

CHAPTER 43

VARIABILITY OF LONGSHORE CURRENTS

BY

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ABSTRACT

Simultaneous measurements were made of the offshore directional spectra of gravity waves, and longshore currents within the surf zone. The goal was to test theories which suggest a direct relationship between mean longshore currents (\bar{V}) in the surf zone and offshore values of the off-axis component of radiation stress (S_{xy}). Seventeen minute averages of both S_{xy} and \bar{V} showed considerable temporal variation, and little^{xy} or no tendency to vary together. There was also considerable longshore spatial variability of the longshore current. Attempts to measure gradients of S_{xy} in the surf zone failed because of small errors in instrument orientation. The measurements suggest that considerable temporal and spatial averaging will generally be required to obtain a representative picture of longshore currents, even if no rip currents are present, due to the presence of "eddy" motions or long edge waves.

INTRODUCTION

Following the introduction of the concept of radiation stress (Longuet-Higgins and Stewart, 1964) many detailed theories for mean longshore currents in the surf zone region have been advanced (for example: Bowen, 1969a; Thornton, 1970; Longuet-Higgins, 1970). Earlier work (Putnam et al (1949), Inman and Quinn (1951) contained much of the essential physics but lacked a quantitative formulation. The newer formulations are fundamentally similar to each other in that they propose a longshore momentum balance between forcing terms related to the mean lateral thrust exerted on the surf zone by non-normally incident incoming gravity waves, and retarding forces associated with bottom drag. Lateral mixing complicates the picture by diffusing longshore momentum across horizontal shear currents. Different authors use

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different assumptions about the behavior of waves inside the surf zone and about the detailed forms for drag and mixing terms. As a result, the predictions of the magnitude of mean longshore currents and the distribution across the surf zone are somewhat different for identical incident wave conditions. The different theories do agree that for plane parallel contours the total lateral thrust on the surf zone is given by the off-axis term of the offshore radiation stress tensor, S_{xy} , or equivalently by, S_{xy}^B , the "break point" radiation stress value. Evaluation of S_{xy}^B involves estimation of a significant breaker angle, period and height, subjective quantities prone to gross errors (different observers on the same day report values of S_{xy}^B commonly differing by more than 100%). Therefore, in order to test the theories for longshore current with observation we have simultaneously measured S_{xy} offshore (10 m. depth) and longshore currents within the surf zone.

Instrumentation

A large scale field experiment was conducted at Torrey Pines Beach near San Diego, California during the month of March 1977. Properties of the incident gravity wave directional spectrum were measured with a 400 m. long, 5 element linear array of Statham pressure sensors; their mean depth was about 9.5 m. Six biaxial Marsh-McBirney electro-magnetic current meters were installed in the surf zone during low tide. A plan view of instrument positions is shown in Fig. 1A. The pressure sensor signals were telemetered to shore using the SAS system described in Lowe et. al (1972). The current meters were powered and sampled from shore using armored cables. The sampling frequency was 64Hz; the data was immediately block averaged and decimated to 2 Hz.

Figure 1B shows typical shallow water depth profiles for range lines A, C, D on East-West transects. The profiles overlay other when put in a coordinate frame rotated 4° N of E (the orientation of the pressure sensor array) suggesting approximately plane parallel contours in this coordinate frame. Contours between the offshore array (not shown) and the current meters show no marked deviation from plane parallel (4° N of E) suggesting that refraction does not lead to significant alongshore gradients of breaker height.

Incident Wave Field

The offshore directional spectrum was analyzed using Fast Fourier transforms in the time domain to obtain phase lags for each frequency band. These phase lags were analyzed using maximum likelihood estimation techniques to obtain the direction distribution of wave energy in each frequency band. Steve Pawka did the offshore wave analysis and subtleties of the analytic methods are discussed extensively in his soon to be completed Ph.D. thesis. We thank him for kindly providing directional spectra for use in this

