Modelling of Physical Influences in Sea Level Records for Vertical Crustal Movement Detection

Edward G. Anderson
Department of Surveying Engineering, University of New Brunswick
Fredericton, N.B., Canada E3B 5A3

Abstract. The analysis of sea level time variations recorded by shore tide gauges for evidence of recent and contemporary vertical crustal movement is an established technique. However, the additional refinement of first modelling the numerous physical influences on sea level--which are of considerable importance, but additional complexity in the coastal zone--has not been fully exploited.

In this paper, attempts to specify and evaluate such physical influences are reviewed with the intention of identifying problem areas and promising approaches. For a routinely viable procedure, it is considered important to limit the input data, which would be needed on a continuing basis to model physical phenomena, to widely and regularly available data records.

An example of linear modelling based on air/water temperatures, atmospheric pressure, river discharges, geostrophic and/or local wind velocities, and including forced period terms to allow for the long period tides and Chandlerian polar motion is evaluated and applied to monthly mean sea levels recorded in Atlantic Canada. Refinement of the model to admit phase lag in the response to some of the driving phenomena is demonstrated. Spectral analysis of the residuals is employed to assess the model performance. The results and associated statistical parameters are discussed with emphasis on ellucidating the sensitivity of the technique for detection of local episodic and secular vertical crustal movements, the problem areas most critical to the type of approach, and possible further developments.

Introduction

Vaníček [1978] has described a method whereby some of the known physical influences on sea level can be removed by a process of mathematical modelling. He concludes that, with such a model restricted to the effects of atmospheric pressure and temperature, river discharge, and three basic tidal constituents: "...we should be able to detect possible local episodic vertical movements (of duration more than 4 months) of magnitude of 10cm and more...". It is further stated that, by extending and refining the model to include additional known effects, it should be possible to see movements down to 5cm in the sea level record.

The work discussed in this paper is merely a continuation and extension of Vaníčeks approach. In particular, the basic model has been substantially retained, but refined by introducing an air-to-water heat transfer model with provision for time lag, and also by including wind stress terms based on either the observed wind vector or the geostrophic wind vector derived from the observed atmospheric pressure field.

So far, only results of preliminary and test computations are available, based on data from eight locations in the Canadian Maritime provinces (fig. 1). However, these results have been adequate to indicate some strengths and weaknesses in the basic approach and to suggest areas where immediate refinement could be advantageous. Also, some model improvements with the best potential for future development have been highlighted.

The Problem and Proposed Approach

A detailed description of the problem, the proposed approach, and the reasons for choosing such an approach have already been set out by Vaníček [1978]. It will suffice here to provide a brief summary.

The problem is to devise a viable technique which would enable use of sea level records, derived from tide gauge observations, to detect contemporary vertical crustal movements over periods from a few months to several years. Both

