I.O.S.

INVESTIGATION OF STORM SURGES IN THE TORRES STRAIT

M. AMIN

REPORT NO 50

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NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF
OCEANOGRAPHIC
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SUMMARY

One year of simultaneous tidal observations from six stations in the Torres Strait have been analysed and in each case 110 harmonic constituents were resolved. The analysis showed that tides in this region are mixed i.e. both diurnal and semi-diurnal components are strong. For the surge analysis, hourly residuals (observed elevations - tidal predictions) were produced by using the resolved constituents to compute the tidal predictions for the full period of available observations. An examination of the residuals showed that Frederick Point and Twin Island have similar responses to meteorological effects, similarly the response of Booby Island, Goods Island and Turtle Head have common characteristics, but differing from those at Frederick Point and Twin Island. The surges observed at Booby Island, Goods Island and Turtle Head are greater in magnitude and opposite in sign from those observed at Twin Island and Frederick Point. Ince Point sea levels are hardly affected by meteorological effects. It was found that the east-west component of surface winds is mainly responsible for the generation and propagation of surges, whereas winds of velocity less than 12 metres/second have very little effect and are insignificant in the generation of surges. Winds from the west develop positive surges on the west of Ince Point and negative surges on the east of Ince Point while the reverse is true for winds from the east. The north-south line through Ince Point appears to act almost as a barrier. A regression technique was used to develop a system for forecasting surges using meteorological data available from near-by meteorological stations. The method proved to be reasonably satisfactory despite the limitations which were imposed by the meteorological observations. The pressure gradients in space may appear to be small but when the distance between two recording stations is of such a length that a low or high pressure zone can be present in the middle, the apparent gradient is clearly not representative of the mechanism investigated in this paper. Some variations in mean sea level, and damped oscillations of periods 3-4 days were observed. These oscillations were not simply related to any local meteorological effects and are considered to have their origin either in the Indian Ocean to the west, or in the Coral Sea to the east. It is suggested that surges generated outside the Torres Strait may affect surge levels within the Strait both directly due to the associated surge level and indirectly by modulating local surges.

INTRODUCTION

In regions of shallow water such as the Torres Strait the effects of both spatial variation in barometric pressure and direct operation of wind force induce surges of such a magnitude that these become of greater importance than tides for navigational purposes. The observed sea level ζ, measured as the deviation of true sea level from the mean sea level value, at a particular place at any time t can be expressed as;

$$\zeta_t = \zeta_t^{(T)} + S_t + Z_t \qquad (1.1)$$

where t is the time,

$\zeta^{(T)}$ is the tidal component,

S is the weather induced perturbation 'surge',

Z is the residual variation which is not accountable in terms of readily measured forces.

The prediction of sea level, therefore requires accurate predicting procedures for both tides and surges. The established methods of predicting tides, the Improved Response method of Munk and Cartwright (1966) and the Extended Harmonic method of Rossiter and Lennon (1968) are both well developed and generally extremely accurate.

Subtracting the tidal component from the observations, equation (1.1) can be rewritten as;

$$R_t = \zeta_t - \zeta_t^{(T)} = S_t + Z_t \qquad (1.2)$$

where the residual R is composed of surge component and noise.

The principal techniques for surge forecasting are (a) a regression on local barometric pressure gradients, first used by Close (1918) and Doodson (1924); (b) a more elaborate regression technique as developed by Cartwright (1968), related to the Response Method for tides; and (c) numerical models, e.g. Heaps (1969). Numerical models have been shown to be the most comprehensive, because of their flexibility in simulating the dynamics of the ocean system. However, meteorological data, used as input for such numerical models must be specified at the grid points of some predesigned representation which precludes these methods being used in the Torres Strait, where suitable meteorological data is available only from a small number of stations. A knowledge of surges, tides and currents at boundary points also contributes to the accuracy of modelling results, again a requirement that cannot be met in this study. The Response method computes a response of sea level, known as the admittance function, to the meteorological variables across a wide band of frequencies. This method, operating in the frequency domain has certain advantages because of its ability to assign different weights to different frequency components in any one parameter, but this method also was developed on the basis of data available at some 6-9 points. Additionally, it would require filtering of meteorological data. The regression technique is similar to the response method but applied in time domain. Although it is less developed than other methods it is capable of operating with considerably less meteorological data which in turn can be incorporated from random locations. Close (1918) and Doodson (1924) applied a regression technique to compute the contribution of pressure gradients on daily and monthly sea level means. Lennon (unpublished report on 'Research into storm surges at Avonmouth and Liverpool') used similar techniques and included the effects of local free oscillations in his investigation of surges in the Bristol Channel and Liverpool Bay. This approach proved to be successful in a regional sense for Avonmouth, but did not assist in the prediction of Liverpool surges because it was difficult to establish any single resonance period. Hunt (1972) and Townsend (1975) applied similar regression techniques to the surges on the east coast of Great Britain but with an additional term to account for the effects of 'external surges', that is surges which originate outside the area of investigation. To deal with external surges they included a surge from some distant port as an additional indepednent variable along with the meteorological variables, a technique also used by Cartwright (1968). This process has proved to be fairly successful and is currently used in Great Britain by the Storm Tide Warning Service. It is interesting to note that in the regression formula obtained by Townsend (1975), the external surge has the largest coefficient. However, the concept of 'external surge' is arbitrary.

DATA

The geographical positions of the stations from which sea levels and meteorological observations were available are shown in Figure 1.

Their latitudes, longitudes and recording times are listed in Table 1. The tide gauges for sea level observations were operated by the Department of Transport, Melbourne and simultaneous analogue records spanning over one and a half years were obtained from the middle of July 1974 to the end of 1975. Commonwealth Scientific and Industrial Research Organisations (CSIRO) digitized these analogue records to a resolution of one millimetre, providing final hourly values to an accuracy of ± 2 cm. There were six gaps, not exceeding 2 or 3 days, when observations were not recorded at Frederick Point. Twin Island records have two gaps each of about 10 days, and Ince Point also has two gaps of 4 and 5 days. Booby Island and Turtle Head records were continuous. However, there were some problems in Goods Island observations due to breakdowns of the tide gauge. These series of observations were checked by CSIRO (details are given in an unpublished report on 'Digitizing of Torres Strait tidal records' by M. Greig, CSIRO) for digitizing errors by comparing each value with a computed level $\zeta^{(c1)}$ based upon seven point Langrangian interpolation formula with a time interval of one hour,

$$\zeta_t^{(c1)} = -0.0049\zeta_{t-7} + 0.0410\zeta_{t-5} - 0.1709\zeta_{t-3} + 0.6836\zeta_{t-1}$$
$$+0.5127\zeta_{t+1} - 0.0684\zeta_{t+3} + 0.0068\zeta_{t+5}$$

and also with computed levels based upon five-point Langrangian interpolations over time intervals of 25 hours and one hour.

$$\zeta_t^{(c2)} = 1/6\ (-\zeta_{t-50} + 4\zeta_{t-25} + 4\zeta_{t+25} - \zeta_{t+50})$$
$$\zeta_t^{(c3)} = 1/6\ (-\zeta_{t-2} + 4\zeta_{t-1} + 4\zeta_{t+1} - \zeta_{t+2})$$

Where the difference $|\zeta_t - \zeta_t^{(c)}|$ exceeded 10 cm., the elevation ζ_t was flagged. Any such value would have been corrected only if a genuine error was found after visual examination of the analogue record. Almost simultaneous data sets spanning over a year at each station were analysed at IOS Bidston to resolve 110 harmonic constituents was based on the consideration that the tides, being mixed, could possibly have shallow water constituents of any origin, i.e. diurnal or semi-diurnal. List of constituents and frequencies is given in Table 2. These constituents, once resolved, were used to compute residuals (observed elevations - tidal predictions). The variances of residuals covering the periods of observations, are listed in Table 3. Some exceptionally high tidal oscillations are observed in Goods Island* residuals, particularly before the breakdown of the tide gauge. This anomaly is not completely resolved but the timing system of the recording device appears to be responsible since the recorded sea levels for that period appeared to be of the correct tidal height. Ince Point residuals have the smallest variance and Booby Island residuals have the largest. The meteorological data were supplied by the Australian and Papua New Guinea Meteorological Offices, and consist of barometric pressures, surface wind speeds and directions, and synoptic charts of north Australia. The observations from the various meteorological stations were recorded at different time intervals. In order to adopt a uniform timing system of three hourly observations, the interpolation of certain data was necessary. In some cases interpolation was not satisfactory because of the many missing values or the unsuitable recording time intervals (e.g. at 9.0 and 15.0 hours only). Meteorological data were tested for exceptionally large errors only. The annual mean of barometric pressures was computed for every station and each series of barometric pressure was adjusted so as to be relative to its annual mean to the least count of 1/10 of a millibar. Surface winds were resolved into two components, a u-component in the east-west direction, and a v-component in the north-south direction. These components were converted into metres/sec. (1 Knot = .51677 metres/sec.) units. The u and v-components were considered as positive when they appear to be coming from the west, and the south respectively. The means and variances of these meteorological variables are listed in Table 4. It should be noted that these statistical functions were computed from recorded values which were not at regular intervals.

Multiple regression technique for the analysis and forecasting of surges

The oceanic system which transforms the meteorological perturbations (input) into storm surges (output) is shown in Figure 2.

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* Because of its location this station was highly influenced by NW surge effects. Shortly after commissioning, the foundations which had been suspect, crumbled and despite repairs the tower tended to vibrate in high winds.

In such a system any surge S_t can be expressed in a multi-regression equation as:

$$S_t - \bar{S} = \alpha_1 (X_t^{(1)} - \overline{X^{(1)}}) + \alpha_2 (X_t^{(2)} - \overline{X^{(2)}}) \ldots\ldots \qquad (4.1)$$

$X^{(1)}, X^{(2)}, \ldots\ldots\ldots$ are meteorological variables, such as, barometric pressures or wind speeds from a station.

$\alpha_1, \alpha_2, \ldots\ldots\ldots\ldots$ are regression coefficients for variables $X^{(1)}, X^{(2)}, \ldots\ldots$ respectively.

$\overline{X^{(1)}}, \overline{X^{(2)}} \ldots\ldots\ldots$ are the means of $X^{(1)}, X^{(2)}, \ldots\ldots\ldots$ respectively,

$\bar{S} \ldots\ldots\ldots\ldots\ldots\ldots$ is the mean of the residual elevations ($\bar{S} = \bar{R}$ as $\bar{Z} = 0$)

Here the means are computed over the time interval selected to cover the appropriate surge event. The definition of time interval of surge, in a broad sense, is that period during which weather conditions are considered to be favourable to generate a surge of sufficient magnitude, such that the event can readily be isolated from the noise of residuals. The selection of this interval can be highly subjective, particularly in any forecasting procedure, when it is not necessarily true that a surge will in fact arise within what would be considered as locally favourable weather conditions. On the other hand it is relatively easy to define such intervals in past observation and these in turn can vary considerably from surge to surge.

