NOAA Western Region Computer Programs and
Problems NWS WRCP - No. 15

TWO FORTRAN APPLICATIONS OF WIND-DRIVEN EKMAN WATER TRANSPORT THEORY: UPWELLING INDEX AND STORM TIDE

National Weather Service Western Region
Salt Lake City, Utah
July 1980

U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Weather Service

PREFACE

This Western Region publication series is considered as a subset of our Technical Memorandum series. This series will be devoted exclusively to the exchange of information on and documentation of computer programs and related subjects. This series was initiated because it did not seem appropriate to publish computer program papers as Technical Memoranda; yet, we wanted to share this type of information with all Western Region forecasters in a systematic way. Another reason was our concern that in the developing AFOS-era there will be unnecessary and wasteful duplication of effort in writing computer programs in National Weather Service (NWS). Documentation and exchange of ideas and programs envisioned in this series hopefully will reduce such duplication. We also believe that by publishing the programming work of our forecasters, we will stimulate others to use these programs or develop their own programs to take advantage of the computing capabilities AFOS makes available.

We solicit computer-oriented papers and computer programs from forecaste for us to publish in this series. Simple and short programs should not b prejudged as unsuitable.

The great potential of the AFOS-era is strongly related to local compute facilities permitting meteorologists to practice in a more scientific environment. It is our hope that this new series will help in developing this potential into reality.

1 Standardized Format for Computer Series.
2 AFOS Crop and Soil Information Report Program. Ken Mielke, July 1979.
3 Decoder for Significant Level Transmissions of Roabs. John A. Jannuzzi, Aug. 19
4 Precipitable Water Estimate. Elizabeth Morse, October 1979.
5 Utah Recreational Temperature Program. Kenneth M. Labas, November 1979.
6 Normal Maximum/Minimum Temperature Program for Montana. Kenneth Mielke, Dec.1979
7 Plotting of Ocean Wave Energy Spectral Data. John R. Zimmerman, December 1979.
8 Raob Plot and Analysis Routines. John Jannuzzi, January 1980.
9 The SWAB Program. Morris S. Webb, Jr. April 1980.
10 Flash-Flood Procedure. Donald P. Laurine and Ralph C. Hatch, April 1980.
11 Program to Forecast Probability of Summer Stratus in Seattle Using the Durst Objective Method. John Zimmerman, May 1980.
12 Probability of Sequences of Wet and Dry Days. Hazen H. Bedke, June 1980.
13 Automated Montana Hourly Weather Roundup. Joe L. Johnston, July 1980.
14 Lightning Activity Levels. Mark A. Mollner, July 1980.

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I. General Information

A. Summary:

Classical oceanography provides a means of easily calculating transport in the wind-driven layer of the ocean. Ekman (1905) first described the relationship between wind stress and Coriolis effect which results in the "spiral" variation of ocean currents with depth which bears his name. Two major results of the Ekman theory are: 1) surface currents will be directed at 45^{o} to the right (N. Hemisphere) of the driving wind; and 2) when integrated over the entire wind-driven layer, the net mass transport is directed at 90^{o} to the right of the driving wind (N. Hemisphere), and has a magnitude:

$$E=\frac{\tau}{f}$$

where τ is the wind stress and f is the Coriolis parameter.

Two of the primary applications of water mass transport to the duties of the West Coast operational oceanographer and marine weather forecaster are the determination of coastal upwelling magnitudes and the calculation of onshore water movement due to extratropical storms (storm tides) which can cause significant coastal flooding.

Coastal upwelling is caused by northerly and northwesterly winds along the West Coast, setting up an offshore transport of surface water. To replace this offshore-moving water, colder water from deeper layers moves upward inshore. This is extremely important to the fishing industry, as this water from below is very rich in nutrients, and accounts for areas of high biological productivity. Upwelling can also strongly influence coastal weather. A familiar example of this is the frequent occurence of summertime stratus along the California coast, which owes its existence in part to condensation that occurs when warm moist air moves over the cold upwelled water.

