Cold halocline, increased nutrients and higher chlorophyll off Oregon in 2002

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[1] Observed changes in the nutrient levels in the halocline of the California Current during 2002 indicated a natural eutrophication that was accompanied by increased chlorophyll and oxygen in surface water. Decreased oxygen in the lower water column over the shelf indicated that much of the phytoplankton production was respired rather than passed on to higher trophic levels. In 2002 the halocline water was >1°C colder than usual and 0.5°C colder than any previous observation. Four transect lines off the coast of Oregon show a 50% increase in nitrate, phosphate and silicate at 33 psu in 2002 compared to 1998–2001. The increase in nutrients resulted in a 2-fold increase in chlorophyll standing stocks during the summer of 2002 compared with the preceding four years. A significant portion of the increased production was subsequently respired resulting in low oxygen water over the shelf. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 4845 Oceanography: Biological and Chemical: Nutrients and nutrient cycling; 4283 Oceanography: General: Water masses. **Citation:** Wheeler, P. A., A. Huyer, and J. Fleischbein, Cold halocline, increased nutrients and higher chlorophyll off Oregon in 2002, *Geophys. Res. Lett.*, *30*(15), 8021, doi:10.1029/2003GL017395, 2003.

1. Introduction

[2] An invasion of subarctic water into the northern California Current in 2002 resulted in an anomalously cool layer at 30–150 m [*Freeland et al.*, 2003]. The permanent halocline that has salinities of 32.2 to 33.8 was about 1°C cooler in summer 2002 compared with summer 2001. This cool anomaly is likely caused by a stronger than normal southward flow in the California Current and a weaker than normal northward flow in the Alaska and Davidson Currents in spring of 2002 [*Freeland et al.*, 2003]. The halocline water outcrops at the surface during the summer upwelling season (May–September) off the coast of Oregon [*Huyer*, 1977].

[3] The purpose of this study was to examine the differences in the nutrient characteristics of the cooler halocline water and the effects of the changes in nutrient supply on the standing stock of phytoplankton and oxygen levels in the coastal waters off Oregon. Data for this analysis are derived from the U.S. GLOBEC North East Pacific (NEP) Program [*Strub et al.*, 2002], and includes seasonal sampling of five lines extending to between 63 and 157 km offshore between 44°39′N and 41°54′N (Figure 1).

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2. Observations along Newport Line at 44°39′N

[4] The relationship of nutrient concentration versus salinity is similar for the summers of 1998–2001(Figure 2). In comparison, nutrients for summer 2002 are elevated with the largest increases at a salinity of about 33 psu in the core of the halocline. Little difference in nutrients versus salinity is apparent in the deeper water (200–350 m) at salinity of 34, while moderate differences are apparent in the lower salinity waters (Figure 2).

[5] The halocline water is at about 100 m depth offshore and its depth shoals gradually between 126°W and 124.5°W, and more rapidly further inshore as the 33 psu water outcrops at the surface over the shelf (Figure 3). This outcropped water is the source of the nutrients during the summer upwelling season. Note that the depth of the halocline does not vary between 2002 and 1997–2001(Figure 3). Cross-shelf increases in nutrient concentrations at 33 psu for the Newport line during the summer of 2002 are evident between 124 and 125°W but are not significant at 126°W (Figure 4).

[6] Surface nitrate concentrations during the upwelling season vary from non-detectable to a maximum of about 35 μM depending on the oscillations between upwelling and relaxation events [*Dickson and Wheeler*, 1995]. During the upwelling season, nitrate usually goes to depletion before phosphate and silicate [*Corwith and Wheeler*, 2002; *Hill and Wheeler*, 2002]. Consequently the observed increases in nitrate in the 2002 halocline should lead to an increase in phytoplankton biomass. Chlorophyll, an estimate of phytoplankton abundance, indeed shows a dramatic (offscale) increase in biomass, greater than 5-fold near shore (Figure 5). Fluorescence profiles (data not shown) also indicate parallel increases in the subsurface chlorophyll maximum further offshore.

3. Alongshore Observations for 1998–2002

[7] Mean halocline nutrient concentrations for midshelf and upper slope stations off Newport were 17.7 μM nitrate, 1.53 μM phosphate and 20.7 μM silicate for 1998–2001. In 2002, they were elevated by an average of 11.4 μM nitrate, 0.89 μM phosphate and 15.0 μM silicate (Table 1). Changes in nutrient concentrations were compared along the east/west transects for Heceta Head, Coos Bay and Crescent City (Figure 1) for the summer of 2002 versus summers of 1998–2000. Mean halocline nutrient concentrations for 1998–2001 and 2002 for the Heceta Head line were similar to the Newport line as were changes in temperature and nutrients further to the north off Vancouver Island (Frank Whitney, personal communication). In contrast, the two lines to the south were significantly warmer (halocline

