On the relationship between long-term salinity variations and river discharge in the middle reach of the Delaware estuary

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Abstract. Daily averaged salinity measurements made in the middle reach of the Delaware estuary over the past three decades indicate the presence of significant subtidal variability. The salinity signals are dominated by variabilities at seasonal to interannual timescales. For any given month of the year the interannual variability accounted for more than 80% of the total deviations from the climatological mean monthly distributions. Variability at timescales shorter than a month is relatively insignificant. The long-term variations in salinity are closely correlated with the Delaware River discharge, with higher discharge corresponding to lower salinity and vice versa. Contrary to expectation, the long-term variations in the axial salinity gradient appear to have a negative correlation with the river discharge, with an increase in discharge corresponding to a reduction in the axial salinity gradient and vice versa. A number of factors, including the downstream movement of the salt intrusion limit beyond the observational station, the variation in the vertical salinity structure, and the possible existence of significant lateral variability may contribute to the observed response of the axial salinity gradient to different river discharge conditions.

Introduction

By definition, an estuary is a semienclosed body of water within which the seawater is measurably diluted with land drainage [Cameron and Pritchard, 1963]. The determination of the factors controlling the salinity distributions has been a problem of long standing. Beginning with the pioneering work of Pritchard [1952a, b] on the salinity distribution in Chesapeake Bay and some of its tributary estuaries, this topic has received sustained interest during the past four decades. Some of the more recent studies include the work on Mississippi Sound [Kjerfve, 1983], Lake Pontchartrain [Sikora and Kjerfve, 1985], and Laguna Madre [Smith, 1988], to name a few. It is generally known that the salinity distribution can be influenced by a variety of processes over a broad spectrum of timescales. These include tidal advection and diffusion [Kjerfve and Knoppers, 1991; Valle-Levinson and Wilson, 1994a, b], atmospherically induced subtidal motion [Kjerfve, 1986; Smith, 1988], and long-term variations in the river discharge [Schroeder, 1978; Schroeder and Wiseman, 1986].

The determination of the tidally averaged residual salinity distribution is important because it provides an indication as to how water of terrestrial origin, together with its dissolved and suspended materials, ultimately passes from the inland areas to the continental shelf.

On the basis of long-term salinity measurements made over three decades, the present study focuses on the subtidal variability in the axial salinity distribution in the middle reach of the Delaware estuary. The data are examined to determine the dominant timescale of the salinity variability. The relationship between the long-term variability in the axial salinity gradient and river discharge will also be determined.

Study Area and Data Sources

The Delaware estuary is a major coastal plain estuary on the middle Atlantic coast of the United States. It is 215 km in length between the head of tide at Trenton, New Jersey, and the mouth at Cape Henlopen, Delaware–Cape May, New Jersey. The estuary has a 3.5 x 10^4 km^2 drainage basin in New York, New Jersey, Pennsylvania, and Delaware (Figure 1). The Delaware River, with a mean discharge of 330 m^3/s at the head of the estuary, contributes 60% of the total freshwater discharge into the estuary [Sharp et al., 1986]. The Schuylkill River, entering the estuary at Philadelphia, Pennsylvania, contributes another 15%. No other single source is responsible for more than 1% of the total discharge. More than 95% of the total freshwater discharge enters the estuary landward of the mean salt intrusion limit which is located some 100 km upstream from the mouth [Garvine et al., 1992].

Tides in the estuary are dominated by the M_2 motion. At the mouth the amplitude of the M_2 tide is about 50 cm, and the accompanying M_2 current am-
The amplitude is about 70 cm/s. The amplitude of the $M_2$ tidal volume flux at the mouth has been estimated to be about $1.47 \times 10^6$ m$^3$/s [Münchow et al., 1992]. The large ratio between the $M_2$ tidal volume flux and the freshwater discharge probably accounts for the fact that the Delaware is a weakly to partially stratified estuary, with surface to bottom salinity difference typically below 3-4 practical salinity units (psu). In addition to the tidal motion, atmospheric forcing produces subtidal currents at timescales of 2-10 days [Wong and Garvine, 1984; Wong, 1991].