Equation (4.1) may be written as:

$$R_t - \bar{R} = \alpha_1 (X_t^{(1)} - \overline{X^{(1)}}) + \alpha_2 (X_t^{(2)} - \overline{X^{(2)}}) + \ldots\ldots + Z_t \qquad (4.2)$$

In equation (4.2) the response of sea level at a particular place is assumed to be instantaneous. However, in reality, various time delays are expected for the sea level at a station to respond to different meteorological variables from different stations. Thus, by introducing a time lag τ associated with each variable, it is possible to account for any effective time delay between the occurrence of a particular meteorological event and the manifestation of the associated storm surge, Equation (4.2) may then be written as,

$$R_t - \overline{R} = \alpha_1 (X^{(1)}_{t+\tau_1} - \overline{X^{(1)}}) + \alpha_2 (X^{(2)}_{t+\tau_2} - \overline{X^{(2)}}) + \dots + Z_t \tag{4.3}$$

or

$$R_t = \alpha_0 + \alpha_1 X^{(1)}_{t+\tau_1} + \alpha_2 X^{(2)}_{t+\tau_2} + \dots\dots\dots + Z_t \tag{4.3a}$$

where

$$\alpha_0 = \overline{R} - (\alpha_1 \overline{X^{(1)}} + \alpha_2 \overline{X^{(2)}} + \dots\dots\dots)$$

giving

$$S_t = \alpha_0 + \alpha_1 X^{(1)}_{t+\tau_1} + \alpha_2 X^{(2)}_{t+\tau_2} + \dots\dots\dots \tag{4.3b}$$

When the 'noise' term Z_t is neglected from equation (4.3a), we get $\hat{R}_t = S_t$, i.e. the estimate $\hat{R}_t$ of residual R_t should approximate the recorded surge S_t, and furthermore if all possible meteorological parameters are not included in equation (4.3b) (i.e. only finite number of terms are retained in it) then equation (4.3b) gives:

$$\hat{R}_t = \hat{S}_t = \alpha_0 + \alpha_1 X^{(1)}_{t+\tau_1} + \dots\dots\dots \alpha_m X^{(m)}_{t+\tau_m} \tag{4.3c}$$

where $\hat{S}_t$ is a surge estimate or predictable surge.

In equation (4.2) the residual elevations R_t and meteorological parameters, barometric pressure and wind speed $X^{(1)}$, $X^{(2)}$, ..., are in different units. This creates difficulties in making any comparison between values of the regression coefficients α_1, α_2, etc. and the selection of criteria for neglecting those meteorological variables to which sea level has little or no response. It is, therefore, useful to convert all these variables into dimensionless quantities by normalising them with respect to their standard deviations. The equations (4.3) and (4.3a) can be rewritten:

$$\frac{R_t - \overline{R}}{s_R} = A_1 \frac{(X^{(1)}_{t+\tau_1} - \overline{X^{(1)}})}{s_1} + A_2 \frac{(X^{(2)}_{t+\tau_2} - \overline{X^{(2)}})}{s_2} + \dots + Z_t \tag{4.4}$$

$$\frac{R_t}{s_R} = A_0 + A_1 \frac{X^{(1)}_{t+\tau_1}}{s_1} + A_2 \frac{X^{(2)}_{t+\tau_2}}{s_2} + \dots\dots\dots Z_t \tag{4.4a}$$

where $A_0 = \frac{\overline{R}}{s_R} - (\frac{A_1}{s_1} \overline{X^{(1)}} + \frac{A_2}{s_2} \overline{X^{(2)}} + \dots\dots\dots$ and

s_R, s_1, are standard deviations of R, $X^{(1)}$, ... respectively, it is seen that $\alpha_1 = A_1 \, s_R / s_1$, ... (4.4b)

and equation (4.3b) enables one to compute α's from A's.

Statisticians find preference in equations of type (4.3) and (4.4) which have only m regression coefficients for m independent variables. These equations cannot be used in surge forecasting because the means $\overline{R}$, $\overline{X^{(1)}}$, ..., which always vary from one surge to another surge, will be unknown. In analysis, these means are also heavily biased by short and variable duration of surges and introduce some error in regression coefficients. The errors in these regression coefficients can be linearly combined to give A_0, by rearranging equation (4.4a). For these reasons, it is preferable to use equation (4.4a) with equation (4.4b) for analysis of surges since the means are known, and equations (4.3c) for forecasting, using method described later in this section to estimate .

In the time subset (t=0,1,2 ....N), equation(4.4a) will give a set of N+1 equations (augmenting every meteorological series according to its time lag) which in matrix form, if m variables are included, can be written as:

$$\mathbf{R} = \mathbf{X}\mathbf{A} + \mathbf{Z} \qquad (4.5)$$

where $\mathbf{R}$, $\mathbf{X}$ and $\mathbf{A}$ are transpose of $\mathbf{R}'$, $\mathbf{X}'$ and $\mathbf{A}'$ respectively.

$$\mathbf{X}' = \begin{pmatrix} 1 & 1 & \cdots\cdots\cdots & 1 \\ \frac{X^{(1)}_{\tau_1}}{s_1} & \frac{X^{(1)}_{\tau_1+1}}{s_1} & \cdots\cdots\cdots & \frac{X^{(1)}_{\tau_1+N}}{s_1} \\ \frac{X^{(2)}_{\tau_2}}{s_2} & \frac{X^{(2)}_{\tau_2+1}}{s_2} & \cdots\cdots\cdots & \frac{X^{(1)}_{\tau_2+N}}{s_2} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{X^{(m)}_{\tau_m}}{s_m} & \frac{X^{(m)}_{\tau_m+1}}{s_m} & \cdots\cdots\cdots & \frac{X^{(m)}_{\tau_m+N}}{s_m} \end{pmatrix} \qquad N > m \qquad (4.6)$$

$$\mathbf{R}' = \left(\frac{R_0}{s_R} , \frac{R_1}{s_R} \quad \cdots\cdots\cdots\cdots \quad \frac{R_N}{s_R}\right) \qquad (4.7)$$

$$\mathbf{A}' = (A_0 , A_1 \quad \cdots\cdots\cdots\cdots \quad A_m) \qquad (4.8)$$

Since $\mathcal{Z}$ is assumed as uncorrelated with the input variables, therefore, the least squares solution of the system of normal equations (4.5), will by minimising the $\langle(R-S)^2\rangle$ give;

$$\mathbf{X}'\mathbf{X} \ \mathbf{A} = \mathbf{X}'\mathbf{R} \qquad (4.9)$$

$$\mathbf{A} = (\mathbf{X}'\mathbf{X})^{-1} (\mathbf{X}'\mathbf{R}) \qquad (4.10)$$

The quality of estimate of $\mathbf{A}$ from equation (4.10) depends upon the noise level and the inclusion of all possible meteorological variables which contribute to the surge, however, this is clearly not possible. Equation (4.4b) is used to calculate α from $\mathbf{A}$. In system of equations (4.6), one lag is used for each meteorological variable, but any number of lags which are present can be introduced for each variable by simply inserting additional rows in $\mathbf{X}'$ and $\mathbf{A}$. Hence equation (4.3c) will give an estimate of residuals or surge (R=S), because of the finite number of input variables.

Application of Multiple Regression techniques

To apply the multiple regression technique to forecast the surges at all Torres Strait stations requires:

(1) establishing a correlation between high frequency (>0.8 cycles per day) components of surges and meteorological variables.

(2) subgrouping of stations so that surges at various stations within each subgroup have common characteristics.

(3) choosing effective meteorological variables (e.g. barometric pressure u-component or v-component of surface wind speed, from various meteorological stations), and

(4) determining the mean value of each variable which depends upon the selected interval of the surge.

The preliminary study of extreme surges at the various stations, together with the available meteorological data, failed to establish any significant relationships between high frequency components of surge and the corresponding spectral components of meteorological variables. Reference to Figure 3 shows that there are clearly defined peaks at the frequencies of 1, 2 cycles/day in the spectra of meteorological observations, due to the atmospheric tides. The effects of these peaks in weather spectra on sea level must have been accounted for by harmonic constituents of the same frequency as in the tidal analysis. It has been observed that often barometric pressures were not recorded for 12 hours at an interval of one week. Attempts to interpolate these values were not successful because some values before these gaps were also suspicious. This artificial modulation resulted in side peaks which are separated by a period of about one week. However the spectrum of tidal residuals shows that energy is distributed in wide bands across the same frequencies, indicating a complex distribution which precludes the computation of satisfactory regression coefficients with the meteorological events. Cartwright (1968) was able to obtain relationships by prior elimination of the tidal bands. There is no simple relationship between the high frequency regions of sea level residual spectrum and weather spectra if one includes the tidal bands. The meteorological data were filtered to separate both the high and low frequency components and the interaction of these components with the surges was examined by cross correlation techniques. The results established that the high frequency components of meteorological data bore little relationship to a generated surge, but instead, a high correlation existed between a generated surge and the low frequency component of meteorological parameters. This result suggests that the high frequency components of a surge must be mainly due to a tide-surge interaction or some other non-linear mechanism. To further provide the necessary span of meteorological data in a low frequency form it was desirable to "filter" the original digital data by a technique which did not incur the usual setback of filtering processes, namely, the truncation of data at either end of the series. A suitable procedure was found by using the method of least squares to fit a second degree polynomial function to the meteorological data. This function, with a period of 24 hours is used in a stepwise process to compute the necessary low frequency data required. This method also allows one to incorporate any forecast data available for a particular meteorological parameter, and in turn to self-predict these data if the meteorological data is not available. In a "real time" situation an iterative process is required to continuously match (update) the self-predicted meteorological parameters with any new station forecast of these parameters.

It was possible to sub-divide the six Torres Strait stations into two groups by examining the evidence as indicated in;

(a) Table 3 of residual variance,
(b) cross-correlation functions in Figure 4 and,
(c) filtered components of individual surges in Figure 5a, obtained by applying a low pass filter of response shown in Figure 5b.

One sub-group will consist of Frederick Point and Twin Island and the other sub-group will include Booby Island, Goods Island and Turtle Head. Ince Point behaves in a remarkable way, in that weather effects seem to have very little influence on the sea level there. The surges in each group have common characteristics in that they are almost in phase and can be related, one to another, by an almost constant amplitude ratio. Thus if a surge at one station in a group is predicted, the surges generated at the other stations in that group can be estimated.

In order to determine the regression coefficients, Frederick Point and Booby Island surges were selected because of their high residual variances in the respective groups. Meteorological data (barometric pressure, u-component and v-component of wind) from three stations, Thursday Island, Port Moresby and Willis Island were used as input for the analysis of Frederick Point surges. Initially, each meteorological variable was correlated with the surge individually for a first approximation of the cross-correlations. A simultaneous solution was then sought for regression coefficients using the normal system of equations (4.10). For an optimal solution of the system a slight variation in the time lags obtained by the first approximation was also allowed. For an optimal solution at Frederick Point, the equation (4.3c) assumed the form

$$\hat{S}_t = \alpha_1 X^{(1)}_{t+\tau_1} + \alpha_2 X^{(2)}_{t+\tau_2} + \alpha_3 X^{(3)}_{t+\tau_3} \qquad (5.1)$$

where $X^{(1)}$ is the u-component of wind at Thursday Island,
$X^{(2)}$ is the u-component of wind at Willis Island and
$X^{(3)}$ is the v-component of wind at Willis Island.

