Two Coastal Upwelling Domains in the Northern California Current System

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Introduction

One of the central goals of the U.S. GLOBEC North East Pacific Program's Long Term Observation Program in the California Current was to determine whether the characteristics of the upwelling ecosystems north and south of Cape Blanco differ significantly. To address this goal, a pair of hydrographic sections, one north and one south of Cape Blanco (Figure 1), was sampled in five summers (1998-2000 and 2002-2003); our attempt to sample both sections in a sixth summer (2001) did not succeed.

The NH-line at 44.6N off Newport, Oregon, lies about 130 km south of the mouth of the Columbia River, and spans a relatively wide shelf. The CR-line at 41.9N off Crescent City, California, lies 300 km farther south and spans a narrower shelf. Summer winds are predominantly northerly in both locations but the northerly winds are stronger and more persistent off Crescent City than off Newport. Both sections extend about 150 km offshore from the inner shelf.

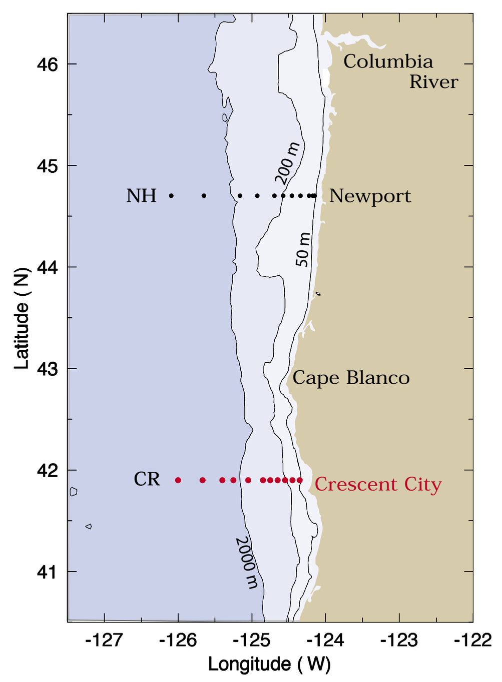

Figure 1. Shelf and coastline geometry in the region of the section pair, showing the standard CTD stations of each section, and the location of Cape Blanco, Columbia River estuary, and the 50, 200 and 2000 m isobaths.

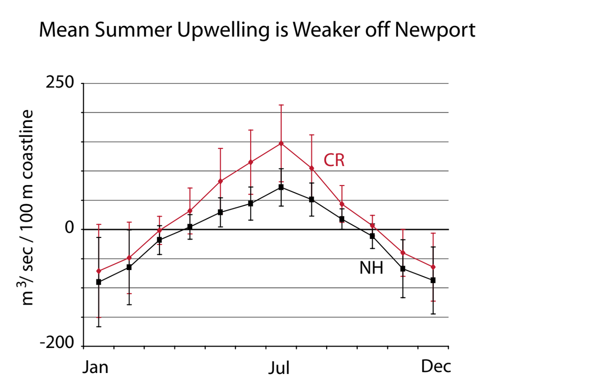

Figure 2. Long-term (1946-2003) monthly means with standard deviations of the coastal upwelling index at 45 N, 125 W (black) and 42 N, 125 W (red). Data provided by Pacific Environmental Group (www.pfeg.noaa.gov).

Paired Sections of Important Properties

For the five pairs of summertime sections off Newport and Crescent City we show the upper-ocean temperature, salinity, spiciness, geostrophic velocity, nitrate and chlorophyll (Figure 3). Offshore surface waters tend to be warmer and fresher off Newport. The surface mixed layer is very thin off Newport, deeper off Crescent City. Off Newport, there is a permanent halocline (32.8 < S < 33.8) with an offshore depth of 100 m rising to the sea surface inshore, and a shallow (5-25 m) halocline underlying a very fresh (S<32) layer; off Crescent City a single halocline coincides with the thermocline. Spiciness is lower off Newport than Crescent City, due to lower salinity in the surface layer (top 20 m or so), and to lower temperatures below. All distributions of geostrophic velocity show the equatorward coastal jet occurring over the shelf off Newport, but it often lies offshore of the shelf-break off Crescent City, where the jet is usually stronger and has more eddies. Nitrate concentrations in the upper 50 m tend to be higher, and the band of recently upwelled surface water (T<10C and nitrates >5 micro-g/l) is much wider off Crescent City than off Newport. Chlorophyll is usually higher and often much deeper at off Crescent City.

