CHAPTER 77

VELOCITY AND STRESS MEASUREMENTS IN A TIDAL INLET

David A. Huntley
Department of Oceanography
Dalhousie University
Halifax, Nova Scotia
B3H 4J1, Canada

Dag Nummedal
Department of Geology
Louisiana State University
Baton Rouge, Louisiana
70803, USA

ABSTRACT

Fast-response electromagnetic flowmeters were used in a marginal flood channel of an ebb tidal delta to assess the importance of wave contributions to the flood dominance of these channels. Measurements were made at a single point in the channel in both ebb and flood currents. The oscillatory motion of waves was a very significant feature of the velocity records, and its magnitude was comparable with the mean flow at all stages of the tide. This observation shows that flowmeters capable of responding accurately to wave velocities are needed to obtain accurate values of mean flow. Some earlier measurements made with slow response flowmeters are probably unreliable. Wave contributions to the mean flow were assessed by looking at the correlation between the low frequency (>17.5s) oscillations of the along-channel current and the low frequency envelope of the wave velocities. Surprisingly little correlation was found for any time lag, suggesting that wave effects were not important in the mean tidal currents in the channel studied. However, close to low tide on the ebb, conditions existed which appear to have been favourable for the "wave pump" mechanism suggested by Bruun and Viggisson (1973). Significant correlation between the wave envelope and low frequency fluctuations was observed at this time. It is therefore suggested that wave effects can be important to the mean flow in marginal channels with rapidly converging and shoaling mouths which are oriented towards the dominant incident wave direction.

INTRODUCTION

A tidal inlet is a complex region whose continually changing morphology is the result of the interaction of wave and tidal forces acting on the nearshore sediments. The most prominent feature of an ebb-tidal delta is a broad relatively deep central channel, usually essentially at right-angles to the coastline, terminating on the seaward side with a deltaic fan of sediment often many kilometres offshore. This channel is flanked on either side by linear bars, and broad sheets of sand known as swash platforms on which shoreward migrating swash bars are commonly observed. On either side of the inlet, between the swash platforms and the beaches adjacent to the inlet, one usually finds marginal channels which are dominated by flood tidal currents (Hayes 1975).

Considerable understanding of the processes responsible for forming and maintaining the topography of these inlets has been gained from study of their morphology, and from measurements of the average tidal and wave parameters, but it is clear that more direct and detailed measurements of wave and tidal forces are needed to clarify some of the dynamic models inferred from these studies. The present investigation was designed as a preliminary look at the relative role of waves and tides in the hydraulics of the marginal flood channels of an inlet.

The dominance of flood currents in marginal channels is generally accepted, on the evidence of bedforms and a few direct measurements of tidal current (Brun and Gerritsen, 1959, Oertel, 1972, 1975, Fitzgerald et al 1977). Clearly the inertia of a jet-like ebb flow through the inlet mouth is likely to result in an assymmetry of the tidal currents on the seaward side, with mean current gyres on either side of the ebb channel tending to enhance flood currents in the marginal channels. Dean and Walton (1975) suggest that flood dominance may also be partly due to entrainment into the ebb jet from the marginal channels.

Fitzgerald et al. (1977) suggest that waves could also be important in contributing to the flood dominance of marginal channels. A longshore variation of the height of waves breaking on the seaward side of the bar which flanks the flood channel creates a longshore gradient of set-up along the bar. Fitzgerald et al. hypothesise that this set-up gradient may be felt over the bar into the flood channel where it could drive a flood-directed current. Waves clearly might also contribute to flood dominance in several other ways. For example, wave refraction over the delta system tends to cause waves to approach the shoreline obliquely towards the inlet throat, so that at breaking they should drive flood-directed longshore currents in a narrow surf zone at the shoreline. In the highly turbulent conditions of a marginal flood channel these surf-zone driven currents might spread beyond the surf zone and influence the overall mean flow in the channel. Similarly longshore currents generated in the surf zone on the seaward side of the outer bar may also spread over the bar into the marginal channel. Also possibly relevant in this context is the description of a "wave pump" by Bruun & Viggisson (1973) and Brunn & Kjelstrup (1978). In their wave pump, some combination of mass transport and wave set-up in waves breaking in a converging shoaling channel drives a current (more than 1 m/s in large laboratory tests with 1.6m waves) into an open discharge channel ahead of the waves. In a tidal inlet these effects could be important, particularly for waves refracted to travel directly along the marginal flood channel.