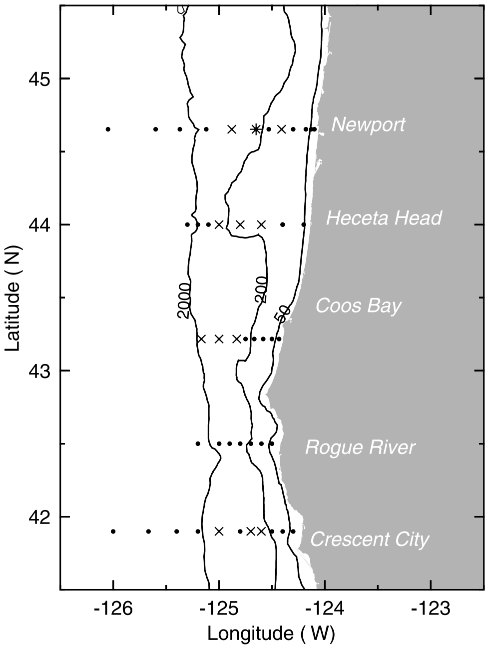

Figure 1. Map of transect lines and CTD station locations. X = the midshelf and upper slope stations used for the alongshore nutrient comparisons. * = station NH-25.

temperature increased by 0.5 to 1.0°C per degree of latitude) and were significantly lower in nutrients (Table 1). There were no significant changes in nutrient ratios (data not shown).

[8] The mean nearshore (depths <200 m) chlorophyll maxima between 45 and 42°N ranged from 4.6 to 6.6 μg/l between 1998 and 2001 and from 93 to 17.4 μg/l in 2002 (Table 2) suggesting at least a doubling of phytoplankton biomass along the coast of Oregon. Further offshore, maximum chlorophyll levels are seen at about 50 m depth and the biomass was 2–4 times greater in the subsurface layer in

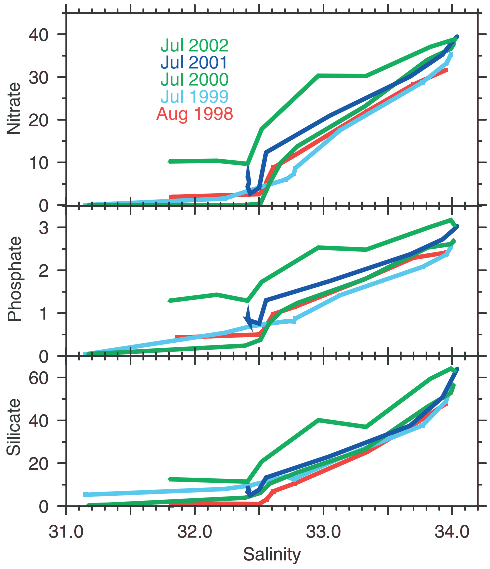

Figure 2. Nutrient concentrations (μM) versus salinity for station NH-25 along the Newport line from 1998–2002.

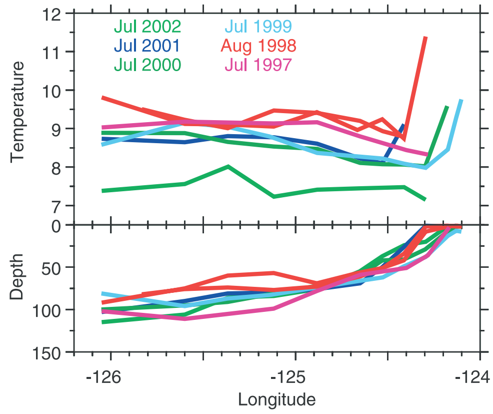

Figure 3. Temperature and depth of 33 psu halocline water as a function of longitude for the Newport line from 1997–2002.

2002 compared with 2000(data not shown). Similarly, SEAWIFS data [*Thomas et al.*, 2003] showed an average doubling of mean August chlorophyll levels between 43 and 45°N.

4. Probable Causes

[9] The 2002 changes in the characteristics of the halocline were evident off Oregon and off Vancouver Island. Alongshore advection could account for the anomalously cool water off Oregon and Vancouver Island, while enhanced eastward flow of the North Pacific Current could account for the similar anomaly 1200 km offshore at Ocean Station Papa [*Freeland et al.*, 2003]. *Kosro* [2003] describes a 1400 km southward displacement of near surface water between January and July of 2002. Cross-track altimeter surface velocities show anomalous southward and on-shore flow during 2002 compared to preceding years [*Strub et al.*,

