Multiplicative Model for Monthly Chlorophyll Series

Supplementary information for
Patterns and Scales of Phytoplankton Variability in Estuarine-Coastal Ecosystems
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Our analysis of chlorophyll *a* time series from many coastal and estuarine sites around the world demonstrates that the standard deviation of chlorophyll is approximately proportional to the mean, both among and within sites, as well as at different time scales. One consequence is that these monthly time series are well described by a multiplicative seasonal model: $c_{ij} = Cy_i m_j \varepsilon_{ij}$, where c_{ij} is chlorophyll concentration in year i and month j; C is the long-term mean; y_i is the annual effect; m_j is the average seasonal (in this case monthly) effect; and ε_{ij} is the residual series, which we sometimes refer to as the "events" component. The annual effect is simply the annual mean $Y_i = (1/12)\sum_{j=1}^{12} c_{ij}$ divided by the long-term mean: $y_i = Y_i/C$. The average monthly effect is given by $m_j = (1/N)\sum_{i=1}^{N} M_{ij}/Y_i$, where M_{ij} is the value for month j in year i, and N is the total number of years. The events component is then obtained by $\varepsilon_{ij} = c_{ij}/Cy_i m_j$.

The R function `decomp.mult` listed here accomplishes this decomposition. It requires input of a time series matrix in which the columns are monthly time series. It allows missing data, but it is up to the user to decide how many data are sufficient and if the pattern of missing data will lead to bias in the results. If so, it would be advisable to eliminate problem years beforehand by setting all month values to `NA` for those years. Our approach has been to require a minimum number of years (e.g., 8) with a minimum number of months sampled (e.g., 10) in each of these years. In addition, we require that every month, January through December, be sampled a minimum number of times (e.g., 6) during the ≥ 8 years to be analyzed. All other years should have all month values set to `NA`. There are two cases of interest here: one in which the seasonal effect is held constant from year to year, and another in which it is allowed to vary by not distinguishing a separate events component. The choice is made by setting `event=T` or `event=F`, respectively, in the input. If no specific starting or ending year is given, the input data will be extended to cover January of the earliest or December of the latest year, respectively.

The output of this function is a list, each element of which is itself a time series matrix containing the original time series for a single site and its multiplicative model components. The decomposition function is as follows:

```
decomp.mult=function(x, startyr=NULL, endyr=NULL, event=T){
#R2.8.0 3/2/09 4:48 PM
   if(class(x)[1]!='mts')dim(x)=c(length(x),1)
   if(is.null(startyr))   startyr=start(x)[1]
   if(is.null(endyr)) endyr=end(x)[1]
   d=window(x, start=c(startyr,1), end=c(endyr,12), extend=T)
   results=vector('list',dim(d)[2])
   names(results)=colnames(d)
   for(site in colnames(d)){
      d1=d[,site]
      #long-term mean
      grandmean=mean(d1,na.rm=T)
      #annual component
      annualmean=aggregate(d1,1,mean,na.rm=T)
      annualmeanreps=as.vector(t(matrix(rep(annualmean,12), ncol=12)))
      interann=ts(annualmeanreps,s=c(startyr,1),f=12)/grandmean
      #remaining components
      if(event) {
         #monthly component
         d2=matrix(d1,nrow=12)
         monthdev=sweep(d2,2,annualmean,'/')
         monthmean=apply(monthdev,1,mean,na.rm=T)
         season=ts(rep(monthmean,endyr-startyr+1), s=c(startyr, 1),f=12)
         #events component
         resids=sweep(monthdev, 1, monthmean, '/')
         events=ts(as.vector(resids),s=c(startyr,1),f=12)
      }
      else {
         #monthly component
         season=d1/(grandmean*interann)
      }
      #prepare output
      if(event) dcomp=ts.union(d1,grandmean,interann,season, events) else dcomp=ts.union(d1,grandmean,interann, season)
      colnames(dcomp)[1]='original'
      results[[site]]=dcomp
   }
   if(class(x)[1]!='mts') results[[1]] else results
}
```

In the main text, we point out that the average seasonal pattern may not resemble observed seasonality in a given year. Patterns that are highly variable from year to year will result in an average seasonal pattern of relatively low amplitude (i.e., low range of monthly values) compared to the amplitudes in individual years. An average seasonal pattern with high amplitude therefore indicates both high amplitude and a recurring pattern for individual years.

