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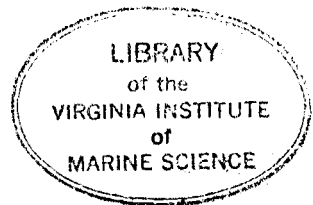# The Response of Estuarine Circulation to Local Wind Events

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# Estuarine Circulation

Edited by

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# Preface

Estuaries exist along the edge of the oceans and seas, and are characterized by the dilution of sea water by inflowing fresher waters. The motion and interaction of these two types of water (fresh and salt water) determine the salinity distribution within the estuary and that, in turn, affects the organisms residing there. The purpose of this volume is to review the status of our understanding of estuarine circulation and how the circulation patterns affect living and nonliving resources in estuaries.

For many years, the primary paradigm for estuarine circulation was the two-layered net or nontidal gravitational circulation pattern first proposed by Dr. Donald Pritchard in his studies of the James River estuary. During the last decade or so, research has focused on the many variations about this theme and the factors that control the transport processes. Many of these aspects are covered in the initial papers in this volume. Water movement, of course, is of interest because it transports marine organisms, sediments, and pollutants. Estuarine circulation has a significant effect on estuarine food chains, and on the distribution and abundance of organisms, such as the American oyster, that are freely transported by the currents during larval stages. The intent is to bring together many of these topics in a single volume.

This volume is dedicated to Dr. Donald W. Pritchard, our colleague and friend, as was the conference held in Gloucester Point in January of 1985. The conference was organized as one means of recognizing his contributions to our understanding of the physical oceanography of estuaries. It was held in conjunction with the 1985 Charter Day exercises of the The College of William and Mary. At that time, Dr. Pritchard was awarded an honorary degree of Doctor of Science.

The editors would like to thank those who atttended the conference and especially those who made presentations, the authors of the

papers included in this volume, the many persons who reviewed these papers, and Mrs. Barbara Cauthorn, who prepared the final versions of the manuscripts.

*Bruce J. Neilson*
*Albert Kuo*
*John Brubaker*

# Contents

# THE RESPONSE OF ESTUARINE CIRCULATION TO LOCAL WIND EVENTS

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## ABSTRACT

An analysis of non-tidal estuarine circulation and local wind events was conducted employing wind and current records taken along the York River.  Three distinct response conditions of non-tidal circulation to wind were observed.  These conditions exhibited significant temporal and spatial variability.  The first was typified by a positive two layer flow response to wind that was significant in the middle section of the York during the first six days of the study.  The second exhibited a positive one layer flow response to wind that was significant in the upper section of the York during the last three days of the study.  The third exhibited no statistically significant relation between current patterns and wind. This condition occurred near the mouth of the estuary, and it may indicate that the currents near the mouth respond more substantially to conditions in the adjacent Chesapeake Bay than to those caused by local winds.

## INTRODUCTION

The present study has several features of interest. A current meter data set was examined that had relatively high spatial resolution, particularly in the vertical coordinate.  A prediction-subtraction method of tidal

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current elimination was employed which resulted in preser-
vation of non-tidal currents in the intra-tidal and higher
frequency ranges. An epochal analysis approach, based on
periods of relatively constant winds, was used as a broad-
band method of synchronously demodulating the specific
effects of winds. These features facilitated the examina-
tion of the horizontal and vertical structure of the
circulation response in the York to wind events on the or-
der of a tidal cycle.

With regards to circulation, wind stress is the major
cause of the eddy flux of momentum across the air-water
interface in coastal plain estuaries (Pritchard, 1956;
Hansen & Rattray, 1965; Dyer, 1973 Officer, 1976; Wang,
1979). The role of wind stress has been formulated by
Hansen & Rattray (1965) and Officer (1976) as part of a
steady state model of estuarine circulation, in which net
flow is equal to fresh water discharge. The vertical
profile of wind induced flow is parabolic in form, with
surface and upper layer flow in the direction of wind,
lower layer flow in the opposite direction, and no flow at
the bottom. Studies by Weisberg (1976) and Farmer &
Osborn (1976) support the general concept of wind induced
flow formulated by Hansen & Rattray (1965). Weisberg's
study demonstrated a significant bottom compensating flow
(on the order of 2-3% of the wind speed) in response to
axial (along the estuary axis) winds. Farmer & Osborn's
study revealed a significant, positive relation between
the near surface current and the local axial wind, and no
significant relation, as expected, between the mid-depth
current and the axial wind.

