Interannual variability of the initiation of the phytoplankton growing period in two French coastal ecosystems

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Abstract. Decadal time series of chlorophyll-*a* concentrations sampled at high and low frequencies are explored to study climate-induced impacts on the processes inducing interannual variations in the Initiation of the Phytoplankton Growing Period (IPGP) in early spring. We specifically detail the IPGP in two contrasting coastal temperate ecosystems under the influence of rivers highly rich in nutrients: the Bay of Brest and the Bay of Vilaine. In both coastal ecosystems, we observed a large interannual variation in IPGP influenced by sea temperature, river inputs, light availability (modulated by solar radiation and water turbidity), and turbulent mixing generated by tidal currents, wind stress and river runoff. We show that the IPGP is delayed by around 30 days in 2019 in comparison with 2010. *In situ* observations and a one-dimensional vertical model coupling hydrodynamics, biogeochemistry, and sediment dynamics, show that the IPGP generally not depends on one specific environmental factor, but on the interaction between several environmental factors. In these two bays, we demonstrate that IPGP is mainly caused by sea surface temperature and available light conditions, mostly controlled by the turbidity of the system before first blooms. While both bays are hydrodynamically contrasted, the processes that modulate IPGP are similar. In both bays, IPGP can be delayed by cold spells and flood events at the end of winter, provided that these extreme events last several days.

Keywords
Phytoplankton biomass, Long-term *in situ* observations, Coastal temperate ecosystems, Extreme events, Climate change.

1 Introduction

Although studied for 70 years (Sverdrup, 1953), the optimal conditions that trigger the Initiation of Phytoplankton Growing Period (IPGP) in ocean waters in early spring are not well understood (Sathyendranath *et al.,* 2015). Three main theories are proposed to date: the Critical Depth Hypothesis (Sverdrup, 1953), the Critical Turbulence Hypothesis (Huisman *et al.,* 1999) and the Disturbance-Recovery Hypothesis (Banse, 1994; Behrenfeld, 2010; Behrenfeld *et al.,* 2013). For Sverdrup (1953), phytoplankton blooms occur when surface mixed layer shoals to a depth shallower than the critical depth, according to light conditions. While Huisman *et al.* (1999) agreed with Sverdrup, he proposed that relaxation of turbulent mixing allows bloom to develop if it occurs below a critical turbulence rate. Behrenfeld (2010) observed blooms in the absence of spring mixed layer shoaling, and declared that the initiation of bloom is controlled by a balance between phytoplankton growth and grazing rate, and suggested a seasonal control of this balance by physical processes. No consensus emerges among these hypotheses – especially because most of these concepts have been defined at specific temporal and spatial scales (Caracciolo *et al.,* 2021; Chiswell *et al*., 2015) – and the debate is still open, in particular due to the use of more efficient models, the availability of new observations, and the ensuing collection of large *in situ* datasets (Boss and Behrenfeld, 2010; Rumyantseva *et al*., 2019). Coastal waters remain highly dynamic and productive ecosystems at the interface between land and sea, and are distinguished from the waters of the open sea (Gohin *et al*., 2019; Liu *et al*., 2019). Because coastal systems are directly influenced by anthropogenic inputs from rivers, no nutrient limitation is observed in late winter. A myriad of factors and mechanisms can then affect the IPGP in coastal areas

(Townsend *et al.,* 1994; Cloern, 1996), but the incident light at the air/sea interface (Glé *et al.,* 2007) and Sea Surface Temperature (SST) (Trombetta *et al.,* 2019) are considered as the main forcings. Low water turbidity also plays an important role, and allows deeper light penetration (Iriarte and Purdie, 2004). This occurs by low vertical mixing conditions in shallow waters (Ianson *et al.*, 2001), *i.e.* limited advective exchanges, weak wind (Tian *et al.,* 2011), neap tide (Ragueneau *et al.,* 1996), and in absence of flooding events (Peierls *et al.,* 2012). Depending on the morphology and hydrodynamics of coastal zones (estuaries, bays, lagoons), the importance of controlling factors can be variable (Cloern*,* 1996). Temporal variation in IPGP is of great importance in coastal ecosystems because it impacts not only phytoplankton by changing species composition or the succession of species (Ianson *et al.,* 2001; Edwards and Richardson, 2004; Chivers *et al.,* 2020), but also several other biological compartments, such as zooplankton and fish, by species replacements (Sommer *et al.,* 2012).

By amplifying or modifying environmental forcings, it is now well-documented that global climate change may influence the IPGP in coastal areas (Smetacek and Cloern, 2008; Barbosa *et al.,* 2010; Pearl *et al.,* 2014; IPCC, 2021). Heat waves - as opposed to cold spells - have become more frequent in recent years and can advance or delay the IPGP (Gomez and Souissi, 2008). Wind storms, by inducing vertical mixing and sediment resuspension, can have a significant effect on water turbidity, which in turn limits light penetration and therefore influences the IPGP. Floods, following heavier rainfall, may increase continental erosion and ultimately nutrient inputs to coastal ecosystems. Because coastal ecosystems are strongly influenced by human activities such as changes in land use, quantifying the contribution related to long-term climate-induced signals is challenging (Krompkamp and Van Engeland, 2010).

Our study is based on two geographically close, but hydrodynamically different, nearshore ecosystems: (1) the Bay of Brest, a shallow semi-enclosed bay with well-mixed waters (Le Pape and Menesguen, 1997) and (2) the Bay of Vilaine, a shallow open bay with long water residence times (Chapelle *et al*., 1994). These two coastal ecosystems are strongly impacted by anthropogenic pressures, such as intensive agriculture (Ragueneau *et al.,* 2018; Ratmaya *et al.,* 2019), which induces highly rich nutrient waters.

In this study, we aim to better understand interannual local changes in the IPGP in coastal temperate ecosystems in the current context of global climate change over the last 20 years. As most studies dealing with IPGP are mainly based on discrete water sampling (Iriarte *et al*., 2004; Tian *et al*., 2011) or modeling (Townsend *et al.,* 1994; Philippart *et al.,* 2010), we focus here on the use of long-term high-frequency observations to assess interannual variability of the IPGP, and to identify the triggering and controlling factors. We detect and analyze the temporal variability of the IPGP and quantify how environmental forcings influence its dynamics. To detect and analyze IPGP in coastal environments, we develop a numerical framework that combines high-frequency decadal *in situ* observations and a one-dimensional vertical (1DV) hydro-sedimentary and biogeochemical coupled numerical model. The potential impact of hydro-meteorological extreme events, such as cold spells, flood events and wind bursts, on the IPGP is then investigated.

2 Data and methods

2.1 Study areas

Our study focuses on two northwestern French coastal temperate ecosystems located in the Bay of Biscay, the Bay of Brest and the Bay of Vilaine, two ecosystems impacted by excessive nutrient inputs from watersheds, but exposed to different hydrodynamic conditions.

The Bay of Biscay is a region with a complex system of coastal currents influenced by the combined effects of seasonal wind regimes and important river discharges modulated by large-scale gyre circulation patterns (Ferrer *et al*., 2009; Lazure and Jégou, 1998; Lazure *et al*., 2006; Isemer and Hasse, 1985; Pingree and Le Cann, 1989, 1990; Le Boyer *et al*., 2013; Lazure *et al*., 2006; Charria *et al*., 2013). In the Iroise Sea, at spring tide close to the islands and capes, tidal currents can reach 4 m s^{-1} (Muller *et al.*, 2010). This tidal circulation combined with meteorological forcings and sharp thermal gradients generate a strongly variable local circulation. In the vicinity of the Loire estuary, the freshwater discharges in the surface layers induce important density gradients driving a poleward circulation (about 10 cm s^{-1}) modulated by wind forcings (Lazure and Jégou, 1998; Lazure *et al*., 2006). The river plumes can propagate under specific conditions towards the South-West.

Under these hydrodynamic conditions, the Bay of Brest is a semi-enclosed bay (180 km^2) with 50% of the surface shallower than 5 m depth. The Bay is connected with the Atlantic Ocean (Iroise sea) through a narrow and shallow strait. Tidal variation reaches 8 m during spring tides, which represents an oscillating volume of 40% of the high tide volume. Freshwater inputs come from the Aulne river (catchment area 1875 km^2, mean river flow 26 m^3 s^{-1}), and two smaller rivers, the Elorn (catchment area 385 km^2, mean river flow 6 m^3 s^{-1}) and the Mignonne (catchment area 111 km^2, mean river flow 1.5 m^3 s^{-1}). Due to the macrotidal regime, associated with a strong vertical mixing, the high nitrate concentrations do not generate important green tides (Le Pape *et al.*, 1997). Strong decreases in the Si:N and Si:P ratios did not exhibit dramatic phytoplankton community shifts from diatoms to non-siliceous species in spring (Del Amo *et al.*, 1997), because of the high Si recycling (Ragueneau *et al.*, 2002; Beucher *et al*, 2004).

The Bay of Vilaine is a mesotidal open bay (69 km^2) under the influence of the Vilaine (catchment area 10 500 km^2, mean river flow 70 m^3 s^{-1}) and the Loire (catchment area 117 000 km^2, mean river flow 850 m^3 s^{-1}) river discharges, with tidal ranges varying between 4 and 6 m (Merceron, 1985). The Loire river plume tends to spread northwestward, with a dilution of 20- to 100-fold by the time it reaches the Bay of Vilaine (Ménesguen *et al.*, 2018). The Vilaine river plume tends to spread throughout the bay before moving westward (Chapelle *et al.*, 1994). The water residence time varies seasonally between 10 and 20 days (Chapelle *et al.*, 1994). The water circulation is mainly driven by tides, winds and river flows (Lazure and Jegou, 1998). This bay is well known as one of the most sensitive European Atlantic coastal ecosystems to eutrophication (Ménesguen *et al.*, 2019). The Bay of Vilaine has undergone eutrophication over recent decades mainly due to high nutrient inputs from the Vilaine and Loire rivers (Rossignol-Strick, 1985; Ratmaya *et al.*, 2019).

2.2 *In situ* observations

COAST-HF-Iroise (Rimmelin-Maury *et al.*, 2020) and COAST-HF-Molit (Retho *et al.*, 2020) are two high-frequency monitoring buoys of the French national observation network COAST-HF[1] (Répécaud *et al.*, 2019; Farcy *et al.*, 2019; Cocquempot *et al.*, 2019; Poppeschi *et al.*, 2021) located respectively in the Bay of Brest (4.582°W; 48.357°N) and in the Bay of Vilaine (2.660°W; 47.434°N) (Fig. 1). COAST-HF-Iroise has been operating in the strait between the Bay of Brest and the Iroise sea since 2000. COAST-HF-Molit buoy has been sampling the plume of the Vilaine river since 2008. Buoys are deployed during the whole year except for COAST-HF-Molit that is only available for part of the year prior to 2018 (from mid-February to early September, i.e. from day 50 to 250 for the period 2008-2017). Depending on the tide, the depth at the mooring sites ranges from 11 to 17 m for both COAST-HF buoys. Environmental parameters (SST, salinity, turbidity, dissolved oxygen and Chl-*a* fluorescence) are measured at 1 to 2 m below the surface every 20 minutes (COAST-HF-Iroise) or every hour (COAST-HF-Molit). The Chl-*a* fluorescence, a proxy of phytoplankton biomass (FFU unit), is measured by a Turner CYCLOPS-7 Sensor (precision $\pm$ 5%).

