

Sensitivity of shelf sea marine ecosystems to temporal resolution of meteorological forcing

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Key Points:

- Higher temporal meteorological resolution increases wind stress acting on the sea surface and water column turbulent kinetic energy
- Consequently, a shorter stratified period occurs resulting in a shorter growing season and delayed onset of the phytoplankton bloom
- Differences in resource limitations across sites may determine the response in ecosystem dynamics to changing meteorological resolution

Keywords:

Phenology, meteorology, ERA5, ecosystem modelling, ERSEM, wind

29 **Abstract**

30 Phytoplankton phenology and the length of the growing season have implications that cascade through trophic levels
31 and ultimately impact the global carbon flux to the seafloor. Coupled hydrodynamic-ecosystem models must
32 accurately predict timing and duration of phytoplankton blooms in order to predict the impact of environmental
33 change on ecosystem dynamics. Meteorological conditions, such as solar irradiance, air temperature and wind-speed
34 are known to strongly impact the timing of phytoplankton blooms. Here, we investigate the impact of degrading the
35 temporal resolution of meteorological forcing (wind, surface pressure, air and dew point temperatures) from 1-24
36 hours using a 1D coupled hydrodynamic-ecosystem model at two contrasting shelf-sea sites: one coastal
37 intermediately stratified site (L4) and one offshore site with constant summer stratification (CCS). Higher temporal
38 resolutions of meteorological forcing resulted in greater wind stress acting on the sea surface increasing water
39 column turbulent kinetic energy. Consequently, the water column was stratified for a smaller proportion of the year
40 producing a delayed onset of the spring phytoplankton bloom by up to 6 days, often earlier cessation of the autumn
41 bloom, and shortened growing season of up to 23 days. Despite opposing trends in gross primary production
42 between sites, a weakened microbial loop occurred with higher meteorological resolution due to reduced dissolved
43 organic carbon production by phytoplankton caused by differences in resource limitation: light at CCS and nitrate at
44 L4. Caution should be taken when comparing model runs with differing meteorological forcing resolutions.
45 Recalibration of hydrodynamic-ecosystem models may be required if meteorological resolution is upgraded.

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48 **Plain Language Summary**

49 Computer models are used to predict the impact of changes in environmental pressures such as climate change on
50 marine ecosystems. To predict these changes models need to accurately simulate the period when marine plants
51 (phytoplankton) grow rapidly, termed the phytoplankton bloom, as these plants act as a food source to the marine
52 food-chain. The models are run by defining meteorological variables, such as light, air temperature and wind speed
53 which are known to strongly impact the timing of phytoplankton blooms. In this paper we investigate the impact in
54 changing the time period between inputs of meteorological variables from 1 hour to 24 hours at two contrasting
55 marine sites. The shorter the timespan between inputs, the more fluctuations in wind speed, resulting in increased
56 wind stress acting on the sea surface and therefore greater turbulence and mixing within the water column.
57 Consequently the predicted length of growing season is reduced with the spring phytoplankton bloom starting up to
58 6 days later and the autumn bloom often terminating earlier. Implications for ecosystem function are site dependent.
59 Caution should be taken when comparing model results using different time gaps of meteorological inputs and
60 models may need retuning if upgraded to hourly meteorological inputs.

61

62 1. INTRODUCTION

63 Phytoplankton phenology, that is, the timing of phytoplankton blooms, has consequences that cascade through
64 ecological trophic levels, with the potential to change ecosystem structure (Edwards & Richardson, 2004; Platt et al.,
65 2003) and the flux of carbon to the sea floor. This is particularly important in shelf seas as they trap a
66 disproportionate amount of carbon from the atmosphere within their sediments compared to the deep global ocean
67 (Bauer et al., 2013; Sharples et al., 2019). The ability of marine ecosystem models to accurately represent and
68 capture changes in phytoplankton phenology, in addition to the magnitude and composition of phytoplankton
69 blooms, is imperative to predict the impacts of environmental change on ecosystem dynamics and the amount of
70 carbon trapped within global shelf seas.

71 Phytoplankton blooms occur when an optimal set of environmental conditions, in particular nutrient and light
72 availability, both of which are mediated by turbulent mixing, support growth rates that exceed losses (e.g. grazing).
73 There are several competing theories regarding the causes of the onset of the spring bloom. The critical depth
74 theory (Sverdrup, 1953) states that phytoplankton blooms will develop when the mixed layer is less than the critical
75 depth: the depth where vertically integrated phytoplankton growth exceeds phytoplankton losses. In more recent
76 years, at least two other hypotheses have been formulated. The critical turbulence theory postulates that a
77 phytoplankton bloom can occur in unstratified waters if turbulent mixing is weak enough that phytoplankton stay
78 within the photic zone long enough to photosynthesize (Huisman et al., 1999; Taylor & Ferrari, 2011) while the
79 disturbance-recovery hypothesis (Behrenfeld, 2010; Behrenfeld et al., 2013), states that the phytoplankton bloom is
80 dependent on the balance of phytoplankton loss and production due to grazing pressures and physical properties. On
81 shelves where light rather than nutrient availability limits phytoplankton growth, the spring bloom typically occurs
82 during a period of low grazing pressure when a reduction in turbulent mixing and shoaling of the actively mixing
83 surface layer eases light limitation.

84 In contrast to the spring bloom, the autumn phytoplankton bloom typically occurs when light is still non-limiting
85 and is fueled by entrainment of nutrients into the euphotic zone as convection and wind mixing deepen the surface
86 mixed layer. In addition, the phytoplankton composition within the autumn bloom is different to that of spring: more
87 motile species are present which have the ability to migrate across the mixed layer between nutrient rich and nutrient
88 poor regions of the water column (Smyth et al., 2014). Although not studied as intensively as the spring
89 phytoplankton bloom, the autumn phytoplankton bloom can also make a substantial contribution to annual gross
90 primary production (Wihsgott et al., 2019).

91 In all hypotheses for phytoplankton bloom initiation, the timing of the phytoplankton bloom is closely coupled to
92 meteorological indices such as light, temperature and wind speeds. Wind and temperature alter the timing of
93 stratification events in spring and autumn and the strength of stratification in summer, in addition to the amount of
94 turbulent kinetic energy present throughout the water column. Chiswell (2011) links the timing of the spring bloom
95 to a reduction in wind-driven surface mixing with wind intensity estimated to explain up to 60% of the interannual
96 variability in the timing of phytoplankton blooms along the Norwegian shelf (Vikebø et al., 2019). Changing wind

97 conditions have also been shown to both advance and delay the onset of spring phytoplankton blooms (Follows &
98 Dutkiewicz, 2002; Ruiz-Castillo et al., 2019; Sharples et al., 2006; Waniek, 2003). A decrease in wind stress is
99 often correlated with an earlier phytoplankton bloom in open oceans such as in the Japan Sea (Kim et al., 2007;
100 Yamada & Ishizaka, 2006), North Atlantic (González Taboada & Anadón, 2014; Henson et al., 2009; Ueyama &
101 Monger, 2005), the open ocean off the South West Iberian peninsula (Krug et al., 2018) and shallower systems such
102 as the North West European Shelf (González Taboada & Anadón, 2014) and Baltic Sea (Groetsch et al., 2016).
103 However, in the coastal zone of the South West Iberian shelf and at station L4 in the English Channel, an increase in
104 wind speeds was linked to increased chlorophyll peaks and earlier bloom starts due to relief of nutrient stress
105 (Barnes et al., 2015; Krug et al., 2018). Winds have also been highlighted as important in influencing the autumn
106 bloom by breaking down stratification enabling nutrients to reach the surface (Kim et al., 2007; Wihsgott et al.,
107 2019).

108 Hydrodynamic-ecosystem models are forced by meteorological data. It has long been recognised that temporal
109 meteorological resolution within these models impacts ecosystem dynamics (Backhaus, 1985; Pohlmann, 1996b;
110 Ridderinkhof, 1992). In particular, low temporal and spatial resolution meteorological data may miss short-lived
111 events, especially in wind speed or cloud cover, which could be important for phytoplankton phenology and
112 consequently ecosystem dynamics. Pre 1980s annual or monthly mean atmospheric forcing variables were used in
113 hydrodynamic-ecosystem models until Backhaus (1985) recognised that variable wind fluxes have large influences
114 on surface currents in shelf sea regions (Pohlmann, 1996b). In response, the early versions of the European Regional
115 Seas Ecosystem Model (ERSEM) used observationally derived meteorological data on a 3 to 6 hourly timescale
116 (i.e., Lenhart et al., 1995, 1997; Pohlmann, 1996a). However this data has the caveat that as it is buoy/station based,
117 it is only available at specific sites resulting in a coarse spatial resolution. The production of atmospheric reanalysis
118 products, such as ones by the European Centre for Medium range Weather Forecasting (ECMWF) and National
119 Centre for Environmental Prediction (NCEP) increased the spatial resolution of available meteorological data and
120 thus the ability to model larger areas. Consequently, the temporal resolution of atmospheric forcing data used to
121 force ERSEM since the mid 1990s has varied from monthly to hourly resolution (i.e. Aveytua-Alcázar et al., 2008;
122 Blackford, 2002; Blackford & Burkill, 2002; Holt & James, 2001; Raick et al., 2005; Siddorn et al., 2007; Vichi et
123 al., 1998) depending on the source of the meteorological data. The release of the publicly available globally
124 resolved hourly datasets from the ECMWF (ERA5; C3S, 2017) and NCEP (CFSR; Saha et al., 2010, 2014), will
125 result in an increase in the temporal resolution of the meteorological forcing in hydrodynamic ecosystem models,
126 potentially impacting both phytoplankton phenology and ecosystem dynamics.