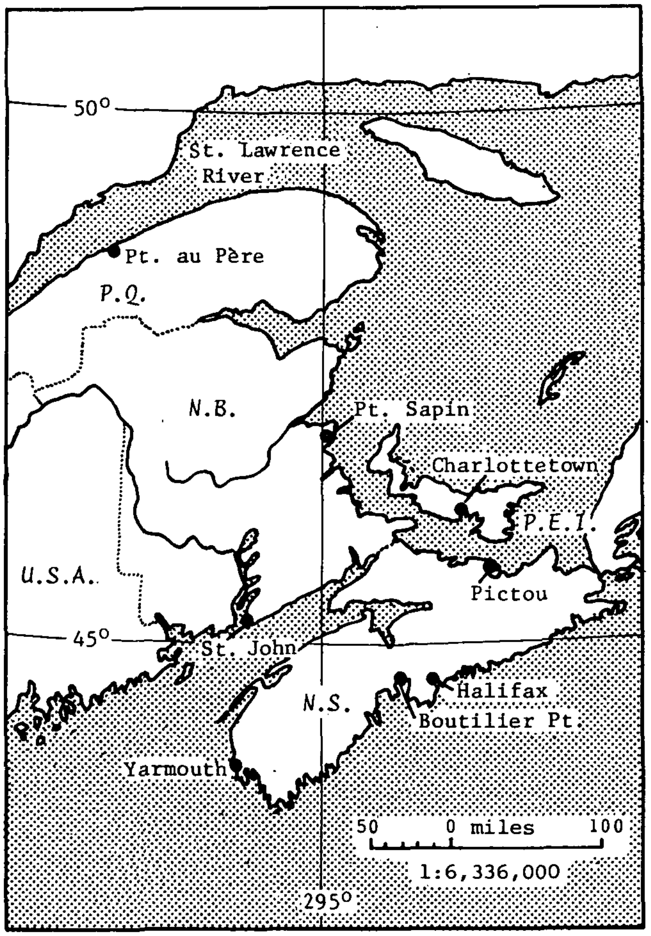

Figure 1. Map of Canadian Maritime provinces showing location of tide gauges

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secular movements (i.e. linear trend) and irregular or episodic movements are sought. To achieve sufficient accuracy in isolating these phenomena, a variety of other known physical influences on the sea level record must be removed. It is proposed that this be done by empirically modelling the known effects, so that much of the variance in the sea level record on that account can be eliminated.

Two critical factors are inherent in this approach. Firstly, the tide gauge environment may be substantially more complex than that which is experienced in the deep oceans. For example, esturine topography, the dynamics of coastal bathymetry, seasonal freezing of coastal waters, and dynamic river discharge influences are some of the many factors which may interact with the meteorological and tidal effects to anomalously perturb the coastal sea level record. Consequently, many of the well proven modelling techniques devised for the deep ocean environment and much of the data observed there may not necessarily be extrapolated with any validity to the tide gauge environment. Secondly, the method of modelling, to be viable for routine monitoring of vertical movements, should rely only on readily available long-term data records, collected on a regular basis. This is a significant and frustrating limitation.

The Basic Model and Method

Basically, the model adopted (table 1) is a linear combination of the physical effects to be represented, so that the method might be referred to as a multiple linear regression analysis. However, certain components of the basic model may be represented by time series data which has been derived from additonal observations through sub-models. This is specifically so in the case of the water temperature and wind stress terms. The sub-models are not necessarily linear.

A solution for the unknown parameters, along with estimates of their variance and a correlation matrix, is obtained by the conventional least squares method. Actual implementation of this solution, however, is just a by-product of the optimum least squares spectral analysis algorithm [Wells and Vaníček, 1977] which is employed. This algorithm, based on the technique developed by Vaníček [1971], primarily provides the spectrum of the residual time series, $R(t_i)$. Two particular advantages claimed for this algorithm are: (a) suppression of the regression model components produces no movement of the inherent spectral peaks; and (b) equally spaced time series data is not mandatory. Spectral analysis of the residuals provides a supplementary quantitative assessment of the success of the regress-

The Linear Regression Model

$$S(t_i) = C_A + C_L t_i + C_P \delta P(t_i) + C_T \delta\tau(t_i) + C_D \delta D(t_i) + C_{W_t} \delta W_t(t_i) + C_{W_n} \delta W_n(t_i)$$

$$+ \sum_{j=1}^{5} A_j \cos(\omega_j t_i - \theta_j) + R(t_i)$$

Unknown Parameters

C_A	datum bias
C_L	linear trend coefficient
C_P	air pressure coefficient
C_T	surface water temperature coefficient
C_D	river discharge coefficient
C_{W_t}	shoreline tangential component of wind stress coefficient
C_{W_n}	shoreline normal component of wind stress coefficient
A_j	amplitude of five periodic tidal components
θ_j	phase angle of five periodic tidal components
R	sea level residual time series

Observed Time Series

(functions of time t_i)

S	monthly mean sea level at tide gauge
δP	monthly mean air pressure variation (with respect to temporal mean)
$\delta\tau$	monthly mean surface water temperature variation
δD	monthly mean (combined) river discharge
δW_t	shoreline tangential component of observed or geostrophic wind stress
δW_n	shoreline normal component of observed or geostrophic wind stress
ω_j	assumed constant frequency of five periodic tidal components as follows: ω_1 = 6 mths. (semi-annual), ω_2 = 12 mths. (annual), ω_3 = 14.33 mths. (chandlerian or polar), ω_4 = 8.847 yrs. (lunar perigee), ω_5 = 18.613 yrs. (lunar nodal).

