a0010 # Longshore Currents

Daniel M Hanes, Department of Earth and Atmospheric Sciences, Saint Louis University, Saint Louis, MO, United States

s0010 ## 1 Introduction

p0010 A longshore current (sometimes called an alongshore current) flows approximately parallel to the shoreline and occurs within or near the surf zone. Surfers and swimmers are typically familiar with the experience of exiting the water far up-coast or down-coast of where they entered the water, having been carried by the longshore current. Sometimes these currents exceed speeds of 1 m/s, which is strong enough to destabilize a person standing in waist deep water and rapidly move a floating or swimming person (e.g., Hanes, 2016). Longshore currents add to other hydrodynamic risks to swimmers, such as breaking waves and turbulence in the surf zone. Longshore currents transport and disperse a variety of suspended materials such as larvae, organic matter, nutrients, and pollutants such as toxic chemicals, plastics, and trash. Longshore currents also contribute significantly to the mobilization and transport of sediment. The term littoral drift, or longshore sediment transport, refers to the alongshore transport of sediment (usually sand) in the surf zone. Understanding and predicting longshore currents is an intrinsic component of estimating or predicting littoral sediment transport. Longshore currents both respond to nearshore bathymetry and they also generate changes in bathymetry though the erosion, transport, and deposition of sediment. Sediment management issues near jetties, inlets, ports, or harbors are often closely related to sediment transport by longshore currents. The scientific understanding of longshore currents is mature but continues to evolve. There are numerous review papers and textbook chapters focused on longshore currents directly or as a component of coastal waves and circulation, for example: Galvin (1967), Svendsen and Jonsson (1976), Battjes (1978), Horikawa (1978), Basco (1983), Komar (1998, chapter 8), Peregrine (1998), Svendsen (1985, chapter 11), Lentz and Fewings (2012), and Kirby (2017).

p0015 Longshore currents are only one of many types and patterns of flows that occur in or near the surf zone, such as circulation cells, rip currents, undertow, and turbulence. Putnam et al. (1949), Shepard (1950), Shepard and Inman (1951), and Inman and Quinn (1951) provided early descriptions of surf zone dynamics, and they suggested that when waves approach the shoreline obliquely and break at even a small angle to the shore-normal, they tend to drive a longshore current. Larger and more obliquely breaking waves up to 45 degrees generate faster longshore currents. These currents are distinct from those generated by tides or local winds, although tidal currents and wind-driven currents may also be directed alongshore and can either augment or reduce the wave-driven longshore current.

s0015 ### 1.1 Early theories for extremely simplified conditions

p0020 Longuet-Higgins and Stewart (1962, 1964) introduced the concept that water waves propagating toward the shore transport momentum toward the shore. Their concept for periodic waves was analogous to Reynold's stresses for turbulent flow. Once averaging over the wave period and water depth, the momentum flux is known as the radiation stress. Any gradients in the radiation stress, due for example to wave breaking, result in a net force upon the water column. This time averaged force must be balanced (in

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the absence of other driving forces such as winds or tides) by either bottom friction, lateral friction, or a pressure gradient due to a sloping mean sea surface.

p0025 Bowen (1969b), Thornton (1970), and Longuet-Higgins (1970a,b), in similar but likely independently developed theories, applied the concept of radiation stress to the generation of longshore currents by balancing the alongshore force due to the radiation stress gradient with the bottom friction induced by the longshore current, with cross-shore mixing/diffusion added due to the wave motions and turbulence. The incident waves and bathymetry were highly simplified. The bathymetry was assumed to be longshore uniform, with straight and parallel depth contours and a cross-shore uniform slope (this bathymetry will be referred to later as a linear beach). The waves were assumed to be steady, mono-chromatic, and long-crested (alongshore uniform). Perhaps most importantly, the wave hydrodynamics were described by linear wave theory, which assumes irrotational flow. The wave height was assumed to be depth limited within the surf zone although there is no explicit description of wave-breaking processes, so the cross-shore gradient in wave height is locally proportional to the bed slope. With these simplifying assumptions the formulation and depth-averaged solutions are simple functions of cross-shore position but not longshore position. The alongshore force, R_y, determined from the cross-shore gradient in the alongshore directed radiation stress, is given by Longuet-Higgins (1970a) by Eq. (1).

$$R_y = \frac{5\rho g a}{4h} \cdot s \cdot \sin\theta = \frac{5\rho}{4} u_m^2 \cdot s \cdot \sin\theta \qquad (1)$$

where ρ is water density, g is the gravity constant, a is wave amplitude, h is water depth, s is the cross-shore slope, θ is wave propagation angle relative to the shore-normal direction, and u_m is the maximum wave orbital velocity.

p0030 The longshore directed component of the bed shear stress, τ_y, was given by Longuet-Higgins (1970a) by Eq. (2).

$$\tau_y = \frac{2}{\pi} C_f \rho u_m V_l \qquad (2)$$

where C_f is the bed shear stress coefficient, and V_l is the longshore current velocity.

p0035 Setting the alongshore force equal to the friction results in the longshore current given by Eq. (3) below.

$$V_l = \frac{5\pi}{8c_f} u_m \cdot s \cdot \sin\theta = \frac{5\pi}{8c_f} a\sqrt{\frac{g}{h}} \cdot s \cdot \sin\theta \qquad (3)$$

p0040 In this solution the longshore current increases from zero at the shoreline to a maximum at the seaward extent of the surf zone where waves begin to break and decreases abruptly to zero outside the surf zone. With the beach slope assumed constant, the longshore current increases linearly with distance from the shoreline, just like the water depth. The average longshore current in this case is located at the midpoint of the surf zone. However, once horizontal momentum mixing is added to the theory, the cross-shore profile of the longshore current is significantly modified, as will be seen below.

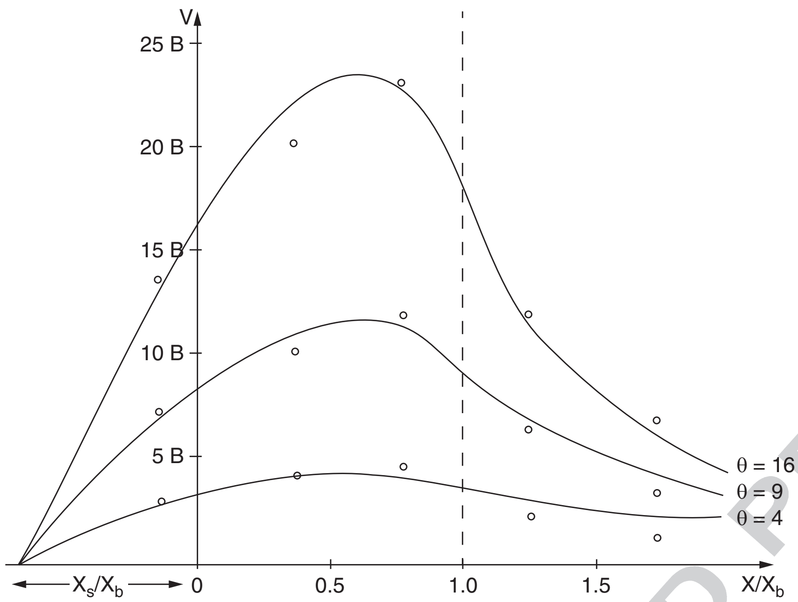
s0020 1.2 Lateral mixing

p0045 Lateral (cross-shore) mixing modifies the distribution of the longshore current, and smooths out theoretical discontinuities, such as at the wave break point. There have been many models proposed for lateral mixing and the precise form of the mixing has been controversial (e.g., Svendsen and Putrevu, 1994; Putrevu and Svendsen, 1999). Lateral momentum mixing is difficult to measure directly, so most investigators rely on accuracy of the predicted cross-shore distribution of the longshore current to evaluate the correctness of the lateral mixing model. Although the form assumed for lateral mixing has been controversial, the main effect of all the mixing models is to smooth the cross-shore distribution of the longshore current and shift the maximum current toward the middle of the surf zone. As will be discussed later, these effects can also be achieved through other physical mechanisms such as a distribution of various wave heights with each wave beginning to break at different locations across the surf zone.