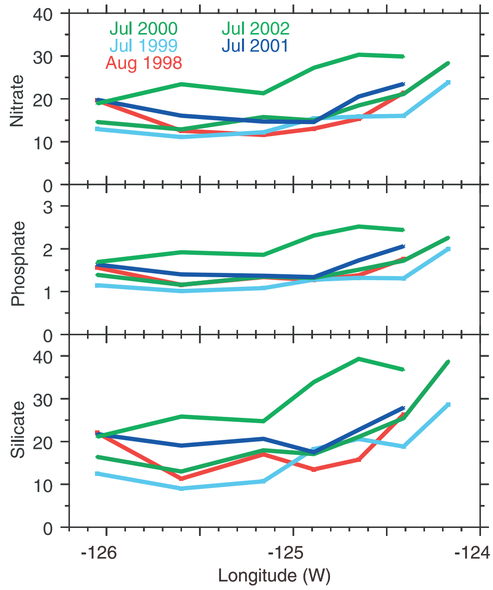

Figure 4. Nutrient concentrations (μM) at 33 psu as a function of longitude along the Newport line from 1998–2002.

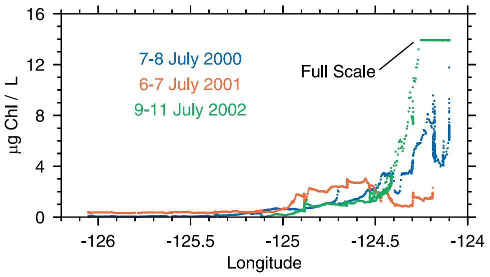

Figure 5. Chlorophyll concentrations calculated from underway fluoresence vs extracted chl a in nearsurface water along the Newport line during July cruises from 2000–2002.

2003]. It is clear that this water was transported southward during the first half of 2002 and its characteristics were evident from Line P off Vancouver Island (50°N), along the coast off Oregon (45 to 42°N), to as far south as southern California (33°N). These subarctic water properties are most evident close to shore in the northern half of this region and are further offshore in the southern California Current system [*Bograd and Lynn*, 2003] following the general location of the California Current as it flows southward.

5. Ecosystem Responses

[10] The change in the characteristics of halocline water in the northern California Current include a significant increase in nutrients that is correlated with an increase in phytoplankton standing stock. This response is expected since primary production in these waters is predominantly nitrate limited [*Corwith and Wheeler*, 2002; *Hill and Wheeler*, 2002]. Analysis of SEAWIFS data [*Thomas et al.*, 2003] also indicates the dramatic increase in phytoplankton standing stocks along the Oregon coastline in 2002 compared to 1998–2001. Increases in nutrients and chlorophyll were also seen in 2002 in the core of the southern California Current but were much smaller, i.e. nitrate increased to 4.8 µM and chlorophyll increased to 0.8 µg/l [*Bograd and Lynn*, 2003]. This weaker response off California is consistent with the latitudinal changes in the halocline water [*Fleming*, 1958; *Reid*, 1997].

[11] Broad scale changes in productivity of the Pacific Ocean have been attributed to "regime shifts" [*Chavez et al.*, 2003]. Satellite derived data show a 15% increase in net primary production in the southern California Current between 1996 and 2001 [*Kahru and Mitchell*, 2002]. *Chavez et al.* [2003] attribute this change in chlorophyll to large-scale climate oscillations (relaxation of the Aleutian Low) and a return to a cool "anchovy regime" during the late 1990s. How our observations are related to the broader scale changes in the Pacific Ocean is yet to be determined and is beyond the scope of this paper.

[12] Two possible fates of the increased primary production are an increase in zooplankton or other higher trophic level standing stocks or sinking of the phytoplankton and increased water column and benthic respiration. Copepod abundance appears to have decreased in 2002 compared to 1998–2001, so the increase in primary production did not transfer to higher trophic levels (William Peterson, personal communication). Unusually high abundances of jelly fish (which graze on copepod and euphausid eggs) may have contributed to the usually low copepod biomass during the summer 2002(Cynthia Suchman, personal communication).

[13] Although sinking fluxes were not determined during this sampling, lower than normal oxygen concentrations in bottom water over the shelf along the Newport line (Figure 6) and the Crescent City line (41°54′N, Table 3) both suggest that a major fate of the increased primary production was sinking to the bottom and subsequent respiration. Very low values of dissolved oxygen are normal at depths below 300 m over the continental slope, but no

Table 1. Mean ± SD for Temperature (°C) and Nutrient Concentrations (µM) at Mid-shelf and Slope Stations in the Halocline at 33 psu