As a preliminary test of some of these ideas, fast response flowmeters have been used in a marginal flood channel to measure accurately the wave and tidal currents during both ebb and flood flows.

THE FIELD MEASUREMENTS

The site chosen for this study was Price Inlet, South Carolina, about 15 km north of Charleston Harbour on the Georgian Bight coast of the Southeastern United States (figure 1). An aerial photograph of the inlet a few months before our study shows the general complexity of the region (figure 2). The southern flood channel region is particularly complex. An older flood channel has just been closed to form an isolated pond, and a new flood channel is forming offshore. The

Figure 1: Map showing location of Price Inlet

Figure 2: Price Inlet at Low Tide, March 1977

photograph in figure 2 was taken in March 1977, and by the time of our study in November 1977 the new flood channel had become considerably better defined by continued growth of the offshore bar. The measurements described in this paper were taken in this southern flood channel on November 20th and 21st, 1977.

The flowmeters used in this field study were two-component electromagnetic sensors with a nominal time constant (low pass) of 0.2 seconds (Marsh-McBirney Model 511 OEM). Three of these instruments were mounted on arms attached to an aluminum tripod 0.3m high. Two were mounted so as to measure simultaneously vertical (w) and along-channel (u) flow at 0.75m and 0.35m respectively above the channel floor. The third flowmeter was aligned to measure along-channel (u) and cross-channel (v) flow 0.52m above the channel floor. Figure 3 shows in plan view the location of the instruments and a cross-section showing the postion of the flowmeters in relation to the offshore bar and marginal channel. The sensors appear to be well to one side of the channel, though this may be somewhat deceptive since at the tidal height necessary to cover the sensors this displacement would not be so apparent. In any case there was no evidence of spatial asymmetry in the flow at this point, so that flow past the sensors should be representative of the cross-sectional average. (This was not true for the northern marginal channel at this inlet where the strongest ebb current was displaced well towards the seaward side of the channel while the flood current dominated the landward side of the channel.)

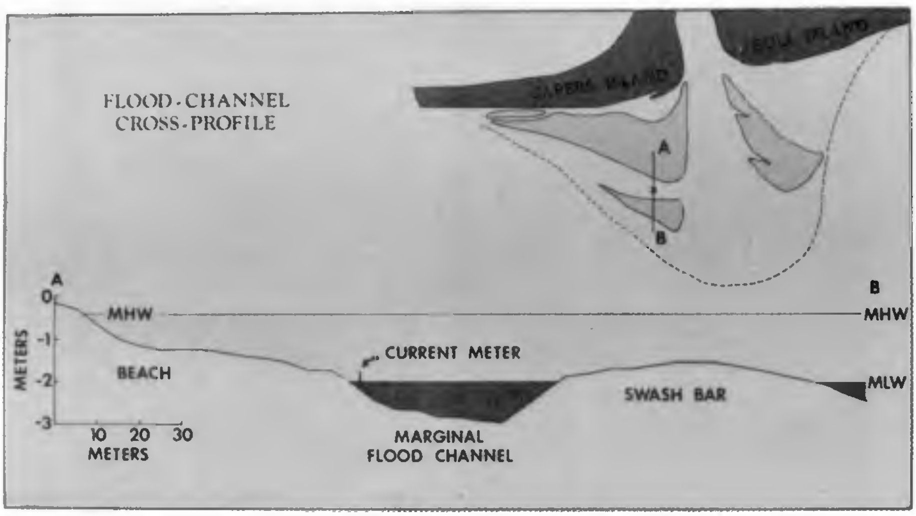

Figure 3: Plan and cross-section of marginal channel

The tripod mount holding the sensors was placed in this location near the time of low water and held onto the channel floor by lead weights placed in a cradle at the base of the tripod. Alignment of the sensor directions was achieved by sighting by eye along a range on the shore defined, from a theodolite survey, to be the across-channel direction; alignment accuracy was estimated to be approximately $\pm 5^{o}$.

