THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

CITATION

Washburn, L., and E. McPhee-Shaw. 2013. Coastal transport processes affecting inner-shelf ecosystems in the California Current System. *Oceanography* 26(3):34–43, http://dx.doi.org/10.5670/oceanog.2013.43.

DOI

http://dx.doi.org/10.5670/oceanog.2013.43

Coastal Transport Processes Affecting Inner-Shelf Ecosystems in the California Current System

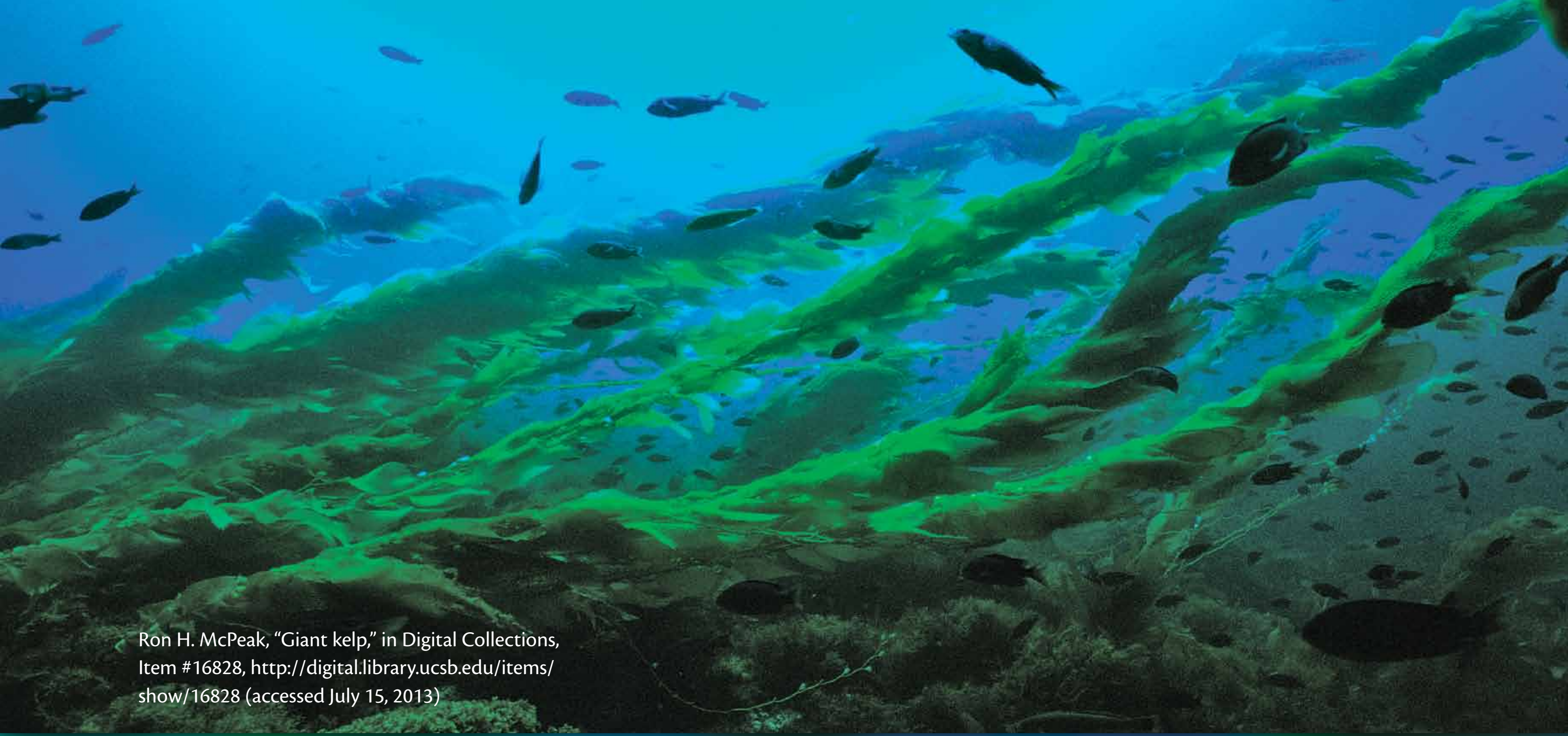
BY LIBE WASHBURN AND ERIKA McPHEE-SHAW

ABSTRACT. Wind-driven upwelling is weak and intermittent in the Southern California Bight, a region sheltered from the strong, prevailing equatorward winds typical of most of the California Current System. Thus, other physical transport processes than wind-driven upwelling supply subsidies of nutrients, biogenic particles, and other water-borne materials to support the highly productive temperate reef ecosystems of the Southern California Bight, including forests of giant kelp (*Macrocystis pyrifera*) and a broad diversity of reef organisms. This article focuses on results from the Santa Barbara Coastal Long Term Ecological Research project related to the various transport processes important for maintaining nearshore ecosystems in the California Current System. It reviews along-shelf and cross-shelf flow mechanisms that deliver these subsidies, discusses how these mechanisms interact, and examines some of the biological patterns that result from these transport processes.

INTRODUCTION

Ecosystems in eastern boundary current upwelling systems are profoundly influenced by the oceanographic regimes in which they are embedded. Broad, meandering equatorward currents such as the California Current System generate eddies, fronts (regions of strong horizontal gradients in water properties that often correspond to convergent flow), and various instability processes that temporarily concentrate organisms and bring nutrients into the euphotic zone to stimulate bursts of primary and secondary productivity. Franks et al. (2013, in this issue) describe recent efforts to model these processes. Although shelf and nearshore ecosystems also derive much of their nutrients and other subsidies from deep water, the mechanics of delivery differ from those offshore.

Wind-driven coastal upwelling, including Ekman pumping in the highly sheared wind fields near the coastal boundary, is the dominant mechanism that makes the California Current System extremely productive. Dynamics on the narrow shelves of the California Current System are distinguished from those of many other coastal systems in that they receive weak river inflow. Away from the Columbia River, at the northern end of the system, rivers have a relatively small influence on both nutrients and buoyancy-driven currents, and river influence continues to wane southward into the Mediterranean climate of central and southern California. Although seasonal upwelling dominates the annual net transport of nutrients to the inner shelf, there are many other important processes at work, and it is particularly important to study those active processes during non-upwelling seasons. Because the high nutrient concentrations found in deep offshore waters are primary drivers of surface productivity even in the shallowest parts of the shelf ecosystem, it is important to observe and quantify transport of subsurface, offshore waters up into the mid and inner shelf in order to understand variations in the productive capacity



Ron H. McPeak, "Giant kelp," in Digital Collections, Item #16828, http://digital.library.ucsb.edu/items/show/16828 (accessed July 15, 2013)

of shallow ecosystems. Understanding cross- and along-shelf transport is necessary not just for describing fluxes to the inner shelf, but also for understanding important mid-shelf processes such as the development of widespread anoxia over Oregon shelves (Chan et al., 2008; Grantham et al., 2004).

