WINDSTAU -- Numerical Modelling of Continental Shelf Circulation with Sigma Coordinates

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1.1 Model Purpose and Structure

(Excerpted from IAPSO Conference Notes, Smith (1985))

WINDSTAU is a finite difference model which uses hourly windstress to compute longshore and cross-shelf currents, and the variation in sea level along a two-dimensional vertical cross-shelf plane. The overall objective is to quantify sea level variations and current speeds occuring in response to meteorological forcing over time scales on the order of one to two weeks.

The model consists of a flexible grid of cells which expands and contracts as water moves from one cell to another within a given layer. The coordinates will be referred to as "Sigma Coordinates", after Mellor and Blumberg (1985). Inter-layer vertical flow is allowed but it is calculated implicitly by readjusting the water level of each column of cells to reflect cross-shelf mass transport.

A rigid lid is placed on the offshore boundary cell by specifying that the seaward and landward cross-shelf flows through that cell are equal. As a result, there is no net convergence or divergence at the offshore boundary. Thus, the only wind effects which the model can reproduce are the coastal set-up and set-down.

The analytical approach is standard:

- A quadratic windstress term drives the model
- A quadratic friction term retards the flow in the lowest layer
- The vertical eddy viscosity is a parabolic function, with maxima at the surface and bottom (the vertical eddy viscosity function may be configured to compute minima at the surface and bottom)
- The horizontal eddy viscosity decreases linearly with increasing distance from the coast
- At the onshore boundary, both longshore and cross-shelf current components are set equal to zero
- The continuity equation, restricted to convergence and divergence in the xz plane, explains the local variation in sea level at any point across the shelf
- By considering upslope and downslope flow two additional processes must be considered:
  - First, there will be a trade-off between potential and kinetic energy -- this will be relatively important near the bottom; negligible near the surface where the wind-driven flow is most pronounced
  - Second, there will be a change in relative vorticity as the layer converges or diverges in the vertical
    - Convergent, shoreward flow will curve anticyclonically -- enough to overcome the decrease in pressure and the slight increase in the Coriolis parameter

Note that, in its present form, the model is barotropic

- Density is constant with depth
- Results representing winter conditions are more realistic than results for stratified summer conditions

2.1 THEORETICAL

Modelling Continental Shelf Circulation with Sigma Coordinates

Sigma coordinates present the modeller with the advantage of accurately specifying flow near bottom boundary layers, as well as surface transport due to windstress while retaining the conceptual and computational simplicity of ordinary rectangular coordinates. The sigma coordinate system is a grid of cells whose lowest layer is parallel to the shelf bathymetry and whose topmost layer is parallel to the sea surface. Each column of cells has an equal number of cells, and all cells have equal horizontal (cross-shelf) dimension. It therefore follows that the vertical dimensions of cells vary from column to column.

When Cartesian coordinates are used in conjunction with undulating or steeply sloping bathymetry, errors are introduced when attempts are made to account for vertical mass transport between two non-adjacent bottom boundary cells in adjacent columns. These errors can be partly corrected by introducing a vertical transport term which is sensitive to abrupt changes in bathymetry or by explicitly coding correction terms for each vertical step in the lowest row of each water column. Neither method is satisfactory for a general circulation model as vertical transport is not correctly accounted for, and excessive time is spent coding correction terms for each new model configuration

Sigma coordinates avoid the above-mentioned problems by modelling horizontal transport along the bottom boundary layer as flow through a continuous layer of cells which are parallel to the bathymetry. During onshore and offshore mass transport, water is transferred into or out of the cell boundaries lying in the yz-plane. In the case of net convergence into a cell, the cell's vertical dimension will increase to reflect increased cell volume. The converse is true for net divergence.

After the net convergence and net divergence of all cells in the model grid have been computed, the model is equalized -- the amount of water in each column is computed and divided by the number of cells along the z-axis to yield the average vertical cell dimension for that column. Water levels are computed from the new column heights and are expressed as total water column depth, and water level with respect to the sea surface at model initialization.

Computational instabilities can arise when the continuity equation fails to compensate for unequal cell volumes in adjacent columns. Flow through unequally proportioned layers gives rise to an error in net cell convergence or divergence. The WINDSTAU model avoids this error by modelling water level change as a result of net convergence or divergence into a cell from both its offshore and onshore neighbor cells. Differences in effective cell face areas (in the yz-plane) are accounted for in the continuity equation and conservation of volume is maintained throughout the simulation.

Additionally, improper initialization of boundary layers, particularly the bottom layer, can give rise to further computational errors. To correctly initialize the bottom layer, WINDSTAU assigns a small, artifactual frictional force to the bottom layer to damp any overcorrections in near-bottom velocity induced by a large initial windstress. This feature is especially useful when modelling circulation in a shallow ocean, driven by a strong longshore wind.

Mellor and Blumberg (1985) discussed new formulation for the diffusive terms used in numerical ocean models and concluded that their implementation of the sigma coordinates, applicable to heat transport, salinity, or any other scalar, provided for an accurate computation of bottom boundary layers, and was computationally more efficient than the conventional formulation (Blumberg and Mellor, 1983, 1985). They noted that the conventional formulation is physically incorrect near sloping bottoms when the horizontal diffusivity exceeds the vertical diffusivity. As a result, a large net flux component normal to the bottom is produced whereas fluctuating velocities must approach zero at the bottom.

The WINDSTAU sigma-coordinate scheme is illustrated in Figure 1. Grid coordinates are defined as follows:

x, u -- cross-shelf displacement, cross-shelf current speed, positive in the offshore direction

y,v -- longshore displacement, longshore current speed, positive into the page (away from the observer)

z -- vertical displacement (depth), positive downward

Model cells are referenced by the coordinates IX,IZ where IX is the cross-shelf distance pointer and IZ is the depth pointer. One row of cells at the top of the model grid and one row of cells at the bottom of the grid provide a computational buffer for boundary conditions; these cells enter into the calculations but are never treated as "present cells". The "present cell" is the cell whose force balance is presently being computed and whose centroid coordinates are the present values of IX and IZ. Likewise, a column of cells at the onshore boundary and another column at the offshore boundary serves as boundary condition buffers.

Because of these extra rows and columns, the total number of cells in the model grid is (NX+2)*(NZ+2) where NX and NZ are the number of user-specified cross-shelf cells and depth cells, respectively. Note that NX and NZ are defined in the control file.

Cell coordinates are arranged as follows:

```
                      :upper neighbor :
                      :cell label: "U":
                      :row: IZ-1      :
                      :col: IX        :
------------------------------------------------------------
 : onshore neighbor:present cell   :offshore neighbr:
 : cell label: "1" :cell label: "2": cell label: "3":
 : row: IZ         :row: IZ        : row: IZ        :
 : col: IX-1       :col: IX        : col: IX+1      :
------------------------------------------------------------
```

Equations governing the WINDSTAU model follow:

Windstress:

$WS = C_{10} \rho_a U_{10}^2$ where $C_{10} = 0.8 + 0.065\ U_{10} \times 10^{-3}$

ρ_a is the density of air, U_{10} is windspeed

Cross-shelf pressure gradient:

$PG = -g\ (\Delta h / \Delta x)$

Bottom friction:

$BF = -\rho_w\ k^2\ v^2\ /\ [\ \ln\ (z/z_0)\ ]$

where ρ_w is the density of water, k is the Karman constant, v is the current speed, z is depth, and z_0 is the roughness length

Vertical eddy viscosity:

$E_v = [\ E_{v_0} - (\Delta E_v / \Delta z)\ (\ (\ z - z_{mid})^2\ /\ z_{mid}^2)\ ]\ (\ \Delta v / \Delta z\ )$

where z_{mid} is the depth at the midpoint of the water column, and v is the current speed.

Horizontal eddy viscosity:

$E_h = [\ E_{h_0} - x\ (\Delta E_h / \Delta x\ )\ ]\ (\ \Delta v / \Delta x\ )$

where v is current speed.

3.1 COMPUTER PROGRAM DOCUMENTATION -- User's Instructions

3.1.1 Installing and Compiling WINDSTAU.FTN

WINDSTAU.FTN is written in ANSI FORTRAN77 and is presently installable on the Prime 50-series computers running under PRIMOS and, with the modifications noted below, should be portable to a variety of computers. No bit manipulations are performed on integer words and no system subroutines are called; the program is readily transportable.