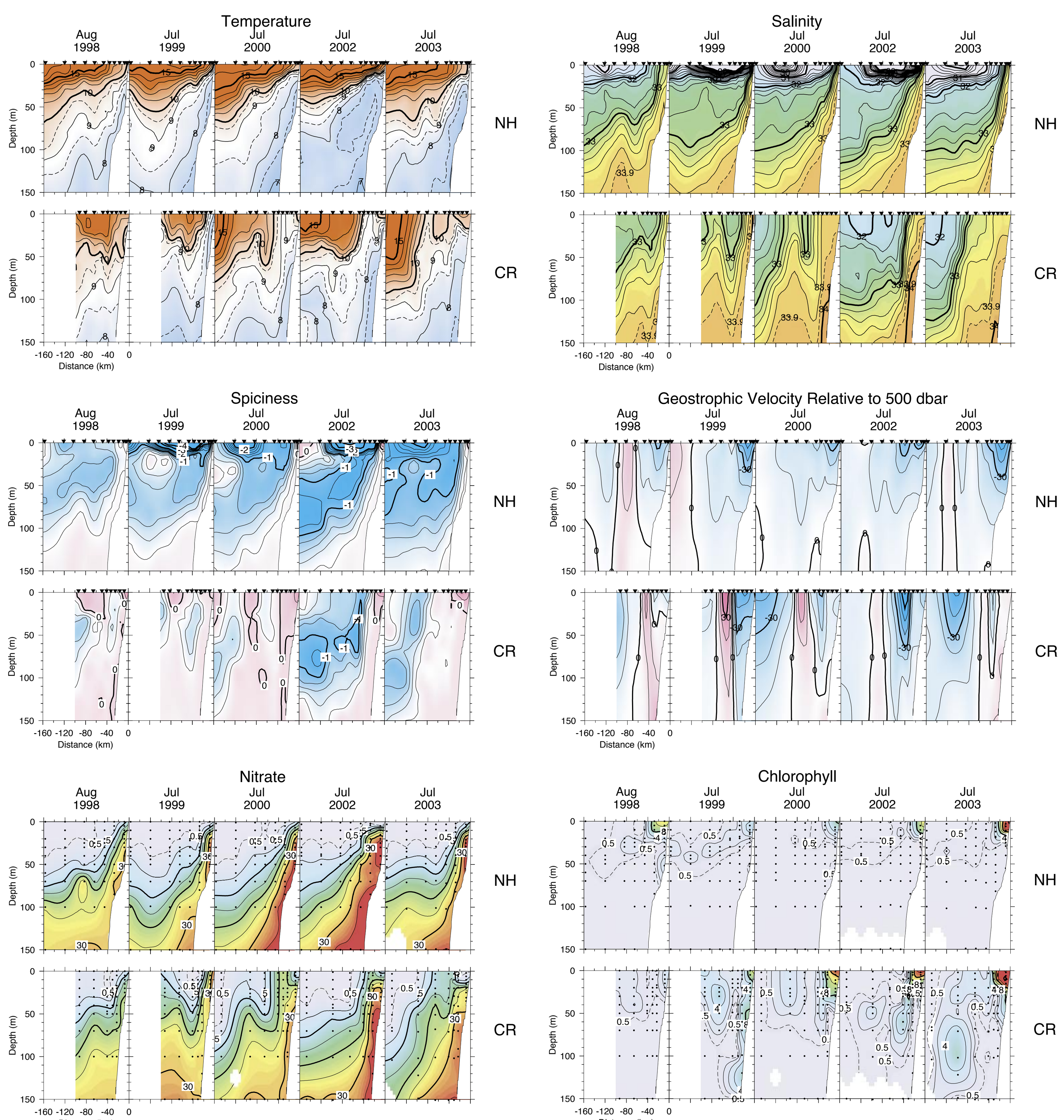

Figure 3. Upper-ocean distributions of (a) temperature (C), (b) salinity (psu), (c) spiciness (kg/m³), (d) geostrophic velocity (cm/s), (e) nitrate (μmol/l) and (f) chlorophyll (grams/m³). Spiciness was calculated from T-S characteristics following Flament (2002). Over the shelf, geostrophic velocity relative to 500 dbar was calculated by the method of Reid and Mantyla (1976).

Significant Differences

Many features of the environment are significantly different in the two domains:

The surface layer is significantly fresher off Newport than off Crescent City, except at the offshore and inshore ends of the sections (Figure 4). Off Crescent City, the lowest salinity occurs at the offshore end of the section and has a value of about 32.1 psu, about 0.5 psu fresher than typical North Pacific Subarctic surface water; salinity increases monotonically toward shore, as we would expect if coastal upwelling were the only determining factor. Offshore surface salinities off Newport are lower (31 psu), and minimum values there (about 29 psu) occur in a band about 30-90 km from shore, coinciding with the summer axis of the Columbia River Plume which is advected southward by the coastal jet and offshore by the Ekman transport.

The surface layer is significantly thinner off Newport than off Crescent City. Off Newport, the reduced surface salinities contribute to enhanced stratification which tends to suppress vertical mixing by the wind. Defining mixed layer depth (MLD) as the depth at which the seawater density exceeds the surface density by 0.1 kg/m³, we find MLD to be significantly thinner off Newport than off Crescent City except over the inner shelf.

The surface layer is significantly warmer off Newport than off Crescent City. Climatological data (Nelson and Husby, 1983) suggest that the net surface heat flux in July is about 230 W/m² off both Newport and Crescent City. The concentration of similar heat storage in a thinner mixed layer can explain the warmer surface water off Newport.

The surface layer is significantly less dense off Newport than off Crescent City. The combination of higher temperatures and lower salinities off Newport explains the large surface density differences over the outer shelf and slope.

The upwelling front is much farther offshore off Cresent City than off Newport. The location of the strongest offshore gradient in temperature and density lies over the continental shelf off Newport (within 30 km of the coast), but lies much farther from shore (at about 120 km) off Crescent City.