The average seasonal pattern does not provide any information about potential secular trends. A solution is to apply the decomposition to a moving time window. The window should be big enough to yield a meaningful average of interannual variability but short enough to allow a trend to manifest. This may be different for different systems, but a decadal window can be used as a starting point. We illustrate the method using a site from the San Francisco Estuary, USGS station 6, where chlorophyll declined markedly after an invasion of the clam *Corbula amurensis* in 1986 (Alpine and Cloern 1992; Figure 1). The annual mean series clearly preserves the drop that took place from 1986 to 1988 (Figure 1B). And the windowed seasonal means for the first and last 10 years of the series, pre- and post-invasion, show a clearly changed pattern after the clams appeared (Figure 1E versus 1F). Formerly, phytoplankton peaked in summer when residence time increased and allowed their buildup. The invasive clams become active in the warmth of summer and their grazing activity is sufficient to outweigh the summer growth rates of phytoplankton. As a result, the peak biomass now occurs in the spring, although at a much lower level (Figure 1B). Note that the amplitude of the seasonality is approximately the same before and after invasion, despite the change in overall biomass level; only the seasonal pattern changes.

References

Alpine, A. E., and J. E. Cloern. 1992. Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary. *Limnology and Oceanography* 37:946–955.

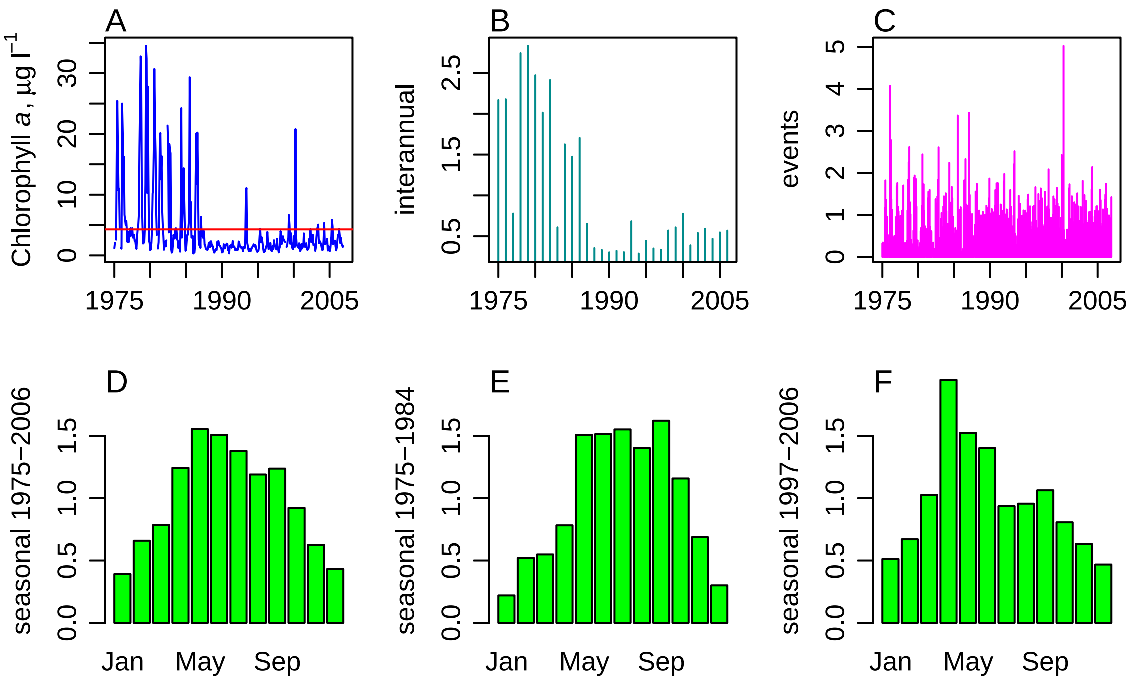

Figure 1: Time series decomposition of monthly mean chlorophyll observations during 1975–2006 at USGS station 6 in the San Francisco Estuary: (A) Original series; *horizontal line,* long-term mean. (B) Annual mean. (C) Monthly residual. (D) Mean seasonal pattern. (E) Mean seasonal pattern for the first 10 years. (F) Mean seasonal pattern for the last 10 years.