To install WINDSTAU.FTN on a PRIME 50-series computer running under the PRIMOS operating system:

1) After copying the program to the target directory, compile with the FORTRAN77 compiler using the following options:

   - 64V : Virtual memory mode, essential as storage may exceed 64K bytes
   - INTL: default all integers to INTEGER*4 type
   - FRN : floating point roundoff enabled (improves accuracy)
   - BIG : enables large arrays to efficiently span segment boundaries

2) Run the program using the command: SEG WINDSTAU

To convert the program for another system, pay special attention to:

1) Variable logical unit assignment:

```
ITRMUN -- FORTRAN logical unit for user interactive terminal
ICTLUN --    "       "     "   "  control file I/O
IINPUN --    "       "     "   "  windstress data file
IOUTUN --    "       "     "   "  output datafile
IRPTUN --    "       "     "   "  execution report
```

2) CHARACTER data type may have to be converted to BYTE statements on older DEC systems

3) OPEN and CLOSE statement syntax

4) Equality-inequality comparisons of floating point numbers may generate warnings at compile time; a range-check may have to be performed in place of FORTRAN "IF" statements comparing real numbers

5) Numerical results may vary slightly from system to system due to CPU precision and floating-point rounding techniques

3.1.2 Control File Generation

After invoking WINDSTAU, a main menu is displayed. To generate a new control file, invoke the feature:

"Create a WINDSTAU Control File"

by entering an integer "1" in response to the prompt:

"ENTER: Choice # (1, 2, or 3):"

Control file creation prompts and their explanations follow, together with probable responses:

\>>>ENTER: Two Lines (80 char. max.) of control file documentation:

These lines will be displayed at the top of the new control file and at the top of the output file and report file.

EXAMPLE:

```
TEXAS CONTINENTAL SHELF CIRCULATION -- RUN #5, 12 JULY 1985, 3 P.M.
MODEL STABILITY TEST: VARYING TIMESTEP AND CROSS-SHELF CELL SIZE
```

\>>>ENTER: New Control Filename (32 char. Max.):
EXAMPLE.CTL

\>>>ENTER: Filename (<33char) (CS-LS Windstress) :

The input windstress file must contain cross-shelf windstress in column one and longshore windstress in column two. Units must be dynes/cm**2.

EXAMPLE: WINDSTRESS.SAMPLE.DAT

\>>>ENTER: Windstress Datafile Format(max. 32 char):

Enter the FORTRAN format of the datafile. Check the program source code to see whether the implementor has changed the format to list-directed (*). If so, you may specify the input format within the READ statement by substituting the variable "INPFMT" for the "*".

EXAMPLE: (2F10.3)

\>>>ENTER: Timestep (integral divisor of 3600 sec.):

The modelling timestep should be chosen small enough so computational instabilities do not result from large long-shore or cross-shelf windstress gradients and large enough so that the model executes efficiently. A sample input datafile of approximately 72 hours with a windstress range of +1.0 to

-1.0 dynes/sq.cm. should be sufficient for trial-and-error testing to find the optimum timestep for your model configuration.

EXAMPLE: 300 (must be integer)

>>>ENTER: Maximum Cross-shelf Distance (km) :

The distance from the onshore boundary (shoreline) to the offshore boundary (rigid lid), in kilometers. This distance, as well as the depth, will be converted to internal model units (centimeters) before execution begins.

EXAMPLE: 60. (real number)

>>>ENTER: Number of Cross-Shelf (X-axis) cells :

The number of cells determines, by default, the cross-shelf cell dimension. If the number of cells is too large, the model will not run efficiently; if too few cells, computational instabilities will result. A trial-and-error approach may be necessary when working with a new model configuration for the first time.

EXAMPLE: 10 (integer)

>>>ENTER: Onshore depth (m) :

This is the depth at the onshore boundary and SHOULD NOT BE ZERO, or computational instabilities will result. If the onshore depth must be zero, enter this number as 0.1000.

EXAMPLE: 10. (real number)

>>>ENTER: Maximum depth (m) :

This depth at the deepest point along the bathymetry. In models with a "well" between the onshore and offshore boundaries, this will not be the offshore depth. The maximum depth, DEPMAX, is used to determine the vertical cell dimension in conjunction with the number of vertical cells, as indicated below.

EXAMPLE: 60. (real number)

>>>ENTER: Number of Depth (Z-axis) cells :

Considerations affecting the choice of this number are discussed under the number of cross-shelf cells, above.

EXAMPLE: 10 (integer)

>>>ENTER: Vertical EDYVIS Constant term (VEO) :

Although vertical eddy viscosity may change with depth, this term is constant, and may, depending upon how vertical eddy viscosity is calculated, be set to zero.

EXAMPLE: 1.00 (integer)

>>>ENTER: Maximum change in Vertical EDYVIS (DEDZ):

The maximum change in vertical eddy viscosity is the difference between the maximum and minimum vertical eddy viscosities. When the distribution of vertical eddy viscosity with depth is modelled as a parabola, DEDZ is the height of the parabola.

EXAMPLE: 0.001 (real number)

>>>ENTER: Horizontal EDYVIS Const. term (HEO) :

As in the vertical eddy viscosity constant term, above.

EXAMPLE: 100. (real number)

>>>ENTER: Change in Horiztl EDYVIS per cm (DEDX) :

When horizontal eddy viscosity changes linearly with cross-shelf distance, DEDX is the change in eddy viscosity per unit change in cross-shelf distance. Previous to model execution, an error check is performed on the product of this number and maximum cross-shelf distance. If the product exceeds the constant horizontal eddy viscosity (HEO, above), an error message is generated and the user is directed to correct this control file entry.

EXAMPLE: 0.00001

>>>ENTER: Bottom Roughness Length (cm) :

The approximate dimension of the major bottom features. A silty bottom would not have a roughness length exceeding 0.5 cm; a gravelly bottom might have a roughness length of several centimeters; a rocky bottom, tens of centimeters, and so forth.

EXAMPLE: 1.0 (real number)

>>>ENTER: Hour to start debug (99999=no debug) :

If the user desires a screen output of the model internal variables (a massive amount of information), he is advised to set the hour to start debugging just before the time he expects the error to occur. For example, if a computational instability was suspected sometime after processing the

27th hour of input data, the user would enter: 26.99998 The approximation is made to avoid any error due to floating point roundoff. If no debugger output is desired, simply enter: 99999 (integer).

EXAMPLE: 27.9998 (start debug at 28th hour)
99999 (no debug)

If debug is indicated, the following prompts will be displayed:

>>>ENTER: CS dist (km) to start debug going offshr:

If the user has an idea at what cross-shelf distance a computational instability will arise, he can start debug at that distance by entering a number slightly less than the cross-shelf coordinate, in kilometers (see Example, below). Debugging will proceed in an offshore direction from that point until the next timestep, when debugging begins at the onshore boundary. This feature is particularly advantageous for large models having many cross-shelf cells as it cuts down on wait time before the debug information for the erroneous cell is displayed.

EXAMPLE: 13.9998 (start debug at 14 kilometers offshore)

>>>ENTER: Depth to start debug downward :

Depth coordinate (in meters) to start debugging. Debugging proceeds downward, with wrap-around at the next timestep, as described for the horizontal debug above.

EXAMPLE: 27.998 (start debug at 28 meters)

>>>ENTER: Output Filename (32 char. max.) :

This is the filename for the output report file. The 32 character maximum references PRIMOS' limit on filename length.

EXAMPLE: SAMPLE.RPT

Model output can be configured in two ways: a) water levels and b) cross-shelf or longshore current speeds. Each of the three examples follow:

<u>WATER LEVEL OUTPUT</u>:

```
>>>ENTER: Output Descriptor (DWL, LSC, CSC)       :
DWL
>>>ENTER: Starting (Onshore) CS Dist (km)         :
15.
>>>ENTER: Ending (Offshore)  CS Dist (km)         :
45.
```

Using the above responses, water levels will be output for model cells from 15 to 45 km, inclusive, from the onshore boundary. The report columns will be appropriately labelled to reflect water level output at each offshore cell.

LONGSHORE CURRENT SPEEDS:

```
>>>ENTER: Output Descriptor (DWL, LSC, CSC)       :
LSC

>>>ENTER: Number of Output Cells (1-12)           :
```

The number of columns in the report. Current speeds of up to 12 cells may be output; the speeds are expressed in E10.3 format, so differences in current speeds beyond 3 significant figures will not be noticeable.

EXAMPLE: 2 (integer)

```
... You will now be queried for each CS-Depth
...    coordinate pair. For example, you would enter
...    the coordinates of a cell 2.5 km offshore and
...    3.6 m deep as:   2.5,3.6
...
... NOTE:  The X (CS) coordinate must not exceed the
...          maximum cross-shelf distance and the Z
...          (depth) coordinate must not exceed the max-
...          imum depth.
...
>>>ENTER: CSdist-Depth pair for Cell#  1 :
2.5,3.6

>>>ENTER: CSdist-Depth pair for Cell#  2 :
14.5,16.4
```

CROSS-SHELF CURRENT SPEEDS:

User enters: CSC instead of LSC, as above. The number of cells and coordinate pairs are entered as for longshore current speed output.

The user will be notified of the new control file, as follows and will be routed back to the Main Menu, where he may exit the program.

```
***
*** Your New Control File is:    EXAMPLE-CTL
***
*** MAIN MENU ***
***
*** Choice#              Description
***    1          Create a WINDSTAU Control File
***    2          Run a WINDSTAU Control File
***    3          EXIT to Operating System Level
***
>>>ENTER: Choice # (1, 2, or 3):
3
**** STOP ***USER-INITIATED EXIT; NORMAL TERMINATION***
```

3.1.3 Editing the Control File

WINDSTAU does not provide an on-board text editor; line editors and/or screen editors are available on most computer systems. Since the control file is an ASCII document, users can edit it with any text editor which produces an ASCII control file. Examples of such editors are: EMACS, EDLIN (IBM-PC), WORDSTAR, SCRIPSIT, and MUSE.

