Response Modes of the Lower Chesapeake Bay Wave Field

Katherine L. Farnsworth

College of William and Mary - Virginia Institute of Marine Science

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RESPONSE MODES OF THE LOWER CHESAPEAKE BAY WAVE FIELD

A Thesis
Presented to
The Faculty of the School of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment
Of the Requirements for the Degree of
Master of Arts

by
Katherine L. Farnsworth
1997
APPROVAL SHEET

This thesis is submitted in partial fulfillment of the requirements for the degree of

Master of Arts

Katherine L. Farnsworth

Approved, April 1997

Dr. John D. Boon, III
Co-Major Advisor

Dr. David A. Evans
Co-Major Advisor

Dr. Carl T. Friedrichs

Dr. Mark R. Patterson

Dr. L. Donelson-Wright
Dedication

In loving memory of my father, David L. Farnsworth and the long walks we took together on the beach.

“The world is round and the place which may seem like the end may also be only the beginning” - Ivy Baker Priest
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I wish to express my gratitude to other members of the VIMS community for providing a variety of opportunities for me and introducing me to the multidisciplinary world of Marine Science. I would also like to thank my students in the Introductory Geology Labs, they taught me more than they will ever know.

It is also important to thank the inhabitants of Reed Hall for helping to keep me sane over the last few years.

Finally much love and thanks to my family for all of their support and encouragement, even if they don’t understand what I am studying (or for that matter why!).

“A teacher affects eternity; he can never tell when his influence stops.”
- Henry Adams
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<td>b:</td>
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Abstract

An extensive wave monitoring program was conducted in the lower Chesapeake Bay from fall 1989 through spring 1995. From October 23, 1992 - April 20, 1993 the Virginia Institute of Marine Science deployed an aluminum tetrapod containing wave and current sensing and recording equipment in the Thimble Shoal region of the lower Chesapeake Bay. Measurements were made in half hour bursts every three hours to document the area's dynamic wave characteristics. It was shown previously by Boon et al. (1990 - 1996) that a bimodal frequency distribution of waves in the Thimble Shoal region existed, which was not seen in other areas of the lower Chesapeake Bay. This study examines the temporal changes in the wave energy spectra at Thimble Shoal, fall 1992 - spring 1993, providing a more complete description of the wave climate of the lower Chesapeake Bay.

I used Q-mode Factor Analysis to examine the temporal changes in the wave energy spectra. This method of analysis reduced the dimensionality of the large data set by decomposing the data into its basic modal components. Using this technique, four primary modes of spectrum shape at this site were described. These modes include calm, bimodal, local and a mode that is modulated by non-local events. Identification of these components (modes) and the systematic variation between them provides important insights about the wave climate of the lower Chesapeake Bay. The onset of a local wind event starts a systematic variation between the modes. The dominance of the calm mode is quickly reduced by the local storm waves. The bimodal mode is seen as a transition from dominance in the previous two. The fourth mode is dominated by very low frequency waves and appears to be modulated by non-local events. This variation is seen for every local wind event, regardless of type or size.
RESPONSE MODES OF THE LOWER CHESAPEAKE BAY WAVE FIELD
1. Introduction and Background

Coastal and estuarine environments are some of the most dynamic of all natural physical environments. The coastal zone is the region where the presence of the shore and reduced water depth allow for significant interaction between gravity surface waves and the sea floor. Within this zone one finds a close mutual interdependence between hydrodynamic processes and morphologic processes. The interaction and mutual modification of these processes occurs relatively rapidly. Many recent studies have been conducted on the wave climate of the inner shelf (e.g. Goldsmith et al., 1984; Short and Trenaman, 1992; Seymour, 1996; Prasado Rao and Baba, 1996), with fewer in the adjoining estuaries (Boon et al., 1990-1996; de Lange and Healy, 1990; Bartel and Ing, 1982; Boon et al., 1997).

Although the Chesapeake Bay is part of the coastal zone, the environment of an estuary differs in several ways from that of the exposed coastline. The antecedent topography of the Chesapeake Bay plays an important role in the evolution of surface gravity waves. Characteristics of the waves such as direction, period and height are greatly affected by the morphology of the bottom and shoreline. The effect the waves have on the bottom of the estuary is also very important. This is true not only for sediment transport considerations, but also for water quality and nutrient exchange between the sediment and the water column.
1.1 Wave Climate

Knowledge of the wave climate of a region is critical to shipping and coastal engineering projects. The dispersal of wave energy in a narrow coastal zone has great impact on shorelines and shoal areas. Wave-induced sediment transport problems include beach erosion, dredging and dredge material placement. Wave characteristics and wave climate are critical factors in virtually all coastal engineering projects.

The need to understand the wave climate of a region came during the Second World War. At that time, predictions of wave conditions were required at the beaches where military landings would take place. The technology available at this time also allowed for electronic methods of wave observation, thus reducing the error imparted by visual observation methods. This development of electronic equipment to measure waves, along with continued visual observations, resulted in the evolution of the first empirical wave prediction methods. These studies were conducted in shallow coastal waters and in 1952 Tucker developed the Ship borne Wave Recorder (Draper, 1979) that allowed models to be developed for oceanic deep water waves. Once this had begun, others realized the application of the data was far reaching.

The objective of this study is to expand the understanding of the wave climate of lower Chesapeake Bay using wave energy spectra, rather than more classical methods of wave field representation. Wave climate is concerned with the long-term statistics of wave parameters (Tucker, 1991). Classical methods for describing the wave climate of an area use two parameters to describe the climate: significant wave height and mean wave
period. These parameters provide a general description of the sea-state and long-term information. To get a more detailed look at the sea state at a particular time, this study examined wave energy spectra. For example, Ewans and Kibblewhite (1992) showed that by examining the joint probabilities of significant wave height and significant wave period for deep-water waves off the coast of New Zealand, they obtained a good description of the long-term wave climate. They also found that by dividing the spectra into calm and storm events, they could study the characteristics of those particular sea states. They calculated the average ‘total’ spectrum, average calm spectrum ($H_s < 1.5$ m) and average storm spectrum ($H_s > 3$ m). The average spectra effectively defined the characteristics of a baseline sea state for each location. The affect of local wave generation would manifest itself in the high frequency range of the spectrum. This division into a “calm” and “storm” spectrum allowed them to have a more detailed description of the local sea state.