127 This paper investigates the impact of meteorological forcing on phytoplankton phenology and ecosystem dynamics
128 within shelf seas. We use a 1D hydrodynamic-ecosystem model to allow multiple simulations with the temporal
129 resolution in meteorological forcing decreasing from 1 hour to 24 hourly. The model is run at two contrasting
130 seasonally stratified shelf sea sites: the coastal L4 station in the western English Channel (Smyth et al., 2010, 2015)
131 and at a site in the more isolated Central Celtic Sea (CCS). Changes in the physical dynamics of the water column

132 and subsequent phytoplankton phenology between the different scenarios are assessed. Results are put into context
133 of the impact to the global carbon cycle and the differences in the responses of the two stations are investigated.

134 **2. METHODS**

135 *2.1. Site locations and observations*

136 L4 is part of the Western Channel Observatory, located 13km offshore from Plymouth, UK (50.25°N, 4.2167°W;
137 Figure 1). It represents a seasonally stratified coastal system with a depth of 50m and is influenced by riverine inputs
138 from the Tamar and Plym rivers. Observational data has been collected at L4 on a weekly basis since 1988. The
139 timeseries initially consisted of sea surface temperature, zooplankton and phytoplankton data and was later
140 supplemented with CTD profiles and nutrient data amongst others, in the early 2000s (Smyth et al., 2015). In
141 contrast, the CCS station represents a seasonally stratified open shelf system. It is situated in the Central Celtic Sea
142 near the edge of the North-West European Shelf 220km south-west of Land's End, UK (49.4°N, 8.6°W; Figure 1). It
143 has a depth of 145m and was the focus of an intense physical, chemical and biological sampling campaign during
144 the Shelf Sea Biogeochemistry project between 2014 and 2015 (Sharples et al., 2019). Observational data was
145 obtained from the British Oceanographic Data Centre (BODC: www.bodc.ac.uk) for both L4 (Fishwick 2018;
146 Woodward and Harris 2019) and CCS (cruises JC105, DY026, DY018, DY021, DY029, DY030, DY033, and
147 DY034, Hull et al., 2017; Wihsgott et al., 2016; Woodward, 2016).

148 *2.2. Hydrodynamic-Ecosystem Model*

149 Here, the European Regional Seas Ecosystem Model (ERSEM; Butenschön et al., 2016) is coupled to the 1D
150 General Ocean Turbulence Model (GOTM; Burchard et al., 1999) using the Framework for Aquatic Biogeochemical
151 Model (FABM; Bruggeman & Bolding, 2014). ERSEM is a high complexity lower trophic food web model
152 including both pelagic and benthic systems. It represents the biogeochemical cycling of 5 elements; carbon,
153 nitrogen, phosphorus, silicon and oxygen, modulated by the cycling between producers, consumers and
154 decomposers using variable stoichiometric ratios. ERSEM uses a functional group approach further partitioning
155 each set using trait and size to form 4 phytoplankton groups, 3 zooplankton groups and 1 bacteria group within the
156 pelagic model. In addition, various sizes and reactivities of particulate organic matter and dissolved organic matter
157 are included as state variables within the pelagic model along with 5 inorganic nutrient groups. The pelagic model
158 is coupled to a benthic model containing particulate and dissolved organic matter, deposit feeders, suspension
159 feeders, meiofauna, anaerobic and aerobic bacteria and inorganic nutrients.

160 The model is configured to simulate a time period covering 2008 to 2015. Model results are reported for 2010-2015
161 with the first two years of the simulation considered the model spin up. Note that the CCS simulation finishes in
162 August 2015 due to a lack of temperature and salinity data beyond this time period. Thus at CCS, results for Spring
163 2015 are included within results presented in this paper but annual results are not included for 2015. The model is
164 run with 100 vertical levels ranging from a minimum thickness of 6 and 18cm near the surface, at L4 and CCS

165 respectively, to a maximum of 87 and 252cm in the middle of the water column. Sensitivity tests show that
166 differences in vertical resolution between the sites have minimal impact on model results (results not shown). All
167 model outputs are saved as daily means.

168 2.3. Site specific setup- 'baseline' model

169 Tidal forcing data was provided to GOTM using hourly depth-averaged horizontal velocities and sea surface
170 elevations at both sites (Cazenave et al., 2016). Hourly meteorological variables (10m zonal (u) and meridional (v)
171 components of wind, sea surface pressure, 2m air temperature, 2m dew point temperature, total cloud cover,
172 precipitation and net shortwave radiation) for the time period 2008-2016 were extracted from the ERA5 reanalysis
173 dataset (C3S, 2017) which is provided at a spatial resolution of 0.25° x 0.25°. Meteorological variables were
174 linearly interpolated to each site location. Due to forcing the model with hourly *net* shortwave radiation, surface
175 reflectance within GOTM was disabled.

176 This study uses the 1D L4 setup provided as a testcase in ERSEM 16.05 (Butenschön et al., 2016) as the baseline
177 model from which changes as outlined below and in Table S1 were made. The 1D model at both sites is relaxed on
178 a yearly timescale to observed temperature and salinity data (Fishwick, 2018; Wihsgott et al., 2016) to avoid drift in
179 these variables during the model run. Note this means the influence of changes in river flow on salinity at L4 and
180 CCS, and thus stratification, is not included in the model simulations. No relaxation was applied to any
181 biogeochemical variables at either site. Model calibration at CCS was performed with the aim of changing the
182 minimum number of parameters from the basic L4 setup as possible.

183 The model at CCS is initialized using average winter nutrient concentrations over 2014 and 2015 (BODC,
184 Woodward, 2016). The benthic model at CCS was spun up so that a quasi-steady state was achieved– this allowed
185 only a two year model spin-up period at the start of each model run. For L4 the published parameter set was
186 assumed to provide a quasi steady state. To prevent the increase of benthic particulate matter and benthic refractory
187 organic matter at both L4 and CCS, the affinity of benthic aerobic and anaerobic bacteria to benthic particulate
188 organic matter was increased to $4 \times 10^{-5} \text{ m}^2 (\text{mg C})^{-1} \text{ d}^{-1}$, and affinity to benthic refractory organic matter to 4×10^{-6}
189 $\text{m}^2 (\text{mg C})^{-1} \text{ d}^{-1}$ (Table S1). The k epsilon turbulent scheme was used within GOTM for both sites with the
190 minimum turbulent kinetic energy (k_{\min}) at both sites increased to match temperature profiles with observations at
191 both sites. The absorption of silt was lowered at the CCS site to improve timing of the phytoplankton bloom and
192 depth of subsurface chlorophyll maximum in summer within the model relative to observations (Hopkins et al.,
193 2019). The nitrification rate constant was also lowered at both sites to improve ammonium dynamics at depth.
194 Finally, the wind speed relative to current velocity, rather than the default setting of absolute wind speed, was used
195 to calculate air-sea fluxes. Both models were validated with observational data using robust statistics. Target
196 diagrams showing bias, mean absolute error (MAE) and correlation coefficient (Butenschön et al., 2016; Jolliff et
197 al., 2009) can be found in the supplementary material (Figure S1).

198 2.4. Meteorological resolution forcing scenarios

199 Meteorological forcing scenarios were created using the instantaneous meteorological data, that is, 10m u and v
200 components of wind, sea surface pressure, 2m air temperature, 2m dew point temperature and total cloud cover.
201 Throughout this paper the term “meteorological forcing” refers to these variables. Six hourly, 12 hourly, and 24
202 hourly meteorological forcing data were subsampled from the hourly meteorological data to create the forcing
203 scenarios. This sampling method was chosen to reflect the potential changes from switching resolution of
204 meteorological products such as from 6 hourly ERA Interim data to hourly ERA 5. Precipitation and hourly net
205 short wave radiation were kept at an hourly resolution for all scenarios as these are time integrated variables that
206 already capture the change throughout the time-interval. Thus, while reduction in the time resolution in precipitation
207 and net shortwave radiation causes their variability to be underestimated, it does not affect total heat or freshwater
208 input. In addition, we chose not to adjust the resolution of shortwave radiation as resultant changes in meteorological
209 forcing may be highly dependent on individual model formulations for light and are also hard to disentangle from
210 other effects such as wind and temperature. Conversely, a reduction in resolution of instantaneous variables causes
211 biases of up to 3% (in u and cloud cover) and 0.8%(u) at L4 and CCS, respectively, in the mean of the timeseries of
212 meteorological inputs for the scenarios compared to the hourly simulation (Table S2); additionally, reduced
213 variability of some instantaneous variables (e.g., wind speed) will impact energy fluxes. In order to identify which
214 meteorological variables the model was sensitive to, the model was run a further 5 times, dropping one by one the
215 temporal resolution of each individual meteorological forcing variable to 12 hourly, leaving all other variables at
216 hourly resolution.

217 *2.5. Physical/Phenological indices*

218 Meteorological resolution impacts the average environment (light, nutrients) experienced by phytoplankton through
219 modulation of turbulence, which controls the depth over which phytoplankton are mixed. This is the cornerstone of
220 the critical depth and critical turbulence hypotheses. Throughout this manuscript we use the mixed layer depth
221 (MLD) as an indicator of the depth of near-surface stratification and as an estimate of the depth of the actively
222 mixing surface layer, quantities most relevant to phytoplankton growth in the euphotic zone. We also calculate the
223 potential energy anomaly (Simpson et al., 1981) as a measure of the overall strength of stratification throughout the
224 water column. Typically, a shallower MLD in the spring is associated with an increase in stratification and often
225 corresponds to a temporal shift in the onset of stratification. A deeper MLD frequently represents weakening
226 stratification and often corresponds with a temporal shift in the breakdown of stratification in autumn.