Note that the following format must be preserved for the control file to be read correctly:

Lines 1 and 2: A80
Following numeric lines: numeric value, blanks to col. 40, text
where "text" is an optional line descriptor for documentation purposes only.
Following character-valued lines: first 40 columns are available for input of character-valued information, such as filenames

Upon reading the control file, WINDSTAU will notify the user of any format/data mismatch errors and the line number at which they occurred.

3.1.4 Running a WINDSTAU Simulation

When you are ready to run the WINDSTAU simulation, invoke WINDSTAU by typing:

SEG WINDSTAU (PRIME computers only)

You will be prompted for the menu choice -- enter integer "2".

You will then be prompted for the control file filename. If the filename does not exist in the directory to which you are attached, the program will terminate abnormally and you will have to manually close the control file. On the PRIME computer, manual closure is accomplished with the CLOSE ALL command.

If the control file does exist, it will be read and error messages will be output, for format/data mismatches. However, if the specified input windstress file does not exist in the current directory or if the specified report/output files already exist, the program will terminate abnormally. Manual file closure will be required, as above.

When the control file is read correctly, the user will be informed that the simulation is under way and the two lines of documentation, from the top of the control file, will be displayed at the user interactive terminal.

Because WINDSTAU contains a run-time debugger, it does not have a wide variety of internal error messages. Some familiarity with computer programming and FORTRAN77, in particular is assumed and is necessary for successful alterations to the computer program.

3.1.5 Report Interpretation

3.1.5.1 General Report Information

a) Program name and revision
b) Number of cross-shelf cells
c) Cross-shelf unit cell dimension (centimeters)
d) Number of depth cells
e) Initial vertical unit cell dimension (centimeters)
f) Control filename

3.1.5.2 Water Level Report Header

Column headers are elapsed days (in terms of input data) since start of simulation and cross-shelf distances, in kilometers, of each water level output to the report.

3.1.5.3 Current Speed Report

Column headers are elapsed days (in terms of input data) since start of simulation and cross-shelf distance and depth coordinates of each cell whose current speed is output to the report.

3.2.1 WINDSTAU Main Menu

The user is greeted as follows:

```
***
*****************************************************
*** Program WINDSTAU.FTN - M. Schmalz, 1985
***   Continental Shelf Circulation Model
***  -------------------------------------
*** Documentation and Operating Instructions:
***   HBF Technical Report:
***     "WINDSTAU - Numerical Modelling of Continental
***         Shelf Circulation with Sigma Coordinates"
***
```

The Main Menu is generated by FORMAT Statement 41, as follows:

```
***
*** MAIN MENU ***
***
*** Choice #              Description
***    1           Create a WINDSTAU Control File
***    2           Run a WINDSTAU Control File
***    3           EXIT to Operating System Level
***
>>>ENTER:  Choice # (1, 2, or 3):
```

The user enters a response (an integer) and range-checking is performed. In case of user error, the menu is redisplayed and the user is re-prompted.

3.2.2 Creating the Control File

Control files are created by invoking Feature #1 on the WINDSTAU Main Menu. Prompts for Control file creation are described, in detail, together with sample responses, in Section 3.1.2 of this Report.

Subroutine CRECTL generates the control file text, and operates as follows:

a) Control file prompts are assigned to array CTLHED, composed of 21 elements of 40 characters each, declared as CHARACTER*40 CTLHED(21).

b) User is prompted for name of new control file (not more than 32 characters in PRIMOS); the new control file is opened on logical unit ICTLUN, which is passed as an input parameter.

c) User is prompted for control file parameters, as documented in Section 3.1.2. Error checking is performed on the constant and linear eddy viscosity terms at the time the control file is read into the program (WINDSTAU execution).

   Note that the prompts are issued by a WRITE statement contained in the DO 200 ICTLPR=1,14 and DO 313 ICTLPR=19,21 loops. These loops reference text stored in array CTLHED, by index ICTLPR.

d) WINDSTAU echoes name of new control file to user and closes logical unit ICTLUN.

Prompt text can be changed by modifying the CTLHED assignments or by expanding the CTLHED array.

Note that Subroutine CRECTL reads user responses as ASCII character strings, with the exception of the number of output cells and cell coordinates. Therefore, the user's reponses to control file prompts will appear in the control file exactly as they were entered.

3.2.3 Reading the Control File

Prior to program execution, the control file is read from logical unit ICTLUN; control file line index ICTLDX is updated before each READ statement. As each parameter is read, data format is checked against variable type. In the case of a format/data mismatch, control is transferred to statement #47, which informs the user of the error and the control file line number where format/data mismatch was detected. After the control file is read, the user is informed whether or not a premature end-of-file marker was encountered, indicating an incomplete or corrupted control file.

3.2.4.0 File Operations and Initialization (Program Section 0)

File operations and initialization are handled as follows:

a) Input and output files are opened on logical units IINPUN and IOUTUN, respectively. Filenames are specified in the control file. If the input file does not exist in the directory to which the user is attached, or if the output file does exist in that directory, program execution will halt and a system error will be displayed.

b) Constant values for water density, acceleration due to gravity, the Karman constant, and the Coriolis parameter are assigned.

c) Initial cell dimensions are computed and all dimensional units are converted to internal model units (centimeters).

d) Working arrays are zeroed and time counters are assigned.

e) Model bathymetry is initialized according to an algorithm which may be changed according to the user's wishes. As of December, 1985, the bathymetry is coded to depict a flat bottom, sloping down linearly as one proceeds offshore. An additional algorithm is included which allows the user to model the Texas Continental Shelf, off Port Aransas, with the following equation:

```
h(x) = 0.106377 x 10**4  +  0.117336 x 10**(-2)  h
                         -  0.243613 x 10**(-9)  h**2
                         +  0.410411 x 10**(-16) h**3
```

where h is the absolute depth, in centimeters, at model initialization and x is the cross-shelf distance in centimeters. In the case of the Texas Continental Shelf, offshore distance is limited to 60km.

f) Loops are initialized and debug flags are set; the model is processed once every sub-iteration, which is performed every MODINC seconds, in data time units.

3.4.2.0.5 Coordinate Assignment (Program Section 0.5)

Cell dimensions are dynamically assigned at the start of each sub-iteration. Nomenclature for cell-oriented variables is as follows:

X12	distance from present cell to nearest onshore neighbor
X1	cross-shelf distance from shore of present cell
X32	distance from present cell to nearest offshore neighbor
X2	cross-shelf distance from shore of present cell
X3	cross-shelf distance from shore of offshore cell
DELZ1	mean vertical dimension of onshore cell
DELZ2	mean vertical dimension of present cell
DELZ3	mean vertical dimension of offshore cell
Z1	mean vertical position of onshore cell
Z2	mean vertical position of present cell
Z3	mean vertical position of offshore cell
ZU	mean vertical position of cell above present cell
ZD	mean vertical position of cell below present cell

Z2MID	vertical position of present water column centroid
DZ12	vertical distance from onshore cell to present cell
DZ32	vertical distance from offshore cell to present cell
DELH32	slope of free surface between offshore and present cell
XYAR2	cross-sectional area of present cell, XY plane
YZAR32	Y-Z crs.area, interface betwn. offshore and present cls
YZAR12	Y-Z crs.area, interface betwn. onshore and present cls.
YZAR2	Y-Z crs.area, middle of present cell
XZAR2	X-Z crs.area, present cell
XZAR1	X-Z crs.area, onshore cell
XZAR3	X-Z crs.area, offshore cell
CLV1OL	cell volume, onshore cell, previous increment
CLV2OL	cell volume, present cell, previous increment
CLV3OL	cell volume, offshore cell, previous increment
ACLV12	average of onshore and present cell volumes
ACLV32	average of offshore and present cell volumes
CLM1OL,CLM2OL,CLM3OL,ACLM12,ACLM32	old and average cell masses, name conventions as in above volumes
U12	cross-shelf surrent speed in onshore cell
U32	cross-shelf current speed in present cell
UU32	cross-shelf current speed in cell above present cell
V12,V32,VU32	lonshore current speeds, named as CS speeds, above

NOTE: Cross-shelf distance is expressed as "x", in centimeters
Depth is expressed as "z", in centimeters
The "present cell" refers to the cell presently being processed.

3.2.4.1 Windstress
(Program Section 1)

Windstress is assigned as that portion of the hourly input windstress which occurs in each timestep (sub-iteration). These computations are accomplished in the sub-iterations loop by:

a) dividing the difference between the present hour's windstress and the previous hour's windstress by the number of timesteps (sub-iterations)

b) multiplying the above quotient by the number of elapsed sub-iterations and adding the product to the previous hour's windstress.