The largest hindrance to the increase in knowledge of local wave climates has been the lack of reliable data. There were many short term data sets available, but to find a statistically significant wave climate, longer records were needed. Pickrill and Mitchell (1979) published a summary of wave data for the coastal waters of New Zealand, but it was not until 1995 that long term data had been acquired for that area. This was done when Macky, Latimer and Smith (1995) reported on the wave climate of the Bay of Plenty using classical methods of estimating the standard parameters.

Knowledge of the wave characteristics in the Chesapeake Bay has been limited by the small amount of reliable observational data. Wave studies have been conducted in the
deep water off the Chesapeake Bay (Seymour et al., 1985), but not until recently has long-term wave monitoring occurred within the bay (Boon et al., 1990, 1992, 1993). This monitoring consisted of bottom mounted wave gages at stations within the bay, including Thimble Shoal Light, Thimble Shoal Entrance and Wolf Trap (Figure 1, Table 1).

During the five years of monitoring the wave characteristics of the lower Chesapeake Bay, many observed patterns have been quantified. Before the monitoring began, information on waves in the vicinity would have been compiled from direct observation and hindcast methods. Using these hindcast methods, wind field data was combined with the local fetch to simulate the characteristics of monochromatic waves in the local area. After the beginning of the monitoring project local wave spectra were examined for the first time. The most notable finding was that a bimodal distribution of waves was found at the Thimble Shoal Wave Station. This bimodal distribution is seen mainly during the fall/winter months when extratropical storms pass through the region. The bimodal distribution features waves with periods > 8 seconds propagating to the west-northwest, combined with waves of 4 to 5 second periods propagating to the south.

These results were not unexpected, but as little work had been done on the wave climate of the lower Chesapeake Bay, the confirmation of bimodal spectra was exciting. This bimodality at the Thimble Shoal Station was not expected throughout the bay, so in an effort to define the boundaries of this region, stations were placed closer to the entrance of the bay (TSE)
Figure 1: Location of Wolf Trap (WLF), Thimble Shoal Light (TSL) and Thimble Shoal Entrance (TSE) wave monitoring sites in the Chesapeake Bay.
Table 1

<table>
<thead>
<tr>
<th>Start Date</th>
<th>End Date</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept. 27, 1988</td>
<td>Oct. 17, 1989</td>
<td>Thimble Shoals Light (TSL)</td>
</tr>
<tr>
<td>Nov. 6, 1989</td>
<td>Aug. 2, 1990</td>
<td>Wolf Trap (WLF)</td>
</tr>
<tr>
<td>Oct. 23, 1992</td>
<td>April 20, 1993</td>
<td>Thimble Shoals Light (TSL)</td>
</tr>
<tr>
<td>Jan. 15, 1993</td>
<td>May 12, 1993</td>
<td>Thimble Shoals Entrance (TSE)</td>
</tr>
<tr>
<td>Oct. 19, 1993</td>
<td>April 14, 1994</td>
<td>Thimble Shoals Light (TSL)</td>
</tr>
<tr>
<td>Sept. 18, 1994</td>
<td>Mar. 13, 1995</td>
<td>Thimble Shoals Light (TSL)</td>
</tr>
</tbody>
</table>

Starting and ending dates for the wave monitoring stations throughout the Chesapeake Bay.
as well as farther up the bay (Wolf Trap). Neither of these stations showed a pronounced bimodal distribution in the wave record. The Wolf Trap station showed the expected distribution of short periods and a north-south direction. The TSE station on the other hand showed longer periods (7-8 seconds) and a west-northwest propagation. These two stations seemed to show the two modes of waves that were combining in the Thimble Shoal Region of the lower Chesapeake Bay.

In past hindcasting studies, the input data used to generate the wave field was the local fetch for a given direction in the bay and the local wind field. This only accounted for the waves generated within the bay, and as was shown by Boon et al. (1990-1996), there is another component which plays a key role. This is the low frequency, west-northwest propagating waves. These waves appear to be the input of waves to the Chesapeake Bay from the inner continental shelf and Atlantic Ocean. They are found to represent more than 50 percent of the waves found in the area during the fall and winter months (Boon et al., 1990). This being the case, the hindcasting models were leaving out a major component of the wave climate of the lower Chesapeake Bay.

Wave energy spectra associated with this region can be diverse. Over time, predominant states can be seen. At any particular time, a single spectrum can be of any shape; however, it is generally associated with a characteristic or modal state. Defining the response of the wave field of the lower Chesapeake Bay to storm events would be simplified if these modes could be defined. A Factor Analysis would be a useful tool to accomplish this.
1.2 Factor Analysis

Factor Analysis was first developed in the early 1900's to explore and explain the subject of human mental abilities. The first form of Factor Analysis was very simple and could be used only on small sample sizes. This was due to the lack of computers to do the analysis. In the beginning Spearman (1904) developed this method in an attempt to understand the relationship of human abilities in the context of each other. With the expansion of technology and more powerful computers, a number of different computational methods have been developed thus expanding the number of different types and uses of Factor Analysis. The development and use of this multivariate procedure became extensive and was soon wide spread in a variety of fields including psychology, biology, climatology, geology and oceanography.

Factor Analysis consists of a number of techniques that aim to simplify complex sets of data. A basic form is Principal Components Analysis which uses an eigenanalysis of a variance-covariance matrix, restructuring the data into principal components or eigenvectors. Two of the most often used methods of Factor Analysis are the R-mode and Q-mode methods. The decision on which method to use is based on what questions are to be answered. R-mode looks at the relationships between variables, while Q-mode examines the relationships between observations.
2. Research Objectives

The primary objective of this thesis is to improve the description of the wave-climate of lower Chesapeake Bay by an examination of the energy spectra of the wave data. To do this, the major modes of spectral composition and their relationship to environmental conditions were determined. To address this research objective, a new way to interpret the data was required. A major obstacle in the analysis of any highly dimensional data is the problem of representing change among more than three variables simultaneously. A secondary objective was then to gain insight into using a multivariate technique such as Q-mode Factor Analysis to describe this complex environment. This technique was applied to a matrix of size \((n \times m)\), where \(n\) is the number of sampling bursts and the \(m\) variables were the relative amounts of energy in each of seven frequency bands representing the local wave energy spectrum. The values of the seven variables for each burst are the percentage of total energy found in each band. This allows for the seven variables to total 100, a preferred state for Q-Mode Factor Analysis, which is often applied to compositional data of this kind.

