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THE RELATIONSHIP BETWEEN MEAN SEA LEVEL AND STERIC HEIGHT AT SYDNEY

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Abstract

Mean sea level data from Sydney were corrected for atmospheric pressure effects and then corrected for shelf wave activity using the model of Gill and Schumann (1974). Steric height from an XBT section perpendicular to the coast was extrapolated inshore. Linear regression analysis gives a 0.008 m rise in adjusted mean sea level for every 0.01 m rise in steric height. The regression accounts for 44% of the total variance and the root mean square departure from this line is 0.063 m over a range in steric height of 0.3 m.

INTRODUCTION

There have been several investigations of the relationship between mean sea level, as determined from tide gauge records, and steric height in deep water adjacent to the tide gauge. Early investigations indicated that mean sea level rises when atmospheric pressure falls such that the pressure on the ocean floor remains constant (the isostatic hypothesis). Additional variations in mean sea level were thought to be due to the heating/cooling and subsequent expansion/contraction of the water column in the deep water offshore from the tide gauge. If these factors accounted for all the observed variations in mean sea level, information on the density of the upper layers of the ocean could be obtained from tide gauges at far less cost and with greater reliability than traditional oceanographic methods. Conversely, oceanographic data could be used as an aid in geodetic land levelling allowing datums to be transferred over large distances at minimal cost.

Using data from many areas of the world, Patullo *et al.* (1955) found that on a seasonal time scale the isostatic hypothesis was generally correct. For Bermuda, Wunsch (1972) found that 70% of the sea level variance was accounted for by the tides and 14% by the combined effect of local atmospheric pressure and local winds. Of the remaining 16%, only 3% was accounted for by the steric height relative to 1500 dB and the remaining 13% was unaccounted for but thought to lie in the lowest frequency barotropic motions. In the Mid Ocean Dynamics Experiment bottom experiment, Brown *et al.* (1975) found that the isostatic model for the response of the sea surface height to changes in atmospheric pressure was good at 0.1 cycles per day but that below this frequency the response was less than expected and above this frequency the response was greater than expected. Brink (1978) in a theoretical and experimental study explained this in terms of the dynamic response of the ocean to a moving pressure disturbance.

Evidence for the dynamic response of shelf waters to weather disturbances came with the work of Hamon (1962) and Hamon and Stacey (1960). Robinson (1964) explained this dynamic response by the phenomenon of shelf waves.

Brunson and Elliot (1974) reported discrepancies between mean sea level corrected for the effects of atmospheric pressure, and steric heights computed with data from the Newport hydrographic line. These discrepancies highlight the difficulties involved in comparing steric height observed in deep water to mean sea level in the shallow water adjacent to the tide gauge. Reid and Mantyla (1976) overcame this problem by using a method suggested by Groen (1948) (described later) for extrapolating steric heights inshore. They then found good agreement between seasonal variations in corrected mean sea level and steric height for data from the Newport hydrographic line.

Comparison of steric heights and mean sea level at Eden (near Gabo Island, Fig. 1) indicated an unusually large scatter (Hamon 1969). However, in that work, no attempt was made to extrapolate steric height in to the shore. The aim of the present work was to see if the large scatter found at Eden could reasonably be explained by the changes in sea level between the coast and the station at which the steric heights were calculated. A further point of interest is that for the work referred to above, the tide stations were not adjacent to strong western boundary currents as in the present investigation. In the present work, an attempt is made to relate daily mean sea level recorded at Fort Denison, Sydney to steric height evaluated from hydrological data collected in the western Tasman Sea. In practice dynamic heights were used. However the numerical difference between dynamic height and steric height is insignificant in the present investigation. Sydney rather than Eden was selected because of the larger data base. The daily mean sea level data are corrected for the effects of atmospheric pressure and shelf wave activity.