Table S1. Data Sets Used by J. E. Cloern and A.D. Jassby, *Estuaries and Coasts* (2009)

Code	Ecosystem	Site	Country	Lat	Long	StartYr	EndYr	Organization	Source
1	Adriatic Sea (North)	SJ103	Croatia	45.0	13.16	1972	2006	Centre for Marine Research, Rudjer Boskovic Institute	Robert Precali
2	Adriatic Sea (North)	SJ107	Croatia	45.0	13.16	1972	2006	Centre for Marine Research, Rudjer Boskovic Institute	Robert Precali
3	Adriatic Sea (North)	SJ108	Croatia	45.0	13.16	1972	2006	Centre for Marine Research, Rudjer Boskovic Institute	Robert Precali
4	Bahia Blanca Estuary	Cuatre	Argentina	-38.8	-62.4	1978	2007	Instituto Argentino de Oceanografia, Universidad Nacional del Sur	Hugo Freije, gmfreije@criba.edu.ar
5	Baltic (northern)	H03	Sweden	58.6	18.2	1981	2006	HELCOM Cooperative Monitoring in the Baltic Marine Environment	http://www.ices.dk/ocean/asp/helcom/helcom.asp
6	Baltic (The Sound)	PQ02	Denmark	55.9	12.8	1974	2006	HELCOM Cooperative Monitoring in the Baltic Marine Environment	http://www.ices.dk/ocean/asp/helcom/helcom.asp
7	Bedford Basin	2	Canada	44.7	-63.7	1970	2006	Bedford Institute of Oceanography	William Li
8	Bilbao Estuary	34-35	Spain	43.4	-3.1	1997	2006	Euskal Herriko Uni bertsitatea	Arantza Iriarte, Fernando Villate, Ibon Uriarte
9	Biscayne Bay	123	US	25.6	-80.2	1996	2007	SERC-FIU Water Quality Monitoring Network; SFWMD/SERC	http://serc.fiu.edu/wqmnetwork/
10	Biscayne Bay	127	US	25.6	-80.2	1994	2007	SERC-FIU Water Quality Monitoring Network; SFWMD/SERC	http://serc.fiu.edu/wqmnetwork/
11	Biscayne Bay	133	US	25.6	-80.2	1993	2007	SERC-FIU Water Quality Monitoring Network; SFWMD/SERC	http://serc.fiu.edu/wqmnetwork/
12	Brest (rade)	Portzic	France	48.4	-4.6	1998	2007	Service d'Observation en Milieu Littoral, INSU-CNRS	http://www.domino.u-bordeaux.fr/somlit_national/
13	Chesapeake Bay	CB1.1	US	37.2	-76.2	1984	2006	Chesapeake Bay Program	http://www.chesapeakebay.net/data_waterquality.aspx
14	Chesapeake Bay	CB4.1C	US	37.2	-76.2	1984	2006	Chesapeake Bay Program	http://www.chesapeakebay.net/data_waterquality.aspx
15	Chesapeake Bay	CB8.1	US	37.2	-76.2	1984	2006	Chesapeake Bay Program	http://www.chesapeakebay.net/data_waterquality.aspx
16	Choptank River Estuary	ET5.1	US	38.8	-75.9	1984	2007	Chesapeake Bay Program	http://www.chesapeakebay.net/data_waterquality.aspx
17	Deep Bay	DM1	Hong Kong	22.3	114.2	1986	2004	Marine Water Quality Monitoring Programme Environmental Protection Department	Kedong Yin
18	Deep Bay	DM5	Hong Kong	22.3	114.2	1986	2004	Marine Water Quality Monitoring Programme Environmental Protection Department	Kedong Yin
19	English Channel Roscoff	Estacade	France	48.7	-4.0	1997	2007	Service d'Observation en Milieu Littoral, INSU-CNRS	http://www.domino.u-bordeaux.fr/somlit_national/
20	Florida Bay	1	US	25.0	-80.7	1991	2007	SERC-FIU Water Quality Monitoring Network; SFWMD/SERC	http://serc.fiu.edu/wqmnetwork/
21	Florida Bay	12	US	25.0	-80.7	1991	2007	SERC-FIU Water Quality Monitoring Network; SFWMD/SERC	http://serc.fiu.edu/wqmnetwork/
22	Florida Bay	19	US	25.0	-80.7	1990	2007	SERC-FIU Water Quality Monitoring Network; SFWMD/SERC	http://serc.fiu.edu/wqmnetwork/
23	Gironde Estuary	Eyrac	France	45.3	-0.7	1997	2007	Service d'Observation en Milieu Littoral, INSU-CNRS	http://www.domino.u-bordeaux.fr/somlit_national/
24	Golfe de Lion	Sola	France	42.5	3.2	1997	2007	Service d'Observation en Milieu Littoral, INSU-CNRS	http://www.domino.u-bordeaux.fr/somlit_national/

