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A REGRESSION MODEL FOR THE STATISTICAL PREDICTION OF EXTREME SEA LEVELS AT LIVERPOOL

D.C. Ovadia

Report No. 102
1980

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF OCEANOGRAPHIC SCIENCES

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ABSTRACT

Annual sea level maxima at Liverpool for a 36 year period were used as a basis for the derivation of a regression model, which could be used for forecasting future extreme sea levels.

It is found that a regression model based on the surge component of sea level maxima produces the best results.

A comparison is made between the method described here, and a method based on an analysis of extreme storm surges.

INTRODUCTION

Recent storm tides in the Liverpool Bay area have resulted in a need to examine more closely the relationship between tides and storm surges on the west coast of Britain. This work considers the annual sea level maxima recorded at Liverpool for a 36 year period up to 1977, and attempts to provide a statistical forecasting technique for extreme sea levels using readily obtainable meteorological data. Such a scheme is not designed for use in either the continuous forecasting of sea levels, a matter which is best achieved using a numerical hydrodynamical model, see for example, HEAPS (1977), nor is it designed for the prediction of extreme storm surges. The latter may occur at times of low water or throughout the tidal regime and may not contribute to an abnormal sea level.

A statistical model is proposed which, when tested, achieves satisfactory results in estimating high sea levels. It relies on an identification of possible flood risk caused by a combination of high tidal levels and certain forecasted weather parameters, and should provide a useful guide to those concerned with flood protection.

In the derivation of the model, a degree of interaction between tide and surge is suggested, and the discussion considers an empirical limiting value of sea level maxima which is supported by observations.

Although a small secular trend in the time series of annual sea level maxima is recognised, this study does not attempt to incorporate this into the proposed prediction model.

Several alternative prediction schemes are discussed, but only a method based on the analysis of the surge components of sea level maxima is considered to have a practical significance.

ANNUAL SEA LEVEL MAXIMA

Sea level records for Princes Pier, Liverpool for the period 1942 to 1977 were examined to find the highest level attained in each calendar year. These data were reduced to the time independent datum of Ordnance Datum Newlyn (O.D.N.), and in each case the exact times of the annual maxima were determined from the original tide gauge charts.

Annual sea level maxima are shown in Figure 1, together with a five year running mean, defined as:

$$X_i = \frac{\sum_{n=-2}^{2} x_{i+n}}{5} \qquad (1)$$

where X_i is the sea level maximum in year i. The purpose of calculating a running mean is to smooth the annual fluctuations, and reveal any long term trends in the data. Long period trends in annual sea level maxima at Liverpool, and other estuarine regions, are described by GRAFF (1980). It is seen in Figure 1 that annual sea level maximum levels at Liverpool show a general increase of some 1 centimetre per year, with a pronounced rise between 1974 and 1977

STORM SURGE COMPONENT OF SEA LEVEL MAXIMA

A storm surge is generally defined as the raising or lowering of sea levels as a result of the influence of atmospheric pressure or wind traction.

Astronomical tides at Princes Pier, for the period for which observed levels are available, may be obtained from Admiralty Tide Tables. The storm surge components of annual sea level maxima may therefore be determined, by calculating the tidal elevation at the time of an observed peak, using non linear interpolation between the predicted high and low waters, and then subtracting this value from the observed level, to obtain the surge.

These surge components are shown in Figure 2, where it will be noted that, neglecting the small secular trend in the data mentioned in the previous section, the sea level maxima throughout the time series maintain an approximately constant level, although there is considerable variation in the relative proportions of tide and surge which make up this level. Therefore, to an approximation:

$$\text{Tide} + \text{Surge} = \text{Constant} \qquad (2)$$

Tide and surge are plotted against each other (Figure 3), where the relationship is seen to be nearly linear, as is expected from (2) above. An interpretation of the results shown in Figure 3 requires some explanation. The linear relationship shown does not, in itself, reveal any interaction between surge and tide, since the data considered represent the single maximum level achieved each year, and as such do not comprise a randomly selected sample. For a specific set of events, such results as are shown in Figure 3 could be expected, since an annual sea level maximum could be composed of either a large surge on a low tide, or a small surge on a high tide, with the distribution of the two components scattered between these two extreme cases.

The theoretical limit of observed sea level maxima, in the absence of any limiting function of interaction between surge and tide, is the sum of the highest astronomical tide (H.A.T.) and whatever weather induced surge may be present. Surges in excess of 1 metre are not uncommon at Liverpool (there were, for example, six such surges recorded during 1975), and surges of more than 2 metres have been recorded. Since H.A.T. at Liverpool is 5.37 metres O.D.N., it would be reasonable to suppose that, at some times during the 36 year period under study, a major surge would have coincided with an astronomical tidal level near H.A.T., producing an observed level in excess of 6.5 metres. In fact, the highest sea level recorded was 6.1 metres in 1977, and if a much longer time period is considered by the inclusion of data from nearby Georges Pier, where records are available from the late nineteenth century, then the 1977 value stands as the highest level recorded at Liverpool is some 100 years or more of observations, and is seen to be much less than the theoretical limit in the event of there being no limiting interaction. In view of this discussion, and the results of equation 2, it is tentatively suggested that there is some interaction between surge and tide at Liverpool, which limits the observed maximum level to some 6.1 metres, with only a small deviation (Table 1) from that value.

It is therefore reasonable to make the general suggestion that large surges are unlikely to occur with very high astronomical tides. This assumption will have a bearing in the subsequent comparison between different methods of predicting extreme sea levels.

TIME DIFFERENCE BETWEEN OBSERVED AND PREDICTED PEAK SEA LEVELS

In the majority of cases, the peak observed sea level occurred in advance of the astronomical high water. This phase relationship was quantified using the following relationship:

$$\rho' = \frac{T_e - T_h}{|T_h - T_l|} \qquad (3)$$

where ρ' is a dimensionless phase index,

T_e is the time of observed sea level maximum,

T_l, T_h are the times of low and high water nearest, in a time sense, to the observed sea level maximum

In each case the time origin is at zero hours on the day of occurrence on the first of T_e, T_l or T_h

The index ρ' is such that:

$\rho' < 0$ indicates that the extreme sea level occurred on a rising tide,

$\rho' = 0$ indicates time coincident extreme sea level and astronomical high water,

$\rho' > 0$ indicates that the extreme sea level occurred on a falling tide.

Since the time difference between an observed sea level maximum and the astronomical high water will affect the size of the residual at the time of the observed peak, the magnitude of ρ' was initially included in the development of a regression equation for the statistical prediction of sea level maxima, but was found to contribute only some 4mm to the regression equation, which was considered to be below the noise level.

The values of ρ' are shown in Table 2, where it is seen that, in the majority of cases, the observed peak level occurred some 5 - 15 minutes before high water. More careful scrutiny of these results does not reveal any significant correlations of ρ' with either the magnitude of the observed level, or that of the astronomical tidal elevation at the time of annual maxima.

It is of interest to note, however, that in the case of the 1977 maximum, the observed peak occurred after high water. This was observed in a study by HEAPS (1979) of several Irish Sea ports, and was regarded as being an anomalous case in comparison with other years of observations at Liverpool. It is suggested that this feature is the result of some local wind effect, the dynamics of which are not clearly understood at present.

METEOROLOGICAL PARAMETERS

Wind and pressure data are available from recordings at Bidston Observatory, some six kilometres distant from Princes Pier, for the same period as the tidal records. It was, however, necessary to interpolate the meteorological data between the standard recording times to obtain values coincident with the time of occurrence of each sea level maximum, and for periods of 12 hours before, and 8 hours after, such events, in time steps of 30 minutes.

