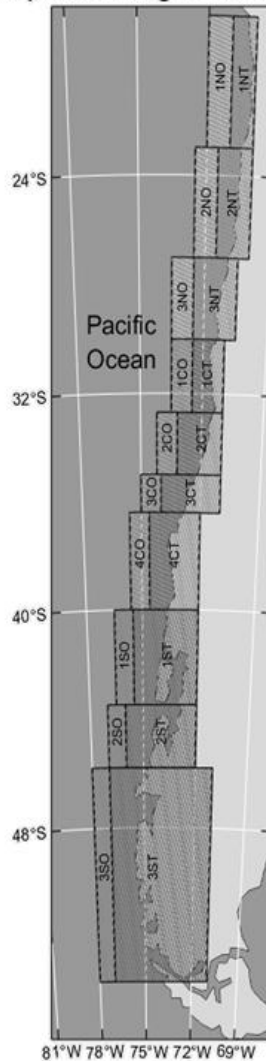
94 **2. Material and Methods**

95 2.1. Study Area

96 Each hydroclimatic zone along the Chilean coast was studied [North[N], Central[C] and South[S]],
97 and these were further subdivided into 3 or 4 subsections [N1, N2, etc] (Figure 2). The main criterion
98 used in generating these zones were (i) to account for the complexity of the coastline, and likely
99 variation in phytoplankton behaviour in relation to significant capes and embayments, and (ii)
100 maintaining a 100-150 km sample width across the coastal edge. The relative simplicity and roughly
101 straight N-S-oriented coastline (Thiel et al., 2007), particularly in the Northern Zone facilitated sub-
102 division into three subsections (Figure 2). On the other hand, the Central Zone geography has a more
103 pronounced curved area, especially in the region 32.7-35°S so here, four subsections were used.
104 Additionally, we note that subsections 3C and 4C have been intensively studied previously due to
105 their relatively high recorded phytoplankton production (e.g. Vergara et al., 2017; Corredor-Acosta
106 et al., 2015). Thus, some of our subdivisions were designed to allow direct comparison with past
107 work. The Southern subsection includes a more complex domain (Lara et al., 2010). Here the sub-
108 subsections were selected to focus on Chiloé Island [subsection 1S], one of the most studied territories
109 (Figure 2). The 2S-3S subsections were chosen to account for an increasing curve in the coastal edge
110 between 45.8°-47°S. Although the area from 47°-50°S is relatively straight, westerly winds start to
111 dominate from 50° to 53.5°S, and thus we adjust the final subsection (3S; 50°-53.5°S) to have a width
112 of 250 km.

113 Within the study area, the Chilean coastal shelf width is variable and locally defines the nearshore
114 and offshore subsection delimitation used here (Thiel et al., 2007). Authors like Vergara et al. (2017),
115 Yuras et al. (2005), and Gómez et al. (2017) considered a 100 km offshore distance to define their
116 study area. However, this value is approximately the maximum Chilean shelf width located in the
117 Southern Zone (Thiel et al., 2007). Both nearshore and offshore subsections, are expected to exhibit
118 different phytoplankton concentrations due to the likely change in depth and other mechanisms
119 (i.e., upwelling) noted above. However, a paired study of each is important because their behaviour
120 might be related over time. For that reason, the coastal strip region studied here was widened to
121 move beyond the coastal shelf and coded as T [Terrestrial], and O [Oceanic]. We include a distance
122 where the surface waters are dragged during the upwelling in Chile's Northern and Central Zones
123 (Thiel et al., 2007). Therefore, the width per subsection was defined as between 1°-1.5°, equivalent
124 to almost 100-150 km. This ensures that the whole shelf is part of each nearshore subsection and is
125 consistent with the width used by the mentioned authors. Typical ocean depths at the edge of the
126 offshore and nearshore subsection vary between 2,600-5,000 m, except for 1NT, which has a
127 maximum depth of 778 m in its edge subsection. This is the shallowest of the sample scheme. This
128 border is at the limit of Peru and presents a curve that increases the shelf width in that area. As
129 such, 1NT is a relatively small subsection that is only impacted by this change in shelf width at its
130 northern termination.

Chilean Map delimitating the zones of the study



131

132 FIGURE 2. CHILEAN MAP DELIMITING THE ZONES (N: NORTH, C: CENTRAL AND S: SOUTH) OF STUDY AND ITS SUBSECTION (T: TERRESTRIAL,
133 O: OCEANIC).

134 2.2. Variables Selection and Data Collection

135 The main variable, Chlorophyll- α (Chl) is a proxy for phytoplankton biomass, which acts as a proxy
136 for phytoplankton concentration, and which it can be routinely obtained via remote sensing e.g.
137 MODIS-Aqua (Franz et al., 2005; Falkowski, 1994). Although Chl measured by MODIS-Aqua [Ocean
138 Color 3M algorithm; <https://oceancolor.gsfc.nasa.gov/>] gives an adequate estimate of phytoplankton
139 concentration, it is known that algorithm retrieves in the shallow coastal region, where
140 phytoplankton is usually present, due to the combined impacts of bottom reflectance and turbidity
141 (Yang et al., 2018; Abbas et al., 2019). However, this relative lack of precision is minimised here as
142 we focus upon monthly Chl tendencies across a relatively long time series [2002-2018].

143 The primary physical mechanism affecting phytoplankton within the study region is upwelling along
144 the Chilean coast. This phenomenon is provoked by equatorward coastal winds (Mogollón and Calil,

145 2017; Vergara et al., 2017). Upwelling also brings deep cold and nutrient rich water to the surface.
 146 So, it creates a temperature decrease in the surface and sub-surface (Ancapichun and Garcés, 2015;
 147 Yuras et al., 2005). Thus, SST, wind speed, and direction are vital factors in the investigation, because
 148 these wind components make it possible to estimate upwelling and therefore the relative nutrient
 149 addition to the surface.

150 The precipitation rate (PR) was included as well. The PR parameter tends to exhibit contrasting
 151 trends in the Northern and Southern Zones, while the Central Zone presents an intermediate
 152 behaviour (Thiel et al., 2007). This parameter is likely to affect phytoplankton differently, depending
 153 on the amount of rain and the season of occurrence. For example, Thompson et al. (2015) found a
 154 positive relationship with the Chl when rainfall occurs during the warm season (spring-summer).
 155 Nonetheless, PR does not have the same effect during the cold seasons (autumn-winter). The data
 156 were mainly collected from satellite imagery and reanalysis methods extracted by the website GES
 157 DISC (Goddard Earth Sciences Data and Information Services Centre) Interactive Online Visualization
 158 and Analysis Infrastructure (GIOVANNI; <https://giovanni.gsfc.nasa.gov/giovanni/>) summarised in
 159 Table 1.