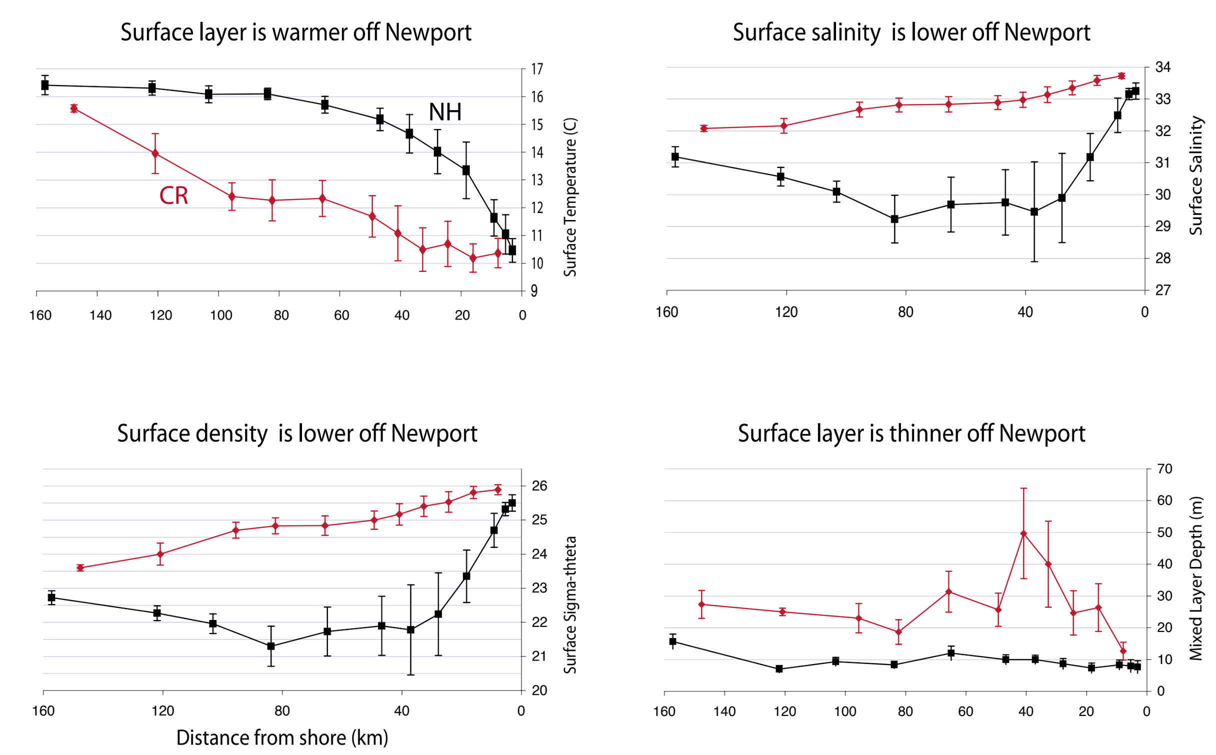

Figure 4. Offshore profiles of the mean with standard errors of (a) surface temperature, (b) surface salinity, (c) surface density, and (d) surface mixed layer depth (defined as the depth at which the in-situ density exceeds the surface density by 0.1 kg/m³).

Sea surface elevation over the outer shelf and slope is higher off Newport than off Crescent City. At Newport surface elevation (steric height relative to 150 cbar) falls monotonically toward shore, but off Crescent City there is a relative extrema over the continental slope (Figure 5), suggesting a recurring eddy there.

The coastal jet is simpler, less variable and closer inshore off Newport than off Crescent City. The geostrophic surface current off Newport has a single core that is confined to the continental shelf (Figure 5). Off Crescent City, the mean southward current has two maxima (one over the upper continental slope, one farther off), and a mesoscale eddy with some northward flow over the outer slope is often present.

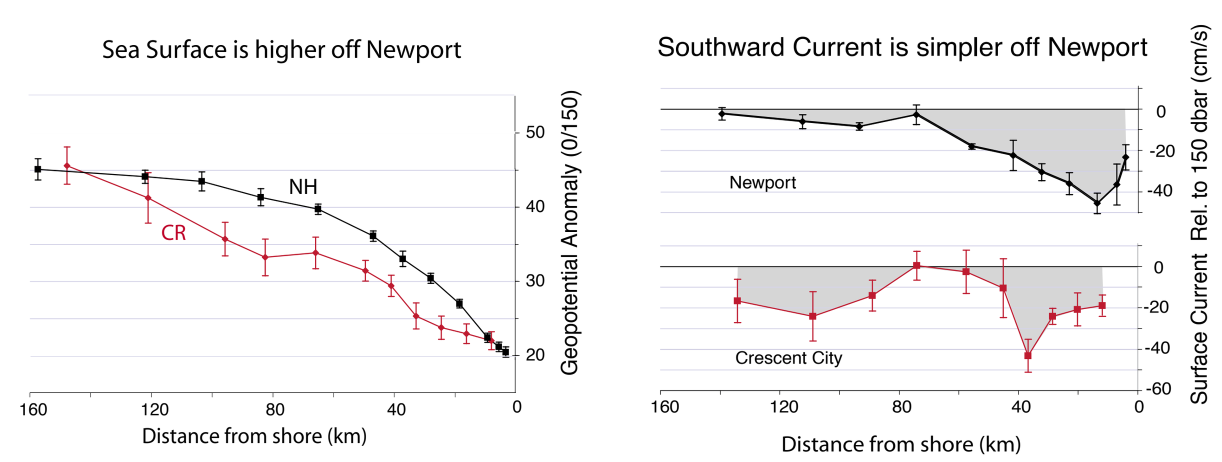

Figure 5. Offshore profiles of the mean with standard errors of (a) surface elevation (steric height relative to 150 dbar), and (b) geostrophic surface current (relative to 150 dbar). A reference level of 500 dbar yields similar results.

Surface nutrients are higher off Crescent City than off Newport. Off Newport, high nutrient concentrations in the surface layer occur inshore of the mid-shelf (Figure 6). Off Crescent City, high nutrient concentrations occur over the entire shelf and slope, and even farther offshore.

Phytoplankton biomass is higher off Crescent City than off Newport. Surface chlorophyll concentrations are similar off Newport and Crescent City, but high values of chlorophyll extend much deeper off Crescent City than they do off Newport (Figure 3f). Values of vertically integrated chlorophyll are 3-4 times as high off Crescent City (Figure 6). High chlorophyll concentrations at depths below the photic zone off Crescent City are confirmed by independent fluorescence data; these are also below the base of the surface mixed layer, and indicate that subduction may be more frequent off Crescent City than off Newport.

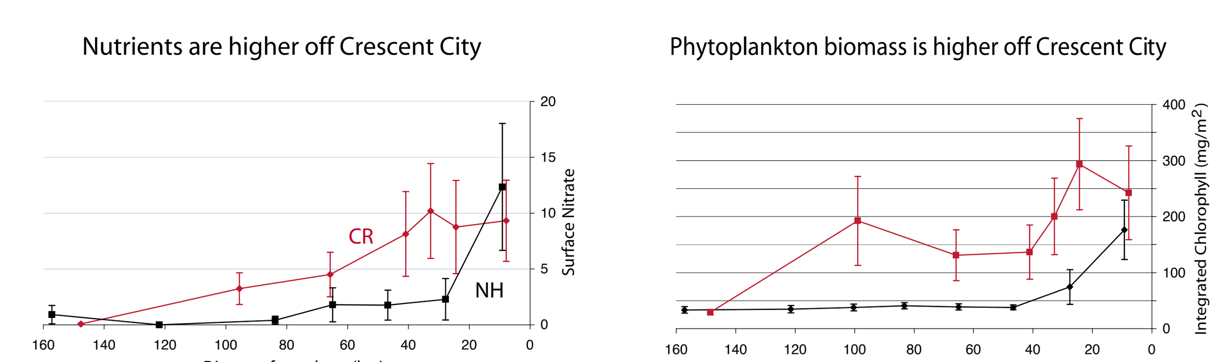

Figure 6. Offshore profiles of the mean with standard errors of (a) surface nitrate (μgm/l), and (b) vertically integrated chlorophyll (gm/m²).

Cause of Differences

These significant differences seem to have two major causes. The first is the summer effluent of the Columbia River, and the second is the spatial variation in the southward winds.

Columbia River Plume. Discharge from the Columbia River peaks in early summer, and the discharge plume extends southwestward from its mouth at 46.25N. The NH line lies only 130 km south of the mouth, but the CR line lies about 400 km south of the mouth. The summer discharge is advected rapidly southward by the coastal jet and slowly offshore by Ekman transport. Thus the NH line off Newport intersects the plume, while the CR line off Crescent City lies mostly inshore of the plume (Figure 7). Although the Columbia River plume is thin, it contains a substantial fraction of the total fresh water in this region, and it clearly accounts for higher stratification, thinner mixed layer and warmer surface temperatures of Newport. It is likely also responsible for the nearshore position of the upwelling front and coastal jet off Newport.