As well as the basic parameters of wind and inverted barometric pressure (the difference between the local pressure and the long term mean value), the time rates of change of wind vector and inverted pressure were calculated, as is appropriate when dealing with the effects of a moving pressure field, LENNON (1963).

STATISTICAL ANALYSIS

Although empirically derived forecasting techniques for extreme sea levels are well established for North Sea ports, see for example, CORKAN (1948), there are no equivalent methods for West Coast ports. The purpose of the statistical analysis used here is twofold

(a) to identify the major weather parameters causing extreme sea levels, and compare these with the main storm generating wind and pressure parameters associated with the generation of large storm surges.

(b) to produce a simple and reasonably accurate forecasting model for extreme sea levels, using forecast meteorological parameters.

METHOD OF ANALYSIS

The annual sea level maxima used in this study range from severe flood danger levels to those which are lower than H.A.T., and therefore produce no danger of coastal flooding. In order to produce a meaningful result for objective (a) above, the series of annual maxima were subdivided into three major groups. The first such group contains the ten highest annual maxima, and represents the most severe flood risk group. The second group extends to include the thirty highest maxima, and as such represents observed sea levels in excess of H.A.T., and the third group includes all the maxima in the time series.

A multiregression technique was designed which estimates each observed annual maximum within the group using selected meteorological parameters and empirically derived coefficients, using a least squares principle. The regression equation has the general form:

$$\hat{\zeta} = \alpha + \sum_{n=1}^{4} \beta_n M_n \qquad (4)$$

where $\hat{\zeta}$ is the estimated (dependent) variable,

M_n are the selected (independent) variables,

α, β_n are empirically derived coefficients.

The number of independent variables, n , was limited to four, the variables being the most significant ones chosen from the full matrix of weather parameters having differing time lags with the sea level maxima, the selection being based on the variables producing the smallest root mean square difference between the estimated and observed sea level maxima, (Table 4).

Using equation (4), the following results were obtained

(a) for the highest ten annual sea level maxima:

$$\hat{\zeta}_0 = \bar{\zeta}_a + 0.143(\bar{p} - p_{t-4}) + 0.0294\left(v_t - \frac{v_{t-8}}{8}\right) \qquad (5)$$

(b) for the highest thirty annual sea level maxima:

$$\hat{\zeta}_0 = \bar{\zeta}_0 + 0.0073(w_{t-4} - w_t) + 0.032 v_{t-4} + 0.0017(\bar{p} - p_{t-8} + \bar{p} - p_{t-4} + \bar{p} - p_t) \qquad (6)$$

(c) for all annual sea level maxima:

$$\hat{\zeta}_0 = \bar{\zeta}_0 + 0.053 v_{t-4} + 0.0029(\bar{p} - p_{t-8} + \bar{p} - p_{t-4} + \bar{p} - p_t) + 0.0012 w_{t-8} \qquad (7)$$

where $\hat{\zeta}_0$ is the estimated annual sea level maximum (metres, O.D.N.),

$\bar{\zeta}_0$ is the mean value of the astronomical tidal elevations at the time of occurrence of the observed maxima within the group (metres, O.D.N.),

p is observed barometric pressure (mb),

$\bar{p}$ is the 15 year mean pressure (1015.4 mb),

v is the onshore wind component (MS^{-1}) given by

$v = -w \sin(\theta - 45)$

w is the wind speed (MS^{-1}),

θ is the direction of the wind, in degrees,

$t - t'$ is the time t' hours before the observed sea level maximum.

The statistical correlations and significance levels are shown in Table 3, and the estimated sea levels, from each equation, are plotted with the observed values, in Figure 4, for each sub-grouping.

DISCUSSION

The relationships (5) to (7) above, based on hindcast regression between annual sea level maxima and various meteorological parameters, illustrate the fact that whilst the weather field associated with the highest group of maxima is sufficiently well defined to produce good correlations, the weather field becomes much less well defined as the group of sea level maxima includes more lower values. With such larger groupings, the approach based on regression using annual sea level maxima, does not achieve satisfactory levels of correlation.

Hence, although the technique is useful in defining the weather parameters associated with each group of maxima, it does not lead to a practical forecasting method. It is therefore necessary to adopt a different approach in order to derive a forecasting model. This is described in the next section.

SURGE COMPONENTS OF ANNUAL SEA LEVEL MAXIMA

A multiregression analysis was used with the surge component at annual sea level maxima as the independent variable in an equation having the same form as equation 4. Again, the four most significant dependent variables were used. The resulting relationship is

$$\hat{S}_t = 0.479 + 0.0041\, v_{t-4} + 0.0029\left(\bar{p} - p_{t-8} + \bar{p} - p_{t-4} + \bar{p} - p_t\right) \qquad (8)$$

where $\hat{S}_t$ is the estimated surge (metres), at the observed sea level peak,

v is the onshore wind component (already defined),

p is the observed barometric pressure,

$\bar{p}$ is the 15 year mean pressure (1015.4 mb),

$t-t'$ is the time lag t' (hours), before the observed sea level peak.

This equation gives a correlation of 87%, significant at the 0.1% level. The surge component estimated in this way, together with the observed surge for each sea level maximum, is plotted in Figure 5, which also shows the estimated and observed sea levels calculated by adding the surge components to the astronomical tide. It is seen that the model produces good agreement with the observed values of sea level maxima, when applied in this way.

As the sea level maximum is likely to occur some 5 to 15 minutes before high water, it is possible to estimate the maximum sea level by adding the estimated surge height, from equation 8, directly to the high water level found from Tide Tables. This will tend to over-estimate the flood danger in most cases by about 8 cms, (the elevation of a spring tide during the 20 minutes prior to high water), but will not under-estimate, since it allows for the predicted surge height to occur exactly at the time of high water.

Since the wind component and inverted barometric pressures may be forecast some 12 hours ahead, equation 8 provides a means of assessing the probable surge height near the time of an astronomical high water.

TESTING OF THE RESULTS

The validity of a regression model is best evaluated when it is applied to data independent of that from which it has been derived.

The data used in the development of the forecasting model were from a 36 year period, 1942 to 1977, for which accurate tidal charts are available. With such a limited period of data, it was not practical to preserve a random sample of events for subsequent independent testing of the results. Independent testing of the data was therefore limited to 3 extreme sea levels, not in themselves annual maxima, but levels selected (Figure 1) as exceeding the mean value of the 36 years of annual maxima, which is 5.48m O.D.N.

These events occurred in March 1967, (5.53m O.D.N.); September 1970, (5.59m O.D.N.); and January 1974 (5.56m O.D.N.). In addition, the annual maximum for 1978, which became available after the regression equation had been defined, was used as a fourth independent test of the model.

Table 5 and Figure 6 show the results of the 44 value surge model (equation 8) being applied. The 1967, 1970 and 1974 maxima are all associated with westerly winds, and although atmospheric pressure was below average in the case of 1967 and 1974, the 1970 maximum occurred under pressure conditions above the long term mean. The phase lag between observed and astronomical high water varied from 20 minutes (1974), to 7 minutes (1970).

Despite these variations, the regression model was able to estimate the sea level maximum to within 11 cms in the case of 1967.

The annual maximum for 1978 was only 30 cms above the astronomical level, under conditions of near normal atmospheric pressure, and moderate westerly winds. In this event, the regression model over-estimated the result by nearly 25 cms. Clearly, the wind factor in the model was too dominant for this type of weather situation. This problem further points to the difficulty of predicting the small residuals sometimes associated with annual maxima, although it must be viewed in the context that the annual extreme level for 1978 was low, and presented little danger of flooding occurring as a result.

