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Ocean's least productive waters are expanding

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[1] A 9-year time series of SeaWiFS remotely-sensed ocean color data is used to examine temporal trends in the ocean's most oligotrophic waters, those with surface chlorophyll not exceeding 0.07 mg chl/m^3. In the North and South Pacific, North and South Atlantic, outside the equatorial zone, the areas of low surface chlorophyll waters have expanded at average annual rates from 0.8 to 4.3%/yr and replaced about 0.8 million km^2/yr of higher surface chlorophyll habitat with low surface chlorophyll water. It is estimated that the low surface chlorophyll areas in these oceans combined have expanded by 6.6 million km^2 or by about 15.0% from 1998 through 2006. In both hemispheres, evidence shows a more rapid expansion of the low surface chlorophyll waters during the winter. The North Atlantic, which has the smallest oligotrophic gyre is expanding most rapidly, both annually at 4.3%/yr and seasonally, in the first quarter at 8.5%/yr. Mean sea surface temperature in each of these 4 subtropical gyres also increased over the 9-year period. The expansion of the low chlorophyll waters is consistent with global warming scenarios based on increased vertical stratification in the mid-latitudes, but the rates of expansion we observe already greatly exceed recent model predictions. **Citation:** Polovina, J. J., E. A. Howell, and M. Abecassis (2008), Ocean's least productive waters are expanding, *Geophys. Res. Lett.*, *35*, L03618, doi:10.1029/2007GL031745.

1. Introduction

[2] The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) mission has been providing satellite-based estimates of surface chlorophyll since September 1997. We now have an unprecedented, almost decade-long, time series of global ocean surface chlorophyll. Subtropical gyres comprise the largest ecosystem in each of the major ocean basins and occupy approximately 40% of the surface of the earth. While the biological productivity of these oligotrophic ecosystems is low, they are sometimes referred to as biological deserts; their large size allows for a significant contribution on the global scale. Temporal trends in the size of these gyres are indicators of changes in ocean biology and due to their large size even modest changes can result in significant impacts on the spatial distribution of surface chlorophyll in the entire ocean.

[3] In an earlier study, *McClain et al.* [2004] used SeaWiFS data to show that the low surface chlorophyll waters within the subtropical gyres of the North Pacific and North Atlantic have expanded. Subsequently *Gregg et al.* [2005] used a 6-year time series of global chlorophyll and sea surface temperature (SST) to show the mean chlorophyll within the subtropical gyres declined as the mean SST increased.

[4] In this paper we use surface chlorophyll data to define the monthly areas of the most oligotrophic habitat in the subtropical gyres in the North Pacific, North Atlantic, South Pacific, South Atlantic, and South Indian Oceans and examine changes in these areas over time. We also examine trends in mean SST in the subtropical gyres. All references to chlorophyll in this paper refer to chlorophyll *a* which is estimated from the SeaWiFS sensor.

2. Methods

[5] The surface chlorophyll data we use are 9-km pixel resolution monthly standard mapped images created from data collected by the SeaWiFS instrument covering the January 1998–February 2007 period. While the performance of SeaWiFS has shown remarkable consistency for most of the mission, slight sensor degradation and calibration drift were detected beginning in late 2005. In July, 2007, NASA reprocessed the SeaWiFS data to correct these problems. Our analyses are based on the data from this latest reprocessing known as version 5.2 data.

[6] In the Pacific equatorial band, 5°S to 5°N latitude, surface chlorophyll densities vary widely in response to El Niño and La Niña events and hence any underlying linear trends would not be detectable from our relatively short time series covering several El Niños and La Niñas. Thus to examine the trends in area of low surface chlorophyll water in the Pacific and Atlantic Oceans, we consider only the portion of the basin north of 5°N latitude and south of 5°S latitude. In the Indian Ocean, we consider only the portion south of 5°S latitude since the portion north of 5°N latitude represents a relatively small geographic region with strong seasonal forcing and hence, is not comparable to our other regions. We bound our study region at 45°N or S latitude to ensure we are only considering subtropical waters, as low surface chlorophyll waters can also be found at high latitudes in response to other physical processes.

