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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL WEATHER SERVICE
OFFICE OF SYSTEMS DEVELOPMENT
TECHNIQUES DEVELOPMENT LABORATORY

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SINGLE-POINT FORECASTS OF WIND-DRIVEN AND TIDAL CURRENTS IN SAN PEDRO CHANNEL

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1. INTRODUCTION

Site-specific forecasts of water currents in the coastal zone are one of the products most desired by mariners and other marine users. Such forecasts generally do not exist, except for a few locations for which the National Ocean Service (NOS) has analyzed a long series of data. One method of providing these forecasts is by the use of numerical models which use the laws of fluid motion to relate the water velocity at one point to known external forcings such as winds and the tide at a nearby station.

A method has been developed in the Techniques Development Laboratory (TDL) to compute water currents at a point located in the San Pedro Channel approximately 1.5 n mi south of the east entrance to Long Beach Harbor (Fig. 1). Development was initiated by a request from Western Region Headquarters to provide guidance for sailing events during the 1984 Summer Olympics. The forecast site (33° 41.2'N, 118° 8.4'W) lies near the center of the sailing area. Although tailored for a specific site, the method is general enough to be applied to other offshore locations.

Our method uses two separate models. First, we ran simulations with a two-dimensional (in the horizontal) barotropic tide model (BTM) which was driven by periodic water level variations. This allowed us to correlate the sea surface slope at the desired off-shore site with the observed tide changes at a shore location. A second model, one-dimensional (in the vertical), uses the shore tide and the wind stress to compute the currents at several levels for one point in the channel. This model is called the single-point currents model (SPCM).

A simple, minicomputer-based version of the SPCM was written for use by a forecaster. For input it requires 1) a wind forecast and 2) a series of tide amplitudes and times for Los Angeles. The output is a list of surface current speeds and directions at uniform time intervals. Directions for running the program are given in Sections 6 and 7.

There are two main limitations to the SPCM. First, only local wind and tidally-induced circulations are included. Density currents, wave transport and large-scale currents like the California current are excluded. Second, only a limited amount of data now exists for the San Pedro Channel, so it is difficult to assess the accuracy of the predicted currents.

2. THE SINGLE-POINT EQUATION

The minicomputer version of SPCM for water currents solves a form of the vector equation of horizontal fluid motion in which only vertical variations are included. We ignore horizontal variations in all quantities except the surface elevation to save computer time. The equation for the horizontal velocity under these conditions is

$$\partial \underset{\sim}{w}/\partial t + f\underset{\sim}{k} \times \underset{\sim}{w} = \underset{\sim}{G} + \underset{\sim}{S} + \partial/\partial z(\nu \partial \underset{\sim}{w}/\partial z) \quad (1)$$

where $\underset{\sim}{w}$ = horizontal velocity vector,
f = Coriolis parameter,
$\underset{\sim}{k}$ = unit normal in the vertical,
$\underset{\sim}{G}$ = horizontal pressure gradient due to the tide,
$\underset{\sim}{S}$ = horizontal pressure gradient due to wind setup,
ν = turbulent eddy viscosity, and
z = vertical direction.

The essential simplification to the full equation is that the entire horizontal pressure gradient is the sum of two independent terms, $\underset{\sim}{G}$ and $\underset{\sim}{S}$. $\underset{\sim}{S}$ is generally much smaller than $\underset{\sim}{G}$ so that any interaction is also small. The term $\underset{\sim}{S}$ is small in the San Pedro channel because the water is deep--23.7 m at the site--and so it will be neglected hereafter.

Evaluation of the turbulence terms will rely on previous work (Barrientos and Hess, 1983) with the Composite Oil Spill Model for Operational Services (COSMOS) program. In that model, we used dimensional arguments to estimate the turbulent viscosity from turbulent velocities and length scales. The COSMOS program is too large and slow to run on a minicomputer. The eddy viscosity formulation is discussed in Section 5.B.

The solution to Eq. (1) is found by an implicit numerical scheme, and is discussed in Appendix I. The horizontal velocity is solved at 21 vertical levels at each time step of 360 seconds. The top boundary condition equates the turbulent stress in the fluid to the wind stress. At the bottom, a linear slip condition is employed.

In order to solve Eq. (1) we need to know the horizontal pressure gradient. For a uniform tide with amplitude η defined as

$$\eta(t) = (R/2)\cos(\sigma t),$$

the gradient term can be expressed (Defant, 1961) as

$$G_{x,y} = \quad A\cos[\sigma(t+t_1) + \pi/2],\ B\cos[\pi(t+t_2)]\} \quad (2)$$

where R = tidal range,
σ = tidal angular frequency,
A,B = amplitudes of the pressure gradient functions,
t_1 = time that G_x leads the tide, and
t_2 = time that G_y leads the tide.

Because the tide is generally non-uniform (i.e., the amplitudes of successive high, or low, waters were unequal), we defined the water level and the gradient functions in a piecewise manner. We used the basic form of Eq. (2), but with values of the constants A and B defined for each half-cycle. A tidal half-cycle is the time interval from one extremum to the next extremum. The values of t_1 and t_2 were fixed. The forms of G_x and G_y used are

$$G_x = -(s/2)\{(A_i + A_{i-1})\cos[\sigma_i(t-t_i^A)] - A_i + A_{i-1}\} \quad (3a)$$

$$\text{for} \quad t_i^A \leq t < t_i^A \text{ and} \quad (3b)$$

$$G_y = (s/2)\{(B_j + B_{j-1})\cos[\sigma_j(t-t_j^B)] - B_j + B_{j-1}\} \quad (4a)$$

$$\text{for} \quad t_j^B \leq t < t_{j+1}^B, \quad (4b)$$

where s = 1 for a falling tide, -1 for a rising tide,
i,j = number of the tidal extremum marking start of half-cycle,
A_i = amplitude of G_x during half-cycle i,
σ_i = tidal frequency for G_x during half-cycle $i = 2\pi/(T_{i+1}-T_{i-1})$,
T_i = time of occurrence of extremum i,
t = time during simulation,
B_j = amplitude of G_y near end of half-cycle j,
σ_j = tidal frequency for G_y during half-cycle $j = \pi/(T_{j+1} - T_j)$,
t_i^A = reference time for $G_x = 0.5(T_i + T_{i-1}) - t_1$, and
t_j^B = reference time for $G_y = T_j - t_2$.

At each time step the conditions (3b) and (4b) are checked. If these conditions are not met, then i (or j) is indexed, and A_i (or B_j) is recomputed. The forms (3a) and (4a) were found to portray the actual variations quite accurately.

3. TIDAL CURRENTS

We used the BTM to relate the tide at a shore site (the Los Angeles gage) to the sea surface slope at the forecast site. Such a relationship exists for two reasons. First, the San Pedro Channel is deep, and the tide propagates rapidly through it. As a result, the tide is nearly in phase throughout the channel, and the tidal amplitude is nearly uniform. The tide at the Los Angeles gage is, therefore, quite representative of the tide at the forecast site. Second, there is a simple relationship between the tide height and the surface slope because the tide can be approximated by a cosine curve. Eq. (2) is therefore a valid approximation.

A. The Tidal Currents in the Channel

The tidal currents in San Pedro Channel are semidiurnal and oriented parallel to the coastline. A revealing description of the currents is given in the NOS Tidal Current Tables (U.S. Department of Commerce, 1983a).

> "San Pedro Channel, 7 miles south of Los Angeles Harbor Breakwater. There are two periodic currents here which are both rotary, turning clockwise, and rather weak. The tidal current has a velocity at strength of about 0.2 knot. The other current, due apparently to daily land and sea breezes, has a period of 24 hours and an average velocity of about 0.2 knot. The greatest velocity during 5 months of observations was 1.5 knots. Currents greater than 1 knot occur infrequently."

As weak as these currents may be on the average, it is useful to attempt to predict them to establish the methodology, and because the currents at the sailing site are closer to shore and in shallower water than those measured by NOS and, hence, may be quite different.