Elliott (1976) observed two significant modes of
response of non-tidal currents (diurnal or greater) to
meterological forcing based on year-long surface, mid-
depth, and bottom current measurements taken at one
station in the Potomac River. The first response mode was
related to local axial winds. Subtidal currents displayed
a two layer flow similar to that formulated by Hansen &
Rattray (1965). Changes in mean water level and surface
slope along the estuary were positively related to local
winds. The second response mode was not well related to
local axial winds or surface slope along the estuary.
Only 50% of the fluctuations in the estuarine data could
be explained by local wind forcing. Elliott proposed that

unexplained fluctuations might be due to interactions between the Potomac and the Chesapeake Bay.

Wang & Elliott (1978) concluded that the short term (2 days or less) response of the Potomac to winds was characterized by two layer flow induced by local winds, and that the long term response was significantly related to Ekman flux at the estuary mouth. For the western tributaries of the Chesapeake Bay, Ekman flux acts in opposition to (so as to balance) the local wind induced flow.

In a study of non-tidal currents (diurnal or greater) in the Chesapeake Bay, Wang (1979) found evidence of a spatial transition from one layer flow in the lower bay to two layer flow in the upper bay, the latter flow being induced by local axial winds. The current data consisted of two month observations taken at one-third and two-thirds depth at a lower and upper bay station. Results indicated large exchanges of water between the Chesapeake Bay and the coastal ocean that were coherent and in-phase with the axial (north-south) wind for periods of 2-3 days and out-of-phase for longer periods. Establishment of one or two layer wind induced flow was also related to vertical eddy viscosity, with two layer flow associated with strong stratification and one layer flow associated with weak stratification.

Current observations in the above studies were taken over varying lengths of time, at one to three depths, at one or two stations along each estuary. The non-local nature of the estuarine response to meterological forcing observed in the Potomac and the different responses of current to wind observed in the lower and upper Chesapeake Bay indicate that the temporal and spatial resolution of estuarine observations greatly influence the resulting conclusions regarding circulation. With the exception of Farmer & Osborn (1976), current records in the above studies were low-pass filtered to remove the effects of the semidiurnal and diurnal tidal currents, thus precluding examination of correspondingly short term wind and current relationships. The studies of the Potomac and Chesapeake Bay indicate that basin geometry and physical factors, such as stratification, may significantly alter the modes of flow in response to induced forces. The

present study, while severely truncated in temporal dura-
tion, does have greater vertical and horizontal spatial
resolution than the studies reviewed above.


FIELD STUDY

   The York River is a coastal plain estuary located on
the southwestern shore of Chesapeake Bay.  It is tidal
throughout its extent.  The form of the tidal wave in the
York is primarily progressive (Hicks, 1964), with maximum
reported tidal currents of about 0.6 $ms^{-1}$ (NOS, 1972).  At
the head of the York, the watershed splits into two fur-
ther branches, the Mattaponi and the Pumunkey Rivers, each
of which possess substantial tidal prisms in their
meandering courses.  During the study period, the York was
partially stratified with surface salinities varying from
4 ppt at the head to 16 ppt at the mouth.   Bottom
salinities were typically 2-4 ppt greater than those of
the surface (Kiley, 1980).

   This study focuses on the response of currents to
relatively short-term (7-46 hours) winds, and examines the
spatial variability of that response within an estuary.
During 10-20 April 1973 currents were measured at 3 m in-
tervals from surface to bottom at 11 locations along the
York (Figure 1).  Although the original study was not
designed for the observation of wind and current interac-
tion, the data set provided an opportunity to examine this
feature.  Stations Y2-1 and Y4-2 were were sampled from
10-20 April, the remaining current meter stations in the
middle and lower York were sampled from 10-16 April, while
those in the upper York were sampled from 16-20 April.
Braincon histogram film recording current meters were
used.  The current data were reduced as described by
Jacobson (1973), resulting in 20 minute samples of current
velocity.  From the 43 current meter locations originally
sampled, 28 useable records were obtained, the rest (15),
including all records at station Y4-1, were lost due to
equipment failure or damage.