Cables ran up the beach from the sensors to a telemetry system at the crest of the beach. This system consisted of a sealed aluminum canister about 2m high and 25cm diameter (designed also to be used as a surface buoy) containing batteries, an analogue multiplexing system for the six data channels and a low power transmitter. The buoy transmitted the data along line-of-sight to a receiving station and analogue data logger at some more convenient location. The receiving stations used in this experiment were either a hut with mains electricity about one km into the inlet or, more commonly for clarity of reception, a boat anchored in the channel throat on which car batteries were used as a power source. The analogue data were subsequently digitized at a sampling interval of 0.3 seconds for computer analysis.

An example of the velocity time series obtained with this system is shown in Figure 4. This record was taken during a flood tide, and a mean current of 62 cm/s in the flood direction has been removed from the along-channel velocity record. Positive velocities represent flood-directed, shoreward, and upward velocities respectively. The great irregularity in the flow is obvious from these records. The incoming waves broke at about 1m height on the margin of the swash platform but were reduced by multiple breaking over the platform to about 0.3m in height as they broke over the bar flanking the seaward side of the marginal channel. The larger of these waves, overtopping the bar, travelled obliquely shorewards in the channel with a large flood-directed component. These can be seen in the velocity records, for example between 38 and 50 seconds in Figure 4, as oscillations of both along-channel and cross-channel flow with a period of about 7 seconds. The time series of the product uv shows that these waves contribute large positive values to the flood-directed stress, for example at 38, 46, and 90 seconds. Superimposed on these waves are smaller higher frequency oscillations of velocity, probably caused by multiple wave crests refracted round the ends of the offshore bar and travelling in both ebb and flood directions along the channel. As is commonly observed in velocities from shoaling waves, the vertical velocity record appears much more spikey than the horizontal velocities, with a proportionally larger high frequency content (c.f. Huntley (in press)). This may in part be simply due to the smaller scale of the trace (peak of 0.25 m/s compared to 1.0 m/s and 0.75 m/s) but is also due to the sharp upward velocity peaks as the steep front of a shoaling wave passes. Notice also the presence of slow variations in the horizontal velocity records at periods much longer than observed wave periods.