In this article, we focus on the eastern boundary California Current System with an emphasis on the nearshore kelp ecosystem of the Santa Barbara Coastal Long Term Ecological Research (SBC LTER) site. We review the major features and drivers of coastal transport in both the along- and cross-shelf dimensions, paying particular attention to mechanisms that control the transport and variability of constituents and attributes important for these ecosystems, including nutrients, oxygen, pH, sediment, and pollutants. Observing these processes is often challenging because they are intermittent and their timing is largely unpredictable. To address these challenges, the oceanographic observational program of the SBC LTER was designed to quantify delivery of subsidies to shallow-water ecosystems through long-term, continuous, and rapid sampling, which increases the likelihood of capturing intermittent phenomena. These observations also allow better estimates of the rates of biologically driven processes such as photosynthetic uptake and remineralization. Complementary physiological and ecological studies within the SBC LTER quantify the responses to these subsidies across a range of trophic levels.

ALONG-SHELF TRANSPORT

Eastern Boundary Currents

Equatorward-flowing eastern boundary currents along almost all western continental boundaries are driven by equatorward winds that also produce coastal upwelling (an exception is the Leeuwin Current on the west coast of Australia, which flows poleward and is driven by along-shelf pressure gradients set up by buoyant water from the Indonesian Throughflow). Over the mid-continental shelf and farther offshore, currents are in geostrophic balance in which pressure gradient forces, caused by horizontal gradients in sea level and seawater density, balance the Coriolis forces caused by Earth's rotation and by the currents themselves. The result is net transport perpendicular to both the pressure gradients and the Coriolis forces; like the winds in large-scale weather systems, geostrophic ocean currents flow along lines of constant pressure. Close to shore, however, continental boundaries alter this balance. Cross-shelf pressure gradients and Coriolis forces can still balance to support along-shelf geostrophic currents, but along-shelf pressure gradients are no longer balanced by along-shelf Coriolis forces. The coastal boundary blocks the perpendicular currents required to achieve this balance. Along-shelf pressure gradients can instead drive along-shelf currents in the coastal region. This is a principal difference between the dynamics of nearshore currents and those of offshore currents, and it is one reason why currents over the shelf are often directed poleward, opposite to the larger-scale transport of the eastern boundary current system. Some northward flows in the California Current System are driven by along-shelf pressure gradients that result from sea level height gradients caused by persistent equatorward winds. In other areas such as offshore of Washington, western Canada, and Alaska, such flows can be driven by input of buoyant water from terrestrial runoff. In the Southern California Bight where the SBC LTER study sites are located, the general coastal current pattern is poleward (Hickey, 1979, 1998; Lynn and Simpson, 1987).

Synoptic or "Weather-Band" Variability in Along-Coast Currents

An important driver of variability in the coastal currents of upwelling systems is the alternation between prevailing equatorward winds and wind relaxations, or reversals, lasting a few to several days. This wind pattern is characteristic of spring, summer, and fall conditions in the California Current System. Episodic reversals of upwelling-favorable winds elevate sea level along the coastline and reverse the direction of cross-shelf pressure gradients. Coastal currents then come into a new geostrophic balance as their transport shifts from equatorward to poleward. Similar poleward flows nearshore are often forced by the strong southerly winds of winter storms. Onshore Ekman transport during downwelling-favorable winds transports nutrient-poor surface water toward shore and suppresses phytoplankton and macroalgal primary productivity within inner-shelf ecosystems.

Coastally Trapped Waves

Changes in the wind field also generate reversals of along-coast currents via propagating coastally trapped waves (CTWs), so named because they exist against a continental margin, with the boundary to the right of wave propagation in the Northern Hemisphere, and to the left in the Southern Hemisphere (Allen, 1980). The waves fall into two broad categories: (1) internal Kelvin waves that propagate much like other long waves traveling along a sharp thermocline, except that the thermocline tilts up or down perpendicular toward shore so the along-shelf currents remain in geostrophic balance; internal Kelvin waves are favored on steeply sloping shelves; and (2) topographic Rossby waves that are propagating disturbances caused by cross-shelf movements of rotating water columns up and down a sloping shelf; topographic Rossby waves are favored on shelves with more gradual slopes. In the Southern California Bight and the SBC LTER study region, coastally trapped waves are hybrids of internal Kelvin waves and topographic Rossby waves (Auad and Hendershott, 1997).

The sea surface and thermocline displacements that initiate CTWs are caused by changes in wind speed and direction along stretches of coastline usually far equatorward of where the CTW effects are observed. The waves then propagate slowly along the continental margin, causing along-shelf currents that constructively and destructively interfere with other types of currents some hundreds of kilometers away from, and some days later than, the initiating wind disturbance. The dissociation between local current fluctuations and local winds made it difficult to pinpoint the forcing of CTWs when coastal oceanographers first identified these features. In the SBC LTER study area and elsewhere in the Southern California Bight, CTWs originating in Baja California account for much of the along-shelf current variability on time scales of a several days to a few weeks (Auad and Hendershott, 1997; Hickey et al., 2003; Pringle and Riser, 2003). Similarly, CTWs caused by wind forcing between Point Reyes and Cape Mendocino in Northern California drive much of the along-shelf current variability far to the north over the Oregon and Washington shelves (Battisti and Hickey, 1984).

Buoyancy-Driven Along-Coast Flows

Buoyancy effects are also important in driving along-shelf currents in the SBC LTER study region and elsewhere in the California Current System. For example, episodic freshwater discharge during winter storms produces plumes of turbid, low-salinity water that often flows along the coastline carrying terrestrial sediment and nutrients (Warrick et al., 2004, 2005). Other buoyant flows result from the interaction among coastal winds, solar heating, and topography. When winds relax along the central California coast, elevated sea level and warm, buoyant water in the lee of Point Conception drive northward currents that propagate 10 to 30 km per day (Melton et al., 2009; Washburn et al., 2011). Similar buoyant flows originating in the lee of headlands occur in the central and northern California Current System (Send et al., 1987; Woodson

Libe Washburn *(washburn@eri.ucsb.edu) is Professor, Marine Science Institute and Department of Geography, University of California, Santa Barbara, CA, USA.* **Erika McPhee-Shaw** *is Associate Professor, Moss Landing Marine Laboratories, San Jose State University, Moss Landing, CA, USA.*

et al., 2009). These flows are important for delivering invertebrate larvae to subtidal and intertidal habitats (Wing et al., 1995; Dudas et al., 2009).