Latitude	1998–2001 Temperature	2002 Temperature
44°39′N	8.54 ± 0.44	7.45 ± 0.03
44°00′N	8.57 ± 0.43	7.56 ± 0.21
43°13′N	9.19 ± 0.61	7.99 ± 0.25
41°54′N	11.28 ± 1.49	8.72 ± 0.52
	1998–2001 Nitrate	2002 Nitrate
44°39′N	17.70 ± 2.73	29 07 ± 1.79
44°00′N	19.18 ± 1.73	27.69 ± 2.60
43°13′N	10.46 ± 4.18	22.61 ± 1.30
41°54′N	6.80 ± 1.07	17.60 ± 0.39
	1998–2001 Phosphate	2002 Phosphate
44°39′N	1.53 ± 0.16	2.42 ± 0.11
44°00′N	1.74 ± 0.23	2.30 ± 0.23
43°13′N	1.02 ± 0.21	1.89 ± 0.10
41°54′N	0.87 ± 0.13	1.64 ± 0.06
	1998–2001 Silicate	2002 Silicate
44°39′N	20.69 ± 3.67	35.66 ± 4.32
44°00′N	21.60 ± 2.13	32.74 ± 3.32
43°13′N	9.49 ± 4.06	25.07 ± 2.06
41°54′N	8.70 ± 4.18	17.71 ± 0.81

Table 2. Comparison of Nearshore Fluorometer-estimated Chlorophyll for 1998–2001 vs 2002

Latitude	1998–2001	2002
44°39′N	6.76 ± 2.87	10.44 ± 7.09
44°00′N	4.44 ± 0.58	9.01 ± 6.12
43°13′N	6.91 ± 2.36	15.40 ± 1.98
42°30′N	5.09 ± 2.45	8.40 ± 2.14
41°54′N	5.59 ± 3.65	9.67 ± 8.06

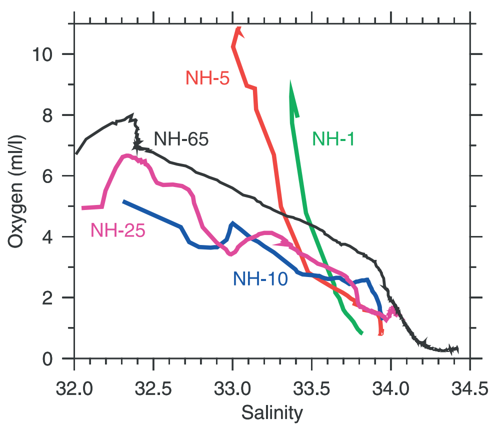

Figure 6. Oxygen versus salinity for 9–10 July 2002 along the Newport line.

Table 3. Mean ± SD for Oxygen Percent Saturation in Surface and Bottom Water at Inner Shelf Stations

Latitude	1999–2001 Surface % Saturation	2002 Surface % Saturation
44°39′N	107 ± 11	159 ± 28
43°00′N	118 ± 9	109 ± 34
42°13′N	115 ± 14	136 ± 32
41°54′N	96 ± 4	116 ± 24
Latitude	1999–2001 Bottom % Saturation	2002 Bottom % Saturation
44°39′N	32.3 ± 11.6	14.4 ± 2.9
43°00′N	24.8 ± 0.6	20.3 ± 3.6
43°13′N	32.5 ± 0.6	28.4 ± 3.6
41°54′N	48.8 ± 7.6	27.1 ± 4.1

values this low <1 ml/L) have been observed previously over the inner shelf off Oregon. Plotting oxygen concentration versus salinity (Figure 6) indicates that low values of oxygen at the inner shelf stations occur at a lower salinity than those at offshore stations. Thus these values are not just the result of vertical advection, but instead must have been modified after upwelling. It is likely that the very high (supersaturated) values of oxygen in the near-surface layer at the inshore stations result from very high primary productivity there. We think that it is likely that respiration of this enhanced plankton biomass contributed to the hypoxic waters near the bottom.

[14] Over Heceta Bank (44°N) Oregon Dept. of Fish and Wildlife found only dead fish and invertebrates during their 2002 July survey of this normally productive fish habitat (Dave Fox, personal communication). The hypoxic zone covered more than 700 km^2 between Newport and Heceta Head. The Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) extended their survey measurements to continue mapping of the hypoxia and nutrient enrichment in shallow waters and estimated that the anomalous nearshore conditions persisted for at least two months (Brian Grantham, personal communication).

[15] Two immediate consequences of this invasion of Subarctic water off Oregon were an increase in primary production and a resulting increase in water column and benthic respiration. Results from the NEP GLOBEC Program have successfully documented the extent of El Niño Oscillations on the physical circulation [*Smith et al.*, 2001; *Huyer et al.*, 2002] and nutrient supply off Oregon [*Corwith and Wheeler*, 2002]. This more recent change in halocline water further documents the potential broad scale climate effects on coastal productivity and clearly illustrates the importance of coordinated observational programs to understanding and predicting the effects of climate changes on the coastal ecosystems.

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