



## Are ocean deserts getting larger?

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[1] The spatial and temporal dynamics of ocean biomes and their provincial subdivisions are affected by the dynamics of Earth's climate system, but the effect of climate change on the distribution and variability of ocean biomes and provinces is largely unknown. A time-series analysis from multiple satellite platforms shows that the lowest productivity provinces have been growing over the last decade and that the growth rates of these provinces increase as they get larger, and decrease as they get smaller. The most oligotrophic provinces of the ocean grow by reducing the size of the slightly less oligotrophic provinces. As a consequence, while the ocean's most extreme deserts are increasing at an accelerating rate, some oligotrophic areas are simultaneously shrinking. The aggregate area of the oligotrophic provinces oscillated in phase with the Pacific Decadal Oscillation Index from 1998–2007. **Citation:** Irwin, A. J., and M. J. Oliver (2009), Are ocean deserts getting larger?, *Geophys. Res. Lett.*, 36, L18609, doi:10.1029/2009GL039883.

### 1. Introduction

[2] The seasonal flux of light and heat and the Earth's rotation creates zonal wind patterns over the global ocean. These winds mix nutrients essential for primary production from the deep to the surface ocean where they are used by marine phytoplankton. Marine phytoplankton are the primary energy gateway for the marine food web and determine the structure and function of pelagic ocean ecosystems. Therefore, the seasonal timing (or phenology) of light, heat and phytoplankton biomass are used to distinguish four major biome types in the global ocean: the Polar, Temperate, Tropical and Coastal Ocean biomes. The spatial and temporal dynamics of ocean biomes and their provincial subdivisions are affected by the dynamics of Earth's climate system [Devred *et al.*, 2007; Hooker *et al.*, 2000; Longhurst, 1998; Oliver and Irwin, 2008; Platt and Sathyendranath, 1999], however the effect of climate change on the distribution and variability of ocean biomes and provinces is largely unknown.

[3] Phenological classification of a water-mass depends on its history, but the movement of water-masses makes inquiries into temporal trends of ocean provinces challenging Longhurst [1998]. To elucidate time-dependent trends in province location, size, and growth, they must be classified independently of time. A time-independent classification

algorithm using ocean color and sea surface temperature can be used to identify discrete province classes in the ocean [Moore *et al.*, 2002; Oliver *et al.*, 2004; Oliver and Irwin, 2008] with similar geographic characteristics to the provinces of Longhurst [1998]. The time-independent province classification largely corresponds to the phenological classifications because ocean color (OC) and sea surface temperature (SST) have a high degree of temporal autocorrelation [Mahadevan and Campbell, 2004] and at a basic level, we use a satellite index of light and temperature to classify provinces. We define dynamic provinces by applying an objective, time-independent algorithm to a 10 year time-series of Sea-viewing Wide Field-of-view Sensor/Advanced Very High Resolution Radiometer (SeaWiFS/AVHRR) data and a 5 year time-series of Moderate Resolution Imaging Spectroradiometer (MODIS/Aqua) data. We then analyze the area of the oligotrophic provinces across the gyres, to test for decadal-scale changes in the lowest productivity areas of the ocean.