Other parameters have little or no contribution to the generation of surges. The computed estimates of partial regression coefficients* averaged over the different surges are as follows:

$\alpha_1 = -0.008$ $\qquad \tau_1 = -9$ hours

$\alpha_2 = -0.008$ $\qquad \tau_2 = -18$ hours

$\alpha_3 = 0.004$ $\qquad \tau_3 = -18$ hours

A similar fitting operation was carried out on Booby Island surges with meteorological data from four stations, Thursday Island, Weipa, N.E. Island and Cape Wessel. The regression model was tested with both linear and squared wind speed as input to account for the large magnitude of surges. In this case an optimal solution was achieved when equation (4.3c) assumed the form

$$\hat{S}_t = \alpha_1 X^{(1)}_{t+\tau_1} + \alpha_2 X^{(2)}_{t+\tau_2} \qquad (5.2)$$

where $X^{(1)} = U_1 . W_1$, U_1 is u-component of wind speed W_1 at Thursday Island,

$X^{(2)} = U_2 . W_2$, U_2 is u-component of wind speed W_2 at Cape Wessel,

$\alpha_1 = 0.0014$ $\qquad \tau_1 = 6$ hours

$\alpha_2 = 0.0018$ $\qquad \tau_2 = -9$ hours

Equations (5.1) and (5.2) show that surges at Frederick Point are linearly proportional to wind speed whereas surges at Booby Island are proportional to the square of the wind speed, but in both cases the major contribution arises from the east-west wind. The forecast surges based on equations (5.1) and (5.2) are shown in Figures 6a and 6b. It is worth noting that the constant α_0 as defined in equation (4.3c) is not given in equations (5.1) and (5.2). During the analyses of various surges it was found that α_0 varied enormously from surge to surge, and consequently, it was difficult to include it into these equations which represent an average response. When regression analysis was based on equation (4.4) which does not have A_0, then the scatter of A_0 is considered to be distributed in A_1 and A_2 and their values obtained from different surges have greater variation than the corresponding values which were computed using equation (4.4a). This is, in fact. the main reason for using

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* when u-component and v-component are in metre/second, and R and S are in metres.

equation (4.4a) in place of equation (4.4) in the analysis. It is evident that the problem of defining the surge datum remains unresolved so long as α_0 is not known. Physically, this means there are low frequency variations in sea level not due to weather (e.g. steric variations). In addition, the diurnal and semi-diurnal components, considered as being due to surge tide interaction required further attention. To investigate this, an autoregressive technique was applied to the residual surge $S_t^{(r)} (=R_t - \hat{S}_t)$. The procedure of Hunt (1972) and Townsend (1975) as applied to a surge propagating in space was modified for auto predictions in the time domain. In the application of the autoregressive technique it was assumed that diurnal and semi-diurnal components, originating from surge-tide interaction would develop, and disappear slowly. This assumption was made on the basis of visual examination of these components when separated after filtering. Thus an estimate can be obtained from the previous tidal cycle to improve the meteorological surge estimate of the next tidal cycle 12 hours in advance. In auto-regression, any future value is expressed in terms of present and past observations as:

$$S_t^{(r)} = b_1 S_{t-1}^{(r)} + b_2 S_{t-2}^{(r)} + \dots\dots \qquad (5.3)$$

The best estimation $\hat{S}^{(r)}$ of residual surge was obtained when equation (5.3) assumed the form;

for Frederick Point $$\hat{S}_{t+12}^{(r)} = 0.10\ S_t^{(r)} + 0.65\ S_{t-12}^{(r)} \qquad (5.4)$$

and for Booby Island $$\hat{S}_{t+12}^{(r)} = 0.20\ S_t^{(r)} + 0.55\ S_{t-12}^{(r)} \qquad (5.4b)$$

Therefore the improved surge forecast $S^{(I)}$ will be given by

$$S_t^{(I)} = \hat{S}_t + \hat{S}_t^{(r)} \qquad (5.5)$$

While this process is able to account for both α_0 and the component resulting from surge-tide interaction to a sufficient accuracy, it has one shortcoming in that it may introduce some error when the surge behaves in an abnormal fashion. This is clear from the surge at Booby Island on January 15, 1975, see Figure 6b, when it fell unexpectedly on 16th January conflicting with the meteorologically forecasted surge, and thus introducing an error in the improved surge forecast (based on auto-regression) for 17th of January. A scheme to compute surges is given in Appendix A.

DISCUSSION ON RESULTS AND CONCLUSIONS

The statistical analyses of surges and meteorological observations show that easterly winds are dominant in the region of the Torres Strait. The weather maps are generally complex with multiple depressions and adjoining high pressure systems. This fact made it difficult to establish any relationship between the spatial pressure gradients and the associated storm surges. The east-west component of wind is mainly responsible for the generation of surges, however it has no significant effect on sea level when its magnitude is less than 12 metres/second. Therefore only those periods when the u-component of wind speed remained above 12 metres/second for more than 3 hours were investigated. Booby Island, Goods Island and Turtle Head (i.e. on the west of Ince Point) surges are positive with a westerly wind and negative with an easterly wind, while the opposite is true of surges at Frederick Point and Twin Island. The cross-correlation functions of Booby Island residuals with residuals from other stations computed from data extending over one year, shown in Figure 4, provide evidence that this relationship must be true, in general, even for very small sea level variations which under ordinary circumstances may not look like surges. Frederick Point surges are linearly proportional to the wind speed while Booby Island surges are proportional to wind stress (i.e. proportional to the square of the wind speed). Although surges in a subgroup have common relationships, these relationships do not hold when surges are very small. A few anomalies which were noted in forecast surges are discussed here:

January 8-27, 1975 Surge:

This is the largest surge observed in a one and a half year period (from July 1974 to December 1975). At its peak it exceeded the tidal predictions by 74cm. It commenced with the development of strong westerly winds (from south) on the north west coast and Cape Wessel on January 13 which reached their maximum on 14th. Two minor depressions simultaneously developed on the 14th January, one near Kowanyama and the other near Cooktown. These started levelling off soon and at about 18.00 hours local time, a new depression known as Gloria, started developing in the middle of Cairn and Cooktown. This new depression deepened and at the same time started moving towards the south-east at a speed of about 15 knots. At noon, on 15th January, its speed decreased and when it approached the position Lat. 17^{o}-30', Long. 148^{o}-30', the barometric pressure was nearly 990.7 m.b. and its speed about 5 knots. By midnight this depression was at the deepest level of 988.8 m.b. This moving field of low pressure gave rise to a very strong westerly wind at Thursday Island which reached its maximum at about midnight of 15th January and continued almost at the same level for one day. The depression started moving further south-east in the early hours of the 17th January and the wind speed at Thursday Island started decreasing. The forecast surge is in good agreement with the observed surge until the surge reached its peak after which recorded and forecast values started diverging. The forecast surge then remained near its peak for one day, as expected from the weather, while the observed surge started decreasing as soon as its maximum was attained. This anomaly is difficult to explain within the limits of the present model, but it may be due to ; (a) a north south pressure gradient or (b) the set up of a sea level gradient, since only a small surge was expected in the south of Booby Island near Kowanyama because of winds of less strength in this region. These aspects of the model could not be investigated because of the inadequacy of the meteorological data. According to the synoptic charts, barometric pressure at Kowanyama was expected to be lower than that of Thursday Island but digitized records show that these were similar in magnitude. It is interesting to note that the forecast of Frederick Point surge during this period is reasonably good.

February 6-25, 1975 Surge:

The forecast of this surge was inaccurate both at Booby Island and Frederick Point. It is worth noting that there was -20cm and 15cm difference in mean sea level at Booby Island and Frederick Point respectively during calm local weather on 5th to 8th February. Obviously, some external forces were acting which led to the mass transport of water from outside thus upsetting the balance of local forces.

A similar discrepancy is observed in September 1-14, 1975, surge at Frederick Point on September 9-14.

It has been found that the problems of the difference in mean sea level, oscillations in Booby Island surges of period 3-4 days and occurrence of surges in calm weather conditions, are observed frequently. The free period of the Gulf of Carpentaria, as computed by Melville and Buchwald (1976) is 30-40 hours. The oscillations of 3 to 4 day period, displayed in Figure 3 and figure 5a, have no contribution from the local meteorology and must have been excited by external forces. Wunsch and Gill (1976) observed similar 4-day oscillations in the equatorial region (bounded by 10th parallels) of the Pacific. They could not establish any relationship between weather spectra and the spectrum of tidal residuals at 4-day cycle which led them to conclude that it could be due to oceanic resonance. However it would be difficult to establish that Booby Island oscillations of 3-4 days period are transported from the Pacific because firstly, no such oscillation is observed at Frederick Point, secondly, as already discussed, the shallow reefs near Ince Point are acting almost as a barrier which tends to stop any communication between the Pacific and the Gulf of Carpentaria. These oscillations are generally damped but appear to be magnified when they occur after the surge which shows they are locally generated seiches. The period of these oscillations differ from surge to surge, varying from 3 to 4 days. This variation in period of oscillation has limited the accuracy of the autoregression process used to estimate the surge-tide interaction. The difference in mean values between the forecast and observed surges, together with the oscillations described above would suggest the presence of a strong current around Cape Wessel. Also the opposite surges observed at Frederick Point and Booby Island will tend to set up a sea level gradient, again resulting in a strong current in the vicinity of Ince Point. It is difficult to answer these questions within the scope of the present regression model. However, it is suggested that if currents were monitored in the regions of Cape Wessel and Ince Point it would provide valuable information to make some qualitative assessment about the interference of external surges. Although the relationships between the surges and wind at distant places have been established, the actual physics of the process requires more research. In general, all these unsolved problems could only be examined by a comprehensive model capable of simulating the physics of the whole system including the related areas beyond the Torres Strait and the Gulf of Carpentaria.

APPENDIX A

ALGORITHM FOR FORECASTING SURGES

When a weather forecast is expected to generate a surge, i.e. the east/west component of surface wind at any related meteorological stations exceeds 12 metres/second, then

A For Frederick Point:

(1) Obtain the surface wind observations of Thursday Island and Willis Island from previous three days as well as those winds forecast.

(2) Resolve each into u and v components.

(3) Smooth these components by the least squares technique fitting a second degree polynomial to observations of one day (9 three hourly values), selecting 12 hours on either side of the value to be estimated. This smoothing operation is not unique, any other procedure can be used even graphic smoothing can achieve similar result. The smooth estimations for the last 12 hours should be computed from the last polynomial and updated as soon as a new forecast is available.

(4) Compute the meteorological surge estimate $\hat{S}$ using equation (5.1).

(5) Calculate tidal residuals R by subtracting tidal predictions from tidal observations for the same interval as meteorological observations are collected.

(6) Compute the residual surge $S_t^{(r)} (=R_t - \hat{S}_t)$.

(7) Predict the residual surge $\hat{S}^{(r)}$ by equation (5.3).

(8) Compute the final improved surge estimate $S^{(I)}$ using equation (5.5).

B For Twin Island surges:

If local tidal observations are available then follow the same steps as in A except step 5 where the tidal observations and predictions of <u>Twin Island should be used</u>.

If local observations are not available then follow the steps 1-6 as in A and then to compute the improved surge estimate use equation,

$$S_t^{(I)} = 0.85 \left(\hat{S}_t + \frac{0.8}{13} \sum_{t=o}^{-12} S_t^{(r)}\right)$$

C For Booby Island Surges:

(1) Obtain the surface wind observations of Thursday Island and Cape Wessel for the previous three days together with those winds forecast.

(2) Resolve each into u and v components.

(3) Same as step 3 in A.

(4) Compute meteorological surge estimate $\hat{S}$, using equation (5.2).

(5) Compute tidal residuals R, by subtracting Booby Island tidal predictions from its observations for the same interval as meteorological observations are collected.

(6) Compute the residual surge $S_t^{(r)}$ ($= R_t - \hat{S}_t$).

(7) Predict residual surge $S^{(r)}$ by auto-regression formula as in equation (5.4).

(8) Compute the final improved surge estimate $S^{(I)}$ using equation (5.5).

D For Goods Island and Turtle Head Surges:

If local tidal observations are available, then proceed as for Booby Island surges but modifying steps 4 and 5 as:-

Goods Island

(4) Compute the meteorological surge estimate $\hat{S}$ using equation (5.2) and then set $\hat{S}_t = 0.8\hat{S}_t$

(5) Compute R, using local predictions and tidal observations.

Turtle Head

(4) Compute meteorological surge estimate $\hat{S}$ using equation (5.2) and then set $\hat{S}_t = 0.5\hat{S}_t$

(5) Compute R, using local tidal predictions and observations.