During and after the passage of intense low pressure systems, the opposite of coastal upwelling occurs. Strong southerly and southwesterly winds force an onshore water transport, which can result in an abnormally high tide (storm tide). This tidal anomaly may be supplemented by a barometric effect due to low atmospheric pressure as well. The prediction of such storm tides allows the protection of life and property that may be threatened by coastal flooding.

B. Environment

These programs were written for, and are completely compatible with, AFOS. Input, which is very simple for both programs, is handled in a conversational mode at the P/K module (dasher). Output is likewise displayed at the dasher. Both programs are written in FORTRAN IV.

C. References

As mentioned above, the theory of wind-driven ocean transport was first described by Ekman (1905). The coastal upwelling index program was originated by Bakun (1973). The procedure for storm tide prediction was developed by this author (Short, 1979), and the addition of the pressure effect relies on a standard formula found in Bowditch (1958). Complete references follow:

Bakun, A., 1973, Coastal Upwelling Indices, West Coast of North American, 1946-1971. NOAA Tech. Rep. NMFS SSRF-671, 103 p.

Bowditch, N., (1958 ed.), American Practical Navigator, U.S. Navy Hydrographic Office, p. 711.

Ekman, V. W., 1905, On the Influence of the Earth's Rotation on Ocean Currents. Ark. f. Mat., Astron. och Fysik 2(11):1-53.

Short, K., 1979, A New Approach to Extratropical Storm Surge Forecasting. Western Region Technical Attachment, No. 79-36

II. Application

A. Complete Program Descriptions

(1) Upwelling Index

The purpose of this program is to compute a coastal upwelling index based on wind speed and direction, latitude, and coastline orientation at a given point. It may be used at any coastal location in the Northern Hemisphere. The program computes a wind stress based on the input wind speed, computes the Ekman transport from the wind stress and the Coriolis parameter, directs the Ekman transport 90° to the right of the wind, and based on the coastal orientation and wind direction, resolves the offshore component of the transport. The basic equations are as follows:

$$\tau = C_D V^2 \rho \qquad (1)$$

$$E = \frac{\tau}{f} \qquad (2)$$

$$\text{Transport direction} = \text{Wind direction} + 270^\circ \qquad (3)$$

$$M = E \times \cos(D) \qquad (4)$$

(where D = Transport direction - Coastline normal)

Definitions: τ = wind stress
ρ = air density (assumed constant)
C_D = drag coefficient (assumed constant)
$f = 2\Omega \sin \phi$ = Coriolis parameter
Ω = earth's angular speed
ϕ = latitude
E = Ekman transport
M = Offshore component of the Ekman transport

(2) Storm Tide Anomaly

The purpose of this program is to compute a predicted positive departure from tide table values of high tide height based on forecast wind speed and direction, and atmospheric pressure for a period of 12 hours prior to the pertinent high tide. This particular program is written for use at one specific location, Astoria, Oregon, and inlcudes a regression equation based on a verification study at that location. However, the method could easily be used at other locations if a similar verification study were to be done.

The first half of the program is almost identical to the upwelling index program. The only difference is that the transport direction is rotated only 45^o to the right of the wind rather than 90^o. This is because the time scale for moving storms is much less than the time scale for the semi-stationary high which leads to upwelling, and therefore most of the wind-induced transport should be near the ocean surface.

The second half of the program takes the computed onshore transport and uses the previously-mentioned regression equation to calculate an actual tidal departure. Next, it uses the Bowditch pressure relation to compute the barometric effect. Adding the wind effect and pressure effect then produces a predicted total departure. The remaining part of the program prints guidance to the forecaster concerning the advisability of issuing a coastal flood statement or warning for the Washington coast based on the output.

Equations (1), (2), and (4) are used for the upwelling program. Equation (3) is the same except that 270^o is replaced by 225^o. The three new equations are:

$$D(W) = 0.46 - .0017M \quad (5)$$
$$D(P) = 0.0325\ (1010 - P) \quad (6)$$
$$D(TOTAL) = D(W) + D(P) \quad (7)$$

Definitions: D(W) = Tidal departure due to wind (ft)
D(P) = Tidal departure due to pressure (ft)
P = Pressure at Astoria at time of high tide (mb)

B. Machine Requirements

These programs require less than 10K to run, and the program files require less than 25 blocks of disk storage. Runtime is insignificant.