Sub-surface Chl-*a* concentrations are provided by two French marine monitoring networks, the SOMLIT coastal observation network[2] and the REPHY (French Observation and Monitoring program for Phytoplankton and Hydrology in coastal waters)[3]. Samples are collected bimonthly at the SOMLIT-Brest (4.552°W; 48.358°N) and the REPHY-Loscolo (2.445°W; 47.496°N) stations, which are close to the COAST-HF stations. Chl-*a* concentrations are measured with either spectrophotometric or fluorimetric methods (Aminot and Kérouel, 2004).

Daily river flows are measured at gauging stations (French hydrology "Banque Hydro" database[4]), located close to the main river mouths [Aulne-Gouezec (4.093°W; 48.205°N), Loire-Montjean (1.78°W; 47.106°N)]. The Vilaine river flow is controlled by a dam, and data are provided by the Vilaine Public Territorial Basin Organization[5] (Fig. 1).

The tide gauge stations (Shom[7]) at Brest (4.495°W; 48.382°N) and Crouesty (2.895°W; 47.542°N) record the sea level every minute.

[1] www.coast-hf.fr, data available on www.coriolis-cotier.org

[2] https://somlit.fr

[3] https://doi.org/10.17882/47428

[4] www.hydro.eaufrance.fr/

[5] https://www.eptb-vilaine.fr/

[6] https://donneespubliques.meteofrance.fr/

[7] http://data.shom.fr

Precipitation, air temperature, wind direction and intensity, and the solar flux data are retrieved every 6 minutes from two meteorological stations from the Météo-France observation network[6]: Guipavas (4.410°W; 48.440°N) and Vannes-Séné (2.425°W; 47.362°N) (Fig. 1). We use the solar flux as a proxy for subsurface PAR (Photosynthetically Available Radiation).

2.3 MARS3D-1DV modeling experiments

2.3.1 MARS3D-1DV model

A 1DV (one-dimensional vertical) model configuration is implemented to simulate changes in biogeochemical variables due to hydrodynamics and sediment dynamics in both bays.

The hydrodynamical model is based on the code developed for MARS3D (3D hydrodynamics Model for Applications at Regional Scale; Lazure and Dumas, 2008). This model is a primitive equation model with a free surface and uses the Boussinesq and hydrostatic pressure assumptions. We use the 1DV configuration of the model, with 10 vertical sigma levels for 15 m depth and a time step of 30s.

The sediment model (MUSTANG - Le Hir *et al.,* 2011; Grasso *et al.,* 2015; Mengual *et al.,* 2017) is designed to simulate the transport and changes in different sediment mixtures. In the sediment, 50 layers (refined near the surface) for a total thickness of 40 cm are implemented. Four sediment classes are considered: muds (diameter 10 μm), fine sand (diameter 100 μm), medium sand (diameter 200 μm) and coarse sand (diameter 400 μm). The sediment dynamics (transport in the water column, exchanges at the water/sediment interface, erosion/deposition processes) are driven by an advection/dispersion equation for each sediment class (refer to Le Hir *et al*., 2011 for a detailed description of the sediment model).

The biogeochemical model BLOOM (BiogeochemicaL cOastal Ocean Model) is derived from the ECO-MARS model (Cugier *et al.,* 2005; Ménesguen *et al.,* 2019) adding major processes of early diagenesis. Nitrogen, phosphorus, and silica cycles are studied considering four nutrients: nitrate, ammonium, soluble reactive phosphorus and silicic acid (sorption/desorption of phosphate on suspended sediment and precipitation/dissolution of phosphate with iron processes are also included). The model is also represented by three phytoplankton classes (microphytoplankton, dinoflagellates, pico-nano-phytoplankton), two zooplankton classes (micro- and meso-zooplankton), and exchanges at the water/sediment interface and inside the sediment compartment.

2.3.2 MARS3D-1DV model sensitivity experiments

These three models (hydrodynamical, sediment and biogeochemical) are coupled online during simulations and allow the nutrient and phytoplankton dynamics in both bays to be reproduced. The simulation for the Bay of Brest does not include nutrient inputs from the sediment because it is considered to be negligible around the COAST-HF-Iroise station.

Dissolved and particulate variables are defined in the water column and in the sediment. Initial values for both bays are uniform over the initial vertical profile (Table 1) and are based on a 3D realistic coupled simulation during the year 2015. Values for the 15th of February are extracted at the position of COAST-HF-Iroise for the Bay of Brest and at the position of COAST-HF-Molit station for the Bay of Vilaine (Plus *et al*., 2021).

To evaluate the sensitivity of the biogeochemical dynamics to environmental conditions, sensitivity experiments are then performed using the coupled MARS3D/BLOOM/MUSTANG 1DV model configuration. All simulations are started at the end of winter (15th February) and run until the end of the year. The range of values used in the sensitivity experiments are derived from the minimum and maximum observed *in situ* data. Each parameter is tested with a constant value for the whole simulation.

Three parameters are individually explored in both bays:

- The air temperature in sensitivity experiments ranges from 4 to 14°C and is controlled by the intensity of solar radiations. Air temperature represents the main controlling parameter of SST in the 1DV model. This parameter drives the radiative fluxes in the model and then constrains SST.
- Wind intensity effect on the IPGP is explored for values between 0 and 10 m s^{-1}. In the 1DV model, wind is a source of vertical mixing in the simulation.

- The Cloud Coverage (CC) sensitivity experiments ranged in value between 0 and 100% CC. This parameter is a driver of Photosynthetic Available Radiation (PAR) in the ocean. For the formulation of radiative fluxes in the 1DV MARS3D model, 100% cloud coverage allows an inflow of 38% of the total solar radiation in the water column. Each individual experiment is associated with a constant CC applied to the seasonal solar radiation.

In the Bay of Vilaine, the sediment plays a role on light penetration and acts as an active source of nutrients: we therefore explored the influence of mud erosion rate (values between 2.10^{-5} and 2.10^{-7} kg m^{-2} s^{-1}) in that bay (sand erosion rate fixed to 0.0001 kg m^{-2} s^{-1}). For the sensitivity experiments, it drives a mass of sediment eroded and resuspended and a bottom input of nutrients in the water column.

A second set of experiments is conducted by combining the individual effect of environmental parameters in order to explore possible cumulative or opposite effects on the IPGP. The upper and lower bounds of the range of environmental parameters are taken into account. Experiments are detailed in Table 5.

2.4 Data processing

2.4.1 Chl-*a* fluorescence data

To analyze high-frequency time series of *in situ* Chl-*a* fluorescence, the Quenching effect (Lehmuskero *et al.*, 2018) - a decrease in fluorescence in the presence of light (Fig. 2) - is removed by analyzing only night-time data, as reported in Carberry *et al.* (2019). Chl-*a* fluorescence data are studied on a daily basis, i.e. averaged from 10 pm to 5 am. Years with less than 75% of valid data are not considered in our analyses: for the Bay of Brest, 2005, 2006, 2008, 2009 and 2018.

2.4.2 Detection of the IPGP

On the basis of literature, we first apply three methods to determine the annual IPGP dates:

- (1) Set an arbitrary beginning and end of the phytoplankton growing period at 20% and 80% of the cumulative Chl-*a* fluorescence measured from January 1st to December 31st (Kromkamp *et al.*, 2010).
- (2) Consider a threshold of 5% above the yearly median chlorophyll (Brody *et al.*, 2013).
- (3) Consider the beginning of the growing period as the maximum daily difference in Chl-*a* fluorescence (Philippart *et al.*, 2010).

Because none of these methods allowed us to obtain a valid IPGP detection - with a too late (method 1) or a too early (method 2) detection, or multiple IPGP dates (method 3) - we elaborate a detection method based on discontinuities of the Chl-*a* fluorescence signal (Fig. 3): daily FFU slopes are calculated based on a linear regression over a $\pm$ 2 day window for each day, from 1st January to 31st December, and each year. The IPGP date is identified when the slope exceeds a threshold value - defined as the median of the daily slopes - for the first time in the year for at least 20 days. The end of the phytoplankton growing period is determined when the slope stabilizes below the threshold for at least 20 days for the last time in the year. The cumulative Chl-*a* fluorescence corresponds to the duration of the growing period.

2.4.3 Pattern of the phytoplankton growing period

The k-means method (Hartigan and Wong, 1979) is used to characterize the annual patterns of the phytoplankton growing period.

We exclude the year 2013 from the analysis of the Bay of Vilaine because of a large number of missing data. When the interval over which consecutive data are missing is no longer than one week, we perform a linear interpolation to replace the missing data. A 5-day running average is applied to the Chl-*a* fluorescence signal and data are then normalized by the maximum value. We analyze Chl-*a* fluorescence every year for 150 days after the IPGP.

Time series from both bays are merged before application of the k-means and the number of clusters (or centroids) is set at 2 to distinguish the dominant patterns of the phytoplankton growth period at both sites. The use of a larger number of clusters is investigated and does not produce a pattern representing a large number of observed growing periods.

2.4.4 Detection of extreme events

The peak over threshold method (see Oliver *et al.*, 2018 and Poppeschi *et al.*, 2021 for further details) is used to detect hydro-meteorological extreme events such as cold spells, flood events and wind bursts. An event is considered as extreme if values are higher than a given statistical threshold for at least 3 consecutive days. In the present study, the 90-percentile threshold is selected to detect floods and wind bursts, and the 10-percentile to detect cold spells. Seasonal anomalies are calculated over at least 20 years, by subtracting raw data from the winter average value (for cold spells) or from the spring average value (wind bursts and floods).

3. Results

3.1 Characterization of the phytoplankton growing period

The high-frequency Chl-*a* fluorescence time series at both sites show an intense seasonal cycle with low values from November to February and high values from March to October (Fig. 4). Focusing on the period from 2010 to 2019 in the Bay of Brest, the minimum *Chl-a* fluorescence is observed during the years 2012 and 2013 and does not exceed 7 FFU. In contrast, some years show Chl-*a* fluorescence values above 15 FFU, but can be up to 20 FFU (such as 2010, 2014, 2015 or 2019). In the Bay of Vilaine, a similar seasonal pattern is observed with higher values reaching 50 FFU in 2013. Small (< 20 FFU) and high (> 35 FFU) Chl-*a* fluorescence amplitude are observed occasionally (in 2014 and 2017 and in 2013 and 2016, respectively). The Chl-*a* fluorescence is higher, almost double, in the Bay of Vilaine compared to the Bay of Brest with a mean cumulative Chl-*a* fluorescence around 580 FFU and 360 FFU, respectively (Table 2). The high phytoplankton biomass of the Bay of Vilaine is corroborated by the concentrations measured by low-frequency observation programs (SOMLIT and REPHY).

The phytoplankton growing period ranges from approximately March 10th to September 30th in both regions (Table 2). The average duration of the phytoplankton growing period is 179 days in the Bay of Vilaine and 200 days in the Bay of Brest (Table 2). The phytoplankton growing period is characterized by successive blooms, whose number and intensity are variable from year to year (Fig. 4).

The main patterns of the phytoplankton growing period are identified by two clusters (Fig. 5). Cluster 0 includes the phytoplankton growing period with two successive marked blooms in early spring and in summer, the intensity of the second bloom being highly variable. Cluster 1 is characterized by a plateau during the two first months of the phytoplankton growing period. Most of the patterns of the Bay of Vilaine are in cluster 0 while those of the Bay of Brest are in cluster 1 (Table 3). The years that stand out in the Bay of Brest (2002, 2010, 2014) correspond to years with the highest cumulative *Chl-a* fluorescence ($\geq$ 450 FFU). The atypical years in the Bay of Vilaine (2011, 2017 and 2019) show the lowest cumulative *Chl-a* fluorescence ($\leq$ 450 FFU).