COMPARISON WITH OTHER PREDICTION METHODS

Prediction schemes for storm surges such as AMIN, (1979), HEAPS et al (1979), LENNON (1963), are frequently based on an analysis of past storm surges.

Although the meteorological forcing mechanisms involved may be broadly similar to those producing extreme sea levels, GRAFF (1978), it does not follow that the annual sea level maxima should include a large storm surge component in every case.

A non-linear statistical regression model, derived by Amin from an analysis of extreme surges in January 1965, January 1976 and November 1977, and tested on independent surges in January 1964, February 1970 and November 1973, uses inverted barometric pressure with north-south and east-west wind components and a simplified surge-tide interaction function as:

$$S_t = \alpha_1(p_{t-\tau_1} - \bar{p}) + \alpha_2 u_{t-\tau_2}|u_{t-\tau_1}| + \alpha_3 v_{t-\tau_3}|v_{t-\tau_3}| + \alpha_4 f(S, \zeta^{\tau}) \qquad (9)$$

where S_t is the meteorologically induced surge at time t (metres),
p is the barometric pressure with annual mean $\bar{p}$ (mb),
u is the east-west component of wind
v is the north-south component of wind
$f(S,\zeta^{\tau})$ is the surge tide interaction function
ζ^{τ} is the tidal component (m),
α are constants derived by the least squares method,
τ are time lags derived by maximum cross-correlation functions.

The model has been shown to be successful in forecasting high positive surges at Liverpool.

Using meteorological data for each incidence of annual maximum sea level for the period 1942 - 1977, the predicted surge component of the extreme level event was computed using equation (9) above, and compared with both the observed surge, and that predicted using the method described in this study (equation 8). The results of this comparison are presented in Figure 7.

It is seen that equation 9, based on peak surge generating factors, is able to predict the surge component of an annual sea level maximum where the surge is large, but generally fails to predict those cases where the annual sea level maximum is composed of a smaller surge component. However, the estimated surges derived from equation 8 are closer to the observed values throughout the series.

The evidence presented here would indicate that annual sea level maxima are composed mainly of moderate storm surges superimposed on high spring tides. These surges, however, would appear to be well correlated with wind and pressure fields not unlike those fields which would, on the occasions of a low tide, produce surge heights of greater magnitudes, since interaction between tide and surge would not be a limiting function. The reason why a surge-derived model, such as Amin's, is not able to reproduce sea level maxima with accuracy, would seem to lie in the fact that the regression equation coefficients were derived under different conditions of tide from those prevailing at sea level maxima.

CONCLUSIONS

The results of this study indicate that the traditional methods of statistically predicting extreme surges have only limited value when applied to the statistical prediction of extreme sea levels observed at Liverpool. This is largely because an extreme sea level is the result of a more complex interaction between tide, surge, and meteorological forcing than generally exists in the generation of extreme surges, as is demonstrated by the difficulty of correlating a synoptic meteorological field with annual sea level maxima.

The statistical model proposed here predicts the surge component of a sea level maximum from the meteorological field, which can then be added to the astronomical tidal elevation, in order to estimate the extreme sea level. As such, it gives better results than other statistical schemes designed for the prediction of extreme storm surges alone.

The method is not intended to compete with forecasting schemes based on numerical modelling, such as the recently developed real-time forecasting scheme for the west coast, FLATHER (1979). Such schemes are better suited to the continuous prediction of sea levels throughout the tidal cycle. Rather, it is suggested that regression equations could be developed in the manner described here, and used for locations where adequate numerical model warning schemes are not yet available. Such an equation, using empirically derived coefficients, would require only simple weather forecasting techniques to give some warning of high flood levels, and would provide a more accurate method of predicting maximum sea levels, than the use of statistical schemes based on an analysis of surges alone.

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APPENDIX A

Details of the weather associated with the 15 highest annual sea level maxima.

Figure A.1.	Depression tracks at the time of annual sea level maxima at Liverpool. The centre of the depression at the time of the sea level peak is shown by an "X". Points show the position of the depression 24 and 48 hours before, and 24 hours after, the sea level peak. Direction of depression tracks are shown by arrow heads.
Figure A.2.	Shaded area encloses the centre of the depressions associated with ten of the fifteen highest sea level maxima shown in Figure A.1.

Table 1.

Statistical Summary of Tide and Surge Components of Annual Sea Level Maxima

(a) Tide, Surge relationships (Figure 2).

	Surge	Tide	Tide and Surge
Mean	0.669	4.934	5.48
Varience	0.161	0.079	0.065
Standard deviation	0.402	0.282	0.256

(b) Tide, Surge relationships (Figure 3).

regression equation :	Tide + 0.544 Surge = 5.298
sum of squares due to regression (tide on surge) :	2.051
sum of squares due to deviation (tide on surge) :	1.366
correlation coefficient :	78%

Table 2.

Table showing the annual sea level maxima, the surge height at the time of each annual sea level maximum, and the phase relationship between observed peak sea level and the astronomical high water level.

Year	Annual Sea Level Maximum (m to O.D.N.)	Surge Height at time of Annual Maximum Sea Level (m)	Phase Index x 10^3 (Equation 3)
1942	5.32	0.67	-6
1943	5.40	0.48	-8
1944	5.42	0.35	-4
1945	5.60	0.53	-1
1946	5.07	0.09	-5
1946	5.07	0.42	-44
1947	5.17	0.93	-9
1948	5.25	0.65	-14
1948	5.25	0.22	6
1949	5.60	0.62	0
1950	5.37	0.82	-14
1951	5.47	0.90	-7
1952	5.15	0.25	-7
1953	5.32	0.56	-28
1954	5.63	0.31	0
1955	5.50	1.17	-3
1956	5.35	0.79	-18
1957	5.65	0.46	-8
1958	5.53	0.24	6
1959	5.47	0.51	-8
1959	5.47	0.51	-8
1960	5.35	0.62	-4
1961	5.38	0.21	0
1961	5.38	1.06	21
1961	5.38	0.78	-12
1961	5.38	0.57	-11
1962	5.63	0.43	-1
1963	5.60	0.82	-22
1964	5.32	0.62	-14
1965	5.57	1.80	-35
1966	5.50	0.78	-14
1967	5.66	0.77	-11
1968	5.66	1.16	-11
1969	5.32	0.88	-25
1970	5.63	0.64	-12
1971	5.35	0.37	-11
1972	5.20	0.05	-18
1972	5.20	0.35	-51

Table 2 (continued)

Table showing the annual sea level maxima, the surge height at the time of each annual sea level maximum, and the phase relationship between observed peak sea level and the astronomical high water level.

Year	Annual Sea Level Maximum (m to O.D.N.)	Surge Height at time of Annual Maximum Sea Level (m)	Phase Index x 10^3 (Equation 3)
1973	5.23	0.71	-53
1973	5.23	0.66	-42
1974	5.75	0.86	-9
1975	5.76	0.61	-21
1976	5.96	2.21	-50
1977	6.11	1.01	9

An index, P', of 14 units is equivalent to a time difference between observed and predicted high water of approximately 10 minutes

Table 3

Results of multiregression analysis using sea level maxima as dependant variables (equations 5,6,7)

Ranked sub-group	Range	Mean	Std.dev.	Correlation	Significance
Highest 10 maxima	6.11 5.63	5.74	0.164	86%	0.1%
Highest 30 maxima	6.11 5.35	5.55	0.182	70%	1%
44 maxima	6.11 5.07	5.48	0.220	56%	1%

Table 4

Table of the main meteorological parameters used in the regression analysis, showing their correlations with groups of ranked sea level maxima. Correlations which are not significant at the 0.1% level are omitted from the table.