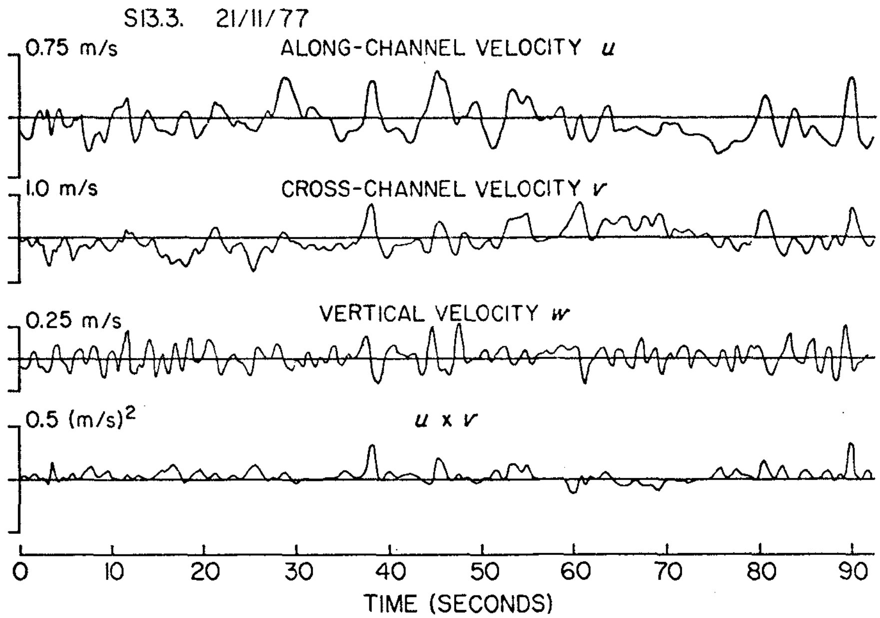

Figure 4: An example of the velocity records

Table 1 summarizes the flow parameters measured in the southern marginal flood channel. The four runs numbered 12. were made between 17:40 hrs and 20:40 hrs local time on November 20th, 1977 during an ebb flow; the three runs numbered 13. were made between 12:50 hrs and 14:45 hrs on November 21st, 1977 during the flood flow. The elevation is relative to chart datum and was measured about 1 km inshore along the ebb channel by a U.S. Department of Commerce NOAA tide gauge. This gauge also was used to give the times of runs relative to high water shown in the second column of Table 1. A second tide gauge was also running on the seaward side of Bull's Island about 1km north of the sensor location. This gave a similar tidal record, with a time lead of only five minutes, so the horizontal distance between tide gauge and sensors was considered unimportant. For reference, the top of the flood channel bar was at about 0.95m above chart datum, so that overtopping was strong only for the records closest to high water. This is reflected in the values of standard deviation of the along channel flow shown in Table 1. The values are large only for runs 12.1 and 13.3. At lower mean water levels the standard deviation has become much smaller and suprisingly constant; these values are probably due predominantly to waves propagating along the channel.

Table of Flow Parameters, Southern Flood Channel, Price Inlet, S. C.
November 20/21, 1977

Run I.D.	Time from H.W. (Hrs Mins)	Elevation (m)	Mean Ebb Flow cm/s	Standard Dev. cm/s	Shoreward Horizontal Stress $(cm.s)^2$
12.1	+1h 30m	1.56	+ 60.5	72.4	------
12.2	+2h 49m	1.07	+ 24.1	17.9	72.1
12.3	+3h 32m	0.84	+ 40.3	14.4	18.0
12.4	+4h 13m	0.60	+ 32.6	15.1	- 12.3
13.1	-4h 01m	0.69	-105.0	17.5	36.3
13.2	-3h 09m	0.98	- 70.5	18.8	109.4
13.3	-2h 25m	1.22	- 61.7	38.3	214.8

The mean flows shown in Table 1 are means over 15 minutes of record. Two things can be concluded from these means.

First, it is clear that they are all of the same order of magnitude as the standard deviations. Thus any current meter used to measure tidal flows at this point in the inlet, and presumably at other positions, must be capable of responding correctly to wave currents so that they can be averaged out of the velocity record properly. It is known that most slow response flowmeters cannot respond quickly enough to fluctuations, particularly of direction, under waves and will tend to rectify wave velocities, thus recording higher than true mean currents. This observation may therefore call into question previous measurements of flow in tidal inlets at locations where wave velocities are significant. In particular the large increase in wave velocities near the time of high water would cause slow-response flowmeters to overemphasise the skewing of maximum flood and ebb currents towards the time of high water (Fitzgerald et al 1977).

The second conclusion from these observed means is that, as expected from previous investigations, flood currents are very much larger than ebb currents at the same water level and time from high water. The tidal range for the ebb was 1.47m while that on the flood was 1.31m, suggesting that the difference in currents would be even greater for the same tidal ranges.

The last column of Table 1 shows the flood directed horizontal stresses uv due to the fluctuations, averaged over 15 minutes. Figure 5 shows these values plotted against tide height and it is clear that they are positive on both flood and ebb for most tide levels, which for these data ranged from about 0.3m to about 1.7m above datum. The radiation stress theory of longshore currents (Bowen 1969, Longuet-Higgins 1970) shows that these positive (flood directed) stresses, if interpreted as radiation stresses, would drive longshore currents in the flood direction in the narrow surf zone on the shoreward side of the flood channel. Estimates of the magnitude of these currents suggest that they reached about 1 m/s near high tide (c.f. Huntley 1977). We will see in the next section how we might estimate the importance of this predominantly surf-zone current to the mean flow in the main channel, seaward of the break point. The observation of larger values of stress on the flood than on the ebb is perhaps to be expected since refraction of incoming flood-propagating waves by the flood and ebb currents will cause this effect. It will not necessarily be reflected in larger longshore currents in the narrow shoreline surf zone where tidal currents are much smaller.

The observation of a negative value on the ebb tide is of some interest. Towards low tide the predominant wave activity in the channel was due to waves which were refracted around the ebb-channel end of the bar and which propagated up the channel in the ebb direction; flood-progagating waves were reduced by the longer shallow path around the opposite end of the bar. The presence of these ebb-propagating waves at this stage of the tide is of particular interest, as we shall see later.