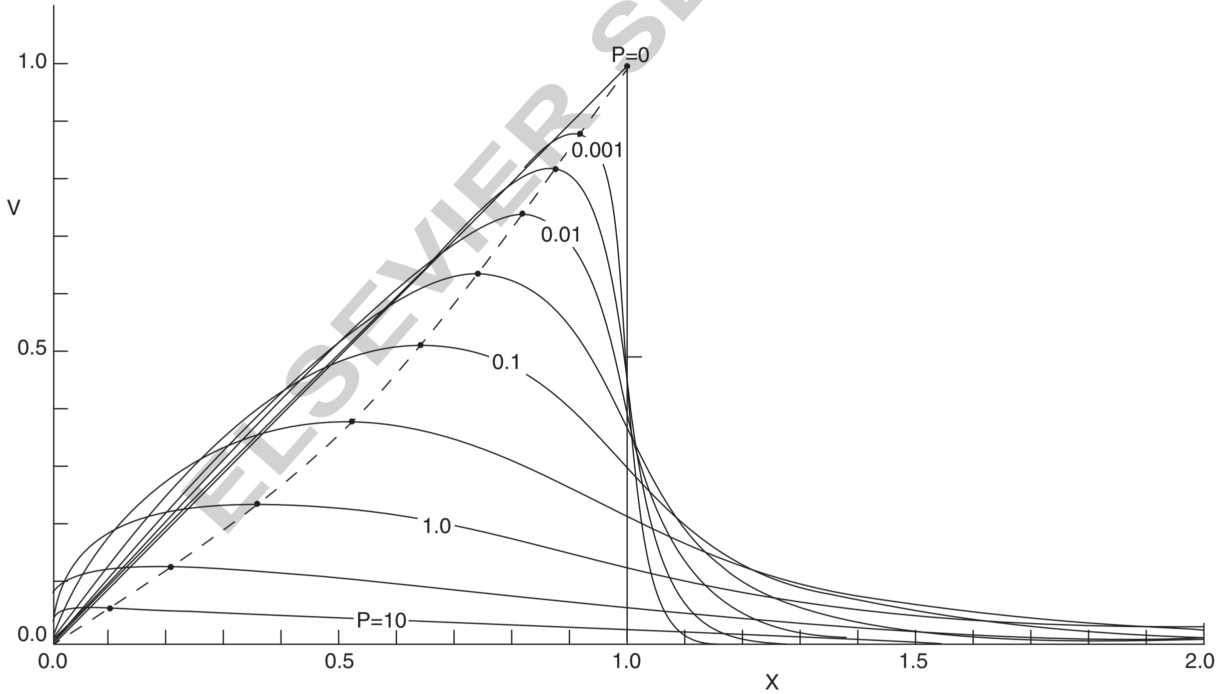
p0050 Bowen (1969b) assumed a constant eddy viscosity to parameterize the cross-shore mixing and found reasonable agreement between measurements and theory. Fig. 1 shows the distribution across the surf zone of the predicted longshore current along with laboratory measurements (few of which existed at that time). Note the longshore current has a generally parabolic shape that reaches a maximum near the middle of the surf zone and decreases toward zero near the shoreline and offshore of the breaker zone. Longuet-Higgins (1970b) presented a family of solutions for the cross-shore distribution of the longshore current with different amounts of lateral mixing, as seen in Fig. 2. The linear solution that drops abruptly to zero at the break point is for no mixing. Kraus and Sasaki (1979) modified the friction and lateral mixing model of Longuet-Higgins (1970b) to more accurately consider wave angle and compared both theories with laboratory observations, as seen in Fig. 3. For both theories, the value for lateral mixing was chosen to best fit the maximum of the longshore current.

s0025 2 Features of longshore currents and complicating factors

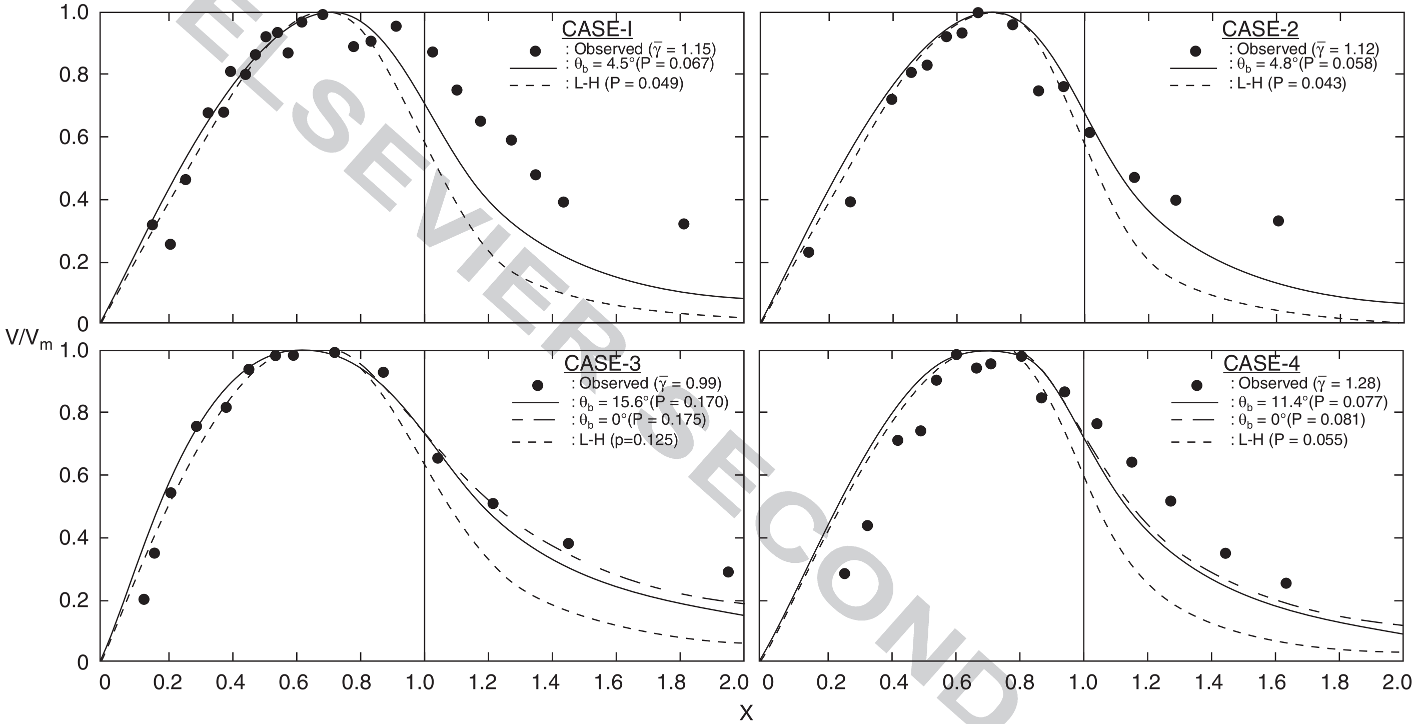
p0055 Beyond the simple balance of forces expressed above, there are a wide variety of factors that affect longshore currents in nature. Laboratory and field work on longshore currents following the basic theories presented above focused on documenting the



f0010 **Fig. 1** Comparison of the theoretical cross-shore profiles of the longshore current with laboratory measurements. In this figure V is the longshore current velocity, X is the seaward distance from the shoreline location in the absence of waves, X_b is breakpoint location of the waves, X_s is the width of the wave setup zone, B and θ are combinations of *several* factors including wave breaker angle and surf zone width. Theory is from Bowen (1969b), data are from Galvin and Eagleson (1965). From Bowen AJ (1969b) The generation of longshore currents on a plane beach. *Journal of Marine Research* 27: 206–215, Fig. 2.



f0015 **Fig. 2** Longuet-Higgins theory for the cross-shore distribution of the longshore current with different values of lateral mixing, P. In this figure V is the longshore current velocity normalized by its maximum value with no lateral mixing, and x is the distance seaward from the shoreline location, normalized by the width of the surf zone. From Longuet-Higgins MS (1970b) Longshore currents generated by obliquely incident sea waves: 2. *Journal of Geophysical Research* 75(33): 6790–6801. https://doi.org/10.1029/JC075i033p06790, Fig. 1.



f0020 **Fig. 3** Comparison of Kraus and Sasaki (1979), solid lines, Longuet-Higgins (1970a,b), dashed lines, and experimental data points of Mizuguchi et al. (1978), circles. In this figure V is the longshore current velocity, V_m is the maximum longshore current velocity for each experimental condition, and X is distance seaward from the shoreline location, normalized by the width of the surf zone. From Kraus NC and Sasaki TO (1979) Influence of wave angle on the longshore current. *Marine Science Communications* 5(2): 91–126, Fig. 4.

distribution and strength of the current, as well as identifying a variety of factors that affect the longshore currents. Some of these results and factors will next be described, with a few examples and case studies provided (out of a vast literature that exists on this subject).