If the present cell is on the top layer (free surface layer) of cells, then windstress is added to the sum of forces on that cell. Otherwise, the windstress is zero.

3.2.4.2 Cross-shelf Pressure Gradient
(Program Section 2)

The cross-shelf pressure gradient force is computed as the difference in height between the present cell and its onshore neighbor cell, multiplied by the acceleration of gravity, multipled by the average cell mass. The average cell mass is the arithmetic average of the masses of the present cell and its onshore neighbor cell.

3.2.4.3 Longshore Horizontal Eddy Viscosity (Program Section 3)

The longshore horizontal eddy viscosity results from the horizontal current shear (longshore component) between the present cell and its nearest onshore neighbor cell. The shear is computed with respect to the present cell; if the present cell's longshore velocity is greater than that of its onshore neighbor, the current shear is positive.

Eddy viscosity can be made to vary as a user-chosen function of the cross-shelf distance, or even of depth, by specifying HEFN32, as follows:

HEFN32 = f(HEO,DEDX,x,z)

where HEO is the constant horizontal eddy viscosity, DEDX is the change in horizontal eddy viscosity with cross-shelf distance, and x and z are the cross-shelf distance and depth, repectively. Note that, in this and following eddy viscosity computations, x and z must be in centimeters to correspond with WINDSTAU's internal units.

3.2.4.4 Longshore Vertical Eddy Viscosity (Program Section 4)

In Program Section 4, longshore vertical eddy viscosity is computed as a function of the longshore component of the current shear between the present cell and its upper neighbor cell and the depth and height of the overlying water column, as follows:

VEFNNU2 = VEDFUN(VEO,DEDZ,z,zmid,watlev,zmax)

where VEO is the constant vertical eddy viscosity, DEDZ is the variation of vertical eddy viscosity with depth, z is the depth, zmid is the depth at the middle of the present water column, watlev is the waterlevel of the present water column with respect to the initial datum, and zmax is the maximum depth of the model grid at initialization.

VEDFUN is a double-precision WINDSTAU function described in Section 3.2.5.1.1 of this Report.

3.2.4.5 Cross-Shelf Vertical Eddy Viscosity (Program Section 5)

Cross-shelf vertical eddy viscosity is computed in a similar manner to longshore vertical eddy viscosity, except that the current shear is computed as the difference in the cross-shelf components of the present cell and its upper neighbor. VEDFUN is the same as for the longshore case, as described above.

3.2.4.6 Bottom Frictional Force (Program Section 6)

Bottom frictional force is computed only if the present cell is on the bottom of the model grid, as follows:

a) If this is the first iteration, the velocity next to the bottom is initialized as the present cell velocity. Thus, some stability is imparted to the bottom water layer.

b) The bottom friction is computed as a function of depth, "roughness length", and current speed, as well as the Karman constant:

```
BF = dens * K**2 * cspd * ABS(cspd)
     ------------------------------
       ( ln ( 0.5 * z'/ ruflen ) )
```

where dens is the density of water, K is the Karman constant, cspd is the current speed, z' is vertical cell dimension, in centimeters, and ruflen is bottom roughness length, in centimeters. Roughness length is also discussed in Section 3.1.2 of this Report.

c) Finally, bottom friction is multiplied by the cross-sectional area of the present cell, in the xy-plane, to yield bottom frictional force acting on that area.

3.2.4.7 Coriolis Accelerations (Program Section 7)

Coriolis acceleration on the present cell is simply computed as the cell velocity multiplied by the Coriolis parameter, 0.6802 x 10**(-4) for the Port Aransas, Texas location.

3.2.4.8 Sum Primary Forces (Program Section 8)

The primary forces are summed as follows:

Force between present cell and upper neighbor:

```
Cross-shelf:  0.5 * cross-shelf vertical eddy viscosity
Longshore:    0.5 * longshore vertical eddy viscosity
```

Force between present cell and offshore neighbor:

```
Cross-shelf:  windstress - cross-shelf pressure gradient
                         - 0.5 * cross-shelf vert. edyvis
                         - cross-shelf bottom friction

Longshore:    windstress - 0.5 * longshore vertical edyvis
                         - 0.5 * longshore horizontal edyvis
                         - longshore bottom friction
```

Force between present cell and onshore neighbor:

Cross-shelf: 0.0
Longshore: 0.5 * longshore horizontal edyvis

Note that the (-) signs denote a retarding force.

3.2.4.9 Convert Forces to Accelerations (Program Section 9)

Since Force = Mass * Acceleration, we can divide the forces computed in the above section by the average cell mass to get accelerations. In the case of the force between the present cell and its offshore neighbor, the Coriolis acceleration is added to the sum of forces.

3.2.4.10 Convert Accelerations to Changes in Speed (Program Section 10)

Changes in speed per timestep are computed by multiplying the acceleration (unit speed/unit time) by the timestep duration (MODINC).

3.2.4.11 Potential/Kinetic Energy Correction (Program Section 11)

The water parcel gains potential energy when it moves closer to the free surface (lesser depth), as described in Section 2.1. WINDSTAU compensates for this energy change as follows:

a) The kinetic energy of the cell is computed before the velocity correction is made.

b) The changes in potential energy of the onshore and offshore neighbor cells as they move along the bottom bathymetry are computed.

c) Kinetic energy is imported into the cell if the sum of the changes in b) is positive; k.e. is exported if the sum is negative.

d) A new kinetic energy is computed for the present cell by adding the energy import/export computed in c) to the previous kinetic energy, computed in a).

e) The cross-shelf velocity due to the energy correction is computed and the previous cross-shelf velocity is subtracted to obtain the velocity correction.

Cross-shelf and longshore velocities of upper neighbor, present cell, and offshore neighbor are corrected by adding the velocity changes computed in Program Section 10 (as described in Section 3.2.4.10 of this Report) to the previous velocities. For the present cell, the velocity correction due to kinetic energy, obtained in part e), above, is also added to the previous velocity.

3.2.4.12 Compute Water Level Changes (Program Section 12)

Water level changes are computed for the water column in which the present cell is located, as follows:

a) Compute the net convergence of water into the present cell by multiplying the current speeds of the onshore and offshore neighbor cells by the yz-plane cell boundary areas.

b) Multiply the net convergence by the timestep to get the actual water volume imported or exported into the water column.

c) Divide the water volume obtained in b), above, by the XY cell area to get change in water level

d) Add the change in water level to the previous total water level (WL) and to the previous water level with respect to the datum (WLDAT).

3.2.5.1 WINDSTAU Functions

Two functions are coded into the WINDSTAU model: VEDFUN, which computes the vertical eddy viscosity coefficient, and GETSGN, which computes the sign of a number.

3.2.5.1.1 Function VEDFUN -- Vertical Eddy Viscosity

VEDFUN is a double precision function with the following input parameters:

EO	- constant vertical eddy viscosity
DELE	- maximum change in vertical eddy viscosity
Z	- depth, centimeters
ZMID	- depth at middle of water column, centimeters
WATDEP	- total depth of water column
DEPMAX	- maximum depth of model grid

VEDFUN is a double precision function which computes the vertical eddy viscosity according to a user-coded algorithm. As of December, 1985, vertical eddy viscosity is computed as a quadratic function (parabola) with its vertex at zmid, and its base at the free surface and bottom, as follows:

```
VEDFUN= VEO - DEDZ * (1 - (z-zmid)**2 / zmid**2 )
```

Note that zmax is not used in this algorithm, but would be useful if the modeller wanted to weight the vertical eddy viscosity for overall depth.

3.2.5.1.2 Function GETSGN -- Sign of a Number

Input parameter is RNUMB. If RNUMB < 0, GETSGN = -1.0. Otherwise, GETSGN = +1.0.

3.2.5.2 WINDSTAU Sample Control File

Note: Documentation starts in column 32 for word processor display convenience, but actual control file documentation begins at column 40.