[7] To examine whether there were changes in sea surface temperature (SST) concurrent with chlorophyll changes we computed mean monthly SST in each of the five subtropical gyres, using spatial regions defined by *McClain et al.* [2004]. We used the NCEP Reynolds Optimally Interpolated SST product. This global product incorporates both in-situ SSTs and satellite derived SSTs from the NOAA Advanced Very High Resolution Radiometer (AVHRR) to produce a global 1° × 1° monthly SST image [*Reynolds and Smith*, 1994].

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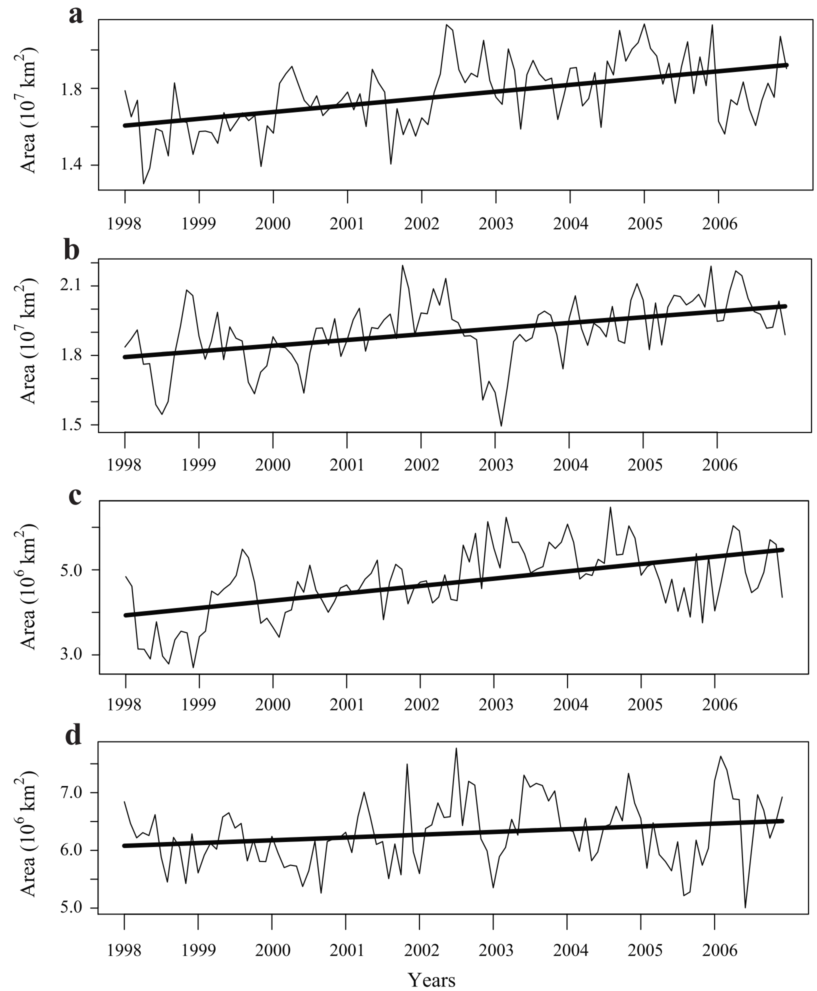

Figure 1. Time series of the monthly mean area (km^2) with surface chlorophyll less than or equal to 0.07mg chl/m^3 between 5°–45° N/S latitude with the seasonal cycle modeled removed in (a) the North Pacific, (b) the South Pacific, (c) the North Atlantic, and (d) the South Atlantic. Straight lines are the linear terms from the GAMs.

[8] The subtropical gyres are sometimes defined based on physical characteristics including vertical downwelling velocity and mixed layer depth [*Sarmiento et al.*, 2004]. However we will follow a biological habitat approach using surface chlorophyll data to define the most strongly stratified and oligotrophic core of the subtropical gyres as the area with surface chlorophyll bounded by 0.07 mg chl/m^3 [*McClain et al.*, 2004]. These areas are termed the oligotrophic regions of the subtropical gyre and depending on the ocean, represent from 40 to 70% of the entire subtropical gyre [*McClain et al.*, 2004]. We use the simplified term oligotrophic gyres for these regions. Maps of depth integrated net primary productivity (npp) show these oligotrophic gyres also correspond with the regions of lowest oceanic npp [*Behrenfeld et al.*, 2006].