Principal components analysis (PCA) has proven useful in analyzing multi-dimensional data sets. It has been used to describe characteristic variability in spatial climate patterns and coastal morphologic features (Resio et al. 1974; Winant et al., 1975).
Vincent and Resio (1977) used this tool to look at wave energy spectra in the Great Lakes. They showed that the number of wave parameters needed to describe the system could be greatly reduced by determining new factors that account for almost all of the variance in a system.
3. Site Description

The study site is located in the Thimble Shoal region of lower Chesapeake Bay. The Chesapeake Bay is the largest estuary in the United States. It is a coastal plain estuary, extending 315 km from North to South. The width varies from 5 - 56 km. The Chesapeake Bay has evolved as coastal plain rivers were drowned by rising sea-level (Rosen, 1976). The bathymetry of the bay is not like that found on the open coast of the Eastern seaboard. It is typical of that found in this type of estuary, with many channels and shoals (Hobbs et al., 1992). The average depth of the bay at mean low water is only 8.4 m (Cronin, 1971). The deepest portion of the bay is found along the main axis where the relict channel of the Susquehanna River is found (Rosen, 1976).

The bay may be characterized as a partially mixed estuary with a mean semi-diurnal tidal range of less than one meter (Wright et al., 1987). The floor of the lower Chesapeake Bay is composed of relatively clean sands, with finer fractions in some low energy environments (Wright et al., 1987). The Thimble Shoal area of the lower Chesapeake Bay has an average salinity greater than 20 ppt and has an average depth ranging from 4 - 7 m (Kimball et al., 1989). An instrumented tetrapod was deployed in the Thimble Shoal area of the lower Chesapeake Bay (Figure 2). It was located along the northeast edge of a broad estuary shoal, in approximately 6 m of water. The bottom at this location is an essentially featureless hard sand, with a small amount of physically or
biologically induced roughness (Boon et al., 1990). This location allowed exposure to waves from the ocean as well as local waves generated within the bay.
Figure 2: Location of the Thimble Shoal Light wave station with relation to the bathymetry of the lower Chesapeake Bay.
4. **Data Collection**

Data was collected during the Fall-Spring seasons from 1988 - 1995. This data was part of a long term study of the wave climate of the lower Chesapeake Bay (Boon et al., 1990 - 1996). For the period from October 23, 1992 - April 20, 1993 the Virginia Institute of Marine Science deployed an aluminum tetrapod containing wave and current sensing and recording equipment (Figure 3). It was deployed in the Thimble Shoal region of lower Chesapeake Bay (37° 2.4' N, 76° 12.5' W) (Boon et al., 1990) (Figure 2). Equipment was retrieved and redeployed on monthly intervals for maintenance and recovery of data. Instrumentation consisted of a directional wave recorder with a Marsh-McBirney 2-axis (u, v) electromagnetic current, a Paroscientific high-precision pressure transducer, a KVH Fluxgate compass and an Onset TattleTale Model 6 data logger. The sensors were mounted on the tetrapod 1.5 m above the bottom.

Data loggers on the tetrapod were programmed for burst-mode sampling once every 3 hours (8 bursts/day) at a rate of 1 Hertz for a duration of 17.1 minutes. Each burst contained 1024 measurements recorded and later edited and processed in the lab to extract summary parameters representing that burst. The standard wave parameters are defined in detail in Boon et al. (1990) and are briefly described in table 2, contained in this study. Of the twenty parameters calculated, 14 were used in this study.
including the 7 energy spectrum variables, peak spectral wave period, burst-mean water depth and the time variables (month, day, year, hour). Wind speed and direction were obtained from NOAA meteorological data measured at Norfolk International Airport (National Climatic Data Center, 1992-1993).
Figure 3: Schematic diagram of the wave gage tetrapod. Instrumentation includes: battery pack (A), an electromagnetic current meter (B), a VIMS data logger (C), pressure sensor (G), a rope can for storage of buoy line (D), an acoustic release (E) to release a locator buoy (F) for retrieval of the tetrapod.
Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Mon</td>
<td>month (1..12)</td>
</tr>
<tr>
<td>Day</td>
<td>day (1..31)</td>
</tr>
<tr>
<td>Yr</td>
<td>year (01..99)</td>
</tr>
<tr>
<td>JDAY</td>
<td>Julian day of the year (1..366)</td>
</tr>
<tr>
<td>Time</td>
<td>24 hr Eastern Standard Time</td>
</tr>
<tr>
<td>Depth</td>
<td>burst-mean water depth (m)</td>
</tr>
<tr>
<td>MC_SPD</td>
<td>mean current speed (m/s)</td>
</tr>
<tr>
<td>MC_DIR</td>
<td>mean current direction (0..360)</td>
</tr>
<tr>
<td>WavDIR</td>
<td>principal wave direction (0..360)</td>
</tr>
<tr>
<td>Rvar</td>
<td>reduction in variance (0..1)</td>
</tr>
<tr>
<td>Hmo</td>
<td>zero-moment wave height (m)</td>
</tr>
<tr>
<td>Tz</td>
<td>zero-up-crossing wave period (s)</td>
</tr>
<tr>
<td>Tp</td>
<td>peak spectral wave period (s)</td>
</tr>
<tr>
<td>%E&gt;20</td>
<td>% of Energy in band of period &gt;20s</td>
</tr>
<tr>
<td>%20-16</td>
<td>% between 20 - 16 s</td>
</tr>
<tr>
<td>%16-12</td>
<td>% between 16 - 12 s</td>
</tr>
<tr>
<td>%12-8</td>
<td>% between 12 - 8 s</td>
</tr>
<tr>
<td>%8-6</td>
<td>% between 8 - 6 s</td>
</tr>
<tr>
<td>%6-4</td>
<td>% between 6 - 4 s</td>
</tr>
<tr>
<td>%&lt;4</td>
<td>% &lt; 4 s</td>
</tr>
</tbody>
</table>

Wave parameters contained in the lower Chesapeake Wave Climate Data Base (Boon et al., 1990 - 1996).
5. **Data Analysis**

Q-mode factor analysis is a multivariate procedure used to reduce, organize and help interpret data. It is useful as a way to predict the original data with maximum efficiency by using factors derived from that data. This is similar to reducing a number into factors which can reproduce the original number (10 = 5 * 2, 5 and 2 are factors of 10). The hope is that the model will allow us to reduce the number of factors needed below that of the original number of variables. The model is calculated in the following manner:

\[
[W] = [Aq][Fq]' 
\]

- \(Z\) = Predicted values (nxm)
- \(Fq\) = Factor Scores (mxm)
- \(Aq\) = Factor Loadings (nxm)

If a sample is defined by \(m\) variables, the sample can be represented as a vector in \(m\)-dimensional space whose position is determined by the value of each of the \(m\) variables. For example, if there are eight variables, the vector sample can be described as a vector positioned in eight dimensional space, by the values of the eight variables. Matrix notation and matrix algebra allow convenient representation of the mathematical steps in factor analysis and will be used in the discussion that follows. The data matrix is denoted
as \([X]\), with dimensions \([n \times m]\) where \(n\) is the number of samples and \(m\) the number of variables (frequency bands). An element, \(x_{ij}\) is the percentage of energy found in the \(j^{th}\) frequency band for the \(i^{th}\) sample. A simple spectrum is then represented by a row in the data matrix, \([X]\), \(x_{i1} ... x_{i2} ... x_{im}\) where \(m\) is the total number of frequency bands.