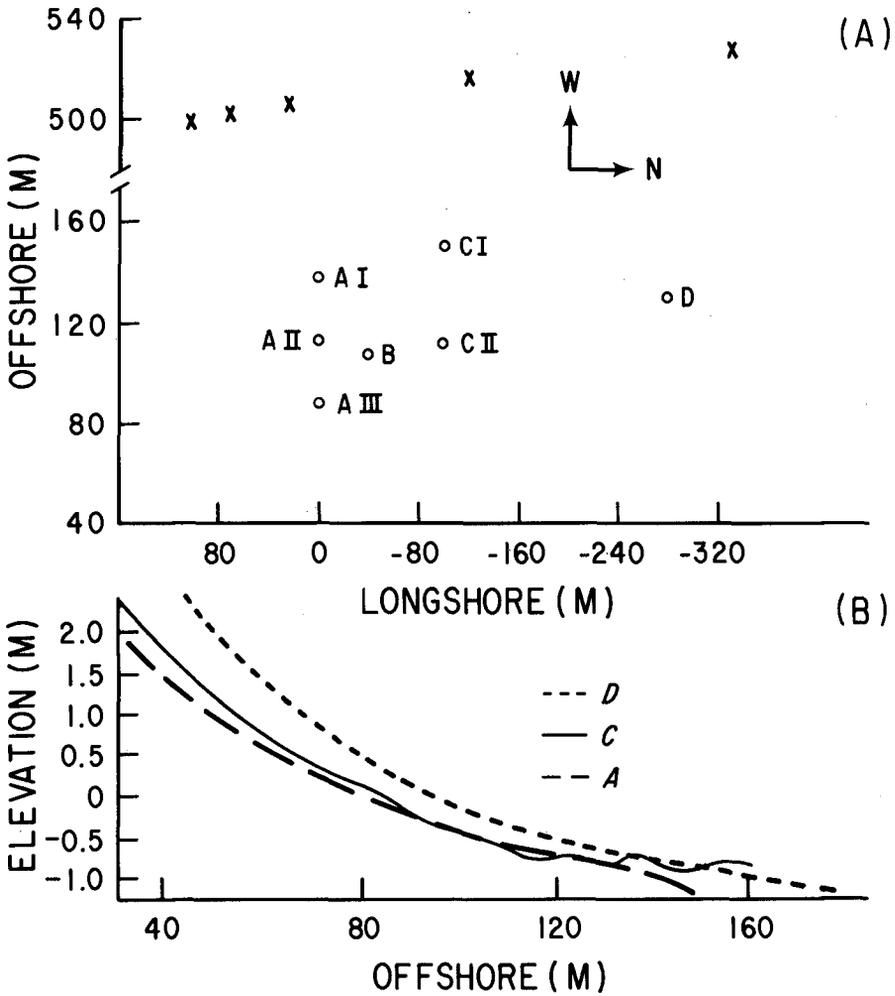


Figure 1. (A) Plan view of instrument locations. x = pressure sensors, 0 = current meters
 (B) Depth profiles for various range lines on E-W transect.

discussion of offshore radiation stress terms. Fig. 2A shows a typical distribution of variance per frequency band. Each band is .0078 hz wide and has 16 degrees of freedom. The record length is 1024 sec. The energy is centered around periods of about 14 sec., with a background of higher frequency waves. Given the directional distribution of energy in each frequency band, $E(f, \alpha)$, the relevant off-axis component ($S_{xy}(f)$) of the radiation tensor is given by

$$S_{xy}(f) = \int_{-\pi}^{\pi} E(f, \alpha) n(f) \sin \alpha \cos \alpha \, d\alpha \quad (1)$$

where $n(f)$ is the ratio of group and phase velocities (assumed given by linear theory) at the array depth and α is the deviation from normal incidence. On plane parallel contours S_{xy} is a conserved quantity if no dissipation occurs (Bowen, 1969b; Thornton, 1970) so S_{xy} at the array gives S_{xy}^{∞} , the deep water value. The entire topography seaward of the array is not plane parallel, but for simplicity we have assumed that it is. Fig. 2B shows that $S_{xy}(f)$ is maximum at the peak energy frequencies. However, the relatively broader frequency band of high frequency "chop" makes a significant contribution to the total S_{xy}^{∞} . In this example, the principal peak contributes -5.7×10^3 g/sec² while the "chop" contributes $+3.5 \times 10^3$ g/sec². Thus, the total lateral stress exerted on the surf zone by all frequencies,

$$S_{xy}^{\infty, T} = \int_0^{\infty} S_{xy}^{\infty}(f) \, df \quad (2)$$

contains significant contributions from a very broad range of frequencies. Visual observations of a significant breaker height and period generally pick out the swell peak and ignore the chop. In certain cases, strong locally wind generated high frequency waves with large angles of incidence may produce a true S_{xy}^T , which is opposite in sign to S_{xy}^{∞} estimated by visual observations biased towards long swell. This may explain some (but probably not all) of Nummedal and Finaley's (1978) observations showing a stronger correlation between local wind and longshore current than between visual observations of S_{xy} and longshore current. More concisely, the eye simply is not a very good directional spectrum estimator when the incident wave field is broadbanded in both frequency and direction. Figure 2C shows the "principal stress angle of approach" $\hat{\alpha}_{\infty}(f)$ defined (rather arbitrarily) using (1),

$$\sin \hat{\alpha}_{\infty}(f) \cos \hat{\alpha}_{\infty}(f) = \frac{S_{xy}^{\infty}(f)}{n_{\infty}(f) E_{\infty}(f)} \quad (3)$$

where $S_{xy}^{\infty}(f)$ and $E_{\infty}(f)$ are the radiation stress and energy per frequency band in deep water. As is obvious from $S_{xy}(f)$,

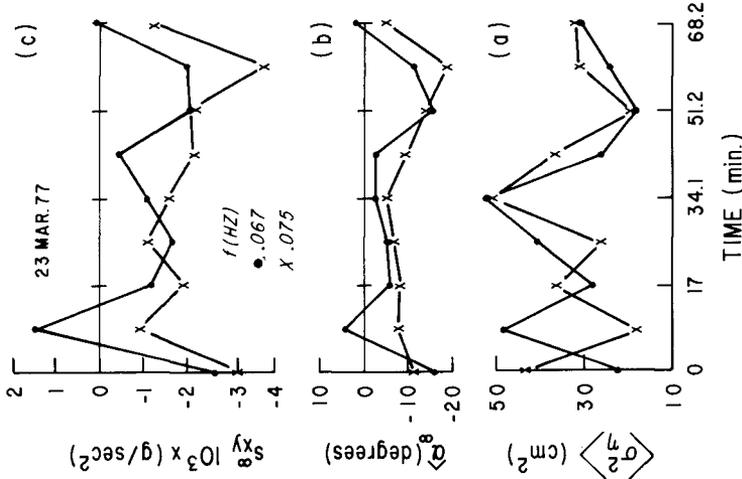


Figure 3. Time series of successive values from records, 1024 secs long, for two adjacent frequency bands in swell peak (Fig. 2) of (a) variance in each band, (b) principal stress angle, (c) radiation stress

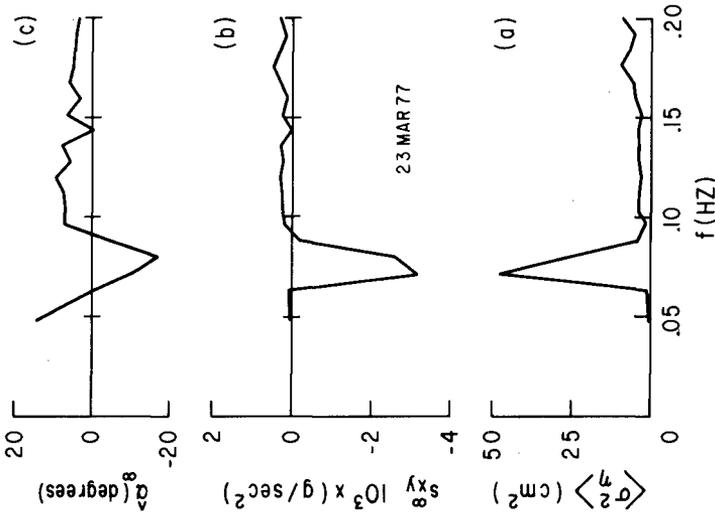


Figure 2. (a) Variance Spectrum, $\langle \sigma^2 \rangle$ per frequency band. (b) Offshore radiation stress, s_{xy} , per frequency band. (c) Equivalent deep water principal stress angle of incidence for each frequency band.