227 A MLD criteria is used to identify different hydrodynamic-biogeochemical regimes observed throughout the seasons
228 to aid analysis. The MLD is often defined as the depth at which the density changes by $0.03\text{-}0.125\text{ kg m}^{-3}$ from a
229 reference level (de Boyer Montégut et al., 2004 and references therein). Here we defined the MLD as a change in
230 density of more than 0.06 kg m^{-3} from the 2m density. The assigned seasons reflect the onset of stratification where
231 the spring bloom occurs and wanes (spring), stable stratification (summer) and the time period where stratification is
232 eroded by a deepening of the mixed layer resulting in nutrients being mixed back into the surface water (autumn).
233 The exact method for defining the time periods is shown in Table S3. All calculations used either 10 day forward or

234 backward running means. The same time period for each regime is used across all years and all scenarios. To define
235 this, the minimum or maximum day of the year over all simulations and all scenarios which fulfilled the criteria in
236 Table S3 were used to delineate the exact start and end of each season in the final analysis. Note that the time
237 periods are slightly different for L4 and CCS.

238 The phytoplankton bloom duration is typically defined as the time period when chlorophyll exceeds 5% of the
239 annual median (Henson et al., 2009; Krug et al., 2018; Racault et al., 2012, 2017; Sapiano et al., 2012; Siegel et al.,
240 2002) with Siegel et al. (2002) indicating that little difference occurs when the percentage is between 1 and 30%.
241 Here, we define the start of the spring phytoplankton bloom as the first day of the year when depth-integrated
242 chlorophyll is more than 10% of the annual median. The end of the phytoplankton bloom is defined when depth-
243 integrated chlorophyll drops below 10% of the annual median for more than 6 consecutive days. The bloom duration
244 is the time between the start and end of the bloom. This metric however does not capture the autumn phytoplankton
245 blooms at our two sites. Therefore we also defined the growing season as the period of time when the 10 day
246 running average of mean water column gross primary production (GPP; $\text{gC m}^{-3} \text{d}^{-1}$) is more than one tenth of the
247 annual maximum GPP at each site. The metrics for chlorophyll and GPP calculated for the hourly simulation are
248 used for all scenarios so that differences between each meteorological scenario can be fairly assessed. Finally, the
249 peak magnitude of the bloom represents the day of the year when depth integrated chlorophyll is greatest.

250 **3. RESULTS**

251 *3.1. Sensitivity tests*

252 The sensitivity tests on individual meteorological variables indicate that changes in the temporal resolution of wind
253 drive differences in physical dynamics between the scenarios presented here at both stations (results not shown).
254 Changing surface pressure, air and dew point temperatures, and cloud cover have minimal impact on phenology and
255 ecosystem dynamics (Figure S2). Thus throughout the rest this manuscript, we will focus on the impact of wind in
256 driving ecosystem dynamics.

257 *3.2. Baseline (hourly) simulation*

258 The density structure of the water column in the hourly meteorological simulation at both sites in addition to the
259 MLD and assigned seasons for the years 2014 and 2015 are shown in Figure 2. The water column at L4 is well
260 mixed for a longer portion of the year than at CCS. There is also a weaker contrast between surface and bottom
261 water densities during summer at L4 indicating that seasonal stratification is weaker than at CCS. A more intense
262 spring bloom is predicted to occur at CCS and, during the summer, the subsurface chlorophyll maximum is deeper
263 (40 m at CCS compared to 15 m at L4; Figure 2). In addition, a later autumn bloom resulting in a longer growing
264 season is predicted in the model simulation at CCS than at L4 (Figure S3). Comparing near-surface chlorophyll-a
265 concentrations observed at both sites with the baseline model (Figure S3) provides confidence that the simulations
266 are satisfactorily predicting the observed phytoplankton phenology.

267 3.3. Impacts of meteorological resolution on physical dynamics

268 Lower meteorological resolution results in a 2-16% and 2-11% reduction in the annual mean magnitude of wind
269 stress acting on the surface water at L4 and CCS, respectively, between all scenarios and the hourly meteorological
270 simulation (Figure 3). This is a result of missing high intensity short lived wind events in the coarser, subsampled
271 resolution meteorology. The strong positive relationship between wind stress and depth integrated turbulent kinetic
272 energy throughout the water column (Figure 3) results in a reduction in turbulent kinetic energy in the scenarios of
273 between 2-12% at L4 and 2-8% at CCS on an annual scale. Tidal forcing dampens the magnitude of change in the
274 response of turbulent kinetic energy to meteorological forcing. Rerunning the model scenarios without tides
275 produces a reduction in turbulent kinetic energy of up to 25% compared to the hourly simulation (4-23% L4; 5-20%
276 CCS; results not shown). The change in turbulent kinetic energy in the upper water column due to meteorological
277 forcing is overwhelmed by the impact of tides throughout the water column. The reduction in turbulent kinetic
278 energy with lower temporal resolution of meteorological forcing gives rise to decreased water column mixing
279 throughout the year resulting in earlier stratification of the water column in spring and later breakdown of
280 stratification in autumn (Figures 4, S4 and S5). Increases in the strength of the stratification as the meteorological
281 resolution is reduced, are greater at L4 than at CCS. In addition, the mixed layer becomes increasingly shallower in
282 summer, and is up to 3m thinner at both L4 and CCS in the 24h meteorological resolution scenario compared to the
283 hourly simulation.

284 3.4. Change in phenology

285 A shift towards an increasingly earlier spring phytoplankton bloom occurs as the temporal meteorological forcing
286 resolution is reduced. The onset of the phytoplankton bloom is up to 4 and 6 days earlier at L4 and CCS respectively
287 in the 24 hourly resolution scenario compared to the hourly simulation (Figure 5A) with similar trends in the timing
288 of peak chlorophyll concentrations (Figure 5G). The trends for the end of the phytoplankton bloom are not as clear
289 as for the onset. On average, the phytoplankton bloom ends later with lowering meteorological resolution resulting
290 in a phytoplankton bloom that is up to 17 and 6 days longer at L4 and CCS, respectively, across all scenarios.
291 However, in some years an earlier and thus shorter bloom occurs at L4 in the scenarios compared to the hourly
292 resolution. The peak magnitude of depth-integrated chlorophyll as the meteorological resolution is reduced is up to
293 15 and 10% lower than the hourly resolution simulation at L4 and CCS respectively, although occasionally up to a
294 5% greater magnitude in chlorophyll concentration does occur (Figure 5H).

295 The weaker trend in the change in the peak amplitude of the bloom to meteorological forcing than other
296 phenological indicators is likely due to the opposing impacts of wind stress on phytoplankton blooms. In some
297 years, differences in the MLDs due to changes in wind stress stimulates a higher magnitude bloom in the hourly
298 meteorological forcing compared to the lower resolution scenarios (i.e 2014, L4; Figure S5a) due to additional
299 nutrients being mixed into the photic zone. However, occasionally a large wind induced mixing event in the hourly
300 simulation relative to the lower resolution of meteorological forcing may cause the cessation of the bloom due to

301 phytoplankton being mixed down to low light environments and hence produce lower peak chlorophyll
302 concentrations (i.e. 2015 L4; Figure S5a).

303 *3.5. Change in length of growing seasons*

304 The increasingly longer period of stratification with lower meteorological resolution supports an increasingly longer
305 growing season of phytoplankton (Figure 5). The start of the growing season is up to 10 days earlier in the 24h
306 scenario at L4 and 11 days earlier at CCS compared to the hourly simulation. The end of the growing season is up to
307 13 and 10 days later at L4 and CCS respectively, although there is little change in the end of the growing season
308 between the hourly and six hourly scenario at L4. The overall effect of reducing meteorological resolution at both
309 sites is to increase the growing season by up to 23 days at L4 and 11 days at CCS.

310 *3.6. Annual changes in carbon reservoirs*

311 Substantial inter-annual variability exists in the dynamics of the spring bloom relative to meteorological forcing and
312 this is demonstrated in the response of carbon stocks (Figure 6). At L4, bacteria and dissolved organic carbon
313 (DOC) biomasses increase with coarsening meteorological resolution, with up to 3% greater biomass in the 24h
314 scenario than the hourly simulation, whilst dissolved inorganic carbon (DIC), phytoplankton, zooplankton, and
315 particulate organic carbon (POC) pools generally decrease with lowering resolution of meteorological forcing. All
316 other carbon reservoirs at L4 show no obvious trend to changing meteorological resolution. In contrast, at CCS,
317 carbon stocks increase with lower meteorological resolution in every year between 2010 and 2015 in all pools
318 except for phytoplankton, dissolved inorganic carbon (DIC) and benthic bacteria. While both the mean and median
319 of phytoplankton and benthic bacterial biomasses increase with lower meteorological forcing, there are some years
320 where lower biomasses occur relative to the hourly forcing scenario.

321 *3.7. Response of carbon fluxes*

322 At L4, decreased meteorological resolution generally results in a lower GPP, reflecting the reduction in
323 phytoplankton biomass (Figure 7). In contrast, at CCS, there is an annual increase in GPP associated with a
324 reduction in resolution of meteorological forcing despite the high variability in changes of phytoplankton biomass at
325 this site (Figure 7). The simulated increase in the mass of DOC at both sites (Figure 6) is reflected in the increased
326 production of DOC from phytoplankton by excretion and cell lysis with lowering meteorological resolution. This
327 positive relationship between the release of DOC by phytoplankton and lower meteorological resolution is greatest
328 during spring while a negative relationship is observed during summer at both sites.

