The evolution and decay of El Niño 1997–8 was observed in coastal waters off Oregon in a sequence of cruises along 44.6°N from the coast to more than 150 km offshore. Hydrographic observations were made during eleven cruises between July 1997 and April 1999 at stations on the Newport Hydrographic Line, which had been occupied regularly from 1961 to 1971. The data from the earlier decade provide a basis for defining ‘normal’ conditions and allow comparisons with the recent El Niño in terms of $T$, $S$, spiciness and geostrophic velocity. Independent of El Niño, the ocean in July 1997 was already anomalously warm offshore of 50 km and above 100 m. By September 1997 there were unambiguous indications of El Niño: isotherms and isohalines sloped down toward the coast indicating poleward flow over shelf and slope, and anomalously spicy water was present at the shelf-break. In November 1997 and February 1998 shelf-break waters were even warmer, and there was strong poleward flow inshore of 100 km, extending to depths greater than 200 m. The April 1998 section closely resembled that of April 1983 (another El Niño year) but by June 1998 the anomalies were mostly gone. November 1998 was near normal and the sections from subsequent cruises resemble the mean sections from 1961–1971.

Four cruises between November 1997 and November 1998 included sampling at several latitudes between 38° and 45°N. As expected, these sections show significant alongshore gradients, but also a surprising degree of homogeneity in the anomalous features associated with El Niño (in the temperature, salinity, spiciness and geostrophic velocity fields). The anomalous signature of El Niño was stronger at its winter peak in 1998 than in 1983, but the signature in the temperature and spiciness fields, and in coastal sea level, did not persist as long as in 1983. By April 1999, the coastal ocean from 38°N to 45°N was significantly colder than it had been in April 1984.

Keywords: El Niño phenomenon; Physical oceanography; Coastal oceanography; Hydrography; California current

Contents

1. Introduction .................................................. 312
1. Introduction

The 1997–8 El Niño was perhaps the strongest of the century in its effects (McPhaden, 1999; Wolter & Timlin, 1998). It was certainly the best observed as it evolved in the tropical Pacific (McPhaden, 1999) and appeared along the west coast of North America. In this paper we look at the manifestation of El Niño 1997–8 in the coastal waters off Oregon and northern California as observed in temperature, salinity and geostrophic currents. The data come from zonal hydrographic sections at 44.6°N, 43.2°N, 41.9°N, and 40.9°N and a section normal to the coastline near 38.6°N during July 1997 to November 1998 (Fig. 1).

The recent observations can be compared with ‘normal’ conditions off Newport, Oregon and with observations made off southern Oregon and northern California during the 1982 El Niño. The first systematic observations of Oregon coastal waters began in June 1961 with regular (at least seasonal) occupations of the zonal hydrographic line off Newport along 44.6°N to about 300 km offshore. This series continued through 1971, providing a basis for defining ‘normal’ conditions. After 1971 the section at 44.6°N was occupied only occasionally until regular sampling was revived in July 1997, just in time to observe the arrival of El Niño 1997–8. The hydrographic lines off southern Oregon and northern California at 43.2°N, 41.9°N, and 38.6°N were occupied during 1981–4, providing evidence of the effect of El Niño 1982–3. El Niño 1982–3 had a major global impact and significantly affected coastal waters off Oregon and northern California (Huyer & Smith, 1985; Rienecker & Mooers, 1986); it and El Niño 1997–8 are the only contenders for the title ‘El Niño of the century’ (Wolter & Timlin, 1998).

2. Background

The 1997–8 El Niño was triggered in the western equatorial Pacific early in 1997 by the reversal of trade winds in January and February, and it propagated eastward via equatorial Kelvin waves (McPhaden & Yu, 1999). The timing of our physical oceanographic observations is given in Fig. 2 along with time series of monthly means of several environmental indices for the period July 1996 to June 1999. The Multivariate ENSO Index (MEI in Fig. 2) began to move from neutral in March/April 1997 and was two standard deviations (s.d.) above its mean from May/June 1997 to April/May 1998 (Wolter & Timlin, 1998). At the Galapagos Islands and along the coast of Peru, the anomalies from monthly mean sea level jumped between April and May 1997 (Fig. 2); a second large rise in monthly mean sea level anomalies occurred between September and December 1997. Coastal sea level varies with changing density of the adjacent ocean and it has been often used in studies of El Niño (e.g. Enfield & Allen, 1980). The two ‘jumps’ in monthly mean sea level coincided with increases in the depth of the 20°C isotherm near the eastern equatorial...

El Niño effects can reach mid-latitudes from the equatorial region through an oceanic path by Kelvin waves propagating along the eastern boundary (Mysak, 1986; Meyers, Melsom, Mitchum, & O’Brien, 1998) and by atmospheric teleconnections producing anomalous meteorological conditions at mid-latitudes (Rasmusson & Wallace, 1983). Northward propagating Kelvin waves can directly displace the thermocline, and anomalies in the local equatorward wind stress can reduce the strength of coastal upwelling, and thus displace the thermocline downward. Anomalies in wind-stress curl could also displace the thermocline, but their effect is weak compared to strictly coastal upwelling, and will be neglected in this paper.

When did El Niño reach mid-latitudes on the west coast of North America? At 41.8°N (Crescent City, CA), near the mid-point of our mid-latitude region, the monthly mean sea level anomaly jumped from 1 s.d. below normal for April 1997 to 1 s.d. above normal for May 1997. It remained modestly above normal during the summer, and then jumped to 2 s.d. above normal for November 1997 (Fig. 2). The sea level response at San Francisco (37.8°N) and Neah Bay (48.3°N) was similar. The rise in sea level at mid-
latitude about a month after it rose at the equator suggests a poleward propagation, which is consistent with the phase velocity of a Kelvin wave. A good proxy for the large-scale local alongshore wind stress is the coastal upwelling index (CUI), which is calculated from synoptic atmospheric pressure fields (Halliwell & Allen, 1987a, b; Schwing, O’Farrell, Steger, & Baltz, 1996). The coastal upwelling indices at mid-latitudes (39°N, 42°N, 45°N) indicate that anomalous local winds were not sustained until winter 1997–8. Although Kelvin waves can rapidly set up poleward geostrophic flow along the eastern boundary, the water characteristics would change on a slower time-scale determined by alongshore advection at the geostrophic velocity.