B. The Barotropic Tide Model

The numerical scheme used to solve the equations of water flow and mass conservation is equivalent to the explicit method of Reid and Bodine (1968). The grid mesh encloses the harbor and part of the deep channel (Fig. 1), with a grid size, ΔL, of 1.0 n mi (1852 m). The flow is driven by applying a periodic water level variation across the southeastern boundary to simulate the tide wave advancing up the coast. A radiation condition outflow (Wurtele, et al., 1971) is specified at the northwestern boundary, allowing the tide wave to pass out freely without reflection. Several trial runs where made to establish the southern, deep-water boundary condition. The one selected was a zero normal flowrate because it was numerically stable and kept the water moving roughly parallel to the deep channel.

The surface pressure gradient terms at any point on the BTM grid mesh (m,n) are calculated by

$$G_x = -(g/\Delta L)\ (\eta_{n+1,m+1} + \eta_{n,m+1} - \eta_{n+1,m} - \eta_{n,m}) \quad .$$

$$G_y = -(g/\Delta L)\ (\eta_{n+1,m+1} - \eta_{n,m+1} + \eta_{n+1,m} - \eta_{n,m}) \quad .$$

For the San Pedro Channel grid mesh, the x-direction is toward 301° true, and the y-direction is toward 211° true (see Fig. 1). The gradients were computed for the site at point (m=24, n=5) and averaged over 120 time steps to eliminate short period oscillations. Fig. 2 shows the tide at the boundary, G_x and G_y at the forecast site, and the x- and y-components of the vertically-averaged current at the site. The input tide range is 1.0 m, which is close to the mean range of 1.2 m at the Los Angeles gage (U.S. Department of Commerce, 1983b). The curves in Fig. 2 confirm that the surface gradient terms closely follows the periodic form of Eq. (2).

C. Empirical Functions Relating Gradient Amplitude to Tide

Eleven computer runs were made to gather data for the empirical functions. Each run consisted of 76 hours of tide and current simulation with the BTM. Only the last 38 hours of each run was used in the data analysis. A total of 29 cases were selected for the development sample. Each case covered a half of a tide cycle and included as variables the tide range over the half-cycle, R_i (m), the duration of the half-cycle, D_i (h), the range and duration of the immediately preceding half-cycle, R_{i-1} and D_{i-1}, and the peak values of the x- and y-surface gradients, A_i and B_i (m/s^2). Here

$$R_i = |\eta_{i+1} - \eta_i| \quad \text{and} \qquad (5)$$

$$D_i = T_{i+1} - T_i .$$

A screening regression technique was used to correlate A and B to the other variables. The results showed that most of the variance about the mean is accounted for by the present and preceding tide range. These two variables explained 98.8% of the variance in A, and 99.0% of the variance in B. The equations derived were

$$A_i = (0.00524 + 0.09566\ R_i + 0.04720\ R_{i-1}) \times 10^{-4} \text{ and} \tag{6a}$$
$$B_i = (-.00240 + 0.11717\ R_i - 0.00471\ R_{i-1}) \times 10^{-4}. \tag{6b}$$

There was negligible further reduction of variance when the duration variables were included.

The equations (6a, 6b) were used to compute values of A_i and B_i for eight cases not included in the development sample. Fig. 3 shows a plot of the computed and the observed (from the BTM) values. The scatter is small. Eq. (6) should be useful for predicting the amplitude of the pressure gradient terms.

4. COMPARISON OF CURRENTS PREDICTED WITH THE BTM AND THE SPCM

A major goal of this study is to reproduce the tidal currents at the site as predicted by the BTM with only the SPCM and the tide at the Los Angeles gage. We compared the vertically-averaged current from the BTM with that from the SPCM for four cases. In the first three cases, the amplitudes (A,B) of the gradient terms were equal to those produced by the BTM for that case, although the form of the gradient terms were periodic functions as in Eqs. (3a) and (4a). In the final case, the amplitudes were determined by Eqs. (6a, 6b). The results from all cases were encouraging.

A. Single-Frequency Tide

The first case we ran was for a single-frequency tide. The southeast boundary (Fig. 1) of the BTM was driven by a tidal elevation with the form

$$\eta(t) = \eta_1 \cos(\sigma t)$$

Cases where the tide consisted of the sum of two or more components are discussed later. For this case, the BTM simulated 6 tidal cycles, each with a period of 12.4 hours. Transients generally died out by the second or third cycle. The tide, components of $\tilde{G}$, and the vertically-averaged components of the current at grid (m=24, n=5) for the fifth tidal cycle are shown as solid lines in Fig. 2.

In conjunction with the BTM run, we ran the SPCM to simulate the barotropic model's tidal currents. The driving surface gradients had the form of Eqs. (3a) and (4a), with

$$A_i=2.25\times10^{-5}\ m/s^2, \quad B_i=1.67\times10^{-5}\ m/s^2, \quad t_1=0.4\ h, \quad t_2=0.8\ h.$$

These values were taken from the BTM output. The input tide, input $\tilde{G}$, and resulting currents for the third tidal cycle are shown as dashed lines in Fig. 2. The amplitudes of the x- and y-components of the peak currents agree to within 8%.

Several tests were made to determine the sensitivity of the output. The value of ν had to be selected carefully since small changes in it produced significant changes in the velocity. Changes in the peak current of only a few percent occurred when the bottom friction coefficient, C_b, was reduced from its nominal value of 0.006 to 0.004. Negligible changes in the currents also occurred when t_1 was changed by the equivalent of plus or minus 0.4 hours. The water currents in the SPCM are initialized to constant values over depth at the start of the run, as described in Appendix II. Initializing with depth-dependent functions which increased the near-surface velocity and diminished the flow near the bottom had little or no effect on the computed currents.

B. Two-frequency Tide

The second group of experiments used a tide composed of two frequencies for the southeast boundary condition. This tide was the sum of a semidiurnal (12.4-h period) and a diurnal (24.8-h period) component, and had the general form

$$\eta(t) = \eta_1 \cos(\sigma t) + \eta_2 \cos(\sigma t/2) \ .$$

The vertically-average currents from the BTM for this case are shown as solid lines in Fig. 4a. The x-component matches quite well. The y-component doesn't match as well, but the magnitude of the error is small and probably unimportant.

C. Historical Tide

The third case run used the tide at Los Angeles as predicted by the NOS method for input. This tide is composed of 37 frequencies. The BTM was run for the time period from 0000 PST 15 July 1984 to 0300 PST 18 July 1984. The comparison was made between currents from the BTM and the SPCM for the period of time starting with the high water at 2246 PST, July 16, 1984, and extending for 26 hours. The results are shown in Fig. 4b. As in the previous case, small errors in phase and amplitude occur, especially in the y-component, although the major characteristics of the flood and ebb currents are reproduced.

D. Historical Tide with Empirical Functions

The final case with pure tidal currents involved running of the SPCM with historical tides and with A_i and B_i computed from the empirical equations (6a, 6b). The results in Fig. 4c show that, for this case, the use of these equations improves the SPCM solution by only a small amount in relation to that in the previous case.

As a result of these studies, we feel that the SPCM can reproduce the BTM tidal currents with acceptable accuracy when only the times and elevations of high and low tide are used as input.

5. WIND-DRIVEN CURRENTS

In direct contrast to the regularity of the tidal currents is the highly variable nature of the wind. Any attempt to predict surface water currents must therefore rely on timely and accurate wind forecasts for frequent intervals. The unsteadiness of the wind in the San Pedro Channel (U.S. Department of Commerce, 1983c) indicates that 3-h forecast winds are desirable.

A. Wind Stress

Development of our spilled oil forecast techniques (Barrientos and Hess, 1983) revealed the importance of wind drag formulations. We assume here that the magnitude of the wind stress can be related to the 10-m wind speed, V_{10}, by

$$\tau_s = \rho_a C_{aw} V_{10}^2,$$

where C_{aw} is an interfacial drag coefficient. The drag coefficient can also be defined in terms of the wind friction velocity, V_*, as

$$C_{aw} = (V_*/V_{10})^2.$$

By assuming that surface roughness is related to friction velocity by Charnock's law (Charnock, 1981), and using the logarithmic law for the wind profile, we have

$$V_* = 0.4\ V_{10}/\ln(10.0g/0.0144\ V_*^2).$$

The above is solved at each time step with the present value of the forecast wind.

