Climate Change Initiative
Living Planet Fellowship

2014

Marie Fanny Racault

PML

4000112798/15/I/SBo

STANDARD COVER PAGE FOR ESA STUDY CONTRACT REPORTS

ESA STUDY CONTRACT REPORT

ESA Contract No: 4000112798/15/I/SBo	SUBJECT: Climate Impact on the Marine Ecosystem State [CLIMARECOS]	CONTRACTOR: Plymouth Marine Laboratory
* ESA CR( )No:	No. of Volumes: 1 This is Volume No: 1	CONTRACTOR'S REFERENCE: Prospect Place, The Hoe Plymouth, PL1 3DH United Kingdom

ABSTRACT:

Oceanic phytoplankton respond rapidly to a complex spectrum of climate-driven perturbations, confounding attempts to isolate the principal causes of observed changes. A dominant mode of variability in the Earth-climate system is that generated by the El Niño phenomenon. Marked variations are observed in the centroid of anomalous warming in the Equatorial Pacific under El Niño, associated with quite different alterations in environmental and biological properties. As the diversity and frequency of extreme El Niño events are projected to increase under climate warming, I have carried out a first and important assessment of the impact of El Niño on phytoplankton chlorophyll, primary production and phenology during my ESA Living Planet Fellowship (Racault et al., 2017a, 2017b). In particular, using the Climate Change Initiative Ocean Colour, Sea Surface Temperature and Sea Level observational datasets and the European Centre for Medium-Range Weather Forecasts reanalysis datasets, I have differentiated the regional physical forcing mechanisms, and compiled a global atlas of associated impacts on oceanic phytoplankton caused by two extreme types of El Niño. I found robust evidence that during Eastern Pacific (EP) and Central Pacific (CP) types of El Niño, impacts on phytoplankton can be felt everywhere, but tend to be greatest in the tropics and subtropics, encompassing up to 67% of the total affected areas, with the remaining 33% being areas located in high-latitudes. My analysis also highlighted considerable and sometimes opposing regional effects. During EP El Niño, I estimated decreases of −56 TgC/y in the tropical eastern Pacific Ocean, and −82 TgC/y in the western Indian Ocean and increase of +13 TgC/y in eastern Indian Ocean, whereas during CP El Niño, I estimated decreases −68 TgC/y in the tropical western Pacific Ocean and −10 TgC/y in the central Atlantic Ocean. In addition, I have developed a novel, state-of-the-art phenology algorithm based on OC-CCI Chlorophyll product at 5-day resolution and evaluated the influence of El Niño on phytoplankton phenology in the global oceans. I found that during positive phase of the El Niño Southern Oscillation, the timings of initiation, peak and termination are delayed by 25 to 40 days in tropical and subtropical regions of the central and eastern Pacific Ocean, the subtropical regions of the Indian Ocean and the Atlantic Ocean, and between 40-50°N in the North Atlantic, and 20-50°S in the western side of the South Atlantic. Conversely, I observed that the timings of the phytoplankton-growing period occurred earlier, between -15 and -30 days, in the eastern equatorial region of the Pacific Ocean, in the equatorial region of the Indian Ocean and in large regions of the Southern Ocean and the eastern side of the South Atlantic Ocean. The results achieved during my fellowship improve the mechanistic understanding of the impact of El Niño on oceanic phytoplankton and provide key climate impact information to better inform fisheries management on possible risks and opportunities associated with El Niño events, and support more effectively mitigation and adaptation plans for ocean resources-dependent societies.

The work described in this report was done under ESA Contract. Responsibility for the contents resides in the author or organisation that prepared it.

Names of authors: Marie-Fanny Racault

NAME OF ESA STUDY MANAGER:	ESA BUDGET HEADING:
Stephen Plummer DIV: EOP-SC DIRECTORATE: EOP	

CCI Living Planet Fellowship Final Report

Marie-Fanny Racault
CLIMARECOS

Background

The ocean plays a major role in the climate system, absorbing, between 1971 and 2010, more than 90% of the energy accumulated from greenhouse effect and approximately 30% of the carbon dioxide (CO_2) emitted to the atmosphere by human activities (IPCC, 2013). This CO_2 sink is part of a very active, natural carbon cycle, through which physico-chemical process transports carbon (as dissolved inorganic carbon) from the ocean's surface to its interior, so-called the solubility pump, and biological process fixes CO_2 into organic matter (a process called photosynthesis, performed by microscopic phytoplankton cells) in the surface layer of the ocean, some of which subsequently sinks below the mixed layer, so-called the biological pump. Through this latter process, phytoplankton help to modulate the increase in atmospheric CO_2 that results from the burning of fossil fuels. Moreover, phytoplankton are at the base of the food chain and transfer energy to higher trophic levels. This transfer of energy has a knock-on effect on fisheries and dependent human societies especially in highly productive and coastal upwelling regions. Thus, phytoplankton are key players in the planetary carbon cycle, and they have a societal relevance. It is therefore important to understand phytoplankton dynamics, which in turn depend on the underlying physical forcing (light, temperature, and winds). However, to what extent can we separate the influence of climate variability (as indicated by El Niño Southern Oscillation) from the impact of climate change? Furthermore, what can we learn about potential impact of climate change on the marine ecosystem by studying its response to El Niño? This is the focus of this fellowship.

The Intergovernmental Panel on Climate Change (IPCC) has recognised in the latest assessment report (AR5) "medium evidence"[1] of how the highly productive regions are responding to recent warming (especially since the 1970s) and "low confidence"[1] in the understanding of how equatorial upwelling systems will change in response to El Niño variability (Hoegh-Guldberg et al., 2014, Chapter 30-The Ocean). The ocean-colour time-series produced by ESA OC-CCI provides an unprecedented global scale, high-quality, error-characterized and longest data record of ocean-colour, that can significantly contribute to improve evidence and confidence in our understanding of the impacts of ENSO and ocean warming on the marine ecosystem. This fellowship investigated the impact of climate variability on the state of the marine ecosystem using the 16-year contemporary ocean-colour time-series produced by ESA OC-CCI, physical observations from other CCI projects (Sea Surface Temperature SST-CCI and Sea Level SL-CCI) and reanalysis products, and global ocean biogeochemical models.

The impact of the dominant modes of climate variability has been assessed by analysing the response of a suite of ecological indicators (chlorophyll, primary production, phenology) to El Niño. The mechanisms driving the biological responses have been assessed by analysing relationships between ecological indicators and environmental variables (SST, SL, precipitation and winds). Finally, the analysis carried out with ocean-colour remote-sensing observations was compared with ecosystem model outputs.

The present report contains information on the work achieved during the full fellowship period April 2015 to March 2017.