[9] For each monthly SeaWiFS image, the areas of the oligotrophic gyres in the five ocean basins were calculated using MATLAB (The Math Works, 3 Apple Hill Drive, Natick, MA 01760). To facilitate the subsetting of the regions from the global data images, the initial data obtained from the 9-km images were regridded to a 0.1° × 0.1° resolution using the Generic Mapping Tools (www.gmt.soext.hawaii.edu). To obtain the areas in km^2, we first transformed the longitudes into corrected longitudes as a function of latitude. The corrected longitudes, in 1° latitudinal increments, equal longitude*cos(latitude). To convert latitude from degrees to km we use the approximation that 1° of latitude = 111 km.

[10] The temporal trends in the monthly area of the oligotrophic gyres and mean SST were computed with a Generalized Additive Model (GAM) [*Hastie and Tibshirani*, 1990]. We fitted the monthly area time series with a model that contains a linear function of time to model the time trend and a smoothed monthly term to model the seasonal pattern. We fitted the same model to all 5 oceans and present results for oceans where the slope of the linear term was statistically significant with p-values less than 0.05.

[11] Trends in the area of the oligotrophic gyres by quarter were also examined. The average quarterly area of the oligotrophic gyre was calculated by averaging the monthly area for each quarter from 1998 to 2006. Temporal trends by quarter were estimated with a linear regression. Results are only presented for regressions with slopes that are statistically significant with *p*-values less than 0.05.

Table 1. The Mean Monthly Areas, by Ocean, of the Oligotrophic Gyres in 1998, the Linear Increase in Area (Rate) of the Oligotrophic Gyre From the Linear Term in the GAM (1998–2006) With *p*-Value[a]

Ocean	1998 Mean Area, km^2	Increase in Area, km^2/yr, (%/yr)	p-Value
North Pacific	16,222,653	353,519 (2.2)	2.48^{-08}
South Pacific	18,041,685	245,766 (1.4)	1.47^{-06}
North Atlantic	4,010,147	172,455 (4.3)	1.41^{-09}
South Atlantic	6,100,571	48,075 (0.8)	2.61^{-02}
Total areas	44,375,056	819,815 (1.9)	-

[a]Only oceans with statistically significant linear trends (p-value < 0.05) are shown.

[12] Interannual variation in the monthly area of cloud cover in the subtropics that might confound any trends in the oligotrophic areas was examined. Cloud cover never exceeded more than 3% of the monthly oligotrophic gyre area in any oceans and no statistically significant trends in the areas of cloud cover in any of the oceans were found.

3 Results and Discussion

3.1 Trends

[13] Over the January 1998 – December 2006 period, the trend in the monthly area of the oligotrophic gyre from the GAM showed statistically significant linear increases in the North Pacific, South Pacific, North Atlantic, and South Atlantic Oceans (Figure 1 and Table 1). The South Indian Ocean showed an increasing but not statistically significant trend. The linear rates of increase ranged from 0.8%/yr for the South Atlantic to 4.3%/yr for the North Atlantic (Figure 1 and Table 1). The average area that the low surface chlorophyll region expanded ranged from about 354,000 km^2/yr for the North Pacific to 48,000 km^2/yr for the South Atlantic (Figure 1 and Table 1). For the four oceans combined, the low chlorophyll waters expanded at a rate of about 0.8 million km^2/yr. When this rate is cumulated over the 9-year period from 1998 to 2006, the combined area of the low chlorophyll waters in the four oceans is estimated to have expanded by approximately 6.6 million km^2 representing a 15.0% increase from the 1998 area (Table 1).

[14] The expansion of the oligotrophic gyres occurred concurrently with statistically significant increases in the mean subtropical gyre SST in each of the four oceans (Table 2).

3.2. Seasonal Trends

[15] The oligotrophic gyres expand and contract seasonally. During the winter months, the area of the oligotrophic gyre is smaller compared to the summer months because winter storms and stronger winter winds increase vertical mixing in the subtropical regions. The regressions of the mean area of the oligotrophic gyres by quarter found statistically significant increases in at least some quarters in the North Pacific, North Atlantic, and South Pacific with the largest rates of increase occurring in quarters 4 and 1 in the North Pacific and North Atlantic respectively and in quarter 3 in the South Pacific (Figure 2). The rates of increase were 3.2%/yr, 8.5%/yr, and 2.9%/yr for the North Pacific, North Atlantic, and South Pacific respectively (Figure 2 and Table 3). These quarters represent the winter quarters in their respective hemispheres. The rates of increase in the area of the oligotrophic gyres during winter are substantially greater than the average annual rates and the combined increase in area during these winter quarters is about 1.1 million km^2/yr (Table 3).

3.3. Spatial Patterns

[16] To examine the spatial aspects of the expansion of oligotrophic habitat we compared the oligotrophic area between the beginning and end of the time series for a month during the winter season that we have shown is the period the gyres were expanding most rapidly. Specifically in the northern hemisphere we compared the areas with surface chlorophyll less than or equal to 0.07 mg chl/m^3 computed from a December 1998 and 1999 mean, to the areas based on a December 2005 and 2006 mean (Figures 3a and 3b). In the South Pacific we compared areas computed from an August 1998 and 1999 mean with an August 2005 and 2006 mean (Figure 3c). The area in grey represents the area with surface chlorophyll less than or equal to 0.07 mg chl/m^3 in both 1998/99 and 2005/06 (Figure 3). This is the area that has not changed between the two time periods. The area in red represents added area with surface chlorophyll less than or equal to 0.07 mg chl/m^3 that was present in 2005/06 and not in 1998/99, while the area in blue represents the area with surface chlorophyll less than or equal to 0.07 mg chl/m^3 that was present in 1998/99 but not in 2005/06. In all basins the area present in 1998/99 and not present in 2005/06 (blue color) is considerably smaller than the area present in 2005/06 and not present in 1998/99 (red color) indicating the oligotrophic gyres are largely stationary and expanding (Figure 3). In the North Pacific the red areas show that the oligotrophic gyre has expanded to the northeast, reaching portions of the Hawaiian Archipelago and well into the eastern Pacific (Figure 3a). In the North Atlantic, the oligotrophic habitat was quite small in December 1998/99 and has expanded substantially, largely toward the southeast (Figure 3b). In the South Pacific the oligotrophic gyre in August 2005/06 has expanded both on the southern and northern sides (Figure 3c). In all three gyres the expansion is generally contiguous with the existing areas but the directions of the expansion vary between basins (Figure 3). The

Table 2. The Intercept, Slope (Rate), and p-Value of the SST Linear Term in the GAM SST Fit to the Subtropical Gyres, by Ocean

Ocean	Intercept, °C	Slope, °C/yr (%/yr)	p-Value
North Pacific	26.5	0.014 (0.1)	8.90^{-04}
South Pacific	22.3	0.02 (0.1)	3.80^{-03}
North Atlantic	25.8	0.036 (0.1)	3.10^{-04}
South Atlantic	21.8	0.015 (0.1)	0.02

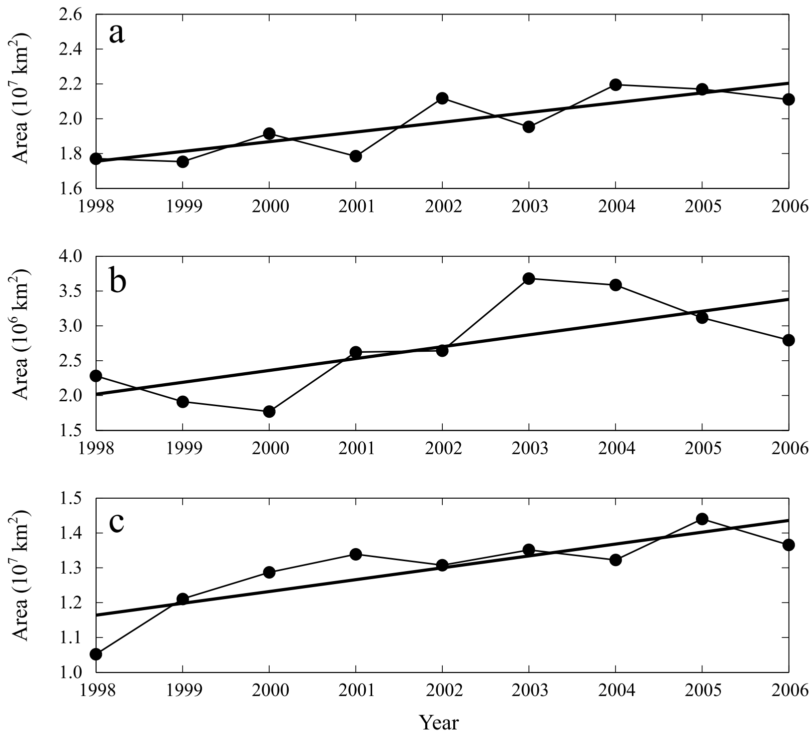

Figure 2. Time series and regression line for the area with surface chlorophyll less than or equal to 0.07 chl/m^3 in (a) quarter 4 in the North Pacific, (b) quarter 1 in the North Atlantic, and (c) quarter 3 in the South Pacific.

South Atlantic is not shown in Figure 3 as the expansion, although also contiguous, was relatively modest in area.

[17] Thus, these expansions may be responding to a global trend mediated by regional ocean structure.

4. Concluding Remarks

[18] Since 1998, the least productive oceanic habitats or the oligotrophic gyres in four of the world's major oceans have been expanding at average rates between 0.8%/yr and 4.3%/yr. The rate of expansion is greater during the winter in three of these oceans. The North Atlantic has a much smaller oligotrophic gyre but it is expanding faster than the other oceans and especially during the winter. For example, the mean gyre size during the first quarter in the North Atlantic has expanded by 56% between 1998 and 2006. The oligotrophic gyres in the northern hemisphere are expanding at a faster rate than those in the southern hemisphere. Mean monthly SST over the subtropical gyres is increasing concurrently with the expansion of the oligotrophic gyres which is consistent with the hypothesis that as the subtropical gyres become warmer they become more stratified and the oligotrophic gyres expand. It is interesting to note that the percent increase in the area of the oligotrophic gyres is an order of magnitude greater than the percent increase in mean SST, suggesting that the area of oligotrophic habitat may be more sensitive to changes in the gyre than the mean SST.

[19] In a previous study using a shorter ocean color time series and computing the relative area of oligotrophic water in the subtropical gyre, *McClain et al.* [2004] found the oligotrophic regions in the North Pacific and North Atlantic were expanding at about 3% and 4% annually while there was no statistically significant change in the areas in the southern hemisphere. The annual rates of increase in the oligotrophic gyres we estimated are consistent with *McClain et al.*'s [2004] findings for the northern hemisphere and our longer time series also indicated that the areas of the oligotrophic gyres have expanded in the South Pacific and South Atlantic as well and that there is a seasonal aspect to the expansion.

[20] Another study by *Gregg et al.* [2005] used satellite ocean color and SST data to show that during the 1998–2003 period, in the subtropical gyres, chlorophyll densities declined and surface temperatures increased. More recently, *Behrenfeld et al.* [2006] showed that since 1999

Table 3. For the North and South Pacific and the North Atlantic, the Quarter With the Largest Rate of Increase in the Oligotrophic Gyre, the 1998 Area of the Oligotrophic Gyre, the Linear Increase in Area (Rate) for That Quarter (1998–2006) With *p*-Value[a]

Ocean	Quarter With Largest Rate of Increase	1998 Area	Increase in Area, km^2/yr (%/yr)	p-Value
North Pacific	4	17,520,884	555,875 (3.2)	0.005
North Atlantic	1	2,021,268	172,609 (8.5)	0.04
South Pacific	3	11,622,915	337,352 (2.9)	0.004
Combined area	-	31,165,067	1,065,836 (3.4)	-

[a]Only oceans with statistically significant linear trends (p-value < 0.05) are shown.