3.2 Variability of the Initiation of the Phytoplankton Growing Period (IPGP)

Calculations performed to determine the IPGP for high- and low-frequency data yield comparable results (Fig. 6). The mean differences between the IPGP calculated with the high- and low-frequency data are 5 and 8 days for the Bay of Brest and the Bay of Vilaine, respectively. A difference of only 4 and 6 days between the model simulations (reference year = 2015) and the high-frequency *in situ* data is observed in the Bay of Brest and the Bay of Vilaine, respectively.

A decadal variability of the IPGP is recorded from mid-February to mid-April in both ecosystems (day 50 to day 102 in the Bay of Brest and day 53 to day 93 in the Bay of Vilaine; Fig. 6). In the Bay of Brest, early IPGPs (day < 53) are observed in 2010 and 2013, whereas late IPGP (day > 93) are observed in 2001, 2017 and 2019. In the Bay of Vilaine, the earliest IPGP is detected in 2012 (day 53) and the latest in 2019 (day 93).

The variability of IPGP in the Bay of Brest shows two linear trends (Fig. 6a), with a decrease of 52 days from 2001 to 2010 (observed in both high- and low-frequency datasets), followed by an increase (+48 days) from 2011 to 2019, a decline also observed in the Bay of Vilaine (Fig. 6b). Over the period 2011-2019, the IPGP is shifted towards a later date by +3.5 days per year in the Bay of Vilaine and +3.7 days per year in the Bay of Brest.

3.3 Analysis of environmental conditions driving the IPGP

3.3.1 Impact of environmental conditions on the IPGP

We next quantify the influence of environmental drivers on the date of IPGP (Fig. 7). These drivers represent the major limiting factors of the phytoplankton growth and comprise input of nutrients (river flow), PAR (incident light), SST (air temperature, incident light) and turbidity in the water column (river flow, wind intensity, tidal range).

The median values of the environmental drivers observed at the date of each annual IPGP are very close in both bays (Table 4): temperate SST (10 °C), weak wind (3 m s^{-1}), a medium PAR (1360 W m^{-2}), a low turbidity (7 NTU), and a weak tidal amplitude (semi-amplitude of 1.6 m in the Bay of Brest and 0.9 m in the Bay of Vilaine). The IPGP occurs mainly during neap tides at 68% in the Bay of Brest and 77% in the Bay of Vilaine. The river flow is low during the IPGP with a runoff of 46 m^3 s^{-1} for the Aulne, 96 m^3 s^{-1} for the Vilaine, and 1196 m^3 s^{-1} for the Loire. These values are considered to be the favorable environmental conditions for this study.

To assess how environmental drivers may impact (i.e. advance or delay) the IPGP, we focus on the 15 days before the mean day of the IPGP (day 68) and of each annual IPGP. The considered 15 days length is related to the typical water residence time in both bays (Frere *et al.*, 2017; Poppeschi *et al.*, 2021 for the Bay of Brest - Chapelle *et al.*, 1994; Ratmaya *et al.*, 2019 for the Bay of Vilaine).

The earliest IPGP dates (IPGP < day 55) are associated with earlier occurrence of favorable environmental conditions than the other years. Earliest IPGP in 2010 and 2013 in the Bay of Brest and in 2012 in the Bay of Vilaine occurred before day 55 (Fig. S1f, 7c - S2a). Early IPGP between day 55 to 60, also associated with favorable environmental conditions, are found in 2002 and 2016 in the Bay of Brest (Fig. S1b, S1j).

The latest IPGP dates (IPGP > day 90) are associated with unfavorable environmental conditions until the date of the IPGP. Latest IPGP occurring after day 90 are observed in 2001, 2003, 2017 and 2019 in the Bay of Brest and in 2019 in the Bay of Vilaine (Fig. S1a,c,k,l - S2g). For example, the delay detected in 2017 in both bays is due to strong wind and a lack of PAR until the day of IPGP (Fig. S1k - Fig. S2e). Late IPGP between day 70 to 90 are recorded in 2004, 2007 and 2012 in the Bay of Brest, and in 2014, 2017 and 2018 in the Bay of Vilaine (Fig. S1d,e,g, 7d - S2e,f).

The interannual variability of the date of the IPGP is therefore not controlled by a unique environmental driver. When the values of the environmental drivers responsible for the IPGP (Table 4) are compared to the mean values of the environmental drivers over a period of 30 days around the IPGP (Table S1), threshold values are observed in both bays: river flow is lower than usual (between 10 and 30 m^3 s^{-1}), temperature is close to the expected value (10 °C), wind is weak (0.5 to 1.5 m s^{-1}), PAR is stronger (>300 W m^{-2}), and turbidity is low (about 1.5 NTU). IPGP starts around day 68 ($\pm$3 days) on average (Fig. 7a,b).

3.3.2 Modeling the importance of the environmental drivers

The relative contribution of each environmental driver on the IPGP is determined by MARS-1DV simulations starting on February 1st (Fig. 8). Environmental drivers tested in the model are controlling:

- sea temperature - explored in the model through air temperature (SST proxy),
- the level of water turbulence - through wind intensity,
- the available light - controlled by Cloud Coverage (CC, as a sea surface PAR proxy) and the erosion rate (turbidity proxy) limiting light penetration in the water column.

Model results show that early IPGP are associated with air temperature higher than 9 °C (resulting in SST higher than 8 °C), low wind intensity, weak CC and low erosion rate. Environmental drivers responsible for early or late IPGP are similar in both bays. Air temperature is the main driver with a potential deviation from the mean IPGP of 25 days in the Bay of Brest and 40 days in the Bay of Vilaine (Fig. 8). Wind, CC and erosion rate have a lower impact on the IPGP (around 6 days in the Bay of Brest and 13 days in the Bay of Vilaine). In the Bay of Vilaine, the environmental drivers can simulate later IPGP than in the Bay of Brest.

In the Bay of Brest (Fig. 8a), only variations in air temperature have a real impact on the IGPG. If air temperature is low (< 8°C), the IPGP is not triggered before day 74 (Table 5, Exp 1). If air temperature is high (>13°C), the IPGP can start on day 49 (Table 5, Exp 2).

In the Bay of Vilaine, air temperature and the erosion rate are the two main drivers impacting the IPGP (Fig. 8b). As in the Bay of Brest, if air temperature is low (< 6°C), the IPGP is late and appears only after day 80 (Table 5, Exp 1). If temperature is equal or above 13°C, the IPGP is early and appears on day 45 (Table 5, Exp 2). If the erosion rate is low (2.10^{-7} kg m^{-2} s^{-1}), the IPGP takes place on day 76 (Table 5, Exp 7). If the erosion rate is high (2.10^{-5} kg m^{-2} s^{-1}), the IPGP occurs late after day 87 (Table 5, Exp 8).

Even if variations in wind and CC induce weaker shifts in the date of the IGPG, i.e. about one week at the most (Table 5, Exp 3,4,5,6), they can however explain some variations in IPGP. For example, the fact that the early IPGPs, observed in 2010 in the Bay of Brest and in 2012 in the Bay of Vilaine, are due to low wind conditions (around 2 m s^{-1}, Fig. S2a - S1f) are confirmed by both *in situ* measurements and the model (Fig. 8b).

The combined effect of the environmental factors can also be explored from the MARS-1DV model simulations (Fig. 9). The modeling conditions (hereafter called "Exp") are detailed in Table 5 and compared to the mean IPGP date (day 68).

The simulations confirm the observations, late IPGP correspond to the most extreme unfavorable combined environmental values (temperature of 4 °C, wind intensity of 10 m s^{-1}, CC of 100% and erosion rate of 2.10^{-5} kg m^{-2} s^{-1} - Exp A). Due to the most unfavorable conditions, the IPGP occurs 9 days and 64 days later in the Bay of Brest and in the Bay of Vilaine, respectively. Late IPGP can also be linked to the combined effect of only two factors such as: "temperature and wind" and "temperature and CC" with a delay of 5 and around 22 days respectively (Exp B and C). In contrast, no delay is observed for the combination "wind and CC" (Exp D) in both bays.

Early IPGP events are found in the model simulations and in the *in situ* observations when conditions correspond to a high temperature (14 °C), no wind intensity and CC, and a low erosion rate (2.10^{-7} kg m^{-2} s^{-1}) - Exp K. All the combined scenarios allow the occurrence of an earlier IPGP (by at least 5 additional days) compared to experiments that consider a single modified parameter.

This analysis enables environmental parameters to be classified with respect to their impact on the IPGP. In both bays, the temperature appears to be the key factor driving the IPGP. By combining the environmental drivers, the IPGP can occur even later or earlier than with a single forcing. In both bays, the combination of wind and CC has no impact on the IPGP, which occurs near the median day (Exp D and N). The extreme couplings of Exp A,E,F,G,J delay the date of IPGP later than detected in the observations for the Bay of Vilaine. All simulations show a higher impact on the date of IPGP in the Bay of Vilaine than in the Bay of Brest (Fig. 9, Table 5).

3.4 Impact of extreme hydro-meteorological events on the IPGP

3.4.1 Cold spells

The impact of cold spells on the IPGP is simulated with the MARS-1DV model based on two criteria: (i) the period of occurrence of the event, set in mid- or end February, (ii) the duration and intensity of the cold spell, which can be either short and weak (8 days, 7 °C) or long and intense (20 days, 5 °C) (Fig. 10).

In both bays, when the cold spell appears in mid-February, the IPGP is not impacted. However, it is delayed by about 15 days when occurring at the end of February. The duration of the cold spell, when longer than 15 days, also has an impact on the IPGP, with a delay of 13 and 12 days in the Bay of Brest and in the Bay of Vilaine, respectively.

Eight cold spells are detected in February in both bays between 2001 and 2019. In 2011, both sites are impacted simultaneously with cold spells. Long cold spells (30 days) are observed in 2009 and 2018, leading to an anomaly of more than -1.9 °C.

The cold spell observed in 2018 in the Bay of Vilaine may explain the later IPGP. There is no change in the IPGP in 2011 and 2013, despite the cold spell, the period of occurrence being too early during winter 2011, and the duration too short in 2013 (only 10 days).

In the Bay of Brest, the cold spells in 2003 and 2004 may explain the delay of the IPGP (respectively days 93 and 85). The presence of long and intense cold spells in 2010 and 2011 do not shift the IPGP (days 50 and 67) because they occur too early (before day 20).

3.4.2 Wind bursts

Based on our model simulations, the wind bursts that occur during at least three continuous days have no impact on the IPGP in both bays, whatever the duration, the period and the intensity ($\pm$ 1 day). In the Bay of Vilaine, only one wind event is detected in 2018 (3 days long and 6 m s^{-1}). In the Bay of Brest, several events are detected, but no significant impact is observed on the IPGP.

3.4.3 Flood events

River floods can delay the IPGP by resuspending sediment in the water column and therefore limiting light penetration in the water column. Inputs of nutrients have no impact during the late winter period because nutrient concentrations are maximal, with no limitation on phytoplankton growth. Flood events are analyzed with observation data collected in the month prior to the IPGP date because the 1DV modeling approach does not allow the sensitivity to hydrological events to be simulated (*i.e.* it is necessary to simulate horizontal advection processes).

In the Bay of Brest, the impact of flood events depends on their duration and intensity: when the flood exceeds 15 days, a delay in the IPGP is detected. Shorter and more intense floods (> 300 m^3 s^{-1}) do not impact the IPGP.

In the Bay of Vilaine, only two flood events are observed close to the IPGP date in 2014 and 2015. The 2015 flood event, which is 10 days longer and more intense (> 100 m^3 s^{-1}) than the 2014 one, delays the IPGP date by 10 days.