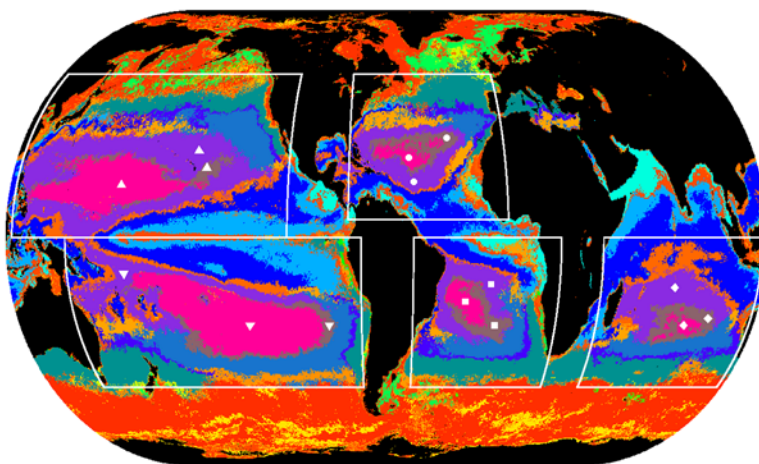
### 2. Materials and Methods

[4] Two sets of biogeographic province distribution maps were produced using an objective clustering technique first developed and validated for coastal regions [Oliver *et al.*, 2004] and modified and applied later to the global ocean [Oliver and Irwin, 2008]. The objective clustering technique classifies province types based on blue (nLw443) and green (nLw551 or nLw555) water leaving radiance and SST (MODIS/Aqua 11 $\mu$  daytime SST or NOAA Pathfinder AVHRR v.5 SST data with quality flag  $\geq 4$ ). Monthly and annual means from 1998–2007 were used as provided by the ocean color processing team [Feldman and McClain, 2007a, 2007b] and PODAAC. Data were processed to a cylindrical grid of 36 km resolution at the equator.

[5] The objective classification algorithm used here is an unsupervised ensemble of clustering algorithms, requires no *a priori* knowledge of provinces and has an objective statistic to determine the appropriate number of province types in the satellite data sets [Oliver *et al.*, 2004; Oliver and Irwin, 2008]. We computed mean SST, chlorophyll *a*, and primary productivity (VGPM [Behrenfeld and Falkowski, 1997]) averaged over oligotrophic provinces in each of the North and South Pacific, North and South Atlantic, and Indian Oceans. We measured the area of each province in each month, restricted to the boxes shown in Figure 1, and summed globally. To investigate how the provinces were changing in size, we de-seasoned the time-series by computing an average for each month over years and subtracting the mean inter-annual effect from each month's data (using the seasonal decomposition function *stl* based on loess smoothing in the R package *stats*). We computed the growth rate of each province from a linear regression of de-seasoned province area over time (for each basin and

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**Figure 1.** Climatological provinces based on SeaWiFS/AVHRR annual average for 2007. Boxes identify ocean basins (North and South Pacific, North and South Atlantic and Indian) in which oligotrophic provinces (indicated by symbols) are studied. Colors were chosen to accentuate contrast between neighboring provinces.

for both sensors) as a function of the mean log area of the province.

### 3. Results and Discussion

[6] We produced monthly province maps from 1998–2007 (Figure 1 and Animation S1 of the auxiliary material).<sup>1</sup> The unsupervised clustering of SeaWiFS ocean color and AVHRR SST data divides the ocean into 72 cluster types, with 19 comprising > 80% of the area while the unsupervised clustering of the MODIS ocean color and SST data divides the ocean into 76 province types, with 18 comprising > 80% of the area. The cluster types form large coherent provinces, especially in the lower latitudes; high latitude provinces tend to be smaller and intermingled. Three large provinces in the Tropical Biome’s oligotrophic gyres are found in the 5 major basins with a concentric structure (identified by symbols in Figure 1).

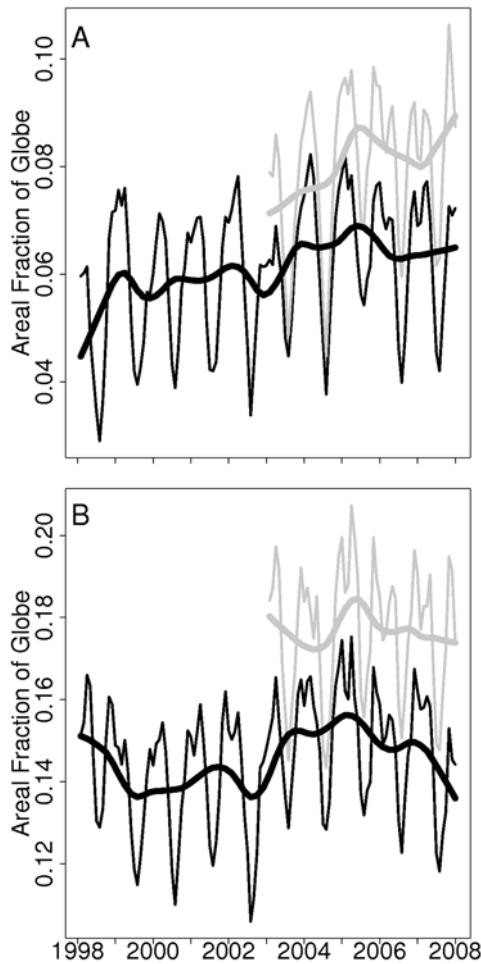
[7] We identify the provinces within the Tropical Biome’s oligotrophic gyre from the center to the edge of the Tropical Biome in each basin as the extreme-oligotrophic, hyper-oligotrophic and oligotrophic provinces. The edges of these provinces show evidence of eddies and planetary waves (Animation S1) and each of these provinces has distinct characteristics (Figure S1). The extreme-oligotrophic province type is the warmest (on average 27°C), has the lowest chlorophyll *a* concentration (chl. *a* usually < 0.06 mg m<sup>-3</sup>), and is least productive (<200 mg C m<sup>-2</sup> d<sup>-1</sup>). Moving outwards, the hyper-oligotrophic and oligotrophic province types have low chlorophyll concentration (usually < 0.08 mg chl. *a* m<sup>-3</sup>) and decreasing temperatures, but comparable productivity and thus different chlorophyll-normalized production. The hyper-oligotrophic province (brown) has greater chlorophyll normalized productivity than the other provinces. Provinces are characterized by SST and OC and without regard to time, but seasonal oscillations are present in provincially averaged SST, remote-sensed chlorophyll, and primary production (not shown). A regression