Table 1. The linear regression model

ion model and provides diagnostic evidence by depicting the distribution of the remaining variance.

Refinement of the Model

Assuming the desirability of a linear model, two further possibilities remain available for improvement. The sub-models may be reformulated to better portray the physical processes or the total linear model may be extended to include additional terms, representing known or suspected physical effects. Both methods were employed, as exemplified respectively by the empirical sub-modelling of water temperature and the addition of wind stress terms to the basic model.

A Water Surface Temperature Model. While thermal variations have been cited as an important contribution to sea level changes, earlier analyses of the Maritimes data, using a simple linear term based on air temperature, produced unexpectedly small and weakly determined regression coefficients. It was suggested that this could be the result of two factors associated with the use of air, rather than water, temperatures. Clearly, the primitive model ignored time lag between air temperature variations and their consequent effect on water temperatures and thus the sea level. Also, air temperatures usually fall below freezing point during Maritime winters but not all of the gauge locations actually freeze, which suggests that a better thermal model, capable of accounting for the "winter non-linearity" should be constructed from water temperatures. Unfortunately, regular long-term records of water temperature are not readily available at most tide gauges. However, the viability of the method could be preserved by constructing an empirical sub-model for the air/water heat transfer process, based on long-term air and water surface temperature records available for the Halifax, N.S. tide gauge. The assumption might then be made, and possibly tested, that such a sub-model could be validly extrapolated to the other gauges. Accordingly, a linear heat transfer sub-model, incorporating time lag, was postulated as follows:

$$\tau(t_i) = hT(t_i + \delta t) + k, \qquad (1)$$

where $\tau(t_i)$ is the predicted water surface temperature at time t_i, $T(t_i + \delta t)$ is the observed air temperature at time $t_i + \delta t$, δt is a time lag, h is a heat transfer coefficient, and k is a constant temperature bias. A least squares solution for the parameters δt, h, and k was obtained using the monthly mean air and water surface temperature series available for Halifax. Since the observed time series comprise discrete values, the admission of a time lag necessitates interpolation of the air temperature data. Though the simplicity of polynomial interpolation was attractive it was found, by experiment, to be considerably less reliable than fourier interpolation; a not entirely unexpected outcome when the "sine wave" form of the air temperatures is considered. When a fourier transformation is introduced into the model (1), the observation equations become, after linearization:

$$T(t_i+\hat{\delta t})\Delta h - [\hat{h}\sum_{j=1}^{m} j\omega A_j \sin(j\omega(t_i+\hat{\delta t}) - \theta_j)]\Delta t$$

$$+ k + [\hat{h}T(t_i+\hat{\delta t}) - \tau(t_i)] = v_i \quad (i=1,n); \qquad (2)$$

where δt and h are estimates of the parameters δt and h respectively, so that $\delta t = \hat{\delta t} + \Delta t$ and $h = \hat{h} + \Delta h$; A_j and θ_j are respectively amplitude and phase fourier coefficients of the air temperature time series; ω is the harmonic frequency; v_i are the discrepancies in the observations; m is the number of harmonics; and n is the number of observations.

Least squares estimates of the parameters and their standard deviations are listed in table 2, along with other relevant information. The estimates are apparently well determined, mainly because of the large number of degrees of freedom, and the overall RMS error of prediction--at about 1°C--is quite satisfactory. Distribution of the residuals was significantly normal. Use of these values in the sub-model (1) also requires fourier interpolation of the air temperature series. Extrapolation to other locations has not yet been attempted, as additional water surface temperature data is being sought so that the spatial coherence of the coefficients δt, h, and k can be tested.