III. Procedures

A. Initiation of the Programs and Input Required

(1) Upwelling Index

The program is initiated by typing UPWELL at the dasher, after shifting to the proper directory. Input is in a conversational, free-format form. The input data required are the latitude of the point, the coastline normal (offshore direction), and the wind speed and direction.

(2) Storm Tide

The program is initiated by typing STRMTIDE at the dasher, after shifting to the proper directory. Input is in a conversational, free-format form. The data required are the tide prediction at Tongue Point (Astoria) for the pertinent high tide, the predicted mean wind speed and direction near Astoria for 12 hours prior to the high tide, and the predicted atmospheric pressure at Astoria at the time of the high tide. Since the program is specifically for Tongue Point, the latitude and coastline normal are constants, and thus are not input as in the case of UPWELL.

B. Output

(1) Upwelling Index

The program outputs the computed wind strees (units: dynes/cm^2) and the upwelling index (units: m-tons/sec/100m).

(2) Storm Tide

In developing this method, only cases of onshore water transport were considered. Therefore, if the input wind direction results in an offshore water transport, a statement is printed out to the forecaster that this program may not be used for such cases. If the transport is onshore, the program outputs the predicted high tide height (ft) and notes how much of this total is due to the storm tide anomaly. For critical height values, it also prints guidance to the forecaster advising the issuance of a Coastal Flood Statement or Warning.

C. Sample Input/Output

(1) Upwelling Index

```
UPWELL
PROGRAM TO COMPUTE UPWELLING INDEX
INPUT LATITUDE
47
INPUT COASTLINE NORMAL (OFFSHORE DIRECTION) . . . DEGS
265
INPUT WIND SPEED . . .KNOTS
25
INPUT WIND DIRECTION . . . DEGS
330
THE STRESS IS  2.6269 DYNES/SQ-CM
THE UPWELLING INDEX IS 223.21 M/TONS/SEC/100M
STOP
R
```

(2) Storm Tide

a. Normal case

```
STRMTIDE
PROGRAM TO PREDICT POSITIVE TIDAL DEPARTURES FOR TONGUE POINT (ASTORIA)
INPUT TIDE TABLE HEIGHT PREDICTION (FT) FOR PERTINENT HIGH TIDE AT TONGUE POINT
9.5
INPUT PREDICTED MEAN WIND SPEED (KT) FOR 12 HRS PRIOR TO THE HIGH TIDE
15
INPUT PREDICTED MEAN WIND DIRECTION FOR 12 HRS PRIOR TO THE HIGH TIDE
180
INPUT PREDICTED ATMOSPHERIC PRESSURE AT ASTORIA AT TIME OF HIGH TIDE
1005
THE PREDICTED HIGH TIDE HEIGHT AT TONGUE POINT IS 10.3 FT.
THIS IS 0.8FT ABOVE THE TIDE TABLE VALUE.
STOP
R
```

b. Case where transport is offshore

```
STRMTIDE
PROGRAM TO PREDICT POSITIVE TIDAL DEPARTURES FOR TONGUE POINT (ASTORIA)
INPUT TIDE TABLE HEIGHT PREDICTION (FT) FOR PERTINENT HIGH TIDE AT TONGUE POINT
9.8
INPUT PREDICTED MEAN WIND SPEED (KT) FOR 12 HRS PRIOR TO THE HIGH TIDE
20
INPUT PREDICTED MEAN WIND DIRECTION FOR 12 HRS PRIOR TO THE HIGH TIDE
350
INPUT PREDICTED ATMOSPHERIC PRESSURE AT ASTORIA AT TIME OF HIGH TIDE
995
THE INPUT WIND DIRECTION PRODUCES AN OFFSHORE WATER TRANSPORT.
THIS PROGRAM WILL NOT WORK FOR SUCH CASES.
STOP
R
```