329 The greater production of DOC from phytoplankton in the 6 hour resolution compared to the hourly simulation at
330 both L4 and CCS is further highlighted in Figure 8. Both stations show an enhanced microbial loop in the 6 hour
331 scenario with greater transfer of carbon between phytoplankton, DOC, bacteria and DIC. The enhanced microbial
332 loop at both sites occurs despite opposing trends in both GPP and zooplankton predation of phytoplankton between

333 sites. The same trends are observed in the 12 hourly and 24 hourly meteorological resolution scenarios (results not
334 shown).

335 Changes in phytoplankton phenology also impact the flux of POC to the sediment (Figure S6). At L4, deposition of
336 POC is marginally earlier in the reduced resolution scenarios relative to the hourly simulation. A reduction in the
337 peak depositional flux of POC by up to 5% also occurs during spring with lowering meteorological resolution while
338 a slight enhancement of POC deposition occurs in autumn. In contrast, at CCS an enhanced and earlier depositional
339 flux of POC occurs during the spring bloom as the meteorological resolution is reduced although there is little
340 difference throughout the rest of the year.

341 **4. DISCUSSION**

342 Phytoplankton phenology is known to be strongly impacted by meteorological variables, particularly wind and solar
343 irradiance. The timing of spring and autumn phytoplankton blooms have consequences that cascade through the
344 food web (Edwards & Richardson, 2004) and have been shown to affect fish stocks and spawning, copepod
345 reproduction and shrimp survival (Kodama et al., 2018; Leaf & Friedland, 2014; Marrari et al., 2019; Platt et al.,
346 2003; Richards et al., 2016). If high resolution meteorological data is not available, the ability of hydrodynamic-
347 ecosystem models to capture the impact of short-term fluctuations in wind stress, light availability and other key
348 meteorological variables on bloom phenology and carbon cycling is limited. Here we show that these short-term
349 fluctuations contribute to the amount of energy available within the water column and thus influence both physical
350 and ecological dynamics within ocean models. Our study is designed to highlight the potential impacts of changing
351 meteorological forcing resolution on ecosystem dynamics. This work provides insight into which variables and
352 processes the phytoplankton blooms at both sites are sensitive to as discussed below, but it is not designed to
353 determine which factors trigger the phytoplankton blooms at both sites.

354 An idealized conceptual model explaining the role of meteorological resolution and ecosystem implications is
355 created from our results (Figure 9). A coarsening in meteorological resolution misses high intensity wind events and
356 thus produces less turbulent kinetic energy within the water column resulting in a longer period of stratification,
357 during which phytoplankton cells remain near the surface and are not mixed down to non-viable, low-light depths.
358 Consequently, the growing season is longer, with the spring bloom starting earlier and the autumn bloom often
359 terminating later. In addition to the bloom starting earlier, changes in wind stress have contrasting impacts on
360 phytoplankton biomass due to: 1) reduced winds mix fewer nutrients across the nutricline leading to weaker spring
361 blooms or 2) the phytoplankton bloom lasts longer with lower meteorological resolution as increased winds can
362 cause an earlier cessation of the phytoplankton bloom by mixing the phytoplankton out of the photic zone (Follows
363 & Dutkiewicz, 2002; Waniek, 2003). The balance between enhanced winds mixing nutrients across the nutricline,
364 alleviating nutrient stress, and mixing phytoplankton out of the photic zone contributes to the direction of change in
365 GPP to meteorological forcing in addition to the changes in the length of the growing season. Consequently,
366 implications for ecosystem function are site dependent and is discussed further in section 4.2. In this study, an

367 enhanced microbial loop occurs at both sites with coarsening meteorological resolution although different
368 mechanisms drive the enhancement.

369 *4.1. Impacts of wind stress on phytoplankton phenology*

370 A coarsening of meteorological forcing resolution causes decreased wind stress on the ocean surface. Our results
371 showing an earlier spring phytoplankton bloom under decreased wind stress are unsurprising given the earlier onset
372 of stratification (Figure 4) and are consistent with the critical turbulence hypothesis of Taylor and Ferrari (2011) and
373 results of Chiswell (2011) and Vikebø et al. (2019) who link the timing of the spring bloom to wind-driven
374 processes. The earlier phytoplankton bloom with decreased wind stress matches trends observed in other shallow
375 systems such as in the European Shelf (González Taboada & Anadón, 2014), Central Cantabrian Sea (Álvarez et al.,
376 2009) and Baltic Sea (Groetsch et al., 2016). However, Barnes et al. (2015) predict that the peak amplitude of the
377 spring micro-phytoplankton bloom at L4 is later in years when there is reduced wind although this tends to coincide
378 with either warmer sea surface temperatures or low salinity. A similar trend for phytoplankton bloom initiation is
379 also shown by Krug et al., (2018) in the shelf slope system off the south west Iberian peninsula. Both studies
380 hypothesized that reduced winds decreased the availability of winter nutrients for phytoplankton due to enhanced
381 stratification and reduced mixing. The differences between our results and those predicted by Barnes et al. are likely
382 due to differences in methods: Barnes et al. average wind speeds at L4 on a seasonal to annual scale so their results
383 are not directly comparable to what we present here.

384 The earlier start of the phytoplankton bloom at CCS with decreasing winds is also in contrast to that predicted by
385 Henson et al. (2009). Using a combination of satellite data and model predictions, these authors indicate that bloom
386 timing is delayed during both positive and negative phases of the North Atlantic Oscillation (NAO), which cause
387 enhanced and decreased winds, respectively, at the approximate location of the CCS study site. However, Henson et
388 al. (2009) use a different set of criteria to define the start of the bloom and predict the onset at CCS 1-2 months
389 earlier than we report here. Earlier in the season, phytoplankton phenology could be more sensitive to other factors
390 associated with the NAO such as light or sea surface temperature, which may offset the changes associated with
391 wind stress that we have found.

392 Earlier phytoplankton blooms which are (at least partially) attributed to a decrease in wind stress are often longer
393 and weaker than phytoplankton blooms that occur later in the season (González Taboada & Anadón, 2014; Groetsch
394 et al., 2016) although, Krug et al. (2018) found the opposite trend on the coastal shelf off the south west Iberian
395 peninsula. Our results also suggest a longer bloom with decreased wind stress due to both an earlier start and later
396 finish to the bloom (Figure 5). In addition, although there is a tendency at both sites towards a diminished bloom
397 magnitude when the bloom starts earlier this does not always happen. In cases where the wind disrupts the
398 formation of stratification, Waniek (2003) predicts that zooplankton biomass will increase relative to years with
399 uninterrupted formation of stratification, due to having more time to respond to changes in phytoplankton biomass.
400 Hence lower phytoplankton biomass and greater primary production, would occur, in addition to greater
401 zooplankton biomass. This mechanism appears to arise during 2014 at CCS and 2015 at L4 when there is a lower

402 peak magnitude of phytoplankton biomass and higher peak zooplankton in the hourly simulation compared to the 24
403 hourly scenario (Figure S5b), although the peak magnitude of GPP is also lower during these years. In all other
404 years where a decrease in phytoplankton biomass occurs in the hourly simulation relative to the scenarios (i.e. 2012
405 L4 and CCS; Figure S5a and b), a lower peak in zooplankton also occurs.

406 In addition to changing phytoplankton bloom length, interannual changes in meteorological variables have also been
407 linked to an increase in the length of the growing season. Increasing delays between spring and autumn blooms
408 have been observed in the temperate North Atlantic, and are attributed to enhanced stratification due to the warming
409 of the ocean (González Taboada & Anadón, 2014). Here, we show that differences in wind stress can also prolong
410 the period of stratification and consequently the length of the growing season (Figure 4). Wihsgott et al. (2019)
411 determine that wind stress is important in controlling the breakdown of stratification and hence the timing of the
412 autumn bloom at CCS. During 2014 and 2015 at CCS, wind stress was predicted to be responsible for controlling
413 the MLD 53% of the time, increasing to more than 60% during the period of the autumn bloom (Wihsgott et al.,
414 2019). Similar to the spring bloom, our results suggest that increased wind stress can enhance the peak magnitude
415 of phytoplankton biomass during autumn at both CCS and L4 (i.e. in 2012, CCS, 2013, L4; Figure S5e and f) but also
416 terminate the bloom earlier (2011, L4). Overall, this leads to enhanced phytoplankton biomass in the hourly
417 simulation compared to the reduced resolution scenarios at both stations during autumn (Figure 7).

418 The timing and magnitude of the autumn bloom, particularly across the outer shelf immediately before a period of
419 net off-shelf transport during the winter (Ruiz-Castillo et al., 2019), could affect the amount of carbon annually
420 exported off-shelf (Wihsgott et al., 2019). Although not captured by the 1D model, wind stress plays an important
421 role in seasonal shelf-scale circulation (Ruiz-Castillo et al., 2018) and can advance (delay) the onset (breakdown) of
422 stratification by ~ 1 week via a horizontal salinity straining mechanism, with corresponding adjustments to the
423 spring and autumn bloom timings (Ruiz-Castillo et al., 2019). The changes in bloom timing reported here that result
424 from differing temporal resolutions of the wind stress forcing are of the same magnitude.