TEST1.WSTS	Filename (<33char) (CS-LS Windstress)
(2F10.3)	Windstress Datafile Format(max. 32 char)
300	Timestep (integral divisor of 3600 sec.)
60.	Maximum Cross-shelf Distance (km)
10	Number of Cross-Shelf (X-axis) cells
10.	Onshore depth (m)
60.	Maximum depth (m)
10	Number of Depth (Z-axis) cells
0.03	Vertical EDYVIS Constant term (VE0)
0.005	Maximum change in Vertical EDYVIS (DEDZ)
50.00	Horizontal EDYVIS Const. term (HE0)
0.0005	Change in Horiztl EDYVIS per cm (DEDX)
1.0	Bottom Roughness Length (cm)
999999999	Hour to start debug (99999 =-no debug)
99999.	CS dist (km) to start debug going offshr
99999.	Depth (m) to start debug downward
EXAMPLE-WL.RPT	Output Filename (32 char. max.)
DWL	Output Descriptor (DWL, LSC, CSC)
0.0	Starting (Onshore) CS Dist (km)
60.0	Ending (Offshore) CS Dist (km)

3.5.2.1 Water Level Control File and Report

```
**********************************************************************************************************
*** WINDSTAU CONTINENTAL SHELF CIRCULATION MODEL -- REPORT          WINDSTAU.FTN, Rev.3.1, M.Schmalz Nov. 85   ***
**********************************************************************************************************

   Number of Cross-Shelf Cells:                  10     Cross-Shelf Cell Dimension (cm):            0.600000E+06
   Number of Vertical (Z-axis) cells:            10     Initial Vertical Cell Dimension (cm):       0.600000E+03

   Control File Information Follows:
        Control File Filename:  example-ctlfil
        (   1)     LINE 1
        (   2)     LINE2
        (   3)     TEST1.WSTS                        Filename (<33char) (CS-LS Windstress)
        (   4)     (2F10.5)                          Windstress Datafile Format(max. 32 char)
        (   5)     300                               Timestep (integral divisor of 3600 sec.)
        (   6)     60.                               Maximum Cross-shelf Distance (km)
        (   7)     10                                Number of Cross-Shelf (X-axis) cells
        (   8)     10.                               Onshore depth (m)
        (   9)     60.                               Maximum depth (m)
        (  10)     10                                Number of Depth (Z-axis) cells
        (  11)     .3                               Vertical EDYVIS Constant term (VEO)
        (  12)     .2                               Maximum change in Vertical EDYVIS (DEDZ)
        (  13)     500.                              Horizontal EDYVIS Const. term (HEO)
        (  14)     7.5E-5                            Change in Horiztl EDYVIS per cm (DEDX)
        (  15)     1.0                               Bottom Roughness Length (cm)
        (  16)     999999                            Hour to start debug (99999=no debug)
        (  17)     999999                            CS dist (km) to start debug going offshr
        (  18)     999999                            Depth (m) to start debug downward
        (  19)     TEST.DWL.RPT                      Output Filename (32 char. max.)
        (  20)     DWL                               Output Descriptor (DWL, LSC, CSC)
        (  21)     0.                                Starting (Onshore) CS Dist (km)
        (  22)     60.                               Ending (Offshore) CS Dist (km)

          ****** WATER LEVELS IN CENTIMETERS (header: cs-coords. in km):
TIME,DAYS 0.300E+01 0.900E+01 0.150E+02 0.210E+02 0.270E+02 0.330E+02 0.390E+02 0.450E+02 0.510E+02
--------- --------- --------- --------- --------- --------- --------- --------- --------- ---------

   0.042-0.779E-01-0.858E-01-0.951E-01-0.882E-01-0.688E-01-0.586E-01-0.494E-01-0.306E-01-0.291E-01 0.996E-03
   0.083-0.270E+00-0.272E+00-0.294E+00-0.308E+00-0.265E+00-0.194E+00-0.174E+00-0.141E+00-0.971E-01-0.112E+00
```

3.5.2.2 Cross-shelf Current Speed Control File and Report

```
*********************************************************************************************************************
*** WINDSTAU CONTINENTAL SHELF CIRCULATION MODEL -- REPORT                      WINDSTAU.FTN, Rev.3.1, M.Schmalz Nov. 85   ***
*********************************************************************************************************************

   Number of Cross-Shelf Cells:                    10     Cross-Shelf Cell Dimension (cm):               0.600000E+06
   Number of Vertical (Z-axis) cells:              10     Initial Vertical Cell Dimension (cm):          0.600000E+03

   Control File Information Follows:
        Control File Filename:  TEST.CSC.CTLFIL
        (   1)
        (   2)
        (   3)     TEST1.WSTS                               Filename (<33char) (CS-LS Windstress)
        (   4)     (2F10.3)                                 Windstress Datafile Format(max. 32 char)
        (   5)     300                                      Timestep (integral divisor of 3600 sec.)
        (   6)     60.                                      Maximum Cross-shelf Distance (km)
        (   7)     10                                       Number of Cross-Shelf (X-axis) cells
        (   8)     10.                                      Onshore depth (m)
        (   9)     60.                                      Maximum depth (m)
        (  10)     10                                       Number of Depth (Z-axis) cells
        (  11)     .3                                       Vertical EDYVIS Constant term (VEO)
        (  12)     .2                                       Maximum change in Vertical EDYVIS (DEDZ)
        (  13)     500.                                     Horizontal EDYVIS Const. term (HEO)
        (  14)     7.5E-5                                   Change in Horiztl EDYVIS per cm (DEDX)
        (  15)     1.0                                      Bottom Roughness Length (cm)
        (  16)      10000000.00000                          Hour to start debug (99999=no debug)
        (  17)     999999                                   CS dist (km) to start debug going offshr
        (  18)     999999                                   Depth (m) to start debug downward
        (  19)     TEST.CSC.RPT                             Output Filename (32 char. max.)
        (  20)     CSC                                      Output Descriptor (DWL, LSC, CSC)
        (  21)      3                                       Number of Output Cells (1-12)
        (  22)     0.0,0.0                                  CSdist-Depth pair for Cell# 1
        (  23)     60.0,0.0                                 CSdist-Depth pair for Cell# 2
        (  24)     60.0,60.0                                CSdist-Depth pair for Cell# 3

         ****** CROSS-SHELF CURRENT SPEEDS (header: cs-dist(km)//depth(m):
         0.000E+00 0.600E+02 0.600E+02
TIME,DAYS 0.000E+00 0.000E+00 0.600E+02
--------- --------- --------- ---------
    0.042 0.590E-01 0.303E+00 0.000E+00
    0.083 0.221E+00 0.884E+00 0.000E+00
```

4.1 Bibliography

Mellor, G.L., and A.F. Blumberg. "Modeling Vertical and Horizontal Diffusivities with the Sigma Coordinate System". (Submitted to Journal of Geophysical Research, printer's proof), 1985.

Smith, N.P. Notes from IAPSO Conference Presentation, Honolulu, Hawaii, August, 1985.

FIGURES AND CAPTIONS:

5.1 Figure 1: WINDSTAU Model Grid

The WINDSTAU model grid, configured for the Texas Continental Shelf off Port Aransas, is depicted with current speeds indicated by arrows within the third column of cells.

5.2 Figure 2: Cumulative Displacement Due to Input Windstress

Hourly windstress, computed from air pressure gradients across the Gulf of Mexico for the calendar year 1974, was used as input to the WINDSTAU model. This Figure depicts the cross-shelf and longshore drift of a parcel of water driven by the input windstress. Note that the longshore axis is elongated approximately three times the cross-shelf axis.

5.3 Figure 3: Onshore Water Levels Output from WINDSTAU

Coastal set-up and set-down for 1974 is illustrated. Input windstress is computed from air pressure gradients across the Gulf of Mexico for the calendar year 1974.

5.4 Figure 4: Mesh Perspective of Continental Shelf Water Levels

WINDSTAU, driven by previously described hourly windstress, was configured to generate the water levels for the continental shelf out to 60km. Note the instability at 263 days, due to insufficient damping of longshore current speeds. Dynamic Graphics' ISM was used to create the perspective plot.

5.5 Figure 5: Water Levels at Aransas Pass, 1974

The Total, Tidal, Non-tidal, Inverse Barometric, and Wind-Driven components of the water level recorded at Port Aransas, TX for the year 1974 are illustrated. Note that the wind-driven water level is identical to the water level depicted in Figure 3.

5.6 Figure 6: Composite Plot: Corpus Christi Bay Flushing, 1974

The accumulation of salt water from the Gulf of Mexico is plotted for the water levels shown in Figure 5. Note that the wind-driven water level contributes little to the overall flushing. The data used in constructing this graph were obtained by using the onshore water levels obtained from WINDSTAU as input to the CHANFLO model, configured for the Corpus Christi Bay estuarine system.

5.7 Figure 7: Composite Plot: Gulfwater Accumulation in Corpus Christi Bay

Gulfwater accumulation is shown, in detail, for the months of September and October, 1974. The upper graph shows cumulative net displacement of a parcel of water driven by the input windstress, previously described. The middle graph shows the inner shelf (onshore) water level depicted in Figure 3, days 240-300. In the bottom plot, the solid lines depict the volume of gulfwater injected into Corpus Christi Bay (millions of cubic meters), while the dashed line indicates amount of gulfwater accumulated in Corpus Christi

Bay, as a result of wind-driven coastal water level changes. Data for this graph were obtained in the same manner as for Figure 6.