160 TABLE 1. PARAMETERS USED FROM THE GIOVANNI DATABASE (NASA, 2018).

Parameter	Unit	Source	Temp res.	Spatial res.
Chl	mg m ⁻³	MODIS-Aqua	Monthly	0.04° x 0.04°
SST 11µm (day)	°C	MODIS-Aqua	Monthly	0.04° x 0.04°
Precipitation Rate	mm mth ⁻¹	TRMM	Monthly	0.25° x 0.25°
Westerly wind (10m)	m s ⁻¹	MERRA-2	Monthly	0.63° x 1.25°
Southerly wind (10m)	m s ⁻¹	MERRA-2	Monthly	0.63° x 1.25°

161 The period studied here was from July 2002 to June 2018. This period was chosen because it aligns
 162 with the availability of a continuous time series of MODIS-Aqua Chl data. In this way it was possible
 163 to avoid uncertainty arising from the use of different sensor and orbital parameters (Franz et al.,
 164 2005). For the first objective, these values were averaged on a monthly basis per Zone and
 165 subsection. These data were initially interrogated using boxplots and summary statistical analyses,
 166 both seasonally and interannually. Following this, relationships between Chl and other parameters
 167 were studied using correlation analysis per subsection. Here, Spearman correlation was selected
 168 instead of Pearson as the variable response in each subsection was typically skewed, thereby not
 169 confirming with assumptions associated with normal distribution (Xiao et al., 2016).

170 The ZET calculation (see below for details) was also done using these data, but it was averaged per
 171 Zone and season. Background nutrient concentrations of NO₃⁻, SiO₄²⁻ and PO₄²⁻ were obtained from
 172 García et al. (2010) in the World Ocean Atlas (2009). Finally, it was compared the nutrient addition
 173 by upwelling, precipitation and main rivers addition.

174 The upwelling nutrient was estimated using the equations below. The rivers addition in the Central
 175 Zone was previously estimated by Masotti et al. (2018), meanwhile the Southern Zone rivers were
 176 computed based on averaged fluxes multiplied by the typical nutrient concentrations reported by
 177 Castro (2010).

178 Even though no studies about the nutrient concentration in the rainfall in the South Pacific were
 179 found in this investigation, they can be inferred from South Atlantic data. Baker et al. (2010), which

180 are approximately 2.8-3.5 nmol m⁻³ and 0.0124-0.0146 nmol m⁻³ for NO₃⁻ and PO₄²⁻, depending on
181 the PR intensity. The SiO₄²⁻ is negligible in the PR, so only NO₃⁻ and PO₄²⁻ were considered.

182 2.3. Upwelling calculation

183 ZET can be calculated to estimate the upwelling and define how much nutrient is supplied to the
184 surface. ZET depends on the meridional wind stress (WS_y). Although this variable is not obtained by
185 satellite imaging, it can be derived from wind speed using the following equation (Gómez et al.,
186 2012).

$$187 \quad WS_y = \rho_a \cdot C_d \cdot (V) \cdot VW \quad (1)$$

188 Where ρ_a is air density (1.2 kg m⁻³), C_d is the drag coefficient (0.0012) based on observational data
189 for winds below 10 m s⁻¹, (V) is the wind speed, and VW is the southerly wind component. Then,
190 the ZET is calculated (Ancapichun and Garcés, 2015; Gómez et al., 2012; Liao et al., 2016). Here, the
191 geostrophic transport is considered negligible (Liao et al., 2016).

$$192 \quad ZET = \frac{WS_y}{\rho_w f} \quad (2)$$

193 Where ρ_w is the seawater density (1026.97 kg m⁻³), and f is the Coriolis effect. The Coriolis effect
194 can be easily estimated by $2\Omega \sin\theta$; where Ω is the Earth's angular velocity ($7.292 \cdot 10^{-5} \text{ s}^{-1}$) and θ is
195 the latitude of the study area. Negative ZET values imply offshore transport or the opposite if it is
196 positive (Ancapichun and Garcés, 2015; Gómez et al., 2012). The vertical speed of the ZET
197 determines the speed of upwelling or downwelling, here called the Ekman pumping (EP), and is
198 defined by the following equations (Ancapichun and Garcés, 2015; Ancapichun, 2012; Bravo et al.,
199 2016).

$$200 \quad EP = \frac{Curl(WS)}{\rho_w f} + \frac{\beta \cdot WS_x}{\rho_w f^2} \quad (3)$$

$$201 \quad Curl(WS) = \frac{WS_y}{\partial x} + \frac{WS_x}{\partial y} \quad (4)$$

202 The second term of Eq.3 is generally rejected because β represents the rate of variation of the
203 Coriolis between the latitudes in the Ekman transport, which is insignificant (Bravo et al., 2016). The
204 Curl represents the Ekman's spiral spin (Bigg, 2003). Finally, the upwelling nutrient concentration
205 (mmol m⁻¹ s⁻¹) can be obtained as total vertical transport multiplied by the concentration of that
206 nutrient at the depth of the Ekman layer (Liao et al., 2016).

$$207 \quad N_{supply} = ZET \cdot (N_D)_{Rossby} + EP \cdot (N_D)_{coastal\ band} \quad (5)$$

208 The depth of the Ekman layer can be estimated in many ways. Vergara et al. (2017) suggest an 80-
209 100m depth in the Central Zone. The concentration multiplied by the ZET is at the coast but with a
210 Rossby radius deformation product of the Coriolis variation along the latitude. Therefore, the radius
211 will be shorter at higher latitudes. In comparison, the EP is multiplied by the concentration at depth
212 D but on the coast edge defined by the shelf width (Liao et al., 2016).

213

214 **3. Results**

215 The overall PR tended to increase poleward, as expected from large-scale climate considerations
 216 (Table 2). Therefore, in general, the further south the subsection was located, the more rainfall there
 217 was. The ocean strip PR (not shown) showed similar values to the coastal strip, but the latter was
 218 slightly lower, except for 3S, where its ocean strip had higher PR. SST was the only parameter that
 219 presented a similar seasonal behaviour across the whole system, with a poleward decrease of 0.5°-
 220 1.5°C per subsection (Table 2), except for subsections 2S to 3S, where there was a difference of -
 221 2°C. The highest value was reached in February (January in 1N) and the lowest value in August. The
 222 seasonal SST variability was very low, except for the warmest months. These high variations during
 223 the summer were more evident at the coast. In general, SST was driven by the annual cycle in the
 224 whole climate system with minor variations.

225 Table 2. Statistical summary of PR (mm month⁻¹) and SST (°C) per subsection in the coastal strip, where μ is the mean
 226 and SD is the Standard Deviation.