The early arrival of El Niño anomalies along the US west coast via an oceanic route is confirmed by time series data from coastal tide gages and several moorings. These suggest a series of anomalous events during spring and summer. Kosro (2002) shows a minor peak in 40-h low-passed sea level propagating north along the coast at least to San Francisco (38°N) in late March 1997, and a stronger peak propagating
northward along the entire US west coast in late May 1997; both lagged peaks in eastern equatorial sea level by about 25–30 days (Kosro, 2002, his Fig. 4). Although sea level had returned to normal by the end of June, it crept upward again during July and August, and rose more rapidly in September. At all 13 west coast tide gages, sea level anomalies remained positive until February 1998 (Kosro, 2002). Shelf moorings at 34°N and 35°N (Dever & Winant, 2002) showed enhanced poleward flow during spring and summer 1997, with temperature anomalies at all depths rising sharply between July and December. A shelf mooring off Davenport at 37°N showed a warm episode at the end in late February 1998 (Ryan & Noble, 2002). Moorings off Monterey Bay showed that peaks in the steric height relative to 200 dbar (1 dbar = 10$^4$ Pa) coincided with peaks in the coastal sea level, though their amplitudes were reduced; steric height off Monterey Bay increased slowly from April through July and more rapidly from September through November (Collins et al., 2002); then in late February, steric height decreased rapidly (Collins et al., 2002) when coastal sea level returned to normal (Kosro, 2002).

The trade-wind reversal in the western Pacific ended by January 1998; in May–June 1998 El Niño was brought to a definite end in the equatorial Pacific by trade-wind intensification along the equator (McPhaden, 1999). The MEI began to decrease in April/May 1998 and became negative in July/August 1998; the MEI remained negative through 1999 indicating La Niña conditions. The mid-latitude coastal sea level anomalies showed a similar pattern to the MEI but they were modulated by the local wind stress (positive upwelling anomalies lead to lower sea level).

3. The Newport hydrographic line

The hydrographic data from the section off Newport, Oregon (Fig. 1) provides the most complete set of observations of El Niño 1997–8 over the mid-latitude continental margin between San Francisco and British Columbia. There is a good historical database for this section collected from 1961 to 1971 (Smith, Huyer, & Fleischbein, 2001), which provides a basis for comparison with El Niño 1997–8 data (Fig. 3). Because of the strong seasonal cycle at this latitude, we use seasonal or monthly averages of the 1961–1971 historical data rather than a single average section. Although the 1961–1971 decade occurred during a cool phase of the Pacific Decadal Oscillation, it is the only period longer than three years for which we have seasonally consistent sampling, and thus is our best estimate of ‘normal’. Following Smith et al. (2001) we calculate averages for Summer, late Fall, and Winter (22 June–31 August, 1 November–21 December, 1 January–29 February, respectively) and monthly averages (September and April) for transition periods in spring and early autumn.

We compare cross-margin distributions for two observed variables (temperature and salinity) and two derived variables (‘spiciness’ and geostrophic velocity). In this region of the California Current System, both temperature and salinity vary rapidly with depth; thus the effects of alongshore advection on the distribution of either of these parameters can be obscured by purely vertical displacements. To elucidate the effects of sustained alongshore advection on water mass distributions, we use the ‘spiciness’ variable, $\Pi$, which is a function of potential temperature and salinity that is most sensitive to isopycnal thermohaline variations and least correlated with the density field (Flament, 2002). In the California Current region, curves of constant spiciness lie roughly parallel to mean $T$–$S$ characteristics (Fig. 4). A spiciness increase (decrease) of $\Delta \Pi = 1 \text{ kg m}^{-3}$ would correspond to a salinity increase (decrease) of 1.25, if temperature remains constant, or to a temperature increase (decrease) of about 6°C if salinity remains constant (Fig. 4). To calculate the geostrophic (alongshore) current, we difference geopotential anomalies at adjacent CTD stations, using an offshore reference level of 500 dbar. Geopotential anomalies in shallower water are obtained by the method of Reid and Mantyla (1976): working from deep water onto the shelf, for each
Fig. 3.a Temperature along the NH-Line during and after the 1997–1998 El Niño (lower two rows), with historical (1961–1971) averages (top row) for the corresponding season or month: summer (22 June – 31 August), September, late fall (1 November – 21 December), winter (1 January – 29 February), and April.
Fig. 3.b Salinity along the NH-Line during and after the 1997–1998 El Niño (lower two rows), with historical (1961–1971) averages (top row) for the corresponding season or month.
station whose deepest observation is shallower than the reference isobar, the value of the geopotential anomaly at its maximum isobar (depth) is calculated by linear extrapolation from its two closest deeper neighbors. We are confident that these geostrophic velocities provide reasonable estimates of the alongshore currents, particularly since they are in general agreement with direct ADCP observations (Kosro, 2002), but we remind readers that shelf and slope currents in this region have strong variability on time scales of several days, consistent with coastal trapped wave dynamics (Huyer, 1990).

The first NH section off Newport during the recent El Niño was made 28–30 July 1997, soon after an anomalous rise in temperature and steric height along CalCOFI Line 90 near San Diego, CA (Lynn et al., 1998; Lynn & Bograd, 2002) and a rapid increase in subsurface temperatures off central California (Dever & Winant, 2002; Ryan & Noble, 2002; Collins et al., 2002). It is obvious that the near surface water off Oregon in July 1997 was much warmer than normal—and also much fresher (Fig. 3a, b). These surface anomalies were probably not caused by El Niño. Schwing, Murphree, deWitt, and Green (2002) showed that a large pool of anomalously warm surface water was already present in the region of 20–50°N, 120–150°W in March–May 1997. Unusually large outflow from the Columbia River during the spring of 1997 (Fig. 2) likely produced a more stable surface layer which would have ‘trapped’ the solar heating and thus enhanced further warming of the surface layer. The fresh Columbia River plume (S<32.5) ‘flooded’ the continental shelf in September under very weak upwelling conditions (Figs. 2 and 3b); because of sustained