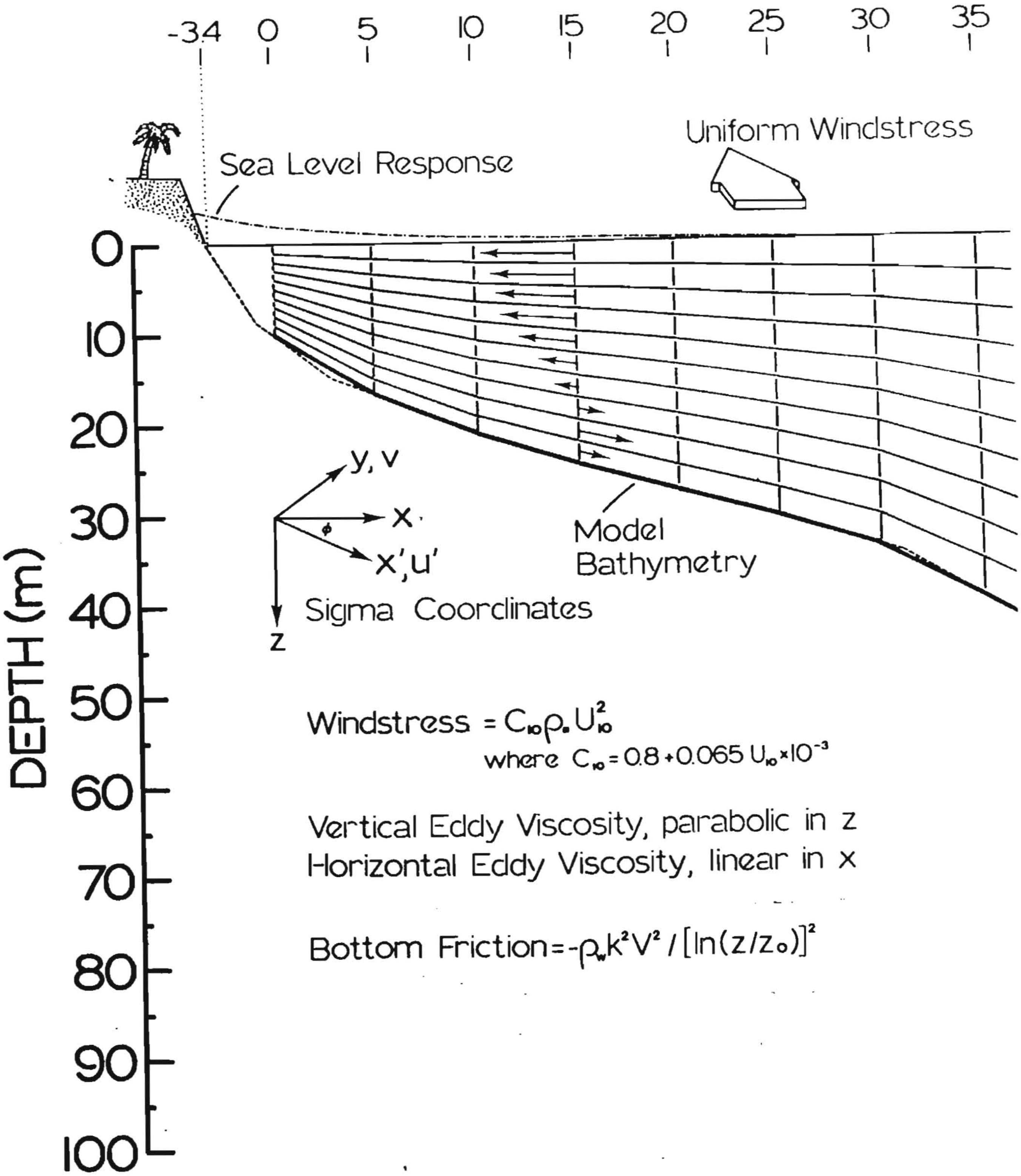

Figure 1: WINDSTAU Model Grid

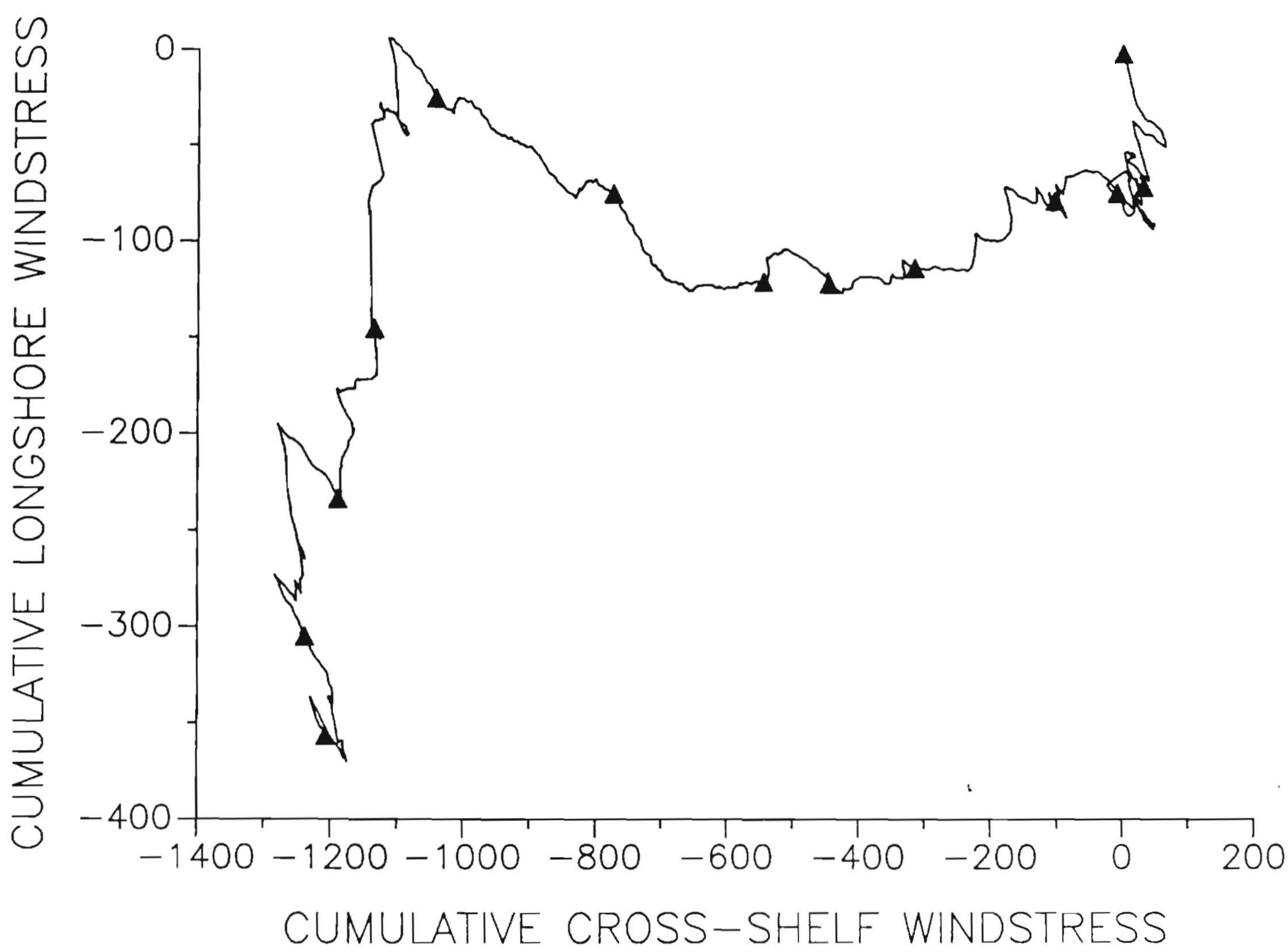

Figure 2: Cumulative Displacement Due to Input Windstress

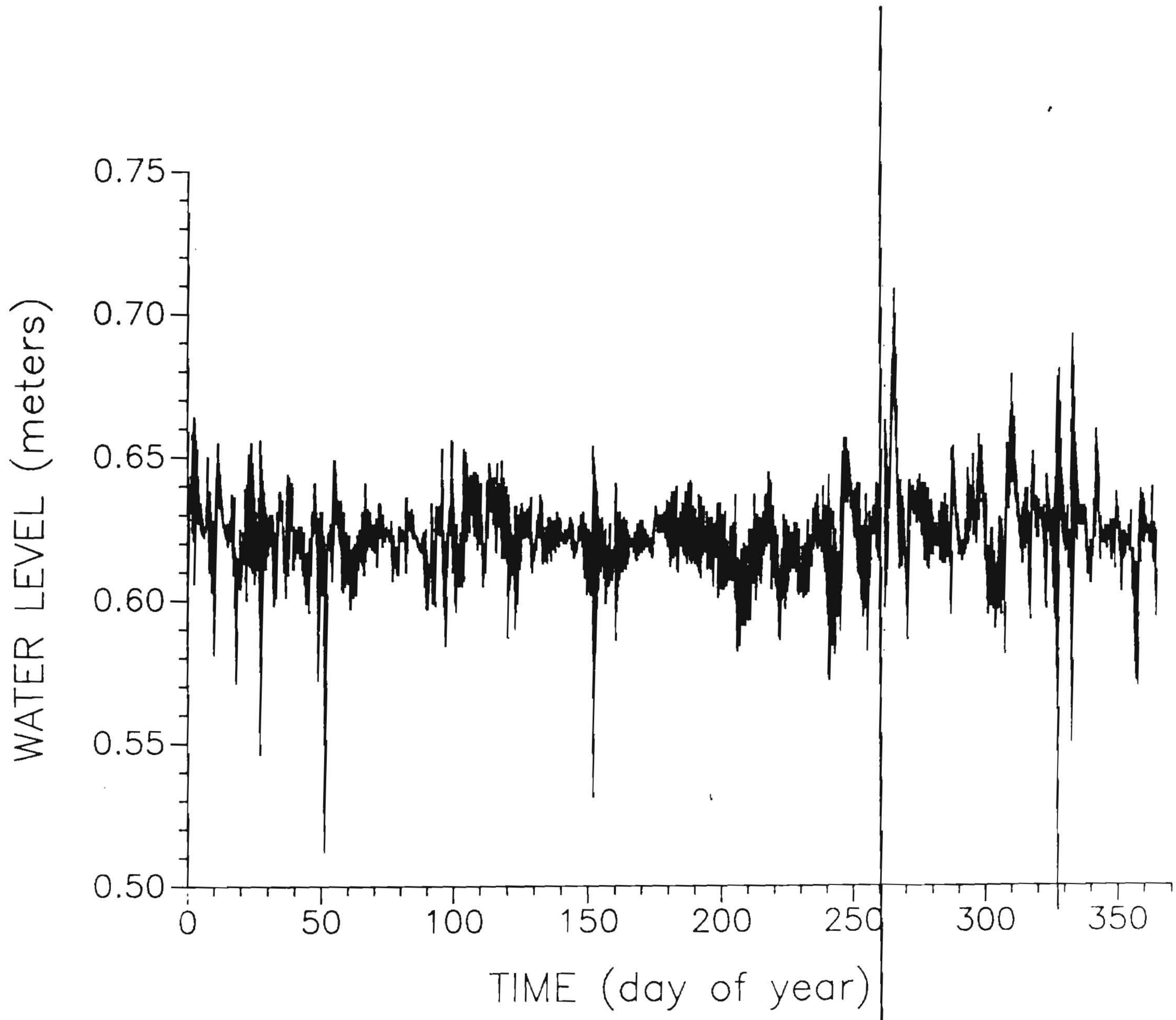

Figure 3: Water Levels Output from WINDSTAU (onshore station)

