

Case Study 11

Spring Algal Bloom and Haddock Larvae Survival on the Scotian Shelf (Northwest Atlantic)

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11.1 Background Information

According to the Hjort-Cushing match-mismatch hypothesis (Hjort 1914; Cushing 1974; 1990), the survival rate of fish and invertebrate larvae is a function of the match between the timing of the hatching of the eggs and the timing of the spring phytoplankton bloom. Testing such a hypothesis has been possible only with the advent of remotely-sensed data, which provides information at the appropriate scales of time and space (Platt et al., 2007). These types of data offer the opportunity to characterize the spring bloom with respect to the timing of initiation, the amplitude of the bloom, the duration of the bloom, and the timing (phase) of the bloom (Figure 11.1). These properties can be calculated for all pixels in the region of interest, in such a way that all spatial structure is preserved. The statistical moments of all of these properties, and their variation between years, can also be calculated and the results used to analyze the effect of ecosystem fluctuations on exploited stocks. The case study presented here shows the relationship between the phytoplankton bloom characteristics computed from remotely-sensed images and haddock (*Melanogrammus aeglefinus*) larvae survival on the Canadian Scotian shelf (Platt et al., 2003).

To understand this example, we will demonstrate how to generate a time-series of satellite ocean-colour images from different sensors, and will also show how to compute a climatology (temporal average) as well as the anomalies (deviation from the normal). Finally, we exemplify the association of these results with independent time-series data (non-satellite), on the larvae survival normalized by the spawning stock. The study area is the "Canadian Atlantic Zone", on the eastern seaboard of

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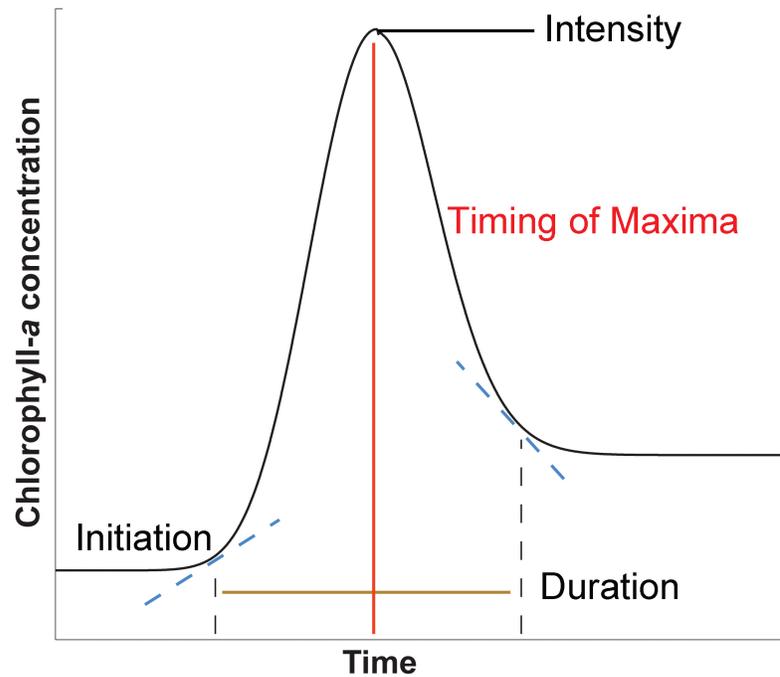


Figure 11.1 Characteristics of the phytoplankton spring bloom: the maximum observed chlorophyll-*a* concentration (an index of phytoplankton biomass) referred to as the intensity; the weeks elapsed since beginning of February when the biomass first exceeded 20% of the maximum (bloom initiation); the weeks elapsed when the maximum intensity occurred (bloom timing); and the period during which the biomass remained above the 20% threshold (bloom duration).

Canada (Figure 11.2).

11.2 Materials and Methods

The ocean-colour images for the original work mentioned in this example (Platt et al., 2003) were captured and processed at the Bedford Institute of Oceanography. Currently, these images can be downloaded freely from the Internet at the sites given below.

Chlorophyll concentration was estimated from three different ocean-colour sensors: Coastal Zone Color Scanner (CZCS), POLarization and Directionality of the Earth's Reflectances (POLDER-1), and Sea-viewing Wide Field-of-view Sensor (SeaWiFS). Data from CZCS and SeaWiFS are available from NASA's Ocean Color website (<http://oceancolor.gsfc.nasa.gov/>). POLDER images are available from the French space agency CNES (<http://polder.cnes.fr/en/index.htm>), and the Japan Aerospace Exploration Agency (JAXA), (<ftp://ftp2.eorc.jaxa.jp/pub/ADEOS/OCTS/GAC3BM/Ver5/CHL0/daily/>).