s0030 2.1 Bottom friction and beach slope

p0060 The concept of bottom friction balancing radiation stress gradients is relatively simple, but the verification of bottom shear stress models in the surf zone is an incredibly challenging observational task. So rather than directly measure the bed shear stress, most approaches time average an assumed instantaneous quadratic drag law, using a bed shear stress coefficient (often called the drag coefficient) to parameterize the basic relationship between the water velocity, the sediment bed, and the bed shear stress. The bed shear stress coefficient is a function of bottom roughness due to grains or bedforms, as well as the level of turbulence in the flow, as will be discussed further later in this paper. Much effort has gone into empirical estimation of the value of the bed shear stress coefficient in surf zones, usually indirectly once again by comparing model predictions to measurements of the longshore current.

p0065 For example, Guza and Thornton (1978) and Thornton and Guza (1981) suggested, based upon field measurements of the longshore current at Torrey Pines, CA, that the bed shear stress coefficient decreases (from approximately 0.01 to 0.002) across the surf zone, with lower values in the inner surf zone. Garcez Faria et al. (1998) examined the vertical structure of the longshore current at Duck, North Carolina, United States in order to estimate the bed shear stress coefficients. They found that the bed shear stress coefficients varied by an order of magnitude across the surf zone (from 0.0006 to 0.012). They also estimated small-scale bed roughness using a sonic altimeter and found that shear stress coefficients were correlated with bottom roughness. Feddersen et al. (1998) also estimated the bed shear stress coefficient Duck, North Carolina, and found it was nearly three times higher (0.0033) inside the surf zone than it is across the inner shelf (0.001). Whitford and Thornton (1996) also estimated the bed shear stress coefficient at Duck, NC, with emphasis on the bar/trough region. The found that the bed shear stress coefficient decreased significantly in the trough (0.001) relative the bar crest (0.004).

p0070 For any given breaking wave height, the cross-shore beach slope determines the width of the surf zone, so it might be expected that the beach slope would be an important factor influencing the longshore current. In fact, in many models (such as Eq. 3) the strength of the longshore current has a linear relationship to beach slope. However, the situation is more subtle than it appears because the sediment grain size has a strong effect on both the beach slope and the bed shear stress coefficient. Coarser grained beaches are typically steeper than finer grained beaches, and coarser grains also have larger bed shear stress coefficients than finer grains. Komar (1979) examined several field and laboratory data sets with varying beach slopes and demonstrated conclusively that inclusion of the beach slope in predictive models significantly decreases the model agreement with measurements. Komar suggested that this might result from the counteracting effect that steeper beaches also have higher bed shear stress coefficients. Haas and Hanes (2004) explored these factors through comprehensive, process-based, numerical simulations of surf zone flows and sediment transport, and confirmed the approximately counteracting and cancelling effects of beach slope and bed friction due to larger sediment grains.

s0035 2.2 Random spectral waves and wave breaking processes

p0075 While the original theories for longshore currents were derived for uniform and monochromatic waves, in reality nearshore waves are irregular and have directional energy spectra that change with time and location. The original theories also assumed extremely simplified wave breaking processes in which the wave height at and following initial breaking was assumed a constant fraction of the water depth. As will be discussed later in this paper, the details of the wave breaking process have an important influence upon the longshore current. For example, through numerical modeling Goda (2006) showed that predictions of the longshore current strength and cross-shore distribution are sensitive to specific wave breaking models.

p0080 Because wave momentum flux, the driving force for longshore currents, will vary with each incident wave frequency and direction, a distribution of wave heights and directions might be expected to result in differing longshore currents. For example, Battjes (1972) considered a series of irregular waves and found that waves breaking at different locations across the surf zone has a cross-shore smoothing effect on the longshore current distribution, much like lateral mixing. Thornton and Guza (1986) describe similar results for field observations of breaking waves and longshore currents. In fact, Thornton and Guza (1986) and Wu et al. (1985) examined the same field data obtained in Santa Barbara, CA, and show that cross-shore distribution of the longshore current can be described approximately equally well by either employing lateral mixing or alternatively by modeling distributed wave breaking! Battjes (1972) also found that for a wide distribution of breaking wave angles the longshore current strength is as much as 50% less than for a narrow distribution of angles. Choi et al. (2015) used a Boussinesq wave numerical model called FUNWAVE, validated with measurements from Duck, NC from the SANDYDUCK experiment in October 1997, and showed that random waves with broader frequency-directional spectrum generate relatively weaker longshore currents.

p0085 Guza et al. (1986) examined field measurements from Santa Barbara, CA during times of an approximately bimodal distribution of breaking wave angles, and they found that the longshore current is consistent with the total wave radiation stress, that is, the sum of the radiation stresses estimated from each spectral wave component. They suggested that for this approximately linear beach, wave breaking "was a broad-band process that extracted energy and momentum simultaneously from many incident-wave frequency bands and directions." This contrasts with a wave by wave breaking process for which different waves break at different locations within the surf zone, which could result in high shear zones or even reversing longshore currents within a surf zone.

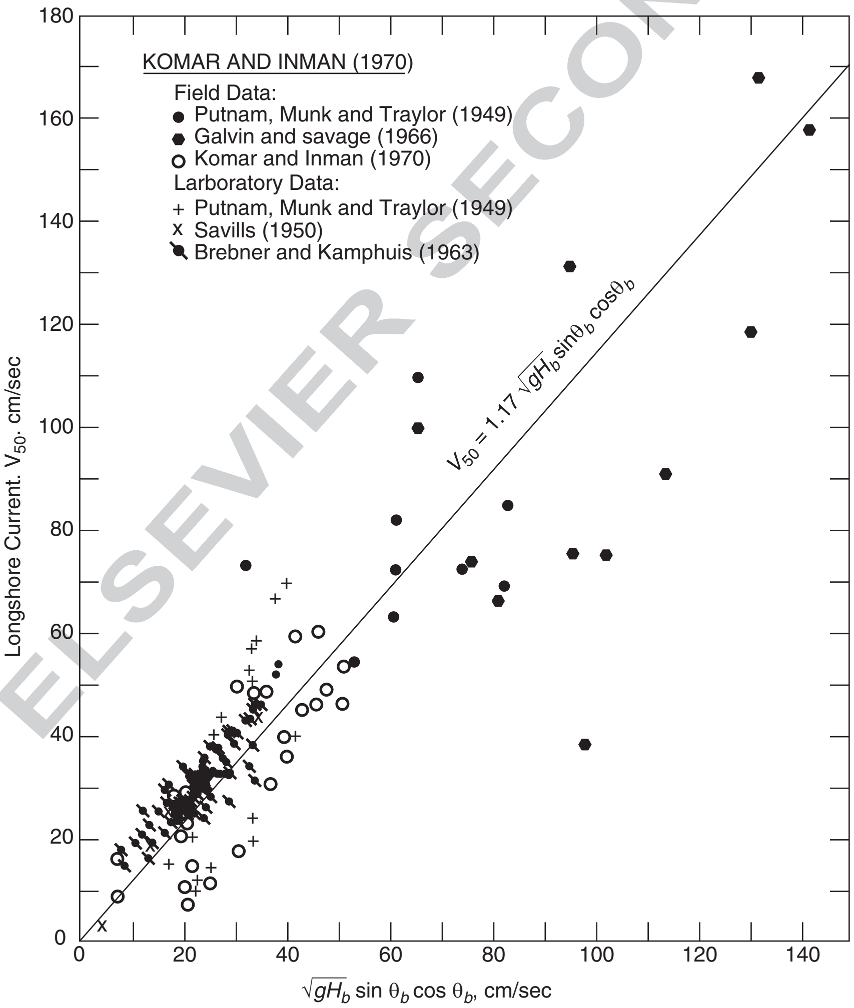
p0090 Johnson and Smith (2005) conducted large scale laboratory measurements of approximately steady longshore currents with random wave forcing. They used arrays of current meters to estimate the momentum flux in the surf zone. They confirmed that the alongshore momentum balance was mainly between radiation stress gradients and bottom friction, but they found the radiation stress gradients were considerably smaller than those that would be estimated using linear wave theory.

s0040
2.3 Cross-shore structure and bathymetry effects

p0095 In recognition that the cross-shore distribution of the longshore current on approximately planar beaches tends to resemble a parabola with a peak near the middle of the surf zone, and decrease toward zero at the shoreline and outside the breaker region, Komar and Inman (1970) suggested that the prediction of the maximum current speed near the middle of the surf zone would represent an excellent characterization of the longshore current. They further showed that the longshore current at the middle of the surf zone can be expressed in terms of the breaking wave conditions by Eq. (4) below. In this formulation the height of the breaking waves was characterized by the root-mean-square of the breaker heights for random waves. Wave angle can be thought of as the breaking angle of the root-mean-square wave height that would result in the total alongshore radiation stress that occurs. The breaking wave height also provides a reasonable estimate of surf zone width, so the basic characteristics of the longshore current can be predicted simply from the breaking wave characteristics. Fig. 4 compares the prediction of Eq. (4) to a variety of laboratory and field measurements of longshore currents.