WAVE EFFECTS ON THE MEAN FLOW

Clearly, with current data from a single point we are unable to study directly the importance of longshore variability of wave height in driving flood currents, although such variability clearly existed. Neither are we able directly to measure local mass transport effects since surface elevation measurements were not made along with the flow measurements.

In fact, separation of mean wave and tidal effects is in general going to be extremely difficult without extensive measurements covering a wide range of incident wave climates.

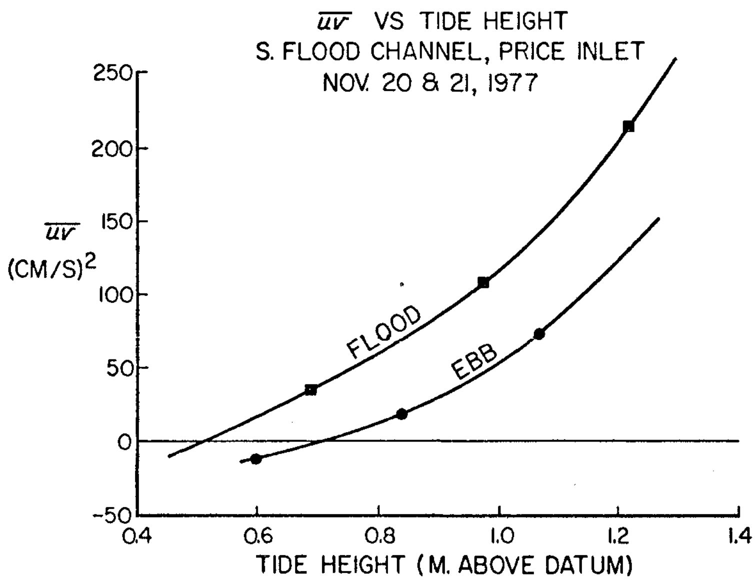

Figure 5:

Nevertheless, we might expect that any wave-driven component of the flow will show variations related to the "groupiness" of the wave record, i.e. to the envelope of wave velocities. This should be true in some sense for currents driven by a set-up gradient over the bar, for longshore current effects and for currents driven by non-local mass transport and set-up in waves propagating along the channel. We have therefore looked at the relationship between the low-passed portion of the along-channel flow and the time series of the envelope of the velocity fluctuations.

In spectral terms this involves dividing an initial spectrum of the alongshore flow (the upper trace of Figure 6) into two portions, using a Cartwright filter of 342 weights, with a half power point at a period of 15 seconds (Cartwright, personal communication). The lower trace in Figure 6 shows the same spectrum as the upper trace, but displaced downwards by an order of magnitude and divided into a low-passed and a high-passed portion. The high-passed portion contains, at each frequency, more than 99% of the spectral energy for periods shorter than 12 seconds, and therefore includes the incident wave energy as well as the energy of higher frequency turbulent fluctuations. The low-passed portion, with the 99% level at 17.5 seconds, contains the longer period variability which may include wave-induced fluctuations as well as longer period turbulence. To obtain the wave envelope the high-passed time series was then squared and low-passed again with the same Cartwright filter.

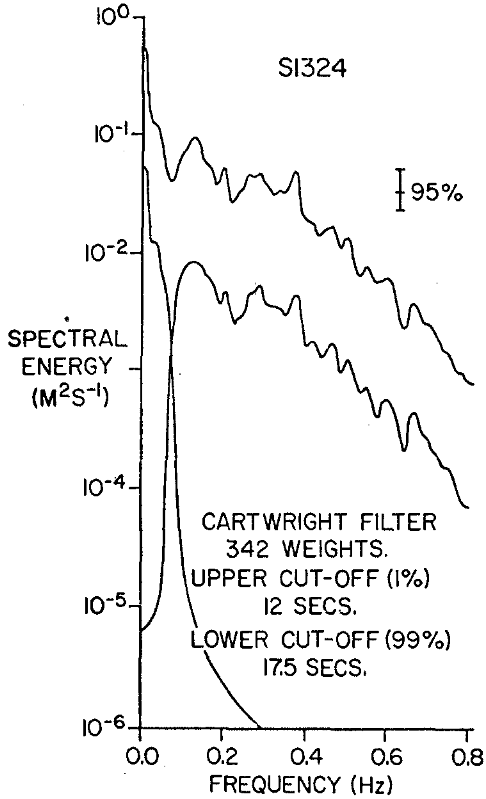

Figure 6: Dividing a spectrum into low and high frequency parts.

Cross-correlation functions, the means of the product of two time series nomalized by their standard deviations, were then calculated between the low frequency part of the original current record and the low frequency part of the wave envelope. These functions were calculated for different time lags between the two records to allow, in some average sense, for non-local forcing of the mean flow by the waves.

The result of these computations is, surprizingly, that all but one of the calculated cross-correlation functions have no significance at the 95% level for any time lag. Figure 7 shows an example of the cross-correlation function for run 13.1 and is typical of all runs except run 12.4. This result appears to suggest that wave forcing in the neighborhood of the sensors is of no importance in driving the mean flow under the wave conditions prevailing at the time of measurement. This does not, of course, preclude the possibility of purely local mass transport effects, but in view of the changing wave amplitudes along the channel this seems unlikely. Neither does it preclude the possibility that driving of the currents occurs at a location well removed from the sensor position and that wave breaking, dispersion and interaction destroys the relevant wave groups by the time they reach the sensors, but this too seems unlikely, particularly near high tide when the marginal channel is deep and relatively unobstructed.

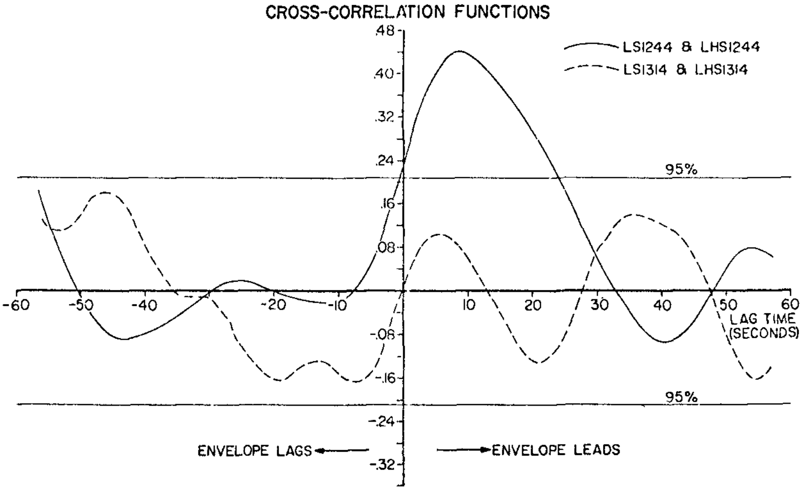

Figure 7: --- Run 13.1
___ Run 12.4.

The one exception, showing significant correlation, is run 12.4. Figure 7 shows that the cross-correlation function has a correlation which rises to about 0.44 when the envelope of the waves leads the current by about 9 seconds. Pre-whitening of the time series before forming this function, in the manner prescribed by Jenkins and Watts (1968), reduces the correlation somewhat (to about 0.26), but does not effect the conclusion of significance at this time lag. Cross-spectra between the original time series and the envelope of the high frequency fluctuations were also calculated to see whether significant correlation existed over a broad low frequency band or was confined to a narrow band. Again significant correlation was only found for run 12.4 and at periods longer than about 40 seconds. Figure 8 shows a section of the time series for 12.4; although the calculated correlation coefficient is small, it is nevertheless possible to see correlation between the two lower records, as indicated by the fine diagonal lines.

Run 12.4 is the run at the low-tide end of the ebb current sequence which gave the ebb directed radiation stress shown in Figure 5. In fact, the positive sign of the correlation between wave envelope and current suggests that a large wave group, propagating in this case in the ebb direction, drives an enhanced current in the ebb direction, though the significance of the time lag is not known.