Meteorological parameters used in the analysis, at time t hours from the time of peak sea level		Correlation Coefficient, R, with:		
		Highest 10 annual sea level maxima	Highest 30 annual sea level maxima	44 annual sea level maxima
Inverted air pressure	-8hr			
	-4hr	.680		.636
	0hr	.641		.581
	+4hr			
Wind speed	-8hr	.927	.742	
	-4hr	.815	.727	.670
	0hr	.916	.716	.609
	+4hr	.867		
Onshore wind component	-8hr			
	-4hr			
	0hr	.785		
	+4hr	.801		

Other meteorological parameters considered, but not producing correlations significant at 0.1%, were:

1. maximum wind gust
2. alongshore wind vector
3. time rate of change of inverted barometric pressure
4. time rate of change of wind speed
5. time rate of change of wind direction

Each parameter was correlated with time differences to the time of peak sea level of -8hr, -4hr, 0hr and + 4hr.

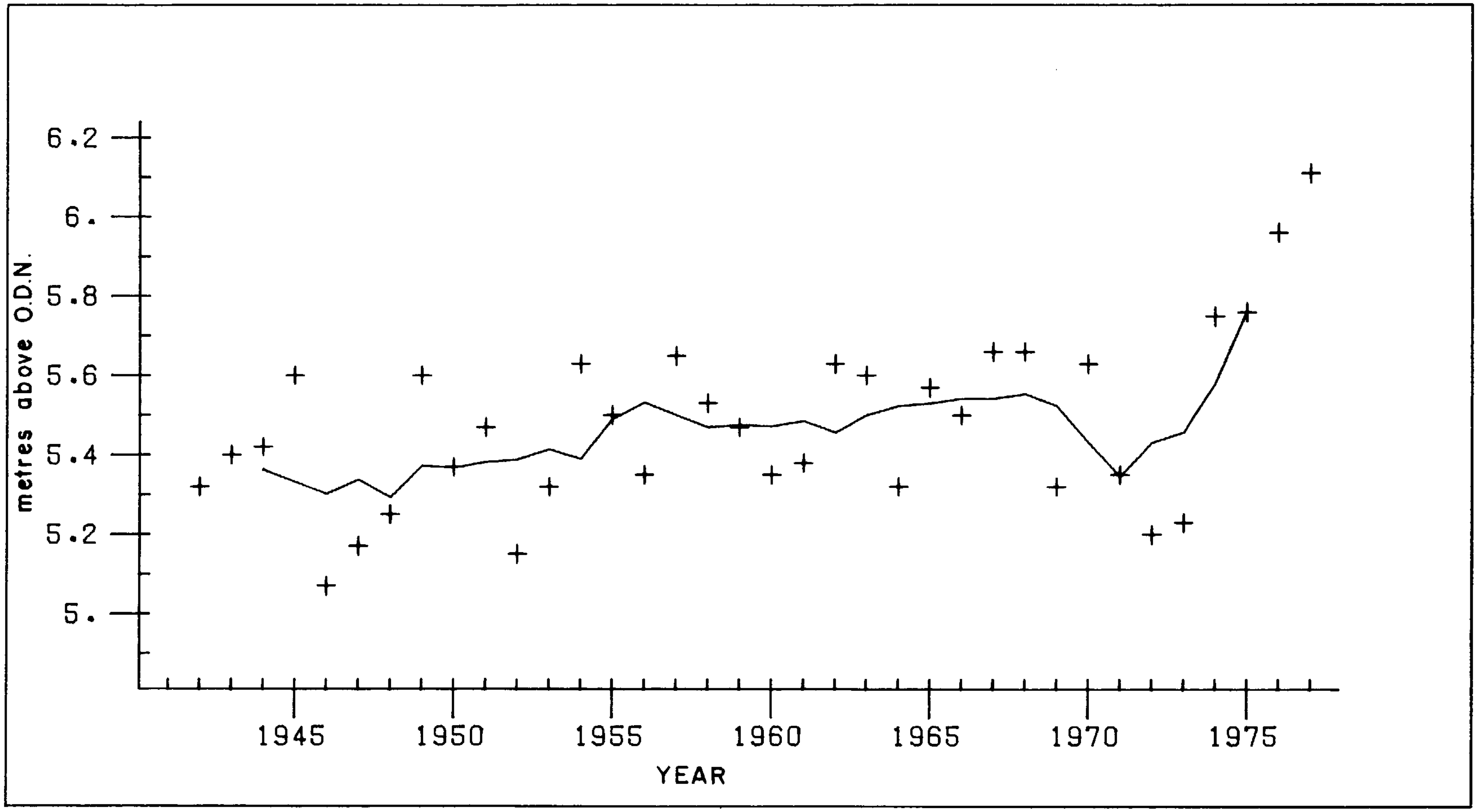
Table 5

Results of testing the regression model on independent data

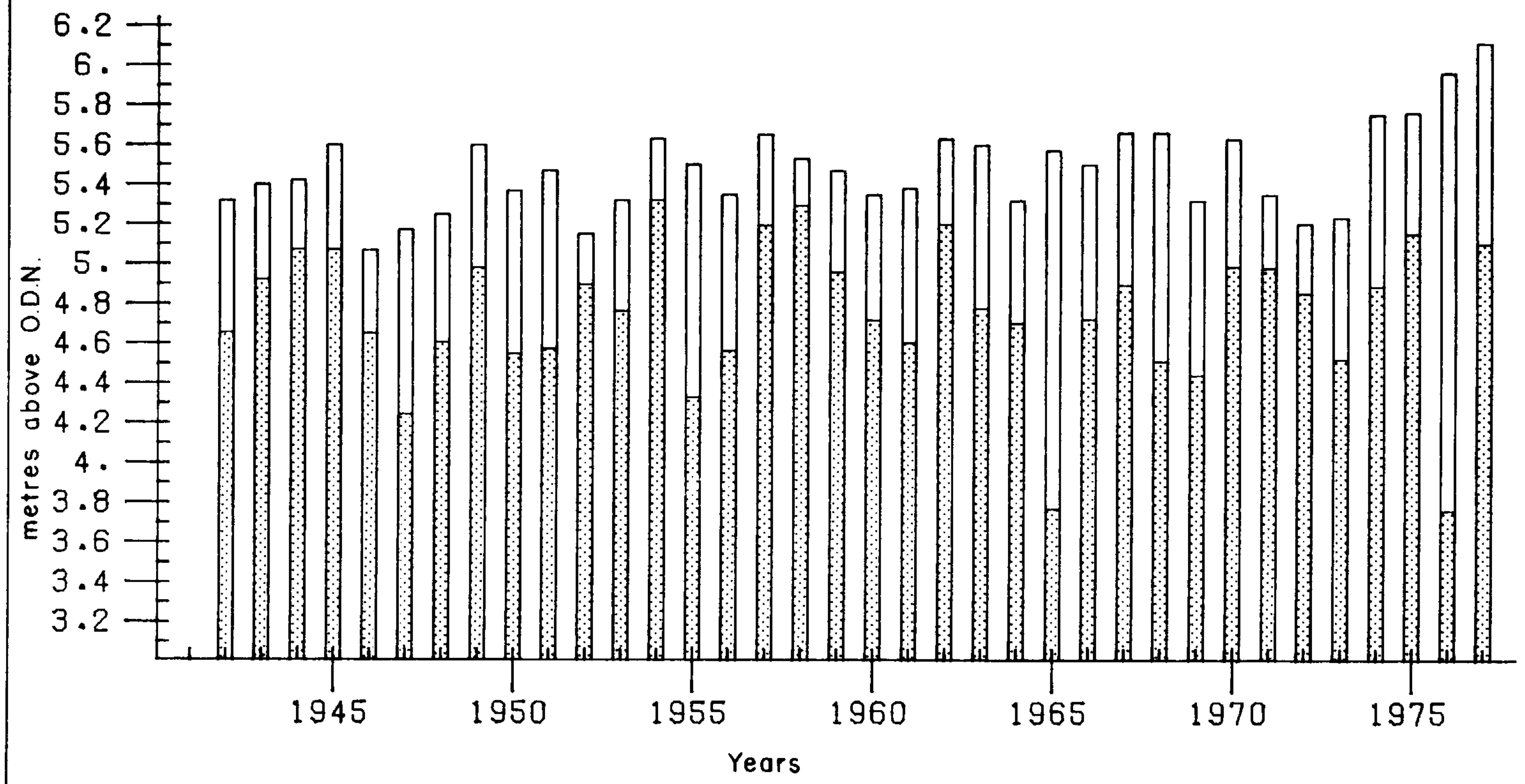
Year	Observed Surge Component (metres)	Estimate Surge Component -eqn. 8 (m)	Observed Extreme Sea Level (m O.D.N.)	Estimated Extreme Sea Level (Tide & Estimated Surge) (m O.D.N.)
1967	0.588	0.696	5.53	5.42
1970	0.427	0.446	5.59	5.61
1974	0.689	0.640	5.56	5.51
1978	0.300	0.547	5.32	5.57