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Code	Ecosystem	Site	Country	Lat	Long	StartYr	EndYr	Organization	Source
25	Great Belt	670005	Denmark	55.5	10.9	1988	1997	County of Funen, Nature Management and Water Environment Division	Nanna Rask, Flemming Norgaard
26	Gulf of Aqaba	Eilat	Israel	29.6	35.0	1988	2006	The Hebrew University, Steinitz Marine Biology Laboratory	Amatzia Genin
27	Gulf of Naples		Italy	40.8	14.3	1984	2006	Stazione Zoologica 'A. Dohrn'	Maurizio Ribera D'Alcalà, Vincenzo Saggiomo, Adriana Zingone
28	Gulf of Trieste	000F	Slovenia	45.6	13.6	1984	2007	National Institute of Biology, Marine Biology Station Piran	Patricija Mozetic
29	Gulf of Trieste	00CZ	Slovenia	45.6	13.6	1984	2007	National Institute of Biology, Marine Biology Station Piran	Patricija Mozetic
30	James River Estuary	RET5.2	US	37.2	-76.8	1984	2007	Chesapeake Bay Program	http://www.chesapeakebay.net/data_waterquality.aspx
31	Kattegat	431	Denmark	56.5	10.5	1974	2006	National Environmental Research Institute	Jacob Carstensen
32	Kattegat	925	Denmark	56.5	10.5	1974	2006	National Environmental Research Institute	Jacob Carstensen
33	Long Island Sound	B3	US	41.2	-72.5	1988	2005	Connecticut DEP Water Quality	http://lisicos.uconn.edu/index.php
34	Long Island Sound	H6	US	41.2	-72.5	1988	2005	Connecticut DEP Water Quality	http://lisicos.uconn.edu/index.php
35	Long Island Sound	M3	US	41.2	-72.5	1988	2005	Connecticut DEP Water Quality	http://lisicos.uconn.edu/index.php
36	Moreton Bay	Site 1	Australia	-27.3	153.2	1990	2007	Queensland Environmental Protection Agency, Moreton Bay Ecosystem Health Monitoring Program	Ray Williams
37	Moreton Bay	Site 2	Australia	-27.3	153.2	1990	2007	Queensland Environmental Protection Agency, Moreton Bay Ecosystem Health Monitoring Program	Ray Williams
38	Nanticoke River Estuary	ET6.2	US	38.3	-75.9	1984	2007	Chesapeake Bay Program	http://www.chesapeakebay.net/data_waterquality.aspx
39	Narragansett Bay	2	US	41.6	-71.34	1999	2008	University of Rhode Island, Graduate School of Oceanography	http://www.gso.uri.edu/phytoplankton/
40	Neuse River Estuary	30	US	35.1	-77.1	1994	2006	University of North Carolina Chapel Hill, Institute of Marine Sciences	Hans Paerl, Benjamin Peierls
41	Neuse River Estuary	70	US	35.1	-77.1	1994	2006	University of North Carolina Chapel Hill, Institute of Marine Sciences	Hans Paerl, Benjamin Peierls
42	Neuse River Estuary	160	US	35.1	-77.1	1997	2006	University of North Carolina Chapel Hill, Institute of Marine Sciences	Hans Paerl, Benjamin Peierls
43	North Inlet Estuary	OL	US	33.4	-79.2	1981	2001	Belle W. Baruch Institute for Marine & Coastal Sciences	http://links.baruch.sc.edu/Data/CoastalData.html
44	Odense Fjord	690001	Denmark	55.5	10.5	1977	1997	County of Funen, Nature Management and Water Environment Division	Nanna Rask, Flemming Norgaard
45	Oosterschelde	OS1	Netherlands	51.6	3.7	1995	2004	Netherlands Institute of Ecology, Centre for Estuarine and Coastal Research	http://www.waterbase.nl , Jacco Kromkamp
46	Oosterschelde	OS5	Netherlands	51.6	3.7	1995	2004	Netherlands Institute of Ecology, Centre for Estuarine and Coastal Research	http://www.waterbase.nl , Jacco Kromkamp
47	Oosterschelde	OS8	Netherlands	51.6	3.7	1995	2006	Netherlands Institute of Ecology, Centre for Estuarine and Coastal Research	http://www.waterbase.nl , Jacco Kromkamp
48	Patos Lagoon		Brazil	-32.0	-52.0	1986	2006	Department of Oceanography, Federal University of Rio Grande	Paulo Abreu, Clarisse Odebrecht