If local tidal observations are not available then repeat step 1-6 as in C and compute the improved surge estimate as:-

Goods Island:

(7) $S_t^{(I)} = 0.8 \left(\hat{S}_t + \frac{0.8}{13}\sum_{t=0}^{-12} S_t^{(r)}\right)$

Turtle Head:

(7) $S_t^{(I)} = 0.5 \left(\hat{S}_t + \frac{0.8}{13}\sum_{t=0}^{-12} S_t^{(r)}\right)$

ACKNOWLEDGEMENTS

I am very grateful to Professor G. W. Lennon and Mr. J. Graff for their suggestions and remarks, and Dr. D. E. Cartwright for his criticism on the work presented in this report.

The report is published with the permission of the Department of Transport, Melbourne, Victoria, Australia, which financed this project.

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FIGURE CAPTIONS

Figure 1 Map of Torres Strait showing the locations of tidal and meteorological stations.

Figure 2 A simple system with multiple input and a single output.

Figure 3 Spectra of tidal residuals of Booby Island, and meteorological observations of Thursday Island, over the period August 1974 to December 1975: R, tidal residuals; u, u-component of wind; v, v-component of wind and P, barometric pressure.

Figure 4 Cross-correlations function of Booby Island tidal residuals with;
(a) Frederick Point, (b) Twin Island, (c) Ince Point,
(d) Turtle Head and (e) Goods Island.

Figure 5a Surges passed through low-pass filter;
(i) tidal surges (a) Booby Island, (b) Turtle Head,
(c) Frederick Point, (d) Twin Island, and (ii) meteorological surges of Thursday Island,
(e) barometric pressures, (f) v-component of wind,
(g) u-component of wind.

Figure 5b The response of the low-pass filter used to eliminate high frequency components of surges and meteorological observations.

Figure 6a Storm surges at Frederick Point;

________ observed storm surge,

xxxxxxxx meteorological surge forecast computed from meteorological observations only, and

.... meteorological surge forecast after improving by autoregression.

Figure 6b Storm surges at Booby Island;

________ observed storm surge,

xxxxxxxx meteorological surge forecast computed from meteorological observations only, and

.... meteorological surge forecast after improving by autoregression.

TABLE 1

A list of tidal and meteorological stations for which observations are used in surge study of Torres Strait.

Station	Lat. South	Long. East	Data	Recording Times
Frederick Point (Albany Island)	10-43,	142-35	Tide	hourly
Twin Island	10-27.5,	142-26	Tide	hourly
Ince Point (Wednesday Island)	10-30,	142-18.5	Tide	hourly
Turtle Head	10-31.5	142-12.5	Tide	hourly
Goods Island	10-34,	142-09	Tide	hourly
Booby Island	10-36.5,	141-54.5	Tide	hourly
Willis Island M.O.	16-18,	149-59	(Barometric Pressure (surface wind	3 hourly
Port Moresby	09-27,	147-12	(Barometric Pressure (surface wind	3 hourly
Iron Range Aero	12-47	143-18	(Barometric Pressure (surface wind	3 hourly
Thursday Island M.O.	10-35,	142-13	(Barometric Pressure (surface wind	3 hourly
Weipa	12-47,	141-53	(Barometric Pressure (surface wind	6 hourly
Cape Wessel	11-01,	136-43	(Barometric Pressure (surface wind	3 hourly
N.E. Island	13-39,	136-57	(Barometric Pressure (surface wind	3 hourly

TABLE 2

List of constituents resolved from tidal observations. Time zone = 'U'.

Name	Speed (deg.hr^{-1})	Booby Island H (mm)	Booby Island g (deg)	Goods Island H (mm)	Goods Island g (deg)	Turtle Head H (mm)	Turtle Head g (deg)	Ince Point H (mm)	Ince Point g (deg)	Twin Island H (mm)	Twin Island g (deg)	Frederick Point H (mm)	Frederick Point g (deg)
1 Sa	0.04107	284	311.34	240	316.00	147	313.88	077	339.54	042	35.42	039	67.84
2 Ssa	0.08214	034	332.51	029	358.06	024	57.91	028	41.79	053	62.56	055	73.86
3 Mm	0.54437	025	70.04	027	53.02	015	191.22	008	266.88	013	281.92	020	254.28
4 Msf	1.01590	028	355.05	023	358.37	034	185.07	011	37.71	008	329.74	006	104.74
5 Mf	1.09803	030	278.15	021	260.65	023	229.72	003	2.60	000	65.89	006	123.36
6 $2Q_1$	12.85429	018	270.43	021	284.47	008	289.05	005	305.70	007	316.60	003	312.84
7 σ_1	12.92714	013	335.31	014	324.23	009	103.57	007	82.82	009	92.04	008	118.93
8 Q_1	13.39866	088	322.93	079	330.48	067	338.83	050	342.30	043	353.69	038	351.17
9 ρ_1	13.47151	018	308.87	019	353.92	017	330.24	015	355.35	013	4.59	012	2.23
10 O_1	13.94304	442	351.84	417	358.85	357	5.73	273	9.37	234	15.15	214	16.11
11 MP_1	14.02517	024	87.71	026	103.82	028	133.50	031	161.02	034	167.73	029	171.12
12 M_1	14.49205	014	9.75	020	29.92	013	27.55	010	32.10	007	59.30	008	50.05
13 χ_1	14.56955	007	355.06	021	36.15	011	346.57	008	33.05	006	29.83	008	24.01
14 π_1	14.91786	016	44.73	025	104.60	017	52.21	013	69.33	013	74.31	012	60.37
15 P_1	14.95893	187	37.97	181	45.20	169	48.26	148	54.55	144	56.81	135	55.88
16 S_1	15.00000	035	250.75	045	270.25	025	257.11	023	247.54	017	256.27	011	237.52
17 K_1	15.04107	715	43.78	679	50.72	629	54.40	546	57.52	501	59.30	466	57.92

cont:

Name	Speed (deg.hr^{-1})	Booby Island H (mm)	Booby Island g (deg)	Goods Island H (mm)	Goods Island g (deg)	Turtle Head H (mm)	Turtle Head g (deg)	Ince Point H (mm)	Ince Point g (deg)	Twin Island H (mm)	Twin Island g (deg)	Frederick Point H (mm)	Frederick Point g (deg)
18 ψ_1	15.08214	016	50.53	020	169.77	012	88.82	014	70.09	015	65.60	010	60.28
19 φ_1	15.12321	014	72.65	029	84.90	013	107.92	010	90.38	009	86.40	009	74.10
20 θ_1	15.51259	010	34.05	004	110.87	007	42.03	005	36.39	005	9.20	005	8.32
21 J_1	15.58544	014	74.14	013	78.75	017	122.60	014	131.06	019	134.47	017	114.56
22 SO_1	16.05696	029	278.80	035	286.55	013	220.68	017	208.82	020	163.91	018	153.88
23 OO_1	16.13910	042	133.68	046	141.73	045	135.62	036	141.88	034	138.60	032	131.96
24 $2MN2S_2$	26.40794	003	152.74	004	164.79	004	210.29	005	193.04	005	198.17	005	198.15
25 $3M(SK)_2$	26.87018	005	235.55	011	228.35	004	289.54	004	300.05	007	305.45	005	349.59
26 $3M(2S)_2$	26.95232	003	101.43	003	55.17	004	296.65	004	324.76	004	348.84	004	325.17
27 OQ_2	27.34171	011	326.27	010	323.68	010	2.04	004	335.03	005	332.65	005	334.46
28 MNS_2	27.42383	005	195.89	004	341.94	002	5.22	011	4.47	013	351.86	010	359.77
29 $M\nu S_2$	27.49669	003	134.74	005	35.11	003	353.58	007	42.81	006	32.83	004	44.21
30 $2N_2$	27.89536	038	128.55	034	136.45	027	126.30	029	93.61	026	74.75	025	50.16
31 μ_2	27.96822	004	5.79	009	246.60	038	35.40	053	44.68	061	33.25	055	33.31
32 SNK_2	28.35759	006	45.34	023	185.00	003	22[illegible].72	006	150.80	010	181.10	005	152.55
33 NA_2	28.39867	004	10.96	022	119.38	004	105.69	005	134.05	013	196.83	002	213.71
34 N_2	28.43973	171	158.29	153	158.27	133	115.65	166	88.74	196	69.41	209	49.81
35 ν_2	28.51257	032	166.96	030	184.16	026	131.23	024	108.83	031	75.80	037	50.77
36 OP_2	28.90198	009	22.78	009	110.06	021	8.59	015	58.74	009	57.27	015	71.37

cont:

Name	Speed	Booby Island		Goods Island		Turtle Head		Ince Point		Twin Island		Frederick Point	
	(deg.hr^{-1})	H (mm)	g (deg)	H (mm)	g (deg)	H (mm)	g (deg)	H (mm)	g (deg)	H (mm)	g (deg)	H (mm)	g (deg)
37 MA_2	28.94304	022	**171.35**	024	**327.04**	031	**169.33**	024	**260.40**	027	**279.25**	017	**278.50** *
38 $\mathbf{M_2}$	28.98410	733	200.10	519	204.71	335	167.32	367	111.94	503	83.08	596	62.10
39 MB_2	29.02518	006	**74.83**	042	**305.65**	030	**15.82**	001	**149.73**	004	**89.63**	010	**286.77** *
40 MKS_2	29.06624	003	299.39	025	319.60	014	354.70	011	28.34	010	**105.39**	012	65.89
41 λ_2	29.45563	002	245.86	015	191.94	006	291.62	012	338.52	020	326.63	009	323.73
42 L_2	29.52847	018	256.69	021	290.91	034	334.14	035	335.44	048	343.69	043	334.23
43 $2SK_2$	29.91786	003	223.40	019	175.26	004	221.90	003	350.19	005	156.58	006	206.97
44 T_2	29.95892	012	291.60	027	33.78	021	15.77	031	16.04	033	21.29	039	6.20
45 S_2	30.00000	138	321.94	194	5.78	299	27.36	419	38.86	503	37.97	512	27.81
46 R_2	30.04108	004	317.32	018	326.50	014	326.67	009	32.99	008	9.67	006	12.17
47 K_2	30.08214	045	290.12	062	337.95	074	8.12	103	29.29	129	31.48	145	21.26
48 MS_2	30.47153	003	87.24	008	23.28	004	12.84	003	177.74	006	233.57	005	261.16
49 MSN_2	30.54437	002	302.77	018	304.23	008	233.80	019	221.83	020	197.15	013	204.10
50 KJ_2	30.62651	005	135.92	018	91.26	004	29.46	001	168.70	008	286.55	004	313.27
51 $2SM_2$	31.01590	013	252.94	024	231.64	019	188.36	022	185.03	022	176.78	025	158.07
52 SKM_2	31.09802	005	298.51	012	113.20	008	142.81	015	**162.30**	019	147.06	015	138.25
53 MQ_3	42.38277	012	126.77	010	147.46	007	46.47	005	267.78	011	283.52	008	267.45
54 MO_3	42.92714	029	163.27	024	172.01	016	77.63	008	**276.31**	017	306.79	012	308.41

*** Values of g for constituents MA_2 and MB_2 are changed according to notes issued by Dr. D. E. Cartwright on November 15, 1977.**

cont:

Name	Speed (deg.hr^{-1})	Booby Island H (mm)	Booby Island g (deg)	Goods Island H (mm)	Goods Island g (deg)	Turtle Head H (mm)	Turtle Head g (deg)	Ince Point H (mm)	Ince Point g (deg)	Twin Island H (mm)	Twin Island g (deg)	Frederick Point H (mm)	Frederick Point g (deg)
55 $2MP_3$	43.00928	005	272.73	007	272.00	009	286.24	007	296.93	005	274.08	005	236.61
56 M_3	43.47617	012	94.48	011	102.54	007	75.94	008	150.84	007	166.97	006	133.54
57 SO_3	43.94304	022	250.20	021	262.98	020	305.86	035	284.65	030	283.40	016	254.59
58 MK_3	44.02518	033	190.66	031	193.78	029	138.66	005	273.80	017	358.64	011	8.20
59 $2MQ_3$	44.56955	001	219.28	003	5.59	001	279.85	002	105.09	004	115.70	000	291.50
60 SK_3	45.04108	016	325.25	019	318.37	023	358.71	024	343.65	020	339.21	014	321.06
61 $2MNS_4$	56.40794	002	221.30	003	177.19	004	149.99	001	168.97	001	303.48	002	61.82
62 $3MK_4$	56.87018	003	309.46	003	9.67	005	303.20	003	78.94	004	95.23	002	3.65
63 $3MS_4$	56.95232	005	207.24	006	171.95	006	197.69	003	334.94	007	346.10	003	1.58
64 MN_4	57.42383	003	297.52	010	20.65	032	342.53	025	48.46	026	52.75	009	31.25
65 $M\nu_4$	57.49669	001	273.59	002	159.69	004	330.78	006	82.94	006	50.92	003	27.61
66 $2MSK_4$	57.88606	001	213.89	005	168.34	004	215.36	003	155.91	006	77.09	004	64.04
67 M_4	57.96822	010	37.55	034	52.26	072	9.82	052	74.88	047	81.91	013	68.37
68 SN_4	58.43973	006	115.56	008	106.60	010	31.36	008	37.28	011	**13.52**	008	335.86
69 $3MN_4$	58.51257	002	125.70	008	95.04	007	25.63	003	358.01	011	330.51	007	312.73
70 MS_4	58.98410	016	110.52	026	95.65	042	16.45	022	99.97	023	80.90	008	192.25
71 MK_4	59.06624	012	93.66	012	87.12	020	15.70	010	56.06	011	18.28	007	336.84
72 $2MSN_4$	59.52847	002	22.11	004	14.24	010	323.05	005	280.34	007	266.96	006	229.88
73 S_4	60.00000	004	61.24	003	71.90	011	9.93	005	347.46	007	359.61	004	328.76

cont:

Name	Speed (deg.hr^{-1})	Booby Island		Goods Island		Turtle Head		Ince Point		Twin Island		Frederick Point	
		H (mm)	g (deg)	H (mm)	g (deg)	H (mm)	g (deg)	H (mm)	g (deg)	H (mm)	g (deg)	H (mm)	g (deg)
74 SK_4	60.08214	001	117.17	002	283.71	007	329.21	008	280.41	007	308.93	007	296.39
75 $2MO_5$	71.91124	008	189.64	007	196.70	007	299.49	006	320.58	006	326.89	003	23.44
76 M_5	72.46027	002	133.79	003	127.88	007	241.27	007	253.16	006	240.03	001	209.86
77 MSO_5	72.92714	011	303.63	009	327.73	013	39.94	011	40.03	008	42.01	005	165.19
78 SMK_5	73.00928	005	249.22	009	256.86	013	332.12	011	349.13	008	344.38	003	198.04
79 MSK_5	74.02518	012	183.31	011	200.82	013	247.22	009	242.11	004	218.09	007	51.33
80 $2(MN)S_6$	84.84767	000	242.29	001	192.62	000	107.93	001	345.09	001	54.45	001	77.70
81 $3MNS_6$	85.39204	001	330.21	001	196.98	000	272.62	001	139.94	003	137.97	003	129.80
82 $4MK_6$	85.85428	002	139.64	002	50.09	002	28.13	003	339.11	003	300.55	004	267.22
83 $4MS_6$	85.93642	001	35.23	000	225.10	002	26.34	001	187.14	003	206.08	003	180.87
84 $2MSNK_6$	86.32581	001	355.34	002	1.12	001	55.29	002	133.17	002	154.99	001	153.69
85 $2MN_6$	86.40794	008	117.71	008	75.29	004	16.54	010	289.80	014	272.59	014	250.68
86 $2M\nu_6$	86.48079	001	77.85	002	124.54	001	48.73	002	253.18	003	223.48	003	226.91
87 $3MSK_6$	86.87018	003	40.10	003	35.55	003	88.02	002	166.34	003	213.24	005	205.04
88 M_6	86.95232	009	138.30	012	88.04	004	15.97	016	304.31	021	291.80	018	272.32
89 MSN_6	87.42383	007	91.34	004	29.24	009	318.04	015	296.87	017	276.17	012	232.60
90 $4MN_6$	87.49669	001	123.46	001	162.71	004	39.91	004	4.63	004	332.57	003	259.42
91 $2MS_6$	87.96822	016	117.93	008	84.45	015	302.46	034	304.02	038	296.15	022	266.35
92 $2MK_6$	88.05035	004	113.29	004	55.78	007	340.49	009	315.09	010	310.73	006	274.88

cont:

Name	Speed (deg.hr^{-1})	Booby Island H (mm)	Booby Island g (deg)	Goods Island H (mm)	Goods Island g (deg)	Turtle Head H (mm)	Turtle Head g (deg)	Ince Point H (mm)	Ince Point g (deg)	Twin Island H (mm)	Twin Island g (deg)	Frederick Point H (mm)	Frederick Point g (deg)
93 $3MSN_6$	88.51257	002	282.11	001	221.59	005	95.36	006	118.24	004	100.64	002	126.42
94 MKL_6	88.59473	001	125.69	002	338.38	003	290.93	001	267.08	001	233.05	000	230.11
95 $2SM_6$	88.98410	003	136.05	004	302.52	012	290.18	016	294.69	014	280.87	005	179.33
96 MSK_6	89.06624	004	120.26	001	256.99	009	283.41	011	284.83	010	279.03	004	228.01
97 $2(MN)_8$	114.84767	001	89.59	000	17.61	001	258.09	001	316.65	001	291.08	000	192.13
98 $3MN_8$	115.39204	002	89.95	001	346.03	006	291.75	003	325.56	001	293.81	001	172.20
99 M_8	115.93642	002	125.67	001	353.47	006	314.53	004	346.06	001	311.95	002	205.15
100 $2MSN_8$	116.40794	002	118.51	002	314.69	008	282.36	003	315.86	001	249.29	002	103.18
101 $3MS_8$	116.95232	003	130.91	005	330.03	011	307.96	002	334.11	002	210.19	003	138.34
102 $3MK_8$	117.03445	002	123.22	001	36.34	003	343.51	002	307.83	002	290.51	001	251.21
103 $MSNK_8$	117.50597	000	255.00	001	85.18	002	331.37	001	284.74	001	298.83	000	133.27
104 $2(MS)_8$	117.96822	001	94.64	002	348.41	004	302.20	002	167.94	003	169.65	001	60.92
105 $2MSK_8$	118.05035	002	111.85	002	330.53	**005**	299.74	003	276.29	003	247.69	001	125.01
106 $4MS_{10}$	145.93642	002	171.52	001	6.21	002	276.95	003	280.09	002	297.83	002	32.76
107 $3M2S_{10}$	146.95232	000	81.52	001	11.90	002	226.40	002	264.74	001	328.08	003	31.48
108 $4MNS_{12}$	174.37614	000	53.85	000	301.88	001	227.93	001	183.90	000	123.38	000	298.93
109 $5MS_{12}$	174.92052	000	91.37	000	305.79	001	270.21	001	213.60	001	172.94	001	16.83
110 $4M2S_{12}$	175.93642	001	69.97	001	270.66	001	258.49	001	192.86	001	184.10	001	290.47

TABLE 3

Variance of observations and residuals (observed sea level-predictions) from various stations.

Station	Observation Variance (cm^2)	Residual Variance (cm^2)
Frederick Point	4967.4	63.5
Twin Island	4619.0	57.8
Ince Point	3844.6	33.5
Turtle Head	4088.9	66.4
Goods Island	5375.1	124.2
Booby Island	7129.0	150.1

TABLE 4

Means and variances of meteorological variables from recorded observations only.

	Barometric Pressure		Wind Speed			
			u-component		v-component	
	mean (mb)	variance $(mb)^2$	mean (m/sec)	variance $(m/sec)^2$	mean (m/sec)	variance $(m/sec)^2$
Cape Wessel*	1006.81	5.64	-2.51	24.62	0.57	6.01
Port Moresby	1002.73	3.91	-0.58	3.45	0.60	2.13
Thursday Island	1002.01	2.28	-3.46	23.24	-0.32	1.36
Willis Island*	1008.91	10.55	-5.64	13.15	0.03	4.84

*Observations were not recorded at regular intervals and there were some gaps of up to a month when no observations were recorded, therefore these statistical parameters are biased.

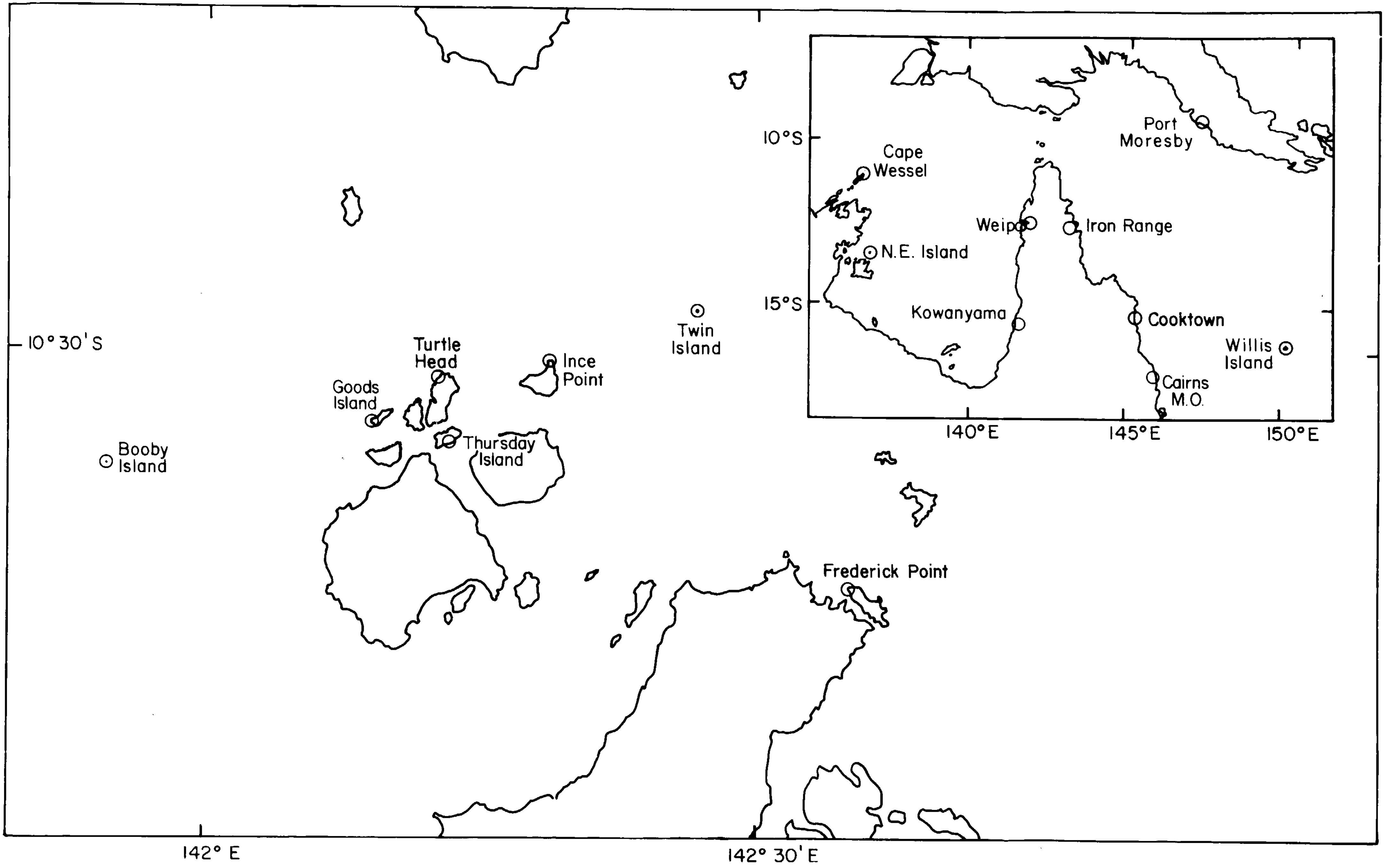
10°30'S
Booby Island
Goods Island
Turtle Head
Thursday Island
Ince Point
Twin Island
Frederick Point
142° E
142° 30' E
10°S
15°S
140°E
145°E
150°E
Cape Wessel
N.E. Island
Weipa
Iron Range
Kowanyama
Cooktown
Cairns M.O.
Willis Island
Port Moresby

FIGURE 1.