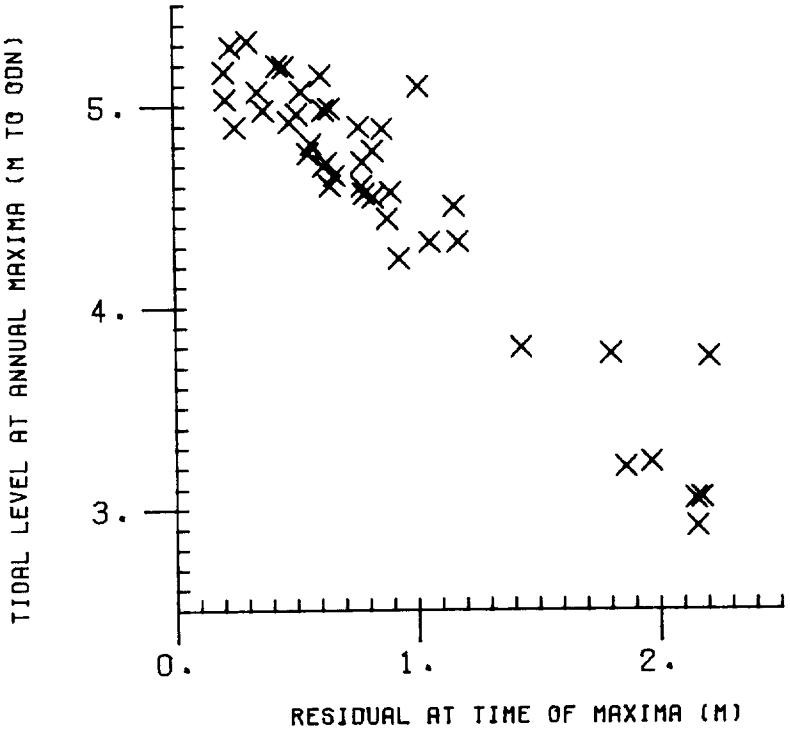
FIGURES

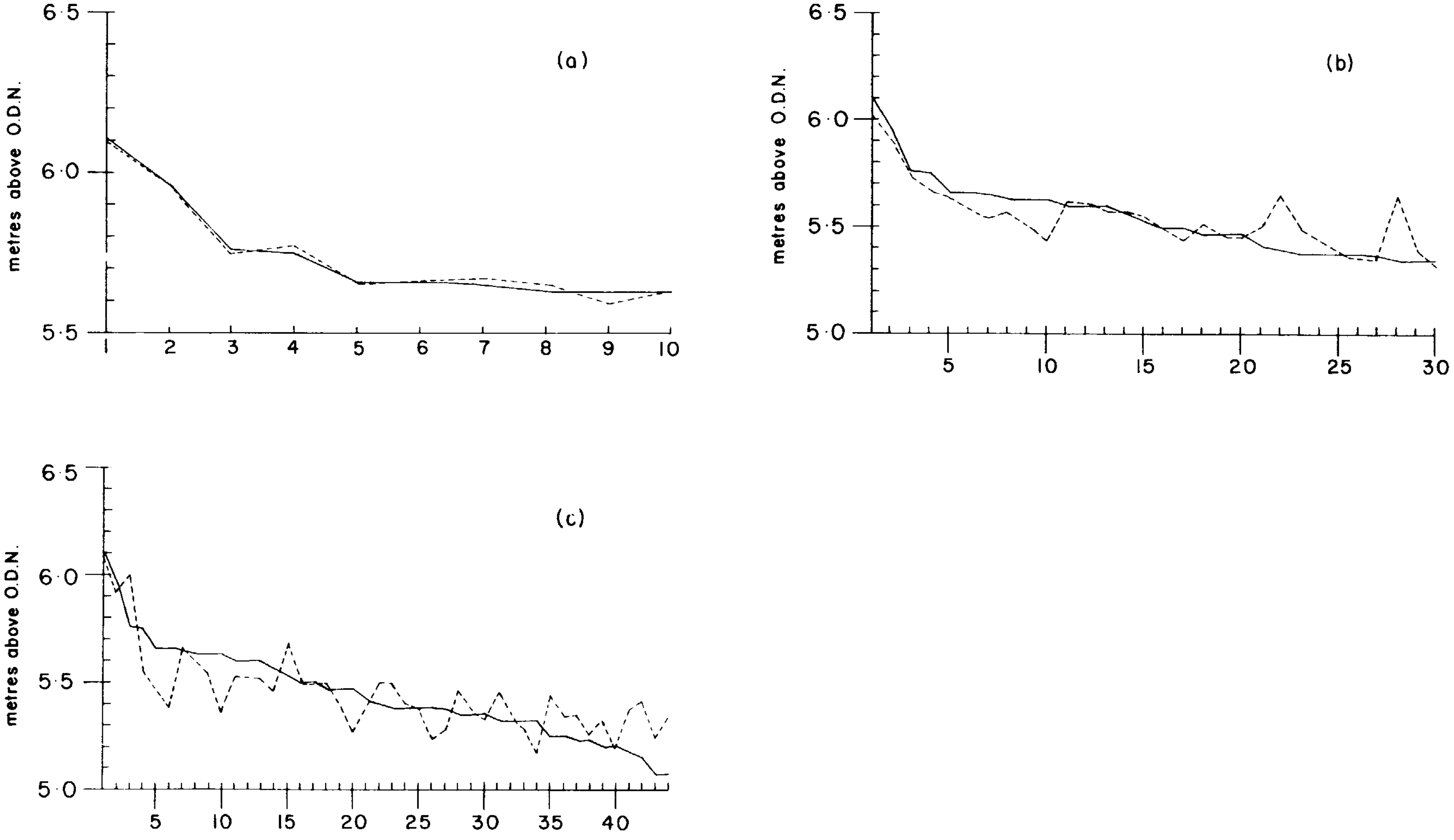
Figure 1	Annual sea level maxima (+), with five-year running mean.
Figure 2	Annual sea level maxima (1942-1977) showing the surge components of the maxima. - The histograms show the height above O.D.N. of each annual maximum; the unshaded part is the surge component of the maximum.
Figure 3	Astronomical tidal elevations at the time of each annual sea level maximum, plotted against the surge component (observed - tide) of the maxima. (44 values)
Figure 4	(a) Annual sea level maxima are plotted as a series arranged in decending rank order (solid line). The estimated values, derived from the regression analysis, are plotted as a dotted line. The highest 10 annual maxima are shown here. (b) As for Figure 4(a). The highest 30 values are plotted. (c) As for Figure 4(a). All 44 values are plotted in decending rank order.
Figure 5	Results of regression model for estimating surges. The lower diagram shows the 44 surge components of annual sea level maxima, arranged in decending order of magnitude (solid line). Also plotted (dotted line) is the estimated surge component in each case, derived from the regression analysis. The upper diagram shows the corresponding observed sea level (solid line), together with the estimated sea level (dotted line), obtained by adding the estimated surge to the astronomical tide.
Figure 6	Results of the regression model (equation 8) tested on independent data. The lower diagram shows the observed and estimated surges, the upper diagram shows the observed and estimated sea elevations.
Figure 7	Comparison of prediction models. The top diagram shows the estimated surges at the time of all 44 sea level maxima, derived from equation 9 (Amin). The centre diagram shows the estimated surges derived using the method detailed in this study (equation 8). The lower diagram shows the observed surges.

