# Using the S2P3 1D physical-biological oceanographic model to investigate the influence of ordered spring-neap on phytoplankton dynamics.

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## Introduction

Climate change is increasingly impacting the marine environment, altering trophic interactions and modifying the structure and functioning of food webs (Ullah et al., 2018) and changing the timing of important events (Eerkes-Medrano et al., 2017). As a result, an increasing number of studies are investigating the influence of daily weather patterns on annual patterns of primary production. However, there may be other factors involved.

Phytoplankton are the basis for most marine food-webs, acting as the food source for larger copepods which themselves are prey for many organisms including forage fish larvae. Therefore, the abundance of phytoplankton can directly and indirectly influence the population dynamics of higher trophic predators (Frederiksen et al., 2006; Turner, 2004; Scott et al., 2006). In temperate coastal regions large spikes in phytoplankton biomass, known as blooms, can occur during spring and autumn as a result of interactions between meteorology and topography (Tian et al., 2011; Wihsgott et al., 2019). The spring bloom, in particular, is an extremely important event for shelf seas, representing up to a third of regional annual phytoplankton production (Carpenter et al., 2016; Townsend et al., 1994).

A key factor impacting primary production by phytoplankton is the degree of vertical mixing in the water column, as it influences nutrient availability and can limit access to light via turbidity levels and altered vertical distribution of phytoplankton cells (May et al., 2003; Smith and Jones, 2014). In shelf seas such as the North Sea, an important driver of vertical mixing is tidal currents (Sharples, 2007; Hetzel et al., 2015; Rippeth et al., 2014). Tidal variability during the spring-neap cycle has the potential to greatly impact primary production, with weak and strong tidal currents estimated to contribute up to 10% and 25% of interannual variability in the timing of the spring bloom, respectively (Sharples, 2007). In estuaries, tidal forcing can significantly influence phytoplankton biomass and production and can impact the composition and distribution of the plankton community, which affects production and plankton species composition (Cloern, 1991; Lauria et al., 1999).

This study investigates the dynamics of daily weather effects on primary production across the spring-neap tidal cycles of a large, 44-year dataset. By basing the analysis on sets of tidal cycles this research differs from most previous fine-scale studies, which often use calendar dates or months for value comparisons. Using a 1D physical-biological model set for a typical location in the Northern North Sea, the timing of bloom onset, mean production and variance during each subsequent cycle and interannual production for each cycle is compared, to assess if any particular tidal-cycles shows higher variance in production levels and if the annual pattern is showing any trend over this time scale.

# Methodology

The Shelf Sea Physics and Primary Production (S2P3) 1D physical-biological model, developed by Sharples (1999), was utilised to model the seasonal cycle of primary production in the Marr bank region of the North Sea.

The model simulates the tidal currents, wind stress, and air-sea heat flux influencing the vertical structure of the water body in question and generates daily values including water temperature, current speed, and both surface layer and depth-integrated chlorophyll concentrations. Required inputs include physical data such as water column depth and meteorological observations, as well as biological data such as phytoplankton growth and grazing rates (see Sharples et al., (2006) and Sharples (2007) for a full description of the model physics and biology). Parameters for water column depth and physics, and phytoplankton characteristics, were obtained from studies in the Marr Bank region (EU IMPRESS project, https://core.ac.uk/download/pdf/38677303.pdf).

Meteorological data were obtained from the Centre for Environmental Data Analysis (CEDA) (http://www.ceda.ac.uk/) for Leuchars Met station (56°38'N, 2°86'W) for the period 1974 to 2017. These data consisted of hourly observations of wind speed (knots) and direction (degrees), mean sea-level pressure (mbar), cloud cover (8ths), air temperature (°C), and percentage relative humidity. In order to run the model, the following formulas were used to convert wind speed to metres per second (m/s), and cloud cover to percentage:

$$\frac{m}{s} = knots * 0.51444$$

$$\% \, Cloud \, Cover = \left( \frac{Cloud \, Cover \, (8th)}{8} \right) * 100$$

Data were averaged into daily values, with duplicate rows removed from the dataset. In the case of years with missing data points the following actions were taken: when a portion of the hourly data for a day was present, the daily average was obtained from the available points; in the absence of a single day, the missing values were taken from the previous day; where numerous consecutive days were missing, a sequence of smoothed "stepped" values was entered.