Long-term surface temperature and conductivity measurements were made by the U.S. Geological Survey (USGS) at two stations (Reedy Island and Ship John Shoal) in the middle reach of the estuary. Reedy Island is located 86 km upstream of the mouth, and Ship John Shoal is 58 km from the mouth (Figure 1). Both stations are located above the deep channel along the axial direction of the estuary. The USGS supplied daily mean surface conductivity and temperature readings, and these data were used to compute the daily mean salinity values. The fact that the salinities were available in the form of daily averages means that the data can only be used to examine variability at subtidal timescales. In a recent study [Garvine et al., 1992] the magnitude of the intratidal salinity variation in the middle reach of the estuary was estimated to about 2.9 psu. The salinity data at Reedy Island were available from 1962 to 1988, and those from Ship John Shoal were available from 1969 to 1987. However, there are frequent and sometimes extensive gaps in the data. As a result, the available data range from 6506 days at Reedy Island to 4849 days at Ship John Shoal (Figure 2). Table 1 shows the summary statistics of the salinity measurements at these two stations.

In addition to the salinity data, the daily mean discharges of the Delaware River were also obtained from the USGS to characterize the freshwater input into the system. Unlike the salinity data, the river discharge provides a continuous long-term time series during the period 1962-1988 (Figure 2). The summary statistics of the discharge data are also shown in Table 1.

### Subtidal Variability in Salinity

The time series shown in Figure 2 suggest that the subtidal fluctuations in salinity may contain variances over a broad spectrum of timescales. However, the presence of frequent and irregular data gaps prevents the decomposition of variances as a function of frequency through autospectral analysis. Instead, the following procedure is adopted to assess the relative importance of the interannual variability, seasonal variation, and variations at timescales shorter than a month.
Table 1. Statistics of the Delaware River Discharge \( Q \) and the Salinity Measurements at Reedy Island (RI) and Ship John Shoal (SJS)

<table>
<thead>
<tr>
<th></th>
<th>RI, psu</th>
<th>SJS, psu</th>
<th>( Q ), m³/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>4.7</td>
<td>13.8</td>
<td>330</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>3.4</td>
<td>4.5</td>
<td>336</td>
</tr>
<tr>
<td>Maximum</td>
<td>14.4</td>
<td>25.6</td>
<td>3667</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.0</td>
<td>1.5</td>
<td>35</td>
</tr>
</tbody>
</table>

All the available time series data from each station are sorted by both the month and year in which the data were collected. For example, the salinity data at Ship John Shoal are designated as \( SJS_{ij} \), where \( i = 1, 2, \ldots, 12 \), \( j = 1, 2, \ldots, M \), and \( K = 1, 2, \ldots, N_{ij} \). Here \( i = 1 \) represents January, \( i = 2 \) represents February, and so forth. The subscript \( j = 1 \) represents 1969, the first year when the data became available at Ship John Shoal, \( j = 2 \) represents 1970, and so on. The value of \( M \) indicates the total number of years in which the data are available. The value of \( N_{ij} \) indicates the total number of available data points from the \( i \)th month of the \( j \)th year. The monthly averaged salinity \( SJS_{ij} \) for the \( i \)th month and the \( j \)th year can then be computed based on an average of the \( N_{ij} \) data points available for that month and particular year. Such monthly averages will be computed only if there are more than 15 days of available data points in any given month. This is based on the assumption that the statistical significance of the monthly averages would be compromised if the gaps in data were to exceed the available data points for any given month. For the \( i \)th month of the year a total of \( M \) different \( SJS_{ij} \) can be computed to represent the monthly averaged values at different years. Figure 3 shows the distributions of \( SJS_{ij} \) as a function of month and year. Because of the way in which the monthly averages are computed, variances at timescales shorter than a month are essentially eliminated from the distributions of \( SJS_{ij} \). A standard deviation \( \langle (SJS_{ij})_{\text{std}} \rangle \) can be computed based on the \( M \) different values of \( SJS_{ij} \). \( (SJS_{ij})_{\text{std}} \) can be used as a measure of the interannual variability in the monthly averaged salinity for the \( i \)th month of the year.

It is apparent from Figure 3 that the salinity exhibits considerable seasonal variation for any given year. It is equally apparent that the monthly averaged salinity for any given month undergoes substantial variation from year to year. For example, the monthly averaged salinity at Ship John Shoal in April 1984 was close to 7 psu. By September of the same year the monthly averaged salinity was 21 psu. In contrast, the monthly averaged salinity only varied from 16 to 21 psu between April and September 1985.

The mean seasonal cycle in the variation of salinity can be examined by taking the ensemble average of all the available data collected in the \( i \)th month of all the years. The ensemble-averaged mean monthly salinity values are designated as \( \langle SJS_{i} \rangle \). As part of the computation, it is also straightforward to obtain the standard deviations \( \langle SJS_{i} \rangle_{\text{std}} \) around \( \langle SJS_{i} \rangle \). Since all the available data points from the \( i \)th month of different years are included in the calculation of the

![Salinity at Ship John Shoal (monthly average)](image-url)

Figure 3. Contours indicate the distribution of the monthly averaged salinity at Ship John Shoal \( SJS_{ij} \) as a function of the month and year in which the data were collected.
ensembled-averaged mean monthly values and the standard deviations, \( <SJS_i>_{\text{std}} \) contains both interannual variability and variability at timescales shorter than a month.