B. Ekman Dynamics

The initial test of the SPCM's ability to simulate wind-driven currents was to reproduce the Ekman (1905) spiral for shallow water flow. For a uniform eddy viscosity of 0.01 m^2/s, the SPCM was run with a constant wind of 10 m/s. The plot of the end-point of the surface velocity vector over time (a hodograph) is shown in Fig. 5. The final angle of deflection is 45.0°, and the current speed is 0.202 m/s, virtually identical to the theoretical values.

Probably a more realistic solution to the problem can be found by introducing an eddy viscosity which varies with depth. We used one which was zero at the surface, increased linearly down to a depth of 2.0 meters, and had a constant value (0.01 m^2/s) down to the bottom. The depth of 2.0 meters was based on studies described in Barrientos and Hess (1983). The spiral for the new eddy viscosity is also shown in Fig. 5. The water velocity near the surface differs from that in the constant viscosity case by having a nearly logarithmic variation in the direction of the wind stress. As a consequence, the surface velocity is stronger in the down-wind direction by roughly 0.20 m/s, bringing the total speed to 0.365 m/s. The deflection angle is reduced to 22.7°. Both values are more in line with the observed behavior of surface currents which transport oil slicks (Barrientos and Hess, 1983).

A test of the spin-up time for wind-driven flow was performed for a typical sea breeze situation. We used three-hourly winds based on data from U.S. Department of Commerce (1983c) tables but inflated by 50 percent to approximate over-water conditions. The following values, starting at 0000 local time, were used: 3605, 0703, 1003, 2006, 2211, 2520, 2516, and 2707. We've used the standard meteorological notation for wind values, which has the form DDSS. Here, DD is the direction from which the wind blows (10's of degrees) and SS is the wind speed (knots). The values for wind were repeated to simulate 3 days of currents. The surface hodograph (Fig. 6) shows that roughly 30 hours are necessary to nearly eliminate transient inertial oscillations.

6. MODEL INPUT AND OUTPUT

A version of the SPCM has been coded to run on the Automation of Field Operations and Services (AFOS) Data General S/230 computer. Data are entered into a preformatted message on the Alphanumeric Display Module (ADM). A sample of the preformat and the message are shown in Fig. 7. The output consists of a list of the input tides and winds, and contains the forecast surface current at 1-h intervals. The output is printed on the Versatec Printer-Plotter Module (PPM). A sample is shown in Fig. 8. The following example shows how a forecast can be made for August 2, 1984.

The SPCM requires both tide and wind data. Tidal information is entered as a series of times and heights of high and low water. These values are readily obtainable from the Tide Tables (U.S. Department of Commerce, 1983b) for Los Angeles (Outer Harbor). Values of height are entered in feet to provide greater accuracy. The time period simulated by the SPCM is 48 hours, and begins one full day before the day of interest so that transients will have time to damp out. Therefore, a series of values must be taken from the tables to cover the 2 days, plus one more value at the start of the third day.

Here is the procedure needed to make a forecast with the SPCM. As a first step, the forecaster consults the tide tables, a portion of which is reproduced in Fig. 9. Looking at the entries for August 1984, we find that there are 3 entries for August 1 and four entries for August 2. Counting these, plus one additional value needed from August 3, we determine that eight pairs of tide values are to be typed in. These numbers appear in the lower panel of Fig. 7.

For the second step, the user must supply forecast winds for 3-h intervals out to 24 hours. Winds from the previous day, at the same interval, must also be given. Winds used in the example are for a typical sea breeze situation, based on climatology. These values (17 in all) are shown in Fig. 7. The time -24 H refers to the start of the previous day (August 1). Wind stress in the SPCM is computed from these numbers by linear interpolation.

Surface current speeds (kt) and directions (to the nearest 10 degrees) toward which the water is moving are printed out at a fixed interval of 2 hours for August 2 as shown at the bottom of Fig. 8. The results show that for the typical situation chosen, the current maximum is approximately 0.9 kt and occurs in the early evening.

7. PROGRAM USE

The material in this Office Note describes an AFOS applications program, and would normally be included in a TDL Computer Program (CP) document. Because the distribution of this program is limited, no CP was issued. However, the following section, which adheres to the CP format, is included to assist the user in runing the program on the AFOS computer.

SINGLE-POINT FORECASTS OF WIND-DRIVEN AND TIDAL CURRENTS IN SAN PEDRO CHANNEL

PART A. PROGRAM INFORMATION AND INSTALLATION PROCEDURE

PROGRAM NAME: SPC

AAL ID: none

FUNCTION: This program produces surface wind and tidal current for a specific site in the San Pedro Channel in southern California (33° 41.2'N, 118° 8.4' W) each hour for one day. Needed input are tide height-and-time pairs for that day and for the previous day, and the first pair for the following day. These are available from the NOS Tide Tables. Also needed are winds at 3-hourly intervals for that day and the previous day.

PROGRAM INFORMATION

Development Programmer:	Maintenance Programmer:
Kurt W. Hess	Kurt W. Hess
Location: Techniques Development Laboratory	Techniques Development Laboratory
Phone: FTS 427-7613	FTS 427-7613
Language: Fortran IV/Rev 5.20	Type: Regular
Save file creation dates:	
Original release/Rev. 01.00	April 2, 1984

Run time: 4 Minutes

Disk space: SPC.SV - 52 RDOS blocks

PROGRAM REQUIREMENTS:

Program Files:

NAME	COMMENTS
SPC.SV	Code to run the model

Data Files: none

AFOS Products:

ID	PURPOSE	COMMENTS
EXFMCPSPC	Holds message composition Preformat	Rename for local use
EXFSPCEXF	Holds data for individual run	Rename for local use

LOAD LINE

```
RLDR/P SPC AFREAD GRADS PRINTO RDSPM READIN RFOS2 SINIT
BG.LB UTIL.LB FORT.LB
```

PROGRAM INSTALLATION

1. Insert floppy disk into DP3.

2. Move SPC.SV to DP0F. Then create a LINK on DP0 for this file.

3. Select a product key, cccMCPxxx, for the preformat and store EXFMCPSPC into it by entering:

   STORE:DP3:EXFMCPSPC cccMCPxxx

   Select another product key, cccnnnxxx, for the SPC message file, and store EXFSPCEXF into it by entering:

   STORE:DP3:EXFSPCEXF cccnnnxxx

SINGLE-POINT FORECASTS OF WIND-DRIVEN AND TIDAL CURRENTS IN SAN PEDRO CHANNEL

PART B. PROGRAM EXECUTION and ERROR CONDITIONS

PROGRAM NAME: SPC AAL ID: none

PROGRAM EXECUTION:

1. Make sure the SV file for SPC exists on either DP0, or DP0F with links to them on DP0, and that the preformat, cccMCPxxx, and the data product, cccnnnxxx, (see Part A) exist in the PIL.

2. Either use the preformat (cccMCPxxx) to create a new run file, or edit an old run file, so that the data are as desired. For hourly current forecasts, the user must enter tide height-and-time pairs for the day of the forecast and the previous day, and the first pair for the following day. Tide data for July, August, and September, 1984, are given in Fig. 9. Tide times are represented as four digit numbers in the form HHMM. Tide heights are entered as integer values in units of tenths of feet. Data pairs are entered consecutively, with no blank lines between values. Also, wind at 3-hourly intervals is required for the day of the forecast and the previous day. The print unit number for the PPM must be entered. Refer to Section 5. for details.

3. Run the program by entering at the ADM:

   RUN:SPC cccnnnxxx

   where cccnnnxxx is the SPC data file.

4. Look for output on the PPM.

ERROR CONDITIONS:

1. Errors are most likely to occur when trying to print. Make sure the PPM is powered on and open for printing.

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APPENDIX I

Finite-Difference Solution of the Velocity Equation

The single-point equation (1) describes the horizontal water velocity in a column of water. Since the total water depth changes over time as the tide rises and falls, it is convenient to substitute for z a new vertical coordinate which maintains the same number of grid levels regardless of water depth. For this purpose we define

$$q = [(\eta(t) - z)/(h + \eta(t))]^{1/2} = [(\eta - z)/H]^{1/2} \qquad (I.1)$$

where η = tidal variation,
h = m.s.l. water depth, and
H = total water depth = $h + \eta$.