4 Discussion

4.1 Comparison of the phytoplankton growing period in both bays

Despite their contrasting hydrodynamics (*e.g.* Petton *et al.*, 2020; Poppeschi *et al.*, 2021; Lazure and Jegou, 1998; Ratmaya *et al.*, 2019; Menesguen *et al.*, 2019), the median dates of the start and the end of the phytoplankton growing period are the same in the Bay of Brest and in the Bay of Vilaine, whether they are calculated from high- and low- frequency datasets or model simulations. The phytoplankton growing period occurs from March to September and lasts about 190 days in both bays. This concordance is related to a similar seasonality of the environmental drivers.

The observed cumulative fluorescence is almost double in the Bay of Vilaine compared with the Bay of Brest. This difference in the amount of chlorophyll produced in surface waters from both bays is also recorded by the low-frequency observation programs and satellite observations (Menesguen *et al.*, 2019). It can be explained by the difference of the hydrodynamics and the influence of different watersheds. The Bay of Brest is a semi-enclosed bay with a macro-tidal regime influenced by two local rivers (Aulne and Elorn) ,whereas the Bay of Vilaine has a weaker tidal regime, is open on the continental shelf and is widely influenced by a large river (Loire river).

Two different patterns of the phytoplankton growing period are identified by the k-means classification in both bays. The flattened, weak and long bloom highlighted in the Bay of Brest can be explained by assuming that nutrients are not limiting the phytoplankton growth during spring. The maintenance of the diatom succession throughout spring since the 1980s (Quéguiner 1982; Del Amo *et al.*, 1997) can be explained by the combination of increasing N and P loads, intense Si recycling and a macrotidal regime (Ragueneau *et al.*, 2019). The phytoplankton growing period in the Bay of Vilaine is characterized by several successive peaks including two main ones. Nutrients drive the seasonal evolution of the phytoplankton growing period through periods of nutrient-limited conditions. These fluctuations are governed by phosphorus and nitrate loads from Vilaine and Loire rivers

(Ratmaya *et al*., 2019), but probably also by the stoichiometry of recycled elements in the water and at the water-sediment interface (Ratmaya *et al*., 2022). At the beginning of the phytoplankton growing period (IPGP), however, the system is not nutrient-limited in terms of nitrate, phosphorus and silicate (Table 4).

4.2 Validation of the method for IPGP detection

The method that we developed to detect IPGP on both high-frequency and low-frequency *in situ* observations shows comparable results and detects similar initiation dates for some years, while a time lag between high- and low-frequency observations can be observed for other years. This difference is mainly explained by the difference in the sampling frequency. The late deployment of the buoy in the Bay of Vilaine (i.e. not deployed until mid-February before 2018) can also explain some differences between both sites. High-frequency data provide a more accurate detection of the day of the IPGP, while an uncertainty of about ± 7 days is observed with low-frequency observations. This comparison between high- and low-frequency based IPGP detection highlights the sensitivity of sampling strategy in the observation of phytoplankton growing periods (Bouman *et al.*, 2005; Serre-Fredj *et al.*, 2021) related to the response of the ecosystem within a few hours after an environmental change (Lefort and Gasol, 2014; Thyssen *et al.*, 2008).

The modeled IPGP, based on the year 2015, is coherent with high-frequency observations (around 5 days of difference between modeled and observed IPGP). Considering the idealized framework for modeling computations (1DV model instead of a realistic 3D model configuration), the agreement between observations and simulations validates the 1DV approach to explore IPGP dynamics. With the 1DV configuration, the vertical dynamics in the water column, coupled with biogeochemistry and sediment dynamics are well reproduced. Atmospheric forcings and interactions with the bottom layer are the main environmental drivers. The full range of impacts related to the horizontal advection (*e.g.* in considered regions, rivers advected plumes can change the hydrodynamics and the nutrient fluxes) are not evaluated, however. In the Bay of Brest and in the Bay of Vilaine, such advected sources exist (Poppeschi *et al.*, 2021; Lazure and Jegou, 1998). But inputs from rivers are not main drivers of the IPGP in nutrient-rich environments. Nutrient loads advected by rivers may impact the phytoplankton community later during the growing period rather than at IPGP (Ratmaya *et al.*, 2019).

4.3 Identification of the environmental conditions supporting the IPGP

The main theories to explain the initiation of phytoplankton blooms (Sverdrup, 1953; Huisman et al., 1999; Banse, 1994) are not relevant in the context of shallow and well-mixed coastal waters under the influence of river plumes. In the studied region, the ecosystem does not evolve with mixed layer dynamics, as observed in deeper environments. Both bays are permanently vertically mixed mainly by tides, and vertical stratification only occurs on a thin surface layer due to river runoffs at short time scales. However, the IPGP is mainly driven and limited by similar local environmental conditions in both bays. The ideal temperature (> 10 °C) and PAR (1300 W m^{-2}) for the IPGP are in agreement with those from previous studies conducted in similar coastal ecosystems (*e.g.* Glé *et al*., 2007; Townsend *et al*., 1994; Trombetta *et al*., 2019). Neap tidal conditions, weak wind (lower than 3 m s^{-1}) and weak river flow can also play a positive role to observe earlier IPGP according to the previous studies (Ragueneau *et al*., 1996; Tian *et al*., 2011). The impact of wind direction on the IPGP is negligible.
Local changes in temperature, incident radiation, tidal conditions, wind conditions and river flow, induce differences in detected IPGP. In this coastal temperate ecosystem, we observe that the beginning of the growing period is limited by light (controlled by incident radiation, turbidity at this season), and water temperature. The IPGP also occurs during low vertical mixing conditions.

The comparison of the individual importance of each environmental driver shows that temperature and light penetration are the key environmental drivers in both bays. When light penetration is reduced by a combined effect of PAR and turbidity (sediment resuspension), the delay of IPGP can be amplified, especially in the Bay of Vilaine. The importance of light availability in the timing and intensity of the spring bloom is also highlighted in the North Sea (Wiltshire *et al*., 2015), in the German Bight (Tian *et al*., 2009) and along the UK South Coast (Iriarte and Purdie, 2004).

4.4 Interannual evolutions of the IPGP

The IPGP in these two bays shows a strong interannual variability with initiation dates varying from late winter to spring, depending on the environmental conditions. A mean difference of 50 days between the earliest and latest IPGP dates is observed. It is important to note that the phytoplankton population during the IPGP is always dominated in both bays by the same centric diatoms, genera *Chaetoceros* and *Skeletonema*, whose abundance varies from year to year depending on climatic conditions (REPHY, 2021). None of the nutrient is limiting the growing of phytoplankton at the IPGP (Table 4).

The earliest IPGP are observed and related to favorable environmental conditions early in the year. For example, the IPGP can occur before day 50, associated with exceptionally weak wind and river flow in addition to a sufficient PAR and nearly-optimal temperature of around 10 °C (*e.g.* 2010 in the Bay of Brest and 2012 in the Bay of Vilaine). But if the environmental conditions are not favorable (*e.g.* 2017 and 2019 in both bays), the IPGP is delayed. This can be due to: 1- strong wind during several days (not a single wind burst) combined with a weak PAR and enhanced sometimes by high turbidity events which further limits the light penetration. 2- low SST.

The IPGP appears to be more controlled by local environmental drivers than by regional environmental drivers, the IPGP being earlier in one site than in the other during half of the studied years: for example, the 2012 IPGP is early in the Bay of Vilaine (day 53), but late in the Bay of Brest (day 80), related to strong wind activity and low PAR on the last bay. The offshore regional dynamics will induce limited impacts on local hydrodynamical features that will change IPGP.

Changes in the IPGP over the last two decades has highlighted its evolution through two trends: it occurs earlier each year until 2010, when the trend is reversed. Changes in environmental conditions over the last 20 years was then studied to seek a possible concordance with one of the environmental drivers, but no significant trend was detected. Because of global warning, earlier phytoplankton blooms are expected (Friedland *et al*., 2018) but not later IPGP as observed in our study regions. However, the mechanisms that trigger blooms in coastal ecosystems - especially eutrophic ones - are not similar to the processes that influence blooms in the open ocean. No link between trends in IPGP and environmental drivers has not been identified in the southern California Bight from 1983 to 2000 (Kim *et al*., 2009). By investigating long-term (1975-2005) daily data, Wiltshire *et al*. (2008) also observe later phytoplankton blooms in the German bight, but no link to global warming was detected. Henson *et al*. (2018) model a bloom shift of 5 days per decade from 2006 to 2025, with later blooms. A possible explanation of these later IPGP may involve a lower spring SST (Hunter-Cervera *et al.,* 2016).

4.5 Extreme events

We show that a cold spell is likely to delay the IPGP if it occurs at the end of winter (after 20th February) or/and if the cold spell lasts long enough (> 15 days). The drop in temperature related to the cold spell prevents the IPGP in both bays. This is in accordance with the study of Gomez and Souissi (2008) in the English Channel where cold spells can delay the date of IPGP, as a result of an increase in water column mixing. Cold spells may also drive local patterns by influencing the phytoplankton communities (Gomez and Souissi, 2008; Schlegel *et al*., 2021).

Flood events have an influence on the phytoplankton biomass when they occur in spring, due to the supply of nutrients. When they occur in late winter, nutrients are already at their maximum. The impact of floods on IPGP is then due to the increase of the water turbulence and to the limitation of light by increasing the turbidity. The IPGP can be delay only if floods are at least 15 days long. This scheme was also observed by Saeck *et al*. (2013) along a river-estuary-bay continuum and explained by a shortened water residence time and limited-light due to flood-induced turbidity in the coastal zone.

No relationship is observed between wind events and IPGP in both bays because they are weakly stratified, contrary to open seas (*i.e.* Black Sea, Mikaelyan *et al*., 2017). In coastal stratified regions (*e.g.* under the influence of river plumes), strong wind and tidal mixing can enhance the mixing and break down stratification, which does not favor phytoplankton growth (Joordens *et al*., 2021). During the IPGP, except during floods, both regions are weakly stratified and are then less sensitive to combined wind/tidal short events.

5 Conclusions

This study provides a new understanding of the IPGP dynamics in coastal temperate areas by using both high and low-frequency *in situ* data, in combination with simulations from a 1DV model. Strong similarities are found in both bays. An important interannual variability of the IPGP is observed, with a trend towards a later IPGP over the last decade (2010-2020). We quantify the importance of environmental conditions on the IPGP. When we compare observed IPGP with favorable environmental conditions and following sensitivity experiments with the 1DV model, water temperature and turbidity (limiting light penetration in the water column) appear as the main drivers explaining interannual IPGP variability. The IPGP is a complex mechanism, usually triggered by more than one environmental parameter. The analysis of the influence of extreme events reveals that cold spells and floods have a strong impact by delaying the IPGP when episodes are long enough and occur after winter. No effect of wind bursts is detected.

While this study shows comparable IPGP dynamics when based on 1DV model simulations or *in situ* observations, we will next investigate the effect on phytoplankton dynamics of a fully realistic hydrodynamics (including horizontal and vertical advections; mixing processes; remote sources of nutrients from rivers) 3D model. We will focus on exploring the variability of phytoplankton communities during IPGP to assess whether community change is occurring, as observed in other studies and for other ecosystems (Ianson *et al*., 2001; Edwards and Richardson, 2004; Chivers *et al*., 2020). When interannual evolutions in the phytoplankton growth are explored, the detection and the understanding of harmful algal bloom dynamics can also be addressed based on similar approaches. Further studies will be dedicated to the simulation of the coastal ecosystem in the future based on numerical simulation through climate scenarios. The investigation of other contrasting coastal environments will allow us to better understand and anticipate the expected impact of global change on coastal phytoplankton dynamics.

Author contributions

CP, GC, AD, RV, PR-M and EGo conceptualized the study. PR-M, EGr and MR collected data. MP and GC developed the model configuration. CP, GC, AD and RV drafted the first versions of the paper. CP carried out all the analyses and wrote the final version of the paper. All authors contributed to the discussions and revisions of the study.