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**Fig. 4.** T–S curves from CTD stations along the NH-Line in November 1997 (red) compared to T–S curves constructed from the 1961–1971 seasonal average temperature and salinity profiles for late fall (1 November–21 December, blue). Light dashed curves sloping up to the right are lines of constant density ($\sigma_t$), and light dotted curves sloping down to the right are lines of constant spiciness ($\Pi$) as defined by Flament (2002).
seasonal heating, this fresh layer was very warm, and thus spicier than normal. Very clear evidence of El Niño was found at depth in September—the water between 100 and 400 m was both warmer and saltier than usual (Fig. 3a, b). It had not simply been displaced vertically but was much spicier than normal (Fig. 5a), suggesting it had been advected from the south; it was also distinctly separated from the spicy water near the surface. In July, there had already been a hint of spicier-than-normal water adjacent to the shelf-break ($\bar{H} > -0.15$ in Fig. 5a) coincident with a zone of poleward geostrophic flow (Fig. 5b), but associating this with El Niño is reasonable only in hindsight. The large increase in this shelf-break spiciness maximum (from $-0.15$ in July to 0.0 in September, Fig. 5a) indicates there had been substantial poleward advection during the intervening period. During the September cruise, we observed poleward flow over the inner shelf and along the bottom over the outer shelf (where spiciness is higher than normal), but not immediately adjacent to the continental slope at depths of 200–400 m (Fig. 5b). Instead we observed a subsurface anticyclonic eddy whose core lay 100 km offshore and 200 m deep (Fig. 5b). Similar subsurface eddies observed farther south in the California Current system (Huyer, Barth, Kosro, Shearman, & Smith, 1998; Garfield, Collins, Paquette, & Carter, 1999) seem to have originated in the California Undercurrent, which flows poleward along the continental margin (Pierce, Smith, Kosro, Barth, & Wilson, 2000). It seems very likely that this eddy had recently separated from the poleward undercurrent along the boundary.

By November 1997 the Columbia River Plume was gone from the region and the warm salty anomalies filled most of the water column over the shelf and slope (Fig. 3a, b). Anomalies were particularly strong at mid-depth over the outer shelf, where salinity exceeded 33.4 (cf. 32.8 in the 1961–1971 fall mean, Fig. 3b) and spiciness exceeded 0.0 (cf. $-0.6$ in the fall mean, Fig. 5a). The large increase in the area of high spiciness ($II>0$) confirms persistent poleward advection and is consistent with the strong (>20 cm s$^{-1}$) poleward geostrophic velocity observed in November (Fig. 5b). These strong poleward currents are especially remarkable because the local winds were normal (Fig. 2).

By early February 1998, seasonal heat loss to the atmosphere had reduced the temperature (and spickness) of the offshore surface waters (Figs. 3a and 5a). Seasonal downwelling-favorable winds had been stronger than normal during both January and February (Fig. 2), causing the surface mixed layer to become deeper than normal, reaching 100 m over the outer shelf. Nevertheless, surface waters over the shelf remained 2°C warmer and 0.5 more saline (0.8 more spicer) than normal (Figs. 3a and 5a). The geostrophic velocity field for February shows broad, surface-intensified poleward flow (Fig. 5b), consistent with local forcing by the stronger-than-normal poleward wind stress. Wind-driven shelf and slope currents in this region typically take the form of first-mode coastal trapped waves whose amplitude is greatest at the surface and inshore, decaying gradually offshore across the continental margin and with depth (Battisti & Hickey, 1984; Chapman, 1987; Brink, 1991). There was no longer any suggestion of the poleward shelf-break undercurrent that had been observed during the preceding autumn. The subsurface spiciness maximum was less intense than it had been in November, but it extended farther offshore.

In March 1998, local winds off Oregon and northern California returned to normal, although El Niño conditions persisted in the equatorial Pacific (sea level in the Galapagos Islands and the MEI both remained higher than normal, Fig. 2). In April, local winds were normal and favorable for coastal upwelling, and sea level at Crescent City and Neah Bay fell to normal levels (Fig. 2). Some dense water ($T<10°C$ and $S>33$) had upwelled onto the shelf off Newport in April (Figs. 3a,b), and currents over the inner shelf were southward, as is usual for this time of year (Fig. 5b). Nevertheless, surface waters over the shelf in April remained warmer (by 2°C) and spicier (by about 0.5) than normal. The spiciness of waters at the depth of the shelf-break (200 m) had decreased since February but was still above normal, although the maximum value no longer lay adjacent to the continental margin but was instead located 100 km from shore.

In May and June 1998, El Niño was fading but was still present in the equatorial Pacific, and coastal sea levels as far north as San Francisco were still anomalously high (Fig. 2). During this period, local winds along northern California and Oregon continued to be more strongly favorable for upwelling than normal, and coastal sea levels at Crescent City and Neah Bay were near normal (Fig. 2). In early June,
Fig. 5.a Spiciness along the NH-Line during and after the 1997–1998 El Niño (lower two rows). The top row shows the spiciness distributions calculated from the historical (1961–1971) temperature and salinity averages for the corresponding season or month.
Fig. 5.b Geostrophic velocity (relative to 500 dbar) along the NH-Line during and after the 1997–1998 El Niño (lower two rows). The top row shows the historical (1961–1971) average for the corresponding season or month.
geostrophic flow was southward across the entire continental margin (Fig. 5b). Nevertheless, temperature (and spiciness) of the upper ocean remained above normal, presumably because these normal southward currents were not sufficient to offset the cumulative effect of the abnormally strong poleward flow of the preceding autumn and winter.

The MEI fell to nearly zero by July 1998 (Fig. 2), signalling the end of El Niño in the equatorial Pacific. Upwelling off northern California and Oregon was anomalously strong through September 1998. Though geostrophic flow over the inner shelf was southward in both August and September (Fig. 5b), most of the water over the shelf off Newport remained $\geq 1^\circ$C warmer than normal (Fig. 3a). Local winds were near normal during autumn and early winter, and geostrophic currents in November were weakly northward over most of the upper shelf and slope, while surface waters remained slightly warmer than normal. Although a succession of winter storms in February 1999 precluded full sampling of the NH-line (and resulted in a record low CUI value, Fig. 2), the partial section showed that shelf waters were finally cooler than normal (Fig. 3a). Local winds were near normal during March, but during April winds off northern California were more strongly favorable for upwelling than normal (Fig. 5b), and this is reflected in strong southward geostrophic flow and near-normal temperature off Oregon (Fig. 3a).