The transformation of Eq. (1) to the (x,y,q,t)-system adds a few terms. The resulting equation is

$$\partial \underset{\sim}{w}/\partial t + (1-q^2)/(2Hq)\,\partial\eta/\partial t\;\; \partial\underset{\sim}{w}/\partial q = \underset{\sim}{G} - f\underset{\sim}{k} \times \underset{\sim}{w} + 1/(4H^2q)\,\partial/\partial q(\nu/q\,\partial\underset{\sim}{w}/\partial q) \qquad (I.2)$$

The finite-difference equation for the x-component of $\underset{\sim}{w}$ is

$$\begin{aligned} u_m^+ &= u_m + \Delta T G_x + \Delta T f v_m \\ &- (\partial\eta/\partial t)(\Delta T/4H\Delta q)[(u_{m-1}^+ - u_m^+)(1-q_{m-1/2}^2)/q_{m-1/2} + (u_m^+ - u_{m+1}^+)(1-q_{m+1/2}^2)/q_{m+1/2}] \\ &+ \Delta T/(4qH^2\Delta q^2)[\,\nu_{m-1/2}\,(u_{m-1}^+ - u_m^+)/q_{m-1/2} - \nu_{m+1/2}\,(u_m^+ - u_{m+1}^+)/q_{m+1/2}] \end{aligned} \qquad (I.3)$$

The equation for v_m^+ is similar, but the Coriolis term is negative.

Here u_m^+, v_m^+ = velocity components at level m and time $t+\Delta T$,
u_m, v_m = velocity components at level m and time t,
Δq = grid interval in vertical direction.
ΔT = time step,
f = Coriolis parameter, and
ν_m = eddy viscosity at level m.

The explicit method of solution is stable provided

$$\Delta T \leq (H\Delta q)^2/2$$

In practice the explicit time step is too small, so an implicit technique is used to solve (I.3).

The top $(z=\eta)$ boundary condition includes the wind stress $\underset{\sim}{\tau}_s$ as follows.

$$\partial\underset{\sim}{w}/\partial z = \underset{\sim}{\tau}_s/\nu\rho_a,$$

and at the bottom (z=-h)

$$\partial \underset{\sim}{w} / \partial z = C_b W \underset{\sim}{w},$$

where C_b = bottom friction coefficient, and
W = vertically-averaged magnitude of $\underset{\sim}{w}$.

APPENDIX II

Initial Conditions for the Velocity Solution

Special care must be taken to initialize the solution of the water velocity equation properly to eliminate the spurious inertial oscillation. The correct initial values are determined from the analytic solution to the equations for linear, frictionless, depth-independent flow. These equations are

$$\partial u/\partial t - fv = -A\sin(\sigma t) + C = G_x \quad \text{and} \tag{II.1}$$

$$\partial v/\partial t + fu = B\cos(\sigma t + \theta) + D = G_y \tag{II.2}$$

where f, σ, θ, A, B, C, and D are assumed to be constants. These equations are now combined into a single equation with complex variables by multiplying (II.2) by i and adding it to (II.1) to get

$$\partial W/\partial t + ifW = P , \tag{II.3}$$

where $W = u + iv$, and
$P = G_x + iG_y$.

Eq. (II.3) can be solved by making use of an integrating factor to give

$$W = e^{-ift} \int e^{ift} P\, dt + Ee^{-ift}. \tag{II.4}$$

Now since

$$P = A \sin(\sigma t) + B\cos(\sigma t)\cos\theta - iB\sin(\sigma t)\sin\theta + C + iD$$

it is a relatively straightforward, although tedious, matter to carry out the integration. The general solution determined by Eq. (II.4) is

$$u = 0.5[(A+B\cos\theta)/(\sigma+f) + (A-B\cos\theta)/(\sigma-f)]\cos(\sigma t)$$

$$-0.5\, B\sin\theta[1/(\sigma+f) - 1/(\sigma-f)]\sin(\sigma t) + Df^{-1} + E\cos(ft) \tag{II.5}$$

$$v = 0.5[(A+B\cos\theta)/(\sigma+f) - (A-B\cos\theta)/(\sigma-f)]\sin(\sigma t)$$

$$+0.5\, B\sin\theta[1/(\sigma+f) + 1/(\sigma-f)]\cos(\sigma t) - Cf^{-1} - E\sin(ft). \tag{II.6}$$

The proper initial conditions are obtained by evaluating Eqs. (II.5) and (II.6) at $t=t_o$ with E=0.

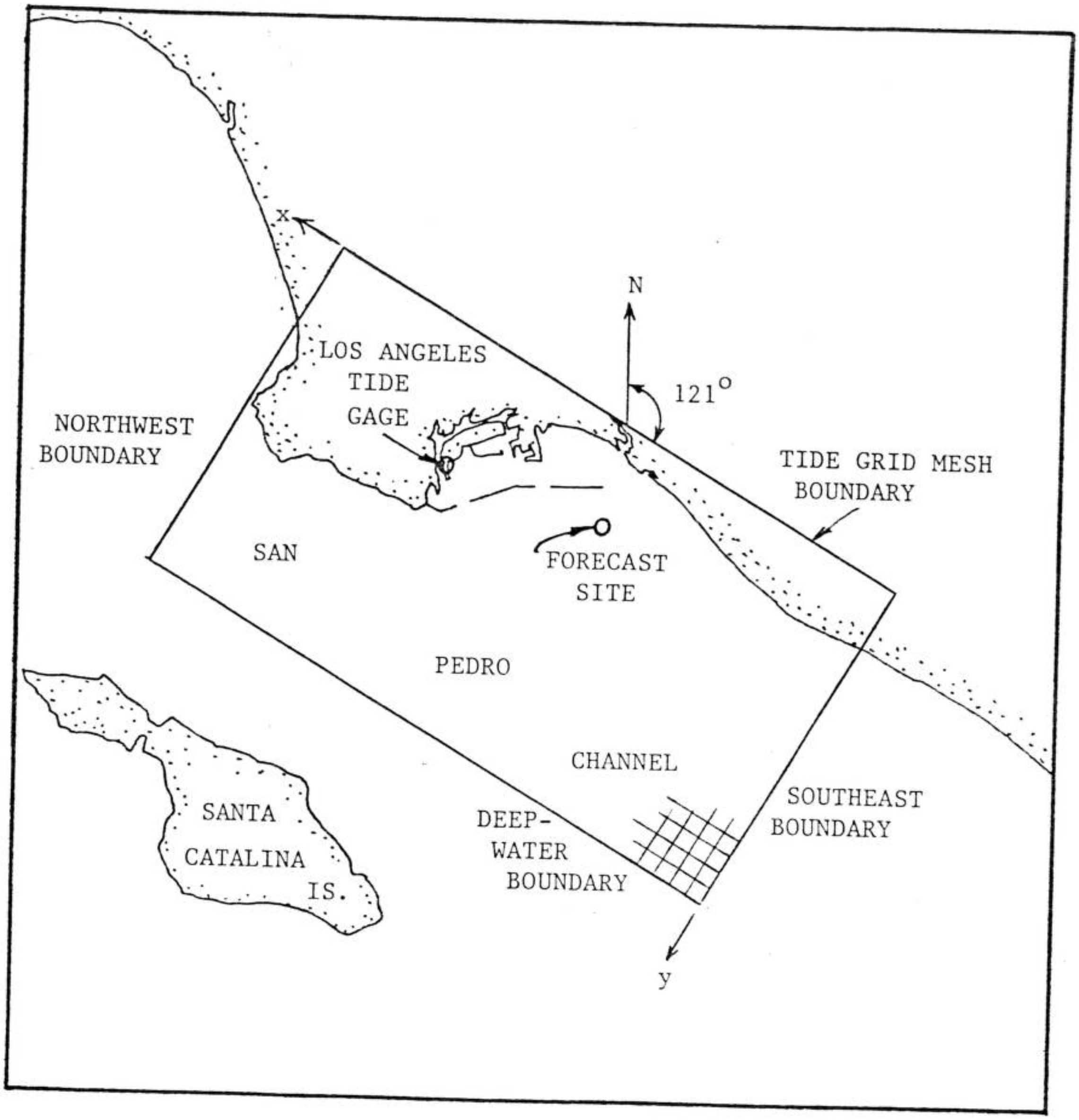

Figure 1. Base map of southern California including the San Pedro Channel, the forecast site at which the SPCM applies, and the BTM grid mesh. The tidal flow is generally parallel to the coast. The California Current flows to the south, offshore of Santa Catalina Island, driving a return flow in the Channel in a westerly direction.