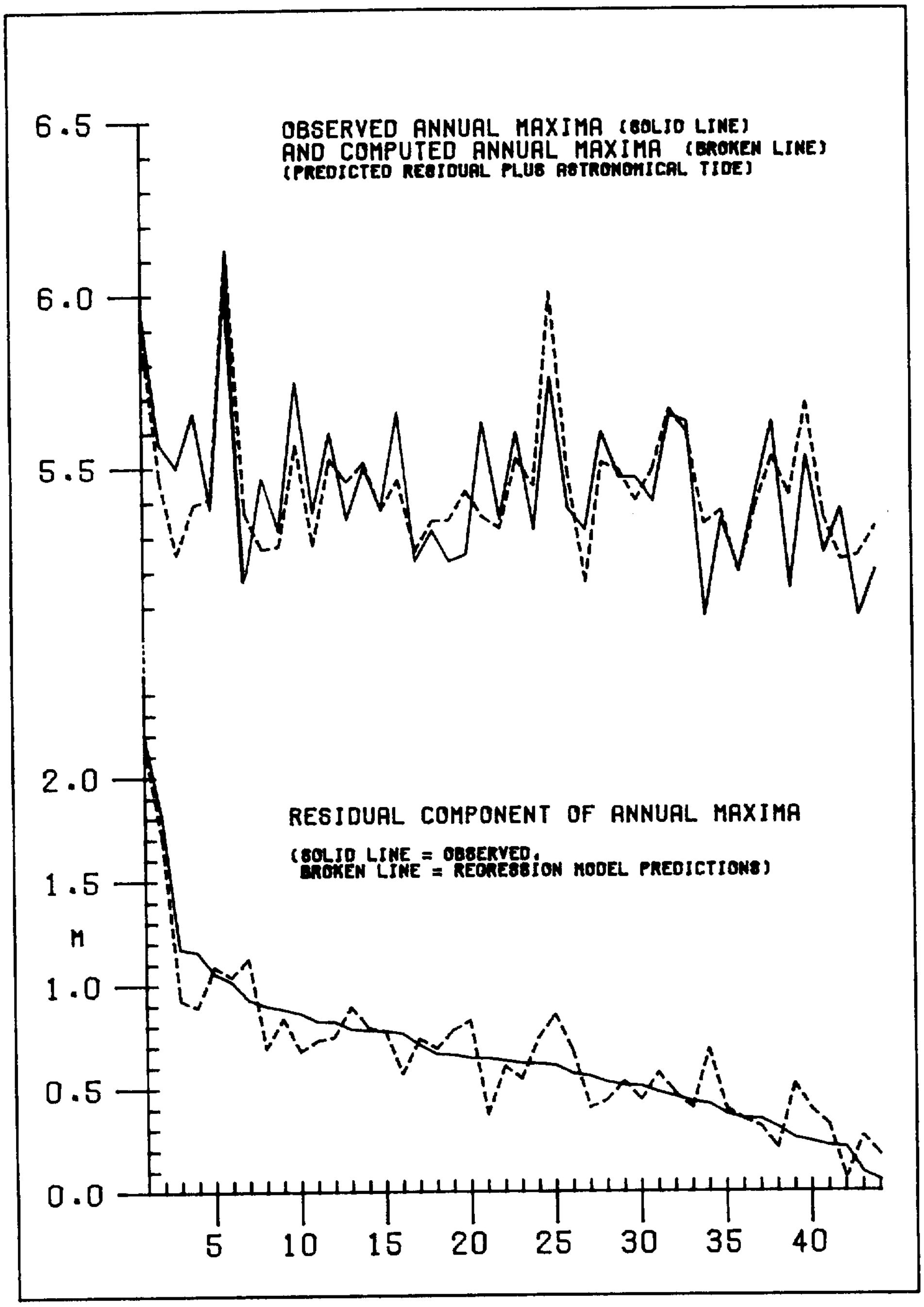


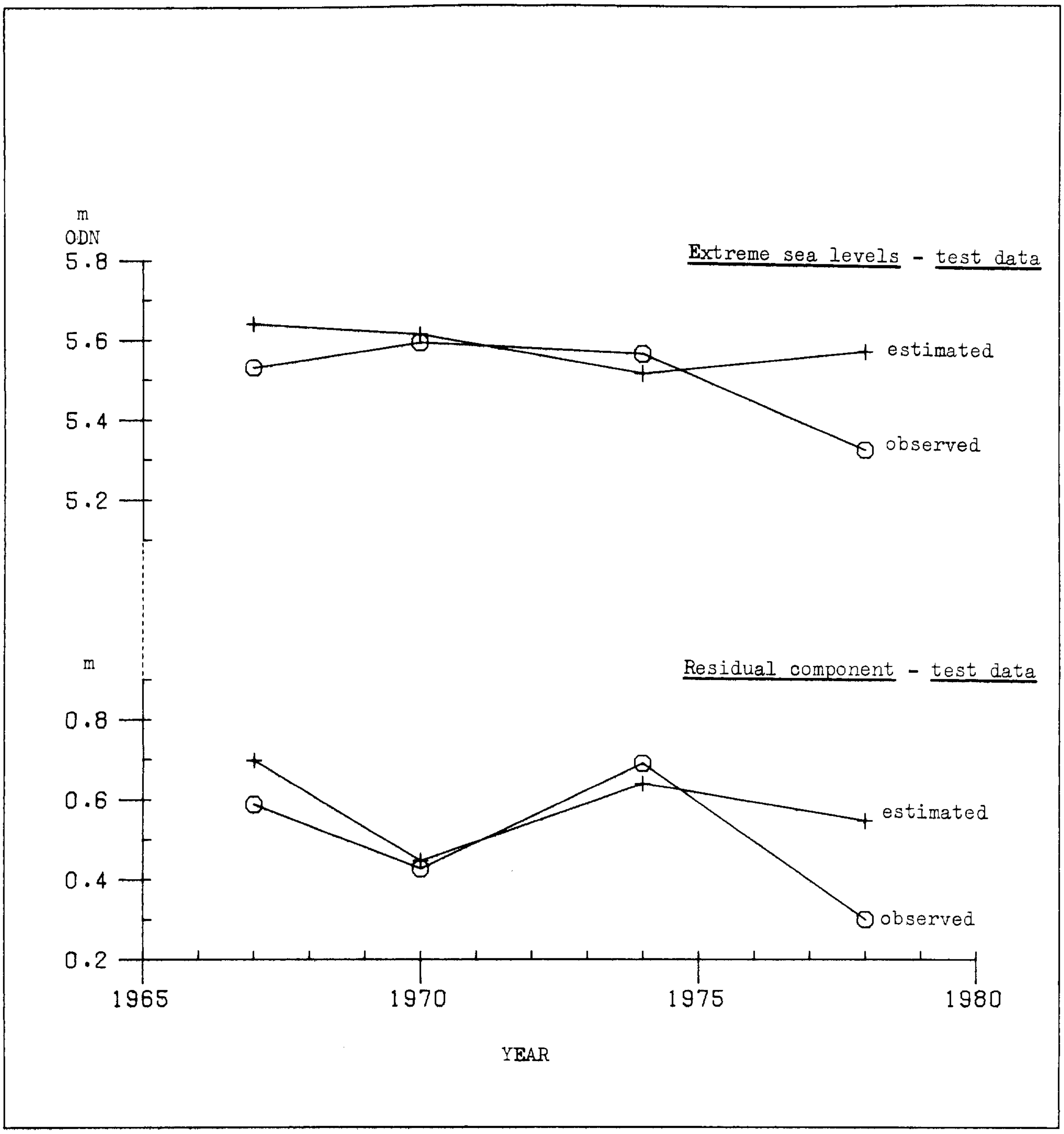
6.2
6.
5.8
5.6
5.4
5.2
5.
metres above O.D.N.
1945
1950
1955
1960
1965
1970
1975
YEAR