METHODS

Data Base

Mean sea level was evaluated from tide gauge records from Fort Denison, Sydney Harbour (33°53'S, 151°10'E) (Fig. 1). The charts were digitised at hourly intervals and Munk's "Tide killer" filter (half amplitude cut off at 0.43 cycles per day used to evaluate mean sea level. Details of the steps involved are discussed by Hamon (1977). Twelve hour mean atmospheric pressure records at Sydney and twelve hour mean wind velocity recordings at Gabo Island, Jervis Bay and Sydney (Fig. 1) were used to correct the sea level data for atmospheric pressure variations and shelf wave activity. The meteorological data are a subset of the data compiled by Hamon (1976) for the evaluation of shelf wave activity on the south-east Australian shelf. The filters used by Hamon on the meteorological data were chosen to have approximately the same half amplitude cut-off frequency as the filter used for the mean sea levels.

The dynamic heights are evaluated from a subset of the Expendable Bathythermograph (XBT) data collected by Boland (1979) from T.S.M.V. "Maheno". The ship operated a fortnightly service between Sydney and New Zealand. On the outbound leg from Sydney approximately along 34°S (Fig. 1), XBTs were dropped at 2 hour intervals beginning at the 200 m isobath (151°42'E). With a normal cruising speed of 18 knots, the station spacing was 60 km. The XBT probes had a depth capacity of 450 m and the manufacturer's stated accuracy is ± 0.2°C and ± 2% of depth. Additional hydrological data were obtained at the Port Hacking 100 m station (34°05'S, 151°12'E, Fig.1) at approximately weekly intervals. All the data used cover the period May 1971 to April 1973, the period during which Hamon (1976) evaluated shelf wave activity at Evans Head.