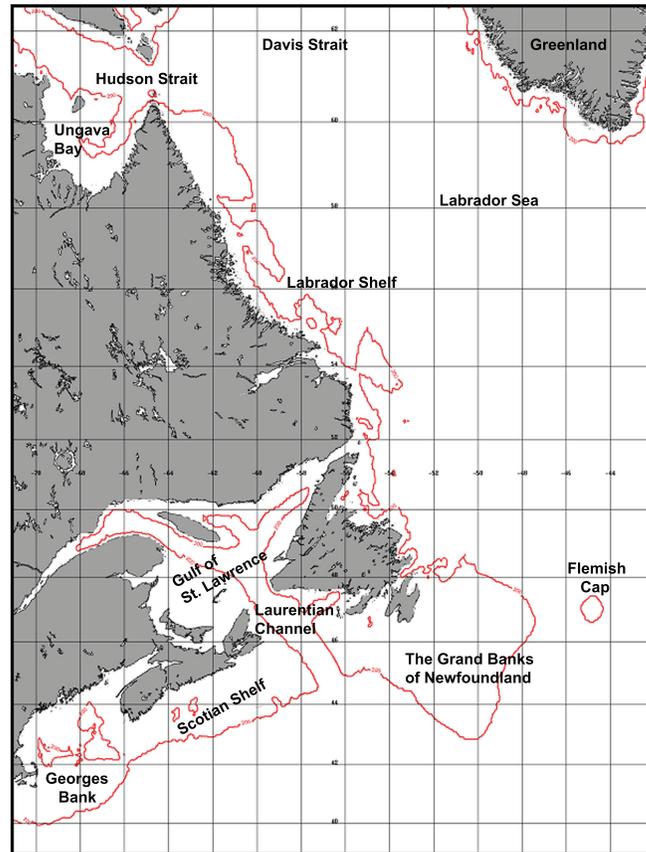


Figure 11.2 The Canadian Atlantic Zone (39°N to 62.5°N and 42°W to 71°W). The 200 m isobath is also indicated.

Current CZCS Level-2 images on the NASA website are computed using the OC3 algorithm from O'Reilly et al. (2000), but tuned for bands at 443, 520, and 550 nm. This sensor provided data for the period between 1979 and 1981 of the example shown here. The current POLDER chlorophyll algorithm uses a bio-optical algorithm with three wavelengths (443, 490 and 565 nm), customized for POLDER data (Loisel et al., 2005). POLDER images for 1997 were used for this exercise. The OC4V4 algorithm is used for SeaWiFS for the interval from 1998 to 2001. Note that NASA has maintained the flow of SeaWiFS data until the present time (May 2010).

In all cases, the algorithms were applied to individual images after selection of cloud free pixels, and stratospheric and atmospheric corrections. Finally, the images were mapped to Mercator projections. The time-series for the study area was created by combining individual satellite passes to make weekly composite images with a nominal spatial resolution of 1 km per pixel. The temporal window used for the phytoplankton bloom characteristics is from February to September. Here we show only half-month composite images for the period mentioned (Figure 11.3).