Objectives

The objectives achieved during this fellowship have been to: 1) to develop a novel phenology

[1] The IPCC Fifth Assessment Report (AR5, 2013) uses five confidence levels to evaluate qualitatively the validity of key findings. The confidence levels are based on the type, amount, quality, and consistency of evidence (summary terms: "limited," "medium," or "robust"), and the degree of scientific agreement (summary terms: "low," "medium," or "high"). The combined evidence and agreement results in five levels of confidence (summary terms: "very high", "high", "medium", "low" and "very low"). A depiction of evidence and agreement statements and their relationship to confidence is provided in the IPCC guidance note, their Figure 1 at: https://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf

algorithm that can quantify up to two phytoplankton-growing periods in the global oceans, and estimate, for the first time, phenological indices at 5-day temporal resolution, based on the OC-CCI chlorophyll product (comprising merged, bias-corrected data from MERIS, MODIS and SeaWiFS sensors), presenting improved spatio-temporal coverage compared with single-sensor chlorophyll products; 2) to provide a comprehensive estimation of the marine ecosystem state based on variations in chlorophyll concentration, primary production and phenology using the merged error-characterized OC-CCI chlorophyll fields; 3) to analyse interannual variability and quantify the sensitivity of the selected ecological indicators to El Niño climate phenomenon in different biogeochemical provinces of the global oceans; 4) to characterise the influence of El Niño variability on phytoplankton chlorophyll concentration and primary production in the global oceans; 5) to develop regionally-tuned phenology algorithms to support fisheries management and ecosystem-health assessment; and 6) to compare phenology indicators estimated in ecosystem models and satellites in the global oceans, and identify relevant metrics for model skill assessment.

Methods

Global ocean phenology algorithm development and metrics estimation

A global oceans' algorithm has been developed to estimate, on a pixel-by-pixel basis, the phenological metrics of timings of initiation, peak and termination, and duration for up to two phytoplankton-growing periods per year. The calculation of the timings is based on a threshold criterion (i.e., chlorophyll long-term median plus 5%) applied to the derivative of the cumulative sum of chlorophyll anomalies. A schematic representation of the phenological method is presented in Figure 1 (from Racault et al., 2017a). The algorithm has been applied to the Level-3 ESA OC-CCI v2 chlorophyll dataset at 5-day temporal resolution and 1x1degree spatial resolution over the period 1998-2009. The resolutions were chosen to minimise gaps in the data while retaining maximum resolution in time. Prior to applying the algorithm, a complete chlorophyll time-series was constructed (i.e., no data gaps): 1) by applying linear interpolation to fill missing data due to cloud cover, and 2) by inserting NASA Ocean Biogeochemical Model (NOBM, Gregg & Casey, 2007; Gregg & Rousseaux, 2014) chlorophyll data to fill persistent missing data due high solar zenith angle in Winter at high-latitudes. In addition, to account for the large variability in timing of occurrence of the phytoplankton-growing periods in the global oceans (Racault et al., 2012), The SST seasonal cycle was used to define specific time intervals during which phenological indices are estimated.

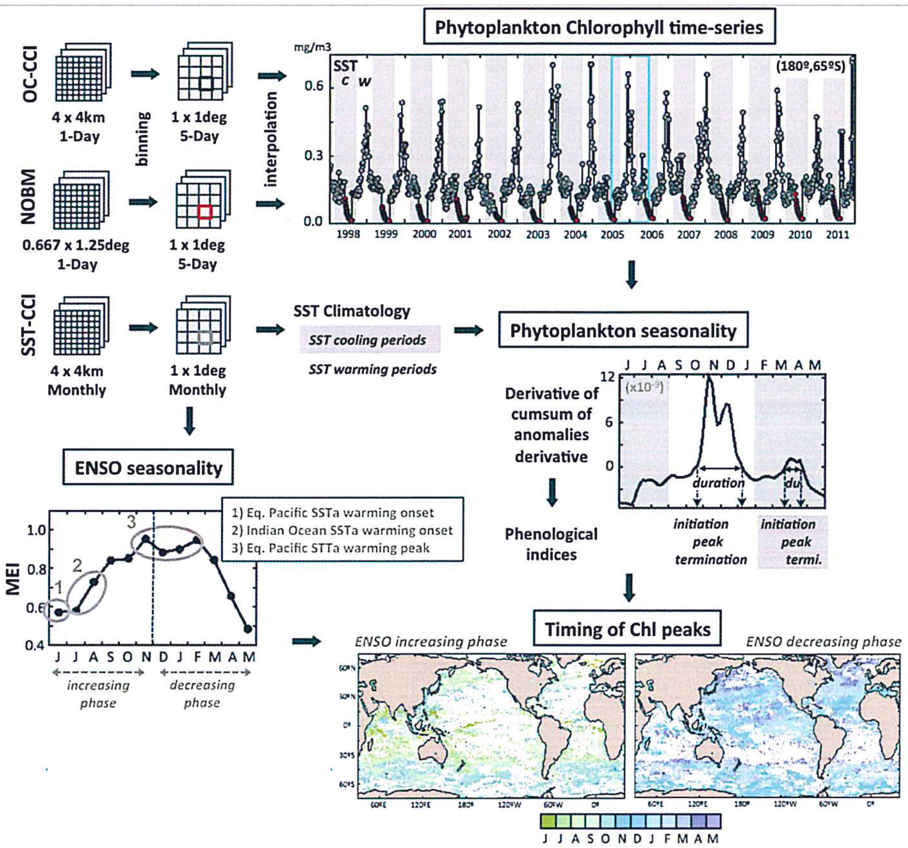

Figure 1. Schematic diagram of the phenology algorithm based on Racault et al. (2017a). The methodology to estimate two chlorophyll peaks per annual cycle has been further developed based Racault et al. (2015). Ocean Colour Climate Change Initiative (OC-CCI) data were used over the period 1998-2010 at 5-day resolution. NOBM model data of chlorophyll concentration were estimated at 5-day resolution and used to fill persistent missing data due to high solar zenith angle at higher latitudes (red dots in the Chlorophyll time-series). Climatology of Sea Surface Temperature (SST) CCI data were used to provide time boundaries to identify chlorophyll peaks in the annual cycle. Multivariate ENSO Index was used to separate the annual cycle in two phases (increasing and decreasing ENSO phases). The plot of the derivative of the cumulative sum of chlorophyll anomalies and maps of timing of chlorophyll peak during ENSO increasing and decreasing phases are displayed here as an example for the 12-month period between Jun 2005 to May 2006.

Regional phenology algorithms development and metrics estimation

The global oceans' phenology algorithm has been tuned and applied to estimate the phenological metrics of timings of initiation, peak and termination, and duration of the phytoplankton-growing period in several regional ecosystems as follows.