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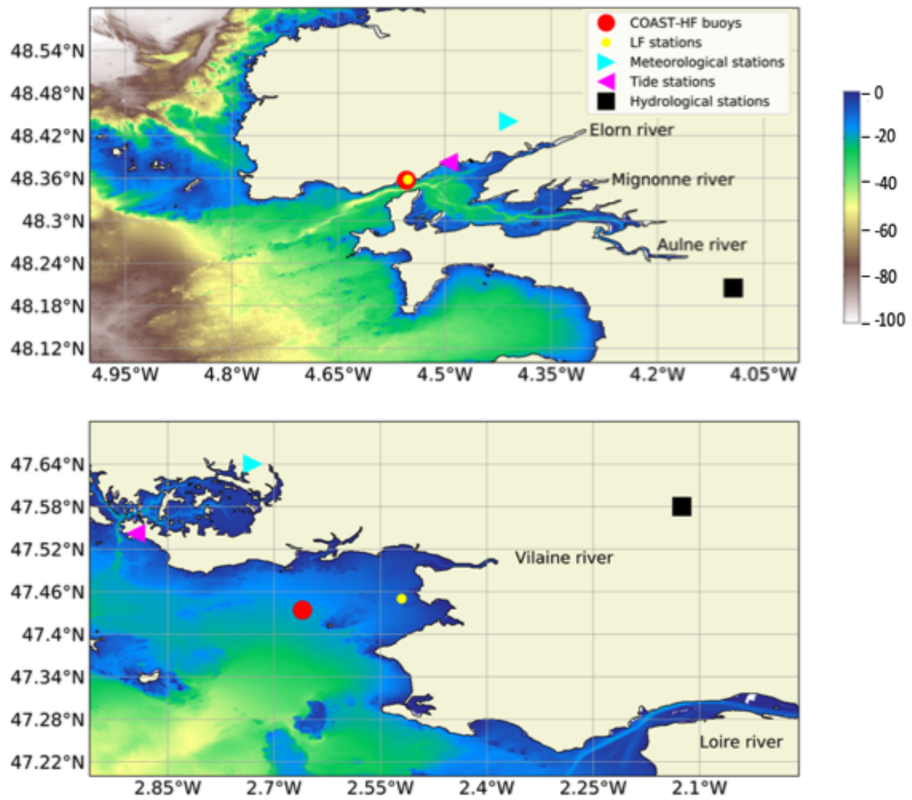


Figure 1: Location of the sampling sites: COAST-HF-Iroise and COAST-HF-Molit buoys (red circles); SOMLIT-Brest and REPHY-Loscolo sampling stations (yellow circles); Brest and Crouesty tide gauge stations (blue triangles); Guipavas and Vannes-Séné meteorological stations (purple triangles); hydrological stations of the Aulne and Vilaine rivers (black squares) with the Loire station off the map.

Parameters	Bay of Brest	Bay of Vilaine
Dissolved O_2 *(mg L^{-1})*	9	10
Mesozooplankton *(μmolN L^{-1})*	0.05	0.1
Microzooplankton *(μmolN L^{-1})*	0.05	0.05
Dinoflagellates *(μmolN L^{-1})*	0.05	0.1
Diatoms *(μmolN L^{-1})*	0.5	0.5
Soluble reactive phosphorus *(μmol L^{-1})*	0.5	0.8
Silicic acid *(μmol L^{-1})*	10	30

Nitrate *(µmol L^{-1})*	16	30
Ammonium *(µmol L^{-1})*	0.5	0.25
Coarse sand *(g L^{-1})*	0	0
Fine sand *(g L^{-1})*	0	0
Mud *(g L^{-1})*	0.03	0.05

Table 1: Initial conditions in the water column for the MARS-1DV model for the beginning of the simulation on the February 15th.

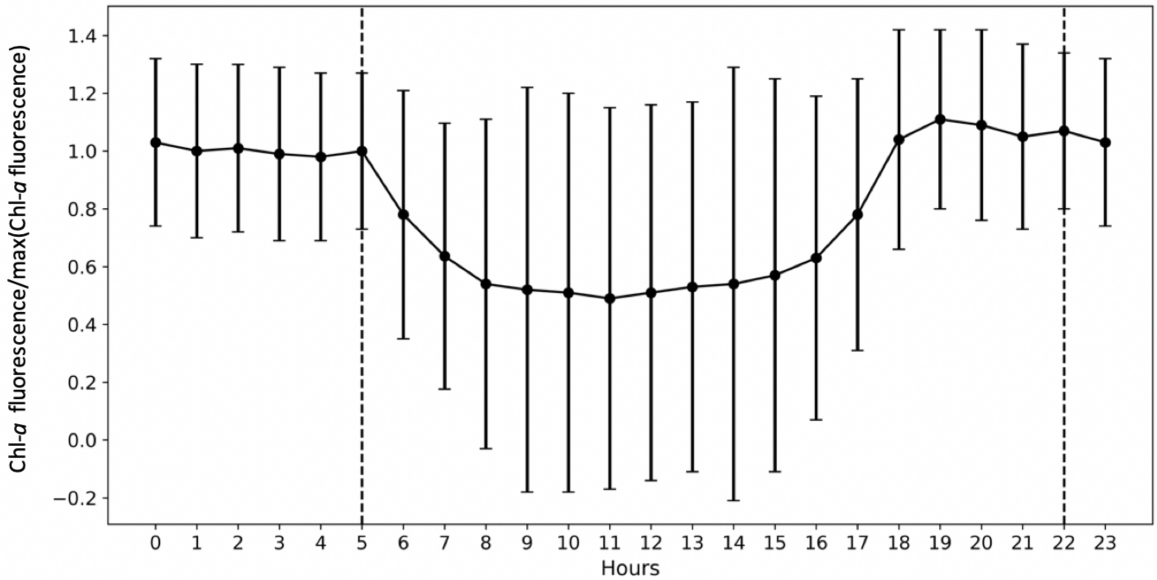


Figure 2: Importance of the Quenching effect on Chl-*a* fluorescence is represented by COAST-HF-Iroise data from 2000 to 2019. The standard deviation is represented by vertical black bars. The dashed lines represent the beginning and end of the selected values for the rest of the study from 10 pm to 5 am.

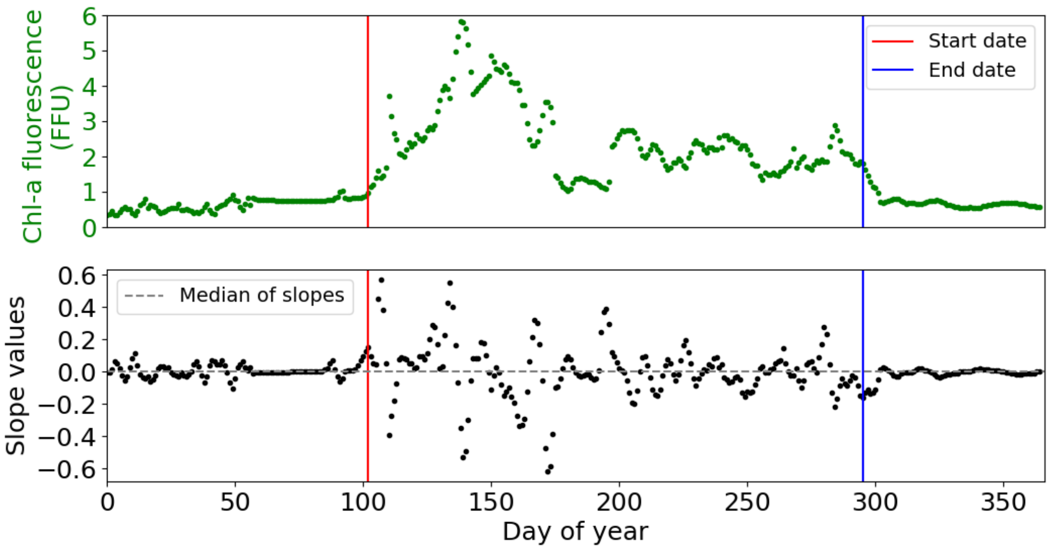


Figure 3: Example of detection of the start (red line) and end (blue line) of the phytoplankton growing period in 2001 at COAST-HF-Iroise. The threshold value - median of slopes - is represented by a dotted grey line.

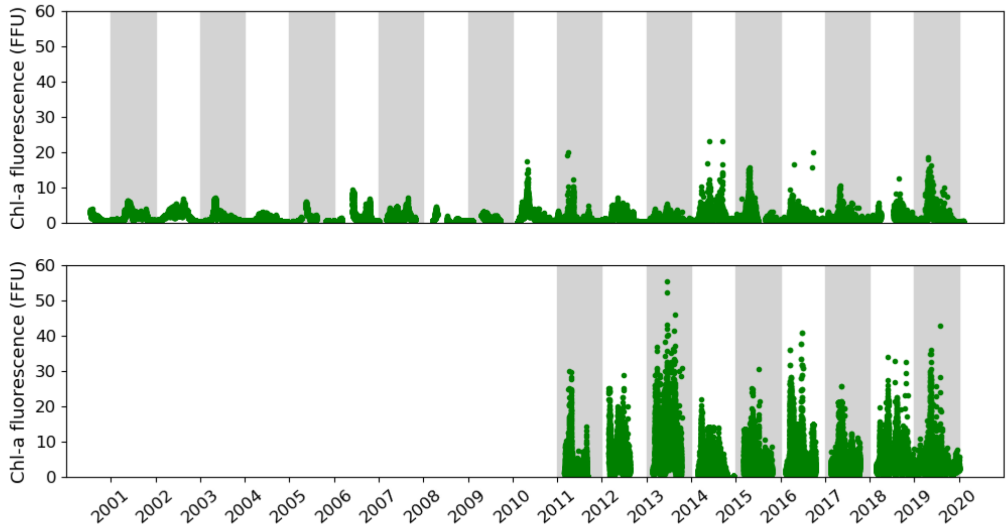
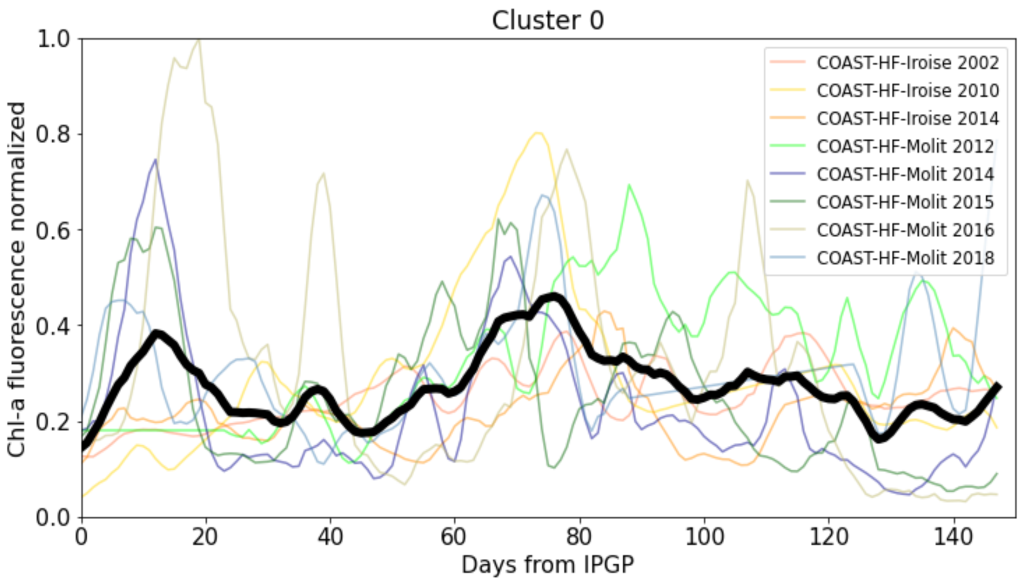


Figure 4: Temporal changes in the *in situ* Chl-*a* fluorescence measured in the Bay of Brest (top) and the Bay of Vilaine (bottom).