Zones	Northern Zone			Central Zone				Southern Zone		
Subsection	PR1NT	PR2NT	PR3NT	PR1CT	PR2CT	PR3CT	PR4CT	PR1ST	PR2ST	PR3ST
Max	15.00	20.52	79.55	108.96	170.94	275.04	289.52	276.03	277.60	164.00
μ	2.43	2.90	3.58	11.38	33.02	56.43	87.49	108.57	124.46	84.40
SD	2.70	3.71	8.00	18.14	42.56	62.09	69.79	59.19	48.41	26.42
Min	0.02	0.01	0.00	0.03	0.05	0.06	2.34	22.38	35.66	35.75
Higher than ($\mu+2SD$)	9	11	7	11	11	10	9	10	6	6
Lower than($\mu-2SD$)	0	0	0	0	0	0	0	0	0	0
Subsection	SST1NT	SST2NT	SST3NT	SST1CT	SST2CT	SST3CT	SST4CT	SST1ST	SST2ST	SST3ST
Max	24.51	23.01	21.94	21.24	20.51	18.84	17.34	16.81	15.48	13.07
μ	19.99	18.40	16.82	15.90	15.44	14.50	13.98	12.93	11.78	9.72
SD	2.00	2.32	2.20	2.04	1.92	1.62	1.71	1.82	1.79	1.53
Min	15.62	13.90	13.01	12.32	11.98	11.42	10.66	9.89	8.89	6.74
Higher than ($\mu+2SD$)	1	0	4	4	5	4	0	2	1	5
Lower than($\mu-2SD$)	2	0	0	0	0	0	0	0	0	0

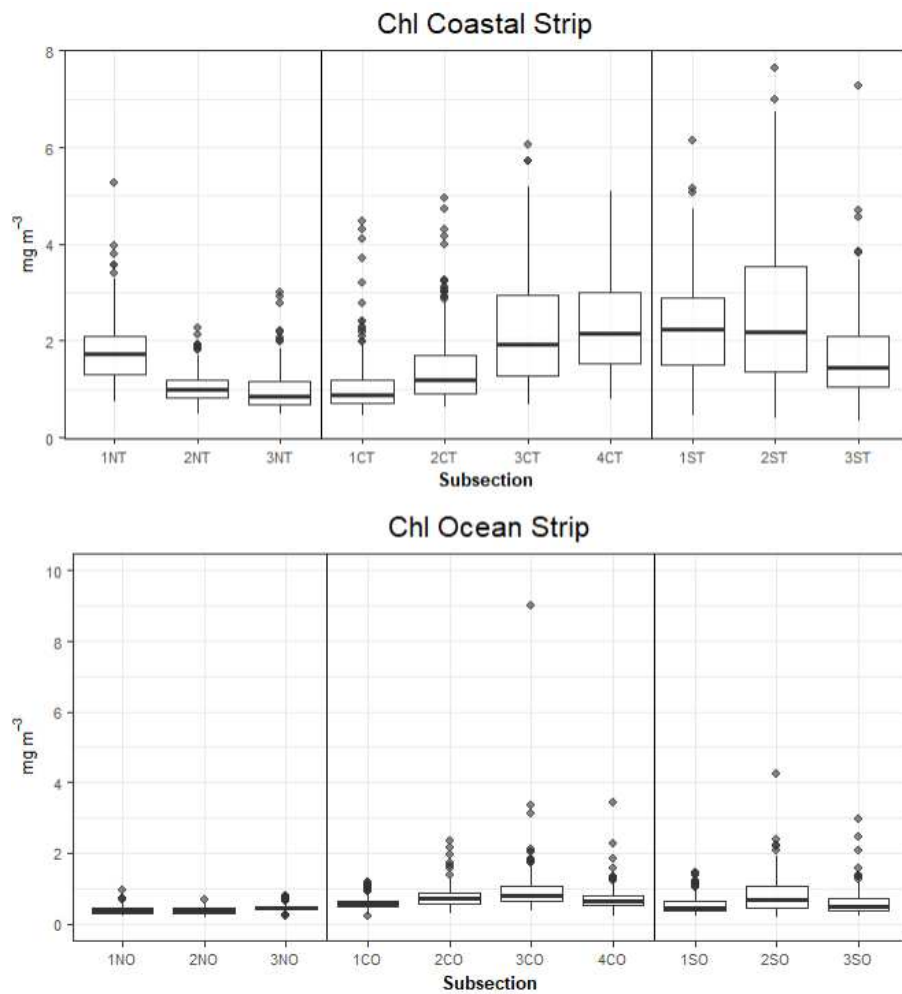
227 Table 3. Statistical summary of southerly and westerly winds VW and UW in (m s⁻¹) per subsection in the coastal strip.

Zones	Northern Zone			Central Zone				Southern Zone		
Subsection	VW1NT	VW2NT	VW3NT	VW1CT	VW2CT	VW3CT	VW4CT	VW1ST	VW2ST	VW3ST
Max	4.88	7.70	10.35	10.78	10.08	11.37	9.41	5.60	5.32	3.83
μ	3.93	5.06	6.51	7.02	5.45	5.27	3.25	0.58	-0.21	-1.79
SD	0.35	0.88	1.36	1.70	2.13	2.83	3.10	2.25	2.09	1.99
Min	2.68	3.01	3.09	2.79	-0.34	-2.69	-4.25	-4.28	-4.89	-7.21
Higher than ($\mu+2SD$)	4	8	5	2	2	1	0	3	8	8
Lower than($\mu-2SD$)	3	1	3	5	6	7	5	2	2	4
Subsection	UW1NT	UW2NT	UW3NT	UW1CT	UW2CT	UW3CT	UW4CT	UW1ST	UW2ST	UW3ST
Max	2.14	2.20	2.99	2.40	3.96	4.30	3.84	5.37	6.94	8.72
μ	1.59	1.75	1.98	1.61	2.38	2.56	1.99	2.48	3.73	5.18
SD	0.31	0.19	0.32	0.42	0.80	0.90	0.92	1.14	1.56	1.92
Min	0.86	1.29	1.25	0.59	0.56	0.25	-1.41	-3.06	-4.03	-3.08
Higher than ($\mu+2SD$)	0	6	3	0	0	0	1	1	2	0
Lower than($\mu-2SD$)	3	4	4	2	5	3	6	5	6	3

228 VW presented a southerly wind dominance with a seasonal behaviour such that this variable's values
 229 reached a maximum in summer and decreased during winter from 1C to 2S (Table 3). This
 230 seasonality increased polewards with 4C reaching the higher range. The Southern Zone exhibited
 231 the opposite effect decreasing the seasonal difference further south (Table 3). 4C and 1S had

232 northerly winds during the winter. The 3S general trend was to have northerly winds the entire year,
 233 whereas 2S's southerly winds were more frequent in the summer, particularly in February. The UW
 234 (Westerly Wind component) showed westerly wind dominance with weak values and a low variation
 235 in 1N-1C, while this component was more significant in 2S-3S (Table 3). The rest of the subsections
 236 had intermediate UW values. The behaviour of this component showed weak values during the
 237 winter and strong during the summer over 2C and 3C. From 4C to 3S, UW's seasonal trend was not
 238 influenced by the seasons, but it had a significant variation. This was more marked in 2S and 3S,
 239 where westerly winds reached magnitudes over 7 m s^{-1} in the winter and 5 m s^{-1} in the rest of the
 240 year.