of provincially-averaged chlorophyll concentration shows a decrease of  $1.4 \cdot 10^{-4}$  mg chl. m<sup>-3</sup> yr<sup>-1</sup> ( $p < 0.05$ ) in the hyper-oligotrophic and oligotrophic provinces and there is no significant trend in the extreme-oligotrophic province. These rates are ~10% of the rates reported by McClain *et al.* [2004] indicating that our provinces are stable compared to regions defined by a 0.07 mg chl m<sup>-3</sup> threshold.

[8] Our results show that four of the five extreme-oligotrophic provinces have been expanding in recent years, consistent with reports of increases in oligotrophic regions of the ocean (Figures 2a and S2–S4) [Behrenfeld *et al.*, 2006; Gregg *et al.*, 2005; McClain *et al.*, 2004; Polovina *et al.*, 2008]. The ENSO signal in 1998–99 is the largest single-year feature in the time-series, but does not account for the overall trend. The extreme-oligotrophic province in the South Atlantic has been shrinking from 2003 to 2007 at a rate consistent in magnitude with the growing provinces. The provinces identified by data from SeaWiFS/AVHRR and MODIS differ somewhat and the biome area are somewhat different in the MODIS provinces (Figures 2 and S2–S4, grey lines), but the month-to-month (symbols) and de-seasoned data show many of the same features. Calibration of satellite ocean color sensors is a constant challenge and data reprocessing has been known to change trends (<http://oceancolor.gsfc.nasa.gov/REPROCESSING/SeaWiFS/R5.2/>), but our consistent results from SeaWiFS and MODIS/Aqua analyses indicate this is an unlikely source of error.

[9] Previous estimates for increasing area of the oceans’ deserts have varied from –0.5% to +4% per year [McClain *et al.*, 2004], 0.8–4.3% per year [Polovina *et al.*, 2008] to 4.0–9.4% per year [Sarmiento *et al.*, 2004]. In contrast with our results, Polovina *et al.* [2008] report that the North Atlantic oligotrophic gyre is both the smallest and fastest growing gyre, based on a definition of oligotrophic gyres as areas below 0.07 mg chl a m<sup>-3</sup>, rather than the joint SST and OC classification scheme we use. Behrenfeld *et al.* [2006] report a strong correlation between changes in SST and phytoplankton productivity in the stratified oceans (Tropical Biome), supporting our method for identifying changes in oligotrophic gyres by tracking biogeographic provinces defined using SST and OC.

<sup>1</sup>Auxiliary materials are available in the HTML. doi:10.1029/2009GL039883.

