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Cold halocline in the northern California Current: An invasion of subarctic water

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[1] Subsurface upper ocean waters off Oregon and Vancouver Island were about 1°C cooler in July 2002 than in July 2001. The anomalously cool layer coincides with the permanent halocline which has salinities of 32.2 to 33.8, suggesting an invasion of nutrient-rich Subarctic waters. The anomalously cool layer lies at 30–150 m. The cool anomaly is likely caused by stronger southward flow in the California Current and weaker northward flow in the Alaska and Davidson Currents during spring 2002. Other factors may include reduced coastal downwelling in late winter and early spring 2002, enhanced eastward flow in the Subarctic Current, and enhanced winter mixing offshore. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 4516 Oceanography: Physical: Eastern boundary currents; 4283 Oceanography: General: Water masses; 4279 Oceanography: General: Upwelling and convergences; 4223 Oceanography: General: Descriptive and regional oceanography. **Citation:** Freeland, H. J., G. Gatien, A. Huyer, and R. L. Smith, Cold halocline in the northern California Current: An invasion of subarctic water, *Geophys. Res. Lett.*, *30*(3), 1141, doi:10.1029/2002GL016663, 2003.

1. Introduction

[2] Subsurface upper ocean waters off Oregon and Vancouver Island were unexpectedly cool in July 2002 — about 1°C cooler than in July 2001, when temperature and salinity were near normal off Oregon. The anomalously cool layer coincides with the 'permanent halocline' in this region, which has salinities of 32.2 to 33.8, suggesting an invasion of nutrient-rich Subarctic waters from the north or northwest. The anomalously cool layer is about 100 m thick, and lies between 30 and 150 m.

[3] The broad coastal region between 35°N and 50°N is often described as the Transition Region [e.g., *Dodimead et al.*, 1963] because its properties are intermediate to those of the adjacent Subarctic, Central North, and Equatorial Pacific regions. In the Central North Pacific and the Equatorial Pacific, stratification is determined primarily by temperature; salinity decreases from the surface to the subsurface minimum at the core of North Pacific Intermediate Water [*Talley*, 1993]. The Subarctic Pacific has a very fresh surface layer because precipitation and runoff greatly exceed evaporation, particularly in the coastal domain along British Columbia and Alaska [*Favorite et al.*, 1976; *Oberhuber*, 1988]. Density in the Subarctic is determined by salinity which increases monotonically from the surface to the bottom. Winter storms mix the surface layer to a depth of 80–100 m, entraining surface waters into the upper halocline and *vice versa*. The winter mixed layer tends to be thicker and more saline in the center of the Alaska Gyre than on the margins [*Uda*, 1963], and thicker and more saline after harsh winters than during mild ones [*Tabata*, 1965]. The bottom of the halocline varies little from a typical depth of 180 m and salinity of 33.8 [*Tully and Barber*, 1960].

[4] Two research program are regularly sampling this region (Figure 1): the U.S. GLOBEC North East Pacific (NEP) Program [*Strub et al.*, 2002], and the Canadian Line-P Program [*Whitney and Freeland*, 1999]. GLOBEC NEP includes seasonal sampling of a line extending 157 km offshore along 44°39'N. The Line-P Program samples a section from the mouth of Juan de Fuca Strait to Station Papa at 50°N, 145°W in the Gulf of Alaska.

2. The Observations off Oregon

[5] The Newport Hydrographic Line (NH-Line) off central Oregon has been sampled five times per year since July 1997. This same line was sampled frequently from 1961 to 1971 [*Smith et al.*, 2001]. The July 2002 section showed mid-depth temperatures over the outer continental shelf and upper slope to be less than 7.5°C (Figure 2), about a degree colder than the previous year, and more than 0.5°C colder than the historical summer average (calculated by Smith et al. [2001]), which might be cooler than a longer-term mean because the 1961–71 decade coincided with a cool phase of the Pacific Decadal Oscillation [*Mantua et al.*, 1997].