   Wind data consisted of continuous wind velocity
measurements reduced to hourly averages.  The data were
collected at the Gloucester Point campus of the Virginia
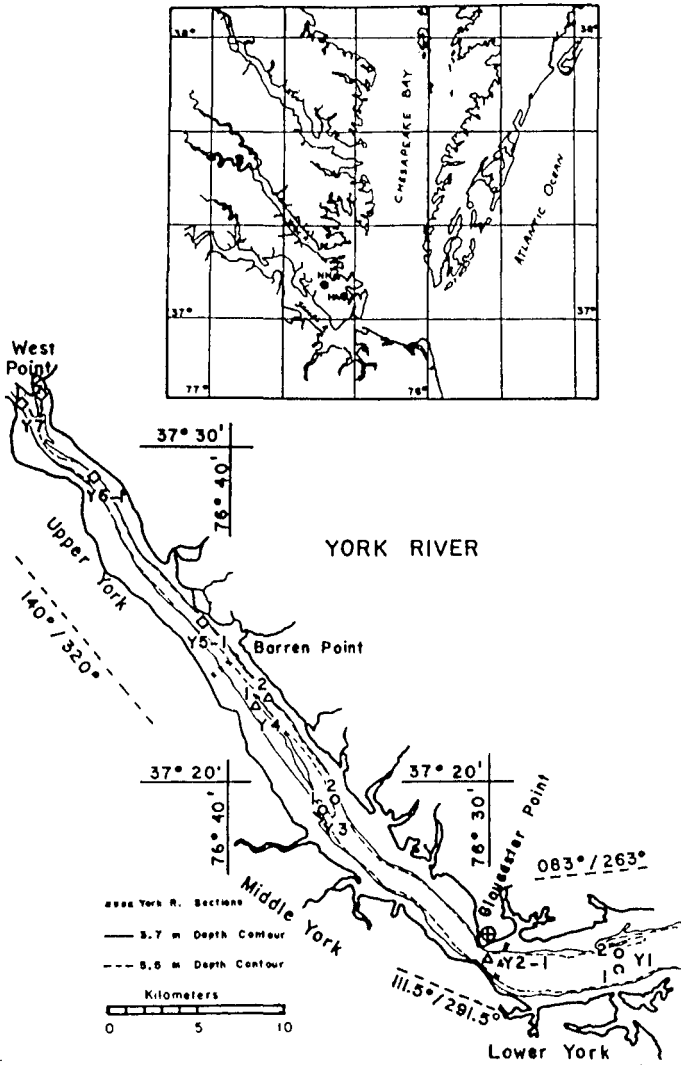Institute of Marine Science (VIMS, Kiley, 1980).

Figure 1. York River Study Area Including Current Meter
Sampling Sites and Local Wind Stations.
A. Current Meter Stations
○ Sampled 10-16 April 1973
△ Sampled 10-20 April 1973
◇ Sampled 16-20 April 1973
B. ⊕ Wind Station

## DATA ANALYSIS

The wind and current vector time series were reduced
to axial components. A prediction-subtraction method of
tidal current elimination was then employed. The mean and
linear trend in the axial wind and current records were
removed by the method of least squares. Semidiurnal and
higher frequency tidal components were estimated from the
reduced current time series by harmonic analysis
(Dronkers, 1964, Boon and Kiley, 1978), and then sub-
tracted from the current time series, resulting in
detrended non-tidal current records (Figure 2a-e).

Initial analysis of the axial wind data identified 12
epochs of steady values (Figure 3). An epochal method was
employed to examine responses that were representative of
the steady state adjustments of current to wind. Mean
values of the detrended axial components of wind and non-
tidal current observations were calculated for each wind
epoch. An analysis of variance was performed on the cur-
rent records to test the significance of the differences
between the mean current values for each epoch. Profiles
of the mean current values were constructed and evaluated
(Figures 4). The degree of association between wind and
current was determined by correlation and regression
analysis of wind and current values for each epoch.
(Figure 2g.)