c. Case where a Coastal Flood Statement is indicated

```
STRMTIDE
PROGRAM TO PREDICT POSITIVE TIDAL DEPARTURES FOR TONGUE POINT (ASTORIA)
INPUT TIDE TABLE HIEIGHT PREDICTION (FT) FOR PERTINENT HIGH TIDE AT TONGUE POINT
10.4
INPUT PREDICTED MEAN WIND SPEED (KT) FOR 12 HRS PRIOR TO THE HIGH TIDE
30
INPUT PREDICTED MEAN WIND DIRECTION FOR 12 HRS PRIOR TO THE HIGH TIDE
200
INPUT PREDICTED ATMOSPHERIC PRESSURE AT ASTORIA AT TIME OF HIGH TIDE
1000
THE PREDICTED HIGH TIDE HEIGHT AT TONGUE POINT IS 11.8 FT.
THIS IS 1.4FT ABOVE THE TIDE TABLE VALUE.
A COASTAL FLOOD STATEMENT FOR THE WASHINGTON COAST IS INDICATED.
STOP
R
```

d. Case where a Coastal Flood Warning is indicated

```
STRMTIDE
PROGRAM TO PREDICT POSITIVE TIDAL DEPARTURES FOR TONGUE POINT (ASTORIA)
INPUT TIDE TABLE HEIGHT PREDICTION (FT) FOR PERTINENT HIGH TIDE AT TONGUE POINT
10.6
INPUT PREDICTED MEAN WIND SPEED (KT) FOR 12 HRS PRIOR TO THE HIGH TIDE
35
INPUT PREDICTED MEAN WIND DIRECTION FOR 12 HRS PRIOR TO THE HIGH TIDE
210
INPUT PREDICTED ATMOSPHERIC PRESSURE AT ASTORIA AT TIME OF HIGH TIDE
990
THE PREDICTED HIGH TIDE HEIGHT AT TONGUE POINT IS 12.5 FT.
THIS IS  1.9FT ABOVE THE TIDE TABLE VALUE.
A COASTAL FLOOD WARNING FOR THE WASHINGTON COAST IS INDICATED.
STOP
R
```

D. Restrictions

The only restriction, as was mentioned previously, is that STRMTIDE cannot be used when the wind direction produces an offshore transport. However, no caution need be taken, since the program will inform the user if this situation occurs (see b above).