Between April 1998 and April 1999, the shelf-break spiciness maximum was much weaker in both size and intensity than it had been during El Niño autumn and winter (September 1997 through February 1998; Fig. 5a). The recent-vs-historical comparisons of subsurface features may be compromised by the large difference in vertical resolution: 1 m for modern data, 50 m for historical data. A modern CTD resolves thin extrema (5–10 m thick) but the historical bottle casts could completely miss features <50 m thick, and the temporal averaging of the historical data is likely to result in further smoothing with depth. Furthermore, the recent sections include some additional stations (e.g. NH-20, NH-55) that were not occupied during most historical sections. Thus the small difference in the maximum spiciness observed in April 1999 ($H = -0.1$) compared to the maximum in the 1961–1971 April average ($H = -0.15$) is probably not significant. We therefore conclude that the shelf-break spiciness maximum had returned to normal strength by April 1999.

4. Alongshore structure

Four cruises between November 1997 and November 1998 included sampling at several latitudes between 38° and 45°N within a single week. The first two cruises, in November 1997 and April 1998, were during the period of elevated MEI, i.e. during El Niño (Fig. 2). The later two, in September 1998 and November 1998, were after the end of El Niño, but still within the period of elevated near-surface temperatures off Newport.

On all of these cruises, we see clear evidence of large-scale meridional gradients in water properties over the several degrees of latitude (Figs. 6–8). At depths of 200–500 m, waters were consistently warmer and more saline (hence spicier) in the south. Isotherms between 5.5° and 8°C lay 50–100 m shallower at 38.6°N than at 44.6°N (Fig. 6), and isohalines between 34.1 and 34.0 isohalines were typically 100 m shallower at 38.6°N than at 44.6°N (Fig. 7); spiciness values at these depths were about 0.1 higher at 38.6°N than at 44.6°N (Fig. 8). At shallower depths, i.e., in the top 100–200 m, meridional gradients vary seasonally in response to the seasonal gradients in wind stress and river runoff (Huyer, 1983). Winds from the southwest in winter are stronger off Oregon, causing stronger downwelling and bringing higher precipitation off Oregon than off California; the northerly winds in summer are stronger off California, causing much stronger upwelling off northern California than off central Oregon. There is little local precipitation in summer, but there is appreciable discharge of freshwater from the Columbia River (see Table A1 in the Appendix). Salinity sections (Fig. 7) show a permanent halocline (32.8–33.9) over the entire latitude range; its thickness decreases with latitude (150 m at 38.6°N, compared with 100 m at 44.6°N). At our most
Fig. 6. Temperature at four latitudes (off Newport, Coos Bay, Crescent City, CODE region), during and after El Niño (November 1997; April 1998; August 1998; November 1998). The horizontal axis for the Newport section is longer (160 km) than the others (100 km).

southern latitude (38.6°N), the top of this halocline coincides with the sea surface, so that surface salinities often reach 33.4 (e.g. in August 1998, Fig. 7), or even 33.8 over the inner shelf during strong upwelling (Huyer & Kosro, 1987). Along our most northern section (44.6°N), the permanent halocline lies at depths of 80–120 m offshore, and intersects the surface over the inner shelf during strong upwelling (e.g. in August 1998, Fig. 7). At this latitude (i.e. 44.6°N), there is also a very shallow seasonal halocline (S<32.5) in spring and summer (e.g., April and August 1998, Fig. 7), which lies at the base of the Columbia River plume (Barnes, Duxbury, & Morse, 1972) and provides an effective barrier for trapping solar heat in a thin surface layer. This summertime difference in stratification and in the strength of coastal upwelling has the surprising result that surface temperatures off Newport, Oregon are up to 5°C warmer than those off Pt. Reyes, California in late summer (e.g. August 1998, Fig. 6). Surface temperatures are relatively uniform in fall, winter and early spring, when there is only a 1–2°C difference over the 600 km range between the sections at 38.6° and 44.6°N (Fig. 6). Since spiciness depends more strongly on salinity than on temperature (in °C), near-surface values of spiciness are generally much higher at 38.6°N than at 44.6°N. Keeping
these meridional gradients in mind, we now turn to a comparison of the structure observed at the various latitudes in November 1997 and April, August and November 1998.

The sections in November 1997 were observed nearly nine months after the onset of El Niño in the equatorial Pacific. These sections show a high degree of alongshore homogeneity in offshore structure. All four sections between 38°N and 45°N showed a warm surface layer (T > 12°C), and upper-ocean isotherms (6–12°C) sloping down toward the continental slope (Fig. 6). Isohalines in the permanent halocline showed a tendency to diverge toward the coast; those above 100 m sloping upward as they approach the shelf-break, while those below about 100 m slope down toward the continental slope (Fig. 7). The deformation scale of the downward sloping isotherms and isohalines is comparable to the width of the continental margin, and consistent with the prior passage of a ‘downwelling’ coastal trapped signal originating in the equatorial Pacific (Mysak, 1986). The downward sloping isotherms and isohalines combine to produce strongly negative zonal density gradients over the upper slope, and hence strong vertical shear in the alongshore current (Fig. 9) with flow increasingly poleward at shallower depths (the thermal wind relation). At all four latitudes, the poleward geostrophic flow was strongest at the surface, with maximum velocities
Fig. 8. Spiciness at four latitudes (off Newport, Coos Bay, Crescent City, CODE region), during and after El Niño (November 1997; April 1998; August 1998; November 1998). The horizontal axis for the Newport section is longer (160 km) than the others (100 km).

of >30 cm s\(^{-1}\) over the shelf or shelf-break (Fig. 9). At all four latitudes, the spiciness at all depths between 50 and 400 m was significantly higher over the continental margin than it was farther offshore; this spiciness maximum was undoubtedly the result of alongshore advection by the poleward current. Even at 39°N, where the spiciness distribution (if taken alone) might suggest downwelling of surface waters (Fig. 9), examination of spiciness along isopycnals confirms that the high spiciness values at the shelf-break must have resulted from poleward advection. All of these features are strongly exaggerated versions of the typical winter regime, but this exaggeration cannot be explained by the local winds which were still near normal.

The seasonal downwelling-favorable winds became much stronger than normal in January and February 1998, but returned to normal in March and became favorable for upwelling in April (Fig. 2). As usual, the upwelling-favorable winds were slightly stronger at 39°N than at 42° and 45°N. The resumption of coastal upwelling is reflected in the sections at all four latitudes, which all show the 10 and 11°C isotherms and the 33.0 isohaline bending up toward the surface near shore (Figs. 6 and 7), and a southward geostrophic
current over the shelf (Fig. 9). The degree of upwelling (as indicated by isopycnal slopes) and the southward coastal jet seem to be stronger in the intermediate sections (Coos Bay and Crescent City) than at the northern end (Newport) where winds were weaker. The shelf-break spiciness maximum that was so strong in November, has all but disappeared from all four sections (Fig. 8) though the layer of relatively high spiciness between 100 and 300 m is a persistent feature.

