Wave Setup and Other Tidal Anomalies in Coastal Rivers

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Abstract

The tailwater level is together with rainfall the most important input to flood modeling in coastal rivers. Thus, the need for an ocean-river interface which can provide tailwater levels for numerical models is obvious. The state of the art is however not very advanced. Detailed waterlevel profiles through the Brunswick River entrance from 500m inside the breakwaters to 150m outside during a wide range of weather conditions revealed that the wave setup through the zone of wave breaking is much smaller than what is being used by practicing modelers in Australia. Barometric effects of the order 1cm per hPa is only a minor part of the tidal anomalies, which range up to 0.8m 500m inside the breakwaters, and wind effects, although not modeled in detail, are estimated to be small on the fairly narrow continental shelf of South East Australia. Tidal anomalies of the order 0.5 to 0.7 metres have been observed in the absence of rainfall and strong local winds during Cyclone Roger in 1993. An offshore record indicated that a substantial fraction of this tidal anomaly (of the order 0.25m) also occurred in 25m of water offshore from the Tweed River on the border between New South Wales and Queensland. This indicates the presence of weather related oceanic forcing of a nature which is not understood in detail.

1. Introduction

The state of the art of flood modeling in coastal rivers at present is not very advanced in general. In particular, the tailwater level, which is an important input to the flood model, is not accurately predicted.

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Precise prediction of tailwater the level is important during both normal and emergency situations. People may benefit from the coastal environment and should be protected from natural disasters. Several past records show that extreme water levels cost millions of dollars to the people and the government. The February 1993 low water level event cost the New South Wales Oyster Industry millions of dollars when the oyster cages became exposed to the air. At the same time, flooding along the coastal rivers costs the NSW Government tens of millions of dollars per annum (Hanslow and Nielsen, 1992). The storm surge event on 17 February 1996 caused heavy inundation in Gold Coast canal jetties and roads (Nielsen, Voisey and Santoso, 1997). Hence, Australia needs better flood models in general and better models of river entrance water levels in particular.

Several weather-related forcing mechanisms have been identified, however, there is still lack of precise quantification for better prediction. A quantitative model of Coriolis effects on longshore currents, as one of the most probable driving forces during cyclone events, is developed.

2. Historical Data

The difference between the measured water levels and the astronomically predicted levels are called tidal anomalies. Extreme water levels, which include large anomalies, have been studied for decades, but still the forcing mechanisms are not quite clear.

2.1. The inverse barometer effect

Extreme water levels usually show significant, negative correlation with the local barometric pressure. Investigations at several tidal stations on the East Coast of Australia found the sea level depressed about half the theoretical amount of 1 cm per hectopascal. Conversely, greater than theoretical values were typical for some locations on the West Coast. On Lord Howe Island the inverse barometer law gives accurate predictions. This is an indication that the continental shelf is influential (Hamon, 1962, 1963, 1966, Robinson 1964). In the Bay of plenty, New Zealand, the inverse barometer law applies accurately over a limited range of periods (Goring and Bell, 1993). Investigation of the Manly Hydraulics Laboratory database shows that the low barometric pressures alone is not appropriate to predict the tidal anomalies. For instance, theoretical barometric set-up during Cyclone Justin (March 1997) accounts for only 25% of the observed tidal anomaly (see Figure 1).

2.2. Wave set-up

Wave set-up, which has been long believed to be an important contributor to extreme water levels, has negligible influence to the overheight water level in most river entrances. Thus, historical data from the Brunswick River (1987 to 1996) show that offshore wave heights are not correlated with the tidal anomalies. In fact, some very high waves coincided with negative tidal anomalies (see Figure 2).