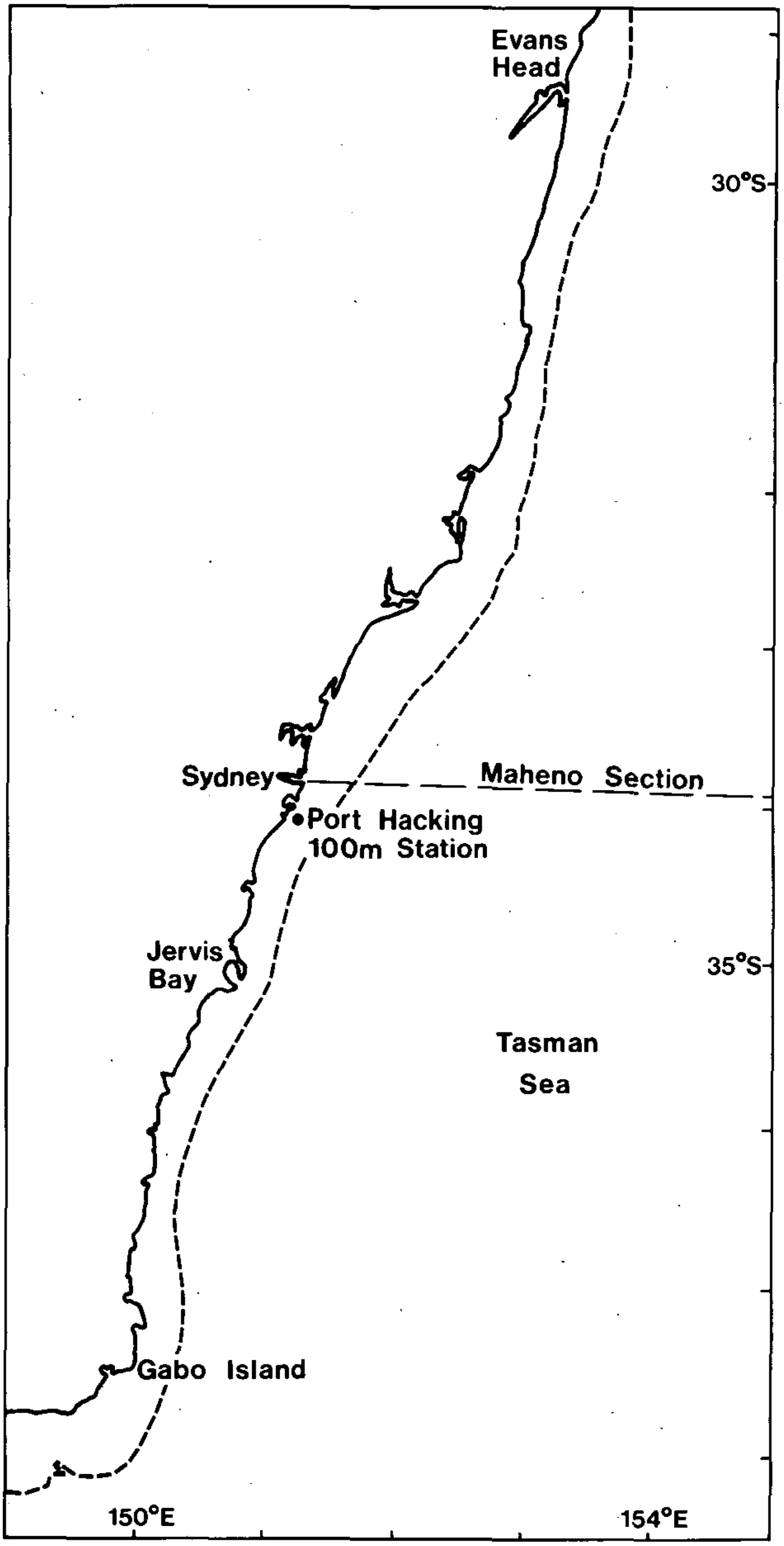

Fig. 1. Locality map.

Adjusted Mean Sea Level

The mean sea level $H(t)$ was corrected for the local atmospheric pressure $P(t)$, and shelf waves $\eta(t)$ to give the adjusted mean sea level $Y(t)$,

$$Y(t) = H(t) + P(t) - \eta(t) \qquad (1)$$

This is consistent with the theoretical work of Adams and Buchwald (1969) which showed that shelf waves are generated by longshore wind stress rather than directly by atmospheric pressure. Hamon (1976) found high coherence between shelf wave activity computed from the model by Gill and Schumann (1974) and mean sea level (corrected for atmospheric pressure) at Evans Head (Fig. 1). For the present application, shelf wave amplitudes were calculated at Sydney using the north-south component of wind stress from Gabo Island, Jervis Bay and Sydney, and, as in Hamon (1976), the model of Gill and Schumann (1974). (The difference between the north-south stress and the component parallel to the coast is less than 3% and is neglected). The assumptions used are:
1) only the first mode was considered,
2) the exponential shelf profile suggested by Buchwald and Adams (1968) was used and assumed to be independent of distance along the coast,
3) winds south of Gabo Island do not contribute to the generation of shelf waves at Sydney,
4) friction can be neglected over the short distances considered (Hamon 1976),
5) the wave propagates at a speed of 4 m s^{-1}.

Steric Heights

The conditions at the Port Hacking 100 m station (30 km south of the "Maheno" section) were assumed to be representative of the conditions at the 100 m isobath on the "Maheno" line. The Port Hacking station was usually occupied within two or three days of the time of any XBT section. Steric heights were evaluated from the observed temperature and salinity using standard methods. For the XBT data, a mean temperature-salinity curve (A.F. Pearce, personal communication) was also used. No account was taken of the contribution to steric height from that section of the water column below 450 dB. Data compiled by Pearce (personal communication) indicates that 30% of the variance in steric height (relative to 1300 dB) is due to variations in the depth range 450 dB to 1300 dB. Thus a theoretical regression of mean sea level against steric height (0/1300 dB) would have a slope of 1.3.

In the present work, the principal problem arises because of the spatial separation of the tide gauge and the location where the hydrological data were collected. On the "Maheno" line, the 100 m isobath is 10 km offshore and the location where the first XBT was dropped is 35 km offshore. Currents parallel to the coast in this region which are to a good approximation in geostrophic balance, will be associated with variations in sea level perpendicular to the coast. Because it is impossible to accurately predict these currents (and thus get the sea level slope) with the available data, some method is required to extrapolate the steric heights measured in the deep water to the shallow water adjacent to the tide gauge. This is done by replacing the area of the cross-section occupied by the shelf by an imaginary section of water. At present, there is no theoretical basis for computing the density structure in this imaginary section. Montgomery (1941) extended the isopycnals inshore with their last observed offshore gradient.