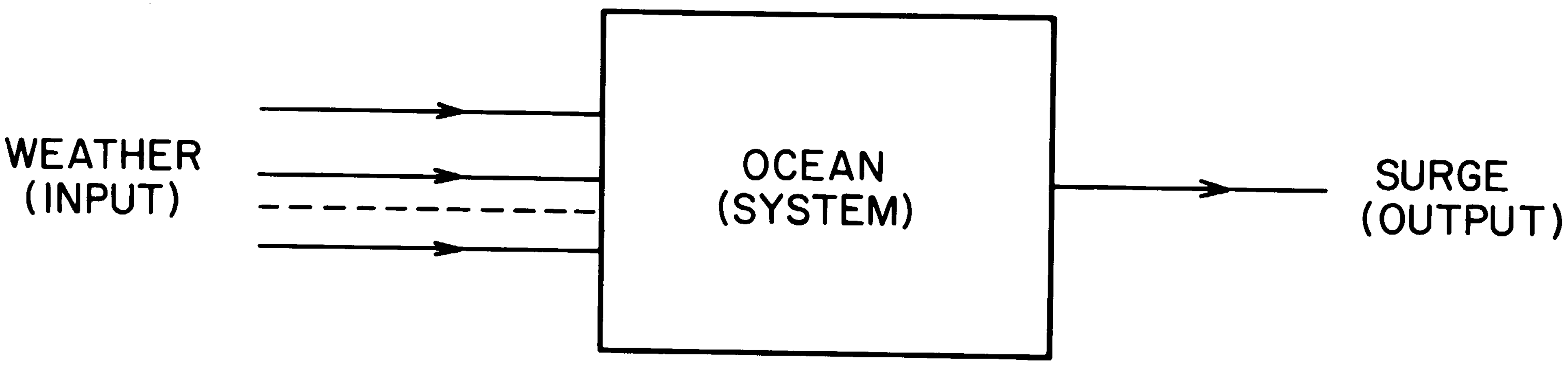

FIGURE 2.

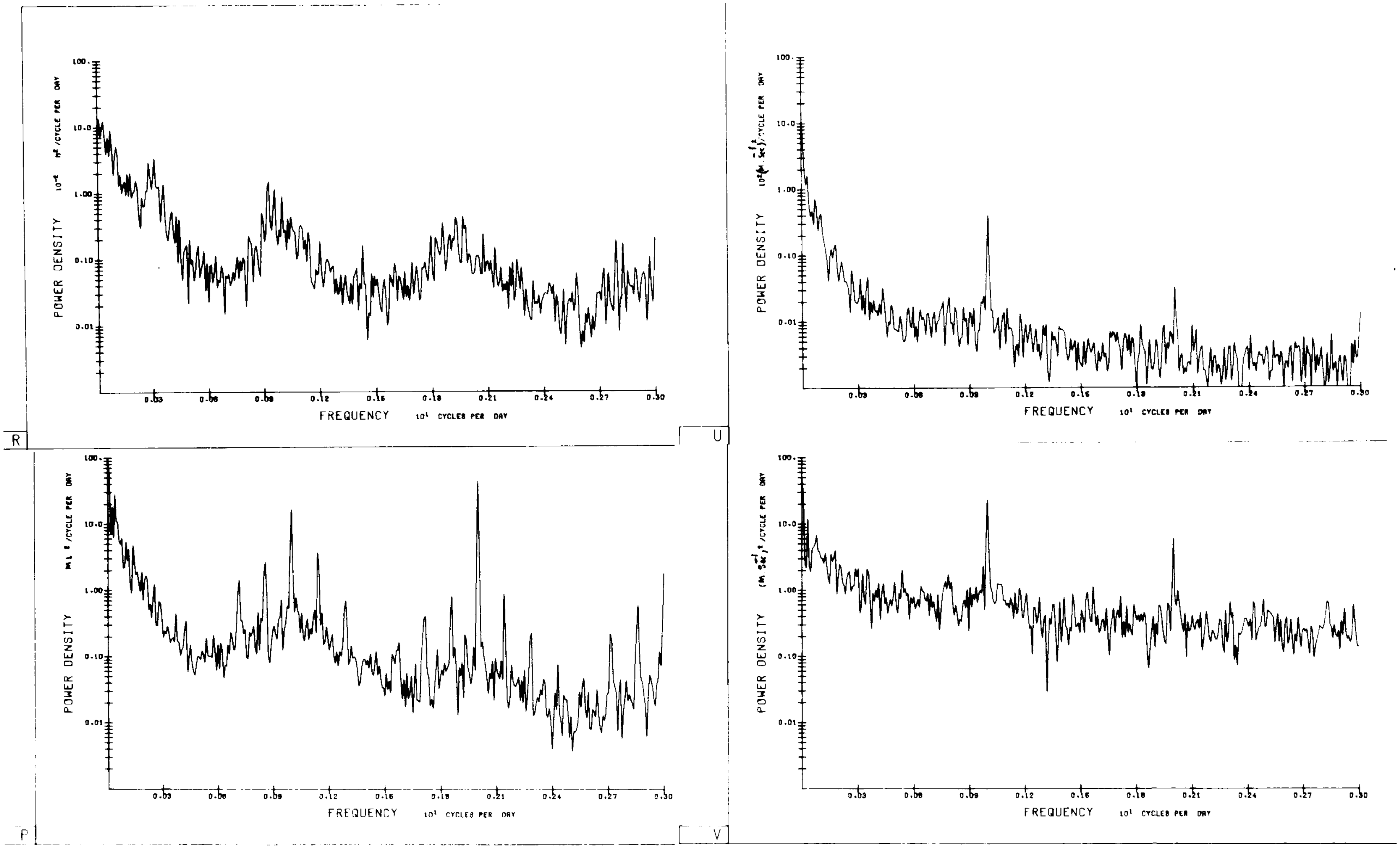
R
POWER DENSITY
10^{-4} M^2 /CYCLE PER DAY
U
POWER DENSITY
10^2(M . SEC^{-1})^2/CYCLE PER DAY
P
POWER DENSITY
MB^2 /CYCLE PER DAY
V
POWER DENSITY
(M . SEC^{-1})^2 /CYCLE PER DAY
100.
10.0
1.00
0.10
0.01
0.03
0.06
0.09
0.12
0.15
0.18
0.21
0.24
0.27
0.30
FREQUENCY
10^1 CYCLES PER DAY

FIGURE 3

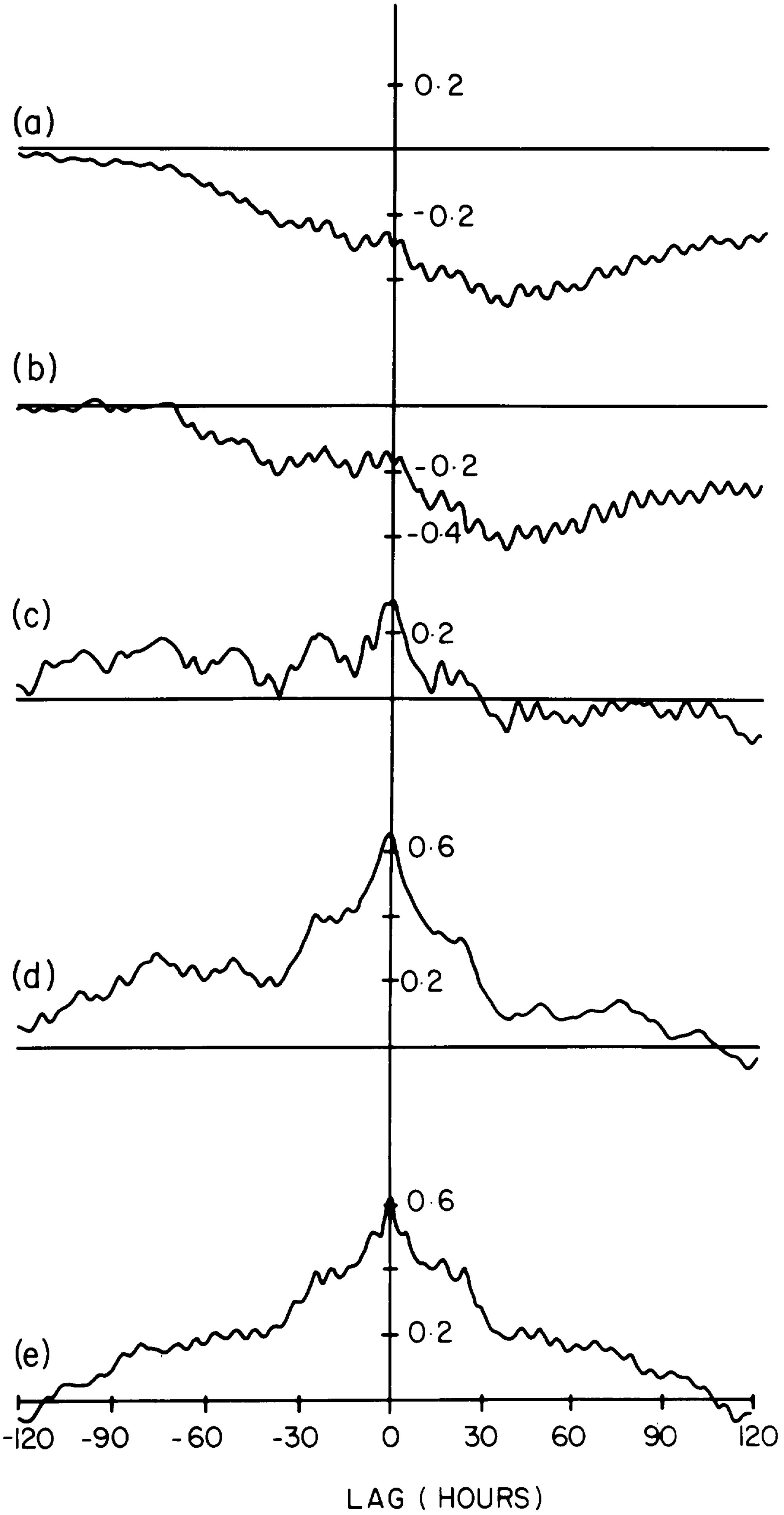
0·2
(a)
-0·2
(b)
-0·2
-0·4
(c)
0·2
0·6
(d)
0·2
0·6
0·2
(e)
-120
-90
-60
-30
0
30
60
90
120
LAG (HOURS)

FIGURE 4.

