

Late Summer chlorophyll blooms in the oligotrophic North Pacific Subtropical Gyre

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[1] In the late summer of 1997, 1999, and 2000 satellite observations of surface chlorophyll from SeaWiFS recorded large blooms in the oligotrophic North Pacific Subtropical Gyre (NPSG) near 30°N and between 130–160°W. The largest blooms covered more than 350,000 km² and lasted as long as 4 months. They are distinct from the surface seasonal cycle of chlorophyll in both timing and amplitude. The blooms are not associated with either SSH or SST anomalies indicative of changes in subsurface structure, nor do they appear to be forced by nutrient fertilization from dust deposition or rainfall. These blooms are compared with summer blooms that have been previously observed in this region by in situ studies, and some potential causes for them are discussed. *INDEX TERMS:* 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689); 4855 Oceanography: Biological and Chemical: Plankton; 4845 Oceanography: Biological and Chemical: Nutrients and nutrient cycling; 9355 Information Related to Geographic Region: Pacific Ocean. *Citation:* Wilson, C., Late Summer chlorophyll blooms in the oligotrophic North Pacific Subtropical Gyre, *Geophys. Res. Lett.*, 30(18), 1942, doi:10.1029/2003GL017770, 2003.

1. Introduction

[2] Intense chlorophyll blooms occurred in the North Pacific Subtropical Gyre (NPSG) near 30°N in the late summer of 1997, 1999, and 2000 (Figure 1). These blooms are consistent with previous research indicating that episodic nutrient inputs into the euphotic zone of the NPSG have significant ecosystem impacts that currently are not well accounted for [Hayward, 1991; Platt *et al.*, 1989; Karl *et al.*, 1997]. It has been suggested that nitrogen fixation could supply as much as half the nitrogen for annual new production, however the timescales (i.e. episodic or related to a regime shift) over which this might occur are not well constrained [Karl *et al.*, 1997]. In this paper, I describe the evolution of the observed chlorophyll blooms, compare them with previously reported blooms in this area, and speculate on the processes responsible for them.

2. Data

[3] Chlorophyll data for the region between 165–125°W and 20–40°N between Sept 1997–Dec. 2002 were obtained from the 8-day and monthly, 9-km, level-3 SeaWiFS (Sea-viewing Wide Field-of-view Sensor) data. To understand the possible forcing behind the blooms 10-day, 1° sea surface height (SSH) anomalies from TOPEX altimetry, weekly 1° sea surface temperature (SST) from NCEP

(National Centers for Environmental Prediction), 8-day Aerosol Optical Thickness (AOT) from SeaWiFS and 6-hour wind data from FNMOC (Fleet Numerical Meteorological and Oceanography Center) are also examined. Nutrient data from the Hawaii Ocean Time-series (HOT) are also used.

3. Chlorophyll Blooms

[4] The observed chlorophyll blooms, defined here as sustained chlorophyll values >0.15 mg/m³, are quite large, covering up to 350,000 km², and persistent, lasting over 4 months in 1997 and 2000 and two months in 1999 (Table 1). The 1997 bloom was the largest; at its maximum extent it covered an area larger than California. While there is longitudinal variation in the location of the blooms, they are consistently centered between 29–31°N. The 1997 bloom propagated eastward, moving from 155°W at the beginning of Sept. to 140°W at the end of Dec. (Figure 2). In contrast, the 1999 and 2000 blooms remained stationary after development, although it is possible that the 2000 bloom originated from a July bloom that appeared north of Hawaii (Figure 1).

[5] Although the blooms all develop in late summer, they are distinct from the seasonal chlorophyll cycle in both timing and magnitude. As seen in Figure 2 the seasonal surface chlorophyll cycle in this region peaks in Jan.–Feb., and its maximum of ~0.12 mg/m³ east of 160°W is less than half the magnitude of the observed blooms, which were as high as 0.3 mg/m³. The slight winter chlorophyll increase is due to mixing of the deep chlorophyll maximum (DCM) to the surface [Venrick, 1993] or to light adaptation [Letelier *et al.*, 1993]. Winter mixing rarely reaches the nutricline so there is no recharge of deep nutrients into the surface later to support a seasonal surface productivity bloom [McGowan and Hayward, 1978; Venrick, 1993].