There are eight steps to complete a Q-mode Factor Analysis (FIGURE 4). The first step is to row-normalize the data matrix. This is done so that each sample is represented by a vector of unit length, allowing for a comparison of energy spectrum shape distributions, regardless of the magnitude of the individual wave energies. Now that all of the vectors have the same length, only their orientation is free to vary. This row-normalization is achieved by dividing every element in the data matrix, \([X]\), by the square root of the sums of squares for that row.

\[
W_{nj} = \frac{x_{nj}}{\sqrt{\sum_{j=1}^{m} x_{nj}^2}}
\]

The second step in Q-mode Factor Analysis is calculating a matrix of similarity coefficients. After determining the position of each row-normalized sample in \(m\) dimensional space, one is able to calculate the angles between each vector and every other sample vector. The cosines of these angles represent the proportional similarity between the samples. If the angle measured is zero, the cosine would be one, telling us that the two samples are co-linear, or compositionally identical. The opposite is found when the cosine of the angle is 0, indicating that the two samples are orthogonal. A matrix formed
Figure 4: Flow chart of Q-Mode Factor Analysis procedure used.
of these similarity values is called a cosine theta matrix, \([H]\). This is found by post-multiplying the row normalized data, \([W]\), by its transpose:

\[
[H] = [W][W]^T
\]

The cosine theta similarity matrix is a \(n \times n\) symmetric matrix where the elements show the similarity, of any two of the \(n\) samples, on a scale of zero to one. An individual element in this matrix is simply,

\[
\cos \Theta_{jk} = \frac{\sum_{k=1}^{m} x_{ik} x_{jk}}{\sqrt{\sum_{k=1}^{m} x_{ik}^2} \sqrt{\sum_{k=1}^{m} x_{jk}^2}}
\]

The cosine theta matrix of proportional similarity gives the relationships between samples. This is the information we were looking for, but it is in a form that makes the relationships between the samples hard to see. By applying a Q-mode factor analysis, we may be able to reduce the number of dimensions needed to represent the data, allowing for a clearer picture of the major relationships. This is done in step 3 by finding mutually orthogonal axes in some multidimensional space that will account for most of the information contained in the data. To do this we calculate the eigenvalues and eigenvectors of the cosine theta similarity matrix. This is done by solving for the eigenvectors, \([V]\), and eigenvalues, \([L]\), matrices from the following association:

\[
H = [V][L][V]^T
\]

With \(m\) variables, \(m\) sets of eigenvectors and eigenvalues are found. Eigenvectors are vectors in \(m\) dimensional space which represent the directions of similarity in the data. The eigenvalues are the amount of similarity in the data that is represented by the
eigenvector. If an eigenvalue is small, it contributes little information about the data - therefore we can simplify the system by not including them and losing very little essential information. This reduces the dimensions of the system. All eigenvectors for symmetric matrices are by definition mutually orthogonal. The location of the first eigenvector is associated with the largest amount of similarity, with the next eigenvector located in the direction of maximum similarity orthogonal to the first. Eigenvectors are linearly independent vectors that are linear combinations of the original variables.

Step 4 of the analysis is the determination of the factor scores and loadings. If the eigenvectors are scaled to the associated eigenvalues, they become factors which can be used to describe the data. These factors can be considered as compositional end-members of the data. Factor scores and loadings are calculated from the eigenvectors of the association matrix. The factor loadings matrix is an n x m matrix, with samples as rows and factor loadings as columns. The factor loadings matrix, $[A_Q]$, is formed when each member of the eigenvector matrix is multiplied by the square root of its corresponding eigenvalue (the singular value). The factors are then proportional to the magnitude of the singular values, which is the amount of the proportionality they account for. Each element in the factor loadings matrix is termed a loading and relates the sample to the orthogonal factors. The factor loadings matrix is found by:

$$[A_Q] = [V][L]$$

The factor scores matrix has dimensions m x m, with the factors as rows and variables as columns. Factor scores represent the estimates of the contribution of the various factors.
to the original observations. The factor scores matrix, \([F_Q]\), is developed by multiplying
the transpose of the scaled data set, \([W]\), by its factor loadings matrix:

\[
[F_Q] = [W]^T [A_Q]
\]

Q-mode scores give the composition of the factors in terms of the original variables.

Step 5 is done to determine the number of factors needed to recreate the original
data with a balance between the fewest factors and the maximum amount of similarity
accounted for. The determination of the number of factors needed is a non-trivial
decision. One method is to use the factors that have eigenvalues greater than a specific
value, one is used often in the literature. Another option is to sum the eigenvalues
cumulatively and calculate the percentage of variance accounted for by one, two or three
factors, and then choose how many factors are needed to give a sound representation of
the original data. Ultimately it depends on the judgment of the investigator, aided by trial
and error along with measures of the 'efficiency' of the factors in the form of sample
communalities. Sample communalities are obtained by finding the sum of the squares
within each row of the factor loadings matrix, \([A_Q]\). The total is a measure of the amount
of proportional similarity accounted for in each sample by the factors. If a sample
communality is not close to one, this indicates that the set of factors chosen are not
adequate for representation of that sample.

Once the number of factors has been specified, rotation of the factors in variable
space is usually needed to ease the interpretation (Step 6). This is usually done to
position the retained factor axes so that the loadings of the \(n\) objects onto the axes are
either maximized or minimized. Before rotation, the first factor tends to fall in the middle
of the object vectors, which in turn load high on that factor and low on other factors.

After rotation, loadings are more evenly distributed among the retained factors. The factor axes tend to bracket that part of variable-space occupied by the object vectors and, in doing so, become compositionally extreme end-members. The particular method used here is a varimax rotation. This is an iterative process in which two factor axes are rotated at a time. This rotation does not affect the relationship between samples and preserves the orthogonality of the factors.