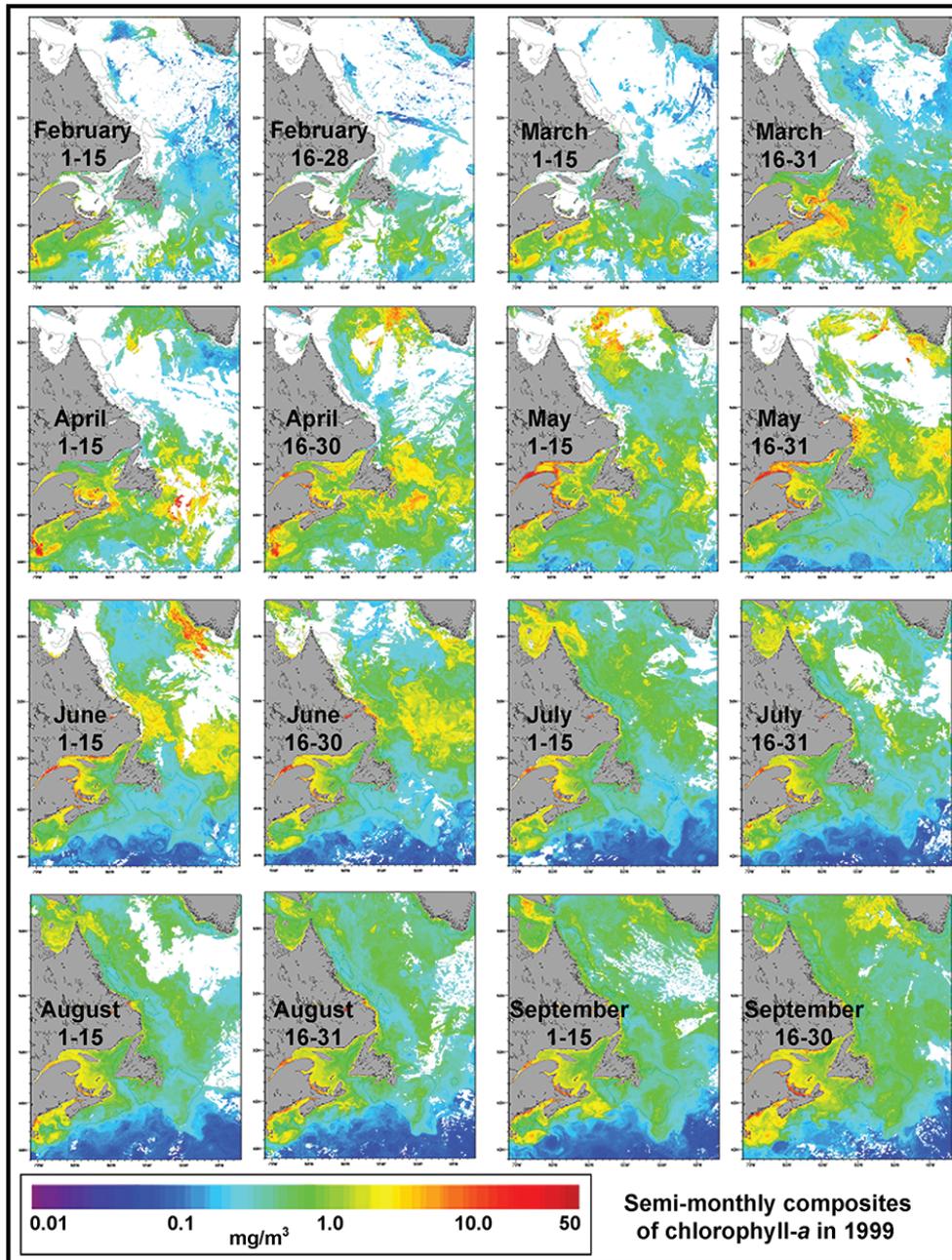


Figure 11.3 Time-series of concentration of chlorophyll-*a* (mg m^{-3}), for the Canadian Atlantic Zone created by combining satellite individual passes to make half-month composite images with a nominal spatial resolution of 1 km per pixel. The temporal window is delimited between February and September 1999.

11.3 Demonstration

11.3.1 Characterization of the phytoplankton bloom

The phytoplankton bloom can be characterized for each of the following ecosystem properties: maximum intensity, initiation, timing of maximum and duration of the bloom. To begin this process, load your 12 semi-monthly images shown in Figure 11.3, using your preferred software (SeaDAS, PCI, ENVI, etc.). For every pixel:

- a) Compute the maximum observed chlorophyll-*a* concentration (an index of phytoplankton biomass) referred to as the intensity.
- b) Compute the bloom initiation by counting the weeks elapsed since beginning of February when the biomass first exceeded 20% of the maximum.
- c) Compute the bloom timing, i.e. the weeks elapsed until the maximum intensity occurred.
- d) Compute the bloom duration, i.e. the period during which the biomass remained above the 20% threshold (bloom duration).

Figure 11.4 shows the spatial distribution of these indices in the study area, corresponding to the time-series between February and September 1999. The ecological indicators can be evaluated for all years in the time-series using data from all the satellite sensors, and the climatology (long-term average) can also be computed (Figure 11.5). The indices can be estimated for every pixel in the composite images, preserving all spatial structure in the fields.

The anomalies (deviations from the normal) for these ecological properties can be computed for particular years, i.e. the indices of the bloom can be calculated for individual years and compared with the climatological average (i.e. for every pixel, the difference between individual years minus the long-term mean value). In this way, it is possible to assess inter-annual variations in properties and also to evaluate whether, in a particular year, events are retarded or advanced compared with the mean. Anomalies for the timing of the maximum chlorophyll concentration can be seen for the years 1998 to 2001 in Figure 11.6. We used local anomalies, i.e. the climatology was calculated separately for each of the three sets of ocean-colour data: CZCS (1979-1981), and POLDER (1997) and SeaWiFS (1998-2001), and the anomalies in each set were calculated from the appropriate climatology.