[6] There were no blooms in 1998 and 2001, and a small bloom in 2002 (centered at 150°W, 32°N), as can be seen in Figure 2. While these blooms appear episodic, they occurred in half the summers observed by SeaWiFS, and in 4 of the 7 CZCS years (1979–1985, not shown); as such they could be an important contribution to the overall ecosystem dynamics.

4. Bloom Forcing

[7] As discussed above, the blooms are not driven by the processes driving the seasonal cycle of chlorophyll in this region (Figure 2.) Assuming a purely nutrient-limited system, surface chlorophyll blooms can be stimulated by shoaling of the nutricline from the passage of Rossby waves [Cipollini *et al.*, 2001], eddies [McGillicuddy and Robinson,

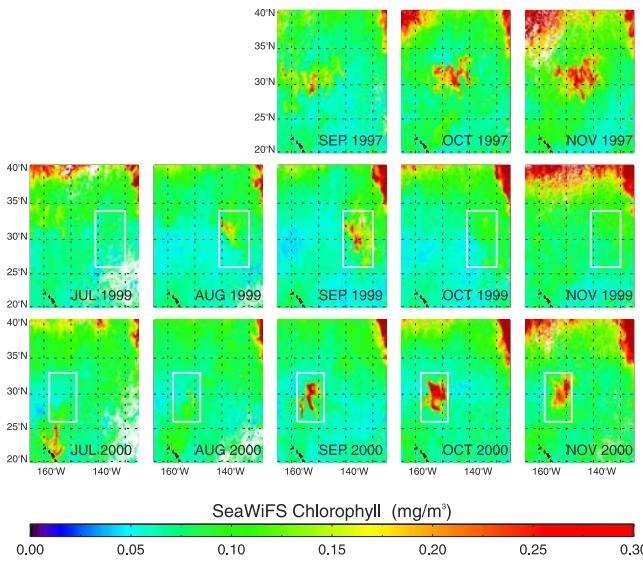


Figure 1. Average SeaWiFS chlorophyll for July–Nov. of 1997, 1999 and 2000 showing large chlorophyll blooms near 30°N, 150°W. No SeaWiFS data are available prior to September 1997. The boxed areas indicate the regions analyzed in Figure 3. White areas have no data due to cloud cover.

1997], or from breaking internal waves [McGowan and Hayward, 1978]. All of these processes generally leave signatures that are evident as negative SSH and/or cold SST anomalies. Summer NPSG blooms have been observed in association with subsurface mixing events and cold SST anomalies [McGowan and Hayward, 1978; Brzezinski *et al.*, 1998]. However, as seen in Figure 2, the SeaWiFS blooms are not associated with any significant negative SSH or SST anomalies indicative of subsurface mixing. It is interesting to note that in 1998, when SST anomalies were coldest, suggestive of increased subsurface mixing, there were no observable SeaWiFS blooms. The location of the blooms coincides with the position of the Subtropical Front [Rodden, 1975]. Niler and Reynolds [1984] suggested that the dynamics of this front could result in localized summer upwelling, which might not have a sea-surface expression. Without concurrent hydrographic data it is difficult to discern the role of the Subtropical Front on the manifestation of the SeaWiFS blooms. However, the SSH and SST data do not indicate any anomalous subsurface mixing coincident with the blooms.