241 Figure 3 and Table 4 indicate that in terms of Zones, the Southern Zone had the highest productivity,
 242 followed by the Central Zone. Although the Northern Zone usually had the lowest Chl coastal levels,
 243 the subsection close to Peru (1NT) had slightly higher productivity. In terms of subsections, 2NT to
 244 1CT showed the lowest Chl concentration but with very similar variability. However, 1CT had more
 245 outliers than the rest, reaching the highest concentrations among this group.



246

247

FIGURE 3. CHL BOXPLOT FOR EACH SUBSECTION, SEPARATED BY ZONE AND STRIP. SEE FIGURE 2 FOR ZONE DEFINITION.

248 The higher productivity was reached in 3CT to 2ST, followed by 3S and 1NT, while the lower
 249 production was in 3NT and 1CT. This was unexpected because the SPSA, responsible for longshore
 250 winds, is more intense in 3NT and 1CT while it generally is not present in the Southern Zone (Table
 251 3; Aguirre et al., 2021; Ancapichun and Garcés, 2015).

252 The ocean strip had lower Chl levels than the coast, with low variability in the complete system
 253 (Figure 3). From 1NO to 1CO, the variability was particularly low, while the rest exhibited a slightly
 254 higher variability. Effectively, from 3CO towards 3SO, the number of extreme outliers increased
 255 significantly.

256 TABLE 4. STATISTICAL SUMMARY OF THE CHL (MG M⁻³) PER SUBSECTION IN THE COASTAL AND OCEAN STRIP, WHERE μ IS THE MEAN AND SD IS THE
 257 STANDARD DEVIATION.

Zones	Northern Zone			Central Zone				Southern Zone		
Subsection	Chl1NT	Chl2NT	Chl3NT	Chl1CT	Chl2CT	Chl3CT	Chl4CT	Chl1ST	Chl2ST	Chl3ST
Max	5.25	2.25	2.99	4.47	4.94	6.06	5.08	6.15	7.64	7.27
μ	1.80	1.04	0.99	1.08	1.45	2.21	2.36	2.28	2.55	1.66
SD	0.68	0.32	0.45	0.64	0.80	1.17	1.04	1.03	1.46	0.90
Min	0.75	0.48	0.50	0.46	0.61	0.68	0.78	0.46	0.39	0.34
Higher than ($\mu+2SD$)	9	10	8	8	10	9	9	7	7	7
Lower than ($\mu-2SD$)	0	0	0	0	0	0	0	0	0	0
Subsection	Chl1NO	Chl2NO	Chl3NO	Chl1CO	Chl2CO	Chl3CO	Chl4CO	Chl1SO	Chl2SO	Chl3SO
Max	0.96	0.67	0.81	1.17	2.34	9.01	3.44	1.45	4.23	2.96
μ	0.39	0.38	0.46	0.59	0.77	0.96	0.70	0.54	0.81	0.59
SD	0.12	0.09	0.10	0.17	0.31	0.72	0.34	0.24	0.50	0.35
Min	0.21	0.18	0.21	0.23	0.31	0.36	0.20	0.23	0.17	0.21
Higher than ($\mu+2SD$)	7	4	8	10	6	3	4	10	8	7
Lower than ($\mu-2SD$)	0	3	2	2	0	0	0	0	0	0

258 These results showed that the three Zones have different Chl concentrations. These connections
 259 were also studied by Spearman correlations in Table 5. This shows that the Northern Zone has
 260 almost no relationship between the Chl and the other parameters except for Chl~VW in 3NT. In the
 261 Central Zone Chl~VW were statistically significant in the whole Zone, excluding 2CT. These were
 262 more statistically significant in 3CT-4CT. Effectively in these subsections all the physical parameters
 263 were statistically significantly linked to Chl, but with negative correlations. On the other hand, the
 264 Chl in the Southern Zone showed significant correlations with both wind components, especially in
 265 1ST. The Chl~PR in this Zone had a significant negative relationship, especially in 1ST, while 2ST and
 266 3ST were slightly lower. Whereas the SST was only statistically significant in 3ST.

267 Table 5. Chl regression with the physical parameters per subsection in the coastal strip, the statistically significant
 268 correlations are underlined ($0.01 < P\text{-values} < 0.05$), and the statistically very significant are in bold ($P\text{-values} < 0.01$).

Rho	Chl~SST	Chl~PR	Chl~VW	Chl~UW
1NT	-0.10	0.14	0.07	-0.12
2NT	-0.13	0.05	0.09	-0.03
3NT	-0.12	-0.08	0.21	0.10
1CT	<u>-0.16</u>	-0.07	0.20	-0.03
2CT	<u>-0.15</u>	0.04	0.08	0.06
3CT	-0.19	-0.20	0.27	0.20
4CT	-0.20	-0.33	0.38	-0.27
1ST	-0.06	-0.39	0.45	-0.41
2ST	<u>0.15</u>	-0.24	0.26	-0.29
3ST	0.20	-0.20	0.23	-0.32

269

270 4. Discussion

271 As it was mentioned in section 2.2 it is known that the algorithm retrieves in the shallow coastal
272 zone, where phytoplankton is usually present. However, this relative lack of precision is not as
273 relevant because here we are discussing monthly Chl tendencies across a relatively long time series
274 [2002-2018] in long extension.

275 The different possible sources of nutrients are discussed in section 4.1, including rough estimations
276 of the nutrient addition by upwelling, precipitation and main rivers per subsection. With this
277 information it is possible to estimate which of these sources is more significant. Finally, the results
278 and the nutrient analysis will be discussed per Zone in section 4.2.