Wind Stress. Two methods of modelling the wind stress effect on sea level have been considered. The first relies on a sub-model for the geostrophic wind component, derived from the air pressure gradient field as follows:

$$\begin{bmatrix} W_E \\ W_N \end{bmatrix} = \begin{bmatrix} (R\rho\omega \sin 2\phi)^{-1} \dfrac{\partial P}{\partial \lambda} \\ (2R\rho\omega \sin \phi)^{-1} \dfrac{\partial P}{\partial \phi} \end{bmatrix}; \qquad (3)$$

where W_E and W_N are the east and north components respectively of the geostrophic wind; R is the earth's radius; ρ is air density; ω is the

Coefficient	Least Squares Estimate	Standard Deviation
δt (mths.)	-0.66	0.03
h	0.628	0.009
k (°C)	3.05	0.12
Data		
Span: Jan. 1927 to Nov. 1973 excluding Jul. 1933 to Jan 1946		
Number of observations, n = 412		
Number of fourier coefficients, m = 206		
Statistical analysis		
RMS residual = 1.035°C		
Maximum residual = 4.4°C		
Variance ratio = 1.06		

Table 2. Air/water heat transfer model coefficients for Halifax, N.S.

earth's angular velocity of rotation; and $\partial P/\partial\lambda$, $\partial P/\partial\phi$ are the components of the barometric pressure (P) gradient with respect to longitude (λ) and latitude (ϕ). Even though this model may only account for part of the actual wind field, it has been introduced for use at gauge locations where suitable observed wind records are not available. The suitability of the wind records is stressed here because, in many instances, monthly mean magnitudes and directions are seperately compiled from the hourly mileages, without proper vector summations. Such data is thus not suitable for modelling wind stress effects. However, early attempts using the geostrophic wind in the Maritimes region--resolved into components tangential and normal to the local shoreline and squared--have not been particularly successful [Vaníček, 1977]. It is now suspected that these results may have suffered from computational difficulties and the present author is attempting to rectify the analyses.

As a means of verifying the significance of the wind stress effect, the second method--which relies on the observed monthly mean wind vector--has been tested at Halifax. Although the Halifax wind records are burdened with the unsuitable compilation techniques previously mentioned, it was possible to recompute, without undue effort, correct monthly vector averages since the records included monthly mean wind mileages within a number of "direction sectors". Prior to 1967 the horizon was divided into 8 such sectors of 45° each, but since that date 16 sectors have been employed. North and east components (W_N and W_E) of the observed monthly mean wind vector were thus easily derived. These components are employed in the wind stress sub-model thus:

$$\begin{bmatrix} W_t \\ W_n \end{bmatrix} = \begin{bmatrix} (W_N \cos\alpha + W_E \sin\alpha)^2 \\ (W_E \cos\alpha - W_N \sin\alpha)\,|(W_E \cos\alpha - W_N \sin\alpha)| \end{bmatrix}; \tag{4}$$

where W_t and W_n are, respectively, tangential and normal to shoreline components of the wind stress and α is the shoreline azimuth.

Results

Results for four of the eight gauge locations are displayed in table 3 and figures 2 and 3. The analyses of the remaining gauge records (i.e. Point Sapin, Pictou, Boutilier Point, and Yarmouth) are not included here because the usefulness of the results is considerable diminished by the short data spans--all less than 9 years. In some cases, these additional results provide evidence of spatial coherence of the phenomena studied. This, as well as any significant disagreements with the results presented, will be mentioned in the relevant discussion below.

Sea Level Data

The first four lines of table 3 quantitatively describe the observed sea level time series $S(t_i)$ for the selected tide gauges and they are depicted graphically in figure 2. The disjoint nature of the Pointe au Père record should be noted.