$$V_{50} = 1.17\sqrt{gH_b}\sin\theta_b\cos\theta_b \tag{4}$$

where V_{50} is the longshore current velocity at 50% of the surf zone width, H is the root-mean-square wave height, and the subscripts b indicate conditions at the breakpoint.



f0025 **Fig. 4** Compilation of field and laboratory observations of the longshore current in the middle of the surf zone, compared with Eq. (4). From Komar PD (1979) Beach-slope dependence of longshore currents. *Journal of the Waterway, Port, Coastal and Ocean Division* 105(4): 460–464, Fig. 1.

p0100 Surf zone bathymetry can modify the distribution of the longshore current relative to that found on a planar beach. One of the common variations in beach bathymetry is the presence of a longshore bar-trough system typically located near the break point of the largest incident waves. Bruun (1963) observed that beaches with a longshore bar/trough tends to have a strong longshore current in the trough. Smith et al. (1993) observed a similar phenomenon at Duck, North Carolina, United States, and suggested that turbulence created by wave breaking and the associated momentum transfer was mainly responsible for the current peak near the bar trough.

p0105 Ruessink et al. (2001) examined longshore currents on barred beaches at Duck and Egmond, The Netherlands, and found that the peak in the longshore current that is typically found in the middle of the surf zone for planar beaches was located near the trough of the longshore bar-trough on these beaches. Like Smith et al. (1993), the strong longshore current in or near the trough of a longshore bar-trough system was explained through modeling as resulting from wave rollers, which is a vortex sometimes formed when waves break. The rollers result in large dissipation and momentum flux in the trough region, and this drives the strong longshore current.

p0110 Current peaks near the trough of a longshore bar-trough are not found everywhere. Greenwood and Sherman (1986) measured longshore currents on a multiple-barred beach on a bay connected to Lake Huron, and found currents were weaker near the outer bar, and stronger near the inner surf zone, than would be expected on a planar beach.

p0115 Another variation sometimes found in beach bathymetry is the occurrence of a sharp change in slope near the shoreline, generally referred to as a beach step, which is associated with waves breaking close to the shoreline. As shown by Kraus and Sasaki (1979) in one of the earliest quantitative studies of longshore current in field conditions, the secondary wave breaking near the beach step results in driving a strong longshore current near the shoreline, whereas for a planar beach the longshore current would typically weaken considerably near the shoreline.

p0120 Alongshore structure in bathymetry can also affect the currents. Bowen (1969a) considered periodic alongshore bathymetries that resulted in rhythmic circulation cells and the generation of periodic rip currents. Noda (1974) confirmed this concept by conducting numerical simulations of wave refraction and longshore current generation over alongshore periodic bathymetry. Sonu (1972) described field measurements of fluctuations in the longshore current observed on the Gulf of Mexico coast of Florida and attributed them to current meanders related to alongshore rhythmic bathymetry. Putrevu et al. (1995) derive semi-analytical solutions for the longshore current in the presence of alongshore variations in bathymetry. They found that the pressure gradients caused by the bathymetry can significantly modify the strength of the longshore current.

s0045 2.4 Vertical structure

p0125 Despite the technical and environmental difficulties, there have been a few laboratory or field measurements of the vertical structure of longshore currents. Visser (1986, 1991), Garcez Faria et al. (1998), Simons et al. (1992), and Zhang and Zou (2012, 2019) suggest the vertical structure of the longshore current is similar to that of open channel flows or tidal flows. It can be described by a logarithmic profile near the bed, and a relatively uniform current above. Zhang and Zou (2019) provide an alternate description using a power law relation to describe the vertical structure. Note that either a logarithmic or a power law description requires an empirical parameter related to the bed friction, and therefore the bed roughness, which is not generally known and probably varies in space and time in natural settings.

s0050 2.5 Alongshore varying waves

p0130 Alongshore gradients in wave characteristics are quite common and caused by a variety of phenomena. Wave refraction due to large scale bathymetry such as curvature in the coastline or offshore islands causes alongshore variations in breaking wave characteristics. Similar gradients in wave height and angle can be found due to refraction and diffraction near inlets, bays, and manmade structures such as offshore breakwaters and jetties. Alongshore gradients, or nonuniform wave conditions, can result in the generation or modification of the longshore current. Irribarren (1947) and Shimano et al. (1958) first documented that alongshore gradients in wave heights, such as those associated with structures like breakwaters or jetties, can force a longshore current. Gourlay (1965, 1975) observed nonuniform longshore currents, referred to as lateral expansion currents, resulting from wave gradients in physical models of a fringing coral reef and a breakwater. Komar (1975) and Gourlay (1977, 1978) explained two mechanisms through which alongshore gradients in wave characteristics result in forcing longshore currents within the radiation stress paradigm. Firstly, variations in wave height and angle alongshore result in corresponding variations in the direct forcing of the longshore current by the alongshore component of the radiation stress. Secondly, the variations in wave height creates an alongshore pressure gradient due to alongshore variations in wave setup in the surf zone (see Bowen et al., 1968). These two mechanisms are often linked to each other through alongshore variations in wave height. The first mechanism is more sensitive to alongshore variations in breaking wave angle, and the second mechanism is only sensitive to variations in breaking wave height. The longshore pressure gradient due to variations in wave setup may occur whether the waves are normally incident or obliquely incident. This creates an alongshore pressure gradient which can drive either a uniform or nonuniform longshore current depending on the spatial distribution of the alongshore pressure gradient, and it may either enhance, weaken, or even cause reversal of the longshore current otherwise due to oblique wave breaking.

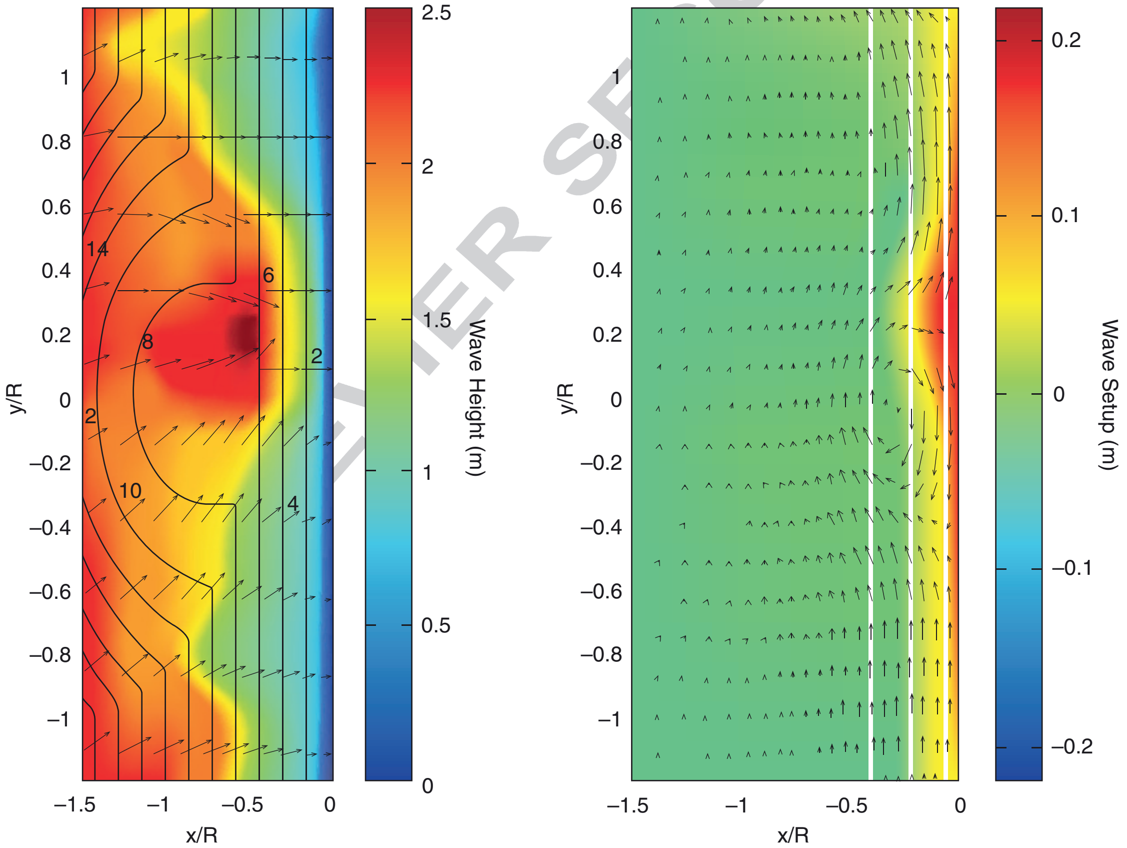
p0135 Keeley and Bowen (1977) measured longshore currents in the field along a beach embayment extending more than 1 km over which the breaking wave height and angle varied due to wave refraction. They found the current strength varied along the beach closely in accordance with the wave radiation stress models of Bowen (1969b) and Longuet-Higgins (1970a) in the manner described above. In a quite different environment, Apotsos et al. (2008) examined wave refraction and its effects shoreward of a submarine canyon in Southern California. The refraction resulted in alongshore variations in breaking wave heights and breaking wave angles, which in turn resulted in alongshore variations is wave set-up and longshore current strength.