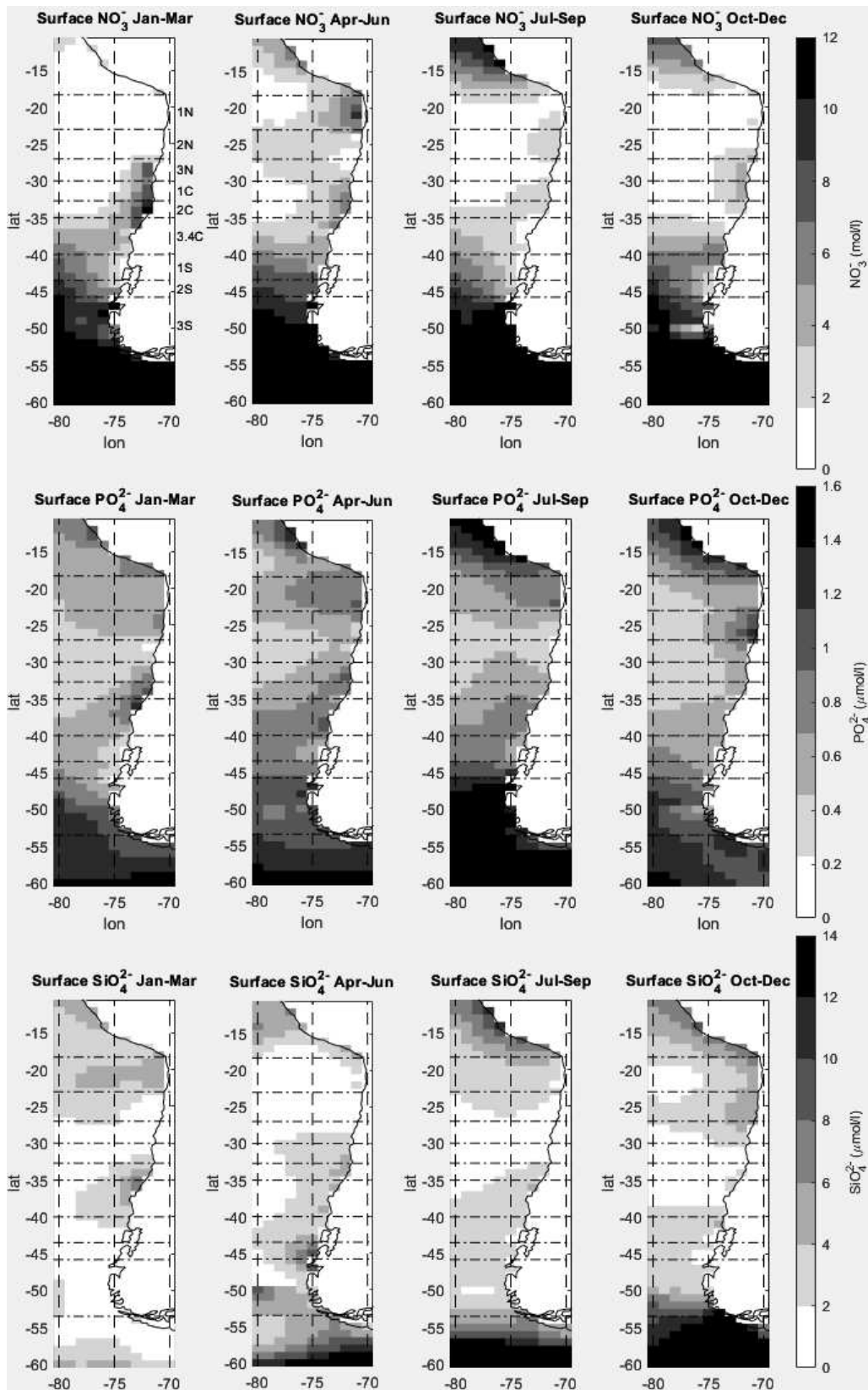
279 4.1. Nutrient Quantification Analysis

280 In this section, the background average nutrients distribution is discussed. Then, nutrients brought
281 by the upwelling (section 4.1.2), precipitation (section 4.2.3) and the main rivers (section 4.2.4) per
282 subsection are estimated. After that, these nutrients will be compared with WS and the PR to
283 determine a possible relationship.

284 4.1.1. Background Nutrients

285 The background nutrient concentrations data were obtained from García et al. (2010) in the World
286 Atlas Ocean (2009). This data was used to create Figures 4 and 5 that show the surface and 100 m
287 depth concentrations of NO_3^- , PO_4^{2-} and SiO_4^{2-} per season. The nutrients at 100 m deep are required
288 to estimate the flux that is brought by the upwelling. This depth is based on Vergara et al. (2017)
289 who reported that 80-100 m is the typical depth of the upwelled water in the Central Zone. The
290 nutrients at the surface will be compared with the PR and WS.

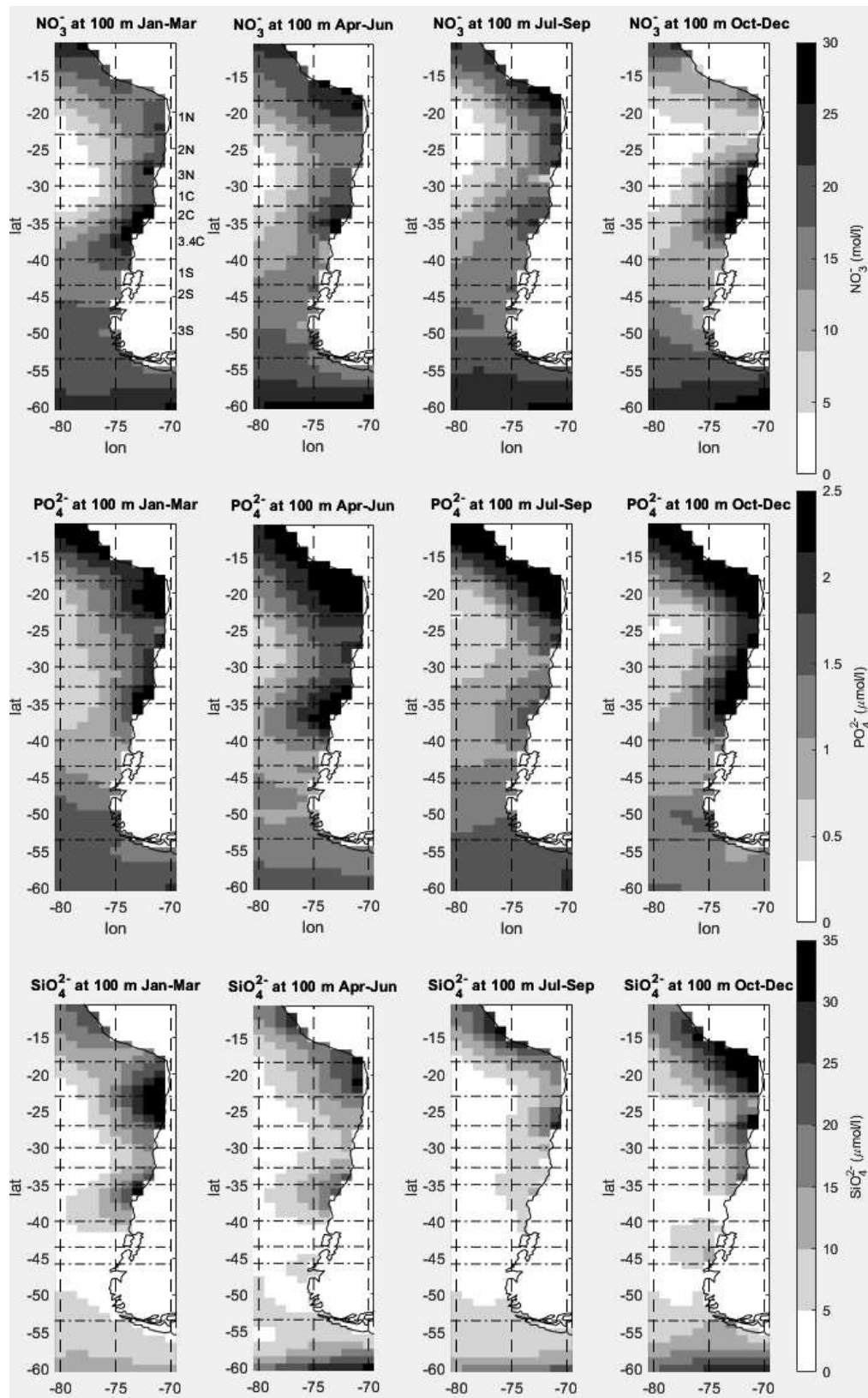
291 The first observation about these nutrients is that they are very high in the extreme Southern Zone
292 (3ST) on the surface, with a higher concentration of NO_3^- and PO_4^{2-} , while SiO_4^{2-} was only in spring
293 (Oct-Dec). Also, the Peruvian Zone has a higher nutrient concentration than other regions except
294 for 3ST. Additionally, NO_3^- showed higher levels at the surface in the Central Zone in the summer
295 (Jan-Mar) and a bit lower in 1NT and 1CT to 3CT during the autumn (Apr-Jun). These subsections
296 also exhibited a high PO_4^{2-} concentration from January to September. For the 100 m depth, NO_3^- was
297 intense from 3NT to 4CT during the warm season. The other two seasons, 1NT, 2CT and 3CT,
298 exhibited higher concentrations. These subsections also exhibited a high PO_4^{2-} concentration during
299 summer, autumn and spring. Winter only showed a high concentration in 1NT.