## RESULTS

The least squares analysis of current over time
revealed that all but two stations at the head of the es-
tuary (Y7-1 and Y7-2) exhibited characteristics of two
layer gravitational estuarine circulation (Table 1).
Stations at the head of the estuary had net downstream
flow at all levels, indicating dominance of river flow
over gravitational circulation. At the lower York tran-
sect the level of no-net-flow is tilted, deeper at the
southern station than at the northern station. Overall,
the classic two layer gravitational circulation pattern
associated with a partially mixed estuary was observed.

Results of analysis of variance of the detrended non-
tidal axial current records indicated that 80% of the
variation in each record occurred within wind epochs as
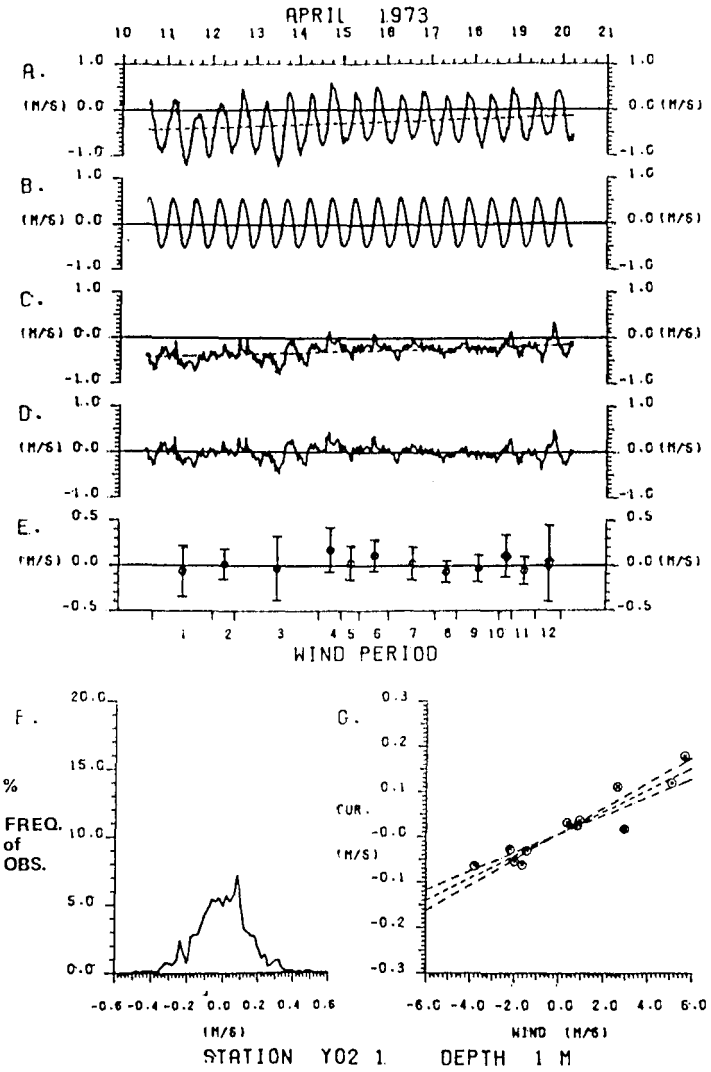
Fig.2. Time Series Plot of Axial Component of Current
Velocity, Histogram of Current Velocity, & Scatter
Diagram of Wind & Current Velocity for Station Y2-1