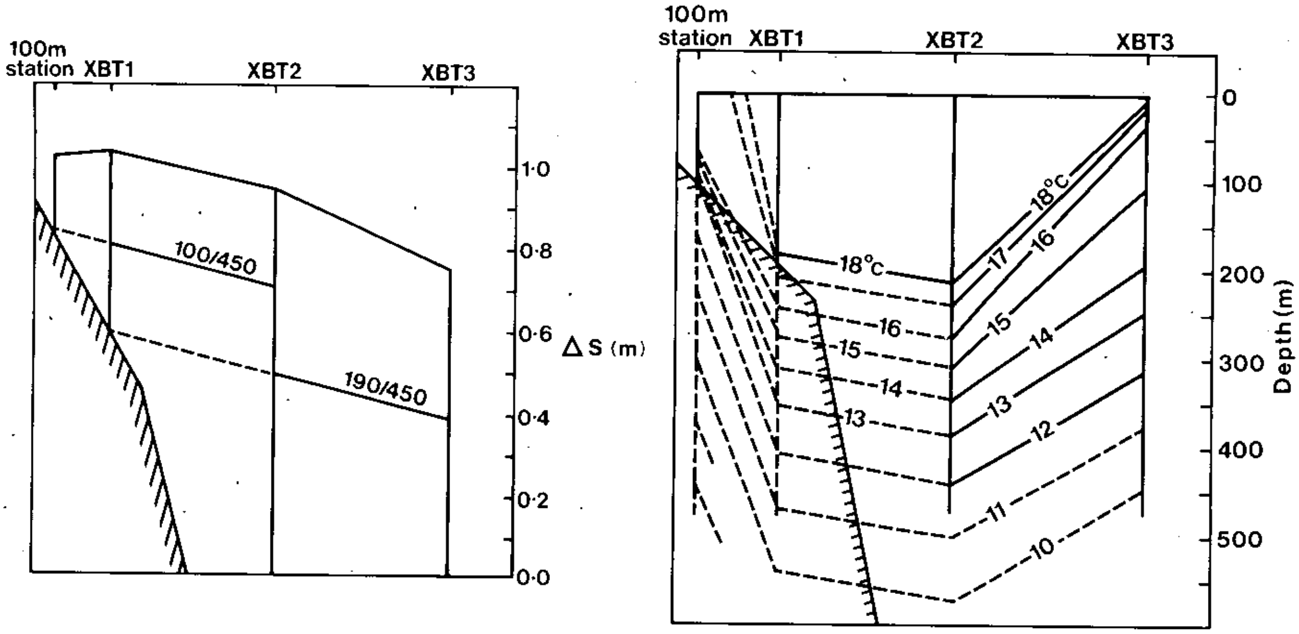

Fig. 2. Methods of extrapolation of the section of 9 September 1971 inshore to the 100 m station.

a. (left). The technique used by Reid and Mantyla (1976) to extrapolate steric heights inshore based on their offshore gradient.

b. (right). The technique used to extrapolate isotherms inshore.

The first method used here (Fig. 2a) is a modification of this in which the extrapolation is carried out on the steric heights rather than the isopycnals (Reid and Mantyla 1976). Starting with the nearest offshore station pair reaching 450 dB (XBT2 and XBT3), the gradient of the steric height along the deepest pressure surface reached by the next inshore station (XBT1) is used to determine the steric height at this pressure at station XBT1. This assumption implies the longshore current at this level is constant over this region and there must be a bottom stress present. This process is repeated using the steric heights 100/450 dB from station XBT2 and XBT1 to determine the steric height 100/450 dB at the 100 m isobath. The steric height 0/100 dB is evaluated from the 100 metre station data and added to the extrapolated value from 100/450 dB. This method of extrapolation is demanding on the data set in that any missing values means the extrapolation cannot be completed.