$\hat{\alpha}_{\infty}(f)$ shows the swell and chop approach from different quadrants.

Measurements of $S_{xy}^{\infty, T}$ on several different days show it to be a statistically noisy quantity. This is not surprising because each $S_{xy}^{\infty}(f)$ depends on both the variance and directional distribution of energy in that band. Figure 3 shows the time history of variance (Fig. 3a), $\hat{\alpha}_{\infty}$ (Fig. 3b), and $S_{xy}^{\infty}(f)$ (Fig. 3c) for the two adjacent bands in the swell peak S_{xy}^{∞} shown in figure 2a. The energy dances about, as does $\hat{\alpha}_{\infty}$. The combination of the two fluctuating quantities going into $S_{xy}^{\infty}(f)$ leads to statistical variation of $S_{xy}(f)$. We note that the behavior of $\hat{\alpha}_{\infty}$ and $\langle \sigma^2 \rangle$ are somewhat correlated for these adjacent frequency bands, but that $S_{xy}(f)$ is apparently less correlated. Considering that S_{xy}^T is made up of many $S_{xy}(f)$ which all fluctuate, it is not surprising that S_{xy} is statistically unstable. We have done no further statistical analysis of S_{xy} and only make the general comment that, at Torrey Pines Beach, 1024 secs (17.1 min) does not appear to be a long enough sampling time to adequately measure the forcing function $S_{xy}^{\infty, T}$.

Surf Zone Longshore Currents

Fig. 4 shows 1024 sec means of longshore currents inside the surf zone and of offshore measurements of $S_{xy}^{\infty, T}$. Fig. 4a demonstrates the significant temporal fluctuations of S_{xy} discussed previously. Visual observations (whatever they may or may not signify) did not indicate any obvious non-stationarity of the incident wave field. Large breakers (1.5 m. height) were present with pronounced angles of approach. All current meters were in the inner half of the surf zone. No obvious permanent rips were observed between A and D ranges. Figs. 4b, c, d show mean values of longshore current for sensors at various longshore and on-offshore locations (Fig. 1). At this particular tidal stage (during high tide with little mean depth change) the shallowest and deepest current meters were in depths of about 60 cm. and 120 cm. respectively. The instruments on the same on-offshore range line show some tendency to vary together, but range lines 100 m. apart in the longshore direction (A and C for example) show little tendency to vary together (Fig. 4). Furthermore, no instrument showed an obvious covariation with $S_{xy}^{\infty, T}$.

Referring back to theory (Longuet-Higgins, 1970, eqs. 54-55) for guidance, we should actually expect the surf zone width to vary with $E^{\infty, T}$, and the current strength at a fixed location (always inside the breakpoint) to vary with $\hat{\alpha}_{\infty}^T$, some measure of an approach angle characteristic of the entire directional spectrum across all frequency bands (recall $\hat{\alpha}_{\infty}(f)$ represents the principal stress angle for a given frequency band). We made an extremely crude estimate of $\hat{\alpha}_{\infty}^T$ using