300

301

Figure 4. NO_3^- ($\text{MOL}\cdot\text{L}^{-1}$), PO_4^{2-} ($\mu\text{MOL}\cdot\text{L}^{-1}$), AND SiO_4^{2-} ($\mu\text{MOL}\cdot\text{L}^{-1}$) SURFACE SEASONAL CONCENTRATIONS DATA FROM GARCÍA ET AL. (2010).



302

303

304

Figure 5. NO_3^- ($\text{MOL}\cdot\text{L}^{-1}$), PO_4^{2-} ($\mu\text{MOL}\cdot\text{L}^{-1}$), AND SiO_4^{2-} ($\mu\text{MOL}\cdot\text{L}^{-1}$) SEASONAL CONCENTRATIONS AT 100 M OF DEPTH DATA FROM GARCÍA ET AL. (2010).

305 4.1.2. Upwelling Nutrient Estimation

306 For the upwelling WS and ZET were computed using Eqs. 1 and 2 (Table 6). As the idea is to establish
 307 which variable is more relevant rather than accurate calculations, EP was not considered.

308 TABLE 6. SEASONAL AVERAGE MERIDIONAL WS ($\text{KG}\cdot\text{M}^{-1}\cdot\text{S}^{-2}$) AND ZET ($\text{M}^2\cdot\text{S}^{-1}$) FOR THE STUDY PERIOD (2002-2018). POSITIVE VALUES INDICATE
 309 UPWELLING WHILE NEGATIVE DOWNWELLING.

Zones	Northern Zone			Central Zone				Southern Zone		
WS	1NT	2NT	3NT	1CT	2CT	3CT	4CT	1ST	2ST	3ST
Summer	0.03	0.03	0.05	0.07	0.07	0.09	0.06	0.01	0.01	-0.02
Autumn	0.03	0.04	0.06	0.06	0.03	0.02	0.00	0.00	0.00	-0.01
Winter	0.02	0.05	0.08	0.07	0.03	0.02	0.00	0.00	-0.01	-0.01
Spring	0.02	0.04	0.08	0.10	0.08	0.08	0.04	0.01	0.00	-0.02
ZET	1NT	2NT	3NT	1CT	2CT	3CT	4CT	1ST	2ST	3ST
Summer	0.49	0.51	0.72	0.89	0.80	1.03	0.68	0.15	0.07	-0.16
Autumn	0.49	0.66	0.82	0.78	0.37	0.25	0.05	-0.02	-0.04	-0.09
Winter	0.47	0.83	1.13	0.96	0.35	0.20	0.02	-0.03	-0.07	-0.12
Spring	0.46	0.60	1.10	1.32	0.94	0.90	0.38	0.06	0.01	-0.15

310 The subsections with highest upwelling in the warm season are 3NT, 1CT and 3CT. As expected, the
 311 Southern Zone showed a downwelling tendency in the cold season, with 3ST showing downwelling
 312 the entire year.

313 The ZET allows determination of the nutrient brought up by upwelling in each subsection. The
 314 Average ZET was multiplied by average subsectional coastal length and then by the average
 315 concentration of each nutrient at 100 m depth (Table 7).

316 TABLE 7. THE AVERAGE ANNUAL NUTRIENT MASS FLUX PER SUBSECTION BROUGHT BY THE UPWELLING.

Subsection	ZET m^2/s	Coast length m	NO_3^- 100m kg/m^3	PO_4^{2-} 100m kg/m^3	SiO_4^{2-} 100m kg/m^3	NO_3^- flux T/yr	PO_4^{2-} flux T/yr	SiO_4^{2-} flux T/yr
1NT	0.47	5.50E+05	1023	2.60E-04	2.50E-03	8.40E+12	2.10E+06	2.00E+07
2NT	0.65	4.90E+05	845	1.60E-04	2.00E-03	8.50E+12	1.60E+06	2.00E+07
3NT	0.94	3.80E+05	1279	1.70E-04	1.60E-03	1.40E+13	1.90E+06	1.80E+07
1CT	0.99	3.50E+05	1256	1.70E-04	1.20E-03	1.40E+13	1.90E+06	1.30E+07
2CT	0.61	3.10E+05	1550	2.40E-04	1.60E-03	9.20E+12	1.40E+06	9.30E+06
3CT	0.60	1.90E+05	1651	2.50E-04	1.60E-03	6.00E+12	9.00E+05	5.70E+06
4CT	0.28	5.10E+05	891	1.50E-04	1.10E-03	4.10E+12	6.90E+05	4.80E+06
1ST	0.04	5.20E+05	984	1.10E-04	4.60E-04	6.40E+11	7.00E+04	3.00E+05
2ST	-0.005	3.60E+05	-	-	-	-	-	-
3ST	-0.13	1.30E+06	-	-	-	-	-	-

317 The upwelling was more significant from 3NT to 2CT. Even though 1ST has a low upwelling, this is
 318 enough to bring considerable nutrients to the surface. The other two southern subsections have a
 319 downwelling tendency, so their ZETs were not estimated.

320 4.1.3. Precipitation Nutrient Estimation

321 The PR concentrations obtained by Baker et al. (2010) were multiplied by the average annual PR
 322 (2002-2018) per subsection and by the ocean area considering 100 km of width to obtain the

323 nutrient mass (Table 8). These results show that precipitation adds a small quantity of nutrients. The
 324 sections with higher inputs are from 4CT to 3ST.