[6] The cool anomaly occurs at depths between 30 and 100 m at the shelf-break (NH-25), and a bit deeper offshore. It coincides with salinities between 32.3 and 33.8, and is strongest in the upper portion of the permanent halocline. At the shelf-break, all of the water between the 24.5 and 26.4 kg m^{-3} isopycnals was cooler and fresher (i.e. less 'spicy') than normal (Figure 3). The difference in spiciness defined by *Flament* [2002] was about −0.25, about the same magnitude, but opposite sign, as the change observed during the 1997–98 El Niño [*Smith et al.*, 2001]. The spiciness anomaly is greatest at the top of the halocline, but extends down to the base of the halocline and up into the seasonal thermocline.

[7] The intensity of the spiciness anomaly is remarkable. Over the shelf-break, the T-S curve lies at the lower limit of all prior observations between the 24.5 and 26.2 kg m^{-3}

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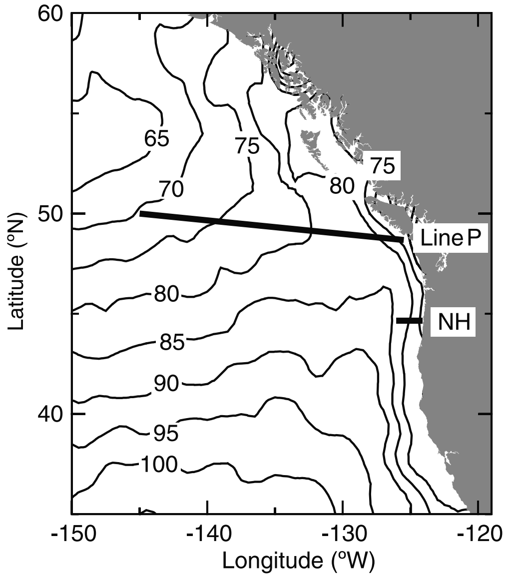

Figure 1. Location of the NH-line and Line-P. Contours show the July–August sea surface elevation in cm [*Strub and James*, 2002].

isopycnals. At the most offshore station, the upper halocline is >1°C colder than normal (Figure 3) and about 0.5°C colder than any prior observation. The low spiciness anomaly penetrates into the lower portion of the halocline, which intersects the photic zone near shore; its properties have the potential to affect the coastal upwelling ecosystem off Oregon.

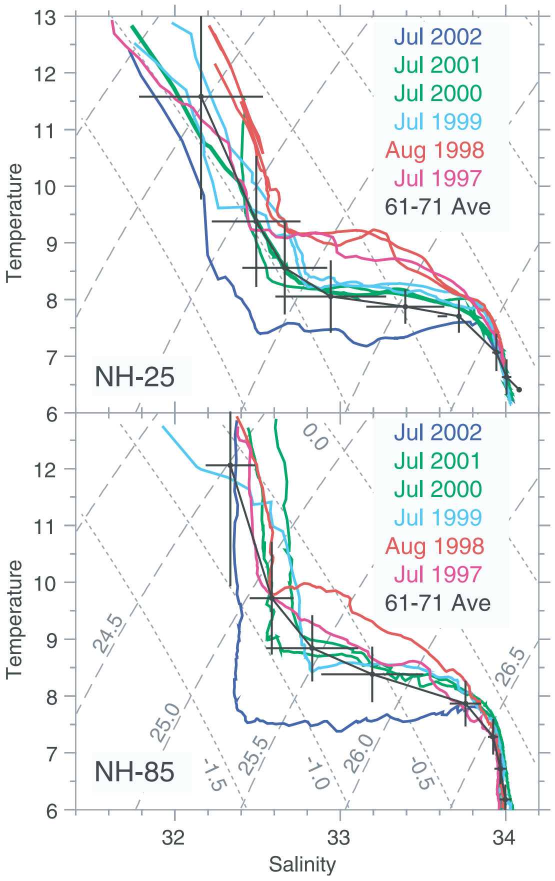

Figure 3. Summer T-S characteristics at the shelf-break (NH-25, top), and offshore (NH-85, bottom) of Oregon. Dashed curves indicate constant density and constant spiciness.