	Start date (Day of year)	**End date** (Day of year)	**Duration** (Days)	**Cumulative Chl-*a* fluorescence** (FFU)
	Min - ***Median*** - *Max*	*Min* - ***Median*** - *Max*	*Min* - ***Median*** - *Max*	*Min* - ***Median*** - *Max*
Bay of Brest (2001-2019)	50 - **69** - 102	253 - **274** - 308	165 - **200** - 256	217 - **364** - 567
Bay of Vilaine (2011-2019)	53 - **68** - 93	218 - **269** - 316	165 - **179** - 239	276 - **582** - 1406

Table 2: Global characteristics of the phytoplankton growing period in the Bay of Brest and in the Bay of Vilaine.

(a)



(b)

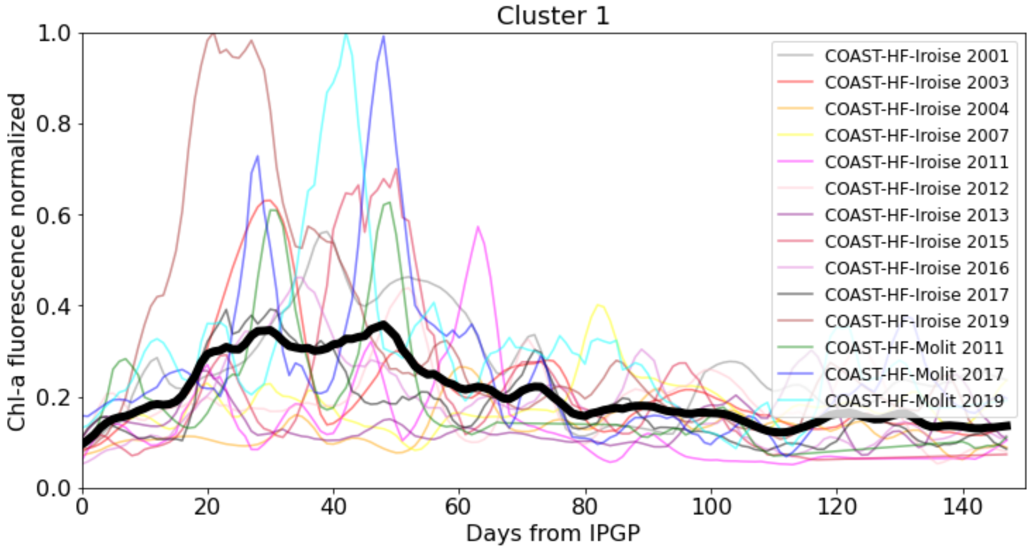
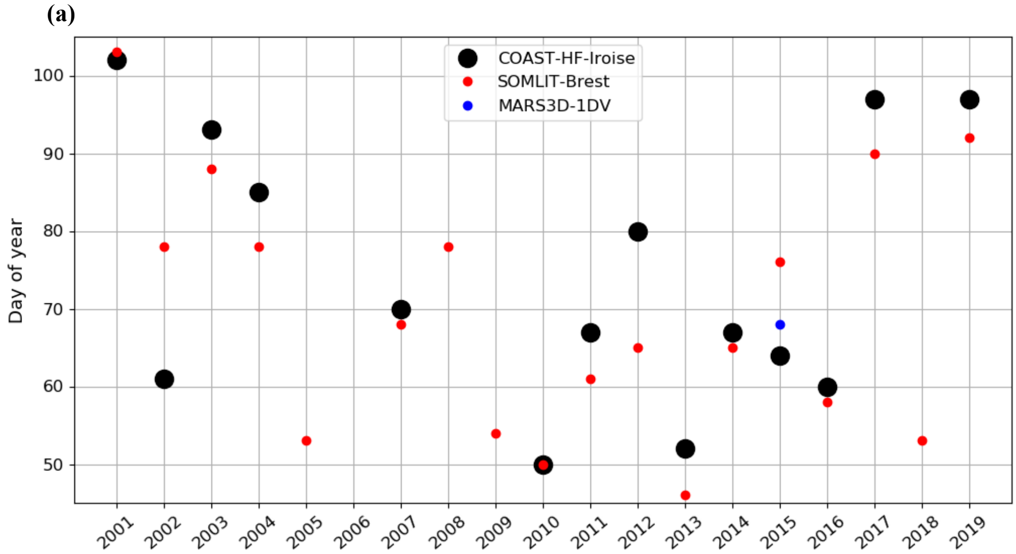


Figure 5: (a) Cluster 0 and (b) cluster 1 representative of the patterns of the phytoplankton growing period observed in both bays. The median pattern is drawn in bold.

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Bay of Brest COAST-HF-Iroise	1	0	1	1			1			0	1	1	1	0	1	1	1		1
Bay of Vilaine COAST-HF-Molit											1	0	X	0	0	0	1	0	1

Table 3: Cluster group assigned to each annual phytoplankton growing period on both sites. Grey boxes represent years with missing data. The cross represents the year 2013 of the Bay of Vilaine not considered.

(a)



(b)

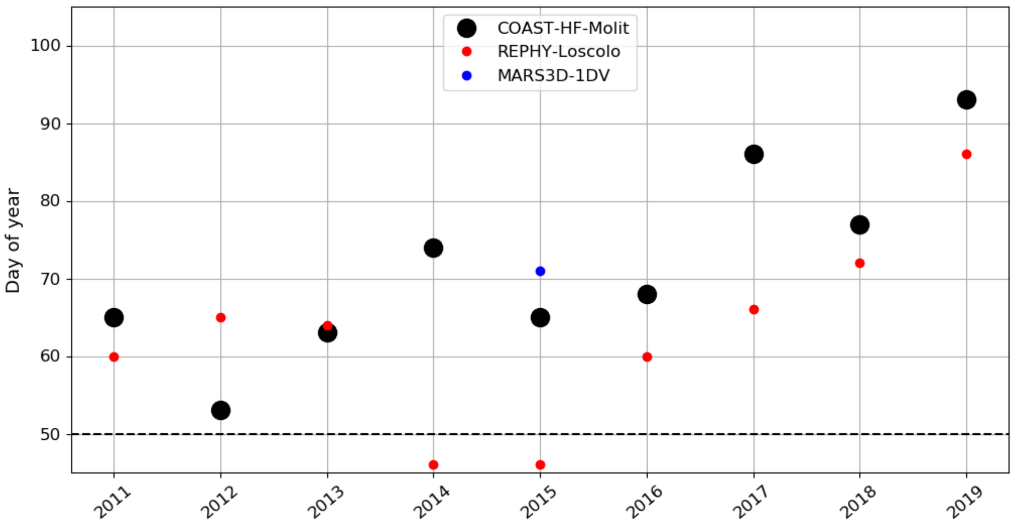
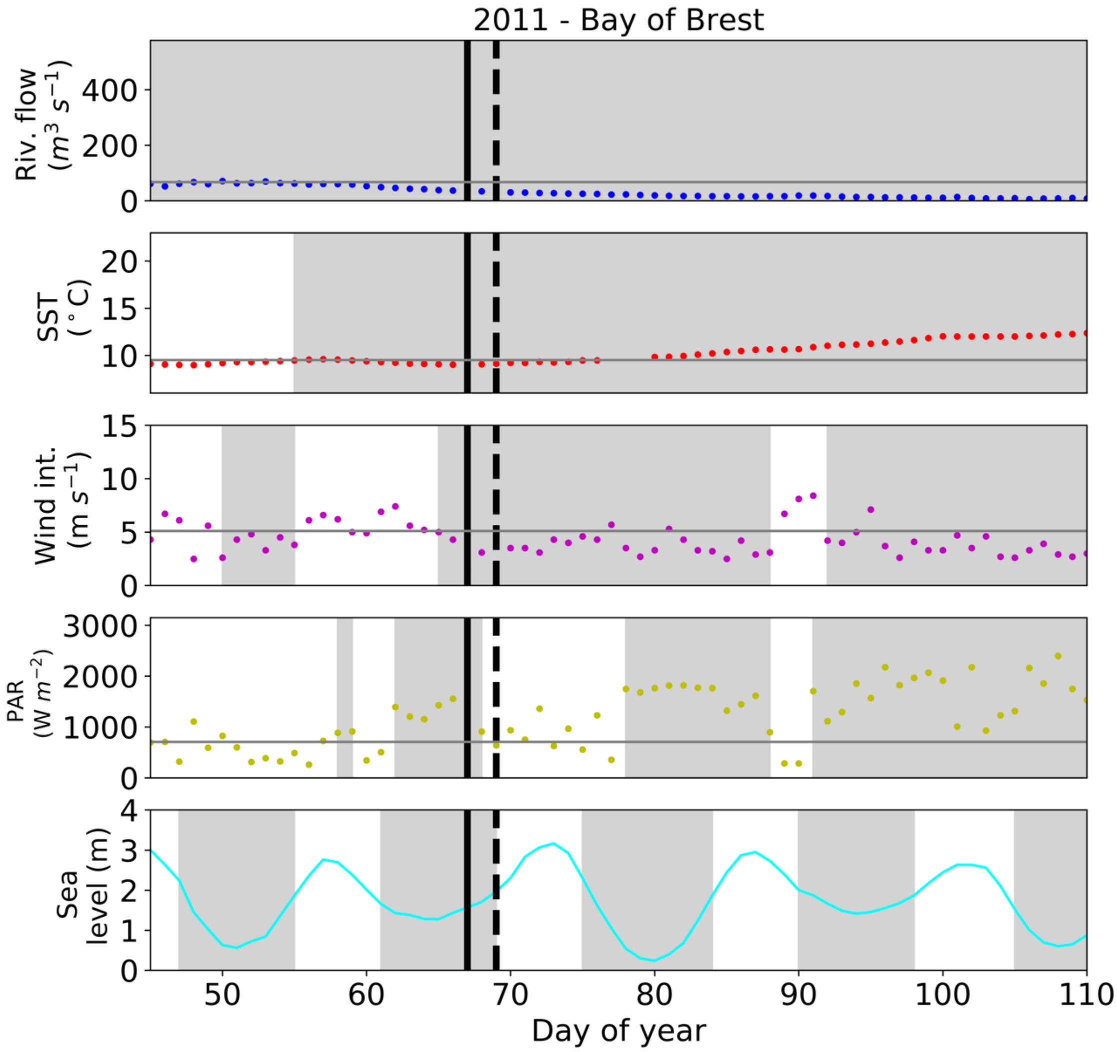
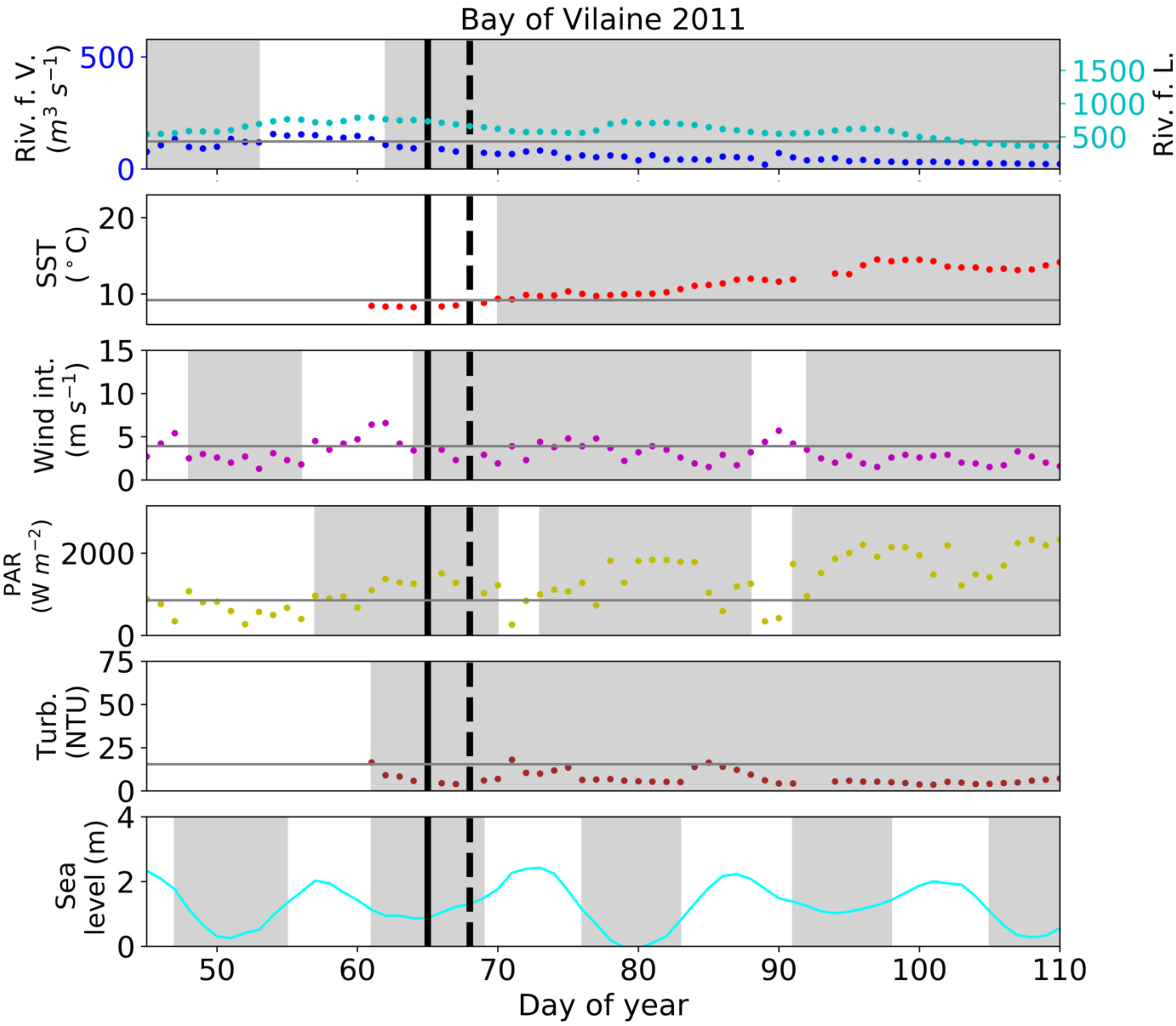