A. Observed Current
B. Harmonic Analysis Estimate of Tidal Current
C. Non-Tidal Current
D. Detrended Non-Tidal Current
E. Avg Detrended Current Velocity During Each Wind Epoch
F. Histogram of Detrended Non-Tidal Current Velocity
G. Scatter Diagram of Average Values of Detrended Wind
and Detrended Non-tidal Current for Each Wind Epoch
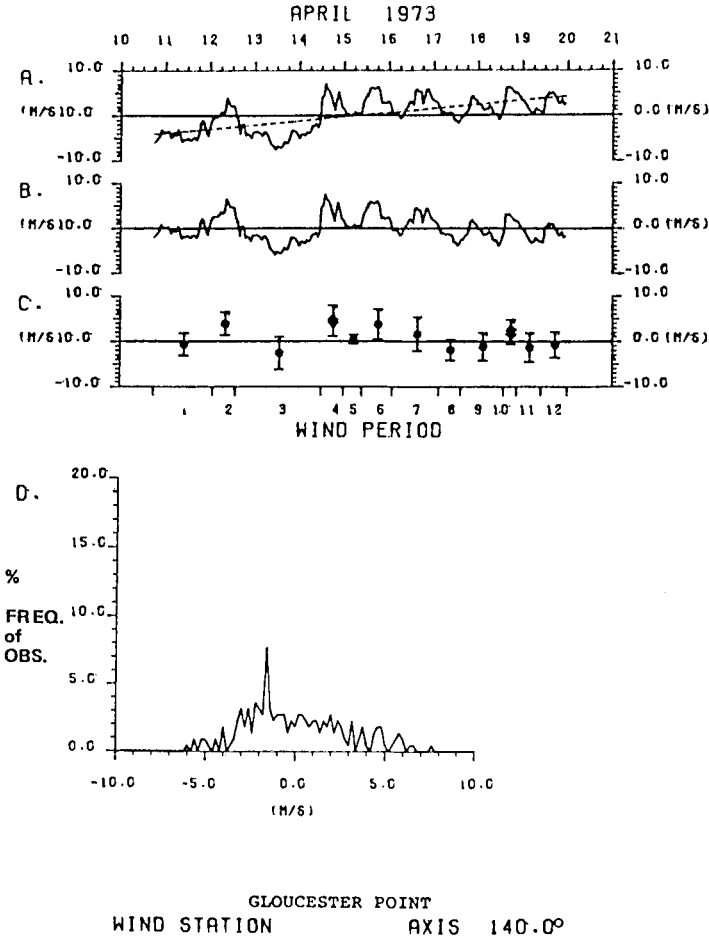
Figure 3. Time Series Plot of Axial Component of Wind
          Velocity and Histogram of Wind Velocity.
   A. Observed Wind
   B. Detrended Observed Wind
   C. Avg Detrended Wind Velocity During Each Wind Epoch
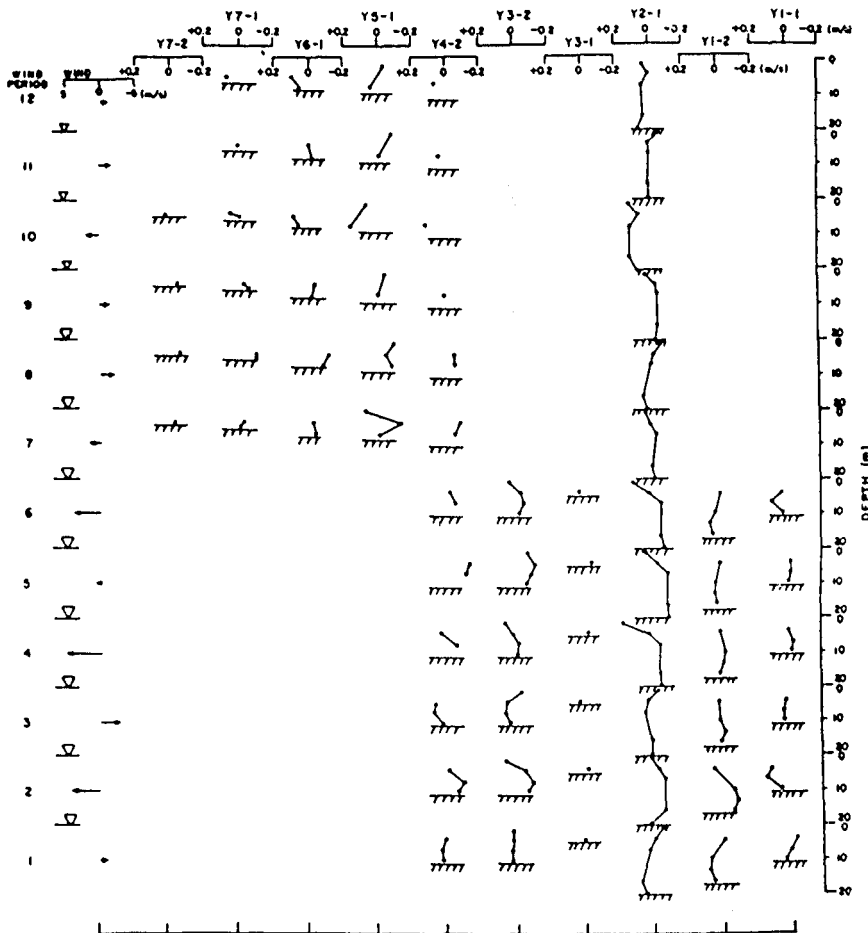   D. Histogram of Detrended Wind Velocity