3. The Observations Along Line P

[8] Oceanographic sampling of Line-P to and from Ocean Weather Station Papa at 50°N, 145°W began in 1959 and continued through 1981 [Whitney and Freeland, 1999] when the weathership program was terminated. Since then, irregular sampling has continued through a variety of programs. At present Line-P is surveyed three times a year, usually in February, May/June and August/September to capture the state of the Gulf of Alaska when the seasonal mixed layers are deepest, at the peak of the spring bloom and in fall just before the storm season begins. Lately this has been augmented by a large array of profiling floats deployed in support of project Argo. These supply profiles of temperature and salinity from 2000 m to the surface at random locations in the Gulf and at 10-day intervals.

[9] The June–July 2002 CTD section along Line P showed a thick layer with temperatures and salinities both lower than normal (Figure 4). The strongest anomalies ($\Delta T < -1°C$ and $\Delta S < -0.4$) lie between 50 and 300 km from the coast at depths between 30 and 150 m. The T-S diagram for P-03 over the upper continental slope (Figure 5) shows this temperature anomaly between the 25.0 and 26.4 kg m^{-3} isopycnals. It is strongest within the upper halocline and extends up into the seasonal thermocline. Its structure is very similar to the low spiciness anomaly off Oregon, and there is little doubt that it is the same feature. Conditions in June 2002 are well outside the bounds of all previous experience at this station. The red line in Figure 5 shows that in summer 2001 the spiciness of this layer was already at the lower bound of previous experience. The minimum temperature in the core of the anomaly is about 1°C colder at this latitude (48°N) than on the NH-line nearly 400 km to the south. The magnitude of the meridional gradient is probably close to normal for this region: *Levitus* [1982] shows the temperature

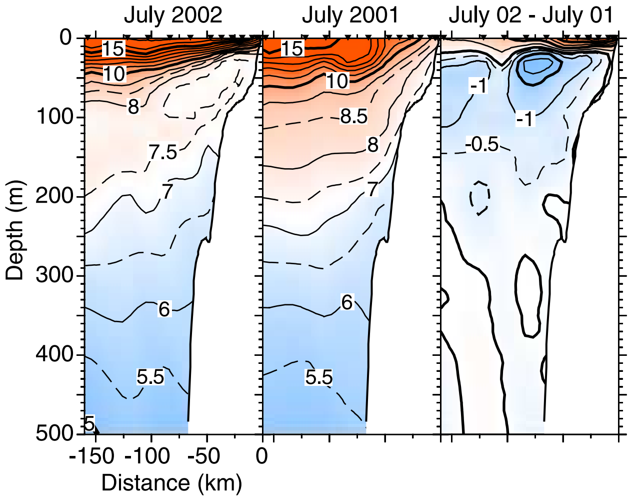

Figure 2. NH-Line temperature in July 2002 and July 2001, and the difference between them.