Sea surface temperature (SST) for the first calendar day of each year was obtained from the European Centre for Medium-Range Weather Forecasts (ECMRWF) datasets ERA-20C (years 1974-1978) and ERA-Interim (years 1979-2017) (https://www.ecmwf.int/). For consistency, all data were extracted for coordinates 56°25'N, 1°50'W, representing the closest possible point to the Marr Bank region in the available datasets.

Model runs were performed for each year separately, with biological parameters kept constant and the appropriate meteorological parameters inputted. The Julian day at which the spring bloom began each year was obtained from the model output files. The onset of the spring bloom was defined as the date at which the surface-chlorophyll concentration exceeded 2 mg/m$^3$ and remained above this level for a minimum of 5 consecutive days. This threshold was selected due to the resulting lower variance and standard deviation in estimated bloom timing relative to other tested values (0.4 & 0.3 mg/m$^3$).

The daily data output from each year was split into individual spring-neap cycles. Spring-neap cycles were identified using the daily mean, depth-averaged current speed (m s$^{-1}$), with neap tides determined to occur on days in which the current speed reached its lowest value, and spring tides determined as occurring on days in which the current speed peaked. Each cycle was labelled with a

number corresponding to its relative position during the year. The model outputs of daily values of depth-integrated chlorophyll (mg m$^{-2}$) were then grouped according to their relevant cycle.

The variation in the timing of the spring bloom was investigated using box- and scatterplots. In order to compare the variation in daily chlorophyll values across all years for each cycle, chlorophyll values for cycles occurring subsequent to the cycle containing the spring bloom onset were extracted and plotted for all years, grouped by cycle. Mean production during the cycles around the spring and autumn blooms was also extracted and plotted in order to investigate the variation in production between years for those key cycles.

## Results

The onset of the spring bloom ranged from Julian day 108 – 132 (Figures 1 & 2). The spring-neap cycle during which the bloom occurred displayed limited variation between cycles 9 and 10 (Figure 3). Similarly, the onset of the autumn bloom displayed some variation between cycles 18 and 19 (Figure 3). Table 1 displays mean depth-integrated chlorophyll values for each cycle, as well as their standard deviation and range.

Across years, primary production within each cycle displayed low variation (Figure 3, Table 1). Within years, primary production displayed low variation across cycles 10-12 following the spring bloom (Figure 4, Table 1). During the autumn bloom period (cycles 18-20), primary production displayed slightly more variation, though this was still quite low (Figure 4, Table 1).
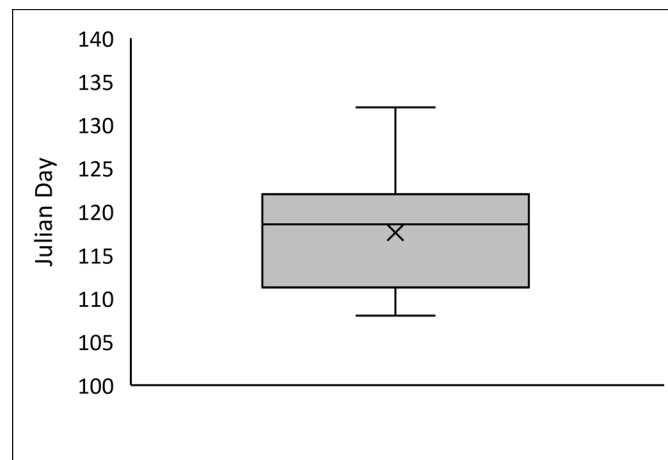