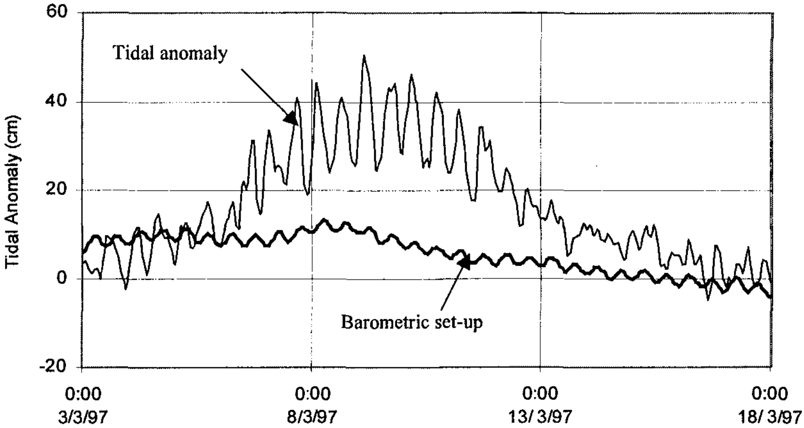

Figure 1. Tidal anomaly and barometric set-up at Rosslyn Bay during Cyclone Justin, March 1997. The theoretical barometric set-up (1 cm/hPa) contributes a minor fraction to the observed tidal anomaly. Data courtesy of National Tidal Facility, Adelaide.

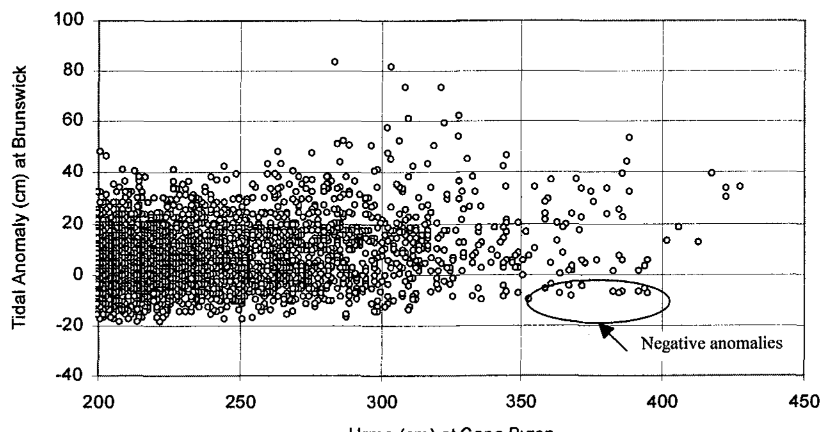

Figure 2. Tidal anomaly versus offshore root mean square wave heights at Brunswick Heads. Even for the very shallow (just navigable by fishing vessels) Brunswick River there is very little correlation between offshore wave height and tidal anomaly just inside the wave breaking in the river. Data courtesy of the MHL, Sydney.

The New South Wales Government has sponsored field investigations at the Brunswick River entrance (Brunswick Heads) over the last decade, headed by Dr. Peter Nielsen. The primary achievement of this work has been detailed water level profiles through the river entrance from 300m inside the breakwaters to 150m outside during a wide range of weather conditions. It was found that different water levels between inner and outer river entrance were caused by hydraulic gradient in the entrance during flood and ebb tides (see page 250, Hanslow and Nielsen, 1992).

2.3. Rainfall

Previous investigations found that rainfall contributes significantly to the tidal anomaly for gauges in rivers with small cross section of river entrance compared with the large river catchment area.

Table 1. The ratio between cross section of river entrance and catchment area. (Data from The Department of Land and Water Conservation NSW, 1997).

Name	Catchment area (km^2)	River entrance cross section (m^2)	Ratio
Gold Coast Seaway	150	3300	2.2×10^{-5}
Tweed River	1100	400	3.6×10^{-7}
Brunswick River	160	160	10.0×10^{-7}
Richmond River	6850	1340	2.0×10^{-7}

Data from the Brunswick River show the correlation between rainfall intensity in the river catchment and tidal anomalies in the river entrance (Figure 3). The plots show vertical clusters, which consist of 6 one-hourly tidal anomalies versus cumulative rainfall for the six hours period. The lower part of each cluster indicates the fresh water flow has not reached the tide gauge yet. The appropriate cumulative time applied in the plot is site specific, dependent on the characteristics of river catchment.