Location of Tide Gauge	Pointe au Père	Charlottetown	St. John	Halifax
Number of observations	422	370	480	564
Number of years	47	31	47	47
Epoch	1927-1974	1943-1974	1927-1974	1927-1974
Number of gaps in data	7	2	5	0
Datum bias, C_A (cm)	27.6 ± 0.9	158.6 ± 0.4	426.4 ± 0.5	110.1 ± 0.3
Linear trend C_L (cm/cent.)	7.6 ± 2.3	27.0 ± 2.2	37.6 ± 1.6	43.4 ± 1.1
Tide: Amplitude A_j (cm)				
Semi-annual	2.2 ± 0.4	0.9 ± 0.3	2.1 ± 0.3	0.9 ± 0.2
Annual	1.5 ± 0.5	4.6 ± 0.4	1.4 ± 0.7	4.0 ± 0.3
Chandlerian	0.7 ± 0.4	0.7 ± 0.3	1.3 ± 0.3	0.6 ± 0.2
Lunar perigee	1.6 ± 0.4	0.7 ± 0.3	0.3 ± 0.3	0.2 ± 0.2
Lunar nodal	0.5 ± 0.4	1.6 ± 0.3	1.2 ± 0.3	0.3 ± 0.2
Tide: Ascending node date, N_j (yrs)				
Semi-annual	1926.81 ± 0.02	1926.83 ± 0.02	1926.81 ± 0.01	1926.81 ± 0.02
Annual	1926.39 ± 0.05	1926.64 ± 0.04	1926.80 ± 0.04	1926.69 ± 0.02
Chandlerian	1926.66 ± 0.10	1926.49 ± 0.07	1926.56 ± 0.04	1926.52 ± 0.06
Lunar perigee	1932.73 ± 0.38	1932.80 ± 0.55	1930.28 ± 1.13	1926.59 ± 1.39
Lunar nodal	1936.50 ± 3.00	1930.16 ± 0.52	1933.54 ± 0.70	1928.21 ± 2.31
Temperature, C_T (cm/°C)	-0.15 ± 0.09	-0.033 ± 0.087	0.22 ± 0.07	0.004 ± 0.076
Air pressure, C_P (cm/mbar)	-0.74 ± 0.11	-0.90 ± 0.06	-0.51 ± 0.07	-0.63 ± 0.05
River discharge, C_D (cm/m^{2}s^{-1})	0.0006 ± 0.0001	---	0.004 ± 0.0004	---
Tangential wind stress, C_{W_t} (cm/m^{2}s^{-2})	---	---	---	-0.04 ± 0.06
Normal wind stress, C_{W_n} (cm/m^{2}s^{-2})	---	---	---	0.85 ± 0.07
St. deviation original record $S(t_i)$ (cm)	7.26	6.53	9.10	7.80
St. deviation of residuals $R(t_i)$ (cm)	5.96	3.44	4.19	3.31
% reduction in variance	33%	72%	79%	82%