Figure 1: Boxplot displaying the range of values (Julian day) for the timing of the onset of the spring bloom across all years 1974-2017. Mean = 118, range = 108-132, N=44. Note vertical axis scale.
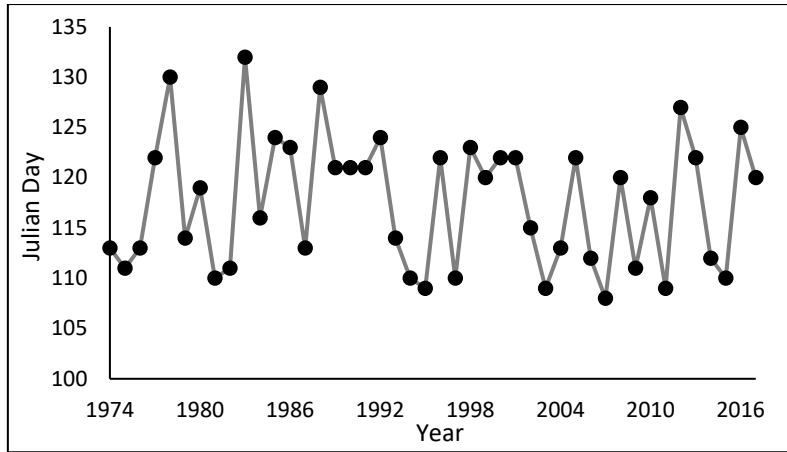
Figure 2: Scatterplot displaying the Julian day at which the spring bloom began, across all study years 1974-2017. Note vertical axis scale. Mean = 118, SD = 6.48, N = 44.
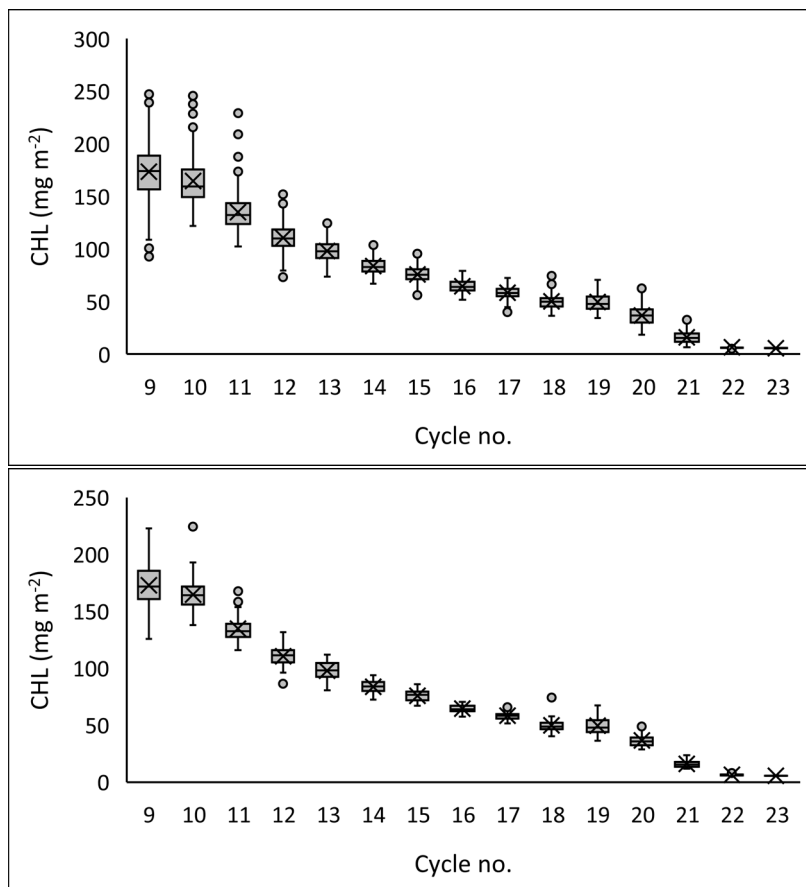


Figure 3: Boxplots displaying the range of depth-integrated chlorophyll (CHL) values produced for each spring-neap cycle following the onset of the spring bloom, across all study years. (Top) = daily values, (Bottom) = mean values. For cycle 9 N=30, while for cycle 10 onwards N=44. Note varying axis scales

Table 1: Mean, standard deviation (SD) and maximum/minimum values for depth-integrated chlorophyll (CHL) values from each cycle following the onset of the bloom, across all years combined. Row order is ranked by decreasing SD.