The Gulf of Aden: the phenological metrics have been estimated based on the climatological time-series of the OC-CCI v2 Level-3 mapped Chlorophyll at 8-day temporal resolution and 4x4km spatial resolution for the period 2003-2012. The tuning involved a threshold criterion based on 20% of the maximum climatological chlorophyll concentration, and searched of the timings of peak chlorophyll concentration during two fixed time-intervals: January-March and July-September, corresponding to possible growth periods in the Gulf of Aden. The spatial resolution of 4x4km was the highest resolution available for Level-3 Mapped Chlorophyll data from the OC-CCI v2 archive. It was desirable to keep high spatial resolution because we are investigating phenology at regional scale. Furthermore, reduction in the number of missing data has been shown to be important to improve accuracy and precision in the estimation of phenological indices (Racault et al., 2014). Hence, the temporal resolution of 8-day was selected to minimise gaps, which are frequent in the region, especially during the summer season (see Racault et al., 2015; Their Figure 2). The temporal coverage was chosen because: 1) only the OC-CCI v2 Chlorophyll archive was available at the time that the research study was initiated; 2) SST data from MODIS 2002-2012 were used to study influence of environmental conditions on Chlorophyll variations (Gittings et al., 2017; please note that SST-CCI data archive is only available until 2010); 3) the region is prone to haze and high-level clouds, which have been reduced by the use of the POLYMER algorithm applied to MERIS (2002-2012) and when data from multiple sensors (SeaWIFS, MODIS, MERIS) are available between Jul 2002- Dec 2012; and 4) we wanted to have complete years, and calculated the climatology from Jan 2003 to Dec 2012.

The Ivorian continental shelf: the phenological metrics have been estimated based on the multi-annual time-series of OC-CCI v3[2] Level-3 mapped Chlorophyll at 8-day temporal resolution and 4x4km spatial resolution for the period 1998-2014. The tuning involved a threshold criterion based on long-term chlorophyll median plus 20%, and searched of the timings of peak chlorophyll concentration during one fixed time-interval between April to October, corresponding to the main growth period in Ivorian waters. Sensitivity analysis has been carried out to select the threshold criterion. Thresholds of median plus 5 to 30% were tested, and showed relatively similar patterns of timings of initiation and termination. Increasing (reducing) the threshold criterion tends to delay (advance) the timing of initiation and advance (delay) the timing of termination. In the Ivorian continental shelf, chlorophyll concentration presents clear seasonal variations, on average, between 0.20 to 1.70 $mgChl.m^{-3}$. The median plus 20% threshold criterion was selected as it gave most coherent results of bloom timings when related to changes in environmental conditions (upwelling index and turbulence, Kassi et al., in prep.). The temporal and spatial resolutions were chosen to minimise gaps in the time-series and maximise the resolution for this regional-scale study. The Gulf of Guinea has been shown to have large number of missing data due to important cloud cover (Nieto and Mélin, 2017; Their Figure 4). The temporal coverage was limited by the availability of Chlorophyll data from the OC-CCI v3 processing at the time that the study was initiated.

The Mediterranean Sea: the phenological metrics have been estimated based on the multi-annual time-series of Level-4 mapped Chlorophyll at 8-day temporal resolution and 1x1km spatial resolution for the period 1998-2014. This dataset was produced for the Copernicus Marine Environment Monitoring Service (CMEMS) by the Plymouth Marine Laboratory (PML) using the ESA-CCI processor. The Rrs were converted to chlorophyll concentration via state-of-the-art regional algorithm MedOC4 (Mediterranean Ocean-Colour 4 bands, Volpe et al., 2007) for better product quality. The entire data set was consistent and processed by PML in one-shot mode (with an unique software version and identical configurations). The product was remapped at 1 km spatial resolution using cylindrical equirectangular projection. In addition to the regional tuning of the Chlorophyll retrieval algorithm, the phenological tuning involved the use of a threshold criterion based on the long-term chlorophyll median plus 20%. This threshold yielded best results avoiding the detection of small peaks, especially in coastal regions and gave most coherent results of bloom timings when related to changes in environmental conditions, including sea surface temperature, wind, and river discharge (Salgado et al., in prep.). The temporal and spatial resolutions of 1x1km and 8-day were selected based on the availability of regionally tuned Mediterranean Sea Chlorophyll data composites. In addition, the resolutions selected allowed to minimise gaps in the time-series and maximise the resolution for this regional-scale study. Finally, the temporal coverage was limited by the availability of Chlorophyll data from the OC-CCI v3 processing at the time that the study was initiated.

Calculation of global ocean phenology in ecosystem model outputs

The novel global oceans' phenology algorithm developed during the fellowship (Racault et al., 2017a) has been applied to the chlorophyll products of four ecosystem models: MRI.COM-MEM (an ocean-ice-Marine Ecosystem Model, available from the Marine Ecosystem Model Intercomparison Project (MAREMIP), https://pft.ees.hokudai.ac.jp/maremip/index.shtml), HadGEM2-ES (a fully coupled Earth System model, also available from MAREMIP), and the NASA Ocean Biogeochemical Model (NOBM) (which assimilates satellite Chlorophyll from sensors SeaWiFS, MODIS and MERIS, provided by C. Rousseaux). It is noteworthy that the NOBM model assimilates and bias corrects Chlorophyll data

[2] The OC-CCI v2 product comprises globally merged MERIS, Aqua-MODIS, and SeaWiFS data, and the processing extended from 1997-2012. The OC-CCI v3 product further included the NASA released VIIRS data (in addition to global MERIS, Aqua-MODIS, and SeaWiFS data), and the processing extended from 1997 to 2014. Temporal coverage was further extended in the updated OC-CCI v3.1, which also included NASA corrected MODIS-Aqua data (R2014.0.1). However, the latter update was released in May 2017, which was after completion of the studies presented in this fellowship.

from SeaWIFS, MODIS, and MERIS (Gregg and Rousseaux, 2014), whereas the OC-CCI merging and bias correction effort is based on the remote-sensing reflectance (Rrs) (Sathyendranath and Krasemann, 2014). The present calculation and comparison of phenologies aim to provide a first assessment of the importance of the temporal resolution used in the models, and of the assimilation of Chlorophyll data to calculate these metrics. However, the present phenologies are not intended to be regarded as strict validations and/or independent comparisons of satellite observations and model outputs.

To make the satellite and model datasets comparable, a systematic approach was followed, as illustrated in Figure 2:

1. Re-projection of all datasets on a 1x1 degree regular grid;
2. Masking model outputs using the satellite mask (accounting for missing data);
3. Calculating 5-day climatology over the period 1997-2005 (this is the period for which the MAREMIP hindcast model outputs are available).