ACROSS-SHELF TRANSPORT

Upwelling

Upwelling, or the slow, bulk transport of deeper waters shoreward during equatorward winds, is the primary form of onshore, cross-shelf transport bringing nutrients toward inner-shelf ecosystems in eastern boundary current systems. Near the surface, net cross-shelf transport is offshore during upwelling. This can affect ecosystems by drawing away from the coast the plankton species that accumulate there (but see Shanks and Shearman, 2009), and by allowing the development of upwelling fronts within which surface plankton blooms can aggregate and slowly advect offshore. After the spring transition to upwelling, spring and early summer are most often characterized by the steady and persistent conditions necessary for such upwelling fronts, which develop over a period of days. Upwelling remains common and causes significant shoreward transport of deep water during late summer and fall. However, fall upwelling is more frequently interrupted by wind reversals and periods of downwelling, when warm, low-nutrient surface waters move back onshore and fill the inner shelf and upper water column over the outer shelf. Importantly, the up-shelf and down-shelf excursions associated with transitions between upwelling and downwelling modulate internal wave transport during a season when conditions over the shelf are more stratified than earlier in the season and can better support internal waves. CTWs can also push waters back and forth across the shelf and tilt the thermocline up and down to cause bulk cross-shelf transport that is mechanistically similar to upwelling, but generally weaker (Pringle and Riser, 2003).

Internal Waves

After upwelling, the most important form of cross-shelf transport for shallow ecosystems is that driven by internal waves. Internal waves oscillate at frequencies ranging from inertial to buoyancy (periods of typically 10 minutes up to about a day) and can expose inner-shelf bottom waters to previously deep, nutrient-laden water for hours at a time. Energetic internal motions, whether diurnal or semidiurnal, are important for delivering high dissolved inorganic nitrogen concentrations (henceforth "nitrate") to the inner shelf during summer when the water column is otherwise nutrient depleted and nutrients become limiting for giant kelp (Zimmerman and Kremer, 1984; Brzezinski et al., 2013, in this issue). Other observations show that ammonia from sediments or other sources may supply nitrogen when ambient nitrate concentrations are low (Brzezinski et al., 2013, in this issue).

Sensor-based nitrate measurements from the Santa Barbara Channel inner shelf showed the bottom half of the water column swinging between 0 and roughly 5 to 8 μmol nitrate over 12 hours (Figure 1). The surface water did not experience the same highs and lows but remained relatively warm and at near-zero nitrate concentration (not

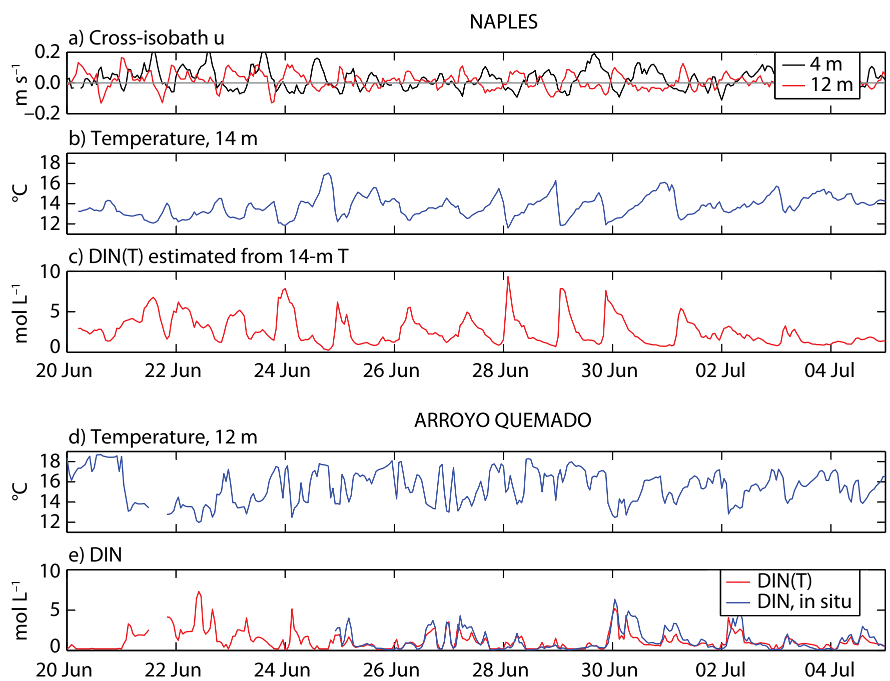


Figure 1. Diurnal period internal waves measured at Santa Barbara Coastal Long Term Ecological Research moorings Naples Reef (a–c) and Arroyo Quemado (d,e). These moorings are identified in Figure 3. Near-surface (4 m depth, black line) and near-bottom (12 m depth or 5 m above seabed, red line) cross-shelf components of currents frequently moved in opposite directions (panel a), exhibiting the baroclinic current structure characteristic of internal waves (onshore is positive, offshore negative). The internal motions were associated with diurnal temperature fluctuations (panel b) that corresponded to strong diurnal nitrate pulses (panels c and e). Nitrate in panel c was inferred from temperature using an empirical temperature-nitrate relationship; in panel e, sensor-measured nitrate is shown in addition to temperature-derived nitrate at the Arroyo Quemado mooring. *Adapted from McPhee-Shaw et al. (2007)*

shown in Figure 1). Although previous temperature-based studies had suggested that internal waves were an important source of deep nutrients to kelp and coral reefs (Zimmerman and Kremer, 1984; Leichter et al., 2003), the SBC LTER study (McPhee-Shaw et al., 2007) was the first to unequivocally document this process with in situ nitrate measurements, and it changed our understanding. The nutrient exposure of inner shelf ecosystems is higher than had been previously understood based primarily on a concept of surface waters and upwelling-downwelling cycles. This was again documented in the Southern California Bight in subsequent studies, including in situ nitrate profiling (Lucas et al., 2011). New studies from the California Current System find that similar baroclinic advective dynamics also affect oxygen and pH over inner shelf kelp forests and reef ecosystems. Deep, cold water with oxygen levels low enough to be physiologically harmful have been documented encroaching into 15 m deep waters via internal waves at several locations in Monterey Bay, Central California (Booth et al., 2012).

Dominant periods of internal waves and internal motions in the Southern California Bight are diurnal and semidiurnal (Pineda, 1995; Lerczak et al., 2001; McPhee-Shaw et al., 2007; Fram et al., 2008; Lucas et al., 2011). The along-shelf coherence scales of the diurnal waves are at least 50 km, and their amplitudes increase with the strengths of stratification and the diurnal sea breeze (Cudaback and McPhee-Shaw, 2009). Because their periods exceed the local inertial period, these internal motions likely do not travel as free waves but rather are forced by processes such as the sea breeze. In contrast, semidiurnal internal waves result from the internal tide and can propagate freely onto the inner shelf (Fram et al., 2008; Lucas et al., 2011). Cross-shelf transport of deep waters by surging internal tides has been shown to control nutrient and heat fluxes in other inner-shelf areas of the Southern California Bight (Nam and Send, 2011).