| Cycle no. | CHL Mean | +/- SD | %Deviation | Max. | Min. |
|---|---|---|---|---|---|
| 9 | 173.24 | 28.37 | 16.38 | 247 | 92.66 |
| 10 | 164.49 | 22.41 | 13.62 | 245.57 | 121.88 |
| 11 | 134.89 | 15.57 | 11.54 | 229.11 | 102.22 |
| 12 | 110.52 | 12.30 | 11.13 | 154.56 | 73.14 |
| 13 | 97.89 | 10.05 | 10.27 | 130.93 | 73.48 |
| 20 | 36.75 | 8.94 | 24.33 | 62.41 | 18.46 |
| 19 | 49.57 | 8.19 | 16.52 | 78.34 | 34.24 |
| 14 | 83.79 | 7.71 | 9.20 | 105.28 | 66.78 |
| 15 | 75.85 | 6.94 | 9.15 | 95.51 | 56.05 |
| 18 | 49.96 | 6.93 | 13.89 | 79.73 | 36.35 |
| 21 | 15.91 | 5.56 | 34.95 | 35.40 | 6.47 |
| 16 | 64.50 | 5.44 | 8.43 | 79.11 | 51.64 |
| 17 | 58.28 | 5.10 | 8.75 | 72.29 | 39.73 |
| 22 | 6.37 | 1.11 | 17.43 | 12.68 | 5.12 |
| 23 | 5.55 | 0.29 | 5.23 | 6.01 | 4.39 |
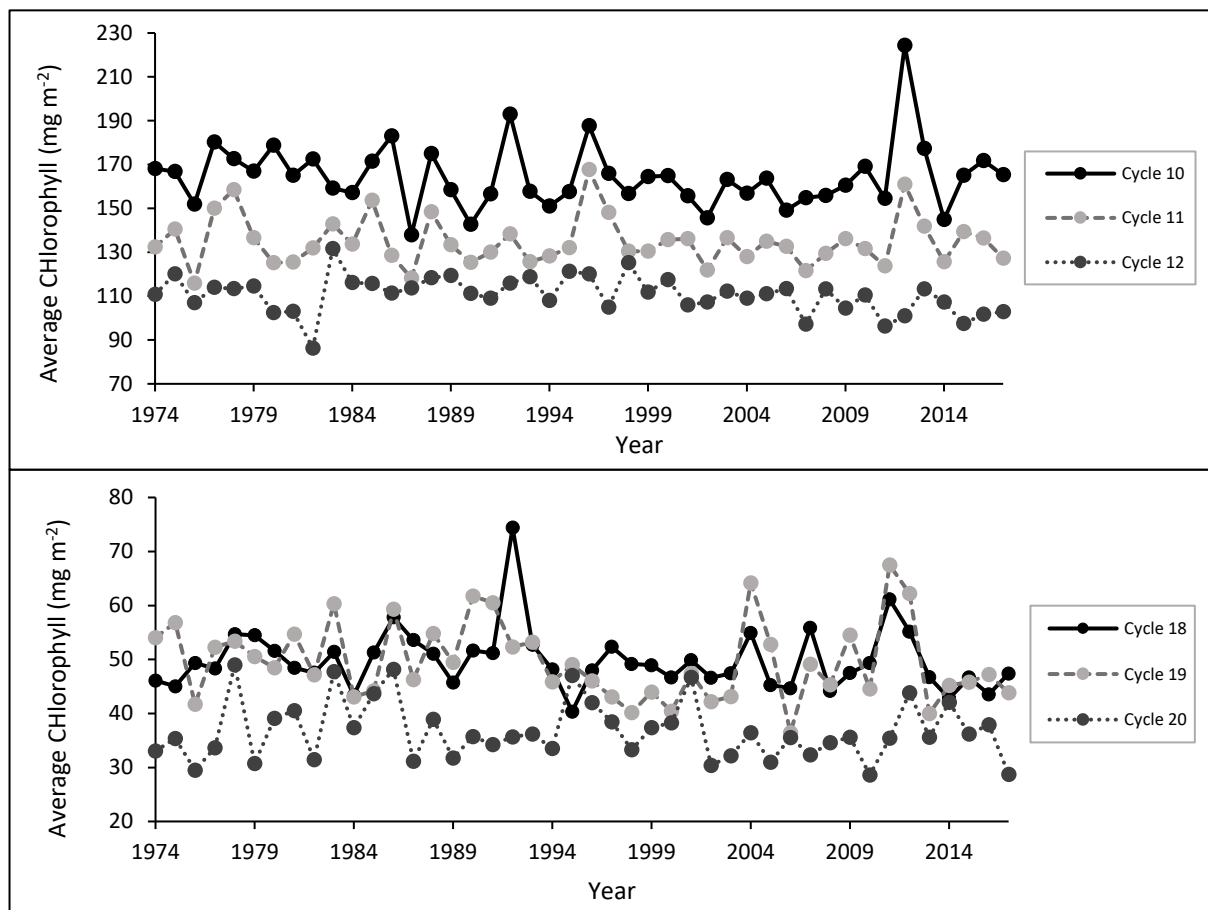