In the second method, the location of the observed isotherms are determined (solid lines in Fig. 2b). The remaining isotherms in the section (dotted lines) are then drawn from their last observed offshore value parallel to the isotherm immediately above. In some cases, the artificial section constructed did not reach to 450 m and it was necessary to vertically extrapolate the temperature profile to 450 m. As the temperature gradient in the thermocline is not exactly linear, this linear extrapolation will lead to an underestimation of some temperatures. The steric height 0/450 dB is then evaluated and compared to mean sea level. This method also has the advantage that it is less demanding on the data set and for the example shown appears more realistic. In this method, the sea level slope (or the longshore currents) is determined from the inshore data as well as the offshore data. At the inshore station, a hypothetical density profile is constructed using the observed temperatures (and in particular the bottom temperature) and the vertical temperature profile offshore. This allows a calculation of sea level slope independent of conditions further offshore and thus allows a horizontal current shear (as would be expected in a western boundary current) and also a non-zero bottom velocity.

RESULTS AND DISCUSSION

The steric heights determined from both extrapolation methods at the 100 m isobath and at the first XBT station were plotted against mean sea level at Sydney. The results using the second method to extrapolate to the 100 m isobath are shown in Fig. 3. The line, Y = 0.51 + 0.80 SH where Y is mean sea level and SH is steric height, obtained by linear regression analysis accounts for 44% of the total variance and the root mean square departure from this line is 6.3 cm. The 95% confidence limits for the slope of the line (0.80) are 0.44 and 1.16. Earlier work in the same area (e.g. Hamon 1969) gave a considerably larger scatter (by at least a factor of 2) than shown in Fig. 3. In the region of an eastern boundary current, Reid and Mantyla (1976) obtained good results when extrapolating steric heights inshore with a station spacing of 36 km. In the present application, their technique was less satisfactory because of the greater station spacing (60 km) and the steeper gradients in steric height experienced in regions of strong western boundary currents.

The section shown in Fig. 2b shows the East Australian Current close inshore (near the 200 m isobath). In this case, the first technique failed to detect the slope of the isotherms at the western side of the current whereas the second technique was at least part successful. Further attempts at regressing adjusted mean sea level and adjusted mean sea level minus steric height against either
(i) offshore steric height,
(ii) temperature at 450 m,
(iii) temperature at 100 m, or
(iv) the steric height at the 100 m, isobath (0/100 dB) failed to reveal any significant correlation.

Hamon (1976) found a difference by a factor of two between the observed and theoretical shelf wave activity at Evans Head. In the present work, the gain at Sydney was not evaluated and only the theoretical shelf wave amplitude was used to adjust the mean sea level. When the departure from the regression line in Fig. 3 is plotted against computed shelfwave amplitude at Sydney, a positive correlation is indicated (Fig. 4). However, for the majority of points, a large gain would be required to decrease these residuals markedly.

The difficulty in extrapolating steric height to the coast can be looked at from the dynamic point of view. The sea surface slope perpendicular to the coast is given by

$$\frac{\partial \zeta}{\partial x} = -\frac{1}{g}\frac{\partial u}{\partial t} - \frac{1}{g}u\frac{\partial u}{\partial x} - \frac{1}{g}v\frac{\partial u}{\partial y} + \frac{1}{g}fv - C_D\,\frac{(v^2+u^2)^{\frac{1}{2}}u}{gh} + \frac{\tau_E}{gh\rho}$$

where x and y are coordinates perpendicular and parallel to the coast, τ_E the easterly component of wind stress C_D the bottom drag coefficient and all other symbols have their usual meaning. Assuming a long shore velocity v varying from zero at the coast to $-1\ \mathrm{m\,s^{-1}}$ (reasonable values for a western boundary current) 35 km from the coast, steric height must rise by 14 cm to balance the Coriolis force and with any reasonable value for other parameters, all other terms are somewhat smaller. However, in shallow water the frictional component may become important.