Coastal Eddies

Small, transient coastal eddies also produce cross-shelf transport of nutrients and other water-borne materials to habitats on the inner shelf. These eddies commonly occur in the Southern California Bight, have horizontal scales of order 10 km, and are transient, typically lasting only a few days (DiGiacomo and Holt, 2001; Bassin et al., 2005; Kim, 2010). They likely result from a number of processes, including oscillating tidal flows around coastal headlands (Signell and Geyer, 1991) and instabilities of larger-scale flows (Eldevik and Dysthe, 2002). Observations in the Southern California Bight have shown that small coastal eddies can deliver waters with high nitrate concentrations to kelp forests on the inner shelf (Bassin et al., 2005). Figure 2 shows one of these eddies near the coast in the Santa

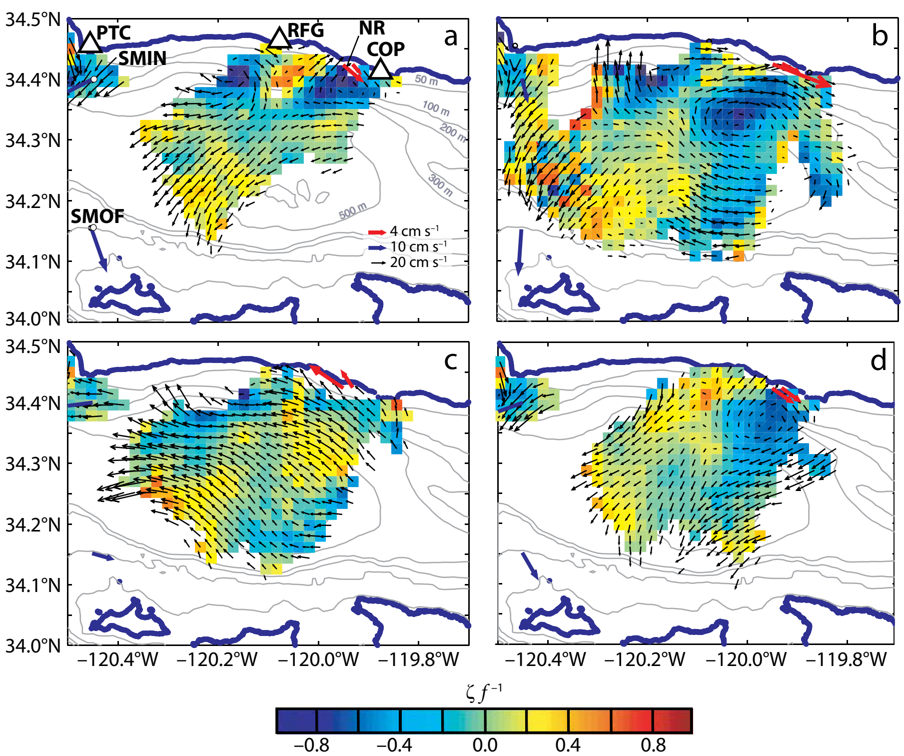


Figure 2. Evolution over four days of a small coastal eddy in 2001 that delivered high nitrate concentrations to the Santa Barbara Coastal Long Term Ecological Research mooring at Naples Reef (NR). Times of the panels are: (a) December 10, 0000 GMT, (b) December 11, 0800 GMT, (c) December 13, 1600 GMT, and (d) December 15, 0000 GMT. Black arrows indicate surface current vectors measured by shore-based high-frequency radars (triangles) at Coal Oil Point (COP), Refugio (RFG), and Pt. Conception (PTC). Colors indicate normalized relative vorticity ζf^{-1} scaled according to the color bar. The symbol ζ indicates twice the rotation rate of surface water parcels and f is Earth's effective rotation rate at the latitude of the study sites. Blue shades in the color bar indicate clockwise rotation and red shades indicate counterclockwise rotation. Red arrows west of COP are current velocities measured 12 m above the bottom by current meters at the Naples Reef mooring (location shown in Figure 3) and the nearby Ellwood mooring (not labeled). Blue arrows are current velocities measured at 5 m depth at moorings named SMIN and SMOF (circles) discussed by Harms and Winant (1998). *Adapted from Bassin et al. (2005)*

Barbara Channel. As the eddy increased in size (Figure 2a,b), sensor-measured nitrate on the inner shelf rose from background values of ~ 1 μmol to 8–9 μmol. The nitrate increase likely resulted from cross-shelf flow, either due to upslope transport of deep water by the eddy or onshore advection by the eddy of nitrate upwelled elsewhere. Because the eddies occur year-round, they may be important in sustaining forests of giant kelp during summer and fall when other sources such as upwelling and terrestrial runoff are weak or absent.

LINKS BETWEEN ALONG-SHELF AND CROSS-SHELF CURRENTS

Understanding links between along-shelf and cross-shelf transport is challenging because the processes acting in the two directions have vastly different temporal and spatial scales. For example, the episodic poleward flows that follow wind relaxations transport waterborne materials about 40 km along-shelf around Point Conception over two days (see arrow in Figure 3). In contrast, the 1–3 km cross-shelf transport due to internal waves (Figure 3) occurs over several hours. Cross-shelf transport does not stand alone and distinct from along-shelf transport. However, a clear, predictive understanding of this connection has not yet been achieved. The two are related by the geostrophic balance over the coastal margin. Cross-shelf transport remains a vexing issue in ocean dynamics because, for fully geostrophic flow in the ocean, currents flow along isobars and isobaths, and cross-isobath currents are essentially zero. The wiggle room comes in via friction (Brink, 2012). Transport in the frictional surface Ekman layer controls how wind momentum is transferred to the ocean and sets up the sea surface height gradients that drive geostrophic along-shelf currents. In the deep ocean interior, on time scales sufficiently long for Coriolis forces to be important, turbulent frictional forces are weak. However, in the coastal ocean, this reasoning falls apart in several different ways, and friction helps explain why cross-shelf transport exists, even if it is generally weak compared to along-shelf transport.

Bottom Ekman layers, the seafloor counterpart of surface frictional Ekman layers, move deep water shoreward when geostrophic currents are equatorward in the California Current System. Onshore bottom Ekman transport enhances the ability of internal waves to add the last push of those offshore waters into the inner shelf and sometimes perhaps to the surf zone. Recent studies suggest CTW motions produce variations in low-frequency, along-shelf currents that set up bottom Ekman transport. Noble et al. (2009) found internal wave transport to shallow waters in the Southern California Bight to depend strongly on the occurrence of low-frequency equatorward shelf currents. Isopycnals tilt upward toward the coast in this scenario, bringing deeper, nutrient-rich waters closer to shore and enabling internal waves traveling along the