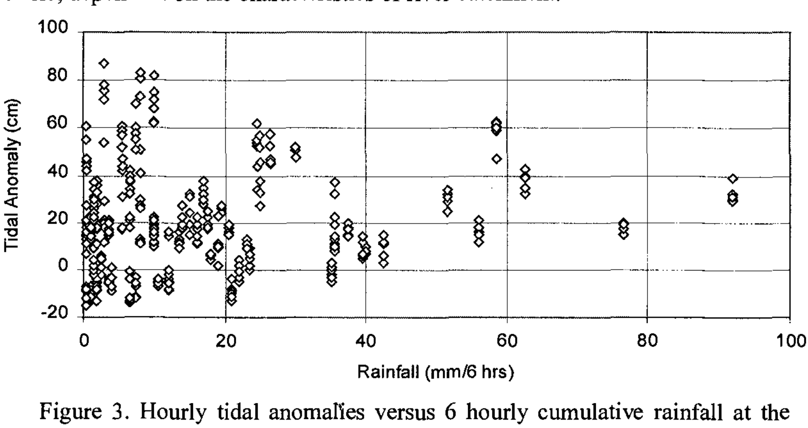

Figure 3. Hourly tidal anomalies versus 6 hourly cumulative rainfall at the Brunswick River. Data courtesy of the MHL, Sydney.

Tide gauges installed in rivers with small entrance to the large catchment ratios such as the Brunswick and the Tweed Rivers are quite sensitive to rainfall. Hence, rainfall over these two catchment areas in the period of 15 to 17 February 1995 contributes significantly to the high tidal anomalies (see Figure 4).

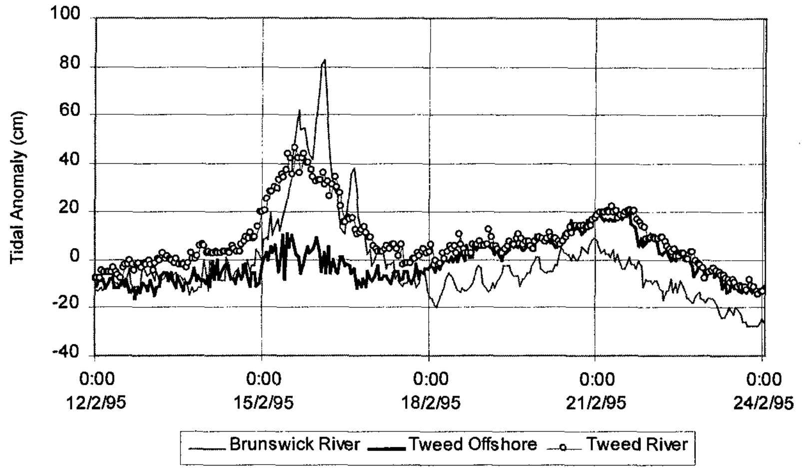

Figure 4. Tidal anomalies generated by heavy rainfall on 16 February 1995 event. Tidal anomalies at the Brunswick and Tweed Rivers are high compared with that of Tweed Offshore, which was not influenced by fresh water flow. Data courtesy of the MHL, Sydney.

2.4. Negative anomalies

Negative anomalies, which cannot be generated by rainfall or wave setup are of interest for evaluating the variation of other driving mechanisms along the coast. Thus, the negative tidal anomalies at the Gold Coast Seaway and at Ballina (at the Richmond River entrance), which are only 80 km apart show quite different trends for the more significant events (see Figure 5). These data imply that along the coast of NSW and Queensland the strength of the oceanic driving mechanisms vary significantly.

3. Long Periodic Waves

Travelling cyclones are some times able to generate long periodic waves. Low barometric pressure at the center of cyclone causes the sea water level to rise in a mound shape. As the cyclone moves into the shallow water, the combination of high wind stresses on the surface and friction on the ocean bed generate long wave (Stark, 1977; Lighthill, 1998).