p0140 Shi et al. (2011) explored nonuniform longshore currents at Ocean Beach, San Francisco, CA, a highly energetic beach which is located onshore of a very large ebb tidal delta. They found that wave refraction over the ebb tidal delta resulted in wave focusing and caused alongshore variations in wave height and angle along the shore of Ocean Beach. Through numerical modeling, validated with field measurements, they found that alongshore pressure gradients due to wave setup were sometimes the dominant term in the momentum balance for the longshore currents. They also found that depending on the offshore (deep water) wave conditions, this mechanism can result in either converging or diverging longshore currents, likely explaining the location of a persistent erosion hotspot. For example, Fig. 5 shows the predicted significant wave height, wave angle, and nearshore current field for an idealized planar beach with a circular shoal (with radius R) lying offshore.

s0055 2.6 Winds, tides, and the alongshore momentum balance

p0145 The simplified models of Bowen (1969b) and Longuet-Higgins (1970a,b) considered the time-averaged alongshore momentum balance in the surf zone to be between the wave radiation stress gradients forcing the longshore current and the bottom friction resisting the longshore current, with lateral mixing diffusing and smoothing the cross-shore profile of the longshore current. There are however other factors in addition to breaking waves that can potentially influence the alongshore momentum balance. Two factors which are sometimes important are wind and tide.

p0150 Wind is an obvious factor that should affect longshore currents due to the shear stress that wind exerts on the water surface (e.g., Shepard and Inman, 1950; Sonu et al., 1973; Nummedal and Finley, 1978; Hubertz, 1986). Wind also generates and affects waves, so isolating the influence of wind verses the influence of waves on longshore currents is observationally challenging. Whitford and Thornton (1993) used a numerical modeling approach to assess the relative importance of wind (directly) and wind-generated



f0030 **Fig. 5** Left panel: Significant wave height (color and length of arrow), wave angle (arrow direction), and bathymetry contours. Right panel: Wave setup (color) and nearshore current field (vectors). Wave conditions: JONSWAP spectrum with deep water significant wave height = 2.5 m, peak wave period = 15 s, and wave angle of 30° (from southwest). The three white lines in the right panel are alongshore transects at depths of 5, 3, and 1 m. In this figure x is distance onshore from the shoreline position, and y is alongshore distance from the center of the simulation domain. From Shi F, Hanes DM, Kirby JT, Erikson L, Barnard P, Eshleman J (2011). Pressure-gradient-driven nearshore circulation on a beach influenced by a large inlet-tidal shoal system. *Journal of Geophysical Research* 116: C04020, Fig. 16.

waves in forcing a longshore current. They found that the relative momentum transfer due to wind, relative to waves, varied from 10% to 100% as the direction of the wind varied from 10 degrees oblique to the shoreline up to 90 degrees oblique (that is, parallel to the shoreline). Masselink and Pattiaratchi (1998) found similar results in the field on a macrotidal, low wave energy, sand beach in southwestern Australia. They found that a shore parallel sea breeze with wind speeds exceeding 10 m/s generated a longshore current with a speed of approximately 1 m/s.

p0155 The study of Ruessink et al. (2001) also examined the importance of various factors in the alongshore momentum balance. While they found the primary balance relevant to the longshore current was between the radiation stress gradient and bottom friction, they also found that factors such as wind, tide, and lateral mixing were not negligible. Feddersen et al. (1998) examined the alongshore momentum balance between the shoreline and the 8 m depth contour at Duck, North Carolina, and suggested that wind was not generally a significant factor influencing the longshore current at this site.

p0160 Tides may affect longshore currents through either direct forcing of the current or through the modification of the incident wave field and nearshore bathymetry. For example, Thornton and Kim (1993) observed that a dominant source of variability in the strength of the longshore current at Duck, North Carolina, United States, was due to tidal modulation of the incident wave field. Castelle et al. (2006) suggested that tides on the Southwest coast of France exert strong modulation of the incident waves and nearshore bathymetry, resulting in substantial modification of the longshore current (as well as rip currents and nearshore circulation cells). Suzuki et al. (2020) found tidal modulation of longshore currents at a double barred beach on the Hasaki coast of Japan.

p0165 Hansen et al. (2013) extended the work of Shi et al. (2011) and found that tides often played an important role at Ocean Beach, San Francisco, CA, likely due to the extremely strong tidal flows resulting from flow in and out of San Francisco Bay through the Golden Gate inlet. They found that the alongshore pressure gradient due to tidal forcing was 30–55% of the alongshore pressure gradient due to wave forcing. They also found that depth modulation due to tides over the ebb tidal delta can influence the breaking wave characteristics near Ocean Beach through refraction and dissipation, and therefore also modulate the longshore current.

s0060 2.7 Instabilities and unsteadiness

p0170 While much of the theoretical and modeling approaches to longshore currents assume that the currents are steady, in reality surf zone currents are generally unsteady on a wide variety of temporal and spatial scales. Even the earliest observations of longshore currents in Southern California indicated significant temporal variations in current strength (e.g., Putnam et al., 1949; Inman and Quinn, 1951). Guza and Thornton (1978) reported temporal and spatial variability for five closely spaced current meters at La Jolla, CA, and concluded “An appropriate temporal averaging time for mean longshore currents is not known.” With the advancement of a variety of instrumentation to measure longshore currents, however, some of the variability has been documented and theories have been developed to explain some of the variability.