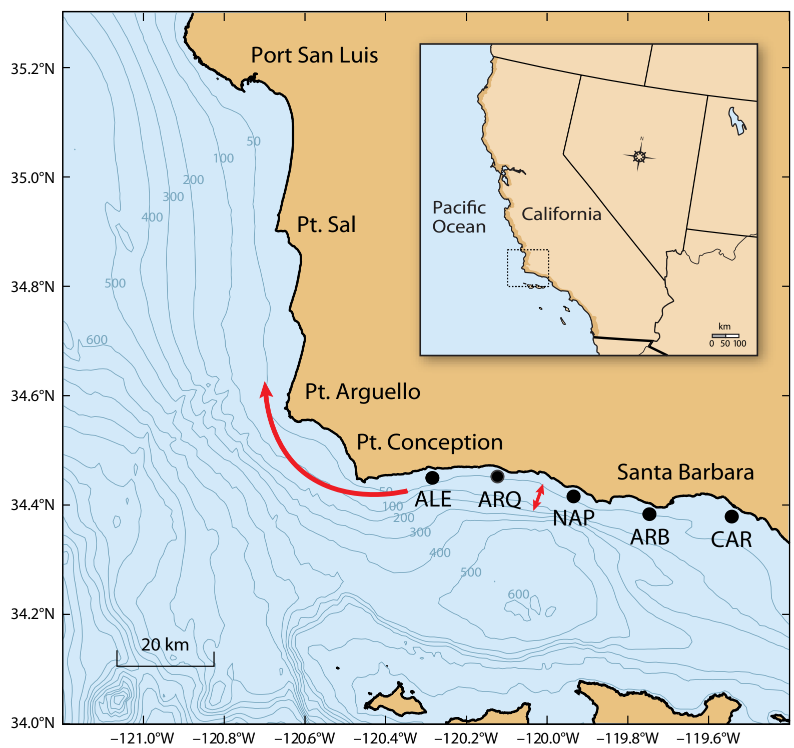


Figure 3. The map and inset show the Santa Barbara Coastal Long Term Ecological Research study area on the California coast. The curved red arrow indicates the displacement caused by an along-shelf transport process with a velocity of 0.2 m s^{-1} over two days. The poleward relaxation flows such as those described by Melton et al. (2009) and Washburn et al. (2011) produce transport over these temporal and spatial scales. In contrast, the small double-ended arrow shows the much smaller cross-shelf excursions of water parcels (somewhat exaggerated for clarity) caused by internal waves on time scales of hours such as those described by McPhee-Shaw et al. (2007) and Lucas et al. (2011). Abbreviations and circles identify moorings at Carpinteria (CAR), Naples Reef (NAP), Arroyo Quemado (ARQ), and Alegria (ALE). Darker blue lines show bathymetry in meters.

thermocline to propagate farther inshore (Figure 4a,b). When the thermocline tilts downward toward shore, onshore transport processes are less effective in delivering nutrients to shallow habitats (Figure 4c,d). These upwelling, downwelling, and CTW cycles linking along-shelf currents with onshore and offshore transport of deep waters may control phytoplankton species distribution patterns to form the so-called coastal "green ribbon" described by Lucas et al. (2011).

Another way friction in the coastal ocean differs greatly from the deeper offshore ocean is that bottom and surface frictional boundary layers no longer comprise insignificant portions of the water column. Within the inner shelf, the two boundary layers instead fill most of the water column and can even merge from above and below (Fewings et al., 2008; Fewings and Lentz, 2010; Kirincich et al., 2005). The dominance of friction within the triangular region of the inner shelf sets this zone apart mechanically from the rest of the ocean: rapid momentum transport due to merged surface and bottom boundary layers leads to a mostly downwind transport and a rapid response to wind forcing in very shallow waters. The scales of coastline and topographic irregularities likely limit the length scales of this direct wind response. Within this region, along-shelf currents weaken toward shore (Nickols et al., 2012).

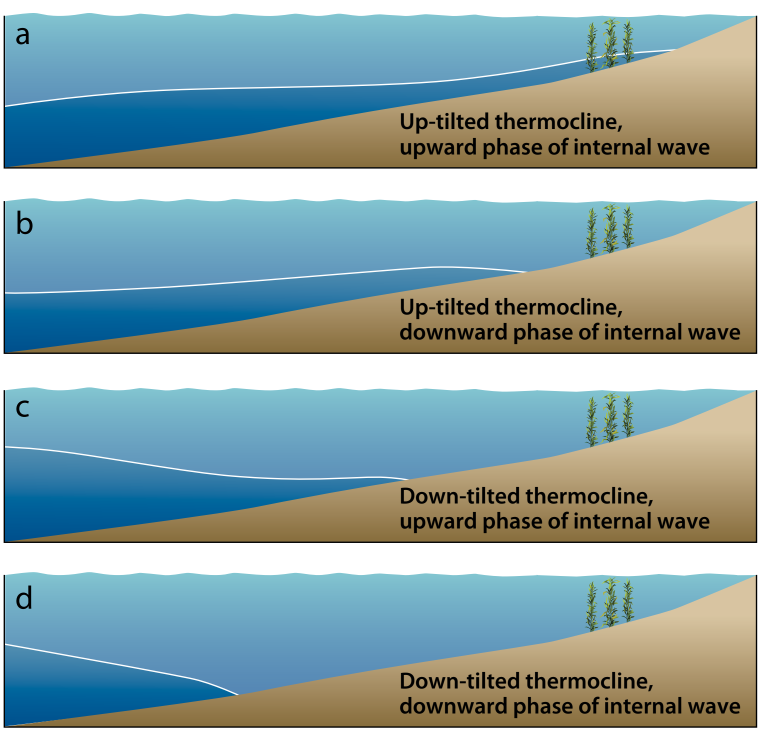


Figure 4. The distances over which internal waves can transport nutrients to habitats near shore such as kelp forests (vertical green plants toward right of diagrams) are controlled by tilts of the thermocline (white line) separating near-surface nutrient-poor waters (light blue shades) from deeper nutrient-rich waters (dark blue shades). When the thermocline tilts upward, the cold phase of an internal wave bathes nearshore habitats in cold, nutrient-rich waters. During the warm phase (panel b), nutrient-rich waters are farther offshore and do not reach the kelp forests. When the thermocline tilts downward, neither phase delivers nutrients (panels c and d) to habitats near shore. Processes including wind-driven upwelling and downwelling cycles and the passage of coastally trapped waves control tilting of the thermocline.

Transport associated with barotropic tides can likewise be relatively more important in shallow coastal regions than offshore because the typical length scale of embayments and headlands may match the transport length scales of tides. For example, a 0.10 m s^{-1} average tidal current speed may nearly equal geostrophic current speeds along the shelf, but with only six hours to flow in one direction before turning around results in an oscillatory excursion of only about 2 km. Such transport, although small compared with open-ocean transport scales, may reach from one headland to the next in small embayments. An example where this scale match-up may play a role is Stillwater Cove, off Pebble Beach on the Central California coast, where, as the name implies, waters seem to stagnate even though the embayment opens onto a larger bay with occasionally energetic surf and immediate access to a deep submarine canyon (Carroll, 2009). In coastal regions, most tidal flow is along-shelf, again emphasizing the importance of internal tides rather than surface tides for accomplishing cross-shelf transport.