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49	Patuxent River Estuary	RET1.1	US	38.5	-76.7	1984	2007	Chesapeake Bay Program	http://www.chesapeakebay.net/data_waterquality.aspx
50	Port Shelter	PM2	Hong Kong	22.3	114.2	1986	2004	Marine Water Quality Monitoring Programme Environmental Protection Department	Kedong Yin
51	Port Shelter	PM8	Hong Kong	22.3	114.2	1986	2004	Marine Water Quality Monitoring Programme Environmental Protection Department	Kedong Yin
52	Potomac River Estuary	RET2.2	US	38.4	-77.2	1984	2007	Chesapeake Bay Program	http://www.chesapeakebay.net/data_waterquality.aspx
53	Rappahannock Estuary	RET3.2	US	37.8	-76.7	1984	2007	Chesapeake Bay Program	http://www.chesapeakebay.net/data_waterquality.aspx
54	Rhode River Estuary	3.8	US	38.9	-76.5	1970	2006	Smithsonian Environmental Research Center	Charles Gallegos, Thomas Jordan
55	Ringkøbing Fjord		Denmark	56.0	8.2	1980	2007	National Environmental Research Institute, University of Aarhus	Jens Kjerulf Petersen
56	Sacramento-San Joaquin Delta	D26	US	38.1	-121.7	1975	2007	Interagency Ecological Program, Environmental Monitoring Program	http://www.bdat.ca.gov/
57	San Francisco Bay (North)	13&D41	US	37.9	-122.4	1976	2007	U.S. Geological Survey; Interagency Ecological Studies Program-Environmental Monitoring Program	http://sfbay.wr.usgs.gov/access/wqdata/ , http://bdat.ca.gov/index.html
58	San Francisco Bay (North)	6&D8	US	37.9	-122.4	1975	2007	U.S. Geological Survey; Interagency Ecological Studies Program-Environmental Monitoring Program	http://sfbay.wr.usgs.gov/access/wqdata/ , http://bdat.ca.gov/index.html
59	San Francisco Bay (South)	21	US	37.6	-122.3	1977	2008	U.S. Geological Survey	http://sfbay.wr.usgs.gov/access/wqdata/
60	San Francisco Bay (South)	27	US	37.6	-122.3	1977	2008	U.S. Geological Survey	http://sfbay.wr.usgs.gov/access/wqdata/
61	San Francisco Bay (South)	32	US	37.6	-122.3	1977	2008	U.S. Geological Survey	http://sfbay.wr.usgs.gov/access/wqdata/
62	Seto Inland Sea	6	Japan	34.3	133.9	1993	2007	Kagawa University	Kuninao Tada
63	Seto Inland Sea	16	Japan	34.3	133.9	1993	2007	Kagawa University	Kuninao Tada
64	Seto Inland Sea	21	Japan	34.3	133.9	1993	2007	Kagawa University	Kuninao Tada
65	Stonehaven, Coastal Atlantic		Scotland	57.0	-2.2	1997	2006	Fisheries Research Services Marine Laboratory	Eileen Bresnan
66	Tampa Bay	8	US	27.9	-82.4	1974	2007	Tampa Bay Estuary Program	Ed Sherwood
67	Tampa Bay	14	US	27.8	-82.5	1974	2007	Tampa Bay Estuary Program	Ed Sherwood
68	Tampa Bay	64	US	28.0	-82.7	1974	2007	Tampa Bay Estuary Program	Ed Sherwood
69	Tampa Bay	93	US	27.6	-82.7	1974	2007	Tampa Bay Estuary Program	Ed Sherwood
70	Ten Thousand Islands	69	US	25.9	-81.5	1994	2007	SERC-FIU Water Quality Monitoring Network; SFWMD/SERC	http://serc.fiu.edu/wqmnetwork/
71	Ten Thousand Islands	73	US	25.9	-81.5	1994	2007	SERC-FIU Water Quality Monitoring Network; SFWMD/SERC	http://serc.fiu.edu/wqmnetwork/
72	Tolo Harbor	TM3	Hong Kong	22.3	114.2	1986	2004	Marine Water Quality Monitoring Programme Environmental Protection Department	Kedong Yin

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Code	Ecosystem	Site	Country	Lat	Long	StartYr	EndYr	Organization	Source
73	Tolo Harbor	TM7	Hong Kong	22.3	114.2	1986	2004	Marine Water Quality Monitoring Programme Environmental Protection Department	Kedong Yin
74	Urdaibai Estuary	30	Spain	43.3	-2.7	1997	2006	Euskal Herriko Uni bertsitatea	Arantza Iriarte, Fernando Villate, Ibon Uriarte
75	Urdaibai Estuary	34-35	Spain	43.3	-2.7	1997	2006	Euskal Herriko Uni bertsitatea	Arantza Iriarte, Fernando Villate, Ibon Uriarte
76	Victoria Harbour	VM1	Hong Kong	22.3	114.2	1988	2004	Marine Water Quality Monitoring Programme Environmental Protection Department	Kedong Yin
77	Villefranche Bay	B	France	43.7	7.3	1997	2007	Service d'Observation en Milieu Littoral, INSU-CNRS	http://www.domino.u-bordeaux.fr/somlit_national/
78	Wadden Sea		Germany	55.0	8.5	1984	1996	Biologische Anstalt Helgoland	Peter Martens
79	Westerschelde	Bath	Netherlands	51.3	3.4	1988	2007	Netherlands Institute of Ecology, Centre for Estuarine and Coastal Research	Jacco Kromkamp, www.waterbase.nl
80	Westerschelde	Doel	Netherlands	51.3	3.4	1978	2006	Netherlands Institute of Ecology, Centre for Estuarine and Coastal Research, Rijkswaterstaat	Jacco Kromkamp, www.waterbase.nl
81	Westerschelde	Vlissingen	Netherlands	51.3	3.4	1978	2006	Rijkswaterstaat	www.waterbase.nl
82	Whitewater Bay	40	US	25.4	-81.1	1994	2007	SERC-FIU Water Quality Monitoring Network; SFWMD/SERC	http://serc.fiu.edu/wqmnetwork/
83	Whitewater Bay	49	US	25.4	-81.1	1994	2007	SERC-FIU Water Quality Monitoring Network; SFWMD/SERC	http://serc.fiu.edu/wqmnetwork/
84	York River Estuary	RET4.3	US	37.5	-76.8	1984	2007	Chesapeake Bay Program	http://www.chesapeakebay.net/data_waterquality.aspx