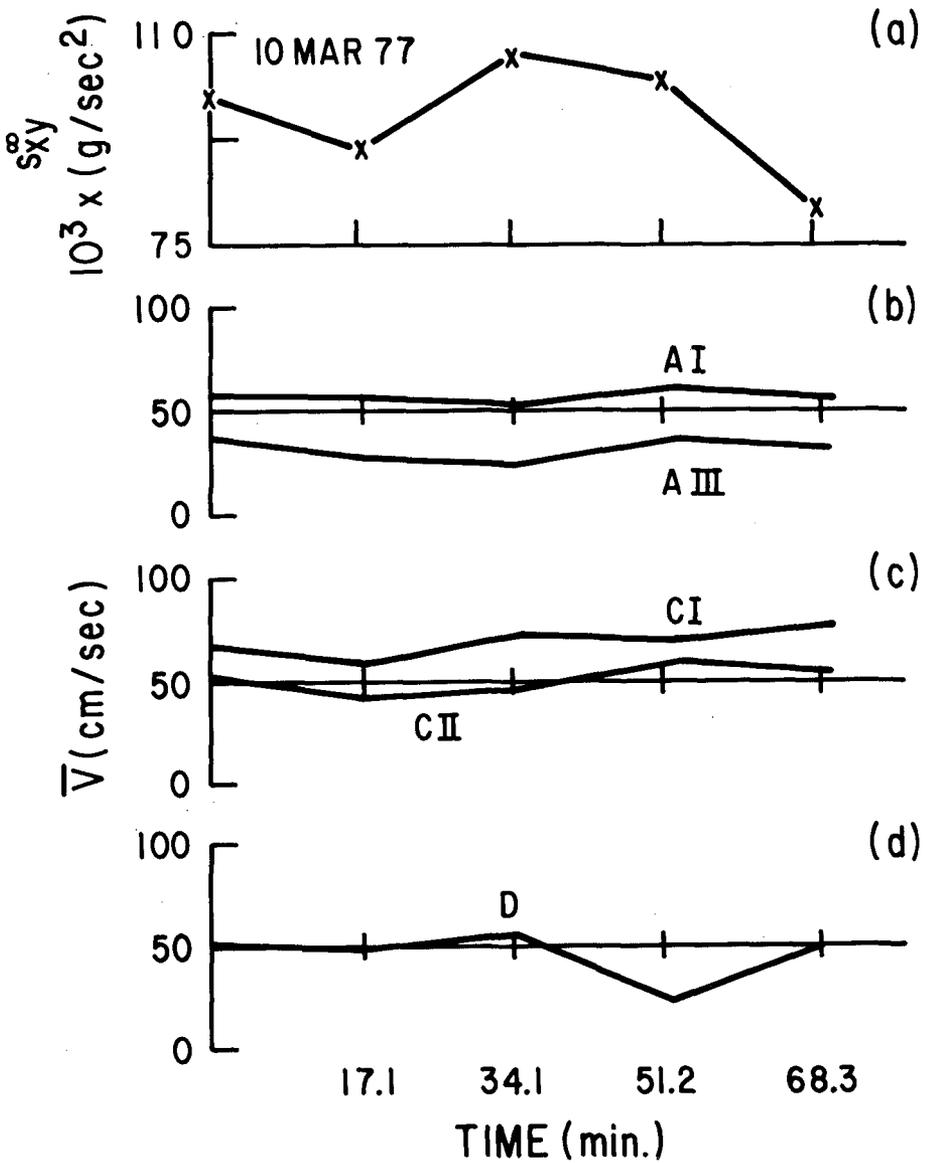


Figure 4. Temporal (1024 secs) averages on 10 March 1977 of
 (a) Total offshore radiation stress
 (b,c,d) Longshore current at different surf zone locations

$$\sin \hat{\alpha}_{\infty}^T \cos \hat{\alpha}_{\infty}^T = \frac{S_{xy}^{\infty, T}}{E_{\infty}^T n_p} \tag{4}$$

where n_p is given by the frequency of the spectral peak. No longshore currents showed an obvious covariation with $\hat{\alpha}_{\infty}^T$. Our conclusion is not a welcome one: considerable longshore variation of mean (temporal) longshore currents can occur even on a relatively straight beach with no obvious rip structures. A large (unknown) amount of longshore spatial averaging, as well as temporal averaging, may be necessary to determine the "mean longshore current" on a given depth contour.

The dominant term in the longshore momentum balance is on-offshore gradients of S_{xy} inside the surf zone, regardless of the contribution of S_{xy} nonlinear terms (for example $\bar{v} \partial v / \partial y$) or alongshore variations in breaker height. If nonlinear terms, longshore variations in mean sea level, and lateral mixing are neglected, the longshore momentum is simply

$$\frac{\partial S_{xy}^T(x)}{\partial x} = \frac{1}{2} \rho C_f \overline{|\vec{U}(x,t)| v(x,t)} \tag{5}$$

where C_f is a Chezy' drag coefficient, $\vec{U}(t)$ and $v(t)$ are the instantaneous total and longshore velocities respectively, $||$ is absolute value, and the overbar indicates time averaging.

Assuming no vertical variations in fluctuating horizontal velocities ($u'(x,t)$ and $v'(x,t)$),

$$S_{xy}^T(x) = \rho h(x) \overline{u'(x,t)v'(x,t)} \tag{6}$$

The usual simplifications of the drag term (Eq. 5) necessary for analytic progress (for example, that $u' > v'$) are not necessary when measured time series are available. We simply computed $S_{xy}^T(x)$ at different offshore locations on the same range line, and solved for C_f

$$C_f = \frac{2(S_{xy}^T(x_2) - S_{xy}^T(x_1))}{\rho \overline{|\vec{U}(x_i,t)| v(x_i,t)}}$$

different values of C_f result from calculating the friction term at location 1 or 2. Fig. 5 shows measured offshore variance, $S_{xy}^{\infty, T}$ and low passed means of surf zone radiation stress gradients. There seems to be a similarity between $S_{xy}^{\infty, T}$ and $\frac{\partial S_{xy}^T}{\partial x}$ in the surf zone. Calculated values of C_f