Table 3. Linear regression analysis of selected tide gauge records

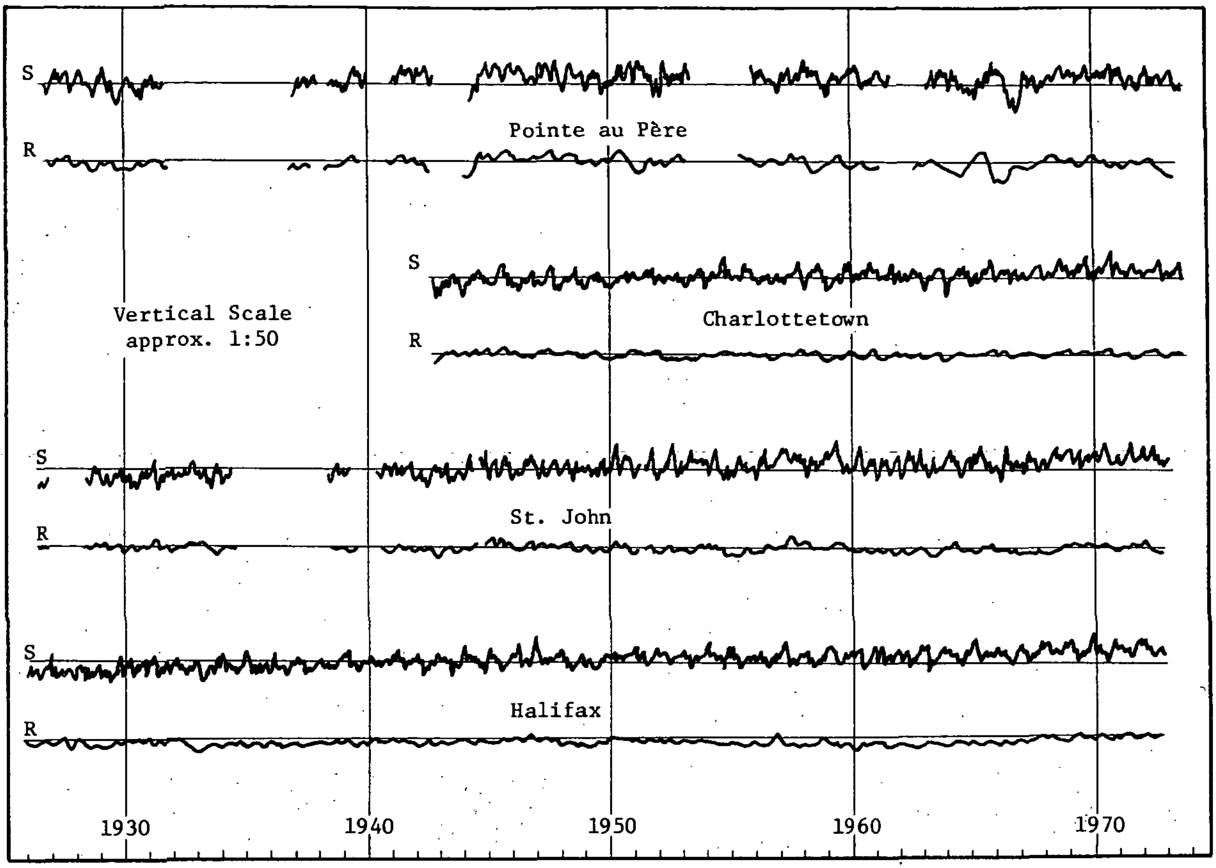

Figure 2. Original tide gauge records (S) and filtered residuals after least squares regression analysis (R) plotted on same vertical scale