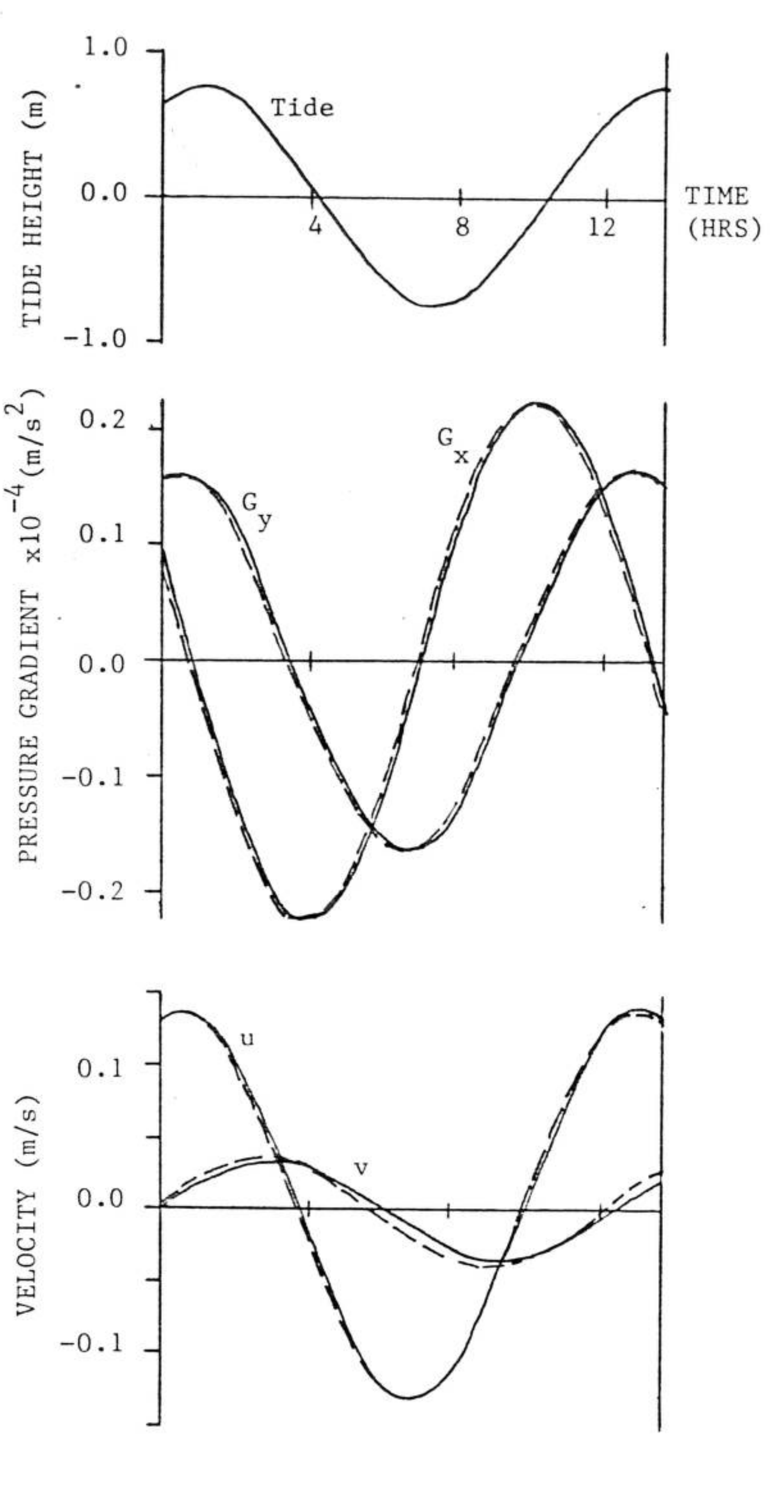

Figure 2. Tide, pressure gradients, and currents for the case of a single-frequency tide. The solid lines represent the output of the BTM and the dashed lines the output of the SPCM.

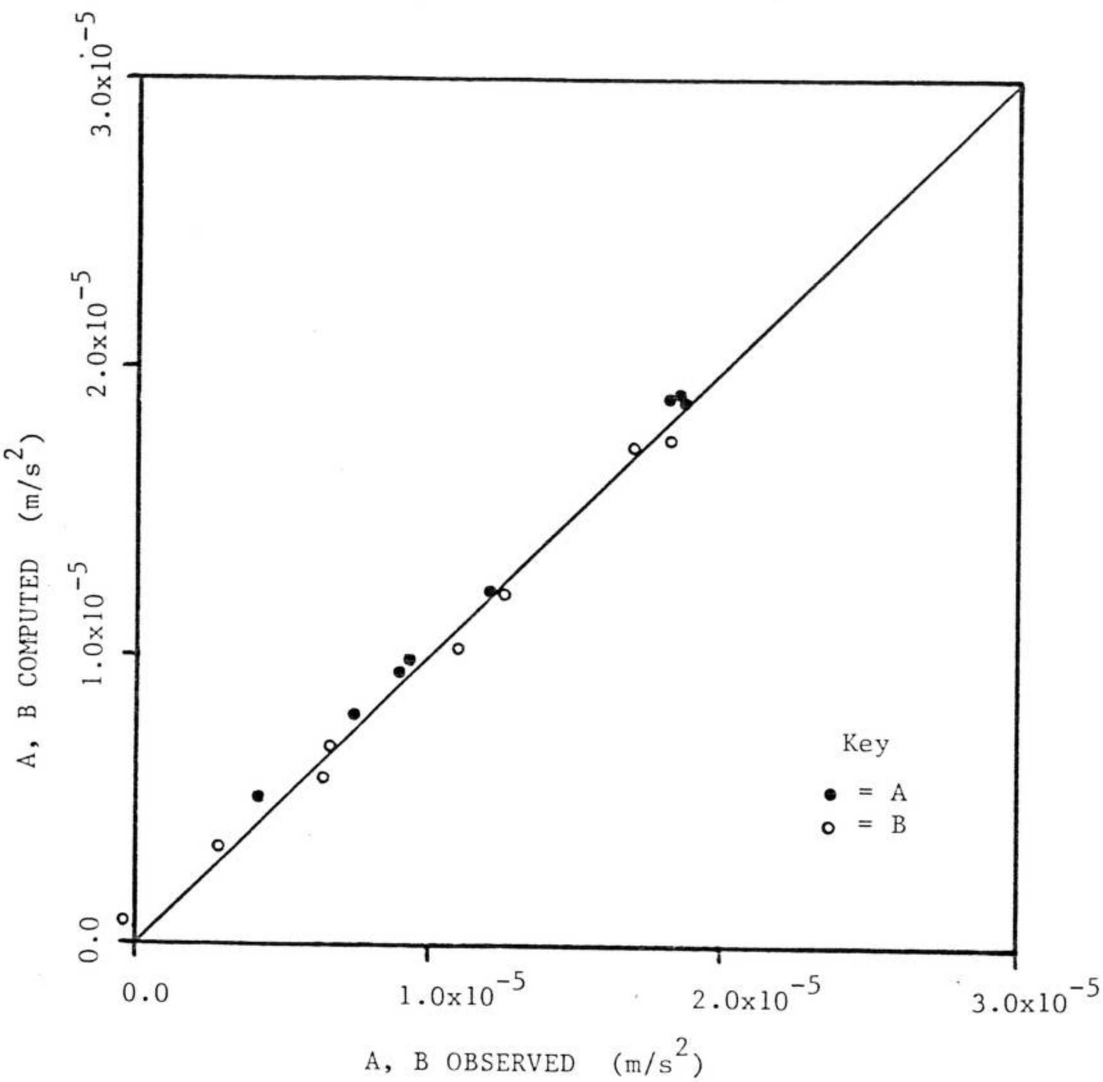

Figure 3. Graph showing the observed values (from BTM runs) of A and B (the peak values of the x- and y-gradients respectively) plotted against the values computed by the Eqs. (5), (6a), and (6b).

