SWINGS Bloom Phenology Methods

Satellite-derived chl-a concentrations were obtained from the European Space Agency ocean colour climate change initiative (OC-CCI; https://esa-oceancolour-cci.org; (Sathyendranath et al. 2019) at 4 km and 8 day resolution (v6.0). Analyses covered the period from 01/01/1998 – 30/06/2022. To reduce missing data, chl-a values were first regridded to a regular 25 km grid through bilinear interpolation using the xESMF Python package (Zhuang 2018). The remaining gaps were filled by applying a linear interpolation scheme in sequential steps of longitude, latitude and time (Racault et al. 2014) using a three-point window. If one of the points bordering the gap along the indicated axis was invalid it was omitted from the calculation, whilst if two surrounding points were invalid then the gap was not filled. Finally, the data were smoothed by applying a moving average filter of the previous and next timestep. For more details on this method see Salgado-Hernanz et al. (2019).

Phenological indices

Phytoplankton blooms typically manifest as a seasonal cycle, with a bloom initiation that identifies the timing of the ramp up in phytoplankton growth and biomass accumulation followed by bloom peaks within the growing season (which could be multiple) and finally the bloom termination, which defines the end of the growing season (Siegel et al. 2002; Greve et al. 2005; Sharples et al. 2006; Vargas et al. 2009; Henson et al. 2009; Thomalla et al. 2011; Racault et al. 2012). The calculation of the phenological indices of bloom initiation, termination and duration are detailed below (Thomalla et al. 2011, 2015; Brody et al. 2013).

(i) Bloom maximum: The climatological date of the bloom maximum was identified for every pixel.

(ii) Individual year bloom peaks were then identified using the climatological mean ±6 months.

(iii) Bloom slices were created by using the timing of the bloom maximum ±6 months.

(iv) Multiple bloom peaks were defined as a second, third, or nth local maxima where the chl-a concentration reached at least 75% of the amplitude of the bloom maximum and were a minimum of 24 days (i.e., 3 x 8-day time intervals) away from the maximum peak. The additional peaks were identified with the Python SciPy

(Virtanen et al. 2020) function ‘find_peaks’. The timing of these peaks and the number per pixel are recorded for every year.

(v) With the identification of the bloom peaks the initiation bloom slice was created as the first bloom peak – 6 months. The termination bloom slice was created as the last bloom peak + 6 months. If only 1 peak was identified (i.e., the maximum bloom peak) then the bloom slice is centred around it.

(vi) Bloom initiation was calculated using three methods:

   a. Threshold method: the first date after the pre peak minimum that the chl-a concentration was greater than the minimum chl-a concentration plus 5% of the chl-a range.
   b. Cumulative Sum method: the first date the cumulative chl-a concentration was greater than 15% of the total cumulative chl-a.
   c. Rate of change method: the first date the chl-a rate of change was greater than 15% of the median chl-a rate of change.

(vii) Bloom termination was calculated using the same methods as above using the termination bloom slice.

(viii) Bloom duration was calculated as the number of days between the bloom initiation and termination dates.

(ix) Integrated bloom chl-a was calculated using the NumPy (Harris et al. 2020) trapezoidal function as the chl-a concentration integrated between the bloom initiation and termination dates.

(x) Mean bloom chl-a was calculated between the bloom initiation and termination dates.

Included in the file is the mean of all three methods. The cyclical nature of the calendar poses a significant issue that needs to be addressed when calculating means of phenological indices. For example, we need to avoid a situation where the mean bloom initiation between 1 method with a bloom in December (e.g., day of year = 340) and another method with a bloom in January (e.g., day of year = 10) is incorrectly calculated as an average bloom initiation date in June (e.g., day of year = 175). To account for this, we used the Python SciPy (Virtanen et al. 2020) function ‘circmean’ which calculates circular means for samples in a range (correct mean = day of year 357).

References

Brody, S. R., M. S. Lozier, and J. P. Dunne. 2013. A comparison of methods to determine phytoplankton bloom initiation. J Geophys Res Oceans **118**: 2345–2357. doi:https://doi.org/10.1002/jgrc.20167

Greve, W., S. Prinage, H. Zidowitz, J. Nast, and F. Reiners. 2005. On the phenology of North Sea ichthyoplankton. ICES Journal of Marine Science **62**: 1216–1223. doi:10.1016/j.icesjms.2005.03.011

Harris, C. R., K. J. Millman, S. J. van der Walt, and others. 2020. Array programming with NumPy. Nature **585**: 357–362. doi:10.1038/s41586-020-2649-2

Henson, S. A., J. P. Dunne, and J. L. Sarmiento. 2009. Decadal variability in North Atlantic phytoplankton blooms. J Geophys Res Oceans **114**. doi:10.1029/2008JC005139

Racault, M. F., C. le Quéré, E. Buitenhuis, S. Sathyendranath, and T. Platt. 2012. Phytoplankton phenology in the global ocean. Ecol Indic **14**: 152–163. doi:10.1016/j.ecolind.2011.07.010

Racault, M.-F., S. Sathyendranath, and T. Platt. 2014. Impact of missing data on the estimation of ecological indicators from satellite ocean-colour time-series. Remote Sens Environ **152**: 15–28. doi:https://doi.org/10.1016/j.rse.2014.05.016

Salgado-Hernanz, P. M., M.-F. Racault, J. S. Font-Muñoz, and G. Basterretxea. 2019. Trends in phytoplankton phenology in the Mediterranean Sea based on ocean-colour remote sensing. Remote Sens Environ **221**: 50–64. doi:https://doi.org/10.1016/j.rse.2018.10.036

Sathyendranath, S., R. J. W. Brewin, C. Brockmann, and others. 2019. An Ocean-Colour Time Series for Use in Climate Studies: The Experience of the Ocean-Colour Climate Change Initiative (OC-CCI). Sensors **19**. doi:10.3390/s19194285

Sharples, J., O. N. Ross, B. E. Scott, S. P. R. Greenstreet, and H. Fraser. 2006. Inter-annual variability in the timing of stratification and the spring bloom in the North-western North Sea. Cont Shelf Res **26**: 733–751. doi:https://doi.org/10.1016/j.csr.2006.01.011

Siegel, D. A., S. C. Doney, and J. A. Yoder. 2002. The North Atlantic spring phytoplankton bloom and Sverdrup's critical depth hypothesis. Science (1979) **296**: 730–733. doi:10.1126/science.1069174

Thomalla, S. J., N. Fauchereau, S. Swart, and P. M. S. Monteiro. 2011. Regional scale characteristics of the seasonal cycle of chlorophyll in the Southern Ocean. Biogeosciences **8**: 2849–2866. doi:10.5194/bg-8-2849-2011

Thomalla, S. J., M. Racault, S. Swart, and P. M. S. Monteiro. 2015. High-resolution view of the spring bloom initiation and net community production in the Subantarctic Southern Ocean using glider data. ICES Journal of Marine Science **72**: 1999–2020. doi:10.1093/ICESJMS/FSV105

Vargas, M., C. W. Brown, and M. R. P. Sapiano. 2009. Phenology of marine phytoplankton from satellite ocean color measurements. Geophys Res Lett **36**. doi:https://doi.org/10.1029/2008GL036006

Virtanen, P., R. Gommers, T. E. Oliphant, and others. 2020. SciPy 1.0: fundamental algorithms for scientific computing in Python. Nat Methods **17**: 261–272. doi:10.1038/s41592-019-0686-2

Zhuang, J. 2018. xESMF: Universal Regridder for Geospatial Data.