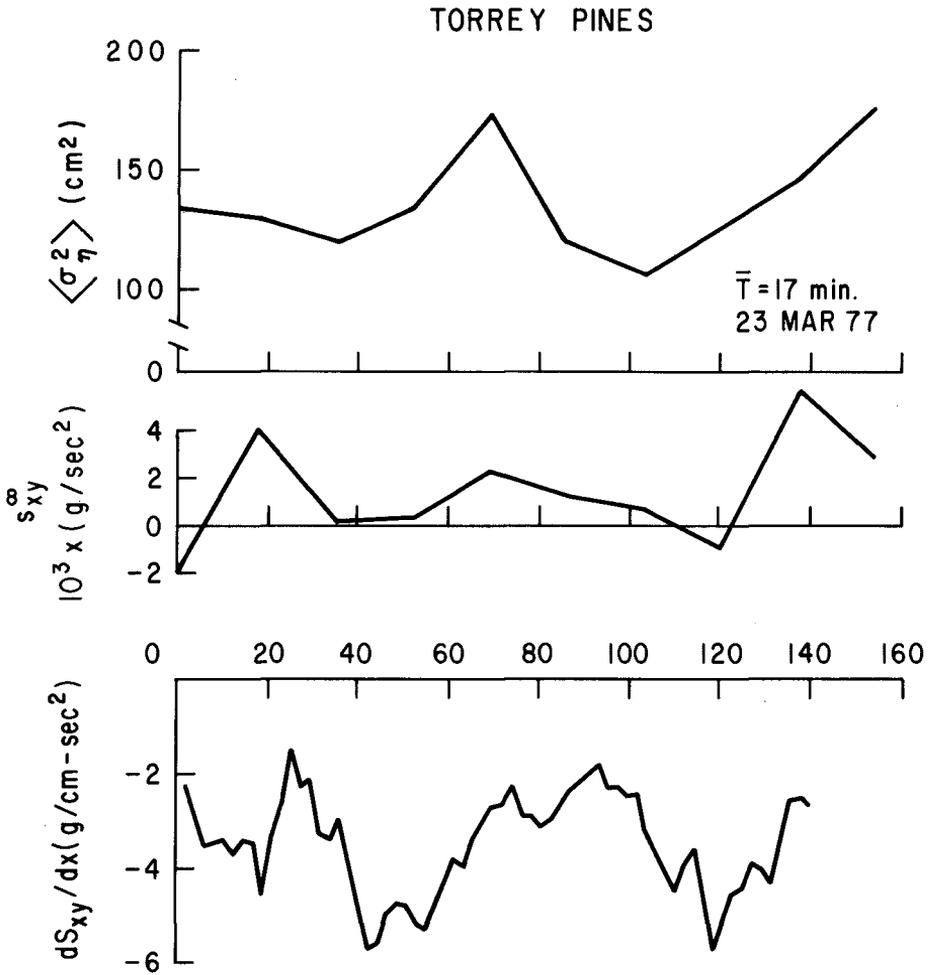


Figure 5. Temporal (1024 sec) averages on 23 March 1977 of total offshore variance, total offshore radiation stress, and running means of dS_{xy}^T/dx inside the surf zone from instruments AII, AIII.

are shown in Fig. 6a. Different C_f values occur depending on whether time series from A II (mid surf zone) or A III (inner) are used in calculating drag terms. Averaging C_f (mid) and C_f (inner) for the whole data set gives $C_f \approx .003$, which is not considerably different than the commonly used value of .01. This was the first data set analyzed and we thought some of the low value of C_f could be due to neglected nonlinear terms, or longshore and vertical variations in S_{xy} . It was more worrisome, however, that the actual magnitudes of S_{xy} at surf zone locations (also shown in Fig. 6) indicated a larger S_{xy} at mid-surf zone than at the offshore array. This does not seem possible since S_{xy} is conserved quantity during non-dissipative shoaling, and theoretically decays monotonically across the surf zone.

We attempted to test the assumption of no vertical variation in $u|v|$ in another experiment (July, 1978) using 6 flow meters horizontally closely spaced. Three meters were installed on the same depth contour, separated by 1 m. in the longshore direction, at different elevations off the bottom. To insure that no interference between closely spaced electromagnetic current meters occurred, the magnet drivers operated in a synchronous master-slave configuration. The flow meters were dynamically calibrated over the entire frequency range of interest using an oscillating arm. Considerable effort was made to carefully align the current meters. The current meters were mounted on a bracket that allowed three degrees of rotation. A special jig was used to orient the mounting bracket vertically with a bubble level and horizontally with a compass. Tests were conducted to insure that deflections of the compass needle by the ferrous mounting bracket were minimized.

The measurements were initially encouraging in that all instruments showed virtually the same on-offshore velocity spectra. For example, the spectra of instruments the same depth above the bottom, and separated by 7 m. in the on-offshore direction (a total depth difference of 8 cm.) are given in Fig. 7; the spectra show similar variance, a very high coherence, and a phase speed slightly faster than \sqrt{gh} with h the measured mean depth. Fig. 8 shows the similarity between longshore velocity spectra.

Particular note in Fig. 8 should be paid to the large low frequency components in the longshore velocity spectra; this is similar to the low frequency longshore current oscillations described in Inman and Quinn (1951), Woods and Meadows (1975), Woods (1976), and more recently by Holman et al. (1978). Without exception every longshore velocity spectra of the hundred or so we examined (corresponding to about 60 hours of observations over a month long period) showed this tendency towards spectral redness, regardless of record length. The longshore current temporal fluctuations are not site or wave regime specific since the present

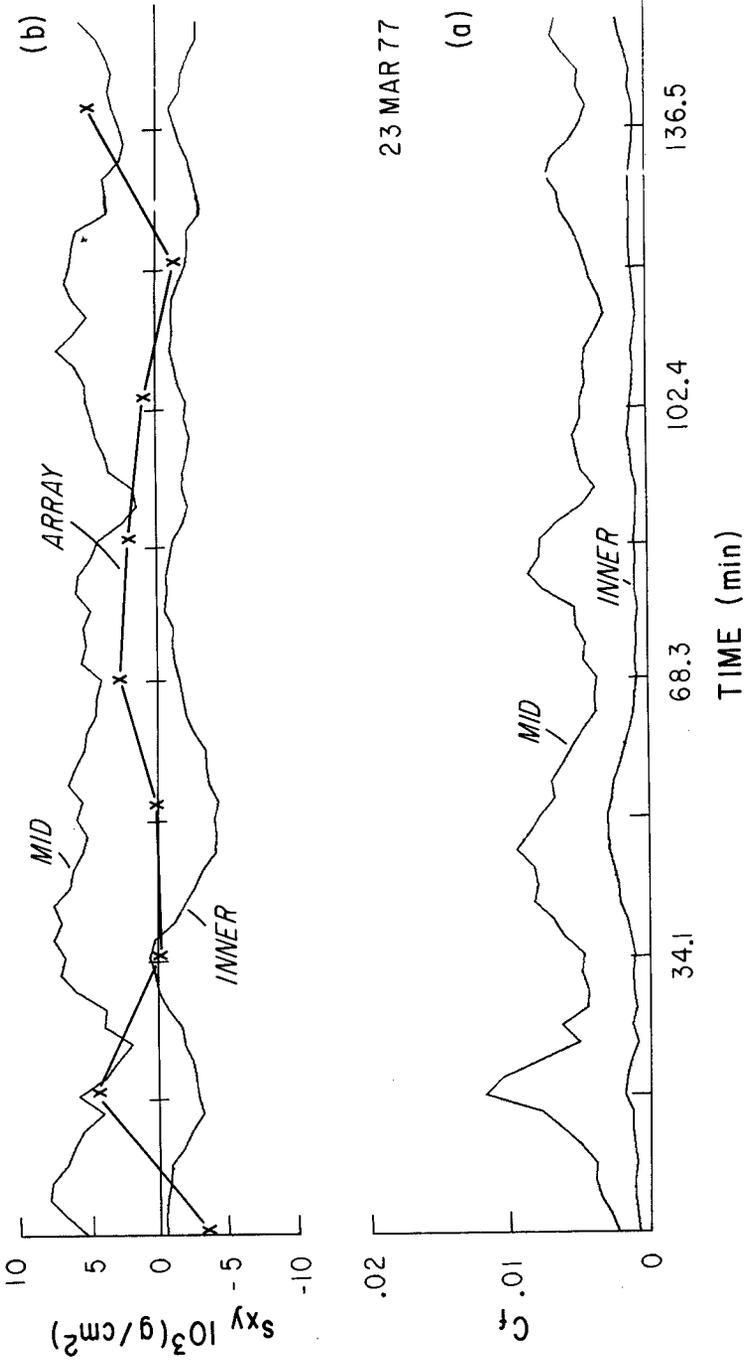


Figure 6. (a) Calculated values of drag coefficient, C_f , at mid and inner current meters
(b) Measured values of S_{xy}^T at the offshore array and mid and inner surf zone locations.