Figure 4 (solid line) shows the distribution of \( <SJS_i> \) as a function of the month of the year. It can be seen that there is a pronounced mean seasonal cycle in the salinity variation, with lowest salinity in April (10.3 psu) and highest salinity in September (17.2 psu). Figure 4 (short-dashed lines) indicates the distribution of \( <SJS_i> \pm (SJS_i)_{\text{std}} \). The results indicate that the interannual variability associated with the monthly averaged salinity for any given month may be as large as the mean seasonal variation in salinity. Figure 4 (long-dashed lines) also gives the distribution of \( <SJS_i> \pm <SJS_i>_{\text{std}} \). A comparison of the magnitudes of \( (SJS_i)_{\text{std}} \) and \( <SJS_i>_{\text{std}} \) show that for any given month of the year most of the deviations around the mean salinity distributions are associated with the interannual variations. Deviations associated with processes at timescales shorter than a month account for only less than 20% of the total variability around the climatological mean value. This suggests that the subtidal salinity fluctuations in Ship John Shoal are dominated by the seasonal cycle and the interannual variation in the seasonal cycle. Similar results are also found for the salinity variations at Reedy Island.

**Relationship Between River Discharge and Axial Salinity Distribution**

Figure 5 shows the ensemble-averaged mean monthly salinity distributions at Reedy Island \( <RI_i> \) and Ship John Shoal \( <SJS_i> \). Figure 5 (solid line) also shows the ensemble-averaged mean monthly discharge \( <Q_i> \). It is apparent that the river discharge carries a seasonal pattern, with highest discharge in April (630.5 m\(^3\)/s) and lowest discharge in September (165.7 m\(^3\)/s). The high-discharge period is primarily caused by the snow melt in the Catskill and Pocono Mountains during the spring. The low-discharge period is caused by the low precipitation and high evaporation in late summer. There is a negative correlation between the seasonal variations in river discharge and salinity, with low salinity corresponding to high discharge and vice versa. The correlation between \( <Q_i> \) and \( <RI_i> \) is -0.76 and that between \( <Q_i> \) and \( <SJS_i> \) is -0.78 (Figure 6). This suggests that most of the salinity variations are caused by the variations in river discharge. The linear regression shown in Figure 6 can only be applied to the normal range of river discharge variations. It is obvious that the linear regression gives unrealistic predictions when \( <Q_i> \to 0 \), since the true values of \( <RI_i> \) and \( <SJS_i> \) should approach the ocean salinity as river discharge is completely shut off. The existence of a negative correlation between the long-term variations in the river discharge and salinity is not surprising. Such correlation has been observed between the salinities in Louisiana estuaries and the Mississippi River discharge [Wiseman et al., 1990a]. It should be noted that the Mississippi river discharge exerts indirect influence on the estuarine salinities in Louisiana by first altering the coastal salinities which propagate downcoast and then up the estuaries. In the case of the Delaware the river discharge influences the salinity in the estuary directly.
Figure 6. Relationship between the ensemble-averaged mean monthly river discharge \(
\langle Q_i \rangle \)
and salinity at Reedy Island \(
\langle RI_i \rangle \)
and Ship John Shoal \(
\langle SJS_i \rangle \).
The solid line represents the linear regression of \(
\langle RI_i \rangle = 7.69 - 0.010 \langle Q_i \rangle \), and the dashed line represents the linear regression of \(
\langle SJS_i \rangle = 17.65 - 0.012 \langle Q_i \rangle \).

Figure 7 (long-dashed line) shows the mean monthly variation in the salinity differences between the two stations. The distribution of \(
\langle SJS_i \rangle - \langle RI_i \rangle \) gives an indication of the seasonal variation in the axial salinity gradient along the estuary. Figure 7 (short-dashed line) indicates the long-term mean salinity difference between the two stations (from Table 1). It can be seen that the axial salinity difference is generally below the long-term mean value during the months of high river discharge. On the other hand, the axial salinity difference is significantly higher than the long-term mean during the months of low river discharge. There is apparently an inverse correlation between the change in the axial salinity gradient along the estuary and the river discharge entering into the system. This is a surprising result. The conventional thinking is that a decrease in river discharge at the head should cause an increase in the salt intrusion length [McCarthy, 1991]. Garvine et al. [1942] have examined a 234-day salinity time series at the mouth of the bay and found that the standard deviation of the subtidal salinity fluctuations there is only about 0.8 psu. This standard deviation is much smaller than that at Ship John Shoal or Reedy Island. Since the salinity at the mouth of the estuary corresponds to the relatively invariant salinity of the continental shelf, an increase in the salt intrusion length should allow a greater distance for the salinity to decrease from a value