Figure 6: Changes in the IPGP date in (a) the Bay of Brest and (b) the Bay of Vilaine are determined with high-frequency time series (black circles), low-frequency time series (red circles) and with the model (blue circle). The dotted black line represents the date of the COAST-HF-Molit buoy deployment.

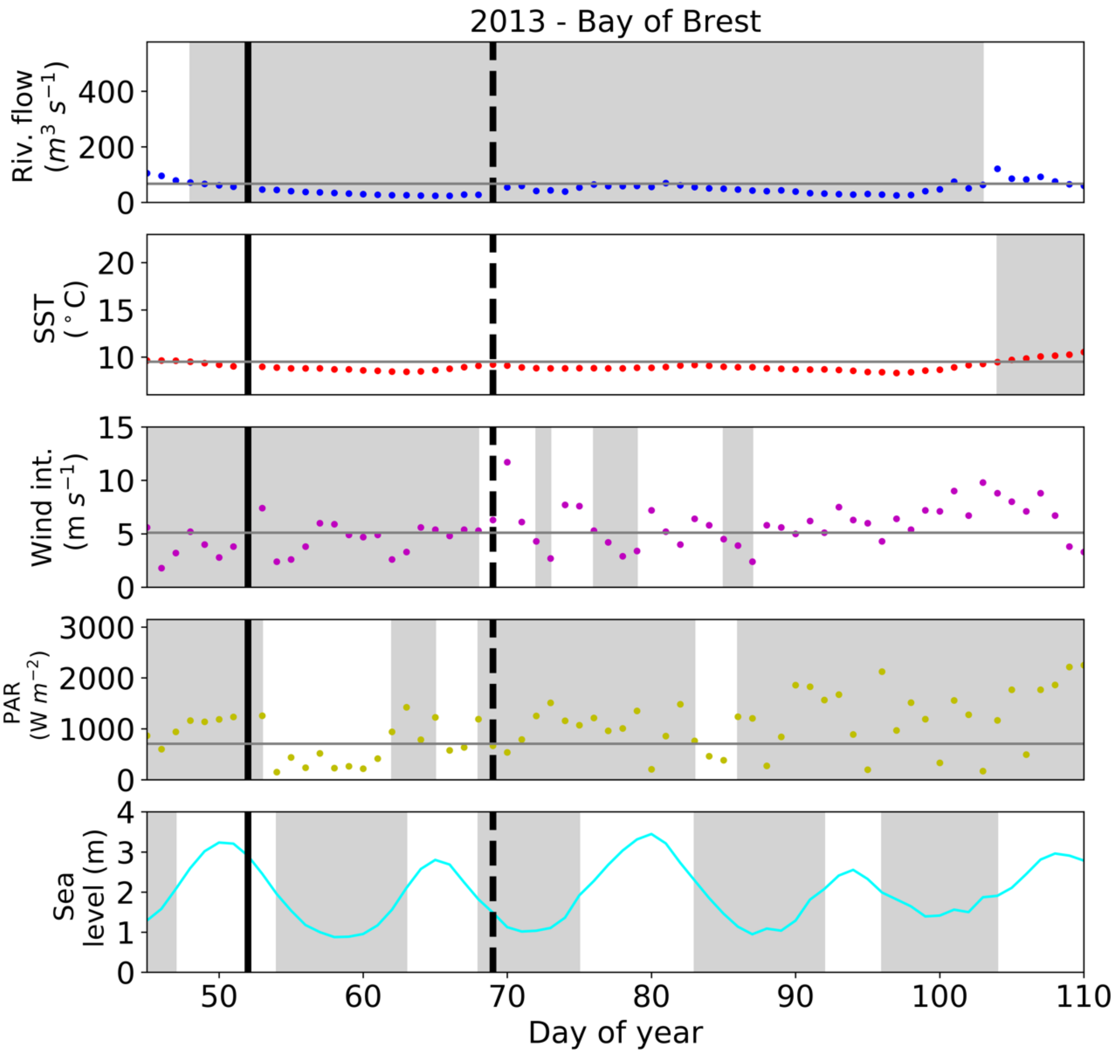
(a)


2011 - Bay of Brest
Riv. flow (m^3 s^{-1})
400
200
0
SST ($^\circ$C)
20
15
10
Wind int. (m s^{-1})
15
10
5
0
PAR (W m^{-2})
3000
2000
1000
0
Sea level (m)
4
3
2
1
0
50
60
70
80
90
100
110
Day of year

(b)


Bay of Vilaine 2011
Riv. f. V. (m^3 s^{-1})
Riv. f. L.
SST (°C)
Wind int. (m s^{-1})
PAR (W m^{-2})
Turb. (NTU)
Sea level (m)
Day of year

(c)


2013 - Bay of Brest
Riv. flow
(m^3 s^{-1})
SST
($^\circ$C)
Wind int.
(m s^{-1})
PAR
(W m^{-2})
Sea
level (m)
Day of year

(d)

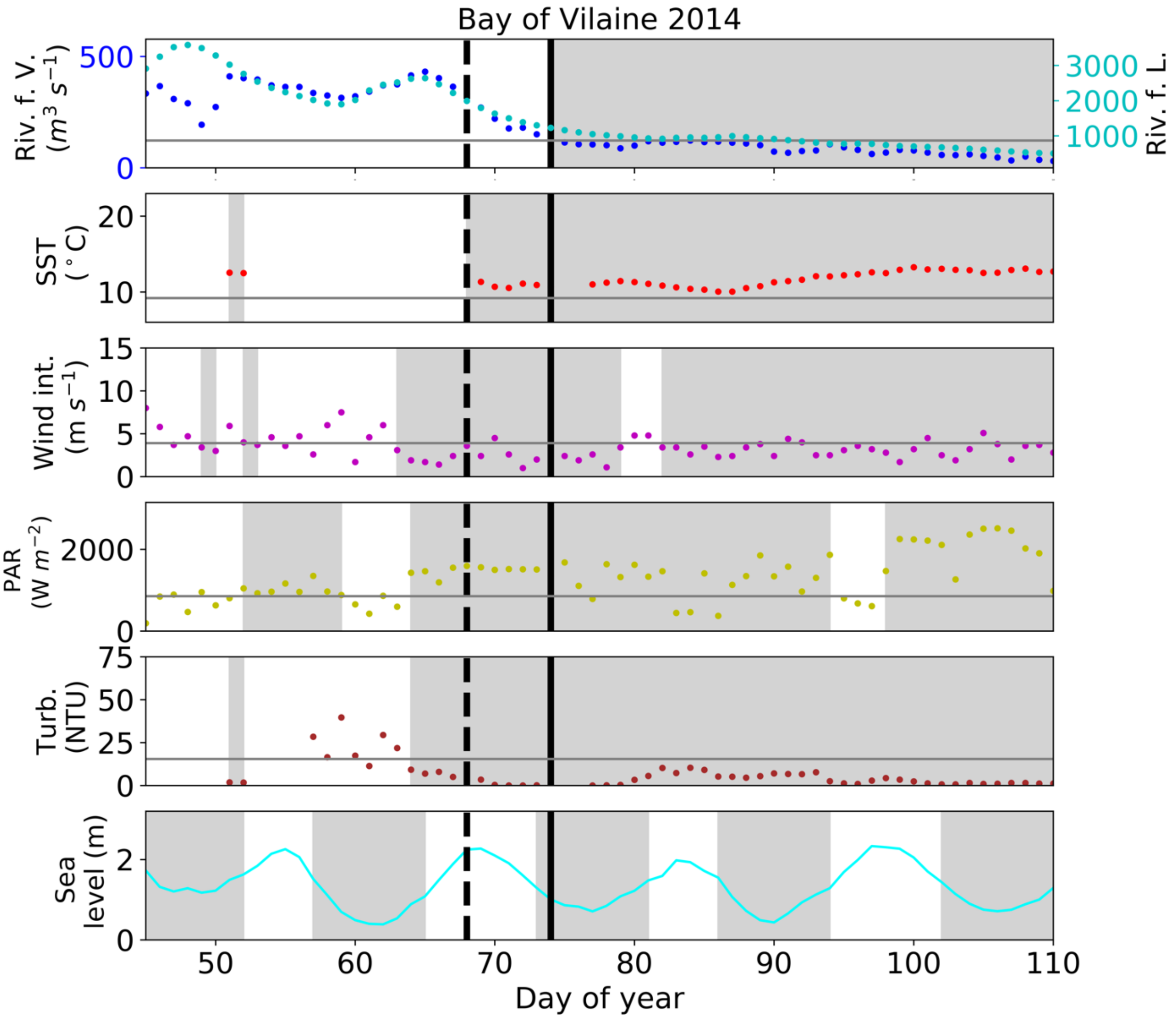
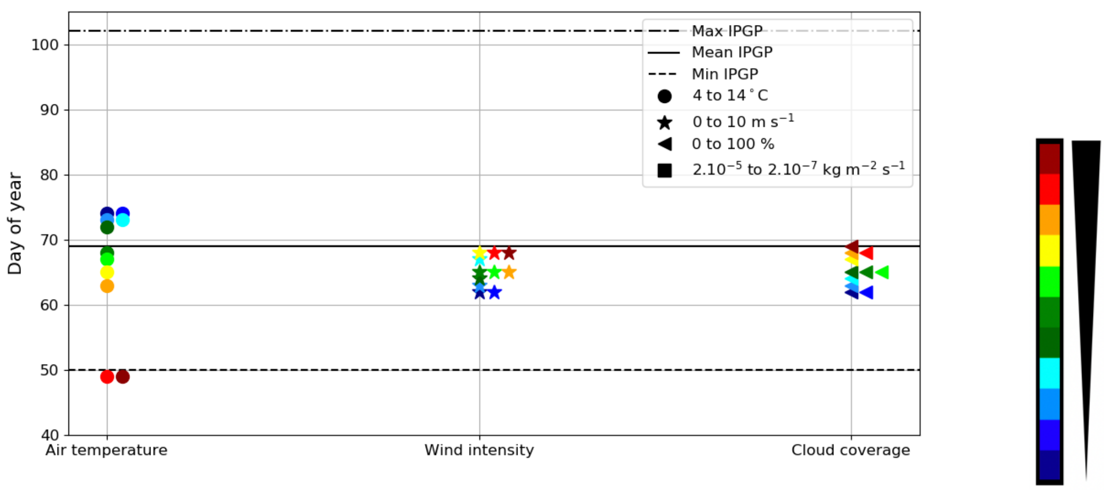