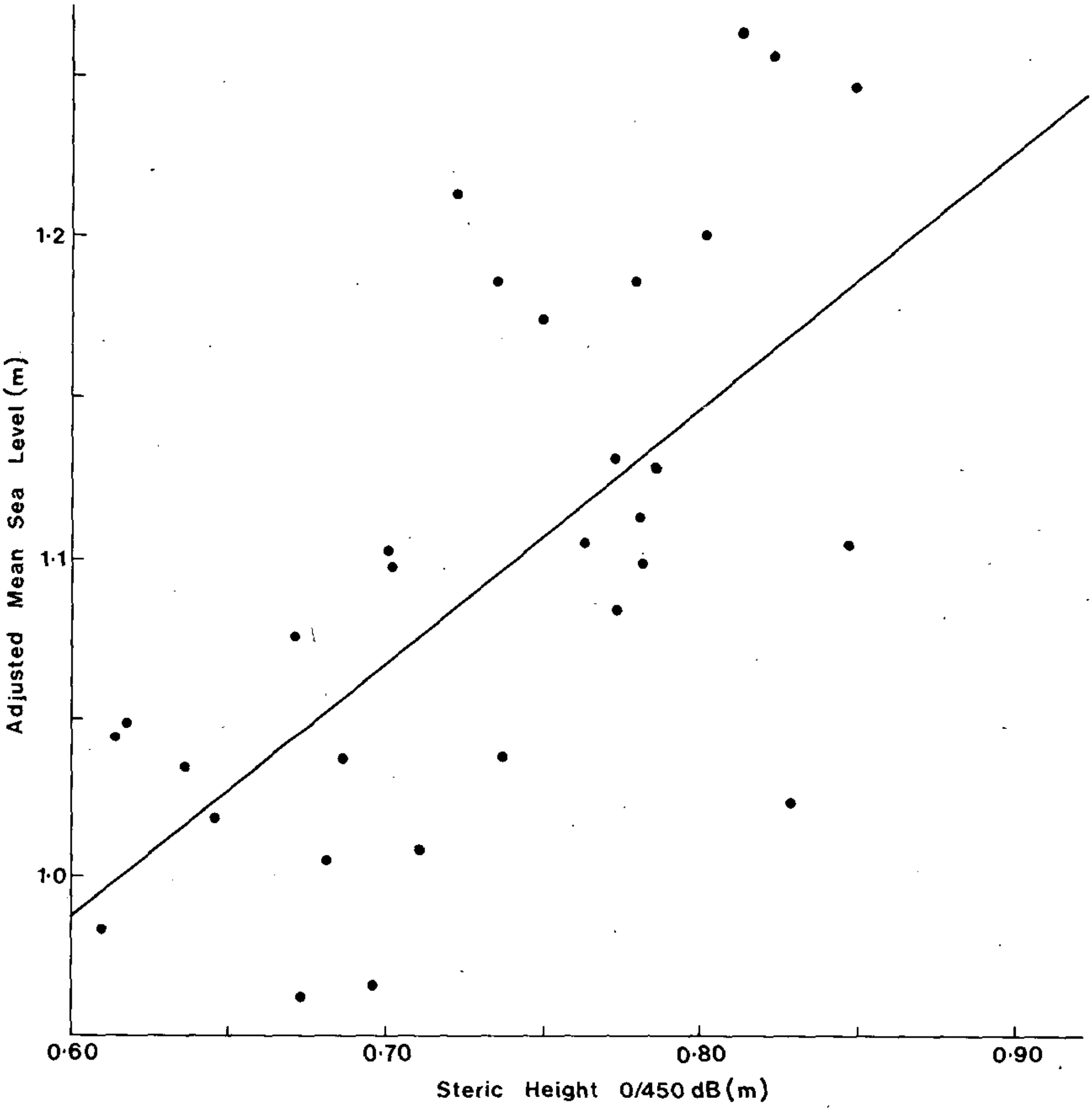

Fig. 3. Adjusted daily mean sea level at Sydney versus steric height (relative to 450 dB) at the 100 m isobath on the "Maheno section. The straight line was obtained by linear regression analysis.