Figure 4. Axial Profiles of Average Detrended Non-Tidal
Currents for Each Wind Epoch
(positive – upstream, negative – downstream)

TABLE 1

Average Axial Currents During Study Period and Correlation
and Regression Coefficients for Wind Epochs 1 - 12
(positive - upstream, negative - downstream)

| Station | Depth (m) | Average (m/s) | Corr. Coef. | Signf. Level | Regres. Slope |
|---------|-----------|---------------|-------------|--------------|---------------|
| Y1-1    | 4         | −0.115        | 0.420       | 0.56         | 0.012         |
| "       | 7         | −0.007        | 0.344       | 0.46         | 0.013         |
| "       | 10        | 0.032         | −0.288      | 0.40         | −0.004        |
|         |           |               |             |              |               |
| Y1-2    | 4         | −0.006        | −0.092      | 0.12         | −0.001        |
| "       | 10        | 0.080         | −0.509      | 0.67         | −0.015        |
| "       | 13        | 0.082         | −0.232      | 0.31         | −0.009        |
| "       | 16        | 0.061         | −0.305      | 0.41         | −0.009        |
|         |           |               |             |              |               |
| Y2-1    | 1         | −0.279        | 0.939       | 0.99         | 0.024         |
| "       | 4         | −0.125        | 0.085       | 0.20         | 0.001         |
| "       | 7         | −0.016        | −0.519      | 0.92         | −0.009        |
| "       | 16        | 0.126         | −0.613      | 0.97         | −0.012        |
| "       | 21        | 0.162         | −0.560      | 0.94         | −0.009        |
|         |           |               |             |              |               |
| Y3-1    | 4         | 0.034         | −0.839      | 0.97         | −0.008        |
|         |           |               |             |              |               |
| Y3-2    | 1         | −0.292        | 0.827       | 0.96         | 0.011         |
| "       | 4         | −0.116        | −0.492      | 0.64         | −0.009        |
| "       | 7         | 0.012         | −0.754      | 0.91         | −0.017        |
| "       | 10        | 0.050         | −0.755      | 0.91         | −0.013        |
|         |           |               |             |              |               |
| Y4-2    | 4         | −0.059        | −0.390      | 0.64         | −0.009        |
| "       | 7         | 0.103         | −0.652      | 0.99         | −0.018        |
| "       | 10        | 0.130         | −0.939      | N/A          | −0.015        |
|         |           |               |             |              |               |
| Y5-1    | 1         | −0.074        | 0.934       | 0.99         | 0.036         |
| "       | 4         | 0.038         | N/A         |              |               |
| "       | 7         | 0.111         | 0.782       | 0.93         | 0.035         |
|         |           |               |             |              |               |
| Y6-1    | 4         | 0.004         | 0.625       | 0.79         | 0.030         |
| "       | 7         | 0.061         | 0.587       | 0.75         | 0.020         |
|         |           |               |             |              |               |
| Y7-1    | 4         | −0.015        | 0.566       | 0.67         | 0.021         |
| "       | 5         | −0.062        | 0.938       | 0.65         | 0.018         |
|         |           |               |             |              |               |
| Y7-2    | 4         | −0.095        | 0.892       | 0.62         | 0.011         |

opposed to between. The mean current values of the epochs were, however, all statistically different, based on an F-distribution value at the 95% confidence level. These results suggested that a significant wind and current relationship was observed in the York for periods of steady axial winds.