Figure 7. Ensemble-averaged mean monthly river discharge distribution (solid line), ensemble-averaged mean monthly variation in the axial salinity difference between Ship John Shoal and Reedy Island (long-dashed line), and long-term mean salinity difference between the stations (short-dashed line).
appropriate for the continental shelf to a value of zero at the limit of salt intrusion, thus causing a reduction in the axial salinity gradient. An increase in the river discharge should have the opposite effect and cause an increase in the axial salinity gradient. This type of positive correlation between the river discharge and axial salinity gradient has been observed in the Hudson estuary [Bowman, 1977] and the Volkerak estuary [van de Kreeke, 1990]. Furthermore, McCarthy [1991] has developed a laterally averaged analytical model to examine the density-driven circulation in Delaware Bay, and the results of his model also suggest an increase in the axial salinity gradient with increasing river discharge. However, the long-term observations in the Delaware appear to indicate the opposite effect.

The fact that the observed axial salinity gradient would decrease with increasing river discharge could perhaps be partially explained by a closer examination of the salinity data. Figure 8a shows the normalized probability density function and the probability distribution function [Bendat and Piersol, 1971] of the Reedy Island salinity data $RI$. The salinity there has an overall mean value $\bar{RI}$ of 4.7 psu and a standard deviation $RI_{\text{std}}$ of 3.4 psu. $RI$ has a highly skewed distribution about $\bar{RI}$. Even though the climatological mean position of the salt intrusion limit is located some 14 km upstream of Reedy Island, the data indicate that the salt intrusion ended short of Reedy Island for almost 10% of the time, making 0.0 psu the most probable of all values of $RI$. Figure 8b shows the normalized probability density function and probability distribution function for the Ship John Shoal salinity data $SJS$. The salinity has an overall mean value $\bar{SJS}$ of 13.8 psu and a standard deviation $SJS_{\text{std}}$ of 4.5 psu. $SJS$ appears to be normally distributed about $\bar{SJS}$. Ship John Shoal is located 42 km downstream of the climatological mean position of the salt intrusion limit, and the data indicate that the limit of the actual salt intrusion always occurred upstream of Ship John Shoal. With an increase in the river discharge the salinity at both stations would decrease. It is conceivable that the increase in discharge would at some point press the salt intrusion limit downstream of Reedy Island. At that point the salinity at Reedy Island would cease to decrease, as the value of salinity cannot drop below zero. At the same time the salinity at Ship John Shoal would continue to decrease with increasing river discharge. Under these circumstances it is possible for the axial salinity gradient between Ship John Shoal and Reedy Island to decrease with increasing river discharge. However, this reason cannot be used to explain the increase in axial salinity gradient under low-discharge conditions.

Figure 9 shows a plot of $<\bar{RI}>$ versus $<\bar{SJS}>$. The distribution indicates that the variation in salinity at Reedy Island is highly correlated with that at Ship John Shoal, with a correlation coefficient of 0.97. It is important to note that the slope of the linear regression between $<\bar{SJS}>$ and $<\bar{RI}>$ is significantly higher than 1. This suggests that while both $<\bar{RI}>$ and $<\bar{SJS}>$ respond to the variation in the river discharge $<Q_i>$ in a similar manner, the amplitude of the salinity response is greater at Ship John Shoal than at Reedy Island. For example, the salinity at both stations would increase with a decrease in the river discharge. However, the salinity at Ship John Shoal would increase more than that at Reedy Island farther up-
stream, thus causing an increase in the axial salinity gradient. The reverse occurs with an increase in the river discharge, resulting in a greater salinity decrease at Ship John Shoal than that at Reedy Island, causing the axial salinity gradient to decrease.