425 *4.2. What drives the enhanced microbial loop?*

426 An enhanced microbial loop occurs at both sites with lowering meteorological resolution (Figure 8). However, the
427 impact on the ecosystem structure and nutrient dynamics due to the change in stratification is different between the
428 two sites, despite similarities in the phenology. A key driver of the microbial loop is the change in DOC production.
429 DOC production provides food for bacteria which enhances remineralization of carbon back to DIC. Extracellular
430 release of DOC by phytoplankton is the main source of DOC to marine systems (Borchard & Engel, 2015).
431 Extracellular release may occur through passive diffusion of low molecular weight compounds across cell
432 membranes (Bjornsen, 1988) or through active release of DOC by exudation (Fogg, 1983) which has been shown to
433 be enhanced by environmental stress such as nutrient limitation (Borchard & Engel, 2015; Goldman et al., 1992;
434 Mühlenbruch et al., 2018; Smith Jr et al., 1998). Within ERSEM, DOC is released by phytoplankton as a fixed
435 portion of GPP through excretion (Butenschön et al., 2016). In addition, phytoplankton within ERSEM release
436 higher proportions of DOC when undergoing nutrient stress through cell lysis and excretion.

437 We propose that different mechanisms are driving the enhanced microbial loop at each site reflecting the site-
438 specific response of GPP, phytoplankton and zooplankton to the meteorological forcing. The small increase in GPP
439 at CCS with lowering meteorological forcing resolution likely reflects the longer growing season due to the
440 increased amount of time that the water column is stratified (Figure 4). The higher GPP could further reflect less
441 turbulent conditions and thus a greater time that phytoplankton remain in the photic zone. The greater GPP in spring
442 as meteorological resolution decreases (Figure 7) supports both these hypotheses. In contrast, at L4 there is a weak
443 trend towards a decreasing GPP on an annual scale with coarsening meteorological resolution which reflects the
444 lower phytoplankton biomass in the scenarios (Figure 7). The decreasing trend is greatest during summer and likely
445 reflects the weaker flux of nutrients across the nutricline during this time period (Figure 10A) as there is reduced
446 kinetic energy within the water column. This mechanism is much weaker at CCS (Figure 10B) as there the nutricline
447 is positioned at greater depth, out of reach of the turbulence produced by surface wind stress. Thus greater wind
448 stress is required at CCS to break down stratification up to the depth of the nutricline. Lower GPP at L4 in the
449 scenarios may also be driven by the thinner mixed layer resulting in a reduction in the total mass of nutrients within
450 the mixed layer available for phytoplankton growth (Figure 4, S5c). This last process is hypothesized to be
451 important for bloom timing in nutrient limited subtropical seas (Henson et al., 2009).

452 The contrasting trends in GPP at L4 and CCS highlight the role that resource limitation plays in the response of a
453 system to external variables. The spring bloom at L4 ultimately becomes limited by nitrate concentrations which
454 remain low within surface waters throughout the summer (Smyth et al., 2010). At CCS the spring bloom is typically
455 both light and nitrate limited with summer phytoplankton growth nitrate limited and the autumn bloom light limited
456 (Poulton et al., 2018). This is confirmed in the model by the light and nutrient limitation factors which show a
457 similar trend between the two sites for nutrients in the hourly simulation and an enhanced light limitation at CCS
458 compared to L4 (Figure S7). Light limitation appears more important in controlling the response of the ecosystem to
459 changes in meteorological forcing at CCS than nutrient limitation due to the correlation between growing season and
460 GPP and the relatively strong stratification in summer reducing the impact of turbulent mixing. In addition, the
461 variation in phytoplankton biomass compared to trends in GPP further suggests, at least in some years, top-down
462 control on phytoplankton by zooplankton. This highlights the potential mismatch within the plankton community to
463 changes (Edwards & Richardson, 2004). Indeed, zooplankton displays the highest relative change out of all the
464 pelagic carbon reservoirs to meteorological forcing at CCS. Although not directly included in ERSEM, a delayed
465 phytoplankton bloom start can further limit phytoplankton biomass due to an enhanced zooplankton population as a
466 result of reproduction (Henson et al., 2009).

467 The fact that the two different sites, one light limited and one nutrient limited, both show increased DOC
468 concentrations with lower meteorological resolution is directly linked to the multiple pathways for DOC formation
469 in ERSEM. The increased GPP at CCS results in greater release of DOC by phytoplankton, as indicated by the
470 similar trend in the production of DOC by phytoplankton and GPP. In contrast at L4, phytoplankton become more
471 nutrient stressed as resolution of meteorological forcing reduces (Figures S7 and S8) which is highlighted by the
472 differing trends between the creation of DOC by phytoplankton and GPP, during spring, autumn and on an annual

473 scale (Figure 7). The increased nutrient stress with lowering meteorological resolution is likely due to a
474 combination of the decrease in mixing which then reduces the amount of nutrients available for phytoplankton
475 growth during the spring and autumn blooms, and the longer growing season with coarsening meteorological
476 resolution resulting in a longer period of nutrient stress and thus increases the stress induced DOC production. The
477 enhanced DOC concentrations intensifies the microbial loop, stimulating bacterial production and hence cycling of
478 carbon back to DIC in the lower meteorological resolution simulations (Figure 8).

479 *4.3. Increasing meteorological resolution in hydrodynamic ecosystem models*

480 The recent release of the ERA5 reanalysis product (C3S, 2017) will result in increasingly higher resolution of
481 meteorological forcing being used in ocean models. Little consideration may be made on how this could impact
482 ecosystem dynamics. Our results show that switching the resolution of meteorological forcing from a dataset such
483 as ERA-Interim (Dee et al., 2011), which provides 6 hourly analysis for meteorological data, to ERA5 could impact
484 both phytoplankton phenology and ecosystem structure. The change in the timing of the start of the bloom of up to 6
485 days due to resolution of meteorological forcing is substantial given that it is on the same order of magnitude as the
486 variability of the start date of phytoplankton blooms observed in the North Sea and that of the response of benthic
487 communities to depositional carbon fluxes (Sharples et al., 2006; Lessin et al., 2019) in addition to the timescale of
488 forecasts made by operational models. Large variability also exists in the response of phytoplankton phenology and
489 ecosystem dynamics to meteorological forcing with some years showing little change. Thus changing the resolution
490 of meteorological forcing enhances the predicted variability in timing of blooms in addition to the changes in the
491 microbial loop and depositional fluxes to the sea floor.

492 We have investigated the impact that wind in a 1D model has on physical and biogeochemical dynamics. The
493 impacts in 3D may be greater than presented here as the spatial resolution of the horizontal grid from ERA-Interim
494 to ERA 5 improves from 79km to 31km adding further fluctuations in wind stress to the surface water. In addition,
495 hourly light and cloud cover data will also result in changes between ERA5 and ERA-Interim. Here, we
496 purposefully kept net shortwave radiation constant in all scenarios as the effect of changes in incoming shortwave
497 radiation as a result of switching from ERA5 to ERA-Interim are likely to be model specific, depending on the
498 model formulations for light. Changes in bias in the ERA-Interim and ERA5 datasets, for example, the higher
499 precipitation rates over Europe in ERA5 than ERA-Interim (ECMWF/C3S/CAMS, 2018.), should also be
500 considered when changing meteorological forcing, but are beyond the scope of this study.

501 There may also be projects when time averaged meteorological variables (i.e. Blackford, 2002; Ridderinkhof, 1992)
502 are used rather than instantaneous values. Time averaging meteorological variables rather than subsampling,
503 produces greater changes than observed here. Running the model with daily (24 hour) averaged data, further
504 dampens the variability in meteorological inputs reducing the wind stress acting on sea surface resulting in larger
505 changes in phytoplankton phenology and ecosystem dynamics than what we predict in the 24 hour subsampled
506 scenario (results not shown).

507 **5. CONCLUSION**

508 This study investigates the response of shelf-sea ecosystems to the resolution of meteorological forcing in
509 hydrodynamic-ecosystem models. This is especially important given the increased availability of hourly datasets
510 such as the ERA5 and NCEP Climate Forecast System products. In general, a higher temporal resolution of
511 meteorological forcing results in greater mixing within the water column with a later development of the surface
512 mixed layer in spring and earlier breakdown in autumn. This produces a shorter growing season and later start to the
513 phytoplankton bloom which directly impacts higher trophic levels within the ecosystem, and at CCS, weakens
514 deposition of POC to the sea floor during spring. The strength of the microbial loop at both sites is reduced: at the
515 coastal L4 station this is a consequence of the relief of nutrient stress resulting in less DOC expelled by
516 phytoplankton, at the offshore CCS station, this is a consequence of the decrease in GPP due to the reduced growing
517 season.

518 Our results show that it is important to consider the impact that changes in meteorological forcing of coupled
519 hydrodynamic-ecosystem models will have on interpreting physical and ecosystem dynamics. Although this work
520 only includes two sites on shelf seas, we believe that our work can be extrapolated to other sites globally and other
521 model setups. We envision that the sites which will show the biggest response to meteorological forcing are those
522 that are seasonally or intermittently stratified, similar to the ones studied here. These sites represent approximately
523 44% of the surface area of the North Sea (van Leeuwen et al., 2015). Permanently mixed sites are unlikely to show
524 any strong impact to changes in meteorological forcing resolution, while permanently stratified sites might show a
525 small response to meteorological forcing. The conceptual model that we present can be used to guide researchers on
526 expected outcomes using their knowledge of stratification of an individual site, resource limitation status and model
527 design (i.e. whether there is a stress release mechanism for DOC). The main effect of changing the meteorological
528 forcing in this study was to increase the variability of winds, consequently adding more energy into the water
529 column. A main limitation of our study is that changes in the frequency of prescribed shortwave radiation, or cloud
530 cover, were not investigated. The ecosystem response to such changes are likely to be dependent on individual
531 model formulations for light which should also be considered when switching meteorological forcing. Thus,
532 recalibration of models may be required when switching meteorological forcing which may give new insights to
533 ecosystem dynamics.