Step 7 and 8 are done together. The communalities are calculated after rotation to determine if the number of factors specified was appropriate. If the number of factors was adequate to represent the data, the Q-mode Factor Analysis is over and interpretation of the factors begins. On the other hand, if the values of the communalities were too low, the number of factors specified was not adequate. In this case, the process reverts to step 3 (specifying the number of factors) and continues from there.

By using a factor analysis, the number of factors needed to describe the samples was reduced. The factor scores and factor loadings are then used to find predicted sample values. This is done using the equation stated at the beginning of the section;
\[ [Z] = [Aq] [Fq]' \]

\( Z \) = Predicted values \( (n \times p) \)

\( Fq \) = Factor Scores \( (p \times p) \)

\( Aq \) = Factor Loadings \( (n \times p) \)

\( d \) = Number of factors retained

\[ \begin{bmatrix}
  \text{sample}_1 \\
  \text{sample}_2 \\
  \text{sample}_3 \\
  \text{sample}_4 \\
  \text{sample}_5 \\
  \text{sample}_6 \\
  \vdots \\
  \vdots \\
  \vdots \\
  \text{sample}_n
\end{bmatrix}
= \begin{bmatrix}
  A_{11} & A_{12} & \cdots & A_{1p} \\
  A_{21} & \vdots & \ddots & \vdots \\
  \vdots & \vdots & \ddots & \vdots \\
  \vdots & \vdots & \vdots & \vdots \\
  A_{n1}
\end{bmatrix}
\begin{bmatrix}
  F_{11} & F_{12} & \cdots & \cdots & \cdots & F_{1p} \\
  F_{21} & \vdots & \ddots & \vdots & \vdots & \vdots \\
  F_{31} & \vdots & \ddots & \vdots & \vdots & \vdots \\
  \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
  F_{p1}
\end{bmatrix}^T
\]

In this study a Q-mode factor analysis was performed on the wave energy spectra to determine the relationships between sample bursts over time. The number of factors was decided by examining the amount of proportional similarity accounted for by each factor. This analysis was implemented and programmed for use with MATLAB (MathWorks, Inc.) (programs listed in appendix).
6. Results

Looking at the data for the fall/winter (October - April) seasons for 1992 - 1993 (92 season), 1993 - 1994 (93 season) and 1994 - 1995 (94 season) (Boon et al., 1990 - 1996), the annual mean wave energy spectra are very similar (Figure 5). There is a distinct bimodal trend seen across the years with peaks found in the 12-8 second and 6-4 second frequency ranges. The maximum peak for the 92 season and the 93 season was found in the 12-8 sec range while the 94 season maximum was in the 6-4 second range.

A Q-mode factor analysis was performed on the data from all three seasons. For all three seasons, four factors accounted for > 96% of the proportional similarity (Figure 6, Table 3). The “fit” of the factor model is also seen in the communalities. Table 4 shows the distribution of the communalities for all three years. Greater than 92 percent of the communalities are >0.9.

6.1 Two Factors

When only two factors were considered, two distinct modes were seen. This accounted for a little more than 85% of the proportional similarity. The first mode (A2) had a maximum peak with a period between 8 - 12 seconds. Energy percentage is also significant in the 12 - 16 second and 6 - 8 second bands (Figure 7a). The second mode
Figure 5: Mean Wave Energy Spectra for the 92 - 94 Seasons (October - April), Thimble Shoal.
Figure 6: Proportional Similarity accounted for by factors, 92 - 94 seasons.
Table 3

<table>
<thead>
<tr>
<th></th>
<th>1992</th>
<th></th>
<th>1993</th>
<th></th>
<th>1994</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E-val</td>
<td>Cum %</td>
<td>E-val</td>
<td>Cum %</td>
<td>E-val</td>
<td>Cum %</td>
</tr>
<tr>
<td>1012.3</td>
<td>70.99</td>
<td>993.12</td>
<td>73.95</td>
<td>921.58</td>
<td>71.94</td>
<td></td>
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<tr>
<td>208.04</td>
<td>85.58</td>
<td>204.81</td>
<td>89.2</td>
<td>197.06</td>
<td>87.33</td>
<td></td>
</tr>
<tr>
<td>88.21</td>
<td>91.76</td>
<td>58.77</td>
<td>93.57</td>
<td>80.06</td>
<td>93.58</td>
<td></td>
</tr>
<tr>
<td>68.41</td>
<td>96.56</td>
<td>49.26</td>
<td>97.24</td>
<td>42.5</td>
<td>96.89</td>
<td></td>
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<tr>
<td>42.92</td>
<td>99.57</td>
<td>33.7</td>
<td>99.75</td>
<td>31.41</td>
<td>99.35</td>
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<tr>
<td>5.5</td>
<td>99.96</td>
<td>2.46</td>
<td>99.93</td>
<td>7.58</td>
<td>99.94</td>
<td></td>
</tr>
<tr>
<td>0.61</td>
<td>100</td>
<td>0.89</td>
<td>100</td>
<td>0.81</td>
<td>100</td>
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</tbody>
</table>

Eigenvalues (E-val) and cumulative percent of similarity (Cum%) accounted for during the 92 - 94 seasons.
Table 4

<table>
<thead>
<tr>
<th></th>
<th>1992 Count</th>
<th>% of Total</th>
<th>1993 Count</th>
<th>% of Total</th>
<th>1994 Count</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;.7</td>
<td>4</td>
<td>0.28</td>
<td>6</td>
<td>0.45</td>
<td>10</td>
<td>0.78</td>
</tr>
<tr>
<td>.7-.8</td>
<td>27</td>
<td>1.9</td>
<td>11</td>
<td>0.82</td>
<td>14</td>
<td>1.09</td>
</tr>
<tr>
<td>.8-.9</td>
<td>62</td>
<td>4.35</td>
<td>47</td>
<td>3.5</td>
<td>71</td>
<td>5.54</td>
</tr>
<tr>
<td>&gt;.9</td>
<td>1331</td>
<td>93.47</td>
<td>1279</td>
<td>95.23</td>
<td>1186</td>
<td>92.58</td>
</tr>
<tr>
<td>Total</td>
<td>1424</td>
<td>100</td>
<td>1343</td>
<td>100</td>
<td>1281</td>
<td>100</td>
</tr>
</tbody>
</table>

Distribution of communalities for the 92 - 94 seasons.
Figure 7: Two Factor Modes from factor analysis with two factors used.

a: Factor A2

b: Factor B2
(B2) peaked with a period of 4 - 6 seconds. With significant energy percentages in the 6 - 8 second and < 4 second bands as well (Figure 7b).