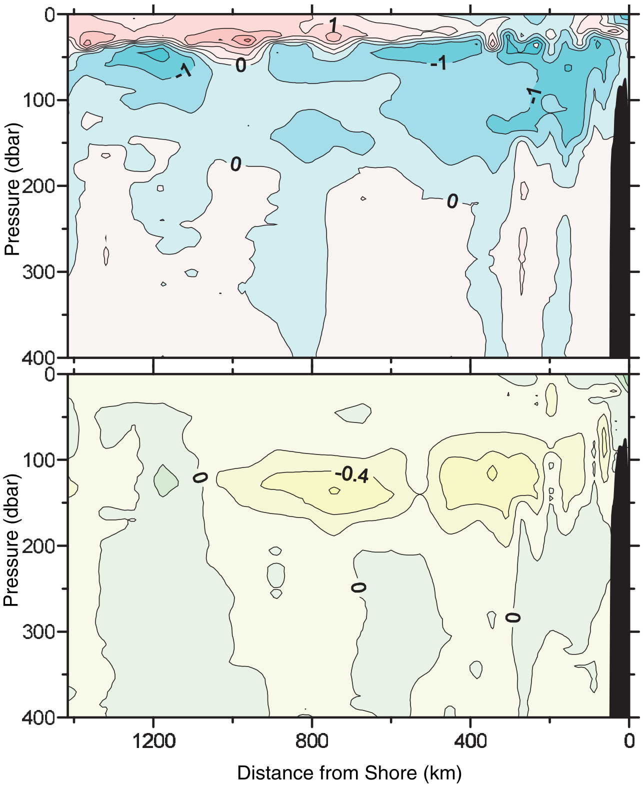

Figure 4. June–July 2002 temperature (top) and salinity (bottom) anomalies along Line-P. Anomalies are computed relative to a climatology including all data 1967 to 1996.

gradient at 150 m depth to be about 0.2°C per degree of latitude. *Reid* [1997] shows the salinity gradient on the 26.0 isopycnal to be about 0.04 per degree of latitude (equivalent to a temperature gradient of 0.2°C per degree). These meridional gradients imply that the waters off Vancouver Island and Oregon in July 2002 were displaced about 500 km south of their normal summer position.

4. Probable Causes

4.1. Anomalous Alongshore Advection?

[10] The flow adjacent to the continent is predominantly alongshore. Off Washington and Oregon, the California Current flows south in spring and summer and the Davidson Current flows north in winter; farther north, the Alaska Current flows northward year-round. *Chelton and Davis*, [1982] suggested that the Alaska Current and the California Current co-vary with opposite phase, so that enhanced southward advection by the California Current is associated with reduced northward advection by the Alaska Current or Davidson Current.

[11] To consider the possibility of enhanced southward advection, we obtained monthly values of coastal sea level from the University of Hawaii Sea Level Center for eight principal tide gauges between Seward, Alaska (60.1°N, 149.5°W) and Crescent City, California (41.8°N, 124.2°W). The sea level values were adjusted for local variations in atmospheric pressure, and anomalies were calculated by subtracting the mean annual cycle for the period of 1975–1996. Sea level anomalies from March through May 2002 were negative at all locations, with values about -10 cm (data not shown here but available from http://ilikai.soest.Hawaii.edu:80/UHSLC). No similarly large-scale, persistent negative anomaly had previously been observed in 27 years of data. Assuming the alongshore current to be in geostrophic balance, and its width to be about 100 km, this sea level anomaly implies an equatorward current anomaly of about 10 cm s^{-1}, and an anomalous southward surface displacement of 1000 km in three months. Subsurface currents at the top of the halocline are likely to be much weaker because currents in this region are strongly baroclinic. Thus alongshore advection is a plausible cause for the anomalously cool halocline along the continental margin off Oregon and Vancouver Island. It is unlikely, however, that this anomalous alongshore advection could also account for the presence of the same or a similar anomaly 1200 km offshore on Line P (Figure 4). We therefore need to consider other explanations.

4.2. Anomalous Eastward Advection?

[12] As well as intersecting the seasonal California and Davidson Currents in summer and winter, respectively, Line-P intersects the northern flank of the large-scale North Pacific Current where it flows east-northeastwards (Figure 1; *Strub and James* [2002]). This 'Subarctic Current' is the southern limb of the Alaska Gyre, and it is conceivable that the eastward flow is enhanced when the Gyre spins up, e.g., in response to stronger than normal cyclonic wind stress curl. There are significant large-scale zonal gradients at 50°N, 145°W: temperature at 150 m increases to the east [*Levitus*, 1982], and salinity on the 26.0 isopycnal increases to the east [*Reid*, 1997]. Thus enhanced eastward advection might explain the occurrence of a cool fresh anomaly along the offshore portion of Line P.