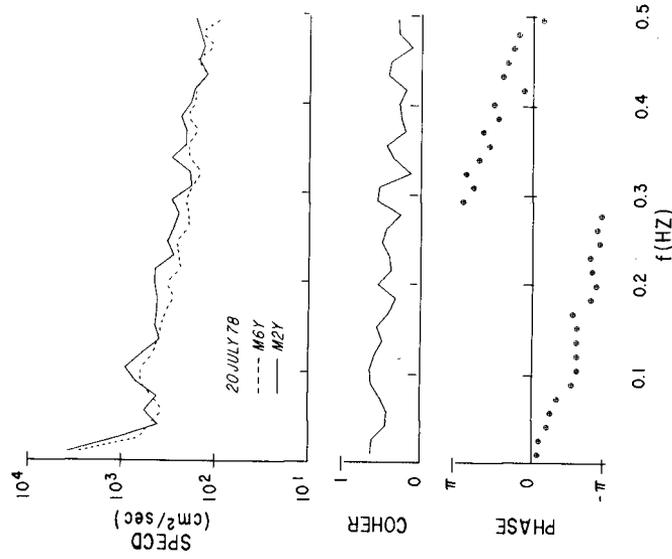


Figure 8. Longshore velocity spectra coherence and phase for the same instruments as in Fig. 7.

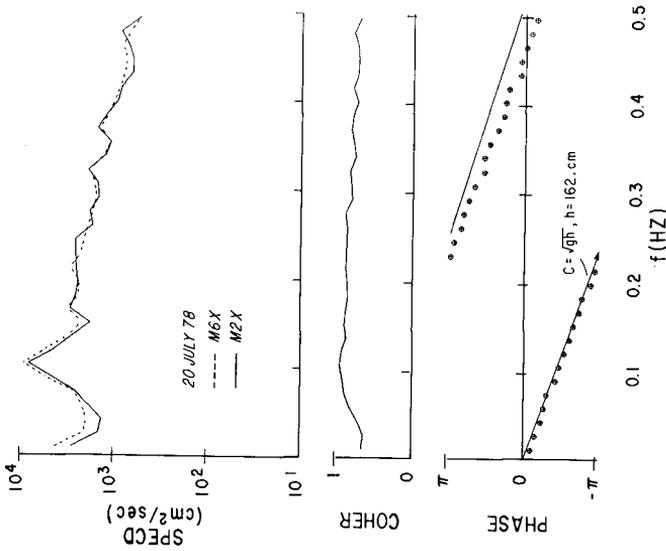


Figure 7. On-offshore velocity spectra, coherence and phase for instruments in depths differing by 8 cm. with an on-offshore separation of 7 m. Record length is 1024 sec. There are 32 degrees of freedom. Solid lines shown on phase curve is for a phase speed given by \sqrt{gh} , $h' = 160$ cm. The actual mean depth was 120 cm.

observations are from Southern California, Woods and Meadows observations are from the Great Lakes, and these of Holman et al. are from the wilds of Atlantic Nova Scotia. This mass of data suggests a grave danger in any assumptions of temporal stationarity such as are implicitly made when profiling "mean" currents with a movable sled or other such device. An appropriate temporal averaging time for mean longshore currents is not known. Woods and Meadows (1975) show 4 successive 15 minute means, and these averages, about 60 cm/sec, differ from each other by less than 5 cm/sec. Clearly, in this case, 15 mins. is a long enough time to obtain a stable average. On the other hand, Fig. 9 shows sequential 256 sec. (4.3 min) averages from 5 closely spaced instruments at Scripps Beach. The instruments vary together suggesting that the observed fluctuations are not due to sensor malfunction. Sequential means at the same location typically vary by as much as 20 cm/sec., so a single 4.3 min. average is not a representative value of the mean over longer time scales.

Upon calculating S_{xy}^T from these current meter records Figs. 7,8, instead of finding very similar values as anticipated, we found order of magnitude difference, sign reversals, and a general scatter suggestive of useless data! The reason for this is as follows. It can easily be shown that, at a particular current meter

$$\begin{aligned} S_{xy}^T &= \rho h(x) \int_0^\infty C_{xy}(f) df \\ &= \rho h(x) \int_0^\infty (E_u(f)E_v(f))^{1/2} \gamma_{uv}(f) \cos\theta(f) df \quad (7) \end{aligned}$$

$E_{u,v}(f)$ are the energy densities of (u and v) respectively, $\theta(f)$ is the phase angle between u and v, and $\gamma_{uv}(f)$ is the coherence between u and v. Figs. 10 and 11 show these spectral quantities for two closely spaced instruments. Although the spectral values are similar (Figs. 7,8), the values of coherence and phase are not. For example, around the spectral peak at .1 hz, Fig. 10 shows a narrower band of higher coherence than Fig. 11, and a phase of about $\pi/2$ compared with π in Fig. 11. This is typical of the difference between sensors and clearly shows (eq. 7) why S_{xy}^T is so different for the two instruments. Why is this occurring?

Large errors in radiation stress can occur due to even small errors in resolving the direction of fluid motion associated with the angle of incident waves. In terms of the measured spectra, the total energy density and the quadrature-spectrum are invariant with coordinate rotation, but the cospectrum used to calculate radiation stress is very sensitive to coordinate rotation.