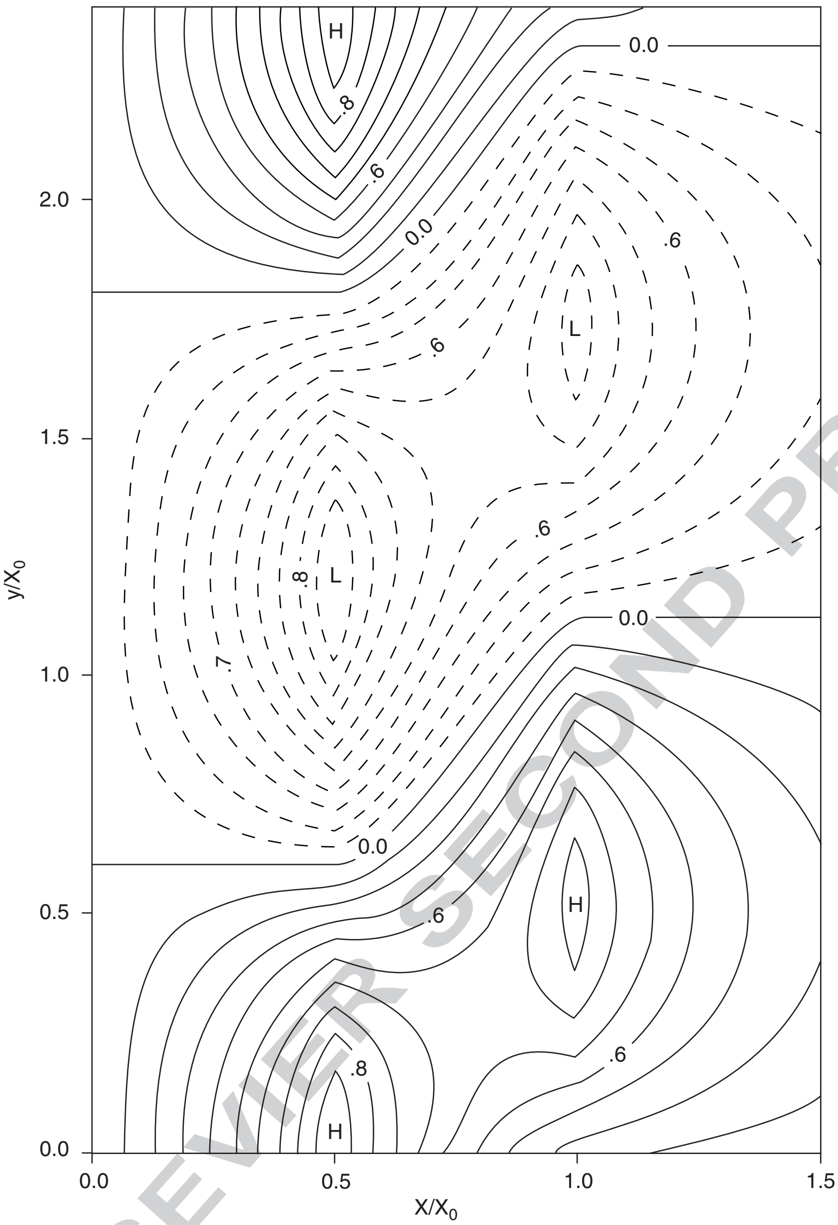
p0175 Oltman-Shay et al. (1989) observed oscillatory-like fluctuations in the longshore current velocity that occurred at low frequencies (0.01–0.001 Hz). These observations could not be explained by infragravity waves and were referred to as shear waves. These shear waves were found to move in the same direction as the longshore current, at about 1/3 of the peak speed of the current. Bowen and Holman (1989), using a linear stability analysis, explained that shear in the longshore current produces vorticity which acts as a restoring force when the current is displaced in the cross-shore direction. This results in shear waves with wave lengths that are approximately equal to twice the width of the surf zone, as shown for example in Fig. 6. Dodd et al. (1992) showed the theory of Bowen and Holman (1989) was consistent with the field observations of Oltman-Shay et al. (1989). Dodd et al. (1992) also examined field data from the approximately planar beach at Santa Barbara, CA, and suggested the generation of shear waves is more prevalent over beaches with longshore breaker bars due to the stronger shear that occurs over longshore bars. Dodd (1994) also suggested that bottom friction can damp shear instabilities, and the shear at the planar beach in Santa Barbara was insufficient to exceed the damping, and therefore did not generate instabilities.

p0180 The dynamics and influences of shear instabilities of the longshore current was explored through numerical simulations of 3 days of observed nearshore circulation at Duck by Özkan-Haller and Kirby (1999). They were able to accurately simulate the observed distribution of the longshore current and the main characteristics of the observed shear instabilities. Their simulations confirmed the important role of bed friction in damping instabilities. The also suggested that shear instabilities, when present, cause significant horizontal momentum mixing and therefore smooth the cross-shore profile of the longshore current. Slinn et al. (2000) conducted numerical model experiments on the nonlinear dynamics of shear waves and evaluated sensitivities to the amplitude and wavelength of periodic bathymetric variability. They also identified the ratio of an advective time scale to a frictional time scale as an important parameter that influences the growth or decay of shear wave instabilities.

p0185 Elgar et al. (2019) observed even lower frequency unsteadiness in the longshore current in the range of 10^{-3}–10^{-4} Hz with wavelengths of 20–100 m. These variations were found to increase with larger incident waves. Although the origin of these extremely low frequency (ELF) oscillations is not well understood, Elgar et al. (2019) suggested they are related to large horizontal eddies in the surf zone, probably similar to the surf zone eddies described by Feddersen (2014).

s0065 3 New wave-current theories relevant to longshore currents

p0190 One of the powerful benefits of process based numerical models for the prediction of longshore currents is the ability to solve momentum and energy conservation equations on a three-dimensional grid. However, doing so requires a depth dependent or



f0035 **Fig. 6** Example of the stream function pattern for the fastest growing shear wave instability. In this figure, x is the cross-shore coordinate, y is the alongshore coordinate, and x_0 is the width of the longshore current. From Bowen AJ and Holman RA (1989) Shear instabilities of the mean alongshore current: 1. Theory. *Journal of Geophysical Research*, 94(C12): 18023–18030. 10.1029/JC094iC12, Fig. 7.

three-dimensional (3D) formulation of wave forcing and wave-current interactions, rather than the original depth integrated concept of radiation stress. There have been many new theories advanced over the past few decades to better describe waves, currents, and their interactions in the coastal and nearshore regions, as summarized by Kirby (2017). Several of these theories/models improve description of the wave breaking process, and the depth dependency of the momentum fluxes due to waves. Many new approaches are under development, including three dimensional, wave-resolving, nonhydrostatic models, turbulence resolving models, and Smooth Particle Hydrodynamics models. While a comprehensive review of the advances in nearshore wave and hydrodynamic modeling is beyond the scope of this review, a few new types of wave models that have been applied to the prediction of longshore currents will be summarized below.

s0070 3.1 Depth dependent radiation stress type models

p0195 A variety of new formulations have been advanced to describe the spatial and depth dependence of the interactions between waves and current in the nearshore region. For example, Mellor (2003, 2005, 2008, 2011, 2013, 2015) derived the depth dependent momentum flux due to waves. Quasi-3D and 3D models for wave stresses have been applied to predict longshore currents. Haas and Warner (2009) compare Quasi-3D and fully 3D models to predict longshore currents. Kumar et al. (2011) modified Mellor's model to better describe wave breaking in shallow water and incorporated the formulation in the ROMS numerical model. They applied the model, which included a wave roller component, to successfully predict many features of nearshore dynamics, including longshore currents. Ji et al. (2017) derived a three dimensional radiation stress formulation that incorporated a Lagrangian description of waves along with beach slope effects.

p0200 Ji et al. (2019) compared the predictions of several three dimensional radiation stress models (Mellor, 2003, 2015; Xia, 2017; Ji et al., 2017) to each other and to laboratory measurements of longshore currents. They found that the models predicted fairly similar results largely consistent with observations, but that the Ji et al. (2017) model was more accurate than the others in predicting the vertical structure of the longshore current both inside and outside the surf zone.

s0075 3.2 Vortex force models

p0205 Vortex force models are based on the formulation of Craik and Leibovich (1976); they are sometimes referred to as CL models. There is a strong link between dissipation in breaking waves, which is a dominant process affecting wave momentum fluxes in the surf zone, and vortex dynamics (e.g., Bühler and Jacobson, 2001). McWilliams et al. (2004) and Ardhuin et al. (2008) developed vortex-force models for nearshore waves that consider the rotational flows that result from breaking waves. Vortex force models are wave averaged but can be applied as either depth dependent or depth integrated. Newberger and Allen (2007) incorporated a vortex force model into a shelf circulation model modified to apply to the nearshore zone. Uchiyama et al. (2009) employed a vortex force model to explore instabilities in the longshore current, and separately evaluated the wave effects upon the current and the current effects upon the waves. Uchiyama et al. (2010) modified McWilliams et al. (2004) for coastal and nearshore applications to include non-conservative wave effects due to wave breaking, associated surface roller waves, bottom streaming, and wave-enhanced vertical mixing and bottom drag. Model results compared well with the field measurement collected in the DUCK94 experiment at Duck, North Carolina. Xia et al. (2020) implemented both (alternatively) Mellor's (2015) 3D radiation stress type formulation and McWilliams et al. (2004) vortex-force theory into a 3D unstructured grid finite volume community ocean model (FVCOM) to study nearshore hydrodynamics. Both 3D wave-current coupled models adequately described wave breaking and the roller induced longshore current.