[8] The blooms could be forced by an atmospheric nutrient source. Dust can deposit both Fe [Duce and Tindale, 1991] and NO₃ [DiTullio and Laws, 1991], and NO₃ can also be supplied by rainfall [Paerl, 1985; Cornell *et al.*, 1995]. However, SeaWiFS aerosol measurements, taken as a proxy for dust deposition, do not indicate any

Table 1. Summary of Observed Chlorophyll Blooms

Year	Duration ^a weeks	Average Size ^b km ²
1997	16 (9/17-1/04)	375,000
1999	10 (8/01-10/11)	92,000
2000	21 (8/05-12/29)	148,000

^aMinimum duration, the 1997 bloom was already developed at the start of the SeaWiFS record.

^bDetermined from the number of pixels >0.15 mg/m³.

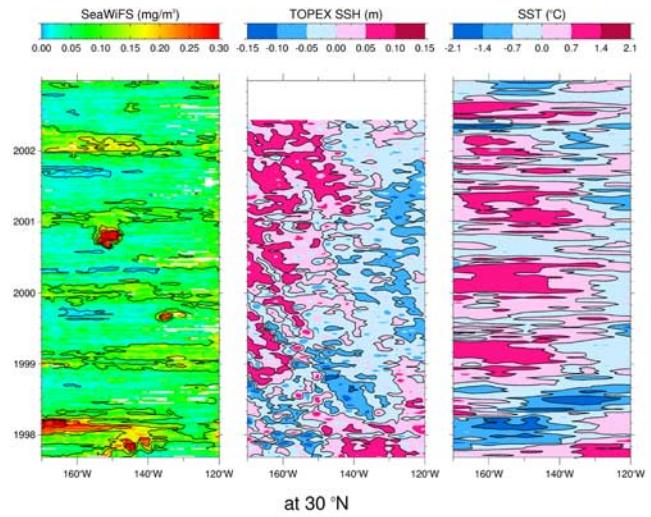


Figure 2. Hovmöller diagrams showing the temporal evolution of (a) chlorophyll, (b) deseasoned SSH, and (c) deseasoned SST along 30°N in the Pacific over the period Sept. 1997–Dec. 2002. Monthly averages were subtracted from the SSH and SST data to remove the seasonal cycle. Contour interval is 0.05 mg/m³ for chlorophyll, 0.05 m for SSH and 0.7° for SST.

dust deposition events preceding development of the blooms (Figure 3). Nor was there any precipitation recorded by the TRMM (Tropical Rainfall Measurement Mission) satellite prior to the blooms (data not shown). Additionally, chlorophyll blooms stimulated from the direct addition of atmospheric NO₃ are generally short lived, lasting only a few days or weeks [Paerl, 1985; DiTullio and Laws, 1991], whereas the blooms observed here last several months. The spatial magnitude and duration of these blooms suggests a larger flux of nutrients than would occur from rain or dust events.

[9] Another possible nutrient source is new N made available from nitrogen-fixing organisms. Summer blooms observed during the CLIMAX program near 28°N were composed primarily of *Rhizosolenia* diatoms containing the

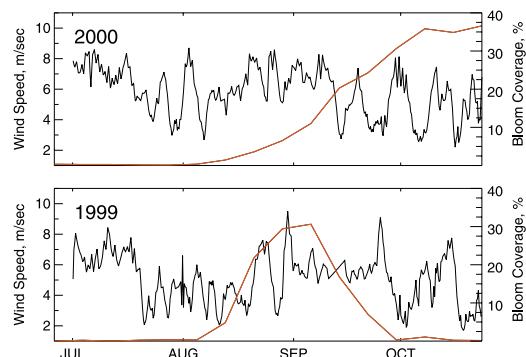


Figure 3. Average FNMOC wind speed in the vicinity of the 1999 (bottom) and 2000 (top) blooms from July through Oct. Averages are taken within the boxes marked on Figure 1. The bloom coverage (red) is calculated as the percentage of values >0.15 mg/m³ within the box using the 8-day data.

nitrogen-fixing endophyte *Richelia intracellularis* [Venrick, 1974; Mague *et al.*, 1974], and blooms of diatoms containing nitrogen-fixing endosymbionts have frequently been observed near the Hawaii Ocean Time-series (HOT) further to the south ($22^{\circ}45'N$, $158^{\circ}W$) [Heinbokel, 1986; Brzezinski *et al.*, 1998; Scharek *et al.*, 1999]. Large summer blooms of nitrogen-fixing *Trichodesmium* have also been observed at HOT [Karl *et al.*, 1992]. However, *Trichodesmium* does not appear to be as common near $28^{\circ}N$ as it is at HOT [Venrick, 1997].