E. Program Listings

```
TYPE UPWELL.FR
C THIS PROGRAM CONPUTES AN UPWELLING INDEX BASED ON EKMAN TRANSPORT THEORY
C AND COASTAL ORIENTATION
    TYPE "PROGRAM TO COMPUTE UPWELLING INDEX"
    TYPE "INPUT LATITUDE"
    ACCEPT XLAT
    TYPE "INPUT COASTLINE NORMAL (OFFSHORE DIRECTION) . . . DEGS"
    ACCEPT COAST
    TYPE "INPUT WIND SPEED . . . KNOTS"
    ACCEPT SPEED
    SPEED=SPEED*51.479
    TYPE "INPUT WIND DIRECTION . . . DEGS"
    ACCEPT DIREC
    OMEGA=.000072921
    RHO=.00122
    CD=.0013
 C COMPUTE WIND STRESS
    STRESS=RHO*CD*SPEED*SPEED
 C CONVERT LATITUDE FROM DEGREES TO RADIANS
    PHI=XLAT*.0174533
 C COMPUTE CORIOLIS PARAMETER
    F=2.*OMEGA*SIN(PHI)
 C COMPUTE EKMAN TRANSPORT
    EKMAN=STRESS/F
 C ROTATE EKMAN TRANSPORT VECTOR
    DIREX=DIREC+270.
 C RESOLVE OFFSHORE DIRECTED COMPONENT OF TRANSPORT
    DIFF=(DIREX-COAST)*.0174533
    UPWELL=EKMAN*COS(DIFF)
 C CHANGE FROM CGS UNITS TO M-TONS/SEC/100M
    UPWEL=UPWELL*.01
    WRITE(10,100)STRESS
100 FORMAT(1X,"THE STRESS IS", F8.4,"DYNES/SQ-CM")
200 FORMAT(1X,"THE UPWELLING INDEX IS",F7.2,"M-TONS/SEC/100M")
    STOP
    END
 R
```

```
TYPE STRMTIDE.FR
C THIS PROGRAM COMPUTES POSITIVE DEPARTUES FROM TIDE TABLE
C VALUES (STORM TIDE ANOMALIES) FOR TONGUE POINT (ASTORIA) BASED
C ON WIND-INDUCED TRANSPORT AND PRESSURE EFFECTS
      TYPE"PROGRAM TO PREDICT POSITIVE TIDAL DEPARTURES FOR TONGUE
     1 POINT (ASTORIA)"
      XLAT=46.
      COAST=253.
      OMEGA=.000072921
      RHO=.00122
      CD=.0013
      TYPE "INPUT TIDE TABLE HEIGHT PREDICTION (FT) FOR PERTINENT
     1 HIGH TIDE AT TONGUE POINT"
      ACCEPT TABLE
      TYPE "INPUT PREDICTED MEAN WIND SPEED (KT) FOR 12 HRS PRIOR
     1 TO THE HIGH TIDE"
      ACCEPT SPEED
      TYPE "INPUT PREDICTED MEAN WIND DIRECTION FOR 12 HRS PRIOR
     1 TO THE HIGH TIDE"
      ACCEPT DIREC
      TYPE "INPUT PREDICTED ATMOSPHERIC PRESSURE AT ASTORIA AT TIME OF
     1 HIGH TIDE"
      ACCEPT PRESS
      SPEED=SPEED*51.479
C COMPUTE WIND STRESS
      STRESS=RHO*CD*SPEED*SPEED
C CONVERT LATITUDE FROM DEGREES TO RADIANS
      PHI=XLAT*.0174533
C COMPUTE CORIOL IS PARAMETER
      F=2.*OMEGA*SIN(PHI)
C COMPUTE EKMAN TRANSPORT
      EKMAN=STRESS/F
C ROTATE TRANSPORT VECTOR
      DIREX=DIREC+225.
C RESOLVE SHOREWARD DIRECTED COMPONENT OF  TRANSPORT VECTOR
      DIFF=(DIREX-COAST)*.0174533
      TRANS=EKMAN*COS(DIFF)
C CHANGE FROM CGS UNITS TO M-TONS/SEC/100M
      TRAN=TRANS*.01
C COMPUTE TIDAL DEPARTURE DUE TO WIND BASED ON REGRESSION EQUATION
      DWIND=.46-.0017*TRAN
C COMPUTE TIDAL DEPARTURE DUE TO PRESSURE
      DPRESS=.0325*(1010.-PRESS)
C COMPUTE TOTAL PREDICTED DEPARTURE
      DTOTAL=DWIND+DPRESS
      IF(TRAN) 20, 20, 10
   10 TYPE "THE INPUT WIND DIRECTION PRODUCES AN OFFSHORE WATER TRANSPORT."
      TYPE "THIS PROGRAM WILL NOT WORK FOR SUCH CASES."
      GO TO 50
   20 TIDE=TABLE+DTOTAL
      WRITE (10,100)TIDE, DTOTAL
  100 FORMAT(1X,"THE PREDICTED HIGH TIDE HEIGHT AT TONGUE POINT IS ",F4.1,
     1  " FT " /,1X,"THIS IS ",F4.1,"FT ABOVE THE TIDE TABLE VALUE.")
      IF(TIDE.GE.12.) GO TO 30
      IF(TIDE.GE.11.) GO TO 40
      GO TO 50
   30 TYPE "A COASTAL FLOOD WARNING FOR THE WASHINGTON COAST
     1 IS INDICATED."
      GO TO 50
   40 TYPE " A COASTAL FLOOD STATEMENT FOR THE WASHINGTON COAST
     1 IS INDICATED"
   50 STOP
      END
```

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