Figure 7: IPGP dates and environmental drivers: flow of the Aulne, Vilaine and Loire rivers, Sea Surface Temperature, wind intensity, PAR, turbidity and sea level at high tide. Illustrations in 2011 for a mean IPGP date in (a) the Bay of Brest and (b) the Bay of Vilaine; in 2013 for an early IPGP date in (c) the Bay of Brest; in 2014 for a late IPGP date in (d) the Bay of Vilaine. The mean IPGP date of each bay is represented by a dotted black line and the IPGP date of the year is represented by a straight black line. Thresholds of each environmental driver are represented by grey vertical lines corresponding to the mean conditions calculated 30 days around the IPGP date. Grey areas are time periods favorable to IPGP.

	Bay of Brest (2001-2019)	Bay of Vilaine (2011-2019)
	Min - ***Median*** - *Max*	*Min* - ***Median*** - *Max*
River flow ($m^3\ s^{-1}$)	13 - **46** - 100	36 - **96** - 205
SST (°C)	8 - **10** - 12	8 - **10** - 11
Wind intensity ($m\ s^{-1}$)	1 - **3** - 6	1 - **3** - 4
PAR ($W\ m^{-2}$)	915 - **1373** - 2220	814 - **1341** - 1939
Turbidity (NTU)	1 - **7** - 21	0 - **7** - 22
Sea level (m)	0.5 - **1.6** - 2.9	0.6 - **0.9** - 1.6
PO_4 (µmol/L)	0.1 – **0.4** – 0.6	0.1 – **0.8** – 1.4
DIN (µmol/L)	8 – **20** – 38	25 - **57** - 244
$Si(OH)_4$ (µmol/L)	4 - **8** - 16	8 - **38** - 112

Table 4: Characteristics of environmental drivers at the date of IPGP except for nutrients from January to March in the Bay of Brest and in the Bay of Vilaine.

(a)



(b)

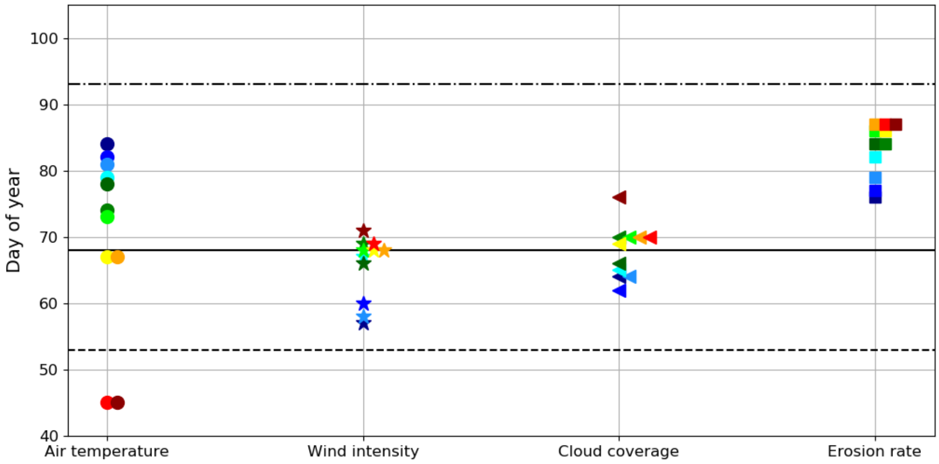


Figure 8: Impact of the variation of environmental drivers on the date of IPGP in (a) the Bay of Brest and (b) the Bay of Vilaine. Steps of: 1°C for the air temperature, 1 m s^{-1} for the wind intensity, 10 % for the cloud coverage and 0.0000036 kg m^{-2} s^{-1} for the erosion rate equivalent to a variation of suspended matter between 0.02 and 0.08 mg L^{-1} at IPGP.

Experiment	Air temperature (°C)	Wind intensity (m s^{-1})	Cloud coverage (%)	Erosion rate (kg m^{-2} s^{-1})	Simulated IPGP Bay of Brest (days)	Simulated IPGP Bay of Vilaine (days)
1	**4**	**3**	**70**	2.10^{-6}	+5	+16
2	**14**	**3**	**70**	2.10^{-6}	-20	-23
3	**10**	**0**	**70**	2.10^{-6}	-1	-11
4	**10**	**10**	**70**	2.10^{-6}	-7	+3
5	**10**	**3**	**0**	2.10^{-6}	=	-4
6	**10**	**3**	**100**	2.10^{-6}	-7	+8
7	10	3	70	2.10^{-7}		+8
8	10	3	70	2.10^{-5}		+19
A	**4**	**10**	**100**	2.10^{-5}	+9	+64
B	**4**	**10**	**70**	2.10^{-6}	+5	+17
C	**4**	**3**	**100**	2.10^{-6}	+5	+28
D	**10**	**10**	**100**	2.10^{-6}	=	+6
E	4	10	70	2.10^{-5}		+48
F	4	3	100	2.10^{-5}		+46
G	10	10	100	2.10^{-5}		+34
H	10	3	100	2.10^{-5}		+19
I	10	10	70	2.10^{-5}		+29
J	4	3	70	2.10^{-5}		+36
K	**14**	**0**	**0**	2.10^{-7}	-20	-11
L	**14**	**0**	**70**	2.10^{-7}	-21	-11
M	**14**	**3**	**0**	2.10^{-7}	-20	-11
N	**10**	**0**	**0**	2.10^{-7}	-11	-11

Table 5: Assumptions are explored in the 1DV model for environmental parameters independently (1-8) and with combined effect (A-N) with the modified values (grey background) and text in bold for the Bay of Brest only (+ for later IPGP, - for earlier IPGP, = for equal IPGP) with IPGP equal the mean observed IPGP of day 68.

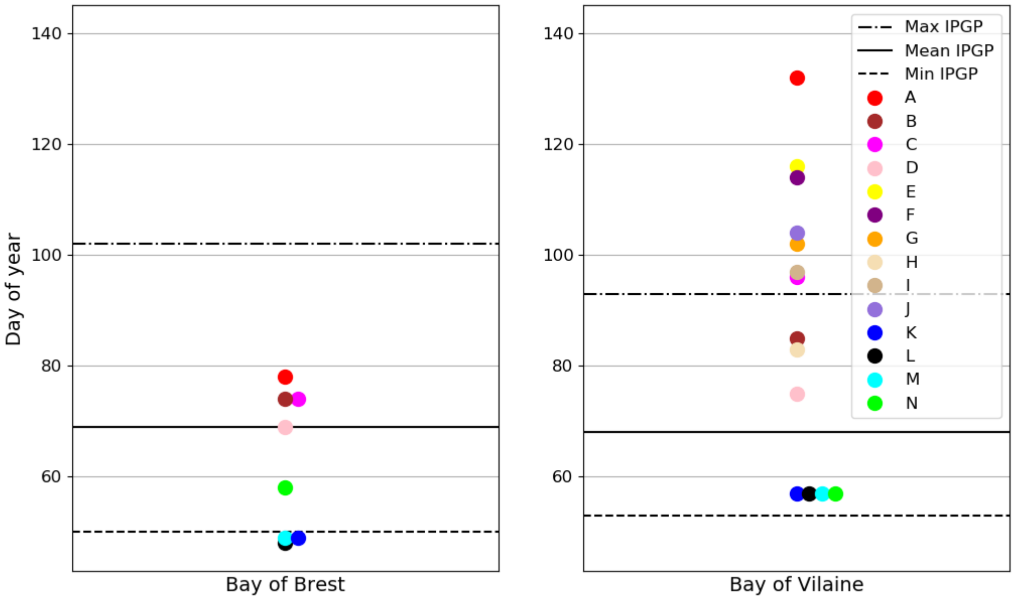


Figure 9: Influence of combined environmental parameters for the MARS-1DV model in both bays (Bay of Brest - left and Bay of Vilaine - right) with detailed experiments in Table 2.

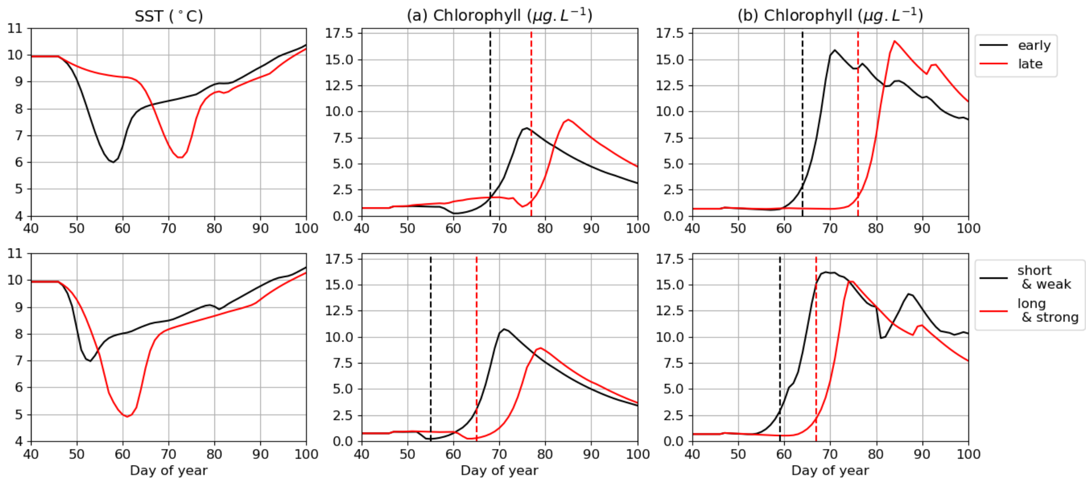


Figure 10: Impact of cold spells on the IPGP date simulated in (a) the Bay of Brest and (b) the Bay of Vilaine. Four conditions of cold spells are explored: an early (mid-February), a late (end of February), a short (8 days) and a long (20 days). The IPGP dates are represented by dotted lines.