4.3. Enhanced Winter Mixing?

[13] Observations off Oregon and along Line P indicate that the surface layer was unusually cold in February 2002

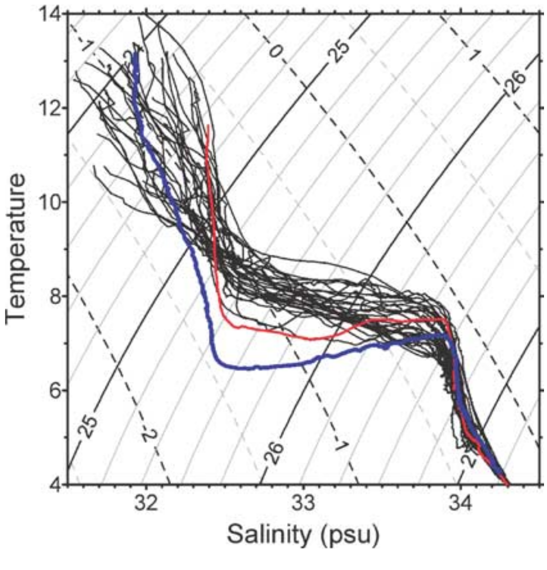

Figure 5. June–July T-S curves for P03 (48.63°N, 126.33°W) over the continental slope, 61 km from shore: 2002 (blue) compared to 2001 (red) and all previous CTD casts.

(data not shown), and thus enhanced winter cooling may have been a contributing factor. Enhanced mixing by strong winter storms tends to deepen and cool the surface layer, cool the upper halocline and steepen the salinity gradient within the halocline [*Tabata*, 1965]. But enhanced surface mixing also tends to increase the salinity of the surface layer, and leaves the integrated heat and salt content constant. Between Ocean Station Papa and station P17, about 750 km offshore, the changes in temperature and salinity appear to be consistent with an increase in the intensity of mixing. However, enhanced mixing alone cannot explain our inshore observations, either off Oregon or along Line P, where we observe both an anomalously cool halocline and an anomalously fresh overlying layer.

4.4. Anomalous Coastal Upwelling or Downwelling?

[14] Coastal waters along British Columbia and Alaska are continuously freshened by runoff, particularly during autumn and winter [*Favorite et al.*, 1976; *Royer*, 1981]. The fresh water pool is normally constrained to a narrow coastal strip by the onshore Ekman transport associated the Aleutian Low Pressure system. Monthly mean anomalies of offshore Ekman transport (coastal upwelling indices) were positive at all locations between Seward, Alaska and Crescent City, California from January 2002 through April 2002 (http://www.pfeg.noaa.gov). This reduction in late-winter downwelling and enhanced spring upwelling would result in less coastal trapping of the runoff and thus fresher surface waters offshore. In combination with strong winter mixing, this anomalous offshore Ekman transport might contribute to the cool, fresh anomaly observed at the top of the halocline.

5. Ecosystem and Climate Implications

[15] Upper ocean waters in the Subarctic Pacific tend to be higher in nutrients than those from the Central Pacific or the Pacific Equatorial Pacific [*Reid*, 1997]. Thus this invasion of Subarctic waters into the coastal upwelling region off Oregon might increase the nutrient supply to the photic zone, and thus increase productivity there. There are preliminary indications that this has in fact occurred, but determining the full extent of ecosystem impacts is beyond the scope of this paper.