6.2 Four Factors

Factor A4 (Figure 8a) has a major peak in the 8 - 12 second band as did A2 (Figure 7a). The difference between these two is a low percent of energy in the 12 - 16 second band in A4 compared to that in A2. There is also a larger percentage in band 4 (8 - 12 second) in A4 as compared to A2. Factor B4 (Figure 8b) has a major peak in the 4 - 6 second range with significant energy percentages in the 5 and 7 bands (6 - 8 seconds and < 4 seconds respectively). This is a higher percentage and lower in the others compared to B2 (Figure 7b). Factor C4 (Figure 8c) has a bimodal distribution of the wave energy. It has peaks in the < 4 second and 8 - 12 second bands with the higher frequency peak being the largest. The final factor is D4 (Figure 8d). This factor accounts for the energy found in the 12 - 16 second interval as well as a portion of that found in the 8 - 12 second.

6.3 Dynamic Environmental Conditions

Factor A4 occurred in its purest form on February 13, 1993 at 1200 hrs. The environmental conditions associated with this mode are expressed in the Principal Wave Direction. The waves are directed to the northwest (285 °). This wave direction is consistent whenever there is a high loading on mode A (Figure 9a). Wave height fluctuates, but rarely exceeds 0.4 meters. Factor B4 was seen at a maximum on March 3,
1993 at 0600 hrs. During times of high dependence on mode B4 there is still a trend in waves to the northwest (Figure 9b). However the bursts where wave height increases, the wave direction is dominated by southward moving waves (175 - 180°).

Factor C4 reached a maximum on January 31, 1993 at 0900 hrs. The principal wave direction was seen to be almost entirely to the west-northwest (275 - 280°) during times of high dominance on mode C4 (Figure 9c). It showed a strong correspondence with an increase in wave height and a shift in wave direction to a south-southeast direction. Factor D4 found a maximum on February 4, 1993, 0300 hrs. Dominance on mode D4 was not strong. The maximum loading found was less than 0.5 (Figure 9d), indicating the presence of other modes at the same time. The affects of the unaccounted for factors are also caught up in mode D4. This may have some affect on the loadings on factor D4 and therefore not allow for the discerning of the environmental conditions of the factor.
Figure 8: Four Factor Modes from factor analysis with four factors used.

7a: Factor A4

7b: Factor B4
8c: Factor C4

8d: Factor D4
Figure 9a: 100 bursts with the maximum loadings on mode A4. A comparison between principal wave direction and wave height. As well as a wave direction and current direction with relation to wave height. (Polar plot has wave height on the radius axis and direction in degrees on the theta axis)
Figure 9b: 100 bursts with the maximum loadings on mode B4. A comparison between principal wave direction and wave height. As well as a wave direction and current direction with relation to wave height. (Polar plot has wave height on the radius axis and direction in degrees on the theta axis)
Top 100 Bursts that Load on Mode B4

- Loadings B4
- Hmo
- PW_D
- Mean PW_D

Waves
- Currents
Figure 9c: 100 bursts with the maximum loadings on mode C4. A comparison between principal wave direction and wave height. As well as a wave direction and current direction with relation to wave height. (Polar plot has wave height on the radius axis and direction in degrees on the theta axis)
Top 100 Bursts that Load on Mode C4

Loadings (0-1), Hm0 (m)

- 350
- 325
- 300
- 275
- 250
- 225
- 200
- 175
- 150
- 125
- 100
- 75
- 50
- 25
- 0

Wavedir

Hm0

Loadings

Wavedir

PWD MEAN

Waves

Currents
Figure 9d: 100 bursts with the maximum loadings on mode D4. A comparison between principal wave direction and wave height. As well as a wave direction and current direction with relation to wave height. (Polar plot has wave height on the radius axis and direction in degrees on the theta axis)
Top 100 Bursts that Load onto Mode D4

- loadings
- hmo
- PWD
- PWD Mean

Waves

Currents
6.4 **Time Series**

The time series for the 1992 season runs from 1330 October 23, 1992 - 1000 April 20, 1993. It contains burst-averaged wave data from every three hours, excluding a few hours during monthly data retrieval. The entire data base contains 1426 bursts, allowing for the identification of patterns and events within the data.

**6.4.1 Tidal Oscillations**

A phenomenon that is seen throughout the time series is a distinct shift in the wave energy spectra at the semi-diurnal tidal period. Figure 10 shows representative data where this modulation can be seen clearly. There is a shift from a prominent peak in the 12 - 8 second band, to a wider distribution in the higher frequencies, shown by a shorter peak in the 6 - 4 second band. The loadings on the factors for this season also show this modulation, with a clear shift from mode A4 to mode B4 in response to the semi-diurnal tide found at Thimble Shoal. The shift from low frequency to high frequency waves is found on the flood tide and occurs regularly.

**6.4.2 Storm Effects on Currents**

Storms passing over and near the Chesapeake Bay can have wide ranging affects on the hydrodynamics of the estuary. These exceptional conditions involve a variety of forcing mechanisms and rapid changes in the flow regime. Changes in the hydrodynamic
Figure 10: November 9, 1992 - November 14, 1992 is representative of the tidal oscillations within the wave energy spectra. Each contour represents a percentage of energy and the inner portions of the enclosed contours (the darker areas) corresponds to higher spectral energy percentages.
flow of the system could either enhance or lessen the regular effect of the tidal modulation. One example of this effect of a strong interaction between storm induced currents and tidal currents can be seen from February 1 - 3, 1993. During this time there are very high winds (sustained > 15 knots) and the regular tidal oscillation was affected. The system became flood dominated with tidal depths that normally range between 6 and 8 meters staying well above 7.5 meters (Figure 11). During this time the periods of the waves were kept very low (around 5 and 6 seconds) as would be seen during a flood tide (Figure 12), due to the wave-current interaction.

This condition was sustained for 45 hours during which the hydrodynamic system of the bay responded to the passing of the storm. After the storm had passed and the winds had subsided, the flow regime of the bay could return to normal. This allowed the tidal cycle to be re-established and a strong seaward flow to occur. During this time a regular tidal oscillation can be seen; however it is ebb-dominated. This allowed for the spectral peak to occur in the very low frequency band (16 - 12 second waves) for a little over two days as the bay rebounded from the passing of the storm. Only by the 6th of February, 1993 (Time index : 842) had the system returned to normal.