325 TABLE 8. THE AVERAGE ANNUAL NUTRIENT MASS FLUX PER SUBSECTION CONTRIBUTED BY THE PR.

Subsection	PR m/yr	Coast length m	PR m ³ /yr	NO ₃ ⁻ flux T/yr	PO ₄ ²⁻ flux T/yr
1NT	0.03	5.50E+05	1.60E+09	2.80E-04	1.90E-06
2NT	0.03	4.90E+05	1.70E+09	3.00E-04	2.00E-06
3NT	0.04	3.80E+05	1.60E+09	2.80E-04	1.90E-06
1CT	0.14	3.50E+05	4.80E+09	8.30E-04	5.60E-06
2CT	0.40	3.10E+05	1.20E+10	2.10E-03	1.40E-05
3CT	0.68	1.90E+05	1.30E+10	2.60E-03	1.70E-05
4CT	1.05	5.10E+05	5.40E+10	1.20E-02	7.40E-05
1ST	1.30	5.20E+05	6.80E+10	1.50E-02	9.40E-05
2ST	1.490	3.60E+05	5.40E+10	1.20E-02	7.50E-05
3ST	1.01	1.30E+06	1.30E+11	2.90E-02	1.90E-04

326 4.1.4. Main River Nutrient Estimation

327 The Northern Zone does not have many rivers due to its intense aridity (Thiel et al., 2007). The
 328 Central Zone has many well-spaced rivers that add nutrients to the mixed layer (Masotti et al., 2018;
 329 Thiel et al., 2007). Examples of these are Maipo (33.72°S), Mataquito (34.98°S) and Maule Rivers
 330 (35.41°S), but the most relevant are the Itata (36.47°S) and Biobio Rivers (36.84°S; Vergara et al.,
 331 2017; Masotti et al., 2018). Masotti et al. (2018) reported that these add 0.16-169 and 0.05-
 332 10.3·10⁶ nmol m⁻³ NO₃⁻ and PO₄²⁻.

333 The nutrient discharge for the main rivers in the Central Zone was studied by Masotti et al. (2018),
 334 showing that the highest flux occurs during the winter and the river with the highest nutrient
 335 contribution is Biobio (Table 9). The nutrients discharged by the main Southern Zone rivers (Table
 336 10) were computed based on the averaged fluxes during the study period (CR2,2018). Then, they
 337 were multiplied by the typical nutrient concentrations reported by Castro (2010). Tables 9 and 10
 338 show the nutrient addition per subsection. As SiO₄²⁻ was not computed by Masotti et al. (2018), it
 339 was not calculated for the southern rivers either.

340 TABLE 9. AVERAGE ANNUAL NUTRIENTS ADDED BY THE MAIN RIVERS IN THE CENTRAL ZONE COMPELLED PER SUBSECTION. COLUMNS 3-6 ARE FROM
 341 (MASOTTI ET AL., 2018).

Subsection	Rivers	NO ₃ ⁻ winter T/mnth	NO ₃ ⁻ rest T/mnth	PO ₄ ²⁻ winter T/mnth	PO ₄ ²⁻ rest T/mnth	Total NO ₃ ⁻ flux T/yr	Total PO ₄ ²⁻ flux T/yr
2CT	Maipo	160	80	12	4	1.29E+03	9.3E+01
	Mataquito	16	5	4	1		
3CT	Maule	40	16	12	4	2.64E+02	7.2E+01
4CT	Itata	120	10	6	2	2.63E+03	3.5E+02
	Biobio	245	160	45	20		

342 The Southern Zone has many rivers with high fluxes. The most relevant are Puelo (41.60°S), Yelcho
 343 (42.98°S), Palena (43.82°S), Cisnes (44.75°S), Aysén (45.41°S), Baker (47.02°S) and Pascua (48.23°S;
 344 CR2,2018). The Southern rivers bring low NO₃⁻ and PO₄²⁻ concentrations on average to the ocean
 345 (1.5 and 0.11·10⁷ nmol m⁻³) with low variations per season, while SiO₄²⁻ varies from 4 to 15 10⁵ nmol
 346 m⁻³ (Castro, 2010; De La Torre, 2016).

347

348

TABLE 10. AVERAGE ANNUAL NUTRIENTS ADDED BY THE MAIN RIVERS IN THE SOUTHERN ZONE COMPELLED PER SUBSECTION.

Subsection	Rivers	Flux m ³ /s	Flux m ³ /yr	NO ₃ ⁻ T/yr	PO ₄ ²⁻ T/yr	Total NO ₃ ⁻ T/yr	Total PO ₄ ²⁻ T/yr
1ST	Puelo	615	1.90E+10	1804	203	3.13E+03	3.5E+02
	Yelcho	452	1.40E+10	1326	149		
2ST	Palena	782	2.50E+10	2293	258	4.45E+03	5E+02
	Cisnes	214	6.80E+09	628	71		
	Aysén	522	1.70E+10	1531	172		
3ST	Baker	870	2.70E+10	2552	287	4.24E+03	4.8E+02
	Pascua	574	1.80E+10	1683	189		

350 Tables 9 and 10 show that rivers add in thousands of tonnes per year, while precipitation (Table 8)
 351 adds a nutrient flux around kilograms per year. The nutrient flux added by rivers was slightly higher
 352 in the Southern Zone. However, this mass is not as significant compared with the nutrient brought
 353 by upwelling (Table 7).

354 4.2. Analysis per Zone

355 The phytoplankton highest concentrations were detected in 3CT-1ST (Figure 3 and Table 4). In
 356 contrast, the Upwelling analysis (Table 7) showed that nutrient addition is relatively similar from
 357 1NT to 4CT with slightly higher values in 3NT and 1CT, while in the Southern Zone it was negative.
 358 This means that other factors must be considered such as the shelf width. The climatic indices
 359 contribution is not explicitly covered here but will be the subject of a later paper.

360 4.2.1. Northern Zone

361 The results revealed that the Northern Zone had a low phytoplankton concentration with small
 362 seasonal variability, except in 1NT. This pattern is due to weak winds (1NT-2NT), and a lack of
 363 precipitation (Tables 4 and 5). However, the upwelling was significant (Table 7). As a result of these
 364 stable weather conditions driven by the SPSA this Zone is a High Nutrient Low Chlorophyll (HNLC)
 365 region (Yuras et al., 2005; Ancapichun and Garcés, 2015; Thiel et al., 2007).

366 1NT presented a higher Chl concentration but this was almost constant, with a slight rise in
 367 September and February. These results are consistent with the background surface nutrient maps
 368 that showed a higher nutrient concentration in this Zone (Figure 4). This Chl activity and high
 369 nutrient level are likely related to the increased production from neighbouring Peruvian waters,
 370 which has a constant Ekman transport that allows a constant nutrient supply (Thiel et al., 2007;
 371 Echevin et al., 2014). Furthermore, these nutrients are transported through Chile by poleward
 372 Equatorial Subsurface Water (ESSW) from northern Peru (Thiel et al., 2007; Echevin et al., 2014).
 373 Also, this subsection has a broad shelf in comparison to the rest of the Northern Zone which in places
 374 is less than 10 km (Ancapichun and Garcés, 2015; Thiel et al., 2007; Cortés et al., 2017).