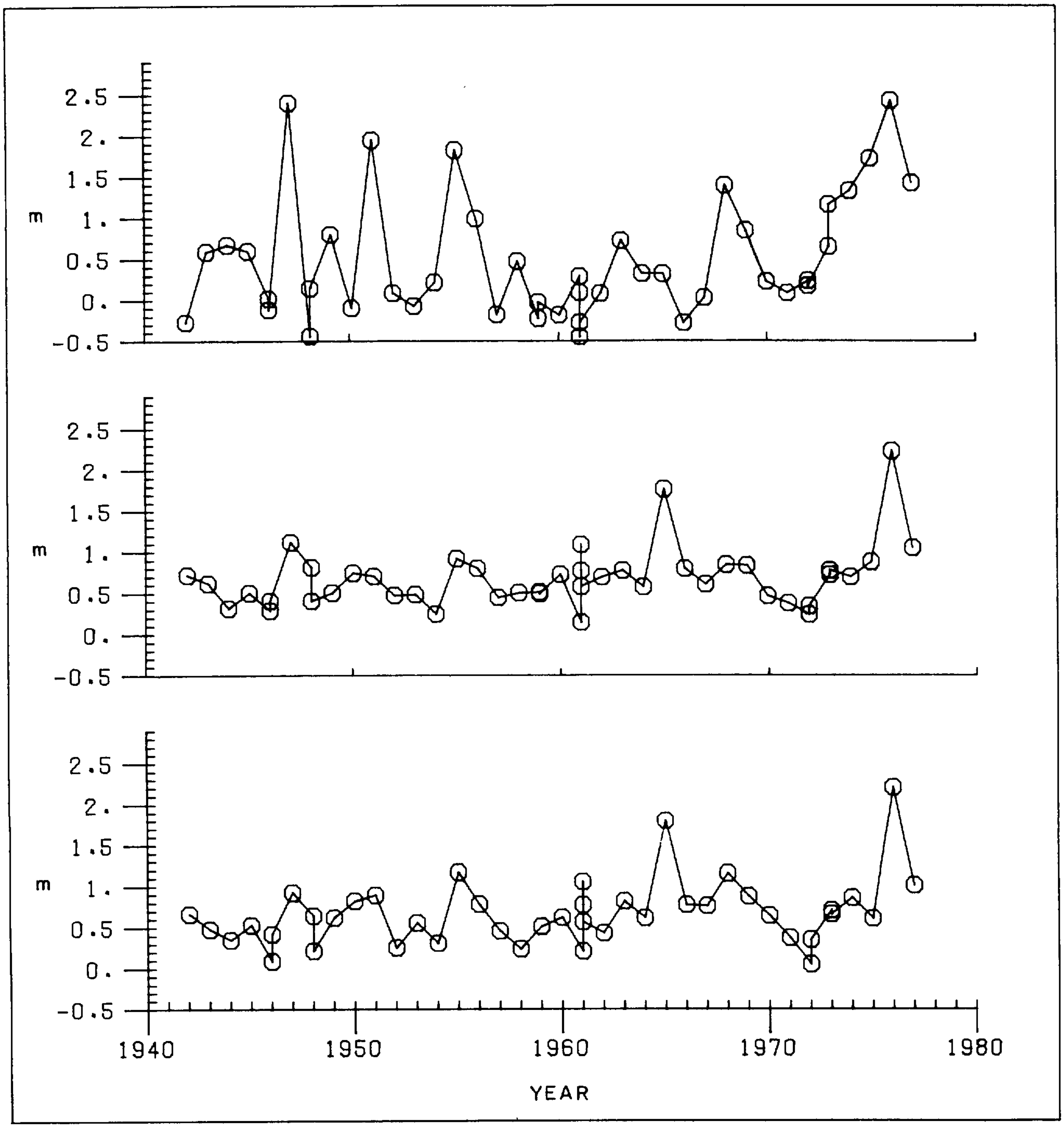

6.2
6.
5.8
5.6
5.4
5.2
5.
4.8
4.6
4.4
4.2
4.
3.8
3.6
3.4
3.2
metres above O.D.N.
1945
1950
1955
1960
1965
1970
1975
Years