6.5 Meteorological Forced Response Patterns

During the winter season, many storms pass through the Chesapeake Bay region. These storms produce an immediate response in the wave field, which will then slowly return to pre-storm conditions. This pattern is seen with each passing storm. When storms are closely spaced, the wave field may not return all the way to pre-storm
Figure 11: Tide and peak period from February 1-13, 1993. Spectral peak response to large extratropical storm.
Thimble Shoals Wave Station: Depth and Peak Wave Period

Graph showing depth and period over time.
Figure 12: Contour plot of wave energy spectra for February 1 - 6, 1993.
conditions before being forced by another storm. This causes a jump in the cycle, skipping past the between-storm conditions, directly into storm conditions.

6.5.1 Calm Conditions

During times of relative calm in the lower Chesapeake Bay, wave heights are low and the system is dominated by ocean swell. From March 20, 1993 1500 - March 22, 1993 0900 the lower Chesapeake Bay experienced an extended period of low winds (Table 5). For the entire duration of this period, the system was dominated by mode A4 (Figure 8a, and 13). This dominance by mode A4 is seen throughout the time-series between wind events. The duration of these calm periods is usually much shorter than is represented by the March 20-23 episode.

6.5.2 Large Storm Events

Each year there are usually 3 - 6 large winter storm events in the lower Chesapeake Bay. These are identified as long duration events with sustained high velocity winds and larger than normal wave heights. During the 1992 - 1993 winter season there were three notable storms. Two of the storms were very similar, consisting of an extratropical storm moving over the region. These storms initially produced strong winds out of the northeast, followed by reduced winds from the north. They shifted to the northwest and finally the west-southwest.

On February 11, 1993 one of these low pressure systems entered the region. The event lasted just over two days and produced wave heights of over 1 meter for 15 hours.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Wind Direction (deg)</th>
<th>Wind Speed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/20/93</td>
<td>1600</td>
<td>60</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>2200</td>
<td>90</td>
<td>4</td>
</tr>
<tr>
<td>3/21/93</td>
<td>400</td>
<td>--------</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>--------</td>
<td>0</td>
</tr>
<tr>
<td></td>
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<td>30</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2200</td>
<td>140</td>
<td>4</td>
</tr>
<tr>
<td>3/22/93</td>
<td>400</td>
<td>--------</td>
<td>0</td>
</tr>
<tr>
<td></td>
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<td>110</td>
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</tr>
</tbody>
</table>
Figure 13: Loadings on the system from March 20 - 23, 1993.
Table 6

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Wind Direction (deg)</th>
<th>Wind Speed (knots)</th>
<th>Date</th>
<th>Time</th>
<th>Wind Direction (deg)</th>
<th>Wind Speed (knots)</th>
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<tbody>
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<td>2/26/93</td>
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<td>8</td>
</tr>
<tr>
<td></td>
<td>1600</td>
<td>40</td>
<td>12</td>
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<td>1600</td>
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</table>

Primary winds during the storm were from the northeast followed by reduced winds and a change in direction (counterclockwise) at 1600 hrs on the 12th of February (Table 6). The other storm began on the 26th of February and also had sustained wave heights of greater than 1 meter for 15 hours. The winds during this storm followed a similar pattern as the February 11th storm, however winds were sustained out of the northeast, and after 20 hours shifted to the north where they remained for the next 20 hours (Table 6). Only after that did they finally move around to the northwest. The most intense winds during this storm were from the north, rather than the northeast.

The response of the wave field for each of these storms showed a similar pattern. Prior to the event, the calm mode (A4) dominated the energy of the system (Figure 14). With the onset of the storm, there was a pronounced jump to dominance in mode C4 before any affect was seen in the wave height or in the dominance of the calm mode (A4). After this initial jump to C4, C4 remained prominent and the dominance on A4 decreased with the growth in wave height. There is then a distinct shift from C4 to B4. In the shorter duration storm of February 11, 1993, the response of the system was to return to the calm state (A4). The 2/26/93 storm showed the same pattern, with a slight variation on the return due to the duration of the storm.

For the February 26, 1993 storm, the shift from calm (A4) to C4 and B4 was the same as the 2/11/93 storm. The difference came with a switch back to a relatively steady dependence on A4 with an increase on D4 before returning back to calm (Figure 15). The time when D4 was significant lasted for a few days.
Figure 14: Loadings on modes for February 11, 1993 storm.
Figure 15: Loadings on modes for the February 26, 1993 storm.
Another large storm passed through the region just a few weeks later. This was a much more severe storm with heavy snowfalls accompanying the extreme low pressure associated with the storm. The winds in this case changed direction in a clockwise rotation (east, south, west then north) (Table 7). The basic response pattern is seen, with slight variation. The initial appearance of mode C4 accompanied soon after with a quick decrease in C4 remains the same (Figure 16). This is followed by a switch from A4 to B4 as well. This storm becomes different in the pattern around March 13, 1300 hours. At that point the wind shifts suddenly from east to southwest and increases to 24 knots. The dominance on C4 continues for hours, finally decreasing once the wind shifts back to the north and decreases in speed, around March 15, 1000 hours. This storm was very strong and produced some interesting responses in the wave field.

Another interesting thing about the March 12th storm is that by examining the significant wave heights for the storm period, it is remarkably similar to that of a storm that followed directly on its heels (Figure 17). The storm of March 17, 1993 also had winds changing from northwest to northeast in a clockwise direction. The storm had sustained winds over 15 knots for 30 hours, half as long as those in the previous storm. This storm affected the system part way through the cycle of the last storm, therefore the dominant mode at the outset was B4 rather than A4. There was a sharp jump to C4 and then to B4 as is usual. After the system had passed, there was then a gradual shift to A4.
Table 7

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Wind Direction (deg)</th>
<th>Wind Speed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/12/93</td>
<td>2200</td>
<td>90</td>
<td>9</td>
</tr>
<tr>
<td>3/13/93</td>
<td>400</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>140</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>1600</td>
<td>200</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>2200</td>
<td>270</td>
<td>28</td>
</tr>
<tr>
<td>3/14/93</td>
<td>400</td>
<td>260</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>260</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>1600</td>
<td>280</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>2200</td>
<td>330</td>
<td>15</td>
</tr>
<tr>
<td>3/15/93</td>
<td>400</td>
<td>320</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>350</td>
<td>10</td>
</tr>
</tbody>
</table>

Meteorological data for March 12, 1993 storm.
Figure 16: Loadings on modes for the March 12, 1993 storm.
Figure 17: Time History of $H_{mo}$ for March 12 and 17, 1993 storms.
Hmo Time Histories for 3/12 and 3/17 Storms
6.5.3 Small Storm Events