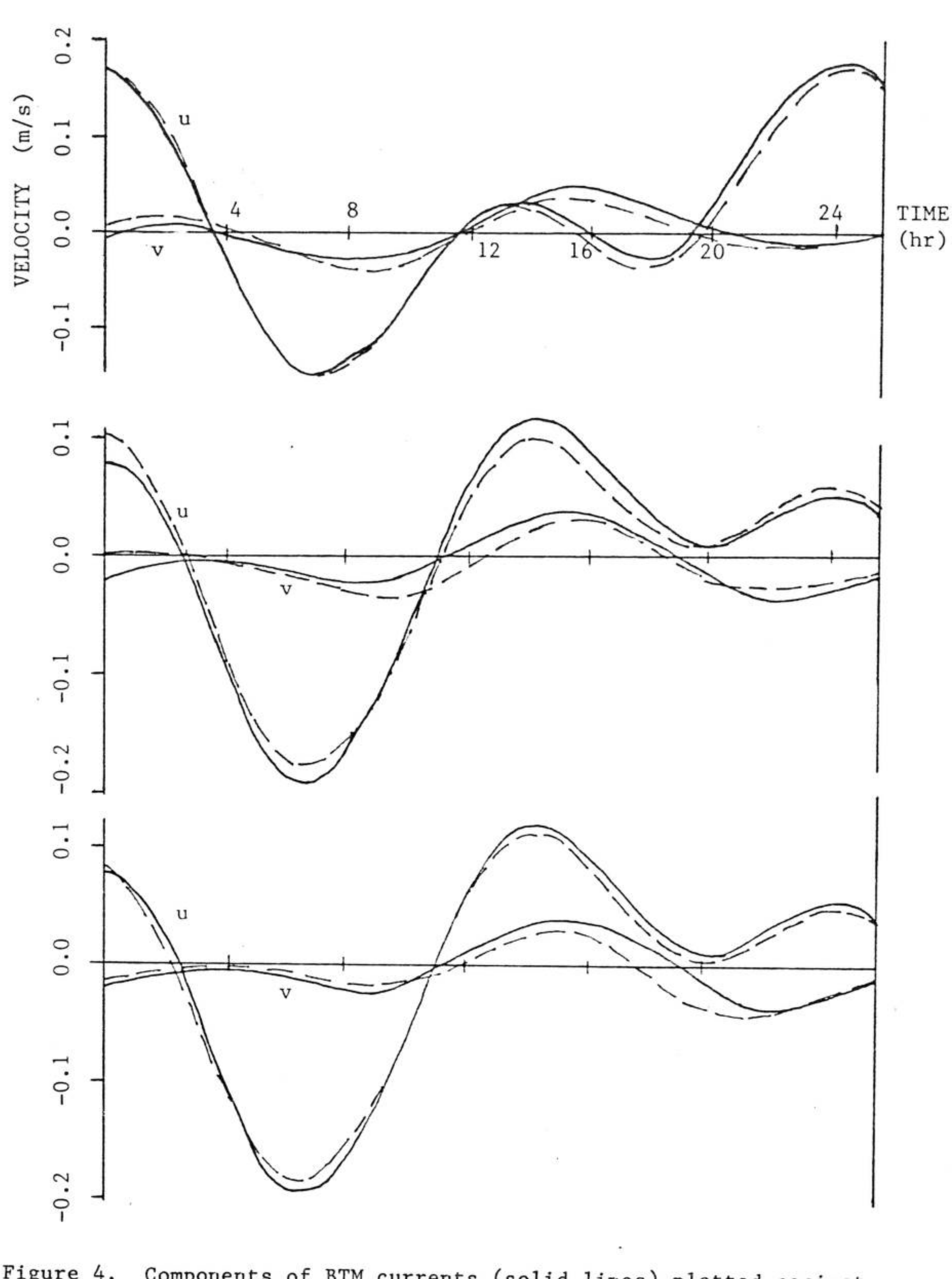

Figure 4. Components of BTM currents (solid lines) plotted against output from the SPCM (dashed lines) for three cases of multiple-component tidal input. The top panel shows data for a two-frequency tide. The middle and bottom panels display data from a historical tide. The SPCM current in the middle panel was computed with BTM values of A and B, while the SPCM current in the bottom panel was computed with values of A and B calculated by Eqs. (5), (6a), and (6b).

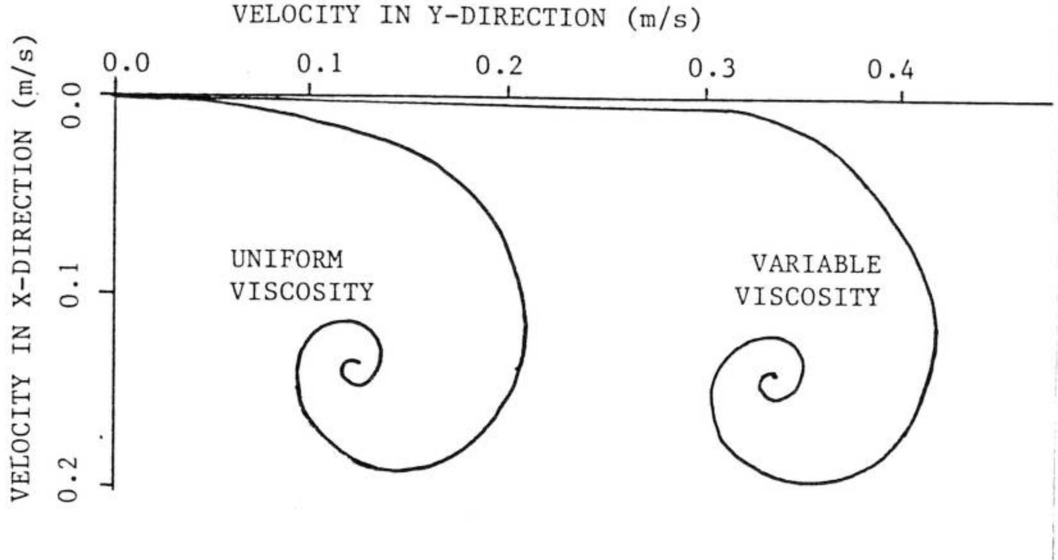

Figure 5. Hodographs of the surface current vector variation with time for a suddenly-applied wind stress in the y-direction. The constant eddy viscosity (0.01 m^2/s) case corresponds to classical Ekman (1905) flow. The variable viscosity is zero at the water surface, increases linearly down to 2 meters, and is constant from there down (0.01 m^2/s). This variation produces a logarithmic velocity profile in the near-surface layer.