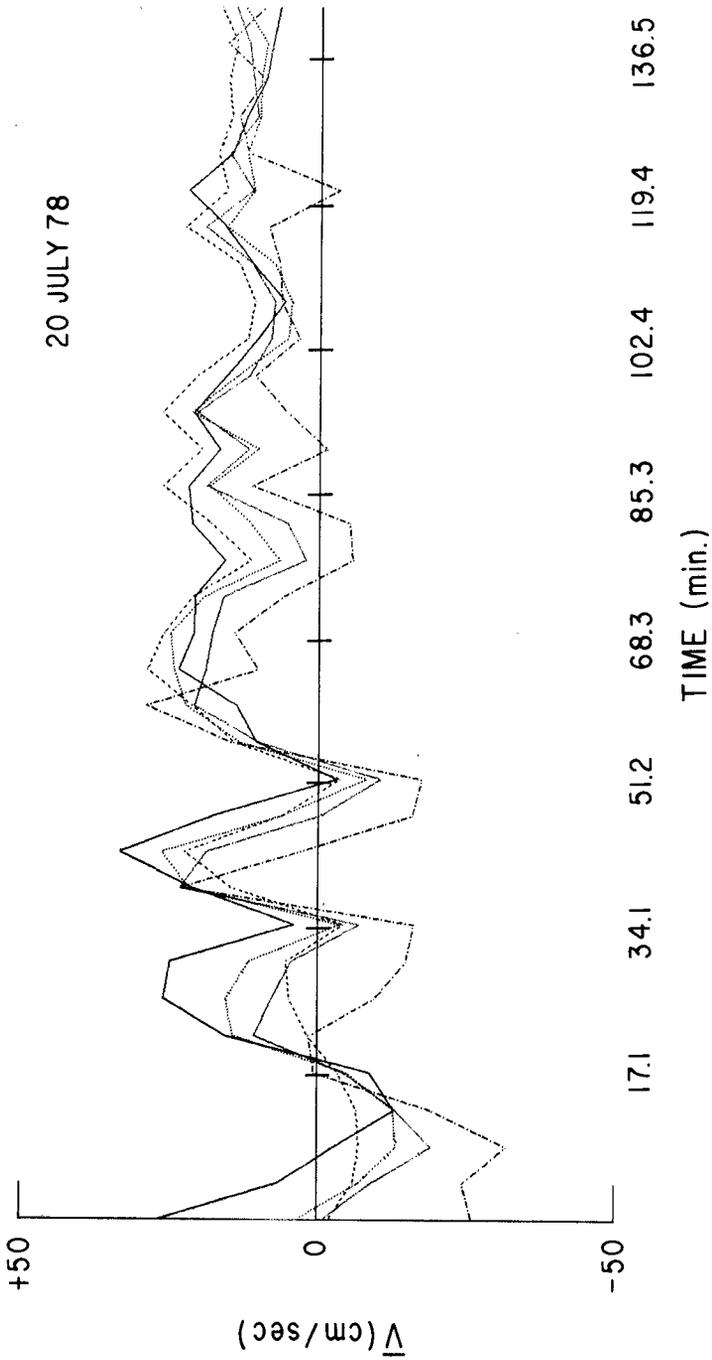


Figure 9. Time history of 256 sec. averages of longshore current from 5 closely spaced current meters, maximum separation is 14 m.

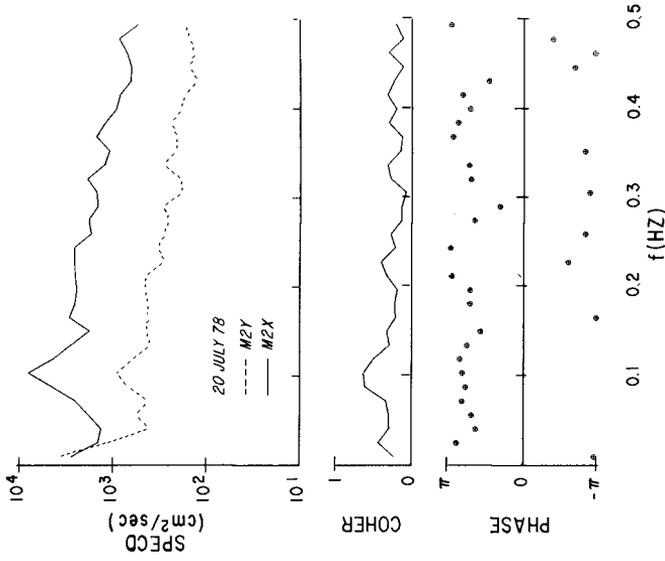


Figure 11. Same as Fig. 10, but the instrument is 7 m shorewards.

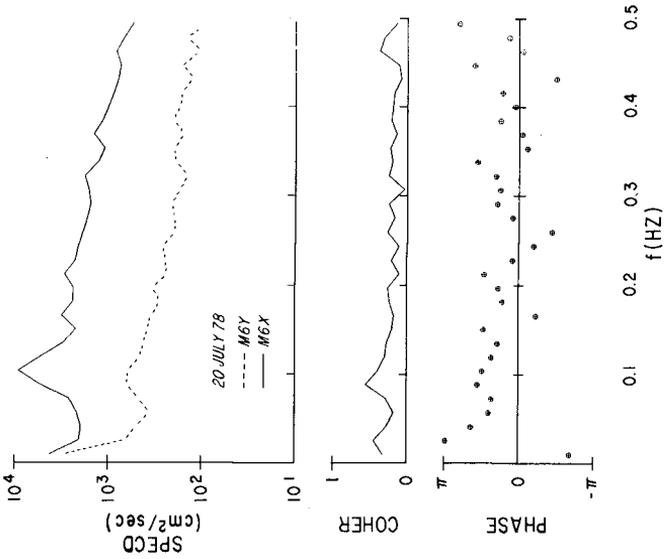


Figure 10. Spectral values, coherence, and phase for on-offshore and longshore currents at one location.