El Niño had ended in the equatorial Pacific by July 1998 (McPhaden & Yu, 1999), and local winds in July and August were more strongly favorable for upwelling than normal, especially at 39°N and 42°N (Fig. 2). This strong upwelling is reflected in all four August sections (Figs. 6 and 7): the seasonal thermocline and the permanent halocline intersect the sea surface over the shelf off Newport, Coos Bay and Crescent City; at Pt. Arena, the entire section has surface salinities >33.3 and temperatures <13°C. A southward geostrophic coastal jet is present in all four sections (Fig. 9). In all four temperature sections (Fig. 6), some isotherms diverge from each other as they approach the continental margin from offshore (6–8°C at 44.6°N; 7–9°C at 43.2°N; 6–9°C at 41.9°N; 9–10°C at 38.6°N); such isotherm spreading suggests a subsur-
face maximum in poleward geostrophic flow. At 41.9°N, the spreading continues eastward until the isotherms intersect the coast (implying the poleward undercurrent was lying adjacent to the margin, as seen in Fig. 9), but in the other three sections the eastward spreading ends offshore of the shelfbreak and isotherms converge eastward over the upper slope (implying either a separated undercurrent or a subsurface anticyclonic eddy, as seen in Fig. 9). The distributions of spiciness in August (Fig. 8) also suggest poleward advection, with a spiciness maximum lying adjacent to the shelf-break off Pt. Arena (38.6°N) and Crescent City (41.9°N) and somewhat farther from shore off Coos Bay (43.2°N) and Newport (44.6°N). Subsurface poleward flow, the California Undercurrent, is normal during the summer upwelling regime (Huyer, Kosro, Lentz, & Beardsley, 1989; Pierce et al., 2000); it seems to strengthen during El Niño.

By November 1998, conditions off Newport were nearly normal, with temperature anomalies of >0.5°C present only in the upper 150 m (Smith et al., 2001). Local winds were near normal during autumn and early winter, with downwelling at 42°N and 45°N, and weak upwelling at 39°N (Fig. 2). This relaxation from upwelling conditions is reflected in the temperature and salinity sections: at each latitude, surface temperature and salinity are nearly uniform across the continental margin. Subsurface isotherms and isohalines are nearly horizontal (at 44.6°N and 41.9°N) or sloping gently down toward the continental margin (at 43.2°N and 38.6°N); these are in sharp contrast to the steeply sloping isotherms and isohalines observed the previous year (Figs. 6 and 7). Geostrophic flow in November 1998 was generally northward over the shelf and upper slope, with maximum velocities (10–30 cm s⁻¹) much weaker than those observed a year earlier (Fig. 9). Similarly the November 1998 spiciness sections (Fig. 8) show values much reduced from the previous year, though there was still a tendency for a local maximum near the shelf-break.


In contrast with El Niño 1997–8, El Niño 1982–3 caught the oceanographic community by surprise. El Niño 1982–3 arrived in the eastern equatorial Pacific later in the calendar year than is usual for El Niños (Cane, 1983) and neither observational nor modeling efforts were ‘in place’ to detect its early phase. Serendipitously, it was recorded by unrelated physical oceanographic programs, which were underway off northern California, Oregon and Peru at the time (Smith, 1983; Huyer & Smith, 1985; Huyer, Smith, & Paluskiewicz, 1987). In contrast with El Niño 1997–8, when sea level and temperatures in the eastern equatorial Pacific began to increase in April 1997, the first hint of El Niño 1982–3 was its arrival at the Galapagos Islands in late August 1982. An abrupt rise of temperature and sea level at the Peru coast in early October 1982 clearly indicated its arrival at the eastern equatorial boundary. Subsequent analyses (e.g., Rasmussen & Wallace, 1983) have shown that sea surface temperatures in the central Pacific began rising much earlier, and MEI values had changed from neutral to positive in April/May 1982, 6 months before the rise in sea level and temperature was detected along the Peru coast (Fig. 10). The effects of El Niño 1982–3 off Oregon were first apparent in the monthly mean shore station temperatures and sea level of October 1982 (Huyer & Smith, 1985). The timing of physical oceanographic sections off northern California and Oregon during the period July 1981–June 1984 is shown in Fig. 10 along with time series of the monthly means of several environmental indices; Fig. 10 can be compared directly with Fig. 2. In this paper we restrict our discussion of El Niño 1982–3 to a comparison with El Niño 1997–8. Were the effects of these two El Niños on the coastal waters off northern California and Oregon similar?

In November 1982 the sea level at Crescent City jumped to more than two standard deviations above the monthly mean, and remained more than a standard deviation above the monthly means until December 1983. On the basis of sea level anomalies at mid-latitudes, it would appear that the effects of El Niño 1982–3 persisted longer than El Niño 1997–8 and that the ocean returned to ‘normal’ more gradually. One gets the impression that El Niño 1982–3 arrived suddenly but left gradually, whereas El Niño 1997–8 arrived gradually at mid-latitude but left suddenly.
In 1982, the first large changes in sea surface temperature and sea level off Oregon occurred within a month after the changes occurred off Peru, a speed which is consistent with the El Niño propagating poleward from equatorial regions as a baroclinic Kelvin wave (Huyer & Smith, 1985). In 1997, the first large changes in the eastern equatorial Pacific occurred between April and May 1997, but only a minor sea level peak reached California and Oregon in late May 1997 (Strub & James, 2002; Kosro, 2002). A second large change occurred between September and October 1997 in the eastern equatorial Pacific, and this change was transmitted quickly to mid-latitude where increases in temperature and sea level were apparent by early November 1997. In both 1982 and 1997, the rise in sea level along the Pacific Northwest clearly preceded (by at least a month) the anomalous increase in the strength of the local downwelling-favorable wind stress (Figs. 2 and 10).