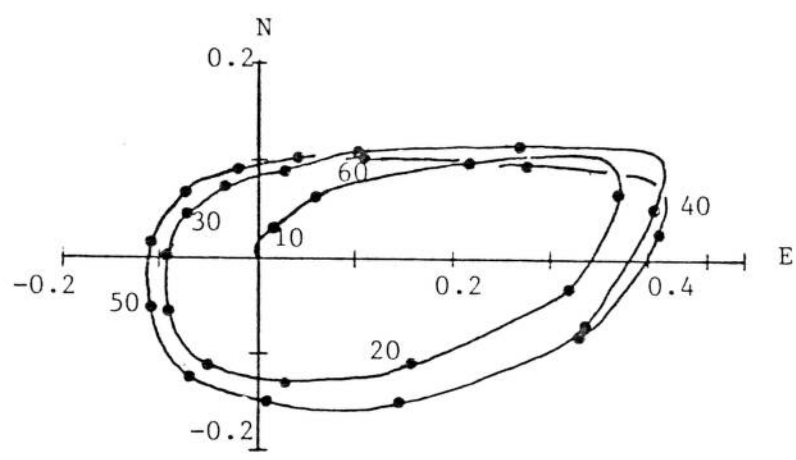

Figure 6. Hodograph showing the surface current from the SPCM for a typical sea breeze situation (see Section 5.B.). The numbers next to the curve denote hours into the simulation. The plot shows that at least 30 hours are needed for spin-up time.

```
EXFMCPSPC
WOUS00 KEX1 191500
SAN PEDRO CHANNEL CURRENTS.  ENTER TIME (HHMM) AND HEIGHT
(TENTHS OF FEET) STARTING AT -24 H.
   TIME    HEIGHT
1.[     ] [     ]
2.[     ] [     ]
3.[     ] [     ]
4.[     ] [     ]
5.[     ] [     ]
6.[     ] [     ]
7.[     ] [     ]
8.[     ] [     ]
9.[     ] [     ]
ENTER WINDS FOR 3-H INTERVALS STARTING AT:
-24 H [     ] [     ] [     ] [     ]
-12 H [     ] [     ] [     ] [     ]
 00 H [     ] [     ] [     ] [     ]
+12 H [     ] [     ] [     ] [     ]
+24 H [     ]
ENTER OUTPUT UNIT (EG 12, 14) [   ]

                                                  [ ]
                                              PAGE  01
```

```
EXFSPCEXF
WOUS00 KEX1 041500
SAN PEDRO CHANNEL CURRENTS.  ENTER TIME (HHMM) AND HEIGHT
(TENTHS OF FEET) STARTING AT -24 H.
   TIME    HEIGHT
1. 0600    -001
2. 1237      50
3. 1827      17
4. 0017      48
5. 0642       6
6. 1327      52
7. 1950      16
8. 0133      40
9. 0000    0000
ENTER WIND OBS AND FCSTS AT 3-H INTERVALS STARTING AT:
-24 H   3605   0703   1003   2006
-12 H   2211   2520   2516   2707
 00 H   3605   0703   1003   2006
+12 H   2211   2520   2516   2707
+24 H   3605
ENTER OUTPUT UNIT (EG 12, 14)  12

                                              PAGE  01
```

Figure 7. Two AFOS data files needed to run the SPCM. The top panel shows the preformatted message, here named EXFMCPSPC, which accepts the values of tide and wind for the program. The bottom panel shows the message, here named EXFSPCEXF, created by the preformat.

```
SPC:SINGLE-POINT CURRENTS IN SAN PEDRO CHANNEL (33 41.2 N, 118 8.4 W)
SPC:INITIAL TIDE DATA
N= 1      HOUR=  600     HEIGHT= -0.1
N= 2      HOUR= 1237     HEIGHT=  5.0
N= 3      HOUR= 1827     HEIGHT=  1.7
N= 4      HOUR=   17     HEIGHT=  4.8
N= 5      HOUR=  642     HEIGHT=  0.6
N= 6      HOUR= 1327     HEIGHT=  5.2
N= 7      HOUR= 1950     HEIGHT=  1.6
N= 8      HOUR=  133     HEIGHT=  4.0
SPC: INPUT WINDS
  3605   703  1003  2006  2211  2520  2516  2707
  3605   703  1003  2006  2211  2520  2516  2707
  3605
SPC:SURFACE CURRENTS
HR (LOCAL)     SPEED (KT)     TOWARD (DEG)
     0             0.3            230.
   100             0.4            240.
   200             0.3            240.
   300             0.3            230.
   400             0.2            210.
   500             0.1            160.
   600             0.2            110.
   700             0.2             90.
   800             0.2             60.
   900             0.2             20.
  1000             0.3              0.
  1100             0.3            350.
  1200             0.4            350.
  1300             0.4              0.
  1400             0.4             40.
  1500             0.7             70.
  1600             0.8             80.
  1700             0.8             90.
  1800             0.9            100.
  1900             0.8            110.
  2000             0.7            120.
  2100             0.5            130.
  2200             0.4            150.
  2300             0.3            180.
  2400             0.3            210.
```

Figure 8. Typical output from the AFOS version of the SPCM. Tide and wind data simply repeat the input shown in Fig. 7.

LOS ANGELES (Outer Harbor), CALIFORNIA, 1984

Times and Heights of High and Low Waters

JULY

Day	Time h m	Height ft	Height m	Day	Time h m	Height ft	Height m
1	0507	-1.2	-0.4	16	0528	-0.2	-0.1
Su	1154	3.9	1.2	M	1212	3.9	1.2
	1617	2.5	0.8		1651	2.6	0.8
	2227	6.1	1.9		2246	5.2	1.6
2	0552	-0.9	-0.3	17	0602	0.2	0.1
M	1242	4.1	1.2	Tu	1251	4.0	1.2
	1721	2.5	0.8		1747	2.7	0.8
	2320	5.6	1.7		2325	4.7	1.4
3	0637	-0.5	-0.2	18	0634	0.6	0.2
Tu	1333	4.3	1.3	W	1333	4.1	1.2
	1842	2.5	0.8		1851	2.7	0.8
4	0023	5.0	1.5	19	0015	4.1	1.2
W	0728	0.0	0.0	Th	0708	1.1	0.3
	1426	4.6	1.4		1415	4.2	1.3
	2009	2.2	0.7		2017	2.5	0.8
5	0141	4.3	1.3	20	0119	3.5	1.1
Th	0817	0.5	0.2	F	0745	1.6	0.5
	1516	5.0	1.5		1457	4.4	1.3
	2141	1.7	0.5		2156	2.2	0.7
6	0311	3.7	1.1	21	0300	3.0	0.9
F	0913	1.0	0.3	Sa	0830	2.0	0.6
	1605	5.4	1.6		1543	4.7	1.4
	2301	1.0	0.3		2309	1.6	0.5
7	0449	3.4	1.0	22	0500	2.9	0.9
Sa	1005	1.5	0.5	Su	0922	2.3	0.7
	1652	5.8	1.8		1625	5.0	1.5
8	0007	0.3	0.1	23	0005	1.0	0.3
Su	0617	3.4	1.0	M	0627	3.1	0.9
	1101	1.9	0.6		1021	2.5	0.8
	1737	6.1	1.9		1711	5.4	1.6
9	0059	-0.3	-0.1	24	0047	0.4	0.1
M	0724	3.6	1.1	Tu	0723	3.3	1.0
	1153	2.1	0.6		1121	2.6	0.8
	1822	6.3	1.9		1754	5.8	1.8
10	0147	-0.7	-0.2	25	0125	-0.2	-0.1
Tu	0820	3.7	1.1	W	0805	3.6	1.1
	1242	2.3	0.7		1213	2.6	0.8
	1904	6.5	2.0		1836	6.2	1.9
11	0229	-0.9	-0.3	26	0204	-0.7	-0.2
W	0905	3.8	1.2	Th	0839	3.8	1.2
	1327	2.4	0.7		1259	2.4	0.7
	1944	6.5	2.0		1920	6.6	2.0
12	0308	-1.0	-0.3	27	0242	-1.1	-0.3
Th	0947	3.8	1.2	F	0917	4.0	1.2
	1406	2.4	0.7		1347	2.3	0.7
	2021	6.4	2.0		2003	6.9	2.1
13	0345	-0.9	-0.3	28	0321	-1.3	-0.4
F	1024	3.9	1.2	Sa	0953	4.2	1.3
	1447	2.4	0.7		1436	2.1	0.6
	2100	6.3	1.9		2048	6.9	2.1
14	0421	-0.8	-0.2	29	0400	-1.3	-0.4
Sa	1101	3.9	1.2	Su	1029	4.4	1.3
	1526	2.5	0.8		1524	1.9	0.6
	2135	6.0	1.8		2133	6.7	2.0
15	0456	-0.5	-0.2	30	0441	-1.1	-0.3
Su	1137	3.9	1.2	M	1108	4.6	1.4
	1609	2.5	0.8		1617	1.8	0.5
	2211	5.6	1.7		2222	6.3	1.9
				31	0520	-0.6	-0.2
				Tu	1150	4.8	1.5
					1718	1.8	0.5
					2315	5.6	1.7