Even shallower than the inner shelf is the surf zone with its own complex set of flows, most associated with breaking-wave processes. Along-shelf transport in the surf zone arises from several factors, including coastline irregularities, variable seafloor slopes, and wave refraction. Cross-shelf transport is associated with wave setup, undertow, and rip currents. These processes affect sediment and pollutant transport in this very shallow zone, albeit at scales that usually do not transport material very far offshore. Some shallow surf zones also appear to experience fluctuations in nutrients and oxygen delivery from deeper waters via internal tides and internal waves (Noble et al, 2009; Lucas et al., 2011), and both can have important effects on shallow-water ecosystems.

NEARSHORE TRANSPORT PROCESSES AND INNER-SHELF ECOSYSTEMS RESPONSES

Subsidies of nutrients, larvae, and particulate organic matter from local and remote sources sustain the highly productive ecosystems of the inner shelf through a variety of more persistent along-shelf and intermittent cross-shelf transport processes. Wind-driven coastal upwelling during spring and summer sustains high primary productivity rates in kelp forests over much of the California Current System. In contrast, in the Southern California Bight, where wind-driven upwelling is often weak especially in summer, other processes sustain this productivity. A nitrate budget estimated by McPhee-Shaw et al. (2007) quantified four major components: spring upwelling delivered about 70% of the dissolved inorganic nitrate to kelp forests in the SBC LTER study area, summer internal waves about 9–12%, winter upwelling about 7–12%, and terrestrial runoff about 2–15%. Fram et al. (2008) estimated a comparable budget based on one-year time series: most nitrate was delivered during spring upwelling and < 9% was delivered by internal waves and terrestrial runoff. However, during stratified periods, mostly in summer, they found that 20% of nitrate was supplied by internal waves.

Internal waves primarily slosh water and nutrients back and forth and so do not necessarily cause net transport toward shallow water. However, when internal waves are nonlinear and behave as bores or breaking waves, they can transport larvae and other materials shoreward (Pineda and López, 2002). Furthermore, even longer-period linear internal waves such as those with diurnal or semidiurnal periods can expose kelp forests to high nitrate concentrations for several hours during their cold phases (Figure 4a). Nitrogen uptake by benthic organisms during that cold phase effectively results in net transport of nitrate from deeper offshore waters into shallow reef ecosystems.

Not only do internal waves subsidize kelp forests through delivery of nitrate and other materials, observations indicate that they maintain cross-shelf gradients in various groups of small organisms drifting in the water column. Freely drifting functional groups such as phytoplankton and bacteria, along with related organic materials, effectively integrate the delivery of subsidies over time scales of a few to several days as they are advected by coastal currents. Their nearshore distributions often exhibit increasing concentrations toward shore consistent with control by cross-shelf transport processes. For example, Halewood et al. (2012) found that distributions of particulate organic carbon, particulate organic nitrogen, and bacterioplankton exhibited this pattern in water depths from about 7 to 65 m. These cross-shelf gradients weakened during upwelling and weak stratification, consistent with rapid exchange with offshore water masses. In contrast, cross-shelf gradients in these parameters strengthened when upwelling relaxed and stratification increased, consistent with reduced cross-shelf exchange and isolation of inner shelf waters from those offshore. Goodman et al. (2012) observed similarly evolving patterns in phytoplankton distributions. During upwelling and weak stratification, diatoms were more uniformly abundant across the shelf as was taxonomic similarity of phytoplankton species. As upwelling relaxed and stratification increased, nearshore phytoplankton concentrations increased while taxonomic similarity decreased across the shelf. This was accompanied by a succession first of diatom blooms and then of dinoflagellates blooms on the inner shelf. Months-long persistence of cross-shelf gradients observed in these studies suggests isolation of inner shelf waters from the mid and outer shelf. Their persistence, coupled with prevailing poleward currents, further suggests they are common features of shelf waters in the Southern California Bight.

Lucas et al. (2011) observed similar patterns in phytoplankton concentrations and related quantities and rates, but with more comprehensive physical oceanographic observations allowing insights into the relevant transport processes. They observed a cross-shelf gradient in phytoplankton community composition ranging from groups such as cyanobacteria and dinoflagellates offshore, where nutrient concentrations were lower in surface waters, to groups such as diatoms near shore, where nutrient concentrations were higher. They concluded that pumping by the semidiurnal internal tide, coupled with isopycnals sloping upward toward shore and offshore shoaling of the nitracline, supplied nitrate to drive nearshore blooms. Weak but persistent along-shelf winds likely uplifted the isopycnals. The upward tilt of isopycnals toward shore allowed semidiurnal internal waves to move nitrate rapidly to shore and drive higher primary productivity such as shown in Figure 4a. An important element in this process was the shoaling of the nitracline depth offshore, possibly in response to modulation of the offshore thermocline depth by coastally trapped waves. A general cooling of surface waters over the entire Southern California Bight during their study was consistent with the effects of coastally trapped waves. This is also consistent with the conclusion of Pringle and Riser (2003) that coastally trapped waves generated off Baja California cause thermocline tilts and upwelling-like flows over the Southern California Bight. Similar patterns of intense phytoplankton blooms near rocky coasts have been suggested to arise not only from nutrient supply but also from purely advective accumulation against the coast due to convergent surface-wave Stokes transport (McPhee-Shaw et al., 2011).

SUMMARY AND FUTURE DIRECTIONS

Ecologists working to understand shallow, nearshore ecosystems also need to understand the diverse flow phenomena affecting these systems through the delivery of nutrients, biogenic particles, and other subsidies. Long-term trends in these ecosystems and the flows affecting them due to factors such as climate change can be challenging to discern because of the strong variability of the coastal ocean on shorter time scales. Other factors such as such as local pollution, invasive species, and management decisions also produce changes in these ecosystems, making longer-term trends difficult to detect.

The last decade has brought greatly improved understanding of the role of not only upwelling and downwelling but also of other important processes such as coastally trapped waves, wind-driven circulation, and internal waves in shallow nearshore waters. We endorse the suggestion of Lucas et al. (2011) that coastal observational programs need to obtain better subsurface measurements that capture, for example, the stratification over both the inner and outer shelf so that other important factors such as the cross-shelf tilt of the thermocline can be determined. These parameters are necessary to develop the ability to forecast important coastal ecological processes such as the timing of nutrient delivery or the occurrence of harmful algal blooms and hypoxic events.

ACKNOWLEDGEMENTS

We thank the many technicians, graduate students, and undergraduates who have worked on the Santa Barbara Coastal Long Term Ecological Research project over the years. We also thank Guest Editor Merryl Alber and two anonymous reviewers for helpful comments that improved the manuscript. Funding was provided to the SBC LTER by the National Science Foundation (OCE 0620276). E.M.-S. and L.W. were supported by NSF awards OCE 096180 and OCE 1031893, respectively. Many grants from other agencies and the National Science Foundation supported research that contributed data to the overall effort.