From coastal sea level it would appear the effects of El Niño 1982–3 persisted in the Pacific waters off North America for longer than those of El Niño 1997–8 (Figs. 2 and 10). In early 1983 and 1998 El Niño was near its peak (Figs. 2 and 10): MEI was very high, sea level at mid-latitudes remained high, and El Niño was having a strong effect on local weather (with strongly negative CUIA values in January–March 1983 and January–February 1998). In both cases, coastal sea level dropped significantly when the anomalously strong downwelling ended in late winter or early spring. However, the local effects of El Niño during the subsequent spring/summer upwelling seasons differed substantially: local upwelling-favorable winds at 42°N and 45°N were near normal or weaker than normal in 1983 (Fig. 10), but stronger than normal in
1998. This difference in local forcing is reflected in the Crescent City and Neah Bay sea levels, which remained 10 cm above normal during spring and summer of 1983 (Fig. 10), but fell to normal levels even before the end of El Niño in July 1998 (Fig. 2).

Hydrographic sampling during El Niño 1982–3 had originally been designed to study large-scale shelf dynamics along the US west coast between 35° and 43°N (Denbo & Allen, 1987). One of the cross-margin sections was the central line of the Coastal Ocean Dynamics Experiment (CODE), which was situated over the shelf between 38° and 39°N (Huyer & Kosro, 1987). The emphasis was on quasi-synoptic sampling of several cross-margin latitudes in all seasons of two years (1981–1983). There was no effort to resolve interannual variability until there were early reports of El Niño arriving off California, when sampling was extended both in time to include a post-El Niño winter survey in January 1984, and spatially by extending observations northwards to include Newport whenever possible. Comparison of sections from the three winters before, during and after El Niño 1982–83 shows surface waters over the shelf and shelf-break were about 2°C warmer in January 1983 than in February 1982, and still about 1°C warmer in February 1984 (Fig. 11). Similarly, the permanent halocline (32.8 to 33.9) was 50–100 m deeper in January 1983 than in February 1982, and still lay about 50 m deeper in February 1984 (Fig. 12). At all four latitudes, the spiciness of both surface waters and shelf-break waters was higher during winter 1982–83 than during either of the other winters (Fig. 13). Local winds during each of these week-long winter cruises were weak and variable but the mean monthly wind stress was much more favorable for downwelling in winter 1982 than during either of the other two winters. Shelf currents off Coos Bay were highly variable during this period, but the mean alongshore current was more strongly poleward (13 cm s\(^{-1}\)) during the 3-month period November through January of the El Niño winter than in the preceding and succeeding winters (Huyer & Smith, 1985). The geostrophic velocities calculated for these winter sections showed little alongshore coherence, either during El Niño 1982–83 or in the preceding and succeeding years, but the poleward flow was strongest at 41.9° and 43.2°N in January 1983.

Of the four sections sampled in winter 1982–83, only one (the FM-line at 43.2°N off Coos Bay) was also sampled in winter 1997–98; this section was incomplete but closely resembles the NH-line section sampled a few days earlier. Though obviously anomalous, the maximum shelf temperature at 43.2°N on 11 January 1983 (11.65°C) was not as warm as on 31 January 1998 (12.80°C, Fleischbein, Hill, Huyer, Smith, & Wheeler, 1999), nor was it as warm as that observed off Newport (44.6°C) on 2 February 1998 (12.44°C, Fig. 2a). Similarly, the depth of the inshore end of the 33.2 isopycnal was not as deep in winter 1982–83 (80 m) as in winter 1997–98 (135 m). The shelf-break spiciness maximum at 43.2°N was not as intense in January 1983 (\(I_{\text{max}} = 0.03\)) as in January 1998 (\(I_{\text{max}} = 0.19\)), and the depth range of the \(I = 0.0\) contours was not as great in January 1983 (125 –243 m) as in January 1998 (51–228 m). We conclude that the effect of El Niño on local water properties was stronger in El Niño winter 1997–98 than in El Niño winter 1982–83.

All five sections between 38°N and 45°N (Fig. 1) were sampled in April 1983 and April 1998, though two stations off Eureka (at 40.9°N) were omitted in 1998 because of adverse weather. In both years, the anomalously strong downwelling winter winds had ended (Figs. 2 and 10), and seasonal upwelling had begun before the April cruises. Comparison of the section pairs (Fig. 14) shows there was an overall similarity in the temperature structure at each latitude (all sections showing a tendency for isotherms to slope upward over the shelf), and there were similar alongshore differences (about 0.5°C warmer in the south than the north) during the two years. Sections of the April temperature difference (1998 minus 1983) all show that waters adjacent to the continental margin were warmer in 1998 than 1983 (Fig. 14), though the difference exceeds 1°C only over the shelf. Farther from shore (beyond the shelf-break), the maximum temperature difference occurred in a layer near the 10°C isotherm at the top of the thermocline. This indicates that the early-spring surface mixed layer was deeper in 1998 than in 1983. The April 1983 and 1998 salinity sections (Fig. 15) are also quite similar at each latitude (all show the permanent halocline sloping upward over the shelf), and similar alongshore differences (the Columbia River plume is present...
Fig. 11. Winter temperature distributions at four latitudes (off Coos Bay, Crescent City, Eureka, and the CODE region) before, during and after El Niño (February 1982; January 1983; February 1984).

Sections of the April salinity difference (1998 minus 1983) all show that waters adjacent to the margin were less saline in 1998 than 1983. Offshore surface waters were generally more saline in April 1998 than April 1983, particularly in the northern sections. The pairing of higher temperatures with lower salinities along the continental margin (in 1998 versus 1983) indicates a vertical displacement of isopycnals rather than a change in water mass characteristics, and Fig. 16 confirms that there was little difference in spiciness. The combination of higher temperatures with lower salinities in 1998 resulted in isopycnals sloping more steeply upward toward shore in April 1983 than in April 1998. This is consistent with the geostrophic velocity sections. Fig. 17 shows that the southward coastal jet was stronger in 1983 than in 1998 at each latitude. This difference in the strength of the coastal jet explains
why the fresh water of the Columbia River plume, which only flows southward during the upwelling season (Barnes et al., 1972; Huyer, 1983), had penetrated farther south (past 40.9°N) in April 1983 than in April 1998 (Fig. 15). The strength of the coastal jet (and all currents over the shelf) is highly variable in response to local wind forcing (time scales of 3–10 days); hence the velocity sections shown in Fig. 17 may represent brief ‘snapshots’ rather than spring season averages for 1983 and 1998. The spiciness sections (Fig. 16), are more representative of a longer period because the spiciness of subsurface waters changes primarily by alongshore advection; an alongshore current of 15 cm s⁻¹ at the shelf-break will take a full month to displace a water mass 500 km north or south. There was little difference in the spiciness sections from
Fig. 13. Winter spiciness distributions at four latitudes (off Coos Bay, Crescent City, Eureka, CODE region) before, during and after El Niño (February 1982; January 1983; February 1984).