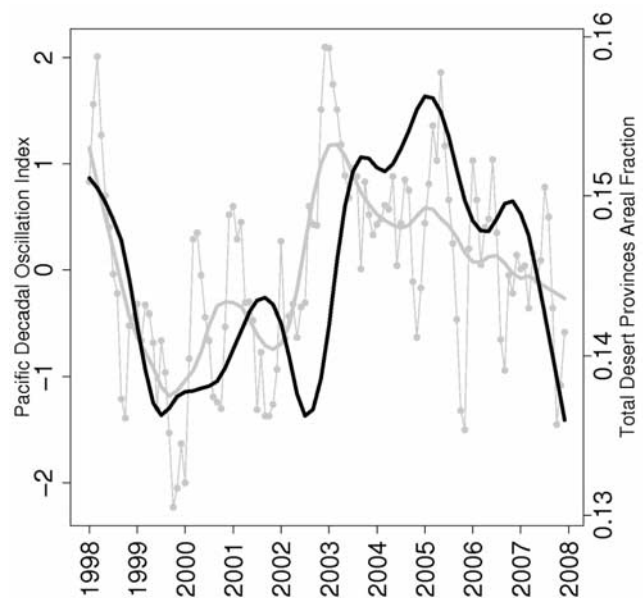


**Figure 2.** The global total area (as a proportion of the Earth's surface area) of (a) the extreme oligotrophic province and (b) the sum of the three oligotrophic provinces for each month in a 10 year time-series (thin line) and the de-seasoned trendline (thick line) for SeaWiFS (black) and MODIS/Aqua (grey). The areas from both records document very similar trends. The area of extremely oligotrophic provinces is increasing and the total area of the three oligotrophic provinces is oscillating.

[10] The decadal expansion of the extreme-oligotrophic provinces is achieved chiefly at the expense of hyper-oligotrophic and oligotrophic provinces (Figure S3). Both the SeaWiFS/AVHRR and MODIS time-series show the combined area of the hyper-oligotrophic and oligotrophic provinces have been shrinking over recent years. This suggests the general makeup of the Tropical Biome is shifting toward an extreme-oligotrophic condition. While the growth in the extreme-oligotrophic provinces is approximately the same magnitude as the shrinkage in the hyper-oligotrophic and oligotrophic provinces, they do not always offset. The combined area of oligotrophic provinces has increased over the last decade (Figure S4). The total global area of all oligotrophic areas is part of a multi-year cycle, showing a pattern similar to the Pacific Decadal Oscillation (PDO); however, the SeaWiFS/AVHRR and MODIS satellite missions are not long enough to definitively show a strong link (Figure 3). Therefore, while we have strong evidence for an increasing trend in the area of extreme-

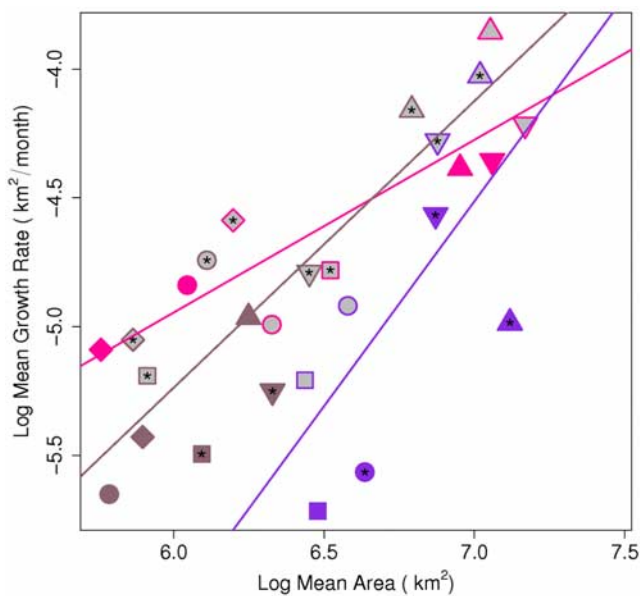
oligotrophic provinces and a decreasing trend in the combined areas of hyper-oligotrophic and oligotrophic regions, it is difficult to tell if the total area of all oligotrophic regions has a long-term trend or is fluctuating in concert with the PDO [McClain *et al.*, 2004].

[11] Within each basin, the magnitude of province growth rates are a power-law function of the average area of the province, therefore the percentage growth rate is larger for larger provinces. Linear regression estimates of de-seasoned growth rate for three different oligotrophic provinces in each of 5 different basins for both SeaWiFS/AVHRR and MODIS satellite instruments yields 27 significant growth rates from 30 time series. Grouping the growth rate magnitudes by extreme-, hyper- and oligotrophic province yields three estimates of the area-scaling exponent for growth rate ( $0.7 \pm 0.3$ ,  $p = 0.003$ ;  $1.1 \pm 0.6$ ,  $p = 0.006$ ; and  $1.6 \pm 0.7$ ,  $p = 0.063$ , respectively; Figure 4). There is substantial uncertainty in these estimates because of small sample sizes, but it is clear that growth rate of these provinces depends on the size of the provinces, so that larger provinces grow (or shrink) faster than small ones. The confidence intervals of the growth rate exponents include  $1/2$ , which is consistent with province expansion at their perimeters. The growth rate exponents for the hyper-oligotrophic and oligotrophic provinces appear to be larger, possibly because of the convoluted interfaces with two different provinces. The constraints imposed by the PDO may be responsible for altering the relationship for the outer provinces compared to the increasing trend of the extreme-oligotrophic province. While previous reports have indicated variable percentage growth rates in oligotrophic areas [Behrenfeld *et al.*, 2006; McClain *et al.*, 2004; Polovina *et al.*, 2008], we find that describing province growth as a power-law function of province size is consistent with the range of growth rates observed. It appears that decadal-scale changes are acting to