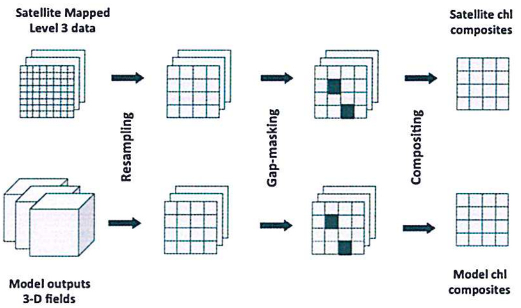

Figure 2. Schematic view of the pre-processing steps to compare satellite data and model outputs.

El Niño impact analysis

The influence of El Niño variability on inter-annual and decadal time-scale have been characterised by performing a linear regression between annual mean anomalies of El Niño indices and annual mean anomalies of biological variables (i.e., chlorophyll concentration and primary production for the period 1997-2012) and physical variables (i.e., SST, SL, wind and precipitation for the periods 1997-2012 and 1979-2014). The time-series of Eastern Pacific and Central Pacific El Niño indices were obtained based on the EOF-analysis in the tropical Pacific Sea Surface Temperature (Kao and Yu, 2009, Yu et al., 2012) at http://www.ess.uci.edu/~yu/2OSC/. The influence of the El Niño Southern Oscillation on phytoplankton phenology was characterised by performing a linear regression between annual mean anomalies of the Multivariate ENSO Index (MEI) and annual mean anomalies of phenological indices. The time-series of MEI defined as the first seasonally-varying principal component of six atmosphere–ocean variable fields in the tropical Pacific basin (i.e. sea level pressure, zonal and meridional wind components, sea surface and air temperatures, and total cloudiness) were obtained at https://www.esrl.noaa.gov/psd/enso/mei/table.html.

To account for auto-correlation in the time-series, the statistical method of Lin and Derome (1998) was applied and the effective degrees of freedom (edf) was estimated. Then, a Student t-test was performed and the significance level was estimated based on the edf.

Sensitivity of ocean-colour indicators to El Niño in different biogeochemical provinces

Relationships between El Niño-related responses shown in ecological indicators were explored using linear regression analysis between relative changes in duration of phytoplankton growth and chlorophyll concentration, and between duration and primary production. Each ecological indicator was estimated using climatologies of positive and negative MEI years over the period 1998-2009. In the latter period, positive MEI years include 2001/2002 to 2004/2005, 2006/2007 and negative MEI years include 1998/1999 to 2000/2001, 2005/2006, 2007/2008, 2008/2009. The relative difference was computed between responses to positive and negative MEI for the annual mean chlorophyll concentration, annual mean primary production, and the duration of phytoplankton growing period. The regression analysis was performed first on a pixel-by-pixel basis and then, averaged the results in each biogeographical province. This averaging procedure allowed to weight evenly the influence of El Niño in the tropics, subtropics and subpolar provinces. The partitioning of the provinces was based on physical, chemical and biological oceanographic knowledge and provides comprehensive geographical units supporting scientific findings interpretation and extrapolation (Longhurst, 1998).

Results and discussion

This section provides key results and figures generated during the fellowship. Further results and additional figures have been reported in peer-reviewed papers (please see publications list at the end of the report).

Global ocean phenology algorithm development and metrics estimation (Racault et al., 2017a)

In subpolar regions, nutrients are generally replenished during the winter season and the timing of chlorophyll peak follows the latitudinal increase in light availability from the months of ~July to November in the Southern Hemisphere and from the months of ~January to May in the Northern Hemisphere. In the tropics and subtropics, phytoplankton growth is primarily limited by nutrient availability, and the timing of phytoplankton growth is not seasonal and may occur throughout the course of an annual cycle.

In addition, with the present phenological algorithm, North and South Hemispheres seasonality could be distinguished: the main growing period (defined by the peak with the highest amplitude) occurs during the months of June to November (i.e., JJASON in Fig. 3a) in the Southern Hemisphere, whereas it occurs during the months of December to May (i.e., DJFMAM in Fig. 3b) in the Northern Hemisphere. Exceptions are found in the Southern Hemisphere in the Pacific Ocean tropics and subtropics, off the east coast of Madagascar and in the Mozambique Channel, and along the west and northwest coast of Australia, which show highest probability to have the main chlorophyll peak in DJFMAM (i.e., which is corresponds to the Northern Hemisphere chlorophyll peak timing).

Furthermore, with the present algorithm development, it was possible to estimate that the probability to have two chlorophyll peaks per year is almost zero in the tropics and subtropics, while it increases almost symmetrically towards higher latitudes in the North and South Hemispheres (Fig. 3c). Moreover, it is noteworthy, that in high-latitude regions, the probability to have two chlorophyll peaks per year reaches values of ~0.5, indicating that two peaks in chlorophyll are only observed in ~half of the years during the period 1998-2009 (i.e., approximately half of the years present two peaks and the other half present one peak per year). The latter probability estimates, which are based on satellite observations, were compared and showed consistency with the latitudinal variations in the occurrence of phytoplankton blooms obtained in the North Atlantic using a model based on simple theoretical assumptions (Platt et al., 2009). This model demonstrates that the main driver explaining the variations in the probability of occurrence of two chlorophyll peak per year is the latitudinal variations in the strength and periodicity of the initial forcing (i.e., variations in the magnitude in the total daily irradiance). Another approach based on 1000 *a posteriori* simulations from a model fitted to remotely-sensed observations of chlorophyll concentration (15 consecutive seasonal cycles from 1998/1999 to 2012/2013), has permitted assessment of the probability of detecting different peaks in chlorophyll concentration and their timing in the Atlantic Ocean (between 15ºS to 80ºN; Gonzales-Taboada & Anadon, 2014). The authors showed higher probability of occurrence of two chlorophyll peaks per year in the North Atlantic subtropical region, which is consistent with the results obtained during the fellowship.

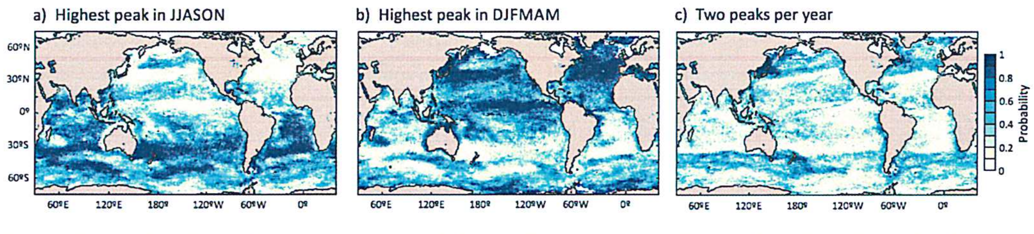

Figure 3. Probability of occurrence of chlorophyll peaks based on the phenological algorithm implemented using OC-CCIv2 chlorophyll data at 5-day resolution during the period 1998-2009. a) Probability that the main chlorophyll peak occurs during the months of June to November (JJASON); b) Probability that the main chlorophyll peak occurs during the months of December to May (DJFMAM); and c) Probability to have two chlorophyll peaks per year. If there are two chlorophyll peaks in one year, the main chlorophyll peak is defined by the peak with the highest amplitude (i.e., highest maximum chlorophyll value).