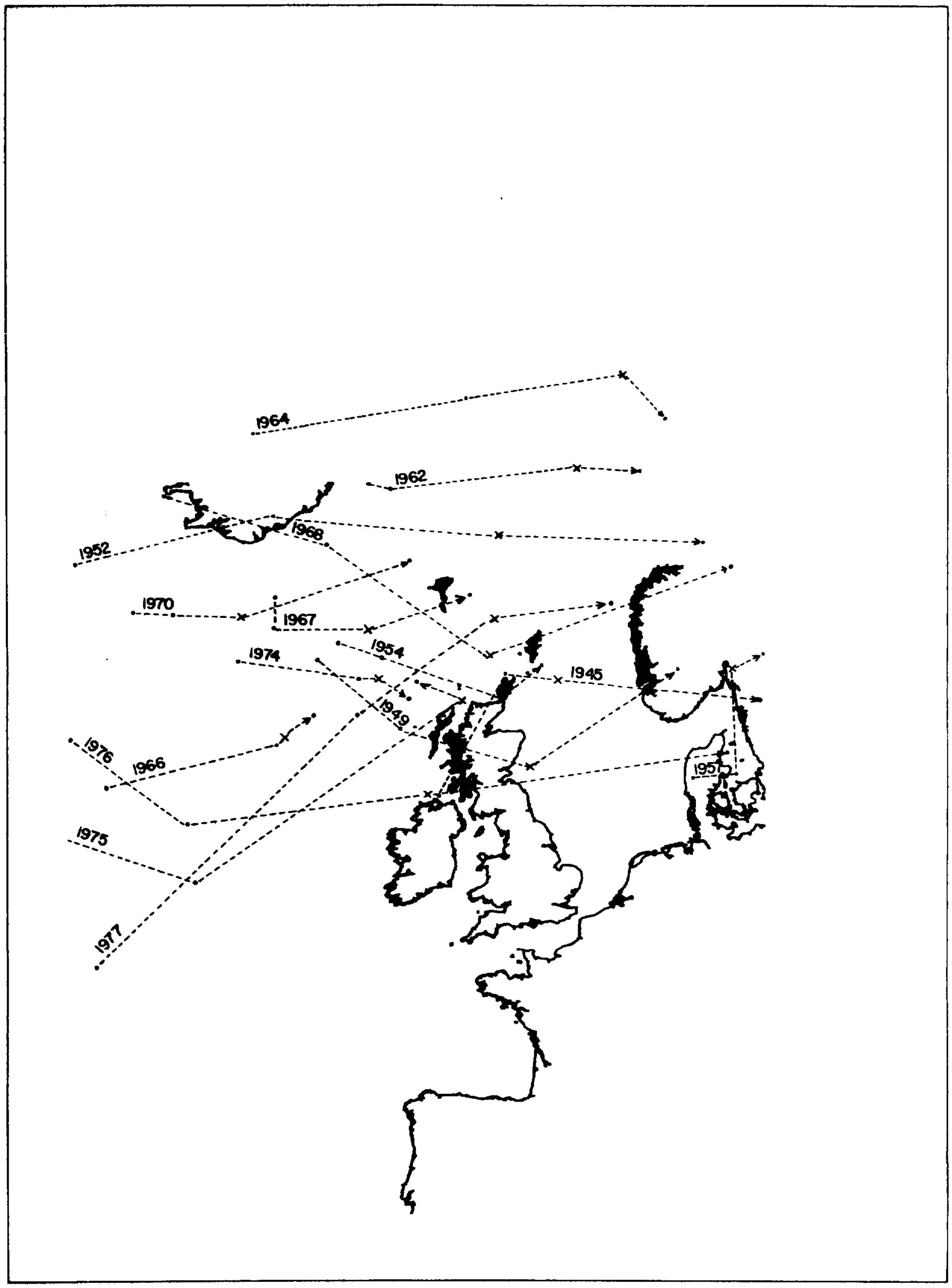

TIDAL LEVEL AT ANNUAL MAXIMA (M TO ODN)
5.
4.
3.
0.
1.
2.
RESIDUAL AT TIME OF MAXIMA (M)

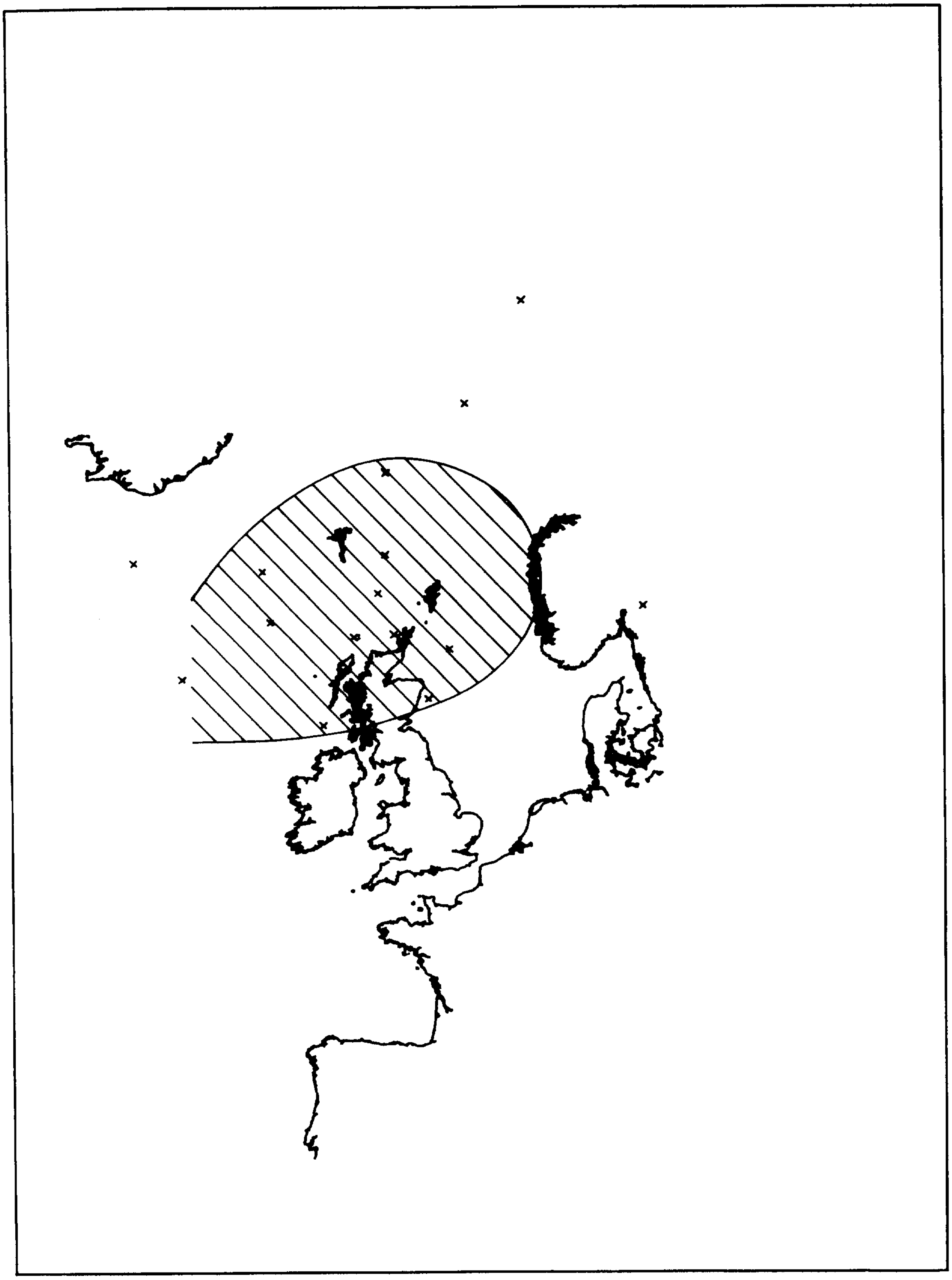

(a)
metres above O.D.N.
6·5
6·0
5·5
1
2
3
4
5
6
7
8
9
10
(b)
metres above O.D.N.
6·5
6·0
5·5
5·0
5
10
15
20
25
30
(c)
metres above O.D.N.
6·5
6·0
5·5
5·0
5
10
15
20
25
30
35
40


OBSERVED ANNUAL MAXIMA (SOLID LINE)
AND COMPUTED ANNUAL MAXIMA (BROKEN LINE)
(PREDICTED RESIDUAL PLUS ASTRONOMICAL TIDE)
RESIDUAL COMPONENT OF ANNUAL MAXIMA
(SOLID LINE = OBSERVED,
BROKEN LINE = REGRESSION MODEL PREDICTIONS)
6.5
6.0
5.5
2.0
1.5
M
1.0
0.5
0.0
5
10
15
20
25
30
35
40


m
ODN
5.8
5.6
5.4
5.2
Extreme sea levels - test data
estimated
observed
m
0.8
0.6
0.4
0.2
Residual component - test data
estimated
observed
1965
1970
1975
1980
YEAR


2.5
2.
1.5
m
1.
0.5
0.
-0.5
1940
1950
1960
1970
1980
YEAR


1964
1962
1952
1968
1970
1967
1954
1974
1945
1949
1976
1966
1957
1975
1977



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