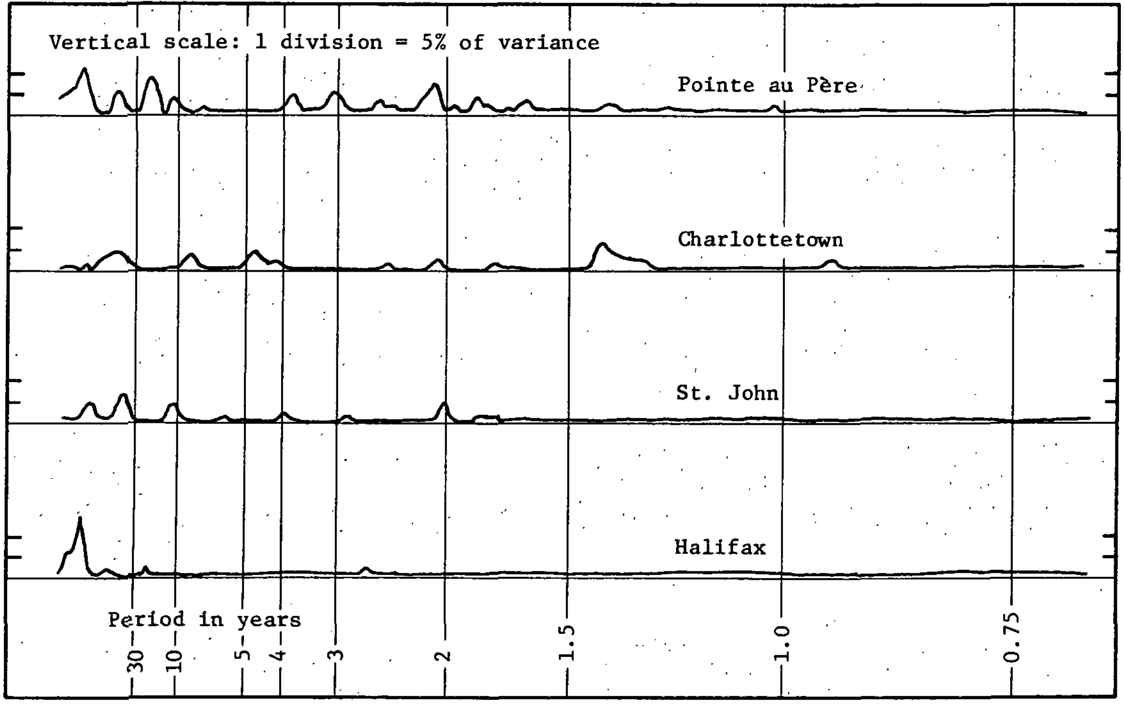

Figure 3. Spectra of unfiltered residuals

Datum Bias

The datum bias terms (C_A) merely reflect the arbitrary origin of the particular tide gauge scale.

Linear Trend

This quantity (C_L) may be expected to combine secular vertical crustal movements and eustatic sea level variations. According to the standard deviations obtained, these results are quite well determined. Generally, there appears to be a high degree of spatial coherence, which is further supported by the results for the four omitted gauges, despite their lower accuracy. Only Pt. Sapin and Pictou were exceptional; the latter displaying a negative trend. Overall, the linear trend appears to increase fairly smoothly for locations towards the south and east. Presumably this reflects a regional crustal movement phenomenon, as the eustatic effect should be similar at all locations.

Tides

Table 3 includes results for both the amplitude (A_j) and the ascending node date (N_j) for the five tidal components. Ascending node date is derived from the phase angle θ_j of the tide by the relationship:

$$N_j = B_j + (\theta_j - \frac{\pi}{2} \pm 2\pi n)/\omega_j, \qquad (5)$$

where B_j is the date of the time origin used for the particular data series (usually the middle of the month immediately preceding the first month of data). The dates given in table 3 have been adjusted as necessary by an integral number of periods (n) for purposes of comparison.

Semi-annual Tide. The phase of this component is very well determined and spatially consistent. A systematic difference in amplitude is apparent between those locations affected by river discharge and those which are not. It seems likely that the greater amplitudes found for the gauges where river discharge is significant may result from poor modelling of that effect. At St. John, moderate correlation was found between the phase of the semi-annual tide and the river discharge.

Annual Tide. Amplitudes of the annual tides are not as well determined and again the spatial coherence seems to depend on the presence, or absence of river discharge. There is, however, also a strong interaction with the temperature effect. For instance, at Halifax fourier transformations of both the air and observed water surface temperature series yielded amplitude coefficients for the annual harmonic at least an order of magnitude larger than those of any other period. High correlation coefficients between both amplitude and phase of the annual tide and the temperature effect (0.60 and 0.87) respectively at Halifax) are thus not unexpected. This evidence suggests that these two effects are not being adequately isolated and, indeed, the philosophy of attempting to do so might be questionable. Ultimately, both the annual tide and the strong annual component of temperature variation are merely different manifestations of the same motivating energy source: the earth's orbital motion. Poor coherence in the phase of the annual tide may also result from the influence of the temperature effect.

Chandlerian (Polar) Tide. Good spatial consistency and satisfactory precision are achieved here. The amplitudes and phases are also quite comparable with results obtained for several east coast ports in the U.S.A. [Currie, 1975; Vaníček, 1978].

Lunar Perigee and Nodal Tides. The precision attained in evaluating these longer period tides is consistent with the total length of the time series analysed. Despite fairly weak determinations, the amplitudes agree reasonably with the empirical knowledge of these effects, and also with the estimated equilibrium tides [Rossiter, 1966].

Temperature Effect

Generally, the temperature coefficient (C_T) is so weakly determined as to be meaningless. Indeed, the negative results obtained at Pt. au Père and Charlottetown would be contrary to expectation based on an understanding of the physical process involved. At all locations except Halifax, air temperatures were used directly in the regression model. However, a test implementation at Halifax of the water surface temperature sub-model described above, does not noticeably improve the result. In view of this outcome, further investigation of the significance of the interaction between the annual tide component and the temperature effects is warranted. It seems possible that the lack of constraints on the amplitude and phase of the annual tide allows undue absorbtion of the data variance at that frequency--thus reducing the temperature effect--and simultaneously falsifying the determination of the tidal coefficients.