Analysis of regional phytoplankton phenology

In the Gulf of Aden (Gittings et al., 2017): the improved spatial coverage of OC-CCI data has allowed, for the first time, to resolve the complete seasonal succession of phytoplankton biomass. The indices of phytoplankton phenology revealed distinct phytoplankton growth periods, starting from the end of June across most of the gulf, and peaking in August in the northern coastline, and eastern and western regions of the gulf (Fig. 4).

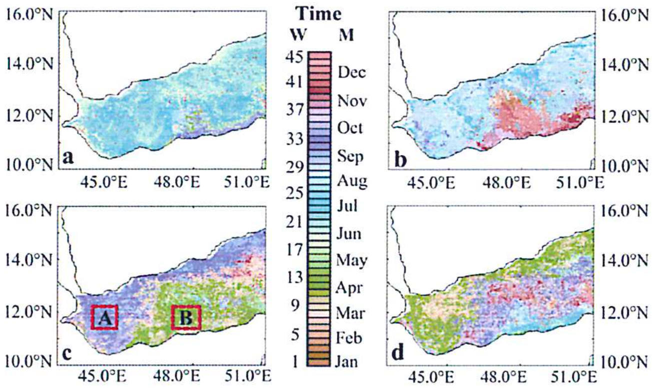

Figure 4. Phenological indices of the main phytoplankton growth period in the Gulf of Aden based on OC-CCIv2 15 year-climatology (2003-2012) of 8-day composites: a) timing of initiation and b) timing of peak, c) timing of termination, and d) duration of the growth period.

In the Ivorian continental shelf waters (Kassi et al., in prep.): typically the phytoplankton bloom starts around May and then peak around July. The bloom occurs at the time of the major upwelling of the Ivorian coast. The index of timing of phytoplankton bloom initiation has been estimated, and in collaboration with visiting fellow J.-B. Kassi from the Centre for Research and Application in Remote Sensing at the University of Abidjan (Ivory Coast), the relationship with data of *Sardinella aurita* catch obtained from the Ministry of Fisheries in Abidjan was analysed. Early (late) timing of initiation of phytoplankton growth was shown to be associated with low (high) *Sardinella* catch in the following year (Figure 5). If the timing of phytoplankton bloom occurs earlier than average conditions, a mismatch may be observed between food availability (phytoplankton) and the arrival of *Sardinella* fish larvae. Under such conditions, survival of *Sardinella* larvae may be low, which may then translate into low adult fish recruitment and their catch in year *t+1*. In contrast, a delay in the timing of phytoplankton bloom (positive anomaly) may bring more favourable conditions for the survival of *Sardinella* fish larvae (good timing of food availability), which may then allow for high adult fish recruitment and their catch in year *t+1*.

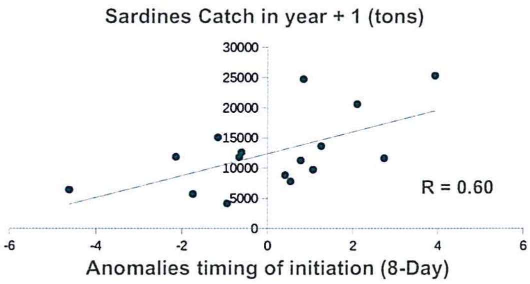

Figure 5. Empirical relationship between interannual variations in *Sardinella* catch and timing of initiation of phytoplankton growth. Note that in this figure, the timing of initiation is shown in year *t* and *Sardinella* catch in year *t+1* as we are investigating the influence of the phytoplankton bloom on the *Sardinella* catch success in the following year. The timing of initiation was calculated using OC-CCIv3 Chlorophyll product at 8-day temporal resolution for the period 1998-2014 (please see Footnote #2 for differences between OC-CCI v2 and v3).

In the Mediterranean Sea (Salgado et al., in prep.): the phytoplankton seasonal cycle in oceanic waters is typically characterised by a single bloom initiating in November and terminating between March and June, whereas in coastal waters, bloom initiation and termination tend to occur earlier, especially in the Gulf of Gabes, Adriatic Sea and along the eastern Mediterranean coast from Egypt to Lebanon (Fig. 6). Furthermore, with the double-peak phenology algorithm developed in the fellowship, it was possible to estimate that the coastal waters are also the areas where the probability of occurrence of a second phytoplankton bloom is highest (>70% probability to have two chlorophyll peak). In collaboration with visiting fellow P. Salgado from the Department of Ecology and Marine Resources at IMEDEA (Spain), significant trends in phytoplankton bloom duration were observed in 30% of the Mediterranean Sea. Blooms have increased in duration in the western part of the basin by up to +5 days, whereas they have decreased in the eastern part of the basin by -2 days. Such changes are anticipated to have a major impact on the energy flow of the Mediterranean Sea ecosystem (Fig. 6).

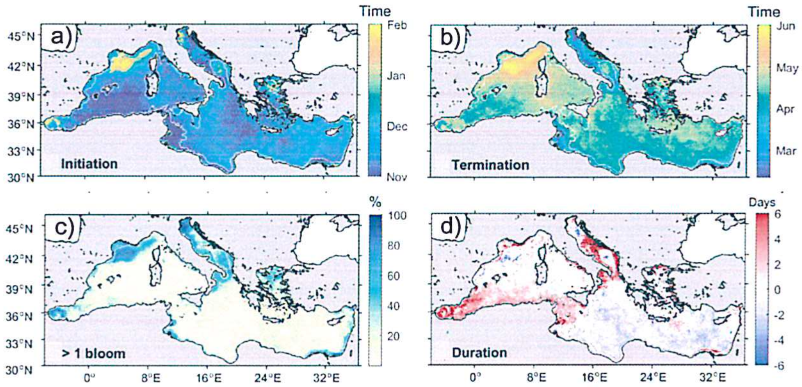

Figure 6. Phytoplankton phenological indices of the main growing period based on the Mediterranean Sea OC-CCI chlorophyll at 8-day temporal resolution during the period 1998-2014. a) Timing of phytoplankton bloom initiation, b) Timing of phytoplankton bloom termination, c) Probability of occurrence of two chlorophyll peaks per year, and d) Trend in phytoplankton bloom duration.