1983 and 1998, and thus we conclude the manifestations of El Niño 1982–83 and El Niño 1997–98 were similar in early spring.

Sections off Newport made in April, July 1983 and April 1984 can be compared with sections made in April, June, August 1998 and April 1999 (Fig. 18). Large portions of the NH-line, particularly in the areas adjacent to the continental margin, were warmer in April 1998 than in April 1983. By summer, the 1998-minus-1983 temperature difference has reversed sign, and had become negative almost everywhere. The warm temperature anomalies of El Niño persisted longer in 1983 than in 1998, presumably because local spring/summer wind stress was much more favorable for upwelling in 1998 than 1983 (cf. Figs. 2 and
Comparison with sections made a full year later shows that the coastal ocean off Newport had returned to normal by April 1999, but remained warmer than normal through April 1984 (cf. Figs. 2 and 18).
6. Conclusions

The onset of El Niño 1997–8 in the central equatorial Pacific and its manifestation in the eastern equatorial Pacific was gradual, with sea level at the Galapagos Islands and at Callao, Peru rising concurrently with MEI between April and July 1997. The manifestation of an El Niño signal in the coastal ocean off Oregon and northern California was similarly gradual and subtle: after a small jump in May 1997, coastal
Fig. 16. Comparison of spiciness in April 1998 and April 1983 at five latitudes (off Newport, Coos Bay, Crescent City, Eureka, CODE region). The horizontal axis for the Newport section is longer (160 km) than the others (80 km).

Sea levels remained 5–10 cm above normal through summer and early fall. The early arrival of El Niño signals through the oceanic wave guide was further obscured by local forcing: upwelling-favorable winds in late summer and autumn 1997 were weaker than normal, and surface waters offshore were already warmer than normal because there was unusually high stratification as a result of above-average Columbia River discharge. Nevertheless, it is clear that subsurface effects of El Niño had reached central Oregon by September 1997, in the form of abnormally spicy waters advected from the south. Poleward advection along the continental slope was further enhanced in late fall, although local wind stress was normal for
the season. Coastal sea level and shelf temperature anomalies peaked in midwinter, when abnormally strong downwelling further enhanced the poleward advection over the shelf. By March 1998, local wind stress had returned to normal and sea levels fell rapidly along the Pacific Northwest coast, although El Niño conditions persisted in the equatorial Pacific until the end of June. Local upwelling-favorable winds were stronger than normal during spring and summer 1998, and coastal sea levels at Crescent City and Neah Bay were near normal. Although geostrophic flow over the central Oregon shelf was southward as usual in summer and early fall 1998, temperature and spiciness of the upper ocean remained above normal,
presumably because normal southward advection was insufficient to offset the abnormally large northward advection that had occurred during the preceding autumn and winter. Shelf and slope waters off Oregon remained slightly warmer than normal through November 1998, but had certainly returned to normal by April 1999.

Cruises with extended alongshore sampling (four cross-margin sections between 38°E and 45°N) were conducted twice during El Niño 1997–8 (in November 1997 and April 1998) and twice more before the end of 1998 (August and November 1998). Each of these cruises shows significant alongshore gradients, which differed radically with depth. At depths of 200–500 m, waters were consistently cooler and less saline at higher latitudes. In the top 100–200 m, meridional gradients varied seasonally with the wind stress.

Fig. 18. Comparison of 1998 and 1983 post-El-Niño temperatures along the NH-Line, in spring of the same year (April 1983 and 1998), summer (July 1983 and June 1998 and August 1998), and spring of the following year (April 1984 and 1999).
(stronger winter downwelling, weaker summer upwelling at higher latitudes), and also with fresh-water flux (more winter rain at higher latitudes, southward advection of Columbia River effluent in summer). Nevertheless, each cruise showed a high degree of alongshore homogeneity in the offshore structure of the temperature, salinity, spiciness and geostrophic velocity superimposed on this meridionally varying background. In November 1997, all four sections showed the 6–10°C isotherms and 33.8–34.0 isohalines sloping down toward the continental slope, and a strong local spiciness maximum coincident with very strong poleward flow over the shelf and upper slope; this is consistent with the prior passage of a ‘downwelling’ coastally-trapped signal originating in the equatorial Pacific. In April 1998, all four sections show the 9–11°C isotherms and 32.8–33.4 isohalines were sloping up toward the coast, equatorward flow over the shelf, and a significant reduction in spiciness had occurred since November. These features are all consistent with the onset of normal seasonal upwelling at the end of the El Niño winter. In August 1998, all four sections show near-surface isotherms and isohalines sloping up toward the coast over the shelf or upper slope, and an equatorward jet over the continental shelf or upper slope; these features are consistent with stronger-than-normal coastal upwelling. All four August sections also show there had been an increase in shelf-break spiciness since April, which suggests there was net poleward advection by the California Undercurrent during the upwelling season. In November 1998, all four sections show near-surface isotherms and isohalines were approximately horizontal, and that the downward slopes of subsurface isotherms and isohalines were much less steep than in the previous years; these observations are consistent with the cessation of seasonal upwelling and a gradual return to normal conditions.

Our comparison of El Niño 1997–8 with El Niño 1982–3 shows both similarities and differences. Both El Niño episodes were very strong (maximum MEI of 3.2 in 1983 and 2.9 in 1997 compared with 2.3 in 1992, 2.1 in 1987, 1.8 in 1973, 1.5 in 1965, and 1.45 in 1958) and probably represent the two strongest events of the 20th century (Wolter & Timlin, 1998). Their duration in the central Pacific Ocean was similar (MEI >0 for 18 months in 1982–83 and for 16 months in 1997–8, extending over similar seasons with mid-points in early January 1983 and mid-November 1997). However, the development of these episodes in the equatorial Pacific was different. In 1982, MEI began to rise steadily from 0.0 in April/May reaching a single peak of 3.2 in February/March 1983, but the rise in sea level anomalies along the eastern equatorial boundary did not begin until July/August, rising rapidly in October/November to a peak of 29 cm in December. In 1997, MEI and eastern equatorial sea levels rose together from March/April through July (first peak, MEI at 2.9, ASL at 23 cm), relaxed a bit, then increased to a further peak (ASL at 29 cm in December, MEI at 2.8 in March/April 1998). The decay of El Niño in the eastern equatorial Pacific occurred more slowly in 1983 than in 1998 (MEI reached 0 in September 1983 and in July 1998).