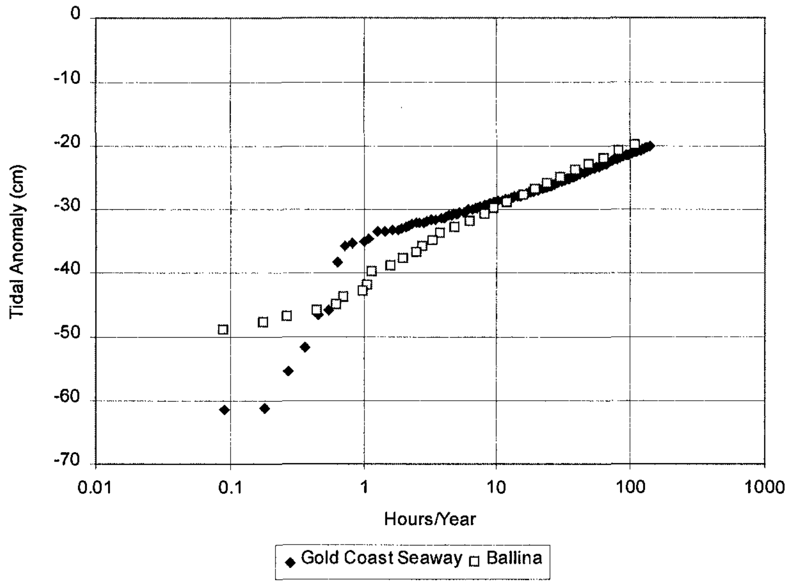

Figure 5. Exceedance plot of negative tidal anomalies at the Gold Coast Seaway and Ballina (at the Richmond River entrance). Data courtesy of MHL, Sydney.

The motion of long waves parallel to a coastline can generate a number of edge wave modes, and only the fundamental mode is stimulated by the large-scale pressure disturbances (Greenspan, 1956). However, Reid (1958) stated that if wind stress is considered, cyclones could generate higher order of edge waves.

The amplitude of the long waves is dependent on the local topography. Shoaling, diffraction and reflection are of primary importance for the extreme water levels along the coast.

The presence of long periodic waves was observed at tidal stations along the East Coast of Australia (Figure 6). The event ten days before Cyclone Violet showed the movement of a long wave. The phase shift of the tidal anomaly peaks of Ballina, Brunswick River and Tweed Offshore around 21 February 1995 were less than a day. This is because the distance between Ballina to Brunswick and Brunswick to Tweed Head are about 30 km and 65 km respectively. The tidal anomaly peaks at Rosslyn Bay and Cape Fergusson, where separated about 700km and 1250km from Brunswick, occurred 3 and 4 days later. Another travelling long wave can be seen in Figure 7, during Cyclone Justin.