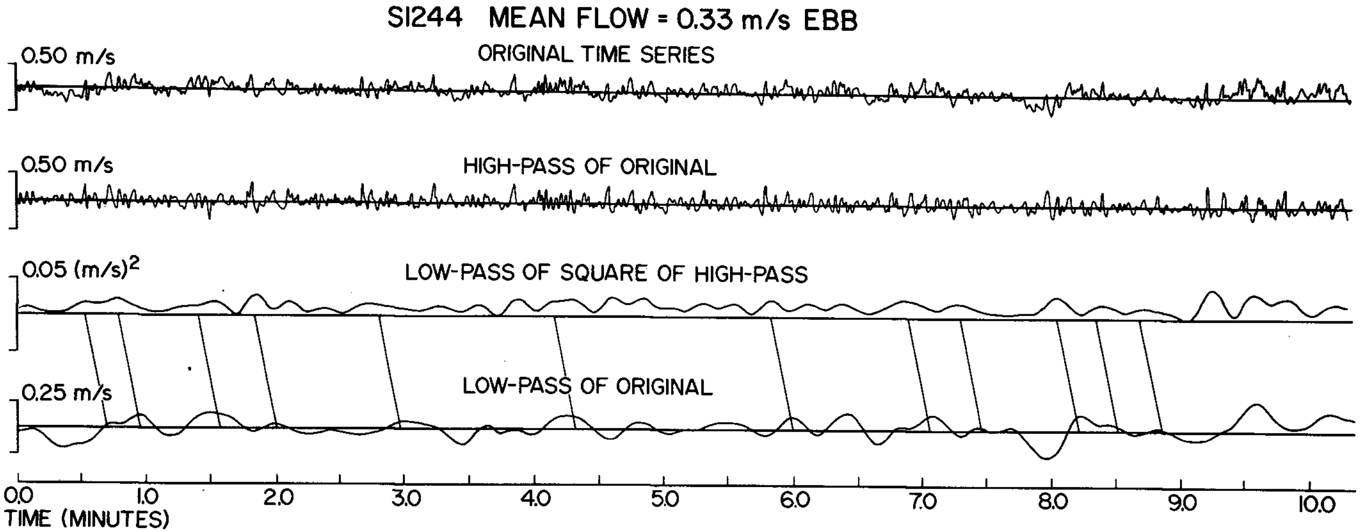

Figure 8: Time series showing correlation between low frequency velocities and the high frequency envelope.

DISCUSSION

It is interesting that wave effects seem to be generally of negligible importance to the mean flow at the measuring point. The significant longshore currents suggested by the calculated stress values must presumably be confined to a narrow region in the vicinity of the surf-zone at the shoreline, and be of no importance at the sensors, except perhaps close to low tide. Surprisingly, the effect of a longshore gradient of wave set up along the outer bar is also probably small; no wave effect in the low-passed flow is observed even when the water level is sufficiently high for significant breaker energy to propagate over the bar into the marginal channel.

Laboratory tests of the "wave pump" effects of set-up and mass transport (Bruun and Viggisson 1973, Bruun and Kjelstrup 1978) show that they are critically dependent on the geometry of the channel along which the waves propagate and on the breaking or non-breaking of the waves. Largest currents are generated when waves propagate directly along a rapidly converging shoaling channel into a basin or channel of constant or increasing depth ahead, and when waves are near to breaking or are spilling. For most of our runs in the southern flood channel none of these conditions seem to have applied. For waves from the flood direction the marginal channel converges very slowly and, except at the entrance, has a relatively flat bed. In addition, since dominant waves approach from the north-east, waves entering the southern flood channel have been refracted a great deal and are therefore relatively small.

However, for the one run that does show some significant correlation, waves from the ebb-channel propagated into the rapidly converging and shoaling mouth of the marginal channel before passing over the sensors a short distance into the channel, and these conditions seem to fit those for wave pump effects quite well. Thus, despite the predominantly null results from these data, it does seem that waves might be important in the marginal flood channels of an inlet if the topographic and wave conditions were right. In fact, the northern marginal channel of Price Inlet has a rapidly converging and shoaling topography at its seaward end (Figure 2) and wave refraction diagrams (e.g. Fitzgerald et al 1977) suggest that waves would propagate much more readily into this channel. Wave effects on the flood dominance of this channel may therefore be much more significant than in the southern marginal channel. Further work is underway to test this idea.

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