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540 doi:10/c4mj, doi:10/c4pk, doi:10/c4mk, doi:10/c4ph, doi:10/c4pk, doi:10/c4pj, doi:10/c4pf., doi:10/c4pg. The
541 model configurations used in this paper to run GOTM-FABM-ERSEM, links to download the model code and nc

542 files containing the model results can be downloaded from: https://zenodo.org/record/3712237#.Xq_UWqhKjD4.

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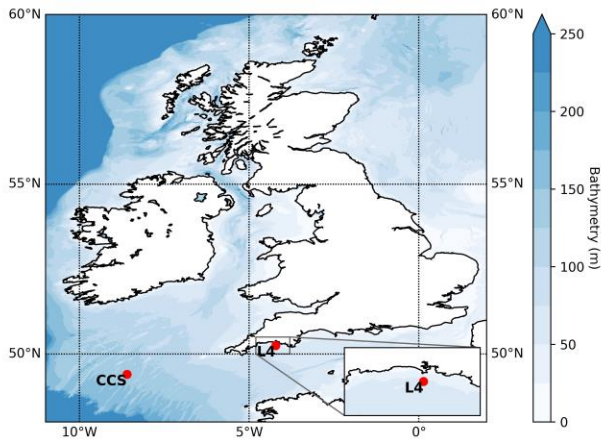
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754 **Figure Captions**

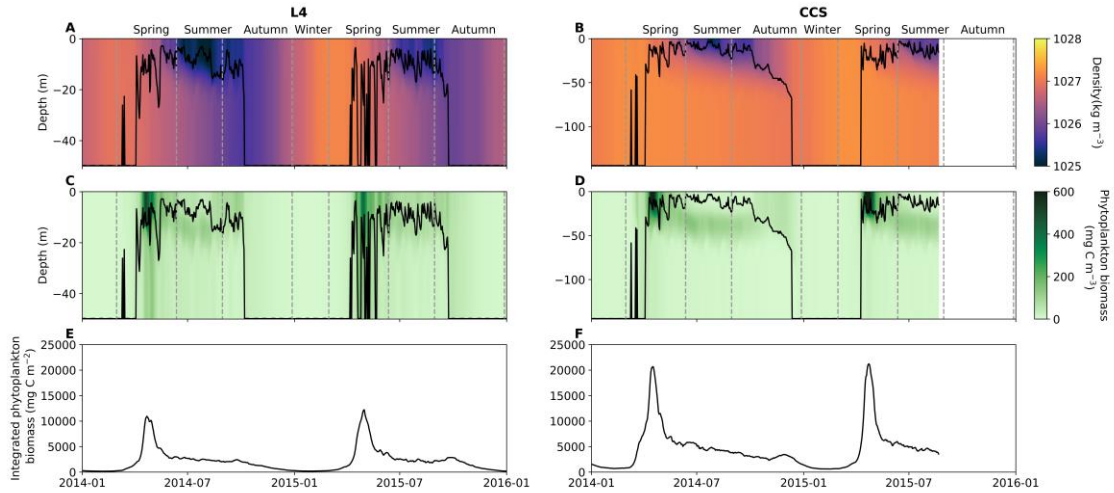
755 **Figure 1:** Map of station locations. Colours represent bathymetry (GEBCO_2019 grid, www.gebco.net)



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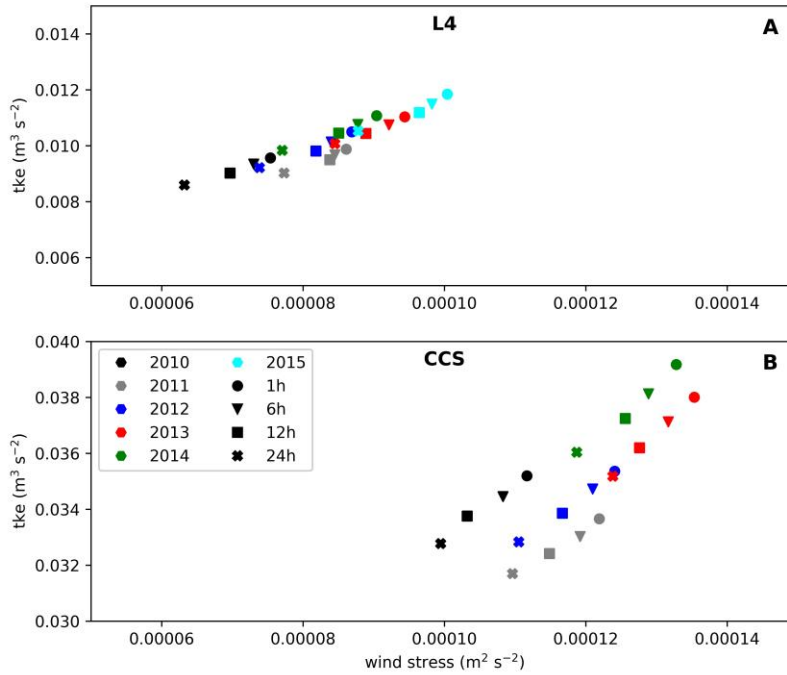
758 **Figure 2:** Density and phytoplankton biomass distributions at L4 (A and C) and CCS (B and D) in 2014 and 2015.
 759 Black line indicates the mixed layer depth, grey dashed lines delineate seasons. Note difference in depth between L4
 760 and CCS.



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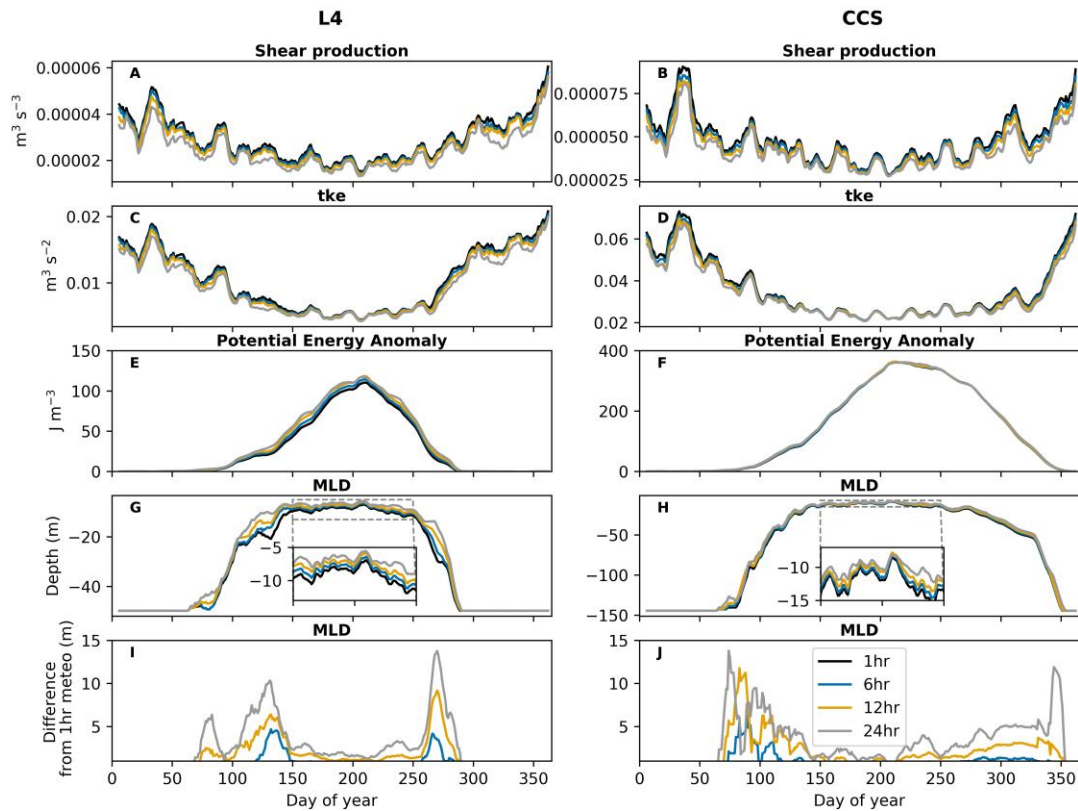
763 **Figure 3:** Correlation between mean annual magnitude of windstress and mean annual depth integrated turbulent
 764 kinetic energy (tke) for different meteorological forcings (shapes) and individual years (colour) between 2010 and
 765 2015.