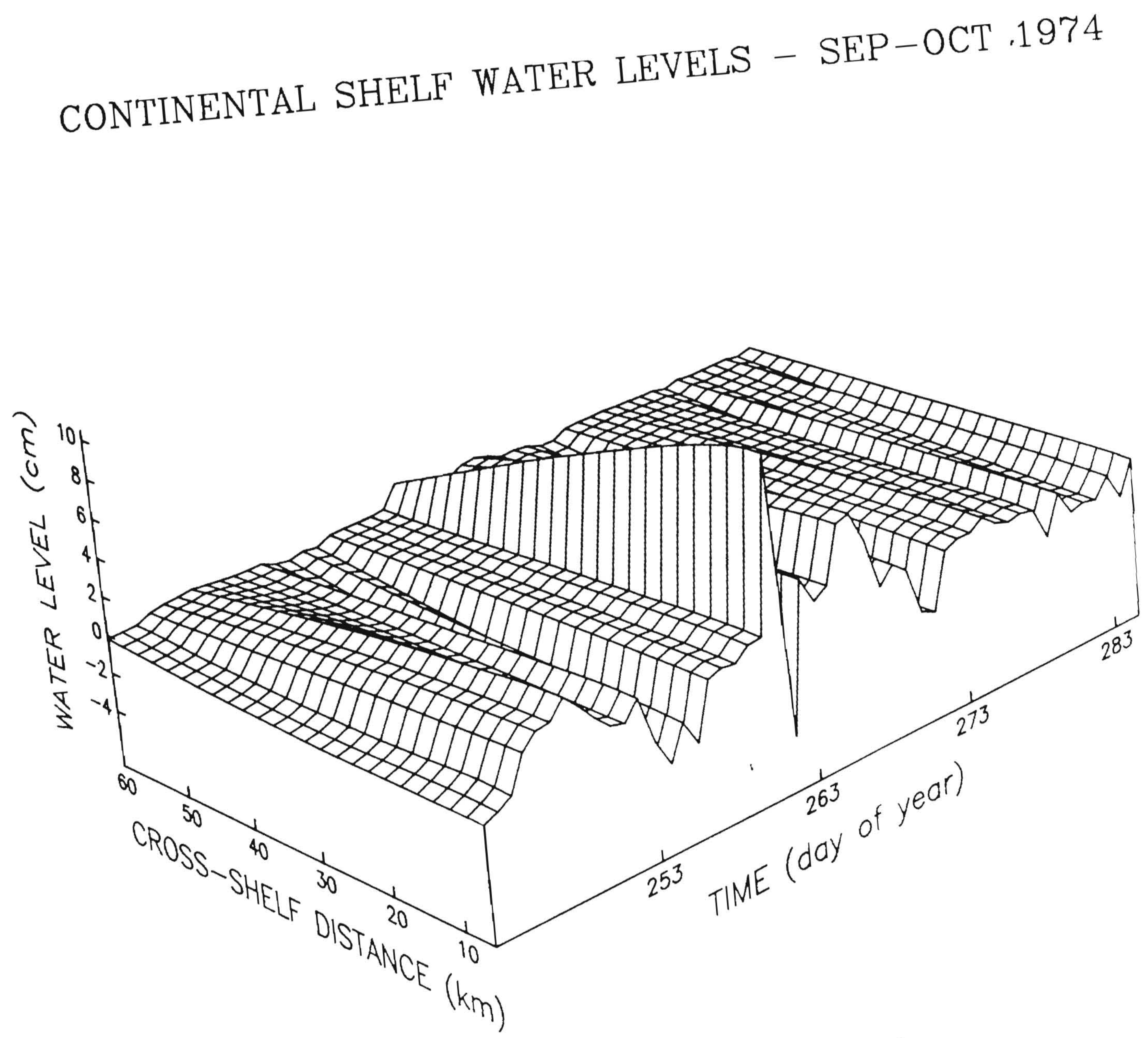

Figure 4: Mesh Perspective of Continental Shelf Water Levels

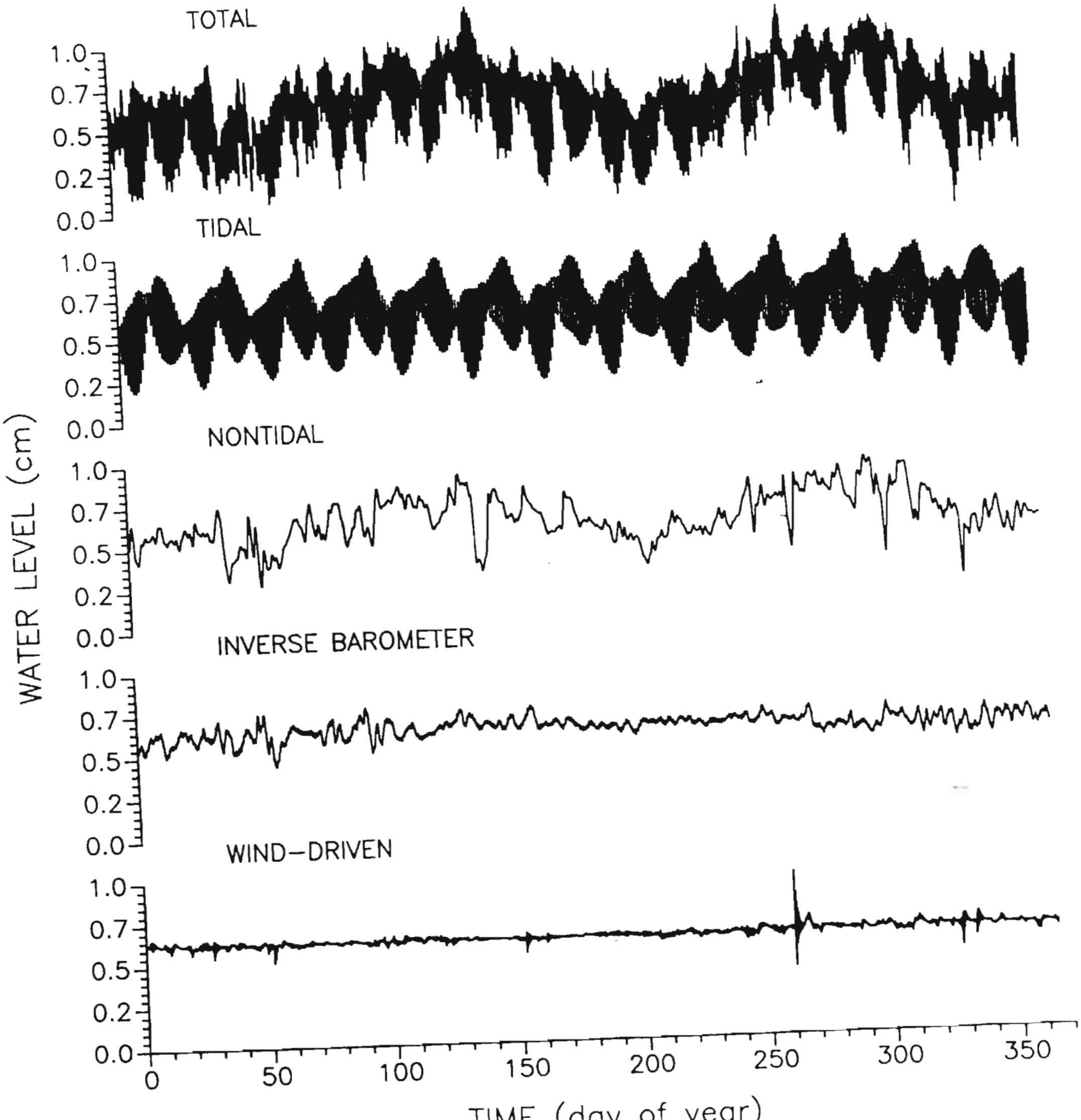

Figure 5: Water Levels at Aransas Pass, 1974