REFERENCES

Allen, J.S. 1980. Models of wind-driven currents on the continental shelf. *Annual Review of Fluid Mechanics* 12:389–433, http://dx.doi.org/10.1146/annurev.fl.12.010180.002133.

Auad, G., and M.C. Hendershott. 1997. The low-frequency transport in the Santa Barbara Channel: Description and forcing. *Continental Shelf Research* 17(7):779–802, http://dx.doi.org/10.1016/S0278-4343(96)00062-3.

Bassin, C.J., L. Washburn, M.A. Brzezinski, and E.E. McPhee-Shaw. 2005. Sub-mesoscale coastal eddies observed by high frequency radar: A new mechanism for delivering nutrients to kelp forests in the Southern California Bight. *Geophysical Research Letters* 32, L12604, http://dx.doi.org/10.1029/2005GL023017.

Battisti, D.S., and B.M. Hickey. 1984. Application of remote wind-forced coastal trapped wave theory to the Oregon and Washington coasts. *Journal of Physical Oceanography* 14:887–903, http://dx.doi.org/10.1175/1520-0485(1984)014<0887:AORWFC>2.0.CO;2.

Booth, J.A., E.E. McPhee-Shaw, P. Chua, E. Kingsley, M. Denny, R. Phillips, S.J. Bograd, L.D. Zeidberg, and W.F. Gilly. 2012. Natural intrusions of hypoxic, low pH water into nearshore marine environments on the California coast. *Continental Shelf Research* 45:108–115, http://dx.doi.org/10.1016/j.csr.2012.06.009.

Brink, K.H. 2012. Cross-shelf transports: The problem that does not die. Abstract, ID:9718. Ocean Sciences Meeting, Salt Lake City, UT, February 20–24, 2012.

Brzezinski, M.A., D.C. Reed, S. Harrer, A. Rassweiler, J.M. Melack, B.M. Goodridge, and J.E. Dugan. 2013. Multiple sources and forms of nitrogen sustain year-round kelp growth on the inner continental shelf of the Santa Barbara Channel. *Oceanography* 26(3):114–123, http://dx.doi.org/10.5670/oceanog.2013.53.

Carroll, D. 2009. Carmel Bay: Oceanographic dynamics and nutrient delivery in a small embayment of the Central California Coast. MS Thesis, Moss Landing Marine Laboratories.

Chan, F., J.A. Barth, J. Lubchenco, A. Kirincich, H. Weeks, W.T. Peterson, and B.A. Menge. 2008. Emergence of anoxia in the California Current large marine ecosystem. *Science* 319:920, http://dx.doi.org/10.1126/science.1149016.

Cudaback, C.N., and E. McPhee-Shaw. 2009. Diurnal-period internal waves near Point Conception, California. *Estuarine, Coastal and Shelf Science* 83:349–359, http://dx.doi.org/10.1016/j.ecss.2008.12.018.

DiGiacomo, P.M., and B. Holt. 2001. Satellite observations of small coastal ocean eddies in the Southern California Bight. *Journal of Geophysical Research* 106(C10):22,521–22,544, http://dx.doi.org/10.1029/2000JC000728.

Dudas, S.E., B.A. Grantham, A.R. Kirincich, B.A. Menge, J. Lubchenco, and J.A. Barth. 2009. Current reversals as determinants of intertidal recruitment on the central Oregon coast. *ICES Journal of Marine Science* 66:396–407, http://dx.doi.org/10.1093/icesjms/fsn179.

Eldevik, T., and K.B. Dysthe. 2002. Spiral eddies. *Journal of Physical Oceanography* 32:851–869, http://dx.doi.org/10.1175/1520-0485(2002)032<0851:SE>2.0.CO;2.

Fewings, M.R., and S.J. Lentz. 2010. Momentum balances on the inner continental shelf at Martha's Vineyard Coastal Observatory. *Journal of Geophysical Research* 115, C12023, http://dx.doi.org/10.1029/2009JC005578.

Fewings, M.R., S.J. Lentz, and J. Fredericks. 2008. Observations of cross-shelf flow driven by cross-shelf winds on the inner continental shelf. *Journal of Physical Oceanography* 38:2,358–2,378, http://dx.doi.org/10.1175/2008JPO3990.1.

Fram, J.P., H.L. Stewart, B.A. Brzezinski, B. Gaylord, D.C. Reed, S.L. Williams, and S. MacIntyre. 2008. Physical pathways and utilization of nitrate supply to the giant kelp, *Macrocystis pyrifera*. *Limnology and Oceanography* 53(4):1,589–1,603, http://dx.doi.org/10.4319/lo.2008.53.4.1589.

Franks, P.J.S., E. Di Lorenzo, N.L. Goebel, F. Chenillat, P. Rivière, C.A. Edwards, and A.J. Miller. 2013. Modeling physical-biological responses to climate change in the California Current System. *Oceanography* 26(3):26–33, http://dx.doi.org/10.5670/oceanog.2013.42.

Goodman, J., M.A. Brzezinski, E.R. Halewood, and A. Carlson. 2012. Sources of phytoplankton to the inner continental shelf in the Santa Barbara Channel inferred from cross-shelf gradients in biological, physical and chemical parameters. *Continental Shelf Research* 48:27–39, http://dx.doi.org/10.1016/j.csr.2012.08.011.

Grantham, B.A., F. Chan, K.J. Nielsen, D.S. Fox, J.A. Barth, A. Huyer, J. Lubchenco, and B.A. Menge. 2004. Upwelling-driven near-shore hypoxia signals ecosystem and oceanographic changes in the Northeast Pacific. *Nature* 429:749, http://dx.doi.org/10.1038/nature02605.

Halewood, E.R., C.A. Carlson, M.A. Brzezinski, D.C. Reed, and J. Goodman. 2012. Annual cycle of organic matter partitioning and its availability to bacteria across the Santa Barbara Channel continental shelf. *Aquatic Microbial Ecology* 67:189–209, http://dx.doi.org/10.3354/ame01586.

Harms, S., and C.D. Winant. 1998. Characteristic patterns in the Santa Barbara Channel. *Journal of Geophysical Research* 103, C2, 3,041–3,065, http://dx.doi.org/10.1029/97JC02393.

Hickey, B.M. 1979. The California Current System: Hypotheses and facts. *Progress in Oceanography* 8:191–279, http://dx.doi.org/10.1016/0079-6611(79)90002-8.

Hickey, B.M. 1998. Coastal oceanography of western North America from the tip of Baja California to Vancouver Island. Pp. 345–393 in *The Sea*, vol. 11. A.R. Robinson and K.H. Brink, eds, John Wiley, New York.