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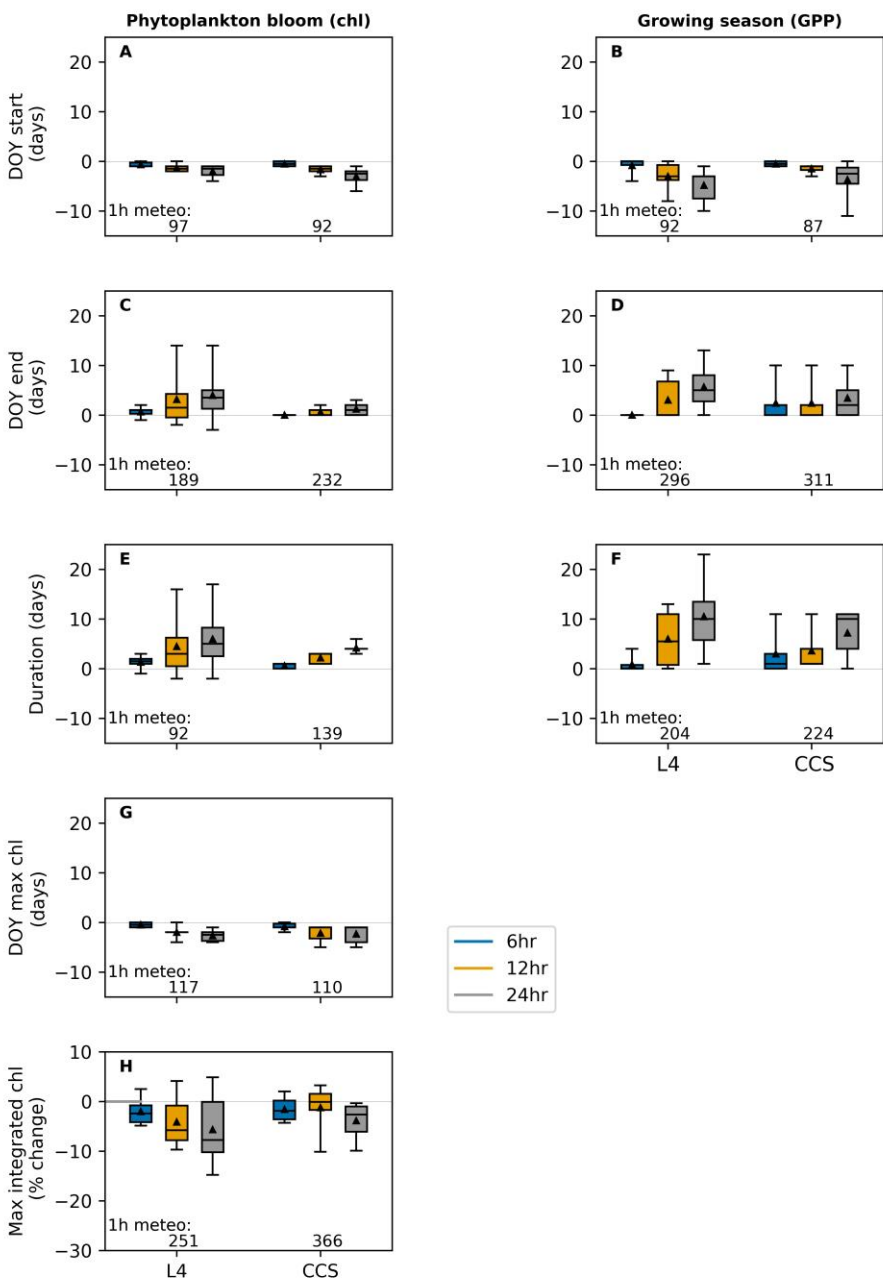
768 **Figure 4:** Impact of meteorological forcing on physical dynamics baseline hourly simulation and 6,12 and 24 hourly
 769 scenarios (A-H), presented as a climatology for the time period 2010 to 2015 calculated using a 10 day running
 770 mean. Panel I-J represents the difference in mixed layer depth (MLD) in the 6h, 12h and 24h scenarios compared to
 771 the hourly simulation with positive values indicating a shallower mixed layer depth. Results for individual years can
 772 be found in the supplementary material. Tke = turbulent kinetic energy, MLD = mixed layer depth. The potential
 773 energy anomaly (Simpson et al., 1981) represents strength of stratification. Note difference in y scales between
 774 graphs



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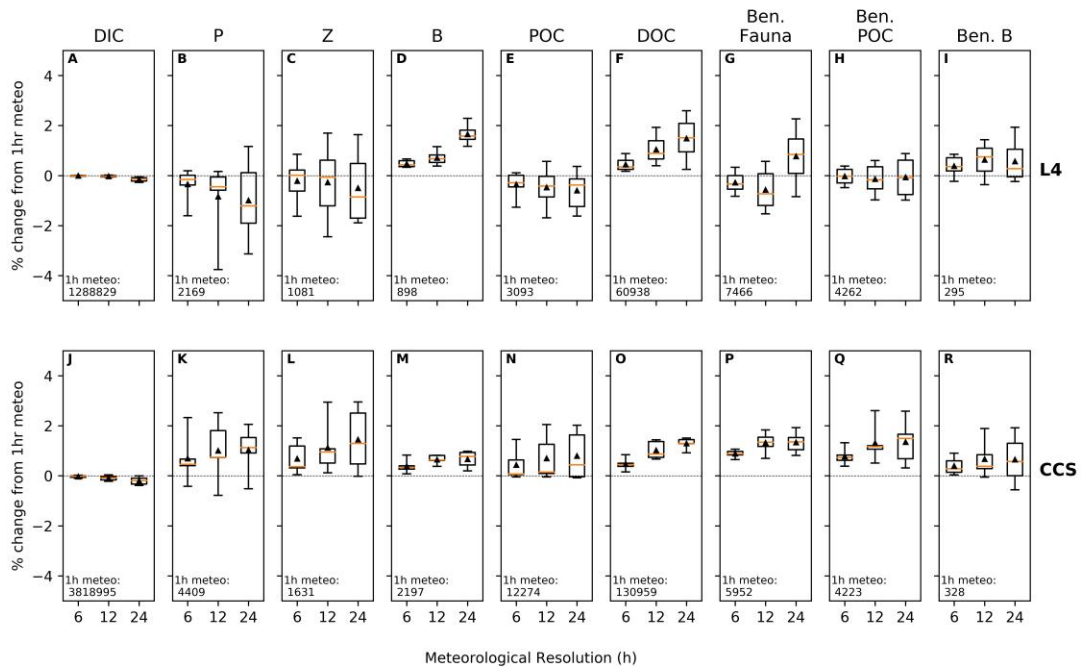
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777 **Figure 5:** Difference in phytoplankton bloom (A, C, E, G, H) and growing season characteristics (B,D,F) between
 778 6,12 and 24h scenarios and hourly meteorological resolution simulation at L4 and CCS for each year between 2010
 779 and 2015. For CCS, 2015 results were not included in metrics for day of the year (DOY) end and duration as the
 780 model simulation ended in August 2015. Lines through middle of box plots represent median, black triangles: mean,
 781 whiskers in the boxplots represent the maximum and minimum range of the data. Numbers on bottom of graph
 782 indicate the mean result of the 1h meteorological forcing simulation. See text for details on methods used to
 783 calculate phytoplankton bloom and growing season statistics. Note the change in y scale in panel H. chl =
 784 chlorophyll a, GPP = gross primary production.



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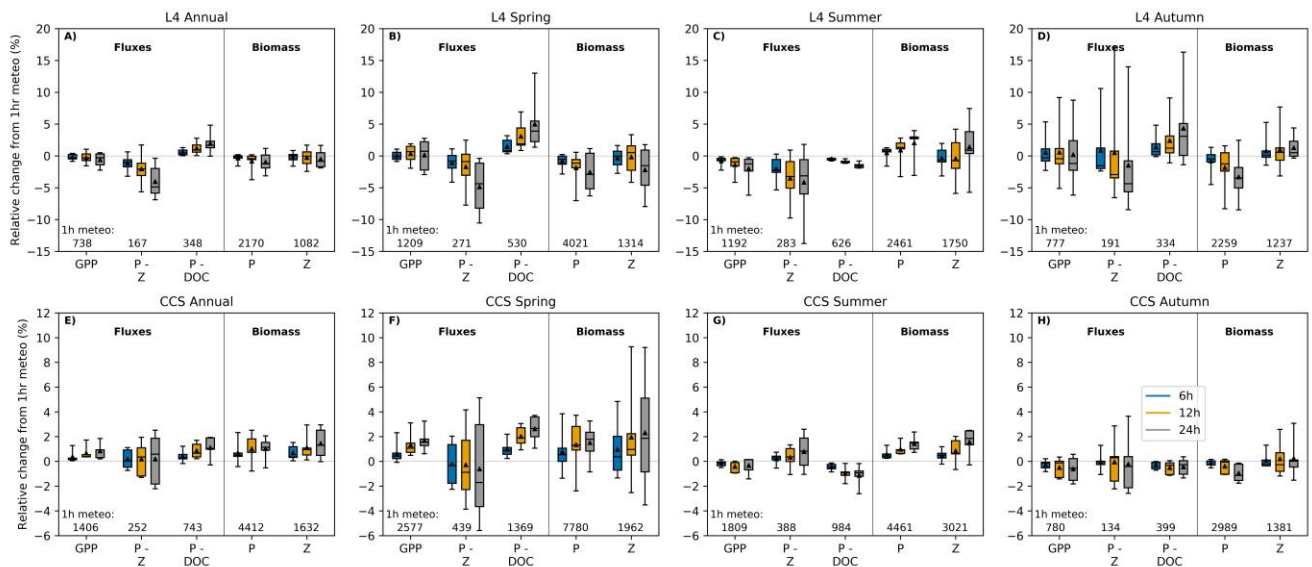
786 **Figure 6:** Percentage change in the annual distribution of depth integrated mean carbon biomass for 6, 12 and 24
 787 hourly resolutions of meteorological forcing relative to hourly meteorological forcing for each year between 2010
 788 and 2015 at L4 (A-I) and CCS (J-R). For CCS, 2015 results were not included as the model simulation ended in
 789 August 2015. Line across box represents median, black, filled triangle represents the mean, whiskers in the boxplots
 790 represent the maximum and minimum range of the data. Positive values indicate 1 hourly meteorological simulation
 791 was lower than the defined scenario. Numbers at the bottom of graphs represent the mean annual biomass for hourly
 792 meteorological resolution in units of mg C m^{-2} . DIC = Dissolved inorganic carbon, P=Phytoplankton, Z=
 793 zooplankton, B = Bacteria, POC = Particulate Organic Carbon, DOC = dissolved organic carbon, Ben. = Benthic.