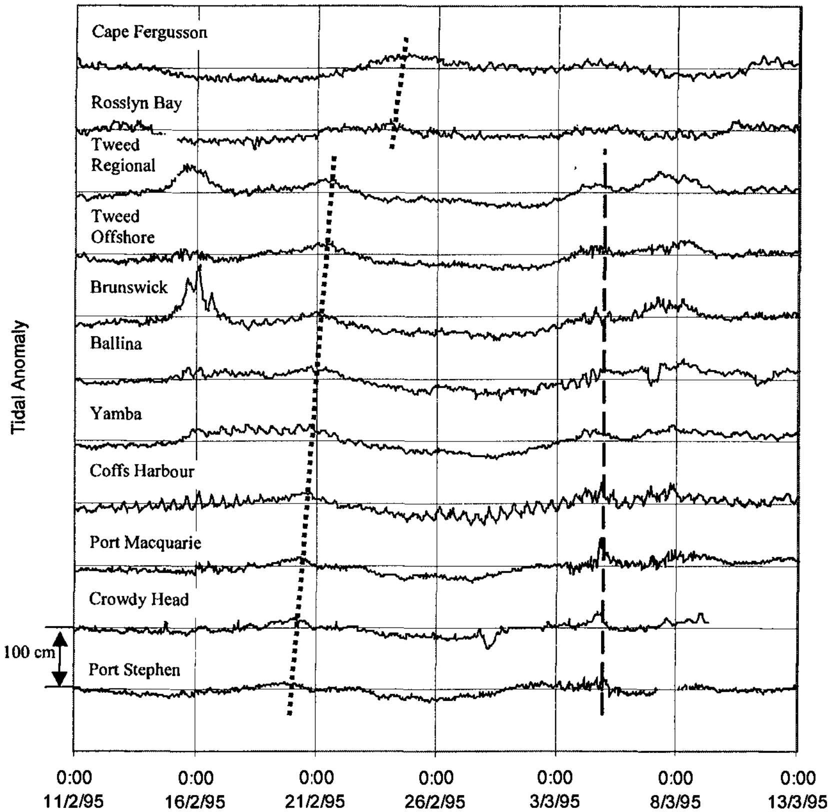

Figure 6. The travelling long wave was marked by north going tidal anomaly peaks during 18-26 February event (dotted line). Cyclone Violet (3-8 March), which came very close to Brunswick generated tiny tidal anomalies along the NSW coast without long wave character (dashed line). Data courtesy of MHL and NTF.

4. Cyclone Justin

As discussed above, travelling cyclones can generate continental shelf waves. Stationary cyclones however, do not have this ability. They generate different types of tidal anomalies. Our best example is Cyclone Justin (March 1997), which was stationary in the Coral Sea, in the North East of Townsville, for about two weeks. Tidal anomalies in the order of 0.5 to 0.8 m were generated along the North Coast of Queensland, but no significant were found south of Mooloolaba (see Figure 7).

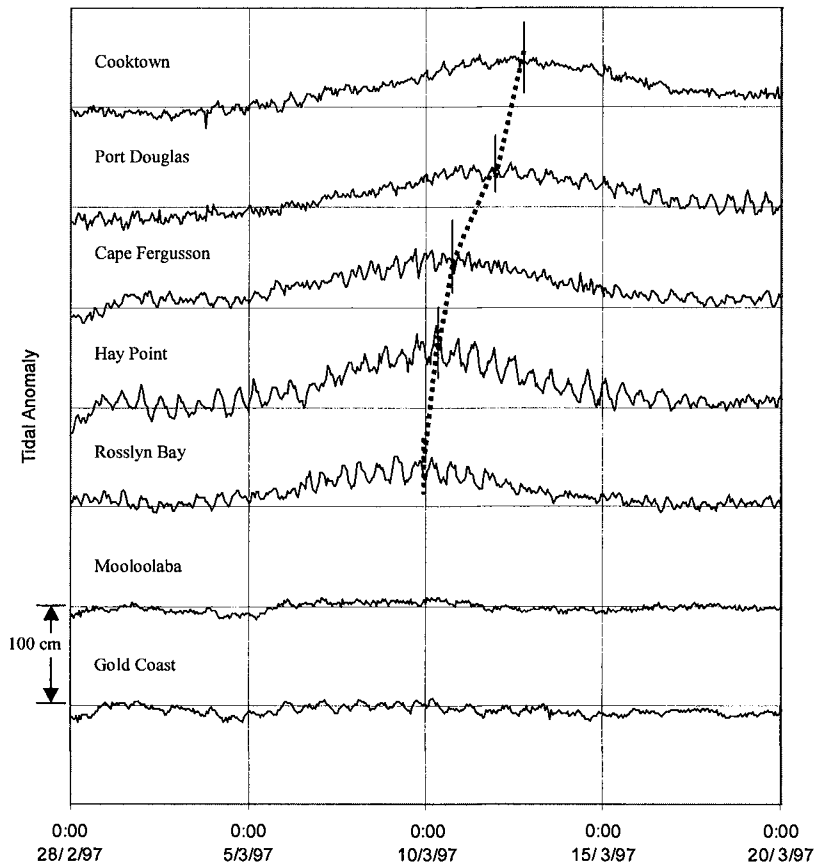

Figure 7: Tidal anomalies generated by Cyclone Justin. The peaks of tidal anomaly move northward from Rosslyn Bay to Cooktown as shown by the dotted line. Data courtesy of MHL, NTF and Queensland Transport.

4.1. Wind set-up

The cyclonic wind component perpendicular to the shoreline may generate set-up in the shallow waters, particularly where the shelf is wide and shallow. The strength and duration of the winds, and the width of continental shelf are important components generating the wind set-up. However, the estimated wind set-up at Rosslyn Bay, about *700 km* southward the center of cyclone, was very small even though it is located on the widest continental shelf in East Australia.