Comparison of phytoplankton phenology in satellite and in ecosystem models

There are some agreements between model and satellite data in terms of phenological patterns, but ecosystem models, which do not assimilate satellite chlorophyll, tend to present large shifts in timing of phytoplankton chlorophyll: in the northern hemisphere, peak timing was earlier in satellite compared to the model, whereas in the southern hemisphere peak timing was later in satellite compared to the model (Fig. 7). In addition, large discrepancies were seen in the ability of ecosystem models, which do not assimilate chlorophyll, to reproduce the probability of occurrence of one to two chlorophyll peaks per year (Fig. 8). The quasi absence of two chlorophyll peaks per year in some ecosystem models may be due to their relatively temporal resolution (i.e., MEM and HadGEM2 are initially available at monthly resolution, whereas NOBM is available at daily resolution). Differences in timing of peak, and ability to reproduce two chlorophyll peaks per year may also result from differences in biogeochemical components of the models. The probability of occurrence of one to two chlorophyll peaks per year revealed in this fellowship is particularly relevant for model projective skill assessment.

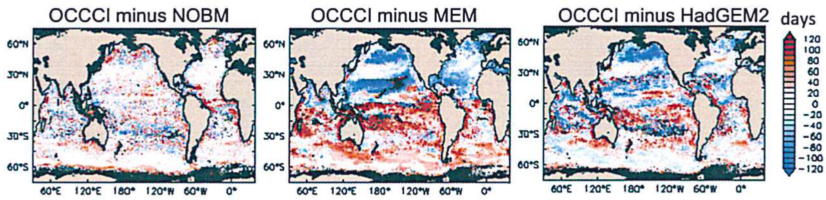

Figure 7. Difference in timing of phytoplankton peak between satellite OC-CCIv2 data minus ecosystem model outputs for a) NOBM, b) MEM, and c) HadGEM2-ES. The period investigated is 1998-2005 corresponding to the availability of ecosystem model hindcasts.

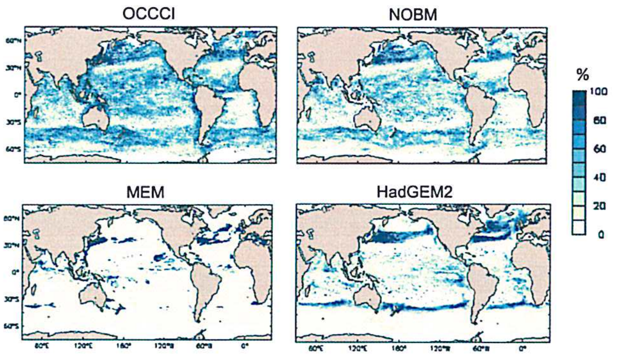

Figure 8. Probability of occurrence of one to two chlorophyll peaks per year in a) OC-CCIv2 satellite data, b) NOBM model output, b) MEM model output, and c) HadGEM2-ES model output. The period investigated is 1998-2005 corresponding to the availability of ecosystem model hindcasts.

Analysis of El Niño impact on phytoplankton phenology (Racault et al., 2017a)

During the positive phase of the Multivariate ENSO Index (Fig. 9a-c), the timings of initiation, peak and termination show delays of from ~25 to 40 days (positive anomalies) in tropical and extratropical regions of the central and eastern Pacific Ocean, in the subtropical regions of the Indian Ocean, in tropical and subtropical regions of the Atlantic Ocean, and also towards higher latitudes, between 40-50ºN in the North Atlantic, and between 20-50ºS in the western side of the South Atlantic. Conversely, the timings of the phytoplankton-growing period occur earlier (between -15 and -30 days, negative anomalies) in the eastern equatorial region of the Pacific Ocean, in the equatorial region of the Indian Ocean, and in large regions of the Southern Ocean, and the eastern side of the South Atlantic Ocean.

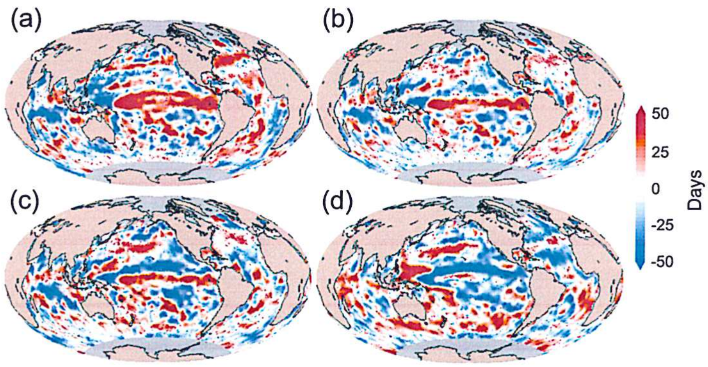

Figure 9. El Niño impact on phytoplankton phenology estimated using linear regression analysis between Multivariate ENSO Index and anomalies of timings of a) initiation, b) peak, c) termination, and d) duration. In all panels, red and blue stippling indicates where the linear regression coefficients are significant at the 90% confidence level. The phenological indices are calculated based on OC-CCIv2 at 5-day temporal resolution during the period 1998-2009.

Sensitivity of ocean-colour indicators to El Niño in different biogeochemical provinces (Racault et al., 2017a)

Based on the linear regression analyses, that the relative changes in annual mean chlorophyll explained 57% of the relative changes in duration, and the relative changes in annual mean primary production explained 47% of the relative changes in duration (Fig. 10a, b respectively, $p<0.01$). The sign and magnitude of the slopes are positive and greater than one, such that increases in MEI-associated changes in duration are accompanied by a two-fold increase in the response of chlorophyll to MEI, and increases observed in MEI-associated changes in duration are accompanied by a four-fold increase in the response of primary production to MEI. The largest MEI-related increases in chlorophyll, primary production and duration were observed in the Indian Ocean Monsoon Gyre province and in the Agulhas and Somali Current Large Marine Ecosystems province, and the largest decreases in the indicator values in the eastern Equatorial Pacific, subtropical and subpolar North Pacific regions (Fig. 10a, b). The emergence of linear relationships amongst El Niño-responses of indicators, which are initially measured in different units (i.e., mgChl.m^{-3} for chlorophyll concentration, mgC.m^{-2}.y^{-1} for primary production, and days for duration), can be particularly useful to analyse and compare indicators estimated from non-continuous data records, and when inter-sensor bias correction cannot be quantified (for instance, to compare changes in phytoplankton population between non-overlapping ocean-colour sensors CZCS (1978-1986) and contemporary sensors, starting in 1997 with SeaWiFS, and follow-on sensors in 2002 with MODIS or MERIS).