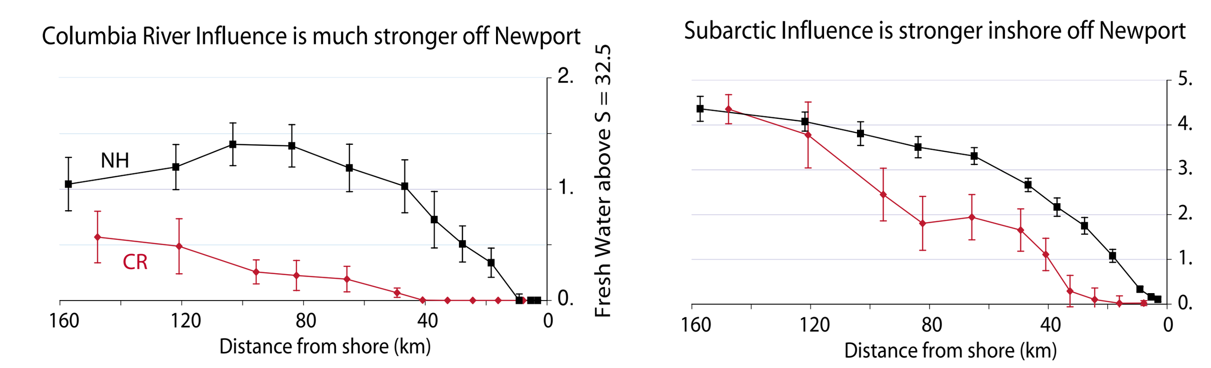

Figure 7. Equivalent depth of fresh water in two layers: (a) between the sea surface and the 32.5 psu isohaline, representing the influence of the Columbia River Plume, and (b) between the 32.5 and 33.8 isohalines, representing the influence of North Pacific Subarctic water. Values were calculated by the method of Tully and Barber (1960).

Spatial Variation of the Coastal Winds. Summer northerly winds off northern California have long been known to be stronger than those off central Oregon (Figure 2). High resolution observations of the wind field by satellite are now available. Samelson, Chelton and colleagues are among the first to use data from the QuikSCAT satellite scatterometer to study coastal winds (Samelson et al., 2002; Perlin et al., 2003). Maps of the summer mean wind stress and wind stress curl calculated from data for two upwelling seasons (1 June – 30 Sept 2000 and 2001) show that winds are strongly enhanced in the lee of Cape Blanco, and that the mean northerly wind stress is 2-3 times as strong off Crescent City as off Newport. The mean Ekman transport inshore is nearly four times as large off Crescent City (1.31 m²/s) as it is off Newport (0.34 m²/s). This large difference in the strength of the coastal upwelling certainly contributes to the high nutrient concentrations and low temperatures observed there.

Wind stress curl is positive along the coast and negative offshore in both locations, but the magnitude of the curl is much greater off Crescent City than off Newport. Furthermore, there is strong negative curl between 125.0 and 125.5 W at 42 N. This fine-scale structure in the mean wind stress curl off Crescent City enhances the upwelling over the shelf and slope, and causes downwelling just beyond the continental margin. Strong upward Ekman pumping over the continental slope and outer shelf off Crescent City likely accounts for the offshore position of the front at this latitude.

This fine-scale curl is likely an important factor in generating mesoscale eddies and high variability in the coastal jet.