Three distinct response conditions of current to wind were observed. Near the mouth of the York (Figure 5), the non-tidal current variability was not strongly related to local winds. In the middle section of the estuary (transects 2 through 4) the two layer, parabolic flow response proposed by Hansen & Rattray (1965), was observed, while in the upper section of the estuary (transects 5 through 7) the flow response, particularly in the bottom part of the water column, was significant and in the direction of the wind.

From the study data, little can be concluded about the effect of wind on currents in the lowest portion of the York. At and above the constriction and axis shift at Gloucester Point, the two layer wind induced circulation pattern was observed with a near-surface (1 m) speed between 1.4 and 2.4 percent of the wind component in the same direction and a lower layer maximum between 0.9 and 1.7 percent of the wind speed in the direction opposite to the wind. The layer of no net wind-driven motion was somewhat above the one third depth level of the parabolic theory and the current extrapolated to the bottom depth does not reach zero. This suggested that the wind-driven current passed through a laminar boundary layer very near the bottom. The appearance of a net transport opposite to the wind may be misleading because of the greater width of the estuary near the surface than in the channel depths.

In the upper part of the York, all of the axial residual currents were in the direction of the wind, at speeds between 1.1 and 3.6 percent of the wind velocity component. Because this response cannot have zero transport, it was clearly not a steady-state response and may have been a reflection of the substantial storage volume available in the branching, meandering rivers above the York. The high rate of the current near the bottom again suggests the presence of a laminar sublayer at the bottom of the water column.
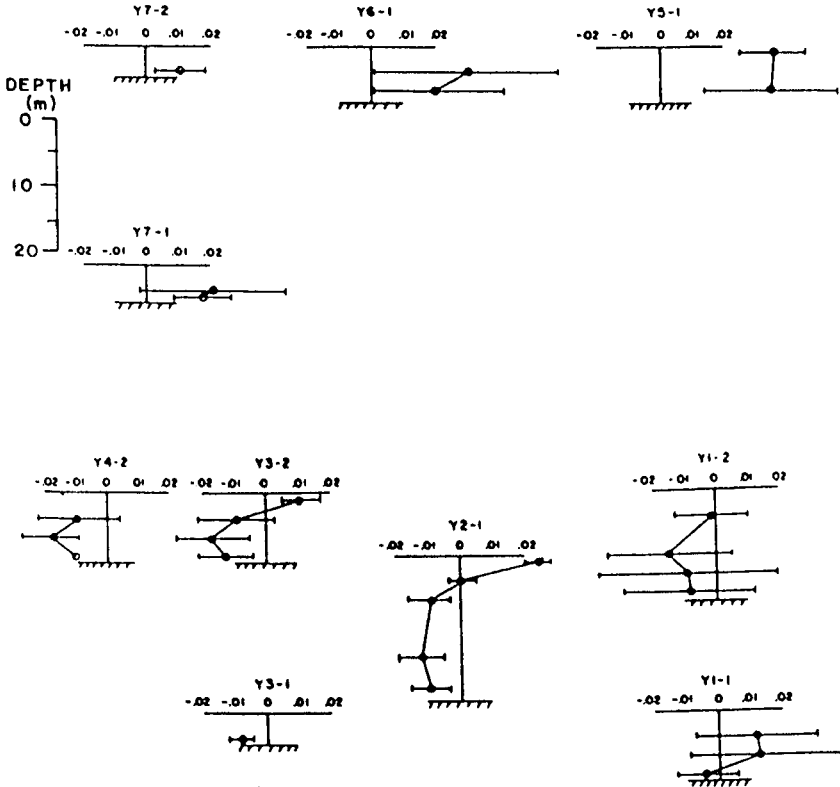
Figure 5. Average Current Dependence on Wind Speed During
         Study. (error bars represent 80 percent sig-
         nificance values)

The responses noted above for the middle and upper York were spatially and temporally separated, due to the overall sampling scheme (Figure 4). In order to determine whether the spatial or the temporal separation was the more important, two stations which were maintained for the duration of the study (Y2-1 and Y4-2), were reanalyzed for each time segment separately (Figure 6). The station at the transition between the middle and lower part of the estuary (Y2-1) showed some indication of a transition to a unidirectional wind response in the latter part of the study, but the results are not clear, because the 80 percent significance limits at all levels showed substantial overlap between the two time segments. At station Y4-2 there was a clear demarcation between the two periods, the record at 7 m, the sole survivor of the second period, clearly changed sign between the subperiods from opposite to wind, indicative of the lower layer in a two layer pattern, to with wind. The evidence from the subsamples, then, is that at least part of the difference in wind response between stations in the middle and upper parts of the York was temporal in nature.