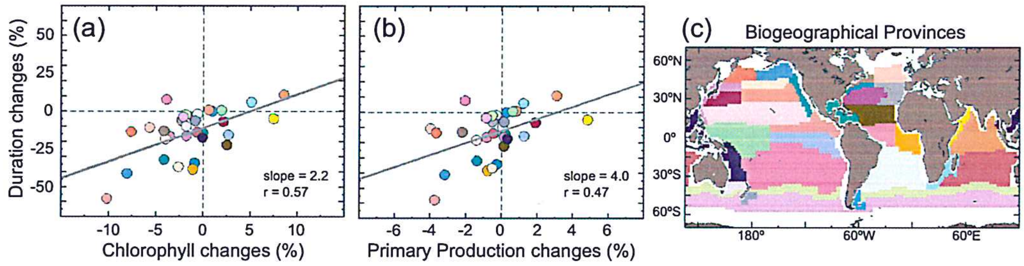

Figure 10. Emergent properties in ecological indicator responses to El Niño activity. a) Relationship between relative changes in chlorophyll concentration and duration of phytoplankton growing period between years of positive MEI and years of negative MEI; b) Relationship between relative changes in primary production and duration of phytoplankton growing period between years of positive MEI and years of negative MEI. The colour of each dot indicates the changes for each biogeochemical province (Longhurst, 1998) delineated in panel c).

Analysis of El Niño variability impact on phytoplankton (Racault et al., 2017b)

the regional physical forcing mechanisms have been differentiated, and compiled in a global atlas of associated impacts on oceanic phytoplankton caused by two extreme types of El Niño (Fig. 11). There is robust evidence that during Eastern Pacific (EP) and Central Pacific (CP) types of El Niño, impacts on phytoplankton can be felt everywhere, but tend to be greatest in the tropics and subtropics, encompassing up to 67% of the total affected areas, with the remaining 33% being areas located in high-latitudes. The analysis also highlights considerable and sometimes opposing regional effects. During EP El Niño, decreases of −56 TgC/y were estimated in the tropical eastern Pacific Ocean, and −82 TgC/y in the western Indian Ocean, and an increase of +13 TgC/y in eastern Indian Ocean, whereas during CP El Niño, decreases −68 TgC/y in the tropical western Pacific Ocean and −10 TgC/y in the central Atlantic Ocean were observed.

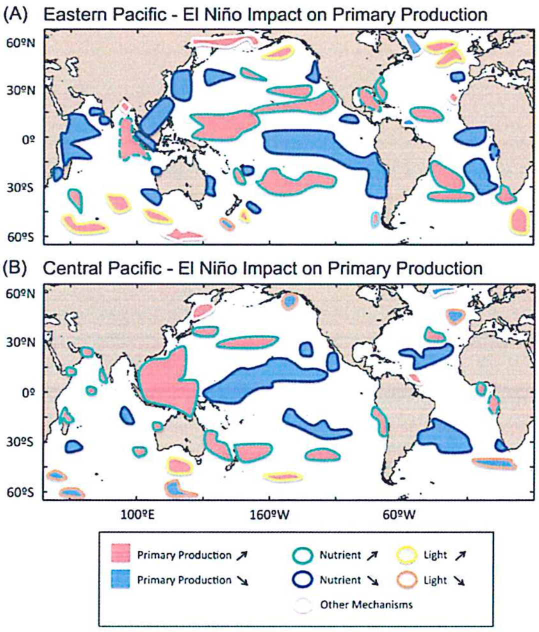

Figure 11. Schematic atlas of the influence of El Niño variability on oceanic phytoplankton in the global oceans. a) Eastern Pacific El Niño influence, and b) Central Pacific El Niño influence. The colour-contours provide information about the controlling biophysical mechanisms: (yellow) nutrient-limited; (dark blue) enhanced by nutrient availability; (orange) light-limited; (turquoise) enhanced by light availability; (light pink or dashed contour) controlled by other mechanisms, such as sea-ice melting, atmospheric dust deposition and availability of trace nutrients. The primary production data are from TWAP based on OC-CCIv2 over the period 1997-2012.

The results of the EP and CP impact were validated on interannual to decadal time-scales by using 35-year reanalysis products of SST, SAT, precipitation and wind. The regression coefficients of the EP and CP impact for two periods 1979-2014 and 1997-2012, corresponding to the OC-CCIv2 period, were estimated and showed similar spatial patterns and frequency distributions for all the physical variables studied. This indicates that the results presented for the shorter period 1997-2012 are not skewed to the 1997-1998 EP El Niño event, and that the impact patterns are stable over multi-decadal time scales (35-year), at least for the physical variables of surface air temperature, SST, precipitation, and wind. Since phytoplankton dynamics are at the mercy of these physical conditions, it can be postulated that the inference may also hold for the biological variable of phytoplankton chlorophyll and primary production.

Main achievements

Satellite applications – Development of phenological metrics

The reproductive success of marine species and their availability to fisheries is affected by the variability in phytoplankton phenology. To support ecosystem-health assessment and help identify risks and opportunities for fisheries, novel, state-of-the-art phenology algorithms based on OC-CCI Chlorophyll product have been developed, for the global oceans (Racault et al., 2017a), and for regional ecosystems of the Gulf of Aden (Gittings et al., 2017), the Ivorian continental shelf waters (Kassi et al., in prep.), and the Mediterranean Sea (Salgado et al., in prep.). Furthermore, an innovative assessment of ecosystem model skills has been performed to reproduce phenological metrics of probability of occurrence of one to two phytoplankton blooms per year. This method has been applied to the OC-CCI data to estimate the phenological metrics and the results compared with the model simulations of four ecosystem models: MEM (an ocean-ice-ecosystem model, available from MAREMIP), and HadGEM2 (a fully coupled Earth system model, available from MAREMIP), and NASA Ocean Biogeochemical Model (NOBM) (which assimilates satellite Chl, provided by C. Rousseaux NASA).

Climate impact assessment on oceanic primary producers
As the diversity and frequency of extreme El Niño events are projected to increase under climate warming, a first and important assessment of the impact of El Niño variability on phytoplankton chlorophyll and primary production has been carried out in the global oceans using climate-quality controlled satellite data products (Racault et al., 2017b). The influence of El Niño on phytoplankton phenology has also been evaluated, and the underlying physical forcing conditions have been further analysed based on satellite SST-CCI and SL-CCI and reanalysis products of winds (Racault et al., 2017a, 2017b). This work improves the mechanistic understanding of the impact of El Niño variability on oceanic phytoplankton, and can support mitigation and adaptation plans for ocean resources-dependent societies.

Publications, Climate reports, Conference abstracts
Five original papers (including two as first author) have been published in high-profile peer-reviewed journals (Impact Factors ranging from 4 to 7.4). A further two papers are in preparation, and one is in review as part of IOCCG book chapter. The detailed publications list is provided below. Novel contributions have been provided to the Ocean-Colour CCI Climate Assessment Report Phase II, i.e. chapters "OC-CCI data to study variability in phytoplankton and production, in relation to El Niño", "Phenological responses to ENSO in the global oceans", and "Use of OC-CCI data in regional phenology studies". Finally, the research findings have been presented at two ESA CCI Collocation meetings in 2016 and 2017, three OC-CCI Progress Meetings, the ESA Living Planet Symposium in 2017, and the ESA Colour and Light in the Ocean from Earth Observation international workshop in 2017.