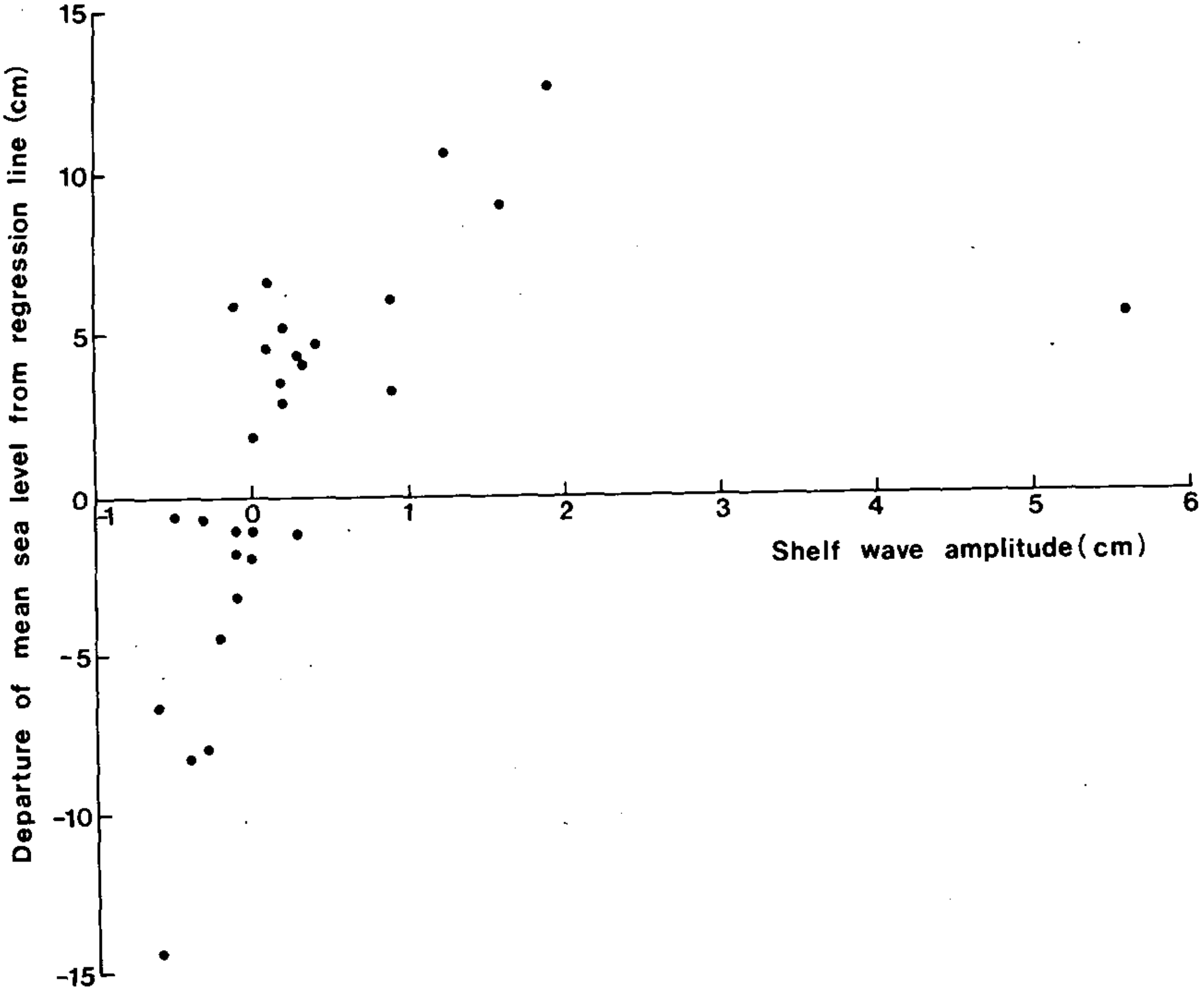

Fig. 4. The departure of adjusted mean sea level from the regression line (Fig. 3) versus shelfwave activity.

Thus while it may be possible to determine corrected mean sea level from oceanographic data, the reverse is not true as a low mean sea level may indicate a low steric height beyond the shelf break or a southward current over the shelf and shelf slope.

Considering the problems of extrapolation of steric heights (or equivalently the magnitude of the Coriolis term, in the above equation) the present data do not appear to contradict the isostatic hypothesis as suggested by Hamon (1969) and it is possible that the scatter in Fig.3 is due to variable alongshore currents. For a more accurate comparison of mean sea level and steric height a closer station spacing (perhaps 20 km or less) with the section extending to the coast is required. Also the methods used for extrapolating steric height to the coast have no theoretical basis and the different methods used led to differences in coastal steric height as high as 20 cm. However, a paper published since this work was completed (Csanady 1979) suggests a theoretically based method of extrapolating steric height inshore which offers hope for future comparisions.

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