Onshore wind speeds at Rosslyn Bay during the cyclone were quite weak. Taking into account the depth of shelf edge h_o=*200 m*, the width of the continental shelf is W_{shelf}, with the constant shelf gradient $dh/dx=200/W_{shelf}$, wind set-up generated by wind blowing perpendicular to the coast can be estimated as follows (see Nielsen and Hanslow, 1995).

$$\bar{\eta}(h) = \frac{\rho_{air}}{\rho_{sw} g h_o} C_f U_{10}^2 W_{shelf} \ln\left(\frac{h_o}{h}\right) \quad (1)$$

where ρ_{air} and ρ_{sw} are the density of air and sea water respectively, U_{10} is wind speed at *10 m* above sea level, C_f is the sea-air friction coefficient, h is the water depth. By taking ρ_{air} = *1.3 kg/m³*, ρ_{sw} = *1025 kg/m³*, W_{shelf} = *260 km*, U_{10} =*2.5 m/s* (see Figure 8), C_f =*0.002* (Toba et al, 1990), wind set-up at Rosslyn Bay; where the tide gauge is located at *1.8 m* water depth, is estimated to be at most *0.01 m*.

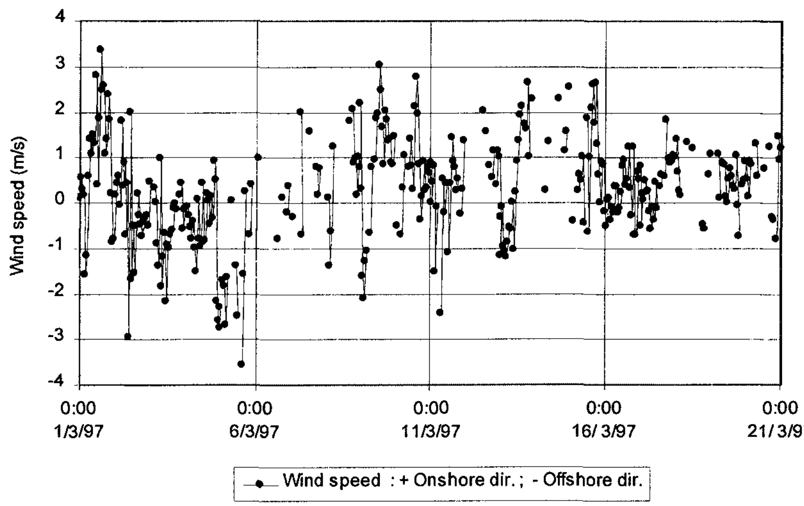

Figure 8. Onshore/Offshore winds at Rosslyn Bay during Cyclone Justin. Taking into account onshore wind of 2.5 *m/s* estimates *0.01 m* wind set-up on the coast.

4.2. Coriolis Effects on Longshore Currents

Cyclone Justin was stationary in the Coral Sea for more than 2 weeks (see Figure 9). Therefore, it is reasonable that clockwise cyclical currents may be generated during the event. Due to the Earth's rotation, north going longshore current will be pushed against the land and that causes a coastal sea level to rise.

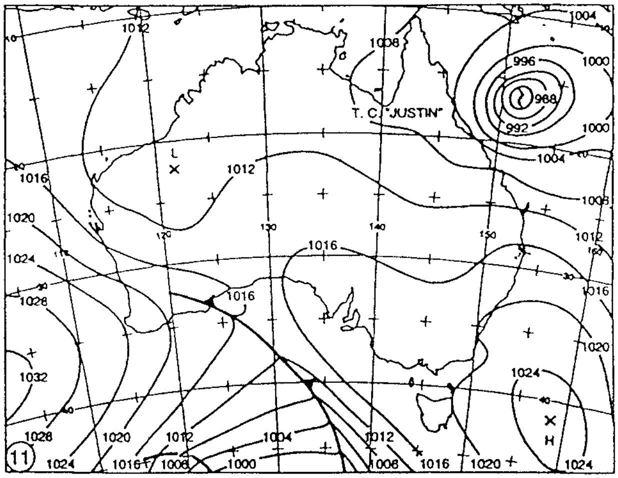

Figure 9. Weather map during Cyclone Justin, March 1997 (Bureau of Meteorology Annual Reports 1997).