The mid-latitude response off northern California and Oregon to these two El Niño episodes also shows important similarities and differences. In both cases coastal sea levels rose more than 1 s.d. above normal, and in both cases the sea level rise preceded an anomalous increase in the strength of the downwelling-favorable wind stress. In both cases, surface waters over the shelf and slope from 38°N to 45°N were anomalously warm during El Niño winters: the El Niño signal definitely reached these latitudes. In both cases, shelf-break waters were anomalously spicy during El Niño winter, indicating enhanced poleward advection along the continental margin during the preceding months. Temperature and spiciness anomalies were stronger in January 1998 than in January 1983 (near the peak in ASL). By April, coastal sea levels and shelf temperatures were about the same in 1998 and 1983. The signal of El Niño at mid-latitudes persisted longer in 1983 than in 1998, largely because of the large difference in local wind forcing (much less upwelling in 1983 than in 1998), but perhaps also a result of the longer persistence of El Niño 1982–3 in the equatorial Pacific. Comparisons between observations made during spring of the year after El Niño shows that coastal waters were still warmer in April 1984 than in April 1999; data from Newport, Oregon shows that temperatures in April 1999 were near normal.
7. Acknowledgments

We are grateful to numerous colleagues who participated in the recent GLOBEC cruises, the 1981–1984 SuperCODE cruises, and the 1961–1971 cruises along the Newport Hydrographic Line. We thank Klaus Wolters, Mark Merrifield, Jo Miller and Pradeep Naik for providing environmental indices. The authors are supported by grants from the National Oceanic and Atmospheric Administration (NA860P0589), the National Science Foundation (OCE-0000733), and the Office of Naval Research (N00014-98-1-0026 and N00014-98-1-0787). This is contribution number 226 of the US GLOBEC program, jointly funded by the National Science Foundation and the National Oceanic and Atmospheric Administration.

Appendix. Data sets

Smith et al. (2001) have provided a summary of sampling along the Newport Hydrographic Line, which includes specific sampling dates within the 1961–1999 period. Standard stations sampled during 1961–1971 were NH-5, NH-15, NH-25, NH-35, NH-45, NH-65, and NH-85, located 5, 10, 15 nm, etc, from shore along 44°39.1′N; extra stations (NH-1, NH-3, NH-10, NH-20, NH-55) were occasionally added, and have been included routinely in the sampling since 1997. Between 1961 and 1971 sampling was by means of discrete casts with bottles at or near standard depths (0, 10, 20, 30, 50, 75, 100, 150, 200, 250, 300, 400, and 500 m). Since 1997, a SBE 9/11 plus CTD system has been used routinely; the processed data have a vertical resolution of 1 m (Fleischbein, Hill, Huyer, Smith, & Wheeler, 1999).

The environmental time series were compiled by other researchers, and most are readily available. The MEI (Multivariate ENSO Index; Wolter & Timlin, 1998) is a single index computed from the six main observed variables which are routinely collected for the tropical Pacific ocean: atmospheric sea level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky. The MEI is calculated as the first unrotated principal component of all six fields combined for bimonthly ‘seasons’ (December/January, January/February, etc); all seasonal values are standardized with respect to each season and to the 1950–93 reference period. MEI values are available from Klaus Wolter, NOAA-CIRES Climate Diagnostics Center, University of Colorado (http://www.cdc.noaa.gov/~kew/MEI/).

Adjusted sea level (ASL) data for many locations in the Pacific Ocean are available from M. Merrifield and K. Wyrtki of the University of Hawaii Sea Level Center (http://ilikai.soest.hawaii.edu/). The values are calculated from hourly coastal tide gage data using atmospheric pressure corrections provided by the National Meteorological Center to adjust for the inverted barometer effect. We use the monthly-adjusted sea level anomaly (ASLA) data, relative to 21-year (1975–1995) monthly means, for Santa Cruz, Ecuador (0.75°S, 90.3°W, in the Galapagos Islands), Callao, Peru (12.05°S, 77.15°W), San Francisco, California (37.8°N, 122.47°W), Crescent City, California (41.75°N, 124.2°W), and Neah Bay (48.7°N, 124.6°W).

Coastal Upwelling Indices (CUI) are computed by the Pacific Fisheries Environmental Laboratory for selected locations along the North American West Coast (http://www.pfeg.noaa.gov). The CUI is the amount of surface layer offshore Ekman transport, in units of cubic meters per second per 100 m of coastline, and is directly proportional to the alongshore component of the local wind stress derived from 6-hourly synoptic pressure fields. A CUI value of 100 m$^3$ s$^{-1}$ per 100 m of coastline corresponds to an alongshore wind stress of −0.1 Pa. Both monthly values (CUI) and monthly anomalies (CUIA, relative to the mean monthly values for 1948–1967) are used in this paper to represent the variability of local large-scale winds.

Columbia River discharge (CRD) estimates are available from the US Geological Survey. The time series of monthly mean estimates for 1928–65 (Orem, 1968) has been updated through September 1984 (S. J. Miller, personal communication USGS). USGS now measures daily streamflow of the lower Columbia
(station 14246900 at 46°10.9′N, 123°11.0′W), and these data were used to estimate monthly mean discharge for July 1991 through May 1999. For the 7-year hiatus, Smith et al. (2001) estimated the discharge at the mouth from streamflow measurements of the middle Columbia (station 14105700 at The Dalles, Oregon, 45°36.5′N, 121°10.3′W) and of the lower Willamette (station 14211720 at Portland, Oregon, 45°31.1′N, 122°40.0′W). CRD is highly seasonal, and the seasonal cycle changed considerably with the doubling of reservoir capacity between 1968 and 1975 (Sherwood, Jay, Harvey, Hamilton, & Simenstad, 1990). Statistics of the estimated discharge for the 20-year period from January 1979 to December 1998 are shown in Table A1.

### Table A1

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