AUGUST

Day	Time h m	Height ft	Height m	Day	Time h m	Height ft	Height m
1	0600	-0.1	0.0	16	0531	1.1	0.3
W	1237	5.0	1.5	Th	1203	4.5	1.4
	1827	1.7	0.5		1802	2.1	0.6
					2344	4.0	1.2
2	0017	4.8	1.5	17	0555	1.6	0.5
Th	0642	0.6	0.2	F	1237	4.5	1.4
	1327	5.2	1.6		1909	2.1	0.6
	1950	1.6	0.5				
3	0133	4.0	1.2	18	0040	3.4	1.0
F	0731	1.3	0.4	Sa	0618	2.1	0.6
	1420	5.3	1.6		1319	4.6	1.4
	2123	1.2	0.4		2044	2.0	0.6
4	0319	3.4	1.0	19	0229	2.9	0.9
Sa	0828	1.9	0.6	Su	0647	2.5	0.8
	1522	5.5	1.7		1415	4.7	1.4
	2249	0.7	0.2		2228	1.6	0.5
5	0514	3.3	1.0	20	0529	2.9	0.9
Su	0936	2.4	0.7	M	0746	2.8	0.9
	1623	5.7	1.7		1530	4.9	1.5
					2336	1.0	0.3
6	0001	0.2	0.1	21	0649	3.3	1.0
M	0644	3.5	1.1	Tu	0943	3.1	0.9
	1049	2.6	0.8		1636	5.2	1.6
	1722	5.9	1.8				
7	0056	-0.2	-0.1	22	0021	0.4	0.1
Tu	0739	3.8	1.2	W	0717	3.6	1.1
	1154	2.7	0.8		1111	2.9	0.9
	1814	6.1	1.9		1729	5.7	1.7
8	0139	-0.5	-0.2	23	0102	-0.2	-0.1
W	0821	4.0	1.2	Th	0745	3.9	1.2
	1246	2.6	0.8		1207	2.6	0.8
	1859	6.2	1.9		1823	6.2	1.9
9	0218	-0.7	-0.2	24	0141	-0.7	-0.2
Th	0853	4.1	1.2	F	0814	4.2	1.3
	1329	2.4	0.7		1257	2.2	0.7
	1937	6.3	1.9		1908	6.6	2.0
10	0251	-0.7	-0.2	25	0216	-1.0	-0.3
F	0922	4.2	1.3	Sa	0842	4.5	1.4
	1407	2.3	0.7		1343	1.8	0.5
	2013	6.3	1.9		1954	6.9	2.1
11	0321	-0.6	-0.2	26	0252	-1.1	-0.3
Sa	0950	4.2	1.3	Su	0914	4.9	1.5
	1440	2.2	0.7		1429	1.4	0.4
	2048	6.1	1.9		2039	6.9	2.1
12	0350	-0.4	-0.1	27	0329	-0.9	-0.3
Su	1015	4.3	1.3	M	0947	5.1	1.6
	1516	2.1	0.6		1518	1.1	0.3
	2120	5.9	1.8		2125	6.6	2.0
13	0416	-0.1	0.0	28	0403	-0.6	-0.2
M	1040	4.4	1.3	Tu	1022	5.4	1.6
	1550	2.0	0.6		1610	0.9	0.3
	2150	5.6	1.7		2217	6.0	1.8
14	0443	0.2	0.1	29	0440	0.0	0.0
Tu	1106	4.4	1.3	W	1059	5.6	1.7
	1627	2.0	0.6		1706	0.8	0.2
	2224	5.1	1.6		2309	5.2	1.6
15	0506	0.7	0.2	30	0518	0.7	0.2
W	1133	4.4	1.3	Th	1139	5.6	1.7
	1712	2.1	0.6		1812	0.8	0.2
	2302	4.6	1.4				
				31	0013	4.4	1.3
				F	0557	1.4	0.4
					1228	5.6	1.7
					1928	0.9	0.3

SEPTEMBER

Day	Time h m	Height ft	Height m	Day	Time h m	Height ft	Height m
1	0139	3.6	1.1	16	0032	3.2	1.0
Sa	0642	2.2	0.7	Su	0502	2.5	0.8
	1327	5.4	1.6		1155	4.8	1.5
	2103	0.8	0.2		1951	1.5	0.5
2	0346	3.3	1.0	17	1253	4.7	1.4
Su	0751	2.8	0.9	M	2141	1.3	0.4
	1442	5.3	1.6				
	2236	0.5	0.2				
3	0545	3.5	1.1	18	1427	4.7	1.4
M	0934	3.1	0.9	Tu	2257	0.8	0.2
	1602	5.3	1.6				
	2345	0.2	0.1				
4	0649	3.9	1.2	19	0637	3.6	1.1
Tu	1105	3.0	0.9	W	0951	3.4	1.0
	1712	5.5	1.7		1559	5.0	1.5
					2348	0.2	0.1
5	0038	-0.1	0.0	20	0648	4.0	1.2
W	0727	4.2	1.3	Th	1111	3.0	0.9
	1206	2.7	0.8		1709	5.5	1.7
	1806	5.7	1.7				
6	0120	-0.3	-0.1	21	0028	-0.2	-0.1
Th	0757	4.3	1.3	F	0710	4.3	1.3
	1254	2.4	0.7		1206	2.4	0.7
	1851	5.9	1.8		1804	6.0	1.8
7	0153	-0.3	-0.1	22	0107	-0.6	-0.2
F	0821	4.5	1.4	Sa	0735	4.7	1.4
	1330	2.1	0.6		1254	1.7	0.5
	1929	5.9	1.8		1856	6.3	1.9
8	0221	-0.2	-0.1	23	0142	-0.7	-0.2
Sa	0843	4.6	1.4	Su	0800	5.2	1.6
	1401	1.9	0.6		1339	1.1	0.3
	2001	5.9	1.8		1942	6.5	2.0
9	0247	-0.1	0.0	24	0217	-0.6	-0.2
Su	0905	4.7	1.4	M	0832	5.6	1.7
	1432	1.6	0.5		1424	0.5	0.2
	2032	5.8	1.8		2031	6.3	1.9
10	0309	0.1	0.0	25	0251	-0.3	-0.1
M	0923	4.8	1.5	Tu	0904	5.9	1.8
	1501	1.5	0.5		1510	0.1	0.0
	2104	5.5	1.7		2119	5.9	1.8
11	0330	0.4	0.1	26	0325	0.2	0.1
Tu	0945	4.9	1.5	W	0936	6.2	1.9
	1533	1.3	0.4		1558	-0.1	0.0
	2133	5.2	1.6		2209	5.3	1.6
12	0352	0.8	0.2	27	0400	0.8	0.2
W	1005	5.0	1.5	Th	1014	6.2	1.9
	1609	1.3	0.4		1654	-0.1	0.0
	2209	4.8	1.5		2307	4.6	1.4
13	0414	1.2	0.4	28	0435	1.5	0.5
Th	1027	5.0	1.5	F	1054	6.1	1.9
	1644	1.3	0.4		1753	0.1	0.0
	2244	4.3	1.3				
14	0432	1.6	0.5	29	0017	3.9	1.2
F	1050	5.0	1.5	Sa	0514	2.2	0.7
	1728	1.4	0.4		1139	5.8	1.8
	2327	3.7	1.1		1909	0.3	0.1
15	0448	2.1	0.6	30	0155	3.5	1.1
Sa	1117	4.9	1.5	Su	0557	2.8	0.9
	1825	1.5	0.5		1236	5.4	1.6
					2038	0.5	0.2

Time meridian 120° W. 0000 is midnight. 1200 is noon.
Heights are referred to mean lower low water which is the chart datum of soundings.

Figure 9. Reproduction of a page from the NOS Tide Table (U.S. Department of Commerce, 1983b) for Los Angeles (Outer Harbor). These values are used in a sample run described in Section 6.