The Coriolis effect on longshore current component can quantitatively be modeled as follows (see Figure 10). The Coriolis acceleration is:

$$f = 2\Omega \sin\phi \tag{2}$$

where, Ω is the angular speed of earth's rotation on its axis, ϕ is the latitude of point on earth. The Coriolis acceleration on longsore current U is then Uf. Combine acceleration of gravity and Coriolis forms tilting water level with gradient of:

$$i = \frac{Uf}{g} \tag{3}$$

Taking Cape Fergusson as an example, which is situated at latitude $19^o S$ and average longshore current at Myrmidon Reef (18^o $16'$S, $147^o 22'$E) of 0.6 m/s. The Coriolis acceleration is $f = 2 \times 7.2{\times}10^{-5} \times \sin 19^o = 4.7{\times}10^{-5}\ s^{-1}$. The gradient of tilting water level will be $i = Uf/g = 0.6 \times 4.7{\times}10^{-5}/9.8 = 2.9{\times}10^{-6}$.

This magnitude indicates that water level to rise $2.9{\times}10^{-3}$ m per kilometer. Assuming uniform flow across the continental shelf near Cape Fergusson, which is approximately $100km$ wide, the extra water level height near the shoreline would be $100 \times 2.9{\times}10^{-3} = 0.29\ m$.

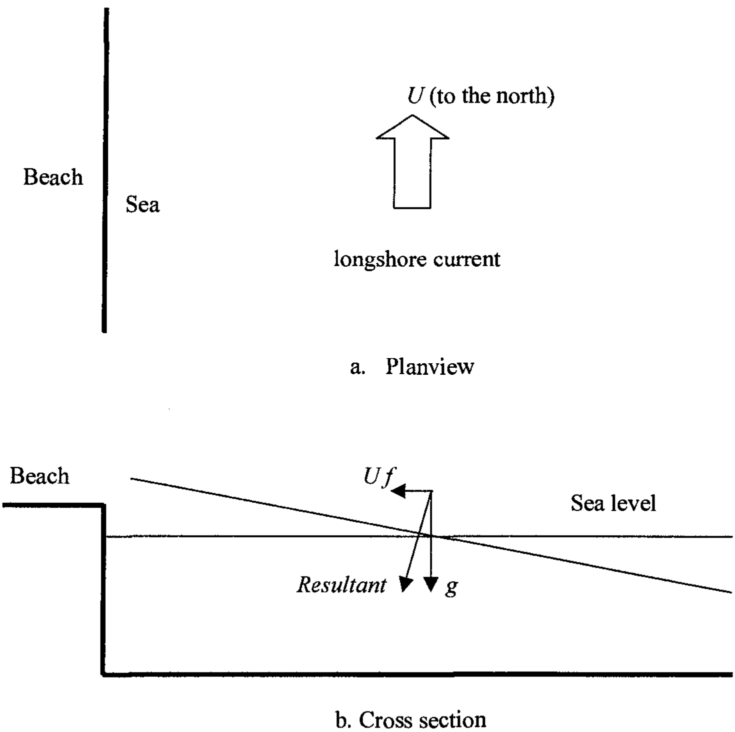

Figure 10. Hypothetical model of Coriolis effect on longshore current at continental shelf. Northwards longshore current is pushed to the left against the land to cause water level rising along shoreline.

5. Conclusion

Detailed water level profiles through the Brunswick River entrance show that offshore wave height has no correlation to the tidal anomaly. Barometric effects of the order 1cm per hPa and wind set-up are minor parts of the tidal anomalies.

The exceedance plot of negative tidal anomalies is of interest for evaluating the variation of other forcing mechanisms than wind waves and rainfall.

Effects of the Coriolis force on longshore currents are another driving mechanism of tidal anomalies along the East Coast of Australia. During Cyclone Justin, tidal anomalies of the order *0.4* to *0.8* meters were generated along the northern Queensland coast. Up to *50%* of these can be accounted for by the Coriolis effect on wind driven longshore currents.

6. References

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