[10] It is sometimes possible to identify the composition of satellite-observed blooms by analysis of the water-leaving radiances. This has been done for coccolithophore blooms [Brown and Yoder, 1994], and for significantly dense *Trichodesmium* blooms. However, *Trichodesmium* blooms with chlorophyll values $<1\text{ mg/m}^3$ appear indistinguishable from other phytoplankton populations [Subramaniam *et al.*, 2002]. The SeaWiFS blooms do not appear to be dominated by either coccolithophores or *Trichodesmium* according to the methods of Brown and Yoder [1994] and Subramaniam *et al.* [2002] (data not shown). However, since the blooms are significantly less than the 1 mg/m^3 threshold, it can not be ruled out that the blooms are *Trichodesmium*.

[11] The strength of satellite observations is that they can quantify the frequency, size and duration of blooms, which is difficult from shipboard observations. A $1,000\text{ km}^2$ *Trichodesmium* bloom occurred in the HOT area in 1989 [Karl *et al.*, 1992], a considerably smaller area than covered by the SeaWiFS blooms (Table 1). However, a *Rhizosolenia-Richelia* bloom in 1972 spanned 8° of longitude [Mague *et al.*, 1974], a similar dimension to the SeaWiFS blooms (Figure 1). The *Rhizosolenia-Richelia* blooms appear to have been relatively short-lived, lasting a few weeks to a month [Venrick, 1974; Mague *et al.*, 1974]. From the SeaWiFS data it is evident that blooms developing in this region in the late summer can last until the end of the year. It is possible that the longevity of the SeaWiFS blooms represents different phytoplankton populations. For example, the blooms might initially be composed of *Rhizosolenia-Richelia*, and upon collapse of this population, which Venrick [1974] observed to take about 10 days, a secondary phytoplankton bloom could develop fueled from the new N introduced by *Richelia* via nitrogen fixation.

[12] Another possible source of N into the surface layer is from vertically migrating mats of *Rhizosolenia*. The extent to which *Rhizosolenia* mats fix nitrogen is uncertain [Martinez *et al.*, 1983; Villareal and Carpenter, 1989]. However, their main supply of NO_3^- appears to be obtained by vertical migration into the nitracline via carbohydrate ballasting [Villareal *et al.*, 1999]. These mats occur extensively during the summer in the region of the observed SeaWiFS blooms, and it has been estimated that they transport up to one third of new N into the mixed layer [Villareal *et al.*, 1999].

[13] Due to their buoyancy, both *Trichodesmium* and *Rhizosolenia* can accumulate at the surface in large numbers during calm conditions [Capone *et al.*, 1997; Villareal and Carpenter, 1989]. The strength of the wind during the initiation and development of the 1999 and 2000 blooms are shown in Figure 3. Both the 1999 and 2000 bloom developed during periods of relatively stronger winds ($>5\text{ m/sec}$). The 1999 bloom occurred following a period

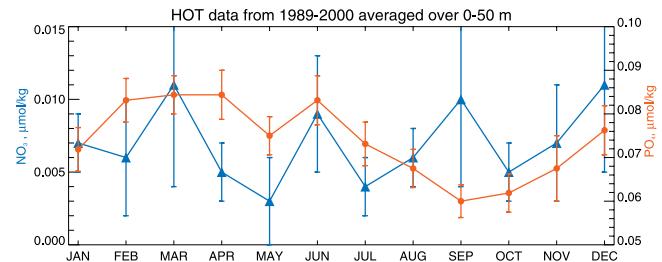


Figure 4. Monthly averages and error of NO_3^- (blue triangles) and PO_4^{2-} (red circles) in the upper 50 m at HOT ($22^{\circ}45'N$, $158^{\circ}W$) from 1989–2000.