375 Even though 2NT has filaments in Mejillones and Antofagasta associated with capes, these were not
 376 productive, likely related to their narrow shelf and anthropic activities there; effectively these were
 377 more productive during the nineties (Thiel et al., 2007; Camus and Hajek, 1998). The Chl in 3NT
 378 showed a weak seasonal cycle with a maximum value in September that seems to be partly triggered
 379 by its high VW, having a more statistically significant correlation (P-value <0.01, Rho=0.21; Table 5).
 380 This subsection should have a significant upwelling, but the narrow shelf seems to affect this region
 381 as well (Table 7).

382 Overall, the constant but low southerly winds and scarce precipitation in this Zone, driven by the
383 SPSA, lead to a low nutrient renovation process in the euphotic layer, which is even more limited by
384 a shelf less than 10 km wide, not allowing a full remineralisation process (Thiel et al., 2007; Marchant
385 et al., 2007). The only exception is in 1NT, which has nutrients from Peru and a slightly broader shelf
386 within the Peruvian limits.

387 4.2.2. Central Zone

388 The Central Zone presented a seasonally varying production, with a high Chl concentration during
389 the summer and spring (Corredor-Acosta et al., 2015; Gómez et al., 2017). This is linked to the SPSA
390 movement and the sunlight reduction during the winter. The SPSA in the warm season leads to
391 production of a strong eddy that enhances the upwelling from 30°S to 38°S (Thiel et al., 2007). The
392 seasonal difference was more pronounced in 3CT-4CT, leading to higher PR with more well-spaced
393 rivers and lower southerly winds with a westerly component during the winter, while 1CT-2CT
394 exhibited more significant longshore winds the entire year (Tables 3 and 4). However, the southerly
395 winds have similar values in the whole Central Zone during the summer. Therefore, Chl~VW were
396 statistically significant in the whole Zone, excluding 2CT. Indeed, the Chl~VW were higher in 3CT-
397 4CT (0.27, 0.38; Table 5) but also Chl~UW (0.2, -0.27).

398 These results demonstrate that 3CT-4CT had a high production compared with 1CT-2CT, despite the
399 last having a more significant ZET driven by the southerly winds (Table 7). One plausible reason for
400 this is that 3CT-4CT has a higher PR and more rivers, but section 3.2 showed that these factors do
401 not increase the nutrient addition as much as the upwelling. However, another factor influencing
402 the differences in these two groups is the shelf configuration, which is less than 10 km wide in 1CT
403 and 2CT, while the average width for 3CT and 4CT is 40 to 70 km, except for the middle section in
404 4CT, where the shelf is 12 km wide. Also, 4CT has a marked Chl filament due to its cape (Thiel et al.,
405 2007; Marchant et al., 2007).

406 Therefore, this Zone can be split into two: 1CT-2CT with higher winds but narrow shelf, leading to a
407 low Chl concentration and 3CT-4CT, with a marked season with slightly low winds but a more broad
408 shelf leading to a high Chl concentration. Thus, the differences in the Chl signal in these two groups
409 are evidently related to the width of their shelves.

410 4.2.3. Southern Zone

411 Although the Southern Zone has a downwelling tendency (Table 7), 1ST and 2ST Chl concentrations
412 showed a seasonal cycle with a high production analogous to 4CT and 3CT, respectively. However,
413 their production was lower during the winter. Meanwhile, 3ST's Chl was almost constant throughout
414 the year but with a moderate Chl concentration, despite the relatively constant northerly winds and
415 few occasions of southerly winds in the winter, with significant westerly winds that were more
416 intense in the winter.

417 These weather conditions occur because this Zone is at the limits of the SPSA effect. Thus, weak
418 longshore winds are often seen in 1ST during the warm season (Table 3), whereas they occasionally
419 appear in 2ST during the summer. Instead, storms with prominent westerly winds coming from the
420 South Pacific frequently arrived, driven by negative AAO (González-Reyes and Muñoz, 2013; Aguayo
421 et al., 2021). In any case, both wind components strongly impacted the Chl concentration in 1ST
422 (VW=0.45, UW=-0.41; Table 5), while UW had a bigger influence on 3ST's Chl (VW=0.23, UW=-0.32),
423 and 2ST's Chl was affected by both but in a minor way (VW=0.26, UW=-0.29).

424 Although the nutrient addition by rivers and precipitation is higher in the Southern Zone (Table 10),
425 with a higher flux during the warm season, studies have mentioned that they generate more
426 stratification reducing the phytoplankton response (Landaeta et al., 2011; Aracena et al., 2011; De
427 La Torre, 2016). Thus, Chl~PR (Table 5) in this Zone showed a significant negative relationship,
428 especially in 1ST (-0.39), while 2ST and 3ST were slightly lower (-0.24, -0.2). This is even more evident
429 considering that the background surface nutrients are significant (Figure 4). Effectively authors like
430 Aguayo et al. (2021) have reported that the big drought of (2010-2018) and the positive tendency
431 of AAO in later years reduced the precipitation and river fluxes in the south with a generally positive
432 effect on phytoplankton.

433 Therefore, the Chl is significant in this region as a result of its high surface nutrient content, and not
434 necessarily just from upwelling. Effectively, the 1ST-2ST high Chl seasonal behaviour likely occurs
435 due to a low PR and river flux during the warm season. Moreover, this effect is even more boosted
436 by a wider shelf width of over 70 km (Strub et al., 2019; Marchant et al., 2007; Aracena et al., 2011).

437 **5. Conclusion**

438 Although 1ST and 2ST typically exhibited westerly winds and excessive precipitation that reduced
439 the phytoplankton proliferation, these are significantly reduced when the SPSA is pushed
440 southwards during the summer leading to higher longshore winds and lower westerly winds and
441 Precipitation events. Recent events such as the big drought of (2010-2018) and the more positive
442 AAO tendency have exacerbated this situation.

443 Although the upwelling analysis showed that the upwelling has a significant role in nutrient addition
444 in the Northern Zone, the southerly wind and ocean temperatures did not show a significant
445 correlation with the Chl. This is possibly related to the narrow shelf here.

446 On the other hand, 1NT and 3ST also have a significant Chl activity associated with a broad shelf and
447 the sub-surface currents adding nutrients on the surface. This is supported by the significant
448 nutrient concentration in the Peruvian Zone (Figure 4). In any case, it can be inferred that the
449 Southern Zone has a high nutrient concentration that does not require upwelling, especially 3ST.

450 Overall, this study has demonstrated the importance of shelf width and the effect the upwelling
451 driven by the presence or absence of the SPSA in the Chilean coast fertilisation, increasing the
452 phytoplankton. Thus, the most productive region is from 3CT to 1ST, owing to both variables being
453 present.

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458 **CReDiT roles**

459 F. Tornquist: Methodology, Investigation, Writing and Original draft.

460 G. R. Bigg: Supervision, Conceptualisation, Reviewing and Editing.

461 R. G. Bryant: Supervision, Conceptualisation and Reviewing.

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