Hickey, B.M., E.L. Dobbins, S.E. Allen. 2003. Local and remote forcing of currents and temperature in the central Southern California Bight. *Journal of Geophysical Research*, 108(C3), 3081, http://dx.doi.org/10.1029/2000JC000313.

Kim, S.Y. 2010. Observations of submesoscale eddies using high-frequency radar-derived kinematic and dynamic quantities. *Continental Shelf Research* 30:1,639–1,655, http://dx.doi.org/10.1016/j.csr.2010.06.011.

Kirincich, A.R., J.A. Barth, B.A. Grantham, B.A. Menge, and J. Lubchenko, 2005. Wind-driven inner-shelf circulation off central Oregon during summer. *Journal of Geophysical Research* 110, C10S03, http://dx.doi.org/10.1029/2004JC002611.

Leichter, J.J., H.L. Stewart, and S.L. Miller. 2003. Episodic nutrient transport to Florida coral reefs. *Limnology and Oceanography* 48:1,394–1,407, http://dx.doi.org/10.4319/lo.2003.48.4.1394.

Lerczak, J.A., M.C. Hendershott, and C.D. Winant. 2001. Observations and modeling of coastal internal waves driven by a diurnal sea breeze. *Journal of Geophysical Research* 106(C9):19,715–19,729, http://dx.doi.org/10.1029/2001JC000811.

Lucas, A.J., C.L. DuPont, V. Tai, J.L. Largier, B. Palenik, and P.J.S. Franks. 2011. The green ribbon: Multiscale physical control of phytoplankton productivity and community structure over a narrow continental shelf. *Limnology and Oceanography* 56(2):611–626, http://dx.doi.org/10.4319/lo.2011.56.2.0611.

Lynn, R.J., and J.J. Simpson. 1987. The California Current System: The seasonal variability of its physical characteristics. *Journal of Geophysical Research* 92(C12):12,947–12,966, http://dx.doi.org/10.1029/JC092iC12p12947.

McPhee-Shaw, E.E., K.J. Nielsen, J.L. Largier, and B.A. Menge. 2011. Nearshore chlorophyll-a events and wave-driven transport. *Geophysical Research Letters* 38, L02604, http://dx.doi.org/10.1029/2010GL045810.

McPhee-Shaw, E.E., D.A. Siegel, L. Washburn, M.A. Brzezinski, J.L. Jones, A. Leydecker, and J. Melack. 2007. Mechanisms for nutrient delivery to the inner shelf: Observations from the Santa Barbara Channel. *Limnology and Oceanography* 52(5):1,748–1,766, http://dx.doi.org/10.4319/lo.2007.52.5.1748.

Melton, C., L. Washburn, and C. Gotschalk. 2009. Wind relaxations and poleward flow events in a coastal upwelling system on the central California coast. *Journal of Geophysical Research* 114, C11016, http://dx.doi.org/10.1029/2009JC005397.

Nam, S.H., and U. Send. 2011. Direct evidence of deep-water intrusions onto the continental shelf via surging internal tides. *Journal of Geophysical Research* 116, C05004, http://dx.doi.org/10.1029/2010JC006692.

Nickols, K.J., B. Gaylord, and J.L. Largier. 2012. The coastal boundary layer: Predictable current structure decreases alongshore transport and alters scales of dispersal. *Marine Ecology Progress Series* 464:17–35, http://dx.doi.org/10.3354/meps09875.

Noble, M., B. Jones, P. Hamilton, J. Zu, G. Robertson, L. Rosenfeld, and J. Largier. 2009. Cross-shelf transport into nearshore waters due to shoaling internal tides in San Pedro, CA. *Continental Shelf Research* 29:1,768–1,785, http://dx.doi.org/10.1016/j.csr.2009.04.008.

Pineda, J. 1995. An internal tidal bore regime at nearshore stations along western USA: Predictable upwelling within the lunar cycle. *Continental Shelf Research* 15(8):1,023–1,041, http://dx.doi.org/10.1016/0278-4343(95)80007-Z.

Pineda, J., and M. López. 2002. Temperature, stratification and barnacle larval settlement in two Californian sites. *Continental Shelf Research* 22(8):1,183–1,198, http://dx.doi.org/10.1016/S0278-4343(01)00098-X.

Pringle, J.M., and K. Riser. 2003. Remotely forced nearshore upwelling in Southern California. *Journal of Geophysical Research* 108(C4), 3131, http://dx.doi.org/10.1029/2002JC001447.

Shanks, A.L., and R.K. Shearman. 2009. Paradigm lost? Cross-shelf distributions of intertidal invertebrate larvae were unaffected by upwelling or downwelling. *Marine Ecology Progress Series* 385:189–204, http://dx.doi.org/10.3354/meps08043.

Send, U., R.C. Beardsley, and C.D. Winant. 1987. Relaxation from upwelling in the Coastal Ocean Dynamics Experiment. *Journal of Geophysical Research* 92(C2):1,683–1,698, http://dx.doi.org/10.1029/JC092iC02p01683.

Signell, R.P., and W.R. Geyer. 1991. Transient eddy formation around headlands. *Journal of Geophysical Research* 96(C2):2,561–2,575, http://dx.doi.org/10.1029/90JC02029.

Warrick, J.A., L.A.K. Mertes, L. Washburn, D.A. Siegel. 2004. A conceptual model for river water and sediment dispersal in the Santa Barbara Channel, California. *Continental Shelf Research* 24:2,029–2,043, http://dx.doi.org/10.1016/j.csr.2004.07.010.

Warrick, J.A., L. Washburn, M.A. Brzezinski, and D.A. Siegel. 2005. Nutrient contributions to the Santa Barbara Channel, California, from the ephemeral Santa Clara River. *Estuarine, Coastal and Shelf Science* 62:559–574, http://dx.doi.org/10.1016/j.ecss.2004.09.033.

Washburn, L., M.R. Fewings, C. Melton, and C. Gotschalk. 2011. The propagating response of coastal circulation due to wind relaxations along the central California coast. *Journal of Geophysical Research* 116, C12028, http://dx.doi.org/10.1029/2011JC007502.

Wing, S.R., L.W. Botsford, J.L. Largier, and L.E. Morgan. 1995. Spatial structure of relaxation events and crab settlement in the northern California upwelling system. *Marine Ecology Progress Series* 128:199–211, http://dx.doi.org/10.3354/meps128199.

Woodson, C.B., L. Washburn, J.A. Barth, D.J. Hoover, A.R. Kirincich, M.A. McManus, J.P. Ryan, and J. Tyburczy. 2009. Northern Monterey Bay upwelling shadow front: Observations of a coastally and surface-trapped buoyant plume. *Journal of Geophysical Research* 114, C12013, http://dx.doi.org/10.1029/2009JC005623.

Zimmerman, R.C., and J.N. Kremer. 1984. Episodic nutrient supply to a kelp forest ecosystem in Southern California. *Journal of Marine Research* 42:605–632, http://dx.doi.org/10.1357/002224084788506031.