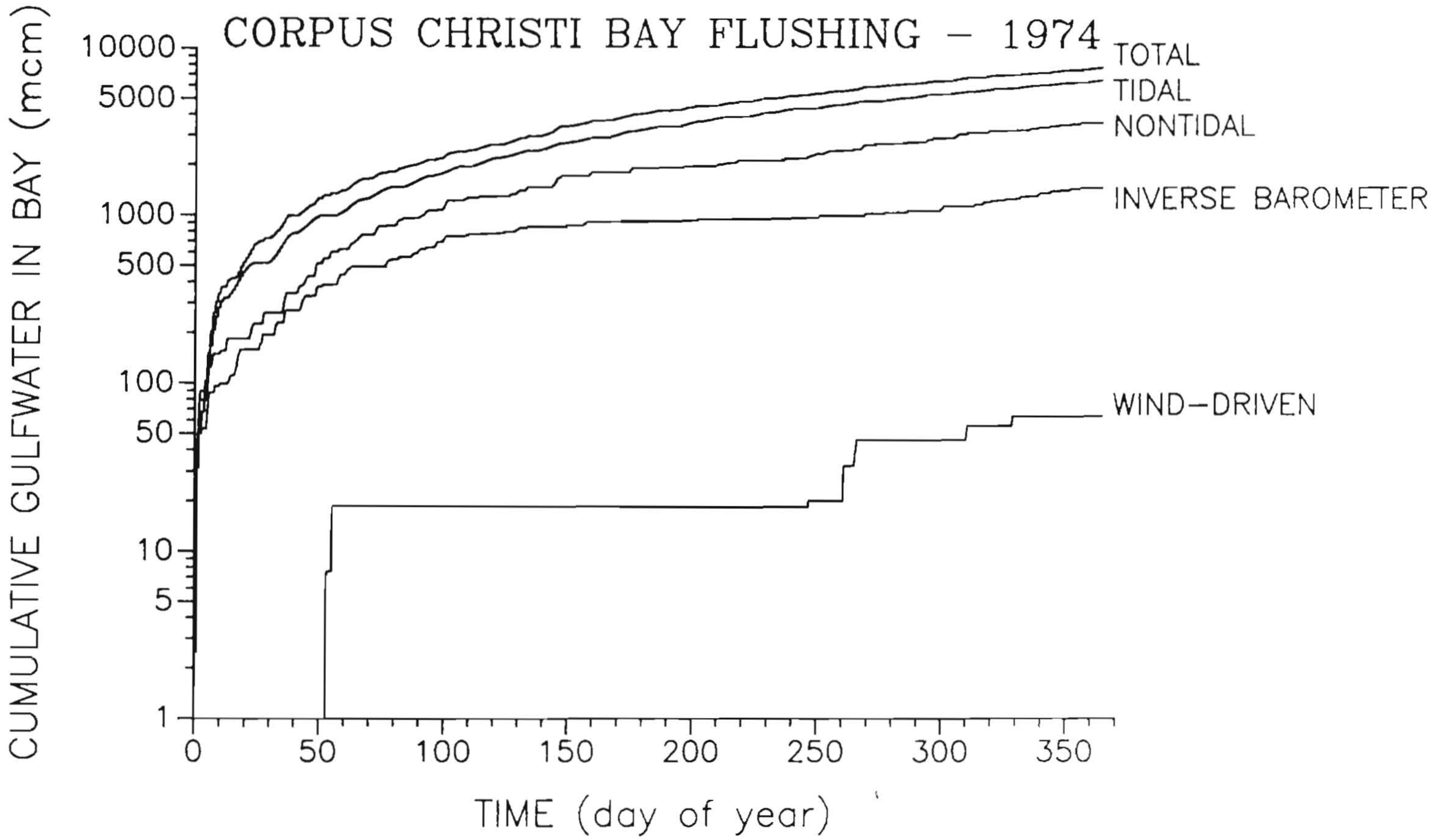

Figure 6: Composite Plot: Corpus Christi Bay Flushing, 1974

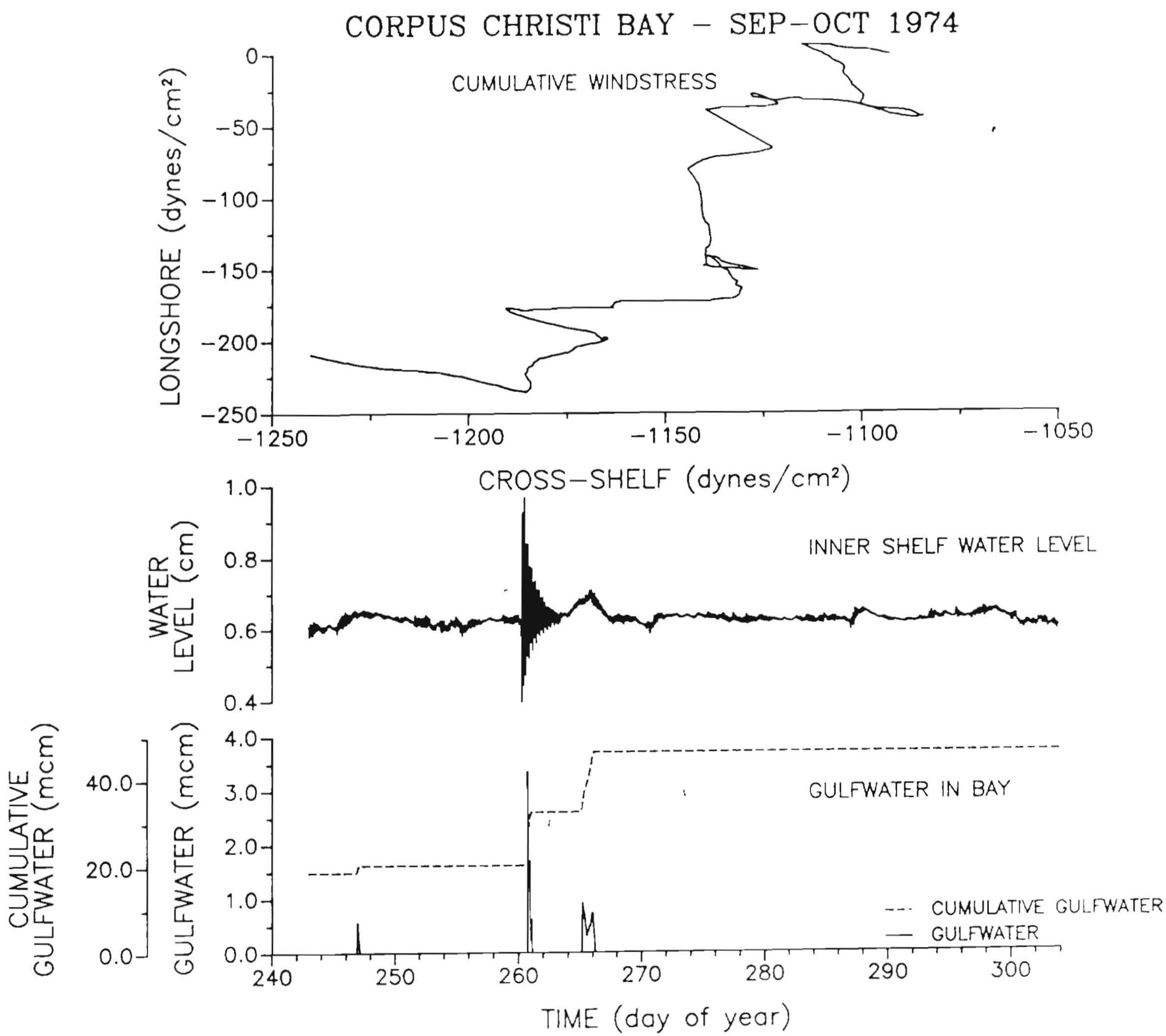

Figure 7: Composite Plot: Gulfwater Accumulation in Corpus Christi Bay