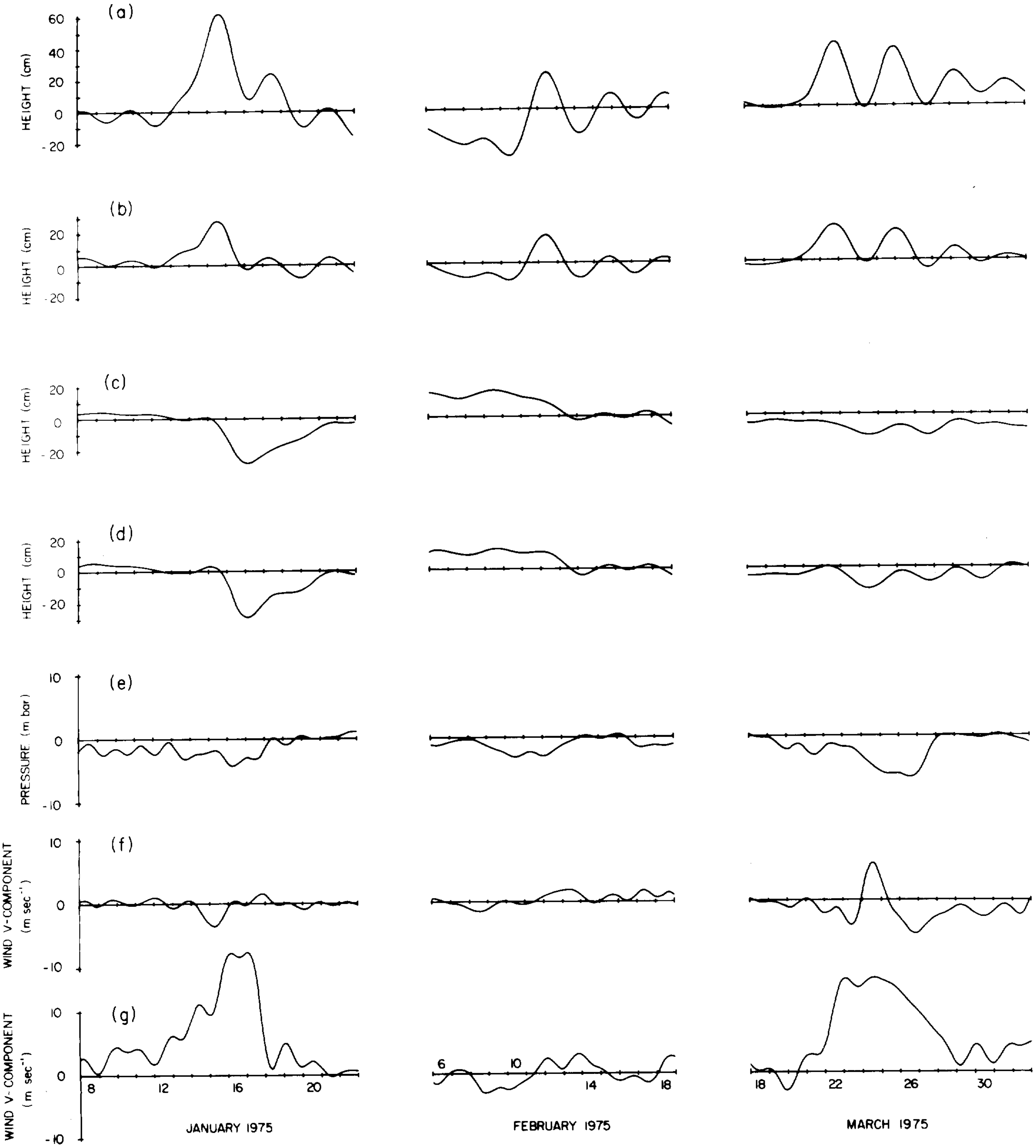
(a)
HEIGHT (cm)
60
40
20
0
-20
(b)
HEIGHT (cm)
20
0
-20
(c)
HEIGHT (cm)
20
0
-20
(d)
HEIGHT (cm)
20
0
-20
(e)
PRESSURE (m bar)
10
0
-10
(f)
WIND V-COMPONENT (m sec⁻¹)
10
0
-10
(g)
WIND V-COMPONENT (m sec⁻¹)
10
0
-10
8
12
16
20
JANUARY 1975
6
10
14
18
FEBRUARY 1975
18
22
26
30
MARCH 1975

FIGURE 5a

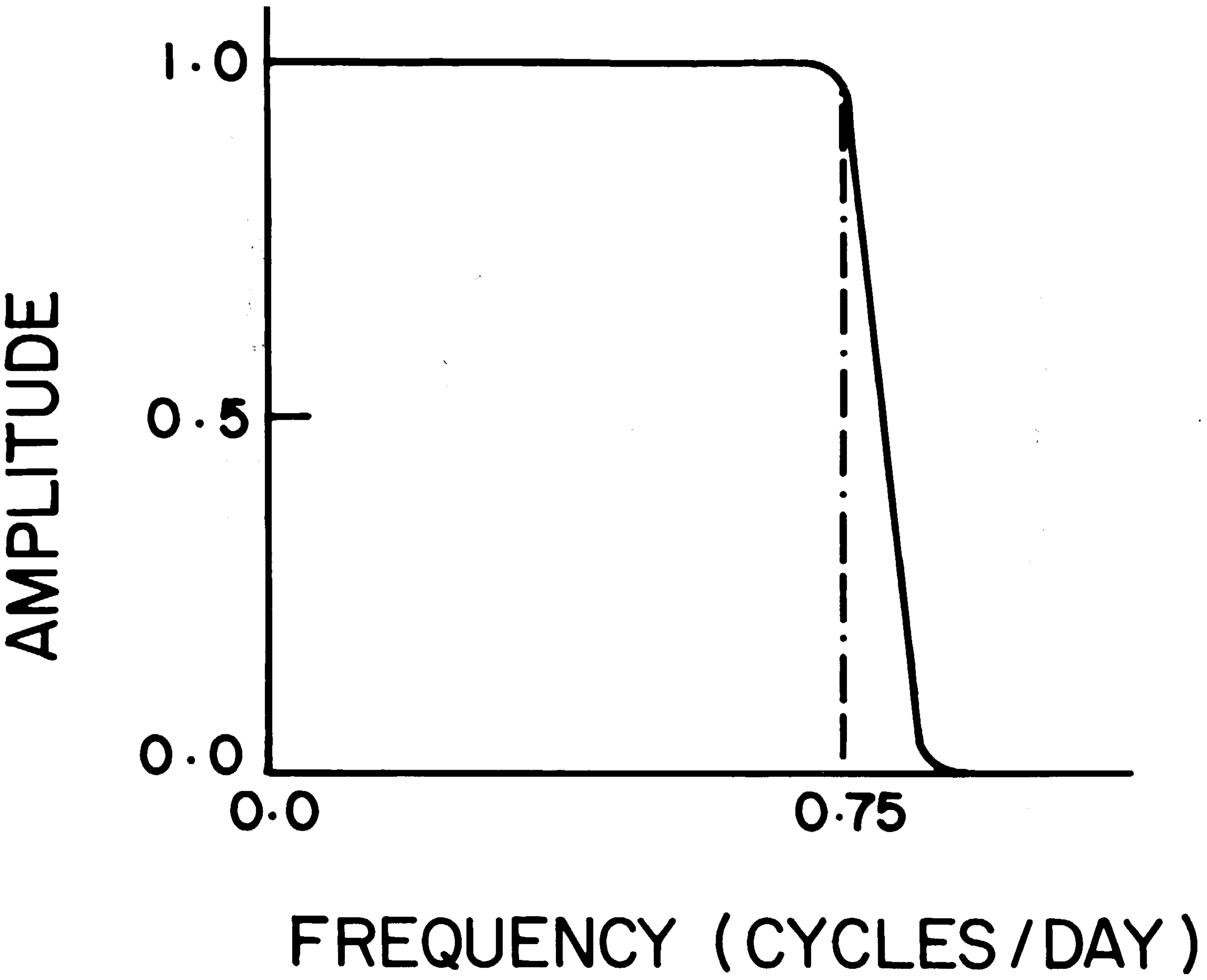

FIGURE 5b

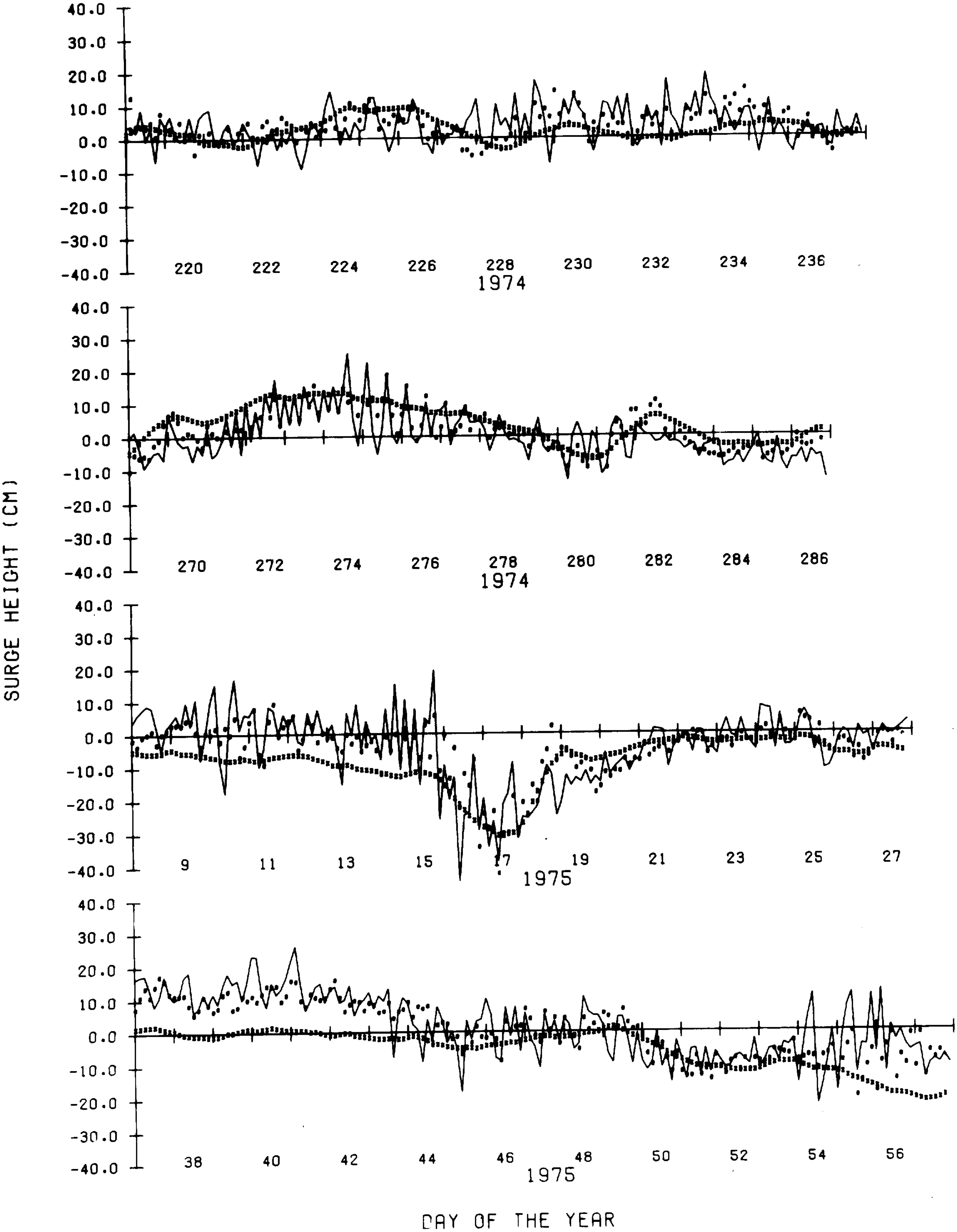
SURGE HEIGHT (CM)
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
220
222
224
226
228
230
232
234
236
1974
270
272
274
276
278
280
282
284
286
1974
9
11
13
15
17
19
21
23
25
27
1975
38
40
42
44
46
48
50
52
54
56
1975
DAY OF THE YEAR