A simple application of Snell's law to a monochromatic plane wave with period 12.6 sec. shows that refraction reduces a deep water angle of incidence (α_∞) to a local angle (α) in a depth of 1 m. given by

$$\frac{\alpha}{\alpha_\infty} = .17$$

Thus, even a relatively large deep water approach angle of 20° is reduced to a small angle of 3.4° . Now consider correctly measured velocity components (u, v) and incorrectly measured velocity components (u_r, v_r) due to a coordinate rotation of angle Δ as shown in Figure 12. Assuming either all waves approach from the same direction or using a monochromatic wave argument, the radiation stress using equation 6 can be stated proportional to

$$S_{xy}^T(x) \propto \overline{u'(x,t)v'(x,t)} = \overline{u'(x,t)}^2 \tan \bar{\alpha}$$

Assuming small angles of approach and small rotation errors, the incorrectly measured radiation stress is proportional to

$$\begin{aligned} S_{xy}^T(x)_r &\propto \overline{u_r'(x,t)v_r'(x,t)} \\ &= \overline{u'(x,t)v'(x,t)} - \overline{u'(x,t)}^2 \sin \Delta \end{aligned}$$

The relative percent error is given by

$$1 - \frac{S_{xy}^T(x)_r}{S_{xy}^T(x)} = \frac{\sin \Delta}{\tan \bar{\alpha}} \approx \frac{\Delta}{\bar{\alpha}}$$

Therefore, since refraction reduces the local angle of incidence to the size of the orientation errors, the error in radiation stress can be very large.

Given perfect instrument directional response and perfect orientation, there is also the more fundamental problem of defining the longshore direction. What spatial scales should be averaged over to determine a contour orientation? Errors associated with choosing a longshore direction even on the relatively straight and parallel contours of Torrey Pines appear to be on the order of several degrees minimum. Therefore, our calculations of C_r (Fig. 6) are probably nonsensical.

Fortunately the small orientation errors discussed above do not introduce serious errors in measurement of mean longshore current because \bar{V} is generally larger than \bar{U} , so the projection of small fractions of \bar{U} onto the \bar{V} signal is not a large error. Our conclusion is that without further sophistication in instrument orientation and design and a better understanding of length scales, it is not possible to measure radiation stress in the surf zone.

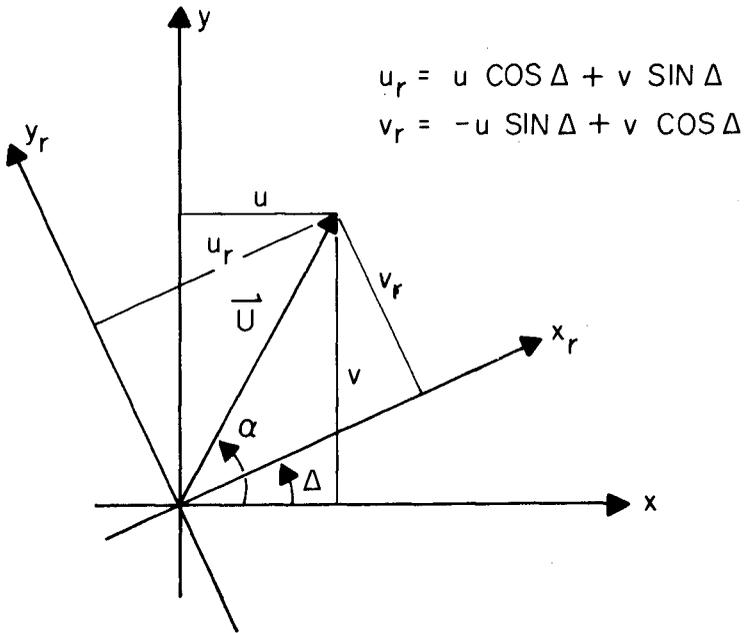


Figure 12. Rotation of coordinate axis for investigation of its influence on radiation stress.

CONCLUSIONS

1. Offshore measurement of radiation stress (the theoretical total lateral thrust exerted on the surf zone) show it to be statistically noisy. This is a preliminary result and it may be site and wave climate specific. Nevertheless, until demonstrated otherwise, short time interval measurements of S_{xy} cannot be considered as necessarily giving an accurate \bar{S}_{xy} estimate of the true mean S_{xy} .
2. Mean longshore currents at a fixed surf zone location are temporally noisy. This has been previously observed by several authors. Mean longshore currents are also spatially noisy, even with no obvious rips, suggesting that nonlinear terms and local short term variations in alongshore breaker height are important in the equations of motion. Free "eddy" motions may also be present in the surf zone.
3. Measurements of S_{xy}^T in the shallow portions of the surf zone are seriously contaminated by even small ($\pm 2^\circ$) sensor orientation errors. This is also true for vertical velocities.
4. A closing philosophical-historical point: the pioneering studies during the early 1950's of Sverdrup, Munk, and Stommel presented a rather simple picture of large scale ocean circulation. The forcing by wind, was represented by a simple long term average. The predicted currents were generally weak and horizontally smooth. The equations used by these authors are basically identical to the standard surf zone equations. They even discussed the relative importance of drag and eddy diffusivity terms, just as is currently done in surf zone dynamics. Nonlinear terms were necessary to explain the jet-like Gulf Stream, just as we currently need these terms to get appropriately strong and narrow rip currents (Arthur, 1962; Bowen, 1969b). Observations with Swallow floats showed, however, that while these theories might correctly predict yearly means, instantaneous (compared to a year) measurements showed large temporal and spatial fluctuations. Even though an enormous amount of energy and money has since been spend on experiments like MODE and POLYMODE to try to determine the importance of shorter scale fluctuations on the longer scale flows, these questions remain unresolved. Considering the strong analogy between developments so far, and the gross nonlinearity of the surf zone, it is probably overly optimistic to hope that out task of accurately difining and understanding mean nearshore flows will be simple.

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