It is important to note that the salinity distribution in an estuary such as Delaware Bay is three-dimensional. This three-dimensionality may have a significant impact on the interpretation of the observed variability. In addition to its direct effect on the axial salinity distribution, a change in the river discharge can also modify the vertical salinity structure in the bay, as the degree of estuarine stratification is largely determined by the interactions of freshwater-induced buoyancy flux and the vertical mixing produced by tide within the water column. The funnel shape of the Delaware Bay tends to concentrate tidal energy and increase tidal current amplitude as one travels up the estuary. With an increase in the river discharge the degree of stratification should increase at both Reedy Island and Ship John Shoal. However, the weaker tidal current at Ship John Shoal may permit a greater increase in stratification there than at Reedy Island farther upstream. With this axial variation in the degree of stratification along the bay, it is conceivable that an increase in the river discharge might actually cause the axial salinity gradient to decrease at the surface and produce the observed response. The situation should be just the opposite in the lower layer of the water column, as the increased stratification at Ship John Shoal should enhance the upstream salinity gradient. This implies that an increase in the river discharge may induce depth-dependent variation in the axial salinity gradient. This phenomenon may, in turn, carry important implications for the response of the gravitational circulation to variations in the river discharge. In addition to the variations in the vertical salinity structure, the lateral salinity distribution may also affect the interpretation of the observed features. Recently, Wong [1994] and Wong and Munchow [1995] observed significant salinity variation of up to 6 psu across the wide, lower reaches of the Delaware estuary. They show that the salinity structure across the bay is strongly influenced by the lateral bathymetric distribution. It is conceivable that significant lateral structure might also exist in the narrower middle reach of the estuary, and the difference between the lateral structure at Ship John Shoal and Reedy Island may contribute to the observed variation in the axial salinity gradient between the two stations.

Discussion

The availability of long-term salinity measurements made in the Delaware estuary over the past three decades permits an opportunity for the examination of the characteristics of the subtidal variability in salinity. The results indicate that the subtidal fluctuations in salinity in the middle reach of the Delaware are dominated by a pronounced seasonal cycle and the interannual variation in the seasonal cycle. As a matter of fact, interannual variability accounted for more than 80% of the total deviations around the mean salinity values for any given month of the year. Variability at timescales shorter than a month is relatively insignificant. The importance of long-term salinity variability at the interannual or even decadal timescales has also been demonstrated for other systems such as the Louisiana estuaries [Wisman et al., 1990b].

As expected, the long-term variation in salinity is closely correlated with the variation in the river discharge, with lower salinity corresponding to higher discharge and vice versa. In the middle reach of the estuary the monthly averaged salinity may vary by 1.2 psu per 100 m$^3$/s of river discharge, resulting in a 7-psu mean seasonal variation in salinity. Most of the variance associated with the seasonal to interannual variations in salinity is apparently associated with the change in the river discharge conditions. The pattern of the Delaware River discharge can be summarized by the autospectrum (Figure 10) computed based on a 78-year time series (1912-1990). One can see the seasonal variability at 0.6 to 0.9 x 10$^{-2}$ cycles/day. The spectral values then decrease sharply with increasing frequency. The most prominent spectral peak, however, occurs at frequencies around 0.3 x 10$^{2}$ cycles/day (timescale of about a year). This indicates the importance of interannual variability in the river discharge. Figure 10 also shows that the spectrum is red at very low frequencies, suggest-
ing that some of the low-frequency variability in river discharge cannot be resolved even with a 78-year time series. The seasonal and interannual variability in the Delaware River discharge may be strongly influenced by the rainfall patterns associated with large-scale weather and climatological phenomena such as the storms from the Gulf of Mexico propagating up along the Atlantic seaboard or the onset of El Niño events. These events, in turn, produce large seasonal and interannual variations in salinity in the Delaware estuary.

Garvine et al. [1992] have shown that, on average, the axial salinity distribution varies linearly between the mouth of the Delaware and the mean salt intrusion limit located some 100 km upstream from the mouth. They also found that the salinity at the mouth remained relatively invariant over time. If the axial salinity distribution were to remain linear as the salt intrusion limit is altered by the change in the river discharge, then the axial salinity gradient should increase with increasing discharge. By the same token, the salinity from the station farther upstream in the estuary should exhibit a greater variation in response to a change in the discharge. However, the opposite was observed here. It is apparent that the large seasonal and interannual variations in the river discharge produce large changes in the salt intrusion length in the estuary. The fact that the actual salt intrusion limit may reside downstream of one of the observational stations may provide partial explanation for the discrepancy. Furthermore, one cannot overlook the possibility of the effect of three-dimensional salinity distribution on the interpretation of the observed variability. The axial variation in the response of the vertical salinity structure to the change in the river discharge may, in part, explain the observed features. The presence of significant lateral variability in salinity in Delaware Bay and other estuaries such as Mobile Bay [Schroeder, 1978], Rio Guayas [Murray and Siripong, 1978], and the York River estuary [Huzse and Brubaker, 1988] suggests that the along-estuary salinity distribution may vary with position across an estuary's cross section. Given the importance of the axial salinity gradient to the strength of the density-induced gravitational circulation, this is clearly an important topic which deserves attention in future studies.

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