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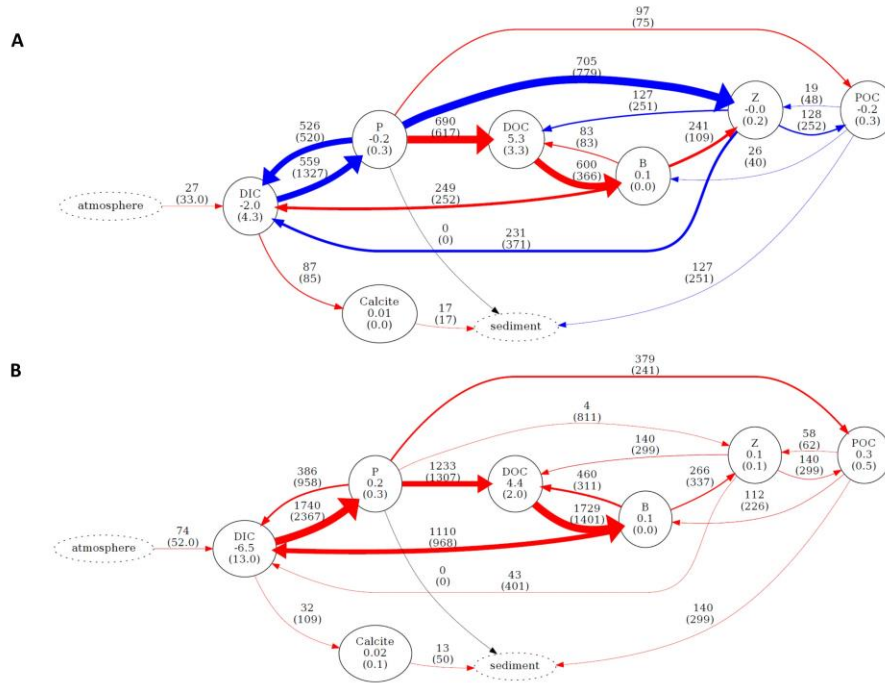
806 **Figure 7:** Impact of meteorological forcing on the depth integrated, mean fluxes controlling phytoplankton and
 807 zooplankton biomass for each year over 2010-2015, shown as the percentage change between 6,12 and 24 hourly
 808 meteorological forcing and the hourly meteorological forcing simulation at L4 (A-D) and CCS (E-H). Seasons
 809 correspond to the days of the year given in Table S3. Positive values indicate 1 hourly meteorological simulation
 810 was lower than the defined scenario. Line across box represents median, black, filled triangle represents the mean,
 811 whiskers in the boxplots represent the maximum and minimum range of the data. Note difference in scales between
 812 stations. Numbers on bottom of graph indicate the result of the 1h meteorological forcing simulation (Fluxes: mg C
 813 m⁻² d⁻¹, biomass: mg C m⁻²). GPP = gross primary production, P-Z=Phytoplankton to zooplankton flux, P-DOC =
 814 phytoplankton to dissolved organic carbon flux ,P = phytoplankton, Z= zooplankton.



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807 **Figure 8:** Flow diagram indicating mean differences in carbon reservoirs and fluxes between 2010 and 2015
 808 between the 6 hourly meteorological resolution scenario and hourly simulation for stations A) L4 and B) CCS.
 809 Numbers in brackets represent the standard deviation of annual fluxes and reservoirs. Width of arrows is
 810 proportional to size of absolute flux, red indicates an increase in the 6 hourly forcing relative to the hourly while
 811 blue indicates a decrease. DIC = dissolved inorganic carbon, P=phytoplankton, Z= zooplankton, B = Bacteria, POC
 812 = Particulate Organic Carbon, DOC = dissolved organic carbon. Reservoir units: mg C m^{-3} ; Flux units: $\text{mg C m}^{-2} \text{ yr}^{-1}$.
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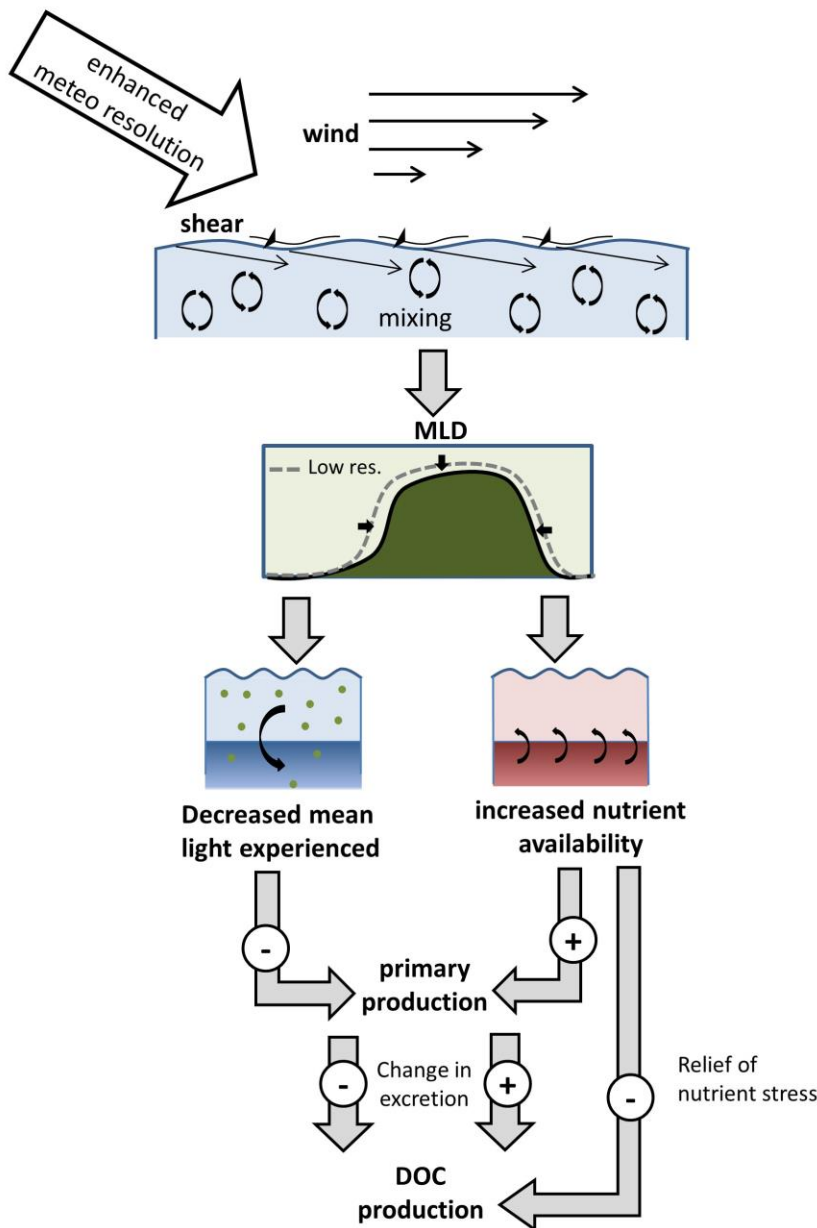


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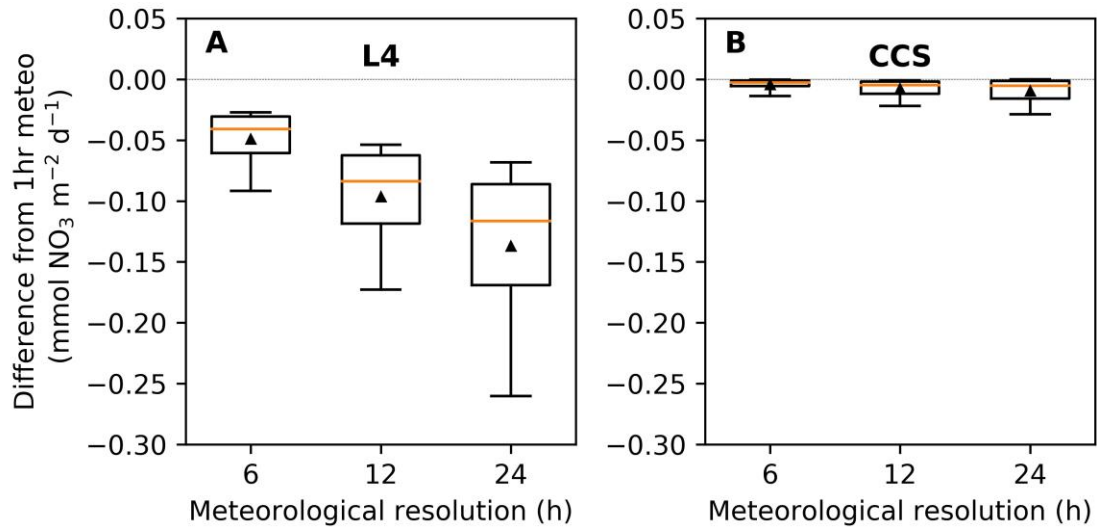
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817 **Figure 9:** Conceptual model highlighting the impact of enhancing the meteorological resolution, and thus wind
 818 stress on primary and dissolved organic carbon (DOC) production. Increased mixing results in more phytoplankton
 819 mixed out of the photic zone, decreasing the average amount of light experienced by phytoplankton, and increased
 820 nutrients being mixed across the nutricline into the photic zone. Note changes in mixed layer depth (MLD) are
 821 exaggerated for purpose of this illustration.



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823 **Figure 10:** Vertical diffusive flux of nitrate within the mixed layer (7.5m L4; 20m CCS) during summer shown as
824 the difference between 6,12 and 24 hourly meteorological forcing and the hourly meteorological forcing simulation
825 at L4 (A) and CCS (B) for years 2010-2015. Line across box represents median, black, filled triangle represents the
826 mean, whiskers in the boxplots represent the maximum and minimum range of the data.



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