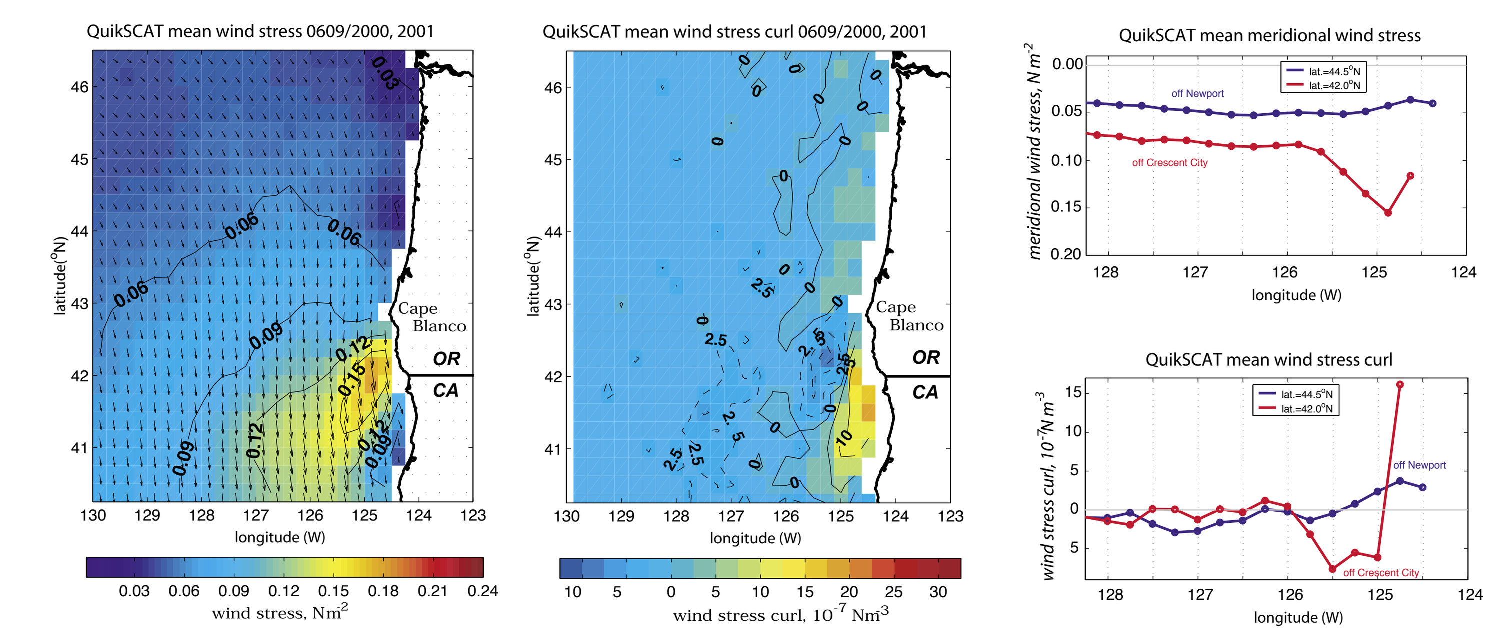

Figure 8. Mean scatterometer winds for two upwelling seasons (1 June – 30 Sept, 2000 and 2001) from the QuikSCAT satellite: (a) map of wind stress vectors, (b) map of wind stress curl, (c) offshore profiles of alongshore wind stress at 42 and 45 N, and (d) offshore profiles of wind stress curl at 42 and 45 N.

Conclusions

There are significant and important differences in the coastal upwelling domains north and south of Cape Blanco at 42.9 N. Compared to the domain off Newport (44.6 N), the domain off Crescent City (41.9 N) has:

- a more saline, cooler, denser and thicker surface mixed layer,
- a wider coastal zone inshore of the upwelling front and jet,
- a more complex southward surface current
- higher nutrient concentrations
- deeper chlorophyll
- higher phytoplankton biomass

We attribute these differences to:

- less influence from the Columbia River discharge
- stronger northerly wind stress, and
- strong fine-scale wind stress curl in the lee of Cape Blanco.

References

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Acknowledgments

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