Air Pressure Effect

These coefficients (C_P) are well determined and are substantially in agreement with the theoretical model and empirical studies of this effect. Taking into account the maximum observed range of air pressure at the gauge locations, the coefficients obtained represent a minimum equivalent sea level variation of about 10 cm at St. John and a maximum of about 20 cm at Charlottetown.

River Discharge Effect

River discharge effects are expected to be highly variable, depending on the local estuary configuration. The coefficients (C_D) obtained are equivalent to maximum sea level variations of approximately 12 cm and 8 cm at Pt. au Père and St. John respectively.

Wind Stress

Replacement of the geostrophic wind sub-model (eq. 3) by the observed wind sub-model (eq. 4) at Halifax appears to have been successful. The tangential wind stress effect is effectively negligible as anticipated. In contrast, the normal component is quite substantial, amounting to an equivalent maximum sea level variation of approximately 20 cm. Further study of this effect will be directed towards establishing an empirical relationship between the geostrophic and observed wind models, with the aim of improving the geostrophic model for use where suitable observed wind vectors are not routinely available.

Residuals

A worthwhile reduction in variance of the sea level record is evident when the standard deviation of the residuals $R(t_i)$ is compared with that of the original data (table 3, last three lines). The same result is depicted graphically in figure 2, where the plot of residuals may be compared visually with the original record. To facilitate this visual comparison, the residuals displayed in figure 2 (but not the results in table 3) have been subjected to a low-pass filter to remove the high frequency components with a period shorter than about 4 months.

Spectra of Residuals. Figure 3 illustrates the small amount of power remaining in the spectra of the unfiltered residuals. If reasonable limits are imposed on the band-width, so as to be consistent with the data span, there are no spectral peaks which exceed about 8% of the variance. The noticeable remaining variance in the Pt. au Père residuals may relate to the disjointed data series or it may reflect the additional complexity of the St. Lawrence River environment.

Conclusions

While the results presented here must be regarded as preliminary--and any dependent conclusions consequently tentative--the following summary will serve to highlight the strengths and weaknesses of the method and hence usefully direct further investigations towards realization of its full potential.

(1) A linear sub-model of the air/water heat transfer process, incorporating time lag, can be constructed empirically with acceptable reliability. However, it would appear that the use of water surface temperatures--either derived from such a model or actually observed--in the overall model for consequent sea level variations, does not produce a reliable or coherent thermal coefficient and does not significantly reduce the variance of the sea level record. It is suggested that a likely cause of this result may be the interaction of the highly correlated annual tide effect. Even though the coefficient for the thermal effect might actually be small--for example, Thompson [pers. comm. reported in Anderson, 1978] has obtained results which suggest that this is the case in the waters near U.K.--its weak determination and poor coherence indicate a remaining problem in the analysis.

(2) Use of properly derived observed wind vectors produces acceptable wind stress coefficients and contributes significantly to the reduction of sea level variance. The utility of a geostrophic wind sub-model remains uncertain, but development of an empirical relationship between such a model and the observed wind field would seem to be worthwhile.

(3) A very satisfactory determination of the linear trend coefficient is possible and this result appears to provide a reliable estimate of regional vertical crustal movement. This is especially significant in the context of tide gauge applications for continental levelling datums.

(4) While the signatures of the polar and longer period tides seem to have been adequately identified and separated from the sea level record, there are remaining difficulties with the annual and semi-annual tides. The treatment as free parameters of both amplitude and phase of these tides, as well as the coefficients of thermal and river discharge effects, apparently fails to adequately isolate their contributions to the sea level variation. Further study of this problem is warranted.

(5) Since modelling of wind stress and barometric pressure effects is reasonably successful, further refinement of the model, by inclusion of steric level and ocean current terms for instance, might usefully be pursued. This may even assist in better resolution of the tidal terms.

(6) Even in its present preliminary status, the modelling process provides sufficient reduction of variance in the sea level record for its utilization in identification of episodic movements at the 10 cm level. This facility may be further enhanced by investigating the differences in the residual variations between pairs of tide gauge locations.

Acknowledgements

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