11.3.2 Test of the match/mismatch hypothesis

The indices derived from the remotely-sensed time-series can be used to evaluate the effect of ecosystem fluctuation on exploited stocks (Platt et al., 2003). The operational test of the match/mismatch hypothesis is assessed under the null hypothesis that 'between-year' variance in recruitment is independent of fluctuations in the properties of the spring bloom. The time-series of the timing of the bloom was compared to an independent data series of haddock (*Melanogrammus aeglefinus*) recruitment, collected on the continental shelf off Nova Scotia. This is a 31-year time

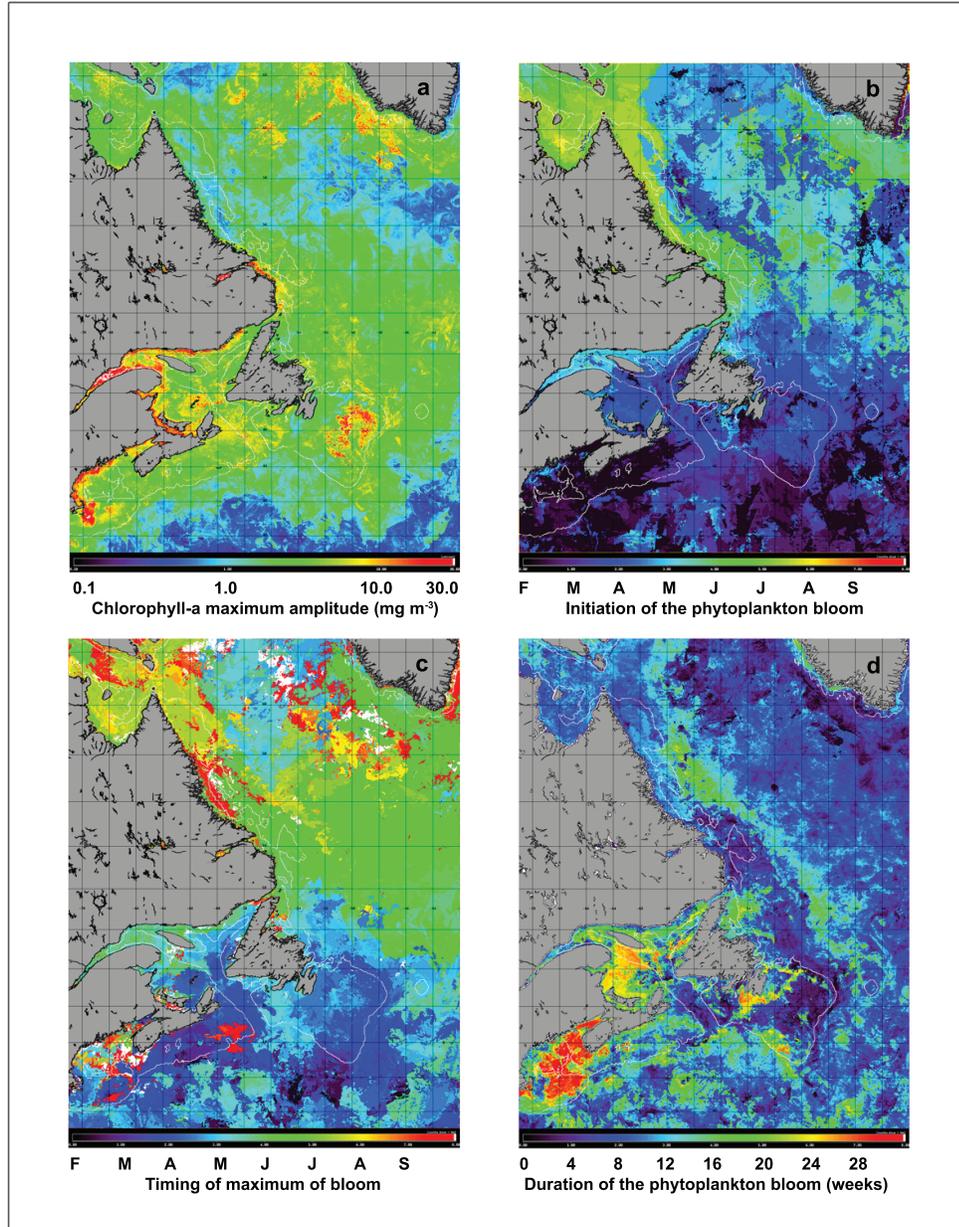


Figure 11.4 Spatial distribution of the ecological indices for phytoplankton blooms in the Northwest Atlantic for the year 1999: a) intensity, b) initiation, c) timing, and d) duration.

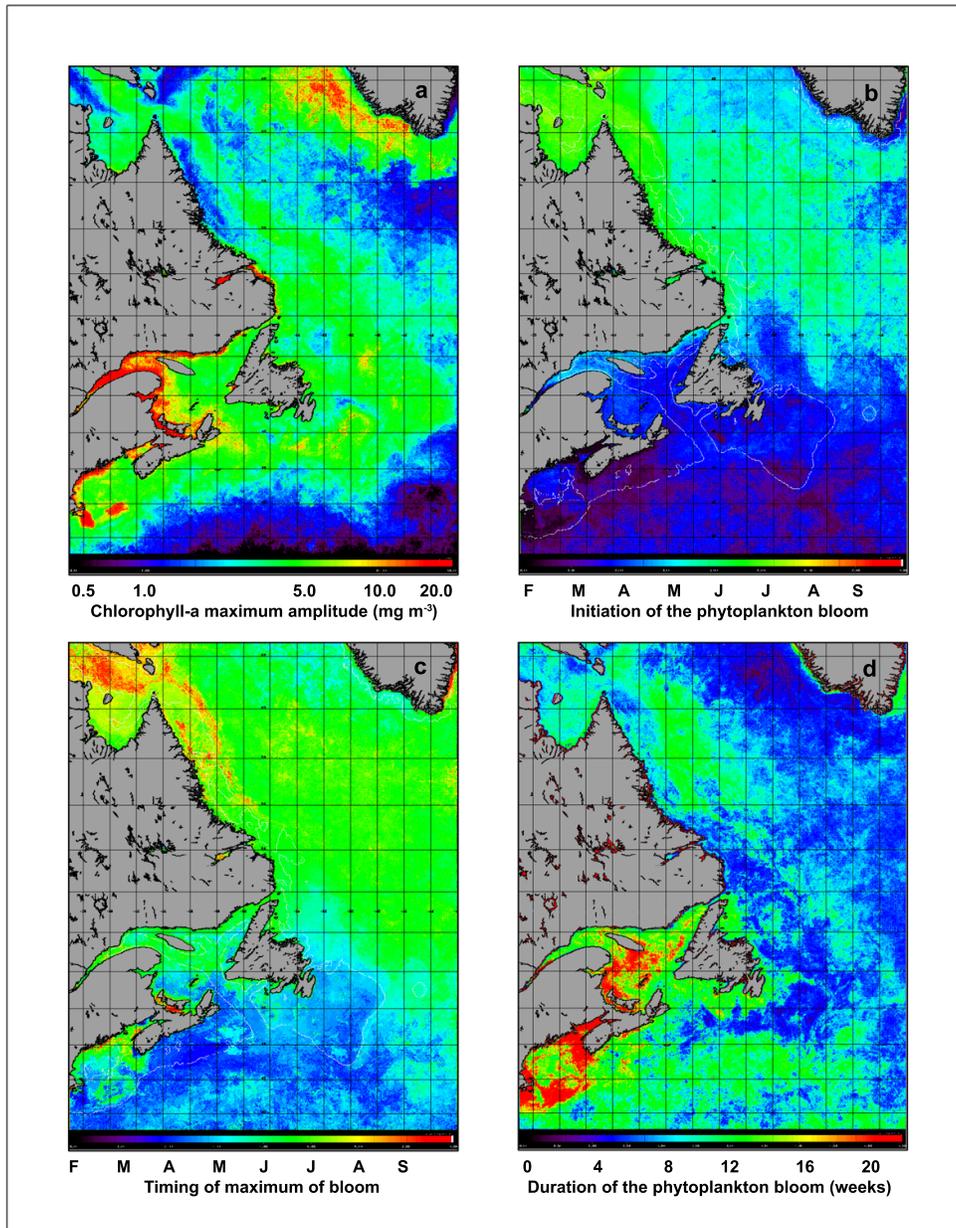


Figure 11.5 Climatology of ecological indicators for the period between 1998 and 2001: a) intensity, b) initiation, c) timing, and d) duration.

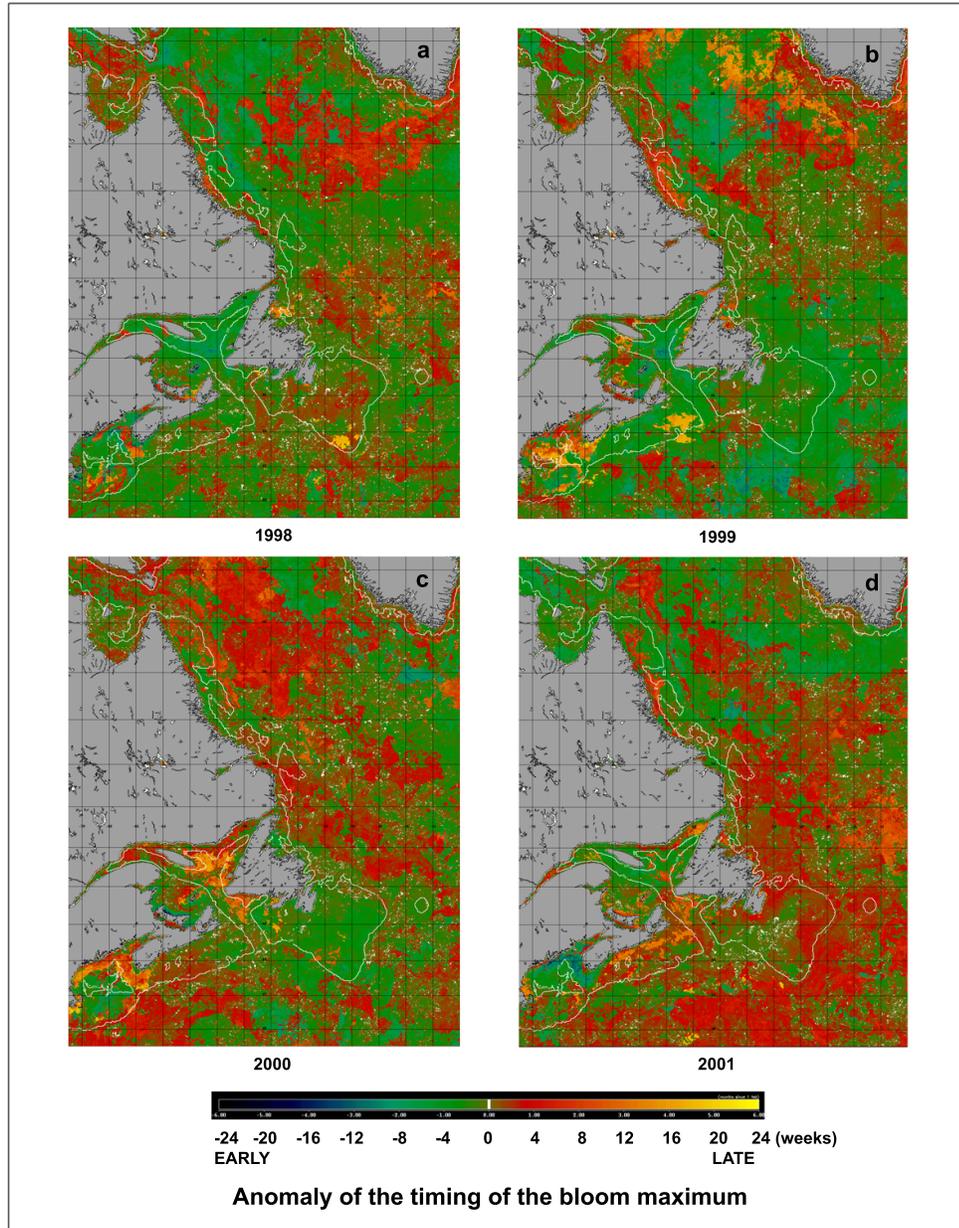


Figure 11.6 Anomalies of the bloom timing (weeks elapsed when the maximum intensity occurred) for the years 1998 to 2001.

series (1970 - 2001) in which two years stand out as having produced exceptional year classes (Figure 11.7). For both years (1981 and 1999), remotely-sensed data of timing of maxima were available. The climatology of the timing of the chlorophyll-*a* maximum concentration from 1998 to 2001 is shown in Figure 11.5c.

For the study area described in Platt et al. (2003), the recruitment of haddock, normalized to biomass of the spawning stock, was highly correlated with the timing of the bloom. Early blooms were associated with better recruitment. The two exceptional year classes occurred in years with unusually early spring blooms. As a consequence, the null hypothesis was rejected. Anomalies of bloom timing accounted for 95% of the variance in normalized recruitment of haddock under a quadratic model (Figure 11.8).

The results shown in this example argue for the importance of a trophic link between phytoplankton and fish stocks, especially the importance of fluctuations between years at the autotrophic level. The tentative explanation advanced for the result was that, for species with protracted spawning (such as haddock), an early spring bloom would confer enhanced survival on early larvae because the larvae will have adequate food supply.

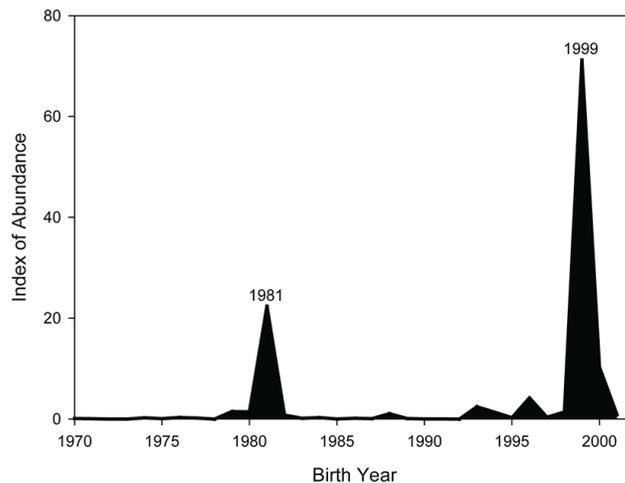


Figure 11.7 Time-series of haddock (*Melanogrammus aeglefinus*) at age-0, sampled on the continental shelf off Nova Scotia between 1970 and 2001.

11.4 Training

In this section you will visualize some examples before making your own time-series to compute the ecological indices. Figure 11.3 represents a time-series of chlorophyll-*a* concentration between February and September 1999 in the northwestern Atlantic Canada region. Each composite image is averaged over a ~15 day period with a nominal spatial resolution of 1 km per pixel. This time-series is used to compute the

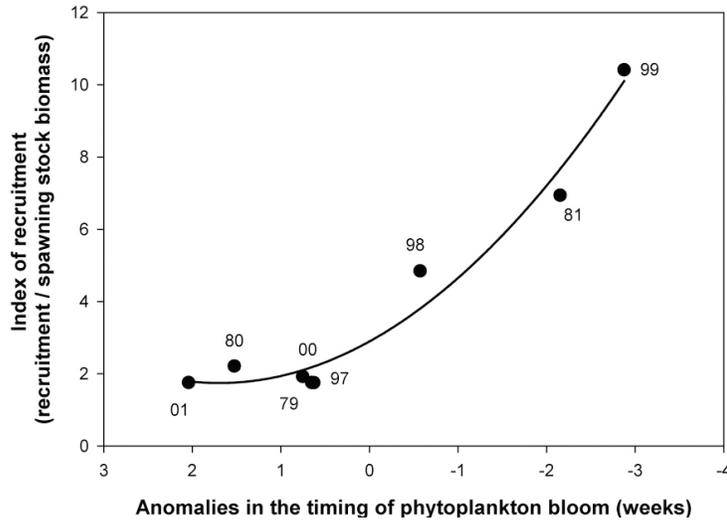


Figure 11.8 Quadratic regression of the recruitment of haddock, normalized to biomass of the spawning stock, with the data of timing of the phytoplankton bloom. Anomalies of bloom timing accounted for 95% of the variance in recruitment of haddock.

ecological indices, described in detail in the text, and illustrated in Figure 11.1. Figure 11.4 shows the ecological indices derived from the phytoplankton bloom in the study area for 1999. The image 11.4a represents the maximum amplitude of chlorophyll concentration (intensity). The most frequent values fluctuate between 1.0 and 10 mg m^{-3} , with areas of higher concentration in the Georges Banks and the Grand Banks of Newfoundland. The Gulf Stream can be identified in the southern part of the study area as the region with relatively low chlorophyll values. It is important to observe that in some coastal regions that are influenced by high river runoff or intense tides, the standard chlorophyll algorithms do not produce viable results as they are affected by the high concentration of detritus, sediments and yellow substances. These waters are referred to as "Case-2" waters and are characterized by an optical signature dominated by substances other than chlorophyll-*a* (e.g. sediments, yellow substances). The resulting estimates of pigment concentration are frequently overestimated in these waters. Figure 11.4b characterizes the onset of an algal bloom, showing the process advancing from south to north. Note that in some northern regions (Davis Strait and western Greenland) the bloom initiation is relatively early in the year, compared with the rest of the region. Typically, the bloom starts later on the continental shelf of Labrador because of winter-ice that delays the event. Figure 11.4c describes the time required to reach the maximum concentration of chlorophyll. The spatial patterns of the ecological index are related to those of the bloom initiation, but they have a time lag determined by local conditions. Figure 11.4d shows the phytoplankton bloom duration. In general, in the northern regions the duration of the bloom is shorter than in southern areas. However, some areas

in the north also maintain significant concentrations of phytoplankton for several months.

Figure 11.5 shows the average (climatology) of ecological indices for the period between 1998 and 2001. Note that the averaging of several years of data moderates the outlier values that are seen in the one-year images (Figure 11.4). Figure 11.5a shows the maximum amplitude of chlorophyll concentration. High values (between 2.0 and 10 mg chlorophyll m^{-3}) occur over the continental shelves and the lower values are in open sea areas. Figure 11.5b displays the onset of the algal bloom and shows a significant front north of Newfoundland. Note how the phytoplankton in the region to the south of this geographical division start to increase well before the northern zone. Figure 11.5c shows the timing of maximum bloom concentration and is closely associated with the initiation of the bloom. However, the front observed in the previous image is less obvious and in fact, some southern regions tend to reach the bloom maximum relatively late. Enlarge the coastal area of central Nova Scotia for a close analysis of the study area of Platt et al. (2003). These data represent weekly measurements averaged from February to September, between 1998 and 2001. Observe that the continental shelf's central region reached the highest concentration of chlorophyll earlier than the western areas. In this region the turbulence due to vertical mixing by tides (the most intense in the world) prevents early stratification of the mixed layer, thus delaying the phytoplankton blooming. The image 11.5d characterizes the duration of the phytoplankton bloom, and clearly illustrates the shorter bloom duration in several parts of the northern study area compared with the southern areas. Note that the northwestern region also exhibits longer blooms, a critical fact for higher trophic strata.

The maps in Figure 11.6 correspond to the anomalies of the timing of maximum concentration of chlorophyll in the years 1998 to 2001. Green colours indicate the pixels where the chlorophyll maximum was reached sooner than the 5-year average, while red colours represent areas where the bloom peaked later than expected. This ecological metric is important for basic research and more directed purposes in several areas such as ecology, oceanography, fisheries, etc. In the present case-study, it is useful to understand that an early phytoplankton bloom can diminish the number of larvae that may suffer from starvation. However, larval stages of different species may not all benefit from an early bloom; some species such as the northern shrimp (*Pandalus borealis*) seem to benefit if the phytoplankton bloom is delayed until the surface waters warm (explore Further Readings).

11.5 Questions

Q 1: Why do we find such apparent high chlorophyll concentrations in the St. Lawrence River and in the southern Gulf of St. Lawrence in Figure 11.3?

Q 2: What approach was used to circumvent the bias introduced by the use of different platforms to construct such a long time-series of ocean-colour data?

Q 3: In Figure 11.4a, why is the peak of chlorophyll concentration during the spring bloom higher over Georges Bank and Grand Banks, and what is the ecological significance.

Q 4: Is it always advantageous for fish larvae to have an early phytoplankton bloom?

11.6 Answers

A 1: The standard chlorophyll algorithms developed for Case-1 waters are affected by high concentrations of detritus, sediments and yellow substances which may dominate the optical signature in coastal Case-2 waters. Thus the chlorophyll concentration estimated using standard Case-1 water algorithms in these waters may be biased. More complex algorithms are required to discriminate the various components in coastal waters. For example, neural network analysis is used to retrieve concentrations of phytoplankton pigment (Algal Pigment Index II), suspended matter and yellow substances from MERIS data. For further information, see the MERIS Product Handbook (<http://envisat.esa.int/handbooks/meris/>) and the Algorithm Theoretical Basis Document 2.12 (ATBD) (http://envisat.esa.int/instruments/meris/pdf/atbd_2_12.pdf).

A 2: The climatologies were calculated separately for each of the three time-series of ocean-colour data (CZCS, POLDER and SeaWiFS). For each mission, the anomalies were calculated in relation to the appropriate climatology, resulting in a long-term time-series of local anomalies. Moreover, the use of the timing of the bloom, instead of actual pigment concentration at the peak of the bloom, is independent of the algorithm used by each mission to estimate chlorophyll concentration.

A 3: The elevated chlorophyll concentration in these regions is likely supported by the vigorous mixing of the relatively shallow waters by tidal currents. The spring bloom typically begins once the critical depth becomes shallower than the water depth. The high chlorophyll concentration in these two ecosystems supports a large marine community and results in two exceptionally productive environments, with extensive fisheries.

A 4: Not necessarily. It is true that some species require an abundant food supply for their early stages, but other species may not benefit from an early surplus of food. Their life cycle may require other ecological conditions, such as warmer surface water, to take full advantage of the seasonal event.

11.7 References

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11.7.1 Further reading

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