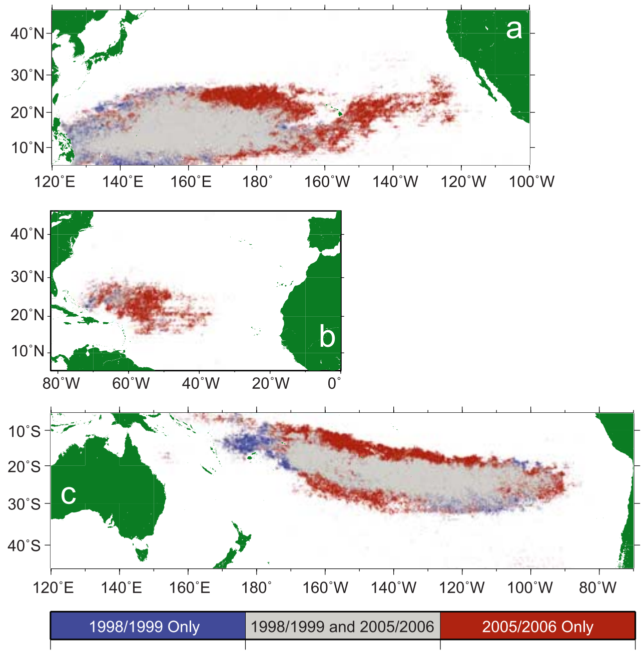

Figure 3. For (a) North Pacific and (b) North Atlantic grey represents the areas with surface chlorophyll less than or equal to 0.07 mg chl/m^3 for both the 2-month mean of December 1998 and December 1999 and the 2-month mean of December 2005 and December 2006. Blue represents the areas with surface chlorophyll less than or equal to 0.07mg chl/m^3 for only the 2-month mean of December 1998 and December 1999. Red represents the areas with surface chlorophyll less than or equal to 0.07 mg chl/m^3 for only the 2-month mean of December 2005 and December 2006. For (c) the South Pacific, the colors represent the same areas based on the month of August.

tropical and subtropical net primary productivity (npp) declined concurrently with an increase in vertical stratification. Our finding that the oligotrophic gyres have expanded concurrently with an increase in the mean SSTs in the subtropical gyres provides further evidence that the subtropical gyres are warming and becoming more oligotrophic.

[21] Ocean models and observations indicating that the heat content and vertical stratification in all oceans have been increasing since the 1950s, with a more rapid increase during the past decade, is highly consistent with the output of model simulations forced by a global warming scenario [*Barnett et al.*, 2001]. Our finding that the oligotrophic gyres in four oceans are expanding is consistent with past stratification results and suggests that the gyres will continue to expand with future global warming forcing.

[22] However recent coupled climate-ecosystem models appear not to have captured this trend. The impact of global warming on ocean ecosystems has been explored with six coupled climate models [*Sarmiento et al.*, 2004]. They defined a set of ocean biomes based on physical characteristics and estimated changes in the areas of these biomes by 2050 based on global warming. They estimated that by 2050 the permanently stratified subtropical gyre would be 4.0% larger in the northern hemisphere and 9.4% larger in the southern hemisphere [*Sarmiento et al.*, 2004]. Further based on output from coupled climate-ecosystem models it was estimated that surface chlorophyll density within the permanently stratified subtropical gyres would increase in the northern and southern hemispheres by 5.5% and 0.8% respectively [*Sarmiento et al.*, 2004]. Our findings, although based on only a 9-year time series, suggest that the most oligotrophic portions of the subtropical gyres of the world's oceans are expanding by 1–4%/yr resulting in a reduction in chlorophyll density and productivity in the larger subtropical gyres.

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