s0080 3.3 Boussinesq type models

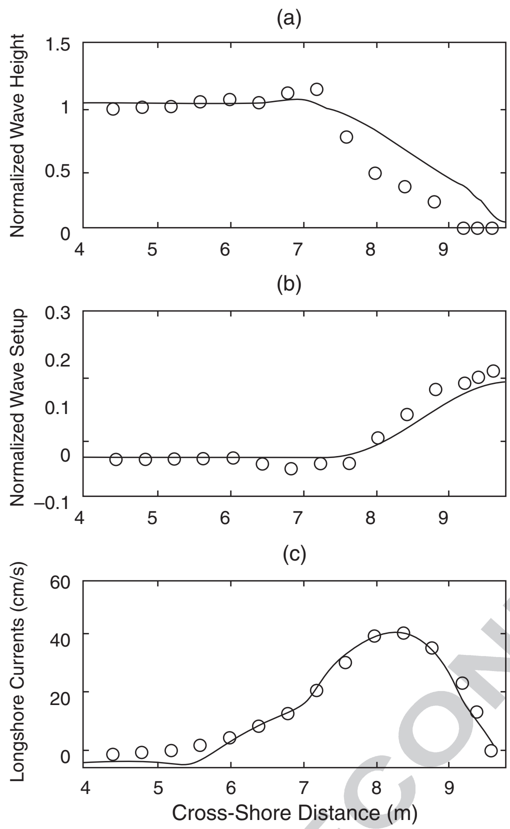
p0210 The development of numerical models that include the Boussinesq (1872) wave approximation (e.g., Madsen and Sorensen, 1992; Schäffer et al., 1993) applied to nearshore hydrodynamics provides a time dependent approach. The essential idea in the Boussinesq approximation is the elimination of the vertical coordinate from the flow equations, while retaining some of the influences of the vertical structure of the flow under water waves. This is useful because the waves propagate in the horizontal plane and have a different (not wave-like) behavior in the vertical direction. This makes Boussinesq models very useful for predicting the propagation and spatial evolution of waves in shallow water. Boussinesq models in the context of nearshore processes (e.g., Wei et al., 1995; Sørensen et al., 1998; Kennedy et al., 2000; Cienfuegos, et al., 2010; Kirby, 2016) are time-domain numerical solutions of wave and current hydrodynamics. They can be applied on a two-dimensional grid that captures the important morphologic scales of variation, and they can be forced in the time-domain with realistic time series of incident waves.

p0215 Chen et al. (2003) modified the Boussinesq model of Wei et al. (1995) to the surf zone to predict wave associated longshore currents. The modified model included partially rotational flow and vertical vorticity in order to describe these important features of breaking waves. Note that the mean flows were derived as a component of the overall solutions to the equations of motion, rather than forced separately by waves as in the radiation stress approach. Chen et al. (2003) successfully predicted the basic two dimensional structure of longshore currents measured under laboratory conditions by Visser (1991), as shown in Fig. 7.

p0220 Chen et al. (2003) further applied the model to the fully three dimensional bathymetry at Duck, NC, and successfully reproduced the observed longshore currents, including the peak current located near the longshore trough. Fig. 8 shows the reasonable agreement between the model and the field measurements. The dashed line in panel (c) includes the one-dimensional solution of Church and Thornton (1993), which does not accurately predict the peak current near the longshore trough. The peak current in the trough was associated with strong momentum diffusion on the forward facing side of breaking waves. For the simulation of field conditions, Chen et al. (2003) employed a bed shear stress coefficient in the model that had spatial variation consistent with Whitford and Thornton (1996), which was lower in the trough region, and contributed to the stronger current there.

s0085 4 Process-based numerical models for coastal geomorphology

p0225 Research and applications in the field of coastal geomorphology has been advanced significantly by the development of a wide variety of process-based numerical models (PBNM) of two- or three-dimensional hydrodynamics, sediment transport, and morphodynamics. The integration of PBNM with newly developed methods of obtaining highly accurate topographic and bathymetric measurements has led to rapid expansion of scientific understanding of the genesis and evolution of morphology in



f0040 **Fig. 7** Comparison of Chen et al. (2003) Boussinesq model results with laboratory data from Visser (1991): (a) wave height, (b) mean water level, and (c) cross-shore distribution of longshore current velocity. From Chen Q, Kirby JT, Dalrymple RA, Shi F and Thornton EB (2003) Boussinesq modeling of longshore current. *Journal of Geophysical Research* 108(C11): 26-1–26-18, Fig. 3.

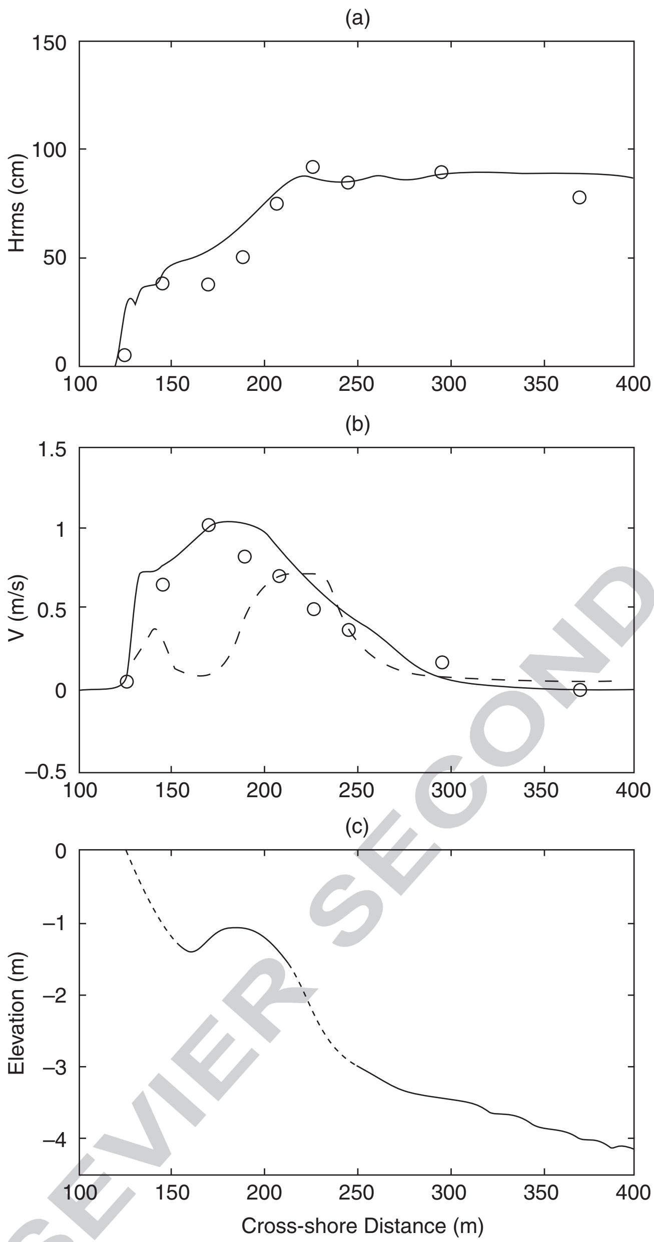
coastal regions, the accretion and erosion of coastlines, and the effects of climate change on fluvial systems, estuaries, and coasts (Hanes, 2009). Applications such as the dredging of shipping channels and harbors, the protection of coastal property from erosion, and evaluation of the risks due to coastal flooding are examples of chronic and enduring societal problems that can now be approached with new optimism through the application of PBNM.

p0230 Process-based numerical models predict bathymetric change by accounting for the basic contributing physical processes of hydrodynamics, water waves, and sediment transport. The ability of increasingly powerful microprocessors to approximately solve the governing equations rapidly on a dense three-dimensional spatial grid has elevated the models to an impressive level of realism. As research into the mechanics of the relevant physical processes progresses, there should be a corresponding improvement in modeling skill. For example, as geomorphic transport sub-models that incorporate mechanistic sediment transport processes are developed, these could be added to both coastal evolution and terrestrial landscape evolution models.

p0235 PBNM typically have powerful visualization tools capable of displaying both data and model predictions, so PBNM and high resolution bathymetric/topographic measurements complement each other well, and their integration provides a quantitative means of evaluating model skill. As quantitative measures of model skill are further refined and gain acceptance by the research community the predictive skill level and uncertainty of PBNM will become better quantified. One of the recent advances in PBNM is the development of a morphodynamic time scale that permits short time scale (seconds to days) results to be applied to longer term (years to decades) bathymetric evolution with significant reduction of the accumulation of numerical errors typically associated with long term simulations (e.g., Roelvink, 2006; Roelvink and Reniers, 2012). These models permit the study of long term interactions between the longshore current and nearshore bathymetry resulting from gradients in littoral sediment transport. These long term models can also explore the morphodynamic response of the coast to slow but enduring changes in sea level.

s0090 4.1 The pitfalls and promises of PBNM

p0240 One caution worth noting here is that PBNM capabilities are so advanced that their output products are often extremely visually appealing, and over-interpretation is tempting under the sometimes false assumption that these products are inherently correct and/or valuable. Generally, the model output under evaluation is the cumulative result of many sub-models intended to capture a variety of physical processes. While the sensitivity of a high level model result can be evaluated (as will be discussed further below) with respect to input variables, parameters, and sub-model formulations, the accuracy of the sub-models is rarely evaluated. When



f0045 **Fig. 8** Comparison of Chen et al. (2003) Boussinesq model results with field data from Duck, NC, United States for a case with a narrow-banded wave spectrum. (a) Root mean square wave height, (b) cross-shore distribution of longshore current, where dashed line depicts the solution of hte 1-D model given by Church and Thornton (1993), and (c) beach profile. From Chen Q, Kirby JT, Dalrymple RA, Shi F and Thornton EB (2003) Boussinesq modeling of longshore current. *Journal of Geophysical Research* 108(C11): 26-1–26-18, Fig. 15.