[16] Why such a strong anomaly has occurred remains an open question. We have considered immediate causes, such as anomalous alongshore and zonal advection, and anomalous offshore Ekman transport, but these are merely particular factors that themselves depend on large-scale ocean-atmosphere interactions. We have not yet found evidence of a new 'regime shift' in the North Pacific: there are no obvious signals in the Pacific Decadal Oscillation [*Mantua et al.*, 1997] which apparently entered a negative phase in 1999, nor in Hurrell's North Pacific Index (http://www.cgd.ucar.edu/~jhurrell/np.html), nor in several standard indices (Pacific North America, North Pacific, Eastern Pacific) available from the Climate Prediction Center (http://www.cpc.ncep.noaa.gov). Without evidence of a large-scale climate perturbation, we might guess the anomaly to be merely the result of a combination of stochastic processes, i.e., coincidence. We are curious whether and how long the cool halocline anomaly will persist, particularly in the face of the impending arrival of a 2002–2003 El Niño signal from the Equatorial Pacific Ocean.

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References

Chelton, D. B., and R. E. Davis, Monthly mean sea-level variability along the West Coast of North America: August 1982, *J. Phys. Oceanogr.*, *12*, 757–784, 1982.

Dodimead, A. J., F. Favorite, and T. Hirano, Salmon of the North Pacific Ocean, Part II, Review of oceanography of the subarctic Pacific region, *Bull. Int. N. Pac. Fish. Comm.*, *13*, 195, 1963.

Favorite, F., A. J. Dodimead, and K. Nasu, Oceanography of the subarctic Pacific region, 1960–71, *Bull. Int. N. Pac. Fish. Comm.*, *33*, 187, 1976.

Flament, P., A state variable for characterizing water masses and their diffusive stability: Spiciness, *Progr. Oceanogr.*, *54*, 491–500, 2002.

Levitus, S., *Climatological Atlas of the World Ocean*, *NOAA Prof. Pap. 13*, 173 pp., U.S. Dep. of Commer., Nat. Oceanic and Atmos. Admin., Rockville, Md., 1982.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteorol. Soc.*, *78*, 1069–1079, 1997.

Oberhuber, J. M., An atlas based on the COADS data set: The budgets of heat, buoyancy and turbulent kinetic energy at the surface of the global ocean, *Rep. 15*, Max-Planck-Inst. für Meteorol., Hamburg, Ger., 1988.

Reid, J. L., On the total geostrophic circulation of the Pacific Ocean: Flow patterns, tracers and transports, *Progr. Oceanogr.*, *39*, 263–352, 1997.

Royer, T. C., Baroclinic transport in the Gulf of Alaska, part II, A freshwater driven coastal current, *J. Mar. Res.*, *39*, 251–266, 1981.

Smith, R. L., A. Huyer, and J. Fleischbein, The coastal ocean off Oregon from 1961 to 2000: Is there evidence of climate change or only of Los Niños?, *Progr. Oceanogr.*, *49*, 63–93, 2001.

Strub, P. T., and C. James, Altimeter-derived surface circulation in the large-scale NE Pacific Gyres, part 1, Seasonal variability, *Progr. Oceanogr.*, *53*, 163–183, 2002.

Strub, P. T., H. P. Batchelder, and T. J. Weingartner, U.S. GLOBEC Northeast Pacific Program: Overview, *Oceanography*, *15*, 30–35, 2002.

Tabata, S., Variability of oceanographic conditions at Ocean Station P in the northeast Pacific Ocean, *Trans. R. Soc. Can.*, *3*, 367–418, 1965.

Talley, L. D., Distribution and formation of North Pacific intermediate water, *J. Phys. Oceanogr.*, *23*, 517–537, 1993.

Tully, J. P., and F. G. Barber, An estuarine analogy in the sub-arctic Pacific Ocean, *J. Fish. Res. Board Can.*, *17*, 91–112, 1960.

Uda, M., Oceanography of the subarctic Pacific Ocean, *J. Fish. Res. Board Can.*, *20*, 119–179, 1963.

Whitney, F., and H. J. Freeland, Variability in upper ocean water properties in the NE Pacific Ocean, *Deep Sea Res.*, *Part II*, *46*, 2351–2370, 1999.

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