**Figure 3.** The Pacific Decadal Oscillation Index (grey) is correlated with the de-seasoned global sum of the three oligotrophic province areas (SeaWiFS/AVHRR, black). The correlation between the de-seasoned data (lines) is  $R = +0.65$ ,  $p < 0.001$ .





**Figure 4.** The area of oligotrophic provinces grows at a rate approximately proportional to the square root of province area. Growth rates ( $\text{km}^2 \text{ month}^{-1}$ ) of the deseasoned area of three different biome types (colors) measured over 1998–2007 for SeaWiFS (filled symbols) and 2002–2007 for MODIS/Aqua (open symbols) are shown as a function of biome area ( $\text{km}^2$ ) in a log-log plot. Symbol shape identifies the basin for each biome as indicated in Figure 1. Regression lines are drawn for each province type. Negative growth rates are indicated with an asterisk and show the same trend as the provinces with positive growth rates. Rates not significantly different from zero were not included in the analysis.

gradually transform one desert province into another by making gradual changes at province interfaces. Intra-annual changes in province type and area dwarf the decadal scale trend, but the gradual change provides evidence for a major reworking of the Tropical Biomes.

[12] Our analysis suggests that two different processes are driving decadal-scale changes in oligotrophic provinces of the Tropical Biome. The growth rate of the oligotrophic provinces within the Tropical Biome is a power-law function of their area. This is likely related to the mechanism of stratification in the provinces, but may be influenced by basin-scale trends such as the PDO. In oligotrophic provinces, constant heating of the surface ocean stratifies the water column, restricting the flow of nutrients to the surface ocean from below the thermocline, although much transport is along isopycnal surfaces [Jenkins and Doney, 2003; Ledwell et al., 1993; Munk and Wunsch, 1998; Sarmiento, 2004]. The latent heat of water is high, therefore the oceans carry a memory signature of previous warming and cooling events which is reflected in their degree of stratification and nutrient transport, which impacts chlorophyll concentration and thus OC. The growth rate exponent for the extreme-oligotrophic province is approximately 1/2, consistent with the extreme-oligotrophic province increasing at a rate proportional to its perimeter, presumably from changes in stratification. The gradual increase in stratification and smooth spatial temperature gradient, means that the area

of ocean ready to be converted to extreme-oligotrophic province should be proportional to the perimeter of that province.

[13] The hyper-oligotrophic and oligotrophic provinces may have a growth rate exponent larger than 1/2. Complicated geometries at province boundaries caused by eddies and planetary waves, suggestive of fractal interfaces (Animation S1) may increase the effective perimeter of the provinces and increase the area-scaling exponent of their growth rates. The total area of the three oligotrophic provinces is not increasing as rapidly as the extreme-oligotrophic province. In fact, the less oligotrophic regions are shrinking as they are converted to more oligotrophic regions. The rate of change of the combined area of the three oligotrophic regions appears to be linked to the PDO and suggests the existence of a second mechanism driving the aggregate areas. The combination of both of these processes will lead to sharper gradients along transects leading out of the oligotrophic gyres. Our analysis of the areas of oligotrophic provinces in the global ocean suggests that the signal of temperature change and the PDO are jointly imprinted on the provinces leading to extreme oligotrophic regions growing at an accelerating rate within the envelope circumscribed by the PDO. The PDO appears to be stable over many centuries which suggests the existence of a stable envelope for the oligotrophic gyres [Biondi et al., 2001; Mantua and Hare, 2002]. This analysis is a first step towards developing a predictive model of the rate of desertification of the ocean and methods for identifying oceanic regions likely to be converted into low productivity areas.

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