FIGURE 6a

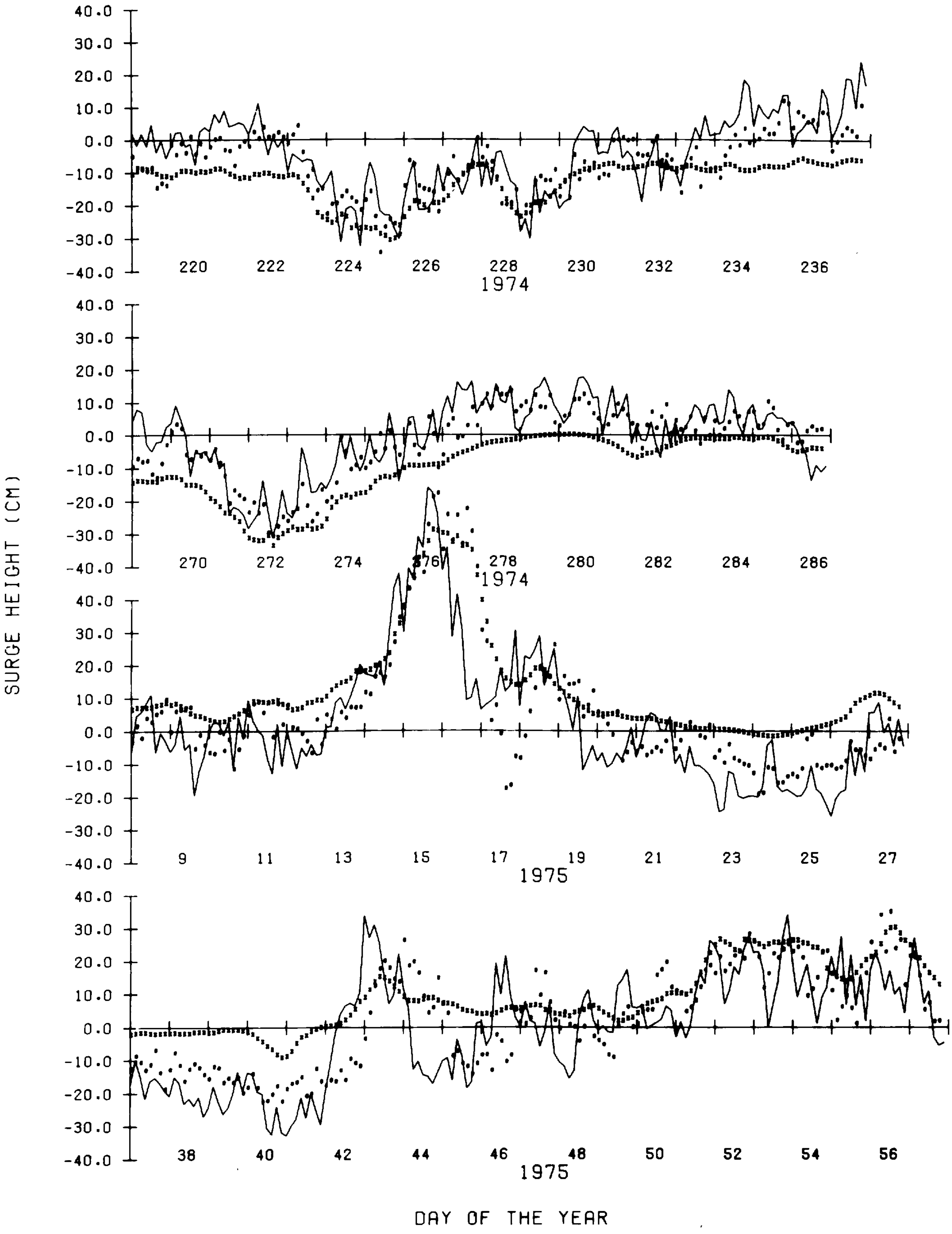
SURGE HEIGHT (CM)
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
220
222
224
226
228
230
232
234
236
1974
270
272
274
276
278
280
282
284
286
1974
9
11
13
15
17
19
21
23
25
27
1975
38
40
42
44
46
48
50
52
54
56
1975
DAY OF THE YEAR

FIGURE 6b

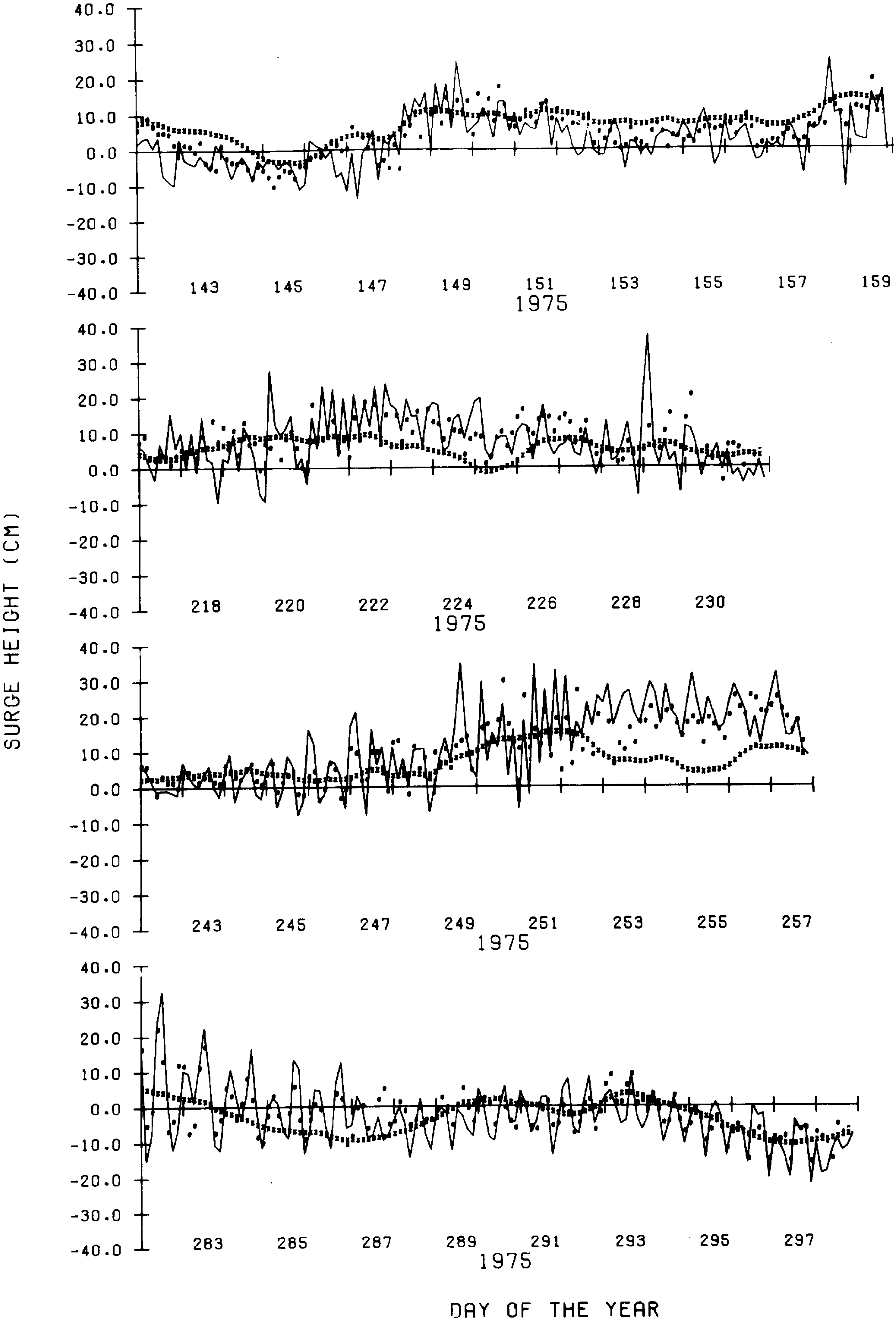

FIGURE 6a cont:

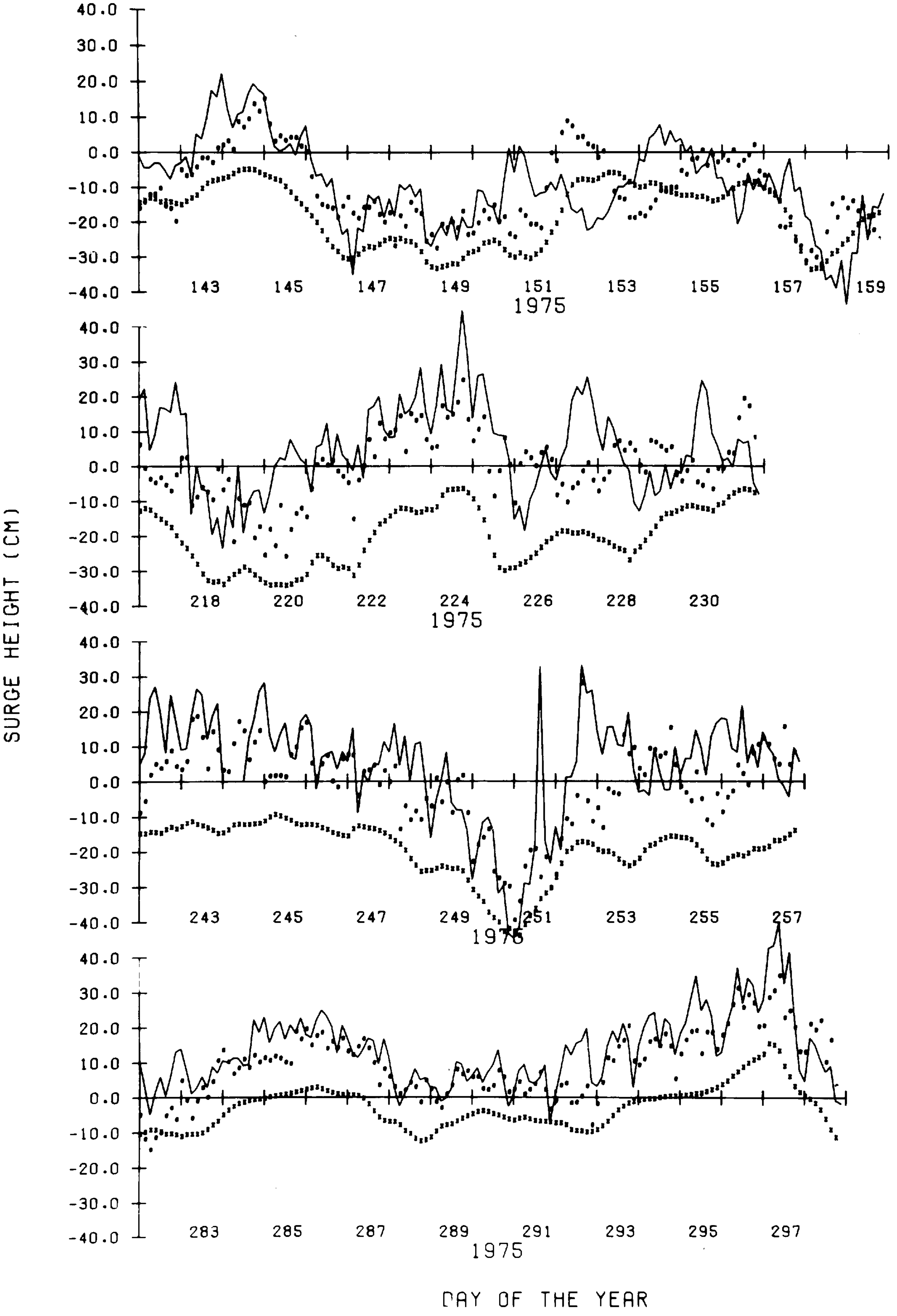

FIGURE 6b cont: