Seasonal and ENSO Variability in Global Ocean Satellite Chlorophyll

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INTRODUCTION

The 4-year, calibrated SeaWiFS data set provides a means to determine seasonal and other sources of phytoplankton variability on global scales, which are important components of the total variability associated with ocean biological and biogeochemical processes. We used empirical orthogonal function (EOF) analysis on a 4-year time series of global SeaWiFS chlorophyll *a* imagery (1ºx1º spatial resolution and 8-day temporal resolution) to quantify the major seasonal (as well as the 1998 ENSO) signals in phytoplankton biomass between 50ºS and 50ºN, and then a second analysis to quantify summer patterns at higher latitudes.

METHODS

- Started with 9-km and 8-day SeaWiFS imagery.
- Averaged on a 0.25º x 0.25º grid and then smoothed using a 1ºx1º median filter.
- Subsampled to a 1ºx1º grid covering the global ocean.
- Log-transformed, then used a 3-point (24 day) running mean to smooth in time.
- Filled in missing points for maximum spatial coverage for EOFs.
- Final x, y, and time cube consisted of 184, 8-day "maps" of Chl *a* (*e.g.,* Figure 1).
- Removed the 4-year temporal mean of each pixel (Figure 2b) from each map.
- Weighted each value using the cosine of latitude (for equal area representation).

VARIABILITY FROM 50ºS to 50ºN

CZCS and SeaWiFS agree qualitatively and show low Chl *a* in the ocean gyres, comparatively high concentrations in ocean margin waters and in the equatorial upwelling systems, and high mean concentrations within the ~40º to 50ºN and S latitude belts. For SeaWiFS, note the persistence of the mean global pattern, *i.e.* the same pattern is more or less evident in the mean, as well as maximum and minimum pixel values (Fig. 2b, c, and d).

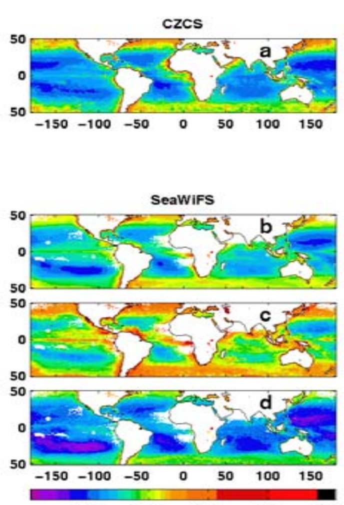

Figure 2. Climatological CZCS mean chlorophyll (a) and 4-year SeaWiFS chlorophyll mean (b), maximum (c), and minimum (d) for 50ºS to 50ºN latitudes. Units are $\log_{10}$(chl *a*) + 2 (*i.e.* a log scale but with no negative numbers). The color "white" outside of land areas indicates insufficient data for EOF analyses.

For EOFs, we used the SVD method to calculate the spatial eigenfunctions, temporal amplitudes, and corresponding eigenvalues. Spatial eigenfunctions are global maps (units are $\log_{10}$ chl *a* concentration) of the spatial pattern associated with each mode, which in our case are deviations from the mean global spatial pattern (Fig. 2b). The amplitude time series of each mode is dimensionless and shows how the modal spatial pattern evolves with time. For any mode, the product of the dimensionless value of the amplitude at a given point in the amplitude time series and the value ($\log_{10}$ chl *a* units) of any pixel in the spatial pattern is a deviation from the mean pixel value (Fig. 2b). We focused our interpretation on the first 6 (of 184) modes, *i.e* those modes are not degenerate (Fig. 3, 4 and 5). EOFSs are an effective way to summarize large amounts of data contained in an image time series if: only a few modes contain most of the variability; the spatial patterns are relatively simple and show large coherent regions of the ocean; and the amplitude time series show smooth temporal patterns.

Mode	PVE(%)	Cumulative PVE
1	41	
2	9.1	50.1
3	6.1	56.2
4	5.2	61.4
5	3.3	64.7
6	2.7	67.4

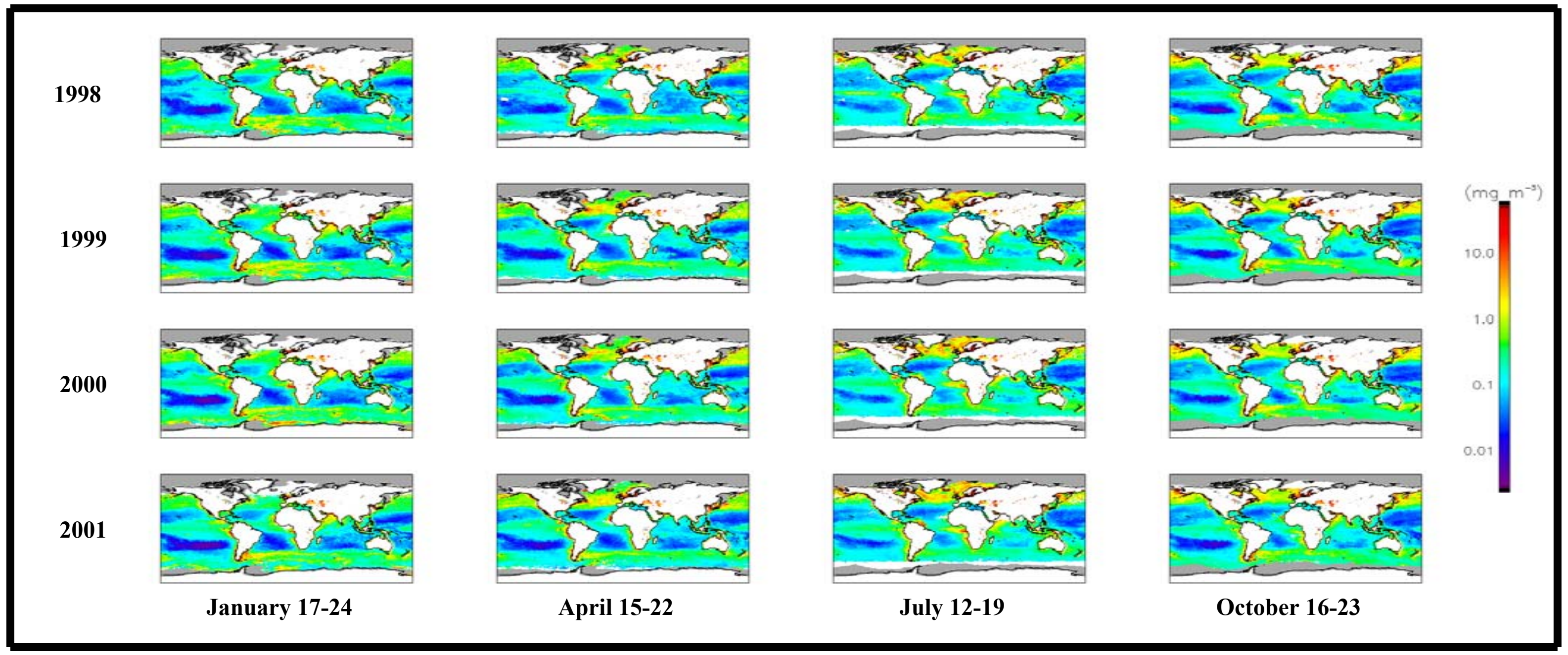

Figure 1. Representative 8-day chlorophyll *a* maps for winter, spring, summer and fall. An animation of the time series can be accessed through our webpage at http://www.po.gso.uri.edu/color/animate.html.

Modes 1-3

Mode 1 shows a 6-month phase shift in peak Chl *a* between subtropical and subpolar waters. The S. Atlantic and S. Indian oceans have similar patterns as for the NH. There is asymmetry in the NH tropical Atlantic due to summer upwelling and river runoff north of Venezuela. Mode 1 also shows a weak seasonal cycle associated with narrow upwelling regions centered on the equator in both the Atlantic and eastern Pacific.

Mode 2 shows the differences in intensity of the spring bloom between the N. Pacific and N. Atlantic. There is a consistent pattern throughout the Southern Ocean with positive spring-summer (Sep-Feb) anomalies. The amplitude for Jan 1998 is slightly negative, while it is strongly positive during Jan 1999-2001 possibly indicative of ENSO effects.

Mode 3 exhibits ENSO components. The amplitude time series is very different in 1998 than in the other 3 years. There is enhanced upwelling and river runoff in ETA as well as positive anomalies for the eastern Indian Ocean off Indonesia during ENSO. Positive anomalies in 1998 also occur in the Southern Ocean, Gulf of Mexico and western subtropical Atlantic.

Modes 4-6

Mode 4 modifies the Mode 1 seasonal pattern and is related to spring and fall blooms and to seasonal minima in summer and winter at high latitudes (> ~ 40º in both hemispheres). The opposite pattern occurs in middle latitudes. Mode 4 captures two max (boreal summer and winter) and two min (boreal spring and fall) in ETA. The spatial pattern poleward of ~25º is similar in both hemispheres (except in parts of the S Atlantic).

Mode 5 is spatially complex and shows ENSO components. It captures the 1998 winter to summer shift from negative to positive anomalies in the Equatorial Pacific and Indian Ocean coincident with the change from El Nino to La Nina.

Mode 6 also modifies the Mode 1 seasonal pattern. As for Mode 4, high latitudes (> ~ 40º in both hemispheres) patterns in Mode 6 are related to spring and fall blooms and to seasonal minima in summer and winter. The opposite pattern occurs in middle latitudes. Maximum amplitude occurs during La Nina in summer 1998.

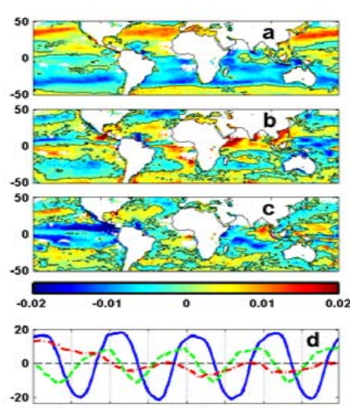

Figure 3. Spatial pattern and 4-year amplitude time series for Mode 1 (a and blue line in d, respectively), Mode 2 (b and green line) and Mode 3 (c and red line). Spatial patterns have units of $\log_{10}$(chl *a*), amplitudes are dimensionless.

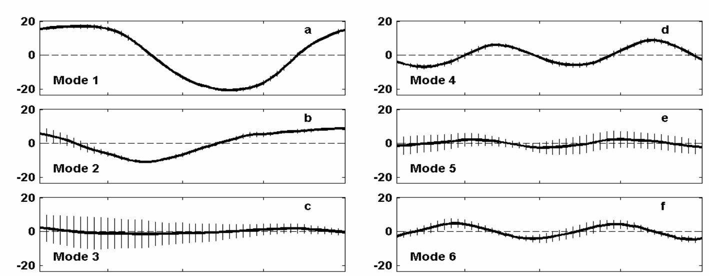

Figure 4. The 4-year mean and standard deviation of the amplitude time series for Modes 1-6.

Interannual variability dominates Mode 3 and that variability is most important during the first part of 1998, *i.e.* the La Nina portion of the ENSO cycle (Figure 4). Interannual variability is also evident in the seasonal patterns captured by Modes 2, 5, and 6. Modes 1 and 4 have very little variability in the amplitude time series (very small standard deviation) indicating very low interannual variability in the winter-summer phase shift between subtropical and subpolar waters (Mode 1), as well as the primary spring-fall bloom pattern of subpolar waters (Mode 2).

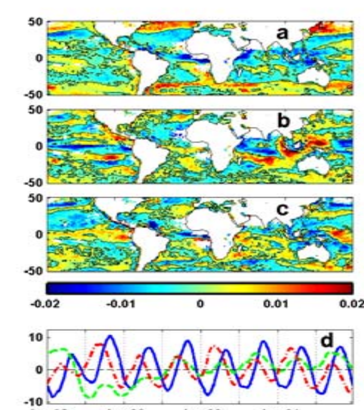

Figure 5. Spatial pattern and 4-year amplitude time series for Mode 4 (a and blue line), Mode 5 (b and green line) and Mode 6 (c and red line).

VARIABILITY AT HIGH LATITUDES

At high latitudes (15º to 80ºN and S) a second EOF analysis was carried out for summer months. Summer is defined as a 26 "week" period centered on the solstice.

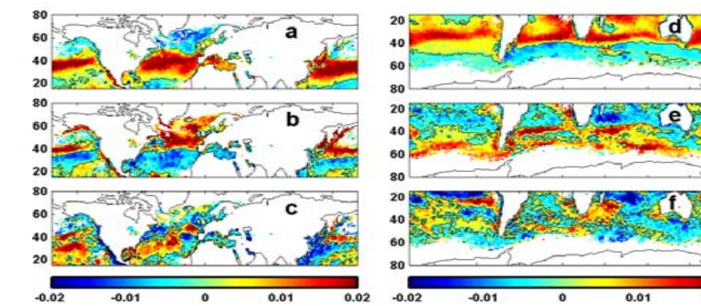

Figure 6. Spatial pattern (15º to 80º) for Modes 1, 2, and 3 for high latitude NH (a, b, and c, respectively) and SH (d, e, and f).

Mode	NH PVE (%)	Cumulative PVE (NH)	SH PVE (%)	Cumulative PVE (SH)
1	49.0		46.3	
2	11.3	60.3	10.9	57.2
3	5.6	65.9	6.5	63.7

Mode 1 show a 6-month phase shift between the mid and high latitudes (*i.e.* mid latitudes have a winter maximum and high latitudes have summer maximum). All 3 years show very similar temporal patterns (Figure 7).

Mode 2 modifies the summer pattern of Mode 1 with positive anomalies at latitudes poleward of ~40º in the Atlantic. The pattern is more complex in the N. Pacific with a latitude band between ~45º-50ºN showing the opposite pattern from the Atlantic.

Mode 3 shows coherent NH patterns primarily south of 40ºN. The amplitude time series are near flat indicating poor resolution of seasonal patterns. The SH time series from the 3 years are different indicating interannual variability, positive amplitudes from September 1998-March 1999, while the other two years are negative.

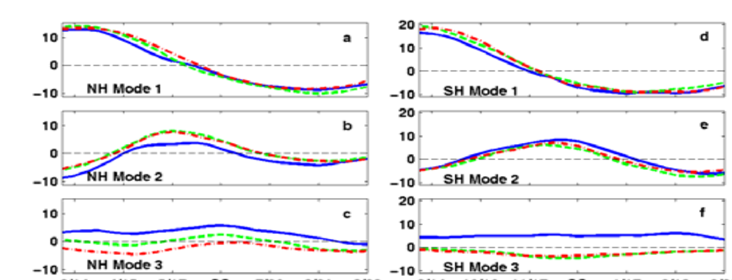

Figure 7. Amplitude time series (centered on the summer solstice) for Modes 1, 2, and 3 for high latitude NH (a, b, and c, respectively) and SH (d, e, and f).

CONCLUSIONS

- The first 6 (of 184 possible) modes account for 67% of the variability within 8-day composite global images from the first 4 years of SeaWiFS chlorophyll imagery.
- The time/space patterns are interpretable in relation to seasonal to inter-annual ocean processes.
- Seasonal cycle of the mid to high latitude global ocean (Mode 1) is nearly identical from year to year.
- The 1997-1998 ENSO was particularly strong and its effects during 1998 are evident in our 4-year record (Modes 3 and 5).
- Seasonal cycles accounted for more variability than did the ENSO effects in 1998.
- About 30% of the variability in our 4-year global data set was not explained by simple patterns.