of calmer winds, while the 2000 bloom was initiated during a month-long period of sustained winds ($>5\text{ m/sec}$), and was maintained during a period when conditions alternated between weaker and stronger winds. The relatively strong winds during the blooms would not favor large surface accumulations of *Trichodesmium* or *Rhizosolenia* [Capone *et al.*, 1997; Villareal and Carpenter, 1989]. It is possible that the stronger winds mixed the DCM to the surface; blooms sampled near $28^{\circ}N$ during CLIMAX had elevated chlorophyll down to the normal depth of the DCM (110 m) [Venrick, 1974]. However, this does not account for the magnitude of the surface blooms. Since chlorophyll values in the DCM are typically 0.3 mg/m^3 or less [Venrick, 1974; Hayward, 1987], to account for surface chlorophyll values of 0.3 mg/m^3 would require a DCM with chlorophyll levels three times higher than normal. Another possibility is that the surface chlorophyll are secondary blooms that have been fueled by new N brought into the euphotic zone either from nitrogen fixation, or from biologically mediated transport across the nutricline.

[14] The hypothesis that the blooms are fueled from new N assumes a N-limited, rather than P-limited, system. While N is generally the controlling macronutrient in the ocean, results from HOT have suggested a recent transition from N limitation to P limitation [Karl *et al.*, 1997]. It is not clear, however, to what extent HOT is representative of dynamics near $30^{\circ}N$ [McGowan, 1995]. Both N limitation [Perry and Eppley, 1981] and P limitation [Perry, 1972] have been observed near $30^{\circ}N$. At HOT the NO_3^- and PO_4^{2-} pools are uncoupled on both seasonal and interannual timescales [Karl *et al.*, 2001], suggesting that the limiting nutrient could fluctuate seasonally and interannually. The seasonal cycle of NO_3^- and PO_4^{2-} at HOT is shown in Figure 4. Data from $30^{\circ}N$ are not shown due to insufficient nutrient data to construct the seasonal cycle (in the NODC database). NO_3^- is consistently low throughout the year ($<0.01\text{ }\mu\text{mol/kg}$) and there is a drawdown of surface PO_4^{2-} in the late summer, suggesting an influx of new NO_3^- . This pattern suggests that NO_3^- could be the limiting nutrient in the summer, and the late summer blooms, fueled by new N sources, are eventually limited by PO_4^{2-} .

[15] In summary, relatively intense late-summer chlorophyll blooms were observed in the NPSG from SeaWiFS in 3 out of 6 years, and in 4 out of 7 of the CZCS years. An interesting aspect of these blooms is their consistent location, being centered near $30^{\circ}N$ between 135° – $160^{\circ}W$. SSH and SST data do not suggest that changes in subsurface

structure are supplying nutrients to the surface to support these blooms, nor is there any indication that nutrient deposition by dust events or precipitation is triggering the blooms. Possible sources of new N to fuel these blooms include nitrogen fixation, either from *Trichodesmium* or *Rhizosolenia/Richelia*, and/or an influx of deep N to the euphotic zone from vertical migrations of *Rhizosolenia*. In situ sampling is needed to understand the cause and composition of these blooms.

[16] **Note added in proof.** Another bloom developed in mid-July of 2003 near 140°W.

[17] **Acknowledgments.** Thanks to the SeaWiFS Project (Code 970.2) and the Distributed Active Archive Center (Code 902) at NASA/GSFC for the SeaWiFS data, and to the NASA Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory, California Institute of Technology for the TOPEX data. The nutrient data were obtained from the HOT website (<http://hahana.soest.hawaii.edu>). Thanks to S. Bograd, A. Leising, F. Schwing, and A. Subramaniam for helpful discussions, and to two reviewers for their comments on earlier versions of this manuscript.

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