considering longshore currents and surf zone processes, models are rarely evaluated against field measurements of the sub-model component processes. For example, one of the terms in the momentum balance in a vortex force model is the curl of the horizontal Stokes drift with the vertical vorticity, yet neither the Stokes drift nor the vertical vorticity can typically be measured under field conditions. In fact, judicious choice and control of PBNM parameters remain challenging enterprises even for the most skilled practitioners. The remarkable capabilities of PBNM provide optimism to approach the challenges that lie ahead for the field of coastal geomorphology research (and earth surface process research in general) with high expectations. The challenge remaining is to discover, explain, and incorporate physical and biological processes that will enable PBNM to ultimately make predictions with quantifiable uncertainties.

p0245 Two powerful capabilities of using PBNM are the abilities to investigate outcome sensitivity to variations in the input forcing and to examine specific aspects of the sub-model formulations. For example, Chen et al. (2003) found that forcing with either monochromatic or random waves results in similar mean longshore currents, but that unidirectional, monochromatic waves results in much stronger shear waves than forcing with random waves. As an example of sub-model evaluation, Spydell (2016) explored cross-shore mixing by eddies by applying a wave resolving Boussinesq model in combination with observations from Duck, NC. He concluded that the presence of a strong longshore current actually suppresses the cross-shore mixing due to eddies in the surf zone.

p9000 There are many other phenomena related to longshore currents that could be better understood through the application of PBNM's. The interactions with the sedimentary seabed are a source of large uncertainty in the prediction of longshore currents (e.g., Sherman and Greenwood, 1984, 1986). The parameterized bed stress coefficient actually depends upon bedforms ranging from small wave ripples up to dunes (Greenwood and Sherman, 1987). Incorporation of time-domain hydrodynamics into PBNM that includes surf zone boundary layer dynamics would provide an approach to predicting the bedforms and reduce the guesswork of specifying the bed shear stress coefficient. Accurate prediction of bedforms would also improve the predictive capabilities for local sediment transport, and therefore for bathymetric evolution.

p9005 Another approach to longshore currents that could be further explored using PBNM is the stochastic nature of the both the waves and the longshore currents (e.g., Restrepo and Venkataramani, 2016). Although PBNM are intrinsically deterministic, they can be applied over many realizations with a stochastic treatment of input parameters, boundary conditions, bathymetric variations, and wave forcing variations. Different shaped incident waves in combination with different beach morphologies would be expected to result in a wide variety of breaking wave characteristics, which should result in different strengths and distributions of longshore currents.

s0095 5 The way forward

p0250 Given the new capabilities for field measurements and numerical modeling, one might ask: What are the most significant remaining conceptual and technical barriers for the field of nearshore geomorphology? Foremost amongst many are (1) the ability to measure hydrodynamics and bathymetry in the surf zone, (2) the ability to predict small scale bedforms and sediment flux accurately, and (3) the inclusion of biological effects, or eco-dynamics.

p0255 Currently the complementary techniques of sonar and laser surveying can provide high resolution measurements of coastal geomorphology, including dunes and coastal cliffs, but neither of these is effective in most surf zones. With the notable exception of a small number of highly specialized and localized vehicles designed to collect bathymetry within the surf zone, there are currently no widely useful techniques to collect such bathymetry. Surf zones typically have rough waves, turbid waters, and strong currents that often render high resolution bathymetric measurement unfeasible. GPS and single-beam echo sounders mounted on personal watercraft can successfully measure bathymetry across portions of the surf zone under common conditions, but these data are spatially sparse, labor intensive to obtain, and too difficult and dangerous to collect under the highest energy conditions. Similarly, acoustic profiling methods to measure high temporal and spatial resolution measurements of the velocity are thwarted in the surf zone due to the presence of air bubble and sometimes high concentrations of suspended sediment. Optical, mechanical, and electro-magnetic current meters are difficult to deploy and maintain, especially under storm conditions. Although the nearshore surf zone is narrow in spatial scale and may represent a small geographic gap in data, obtaining data in this region is extremely important for research on hydrodynamics, shoreline change, coastal erosion, and coastal flooding due to tsunamis, hurricanes, or severe storms. For example, seamless high resolution maps would provide new opportunities to investigate the interactions and morphological feedbacks of the complete coastal system. Similarly, high resolution velocity measurements would permit the direct evaluation of momentum fluxes and other breaking wave model components.

p0260 The prediction of sediment flux is generally quite difficult and traditionally has been highly empirical, with each environment presenting its own features that challenge the application of universally applicable principles. Further, predicting bathymetric change is predicated on the ability to accurately predict gradients in sediment flux, a task which requires very demanding accuracies. Recent advances in the prediction of sediment flux include theories for sand transport using complex, two-phase (water and sediment or water), continuum mechanical approaches, but these approaches are currently too computationally demanding to be utilized in high spatial-grid resolution numerical models. Until computational power is sufficient to enable the solution of two-phase momentum and energy conservation equations on a spatial grid, more-efficient parameterizations and algorithms are required to predict small scale bedforms and the local sediment flux. An additional issue for sediment dynamics modeling is the complex reality that sediment is generally composed of grains of many sizes, shapes, and compositions, all of which, particularly for fine and organic sediments, profoundly affect the physics of sediment transport. With mixed sediments or broad size distributions, the vertical structure of grain characteristics within the seabed and the grain characteristics at the water-sediment interface in particular are crucial to the accurate prediction of sediment transport, and therefore need to be correctly accounted for in numerical models.

p0265 In many shallow water environments living systems interact significantly with morphodynamics, often with non-linear and poorly understood feedbacks between the biology and the morphology. Simple examples include the production of organic sediment as a source of material to accrete the seabed, or the stabilizing effect of vegetation in tidal environments. More complex examples are the biological succession to be expected as a coastal environment changes characteristics as a consequence of rising relative sea level (e.g., Morris et al., 2002; Shepard et al., 2011), such as has taken place in coastal Louisiana during the past century (e.g., Penland and Ramsey, 1990), and the effects of the biological evolution on coastal erosion, for example in combination with a large storm such as a hurricane. Understanding the coupling between eco-dynamics and morphodynamics, and incorporating these interactions into PBNM, is an important and extremely difficult challenge.

s0100 ## 6 Conclusion

p0270 The radiation stress gradient approach of Bowen (1969b), Thornton (1970), and Longuet-Higgins (1970a,b) described the basic balance between wave forcing and bottom friction with the influence of lateral mixing that explains the existence, strength, and general cross-shore distribution of longshore currents. Their basic concept has been modified and expanded in many manners, for example there are many different models for cross-shore mixing, models for spatially variable bottom friction, and models that include wind and tidal effects. There are different methods to parameterize the incident wave field. Specific characteristics such as beach morphology and wave climate of each location typically results in some modifications to the characteristics of the longshore current.

p0275 Much more complex time dependent and three-dimensional hydrodynamic models of waves and currents have also been developed that predict longshore currents without directly using the wave- and depth-averaged radiation stress concept. These models provide powerful techniques to investigate basic nearshore dynamics and help interpret complex observations. When combined with sub-models for sediment flux and bathymetric evolution, they can also be incredibly useful tools applied to specific study applications such as project designs, environmental impacts, storm impacts, etc. But despite the many advances of the past half century, the early basic concept still holds that longshore currents are generated mainly by waves breaking at an angle oblique to the shoreline, with larger and more oblique waves generating stronger currents.

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Non-Print Items

Abstract:

A longshore current (sometimes called an alongshore current) flows approximately parallel to the shoreline and occurs within or near the surf zone. Longshore currents transport and disperse a variety of suspended materials such as larvae, organic matter, nutrients, and pollutants such as toxic chemicals, plastics, and trash. Longshore currents also contribute significantly to the mobilization and transport of sediment. Early theories explained that longshore currents are driven by the momentum flux associated with surface gravity waves approaching the coastline at an oblique angle. A variety of sophisticated process-based models now provide a more complete solution of the hydrodynamic equations of motion related to longshore currents. Some of these models incorporate three dimensional aspects of the hydrodynamics and bathymetry, as well as their temporal evolution.

Keywords: Alongshore; Beach; Circulation; Coastal; Current; Littoral; Nearshore; Surf