Further activities
Building on the successful results of this ESA fellowship, I have successfully applied and obtained a prestigious Japan Society for the Promotion of Science (JSPS) invitational fellowship to study the influence of the Ningaloo Niño/Niña regional climate mode on phytoplankton dynamics in the southern subtropical Indian Ocean. The JSPS fellowship will be held for four months at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) in Yokohama, Japan.
In addition, I have also successfully applied and obtained funding to organise an international Training Course on "Ocean-Colour Data in Climate Studies" for 32 PhD researchers and Early Career Scientists. The course will be delivered at the PML in collaboration with scientists from the OC-CCI team. We will introduce and provide tools to work with the ESA CCI Ocean-Colour products. I will present methods to analyse climate impacts that I have developed during the ESA fellowship. This course will give excellent visibility and allow knowledge transfer from the OC-CCI project and the ESA fellowship.

Publications

Published peer-reviewed

1. **Racault, M.-F.**, Sathyendranath, S., Brewin, R.J.W., Raitsos, D.E., Jackson, T., Platt, T. (2017) Impact of El Niño Variability on Oceanic Phytoplankton. Frontiers in Marine Science, doi:10.3389/fmars.2017.00133.
2. **Racault, M.-F.**, Sathyendranath, S., Menon, N., Platt. T. (2016) Phenological responses to ENSO in the global oceans. Surveys in Geophysics, 38: 277. doi:10.1007/s10712-016-9391-1.
3. Meyssignac, B., Piecuch, C.G., Merchant, C.J., **Racault, M.-F.**, Palanisamy, H., MacIntosh, C., Sathyendranath, S., Brewin, R.W.J. (2016) Causes of the Regional Variability in Observed Sea Level, Sea Surface Temperature and Ocean Colour Over the Period 1993–2011. Surveys in Geophysics, 38: 187. doi:10.1007/s10712-016-9383-1.
4. Gittings, J.A., Raitsos, D.E., **Racault, M.-F.**, Brewin, R.W.J., Pradhan, Y., Sathyendranath, S., Platt, T. (2017) Seasonal phytoplankton blooms in the Gulf of Aden revealed by remote sensing. Remote Sensing of Environment, 189: 56-66. doi: 10.1016/j.rse.2016.10.043.
5. Rêve, A-H, Alvain, S, **Racault, M-F**, Dessailly, D, Guiselin, N, Jamet, C, Vantrepotte, V, Beaugrand, G (2017) Estimation of the potential detection of diatom assemblages based on ocean color radiance anomalies in the North Sea. Frontiers in Marine Science, 4:408, doi:10.3389/fmars.2017.00408

<u>*Submitted or in preparation*</u>

6. **Racault, M.-F.**, Uncertainties in Phenology studies, in the chapter on Requirements from different Applications of Ocean Colour Data, for the International Ocean Colour Coordinating Group (IOCCG) book on Uncertainties in Ocean Colour Remote Sensing, eds. F. Mélin and S. Dutkiewicz, Submitted.
7. Kassi, J.-B., **Racault, M.-F.**, Mobio, B.A., Platt, T., Sathyendranath, S., Raitsos, D.E., Affian, K. Biophysical drivers of *Sardinella aurita* in Ivorian waters: Applications from remote-sensing observations and GIS, Remote-Sensing, In preparation.
8. Salgado-Hernanz, P.M., **Racault, M.-F.**, Font-Muñoz, J.S., Basterretxea, G. Trends in phytoplankton phenology in the Mediterranean Sea, Remote-Sensing, In preparation.

References

Hoegh-Guldberg, O, Cai, R, Brewer, PG et al. (2014) The Ocean. In Field, C.B., et al. (eds) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY, USA: Cambridge University Press.

González Taboada F, Anadón R (2014). Seasonality of North Atlantic phytoplankton from space: Impact of environmental forcing on a changing phenology (1998– 2012). Global Change Biology doi:10.1111/gcb.12352

Gregg WW & Casey NW (2007) Sampling biases in MODIS and SeaWiFS ocean chlorophyll data. Remote Sens Environ 111:25–35.

Gregg WW & Rousseaux CS (2014) Decadal trends in global pelagic ocean chlorophyll: A new assessment integrating multiple satellites, in situ data, and models. J Geophys Res doi: 10.1002/2014JC010158.

IPCC, 2013: Summary for Policymakers. In Stocker, T.F., D. Qin, G.-K. Plattner, et al. (eds) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY, USA: Cambridge University Press.

Kao H-Y, Yu J-Y (2009) Contrasting Eastern-Pacific and Central-Pacific Types of ENSO. J. Climate 22:615–632.

Lin H, Derome JA (1998) three-year lagged correlation between the North Atlantic Oscillation d winter conditions over the North Pacific and North America, Geophys. Res. Lett. 25:2829–2832.

Longhurst, A. (1998) Ecological Geography of the Sea. Academic Press, California.

Nieto K, Mélin F (2017) Variability of chlorophyll-a concentration in the Gulf of Guinea and its relation to physical oceanographic variables, Prog Oceanogr. doi:10.1016/j.pocean.2016.11.009.

Platt T, Sathyendranath S, White GN, Fuentes-Yaco C, Zhai L, Devred E, Tang C (2009) Diagnostic properties of phytoplankton time series from remote sensing. Estuar. Coasts 33:428–439.

Racault M-F, Le Quéré C, Buitenhuis E, Sathyendranath S, Platt T (2012) Phytoplankton phenology in the global ocean. Ecol. Indic. 14:152–163.

Racault M-F, Sathyendranath S, Platt T (2014) Impact of missing data on the estimation of ecological indicators from satellite ocean-colour time-series. Remote Sensing of Environment, doi10.1016/j.rse.2014.05.016.

Racault M-F, Raitsos DE, Berumen M, Sathyendranath S, Platt T, Hoteit I (2015). Phytoplankton phenology indices in coral reef ecosystems: application to ocean-colour observations in the Red Sea. Remote Sens. Environ. 160:222–234.

Sathyendranath S, Krasemann H (2014) Climate Assessment Report: Ocean Color Climate Change Initiative (OC-CCI) – Phase One http://www.esa-oceancolor-cci.org/?q=documents

Volpe, G., Santoleri, R., Vellucci, V., Ribera d'Alcalà, M., Marullo, S., D'Ortenzio, F., 2007. The colour of the Mediterranean Sea: Global versus regional bio-optical algorithms evaluation and implication for satellite chlorophyll estimates. Remote Sens. Environ. 107, 625–638. doi:10.1016/j.rse.2006.10.017

Yu J-Y, Zou Y, Kim ST, Lee T (2012) The changing impact of El Niño on US winter temperatures, Geophys. Res. Lett. 39:L15702.