Figure 4: Scatterplots displaying average depth-averaged chlorophyll values (mg m$^{-2}$) for spring-neap cycles 10-12 (top) and 18-20 (bottom), across the study period 1974-2017. Note varying axis scales.

# Discussion

We initiated this study to investigate interannual variation in tidal dynamics over a 44 year time series (1974-2017) and examined the level of primary production within ordered spring-neap cycles and explored whether the timing and variation in production is changing over time within each spring-neap tidal cycle - as would be expected with climate change.

## Variability in spring bloom timing

Variability in the timing of the onset of the spring bloom may be due to various factors. Climatic forcing through wind speed, cloudiness and temperature is often proposed as being a major driver of fluctuations in bloom timing (Townsend et al., 1994; Hjerne et al., 2019). There is evidence that the tidal cycle can also have significant impacts on bloom phenology in the Northern North Sea, with up to a month delay in models that included tidal forcing parameters compared to those without (Zhao et al., 2019). Over the 44 years studied using the S2P3 model, there is no clear trend in the timing of the start date and the maximum range from the mean bloom date is only 10 days earlier and 14 days later. This implies that there is not a great amount of variance in bloom date even with the wide range of annual weather that has been seen over the study period. This is quite intriguing as it implies that this major seasonal signal is incredibly robust. However, it is important to note that a difference of 2 weeks can make a massive difference in survival and breeding success for animals at critical life phases such as fish larvae and seabird chicks (Platt et al., 2003; Scott et al., 2006).

## Interannual variation in spring-neap cycle production

As the model does not account for the 18.6-year lunar cycle, the timing consecutive tidal cycles remained constant across study years – however the dynamics of these cycles was driven by the daily weather patterns within those years. Therefore, the low modelled interannual variability in production at each cycle can be interpreted as being the result of the interplay of meteorological conditions and the availability of light and nutrients - where light and nutrients must play a larger role in production levels than weather. During the summer months, the water column remains stratified, with recent evidence suggesting that the stratified surface layers and the deep mixed layer of the Northern North Sea become separated sufficiently to negate the influence of the tide on the euphotic zone (Zhao et al., 2019). Consequently, light availability, nutrient availability and grazing would be the main factors limiting primary production during this period. This results in a relatively steady decline in Net Primary Production (NPP) across the season

## Variation in spring-neap cycle production between spring and autumn blooms

The increase in the relative variability of subsequent cycles between the spring bloom and autumn bloom may be due to differences in the physical dynamics of the system between seasons. During autumn, increased mixing of the water column as a result of changing meteorological conditions drives the influx of new nutrients into the surface layer, promoting NPP (Wihsgott et al., 2019). This disruption of stratification could also re-couple the tidal cycle with the euphotic zone, thereby introducing further variability in production through the spring-neap cycle's impact on horizontal movement of water masses and periodical resuspension of phytoplankton cells.

# Summary

The results of this study indicate that, for the Marr Bank region of the North Sea across the period 1974-2017, the annual timing of primary production and the level of that production have been very predictable. This conclusion is very encouraging as it suggests that, in the North Sea at least, marine systems may still be robust to the impacts of climate change. However, different plankton taxa may

display differing responses to environmental variation, as described by Edwards and Richardson (2004), therefore further research would benefit from investigating species-specific phenology and population trends.

The difference in the variation in production between the spring and autumn blooms highlights the complexity of the system governing primary production in shelf seas. It is clear that tidal dynamics must play an important role in modifying phytoplankton population dynamics, however more work is needed to identify exactly how the interplay of meteorology, tidal forcing, irradiation and nutrient availability changes across the bloom period, and how this influences production.

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