## DISCUSSION

The non-tidal wind driven currents observed in this study conform, for the most part, to the two layer, zero net, wind driven flow proposed by Hansen & Rattray (1965). This is especially the case for the station at the estuary's major constriction (Station Y2-1) where the axial components of flow would most likely be greater than the lateral components. The York, as any estuary, is not a closed system and the responses for some of the wind epochs seem to indicate a net landward or seaward wind induced flow. A one layer flow response appears in the upestuary stations, in contrast with the two layer flow response proposed by Wang (1979) for the upper bay. This response is not in keeping with a steady state response of current to wind, and may be due to a number of factors: failure to achieve steady state locally due to the relatively short time frame of the chosen wind epochs, volume flux between the York and adjacent water bodies, or artifacts of diurnal inequalities or other low frequency tidal effects remaining in the current data. Analysis of tidal height records would reveal the significance of the volume flux in the estuary during the study period and
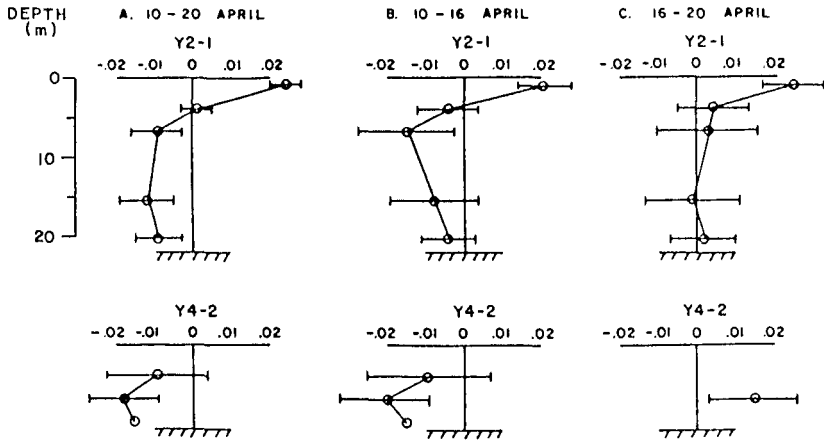
DEPTH
(m)

A. 10 - 20 APRIL          B. 10 - 16 APRIL          C. 16 - 20 APRIL

Y2-1                     Y2-1                     Y2-1

Y4-2                     Y4-2                     Y4-2

Figure 6. Current Profiles at Stations Maintained
          Throughout the Study Analyzed for:
     A. The Entire Study
     B. The Period of 10-16 April
     C. The Period of 16-20 April

might explain the one layer flow observed during the
second part of the study.

## CONCLUSIONS

The present study indicates that both a two layer
response of current to wind, as given by Hansen & Rattray
(1965), and a one layer response, suggestive of an open-
ended channel, occur in the York. These responses are
established in time periods of as little as 12 hours,
periods frequently filtered out of longer term data.
Conservation of mass considerations require that the one
layer response cannot be representative both of the es-
tuary cross-section and of time mean values. In order to
determine the regimes over which a one layer response is
applicable, even for an estuary of such simple geometry as
the York, longer records are required over more dense
horizontal grids across a transect. The vertical spacing
(3 m) seems sufficient for the determination of the verti-
cal profile, at least in depths of 15 m or more. If a

zero bottom velocity is required for the wind-driven com-
ponent, a bottom boundary layer is implied by these data;
complete determination of the profile would require a
dense sampling scheme near the bottom. The importance of
surface height data as a function of time during a current
meter survey is also suggested by the present study, for
it would permit an estimate of time varying water storage
in bounding areas and allow volume budget calculations to
be performed.

## ACKNOWLEDGEMENTS

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