Between times of large storm events are many small storms and periods of calm. I have looked at the cycle for large storm events with high winds and waves sustained over long amounts of time, and it appears to occur in the small events as well. This can be seen in a storm which began late on New Year's Eve 1992. The wind changed from a constant southwest wind to a steady northeasterly wind of an average speed of 10 knots (Table 8). With an increase in wind velocity at 1000 hours on January 1, 1993, the dominant mode shifted from A4 to C4 which soon subsided into B4 (Figure 18). There is a small lull in the wind before it picked back up again causing a short switch back to C4 and then back to B4. Mode B4 slowly decreases in dependence until the calm mode (A4) becomes dominant again. Another short duration wind even occurred from November 15 to late on the November 16, 1992. During this event there is a clockwise shift of the wind from west to northeast and winds around 12 knots. The same pattern I have seen in all the other events was replayed here (Figure 19).
Table 8

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Wind Direction (deg)</th>
<th>Wind Speed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/31/92</td>
<td>2200</td>
<td>250</td>
<td>9</td>
</tr>
<tr>
<td>1/1/93</td>
<td>400</td>
<td>280</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>30</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>1600</td>
<td>30</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>2200</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>1/2/93</td>
<td>400</td>
<td>30</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1600</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>2200</td>
<td>50</td>
<td>6</td>
</tr>
<tr>
<td>1/3/93</td>
<td>400</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 18: Loadings on modes for the December 31, 1992 storm.
Figure 19: Loadings on modes for November 14, 1992 storm.
Comm

Hours from 11/15/92 0430
7. Discussion

The mean wave energy spectra at the Thimble Shoal monitoring station for the three seasons examined are very similar (Figure 5). This represents a well-organized system with very little change over the years. The bimodal trend is also seen throughout the three seasons and in all six seasons of the monitoring from the Thimble Shoal Region of lower Chesapeake Bay (Boon et al., 1990-96).

The Q-mode factor analysis provided a good means of examining the wave energy spectra of lower Chesapeake Bay. For all three seasons examined, greater than 92 percent of the communalities were > 0.9. This indicates the factor model is a good representation of the actual data. The minimal change over the years indicates a well-organized wave climate for the lower Chesapeake Bay. This suggests that any of the years can be considered representative of the long term wave climate. This allowed for the 1992 season to be extensively evaluated in terms of response modes and considered representative of the system as a whole.

7.1 Factor Models

The consideration of only two factors provided a simplified view of the wave energy climate at the site (Figure 7). The two modes indicate a “calm” spectra (A2) and a
“storm” spectra (B2). The bimodal tendency of the wave climate of this region is expressed by these two modes. Factor A2 describes the ocean swell, input from the inner-shelf and Factor B2 represents the waves generated by local wind events. The model composed of four modes increases the accuracy of the factor model, at the same time increasing the complexity. The two factor model accounted for 85 percent of the proportional similarity while an increase to the use of four modes caused an increase to 96 percent accounted for. These four are associated with four stages of systematic variation within the wave field of lower Chesapeake Bay.

7.2 Dynamic Environmental Conditions

Modes A4 through D4 can be related to environmental conditions and dynamic events in the lower Chesapeake Bay. Just looking at the spectra associated with the four factors, those with major peaks in the low frequency ranges account for the ocean swell and those with high frequency the locally generated waves. However, it is rare to find these response modes in a pure form. The system as a whole is very dynamic and the individual spectra may be found to be similar to end members at times of differing environmental conditions. Normally the wave field at a particular time can be defined as a combination of two or more of these response modes, with one being the dominant factor. Much of this depends on the stage of the tidal cycle.
**7.3 Tidal Modulation**

There is a modulation of the wave energy spectra with the tide. A shift from lower frequencies to higher frequencies is seen on the flood tide. There is always a modulation present over time with response to the semi-diurnal tidal period, however it is not always the dominant feature seen in the time series. There are times when this shift is interrupted; the environmental conditions causing this are widely varied over time. During times of high loadings on factor A4, the tidal modulation of the dominant energy peak is very clearly represented by a shift from 12 - 8 second waves to the 6 - 4 second waves. As the loading on A4 decreases, so does the probability of seeing the tidal oscillation in the spectra.

Factor A4 is dominated by the longer period waves from the ocean, rather than shorter period waves that have been locally generated. This seems to indicate that this modulation is not a local interaction between the waves and tides. The interaction appears to occur away from the Thimble Shoal site. The cause of this phenomenon is not a Doppler shift, and is not clearly understood at this time. The Doppler shift is a shift to higher frequency due to a movement of the source toward the observation point. This could be happening with an apparent movement of the source due to the affect of the current. The tidal current is found in a northwest-southeast direction, not allowing for this phenomena to be described by a Doppler shift. Nichols (1994) showed how the tributaries of Chesapeake Bay go through a cycle induced by meteorological events. The steps are: 1) initial response, 2) shock, 3) rebound and 4) recovery. This cycle is seen in
the current regime of Chesapeake Bay with a switch to net landward flow during the initial response. This is closely followed by a net seaward flow during the second step (shock). The hydrodynamics then slowly return to pre-storm conditions by oscillating between net landward and seaward flows. During times of net landward flow, the effect on the tidal modulation is that the dominant mode is that found during flood tides (B4). That is, the majority of the waves have periods between 5 and 6 seconds. As the forcing shifts flow to a net seaward flow, a shift to D4 is seen (Figure 11). These are the very low frequency ocean swell. As the system reaches the pre-storm conditions, the dominant mode returns to A4. This is also ocean swell, but not at as low frequency as found during the dominance of D4.

7.4 Meteorological Forced Patterns

The wave field of the lower Chesapeake Bay responds to forcings from the meteorological conditions found locally. The initial response time is short, with the wave field returning to normal in a few days if not interrupted by other meteorological events. During the fall and winter seasons, the Middle Atlantic Bight experiences a few different types of storm events. These include low pressure systems moving over the region in a northeasterly direction, larger frontal systems moving through the system at a slower rate and those forcings that are non-local events over the ocean. This interaction between the meteorological events and the Bay is represented by the response modes of the wave energy spectra. As these events occur, a pattern is seen in the order that different modes become dominant. By examining times of varying forcings, these patterns are discernible.
During times of relative calm in lower Chesapeake Bay, wave heights are low and the system is dominated by ocean swell. During these times, the dominant wave energy is found in mode A4. These times are interrupted by high energy events produced by winter storms. These events can be both short and long in duration and sometimes are interrupted by the next wind event, not allowing the system to recover from the first event before moving on to the next.

By tracing the movement in factor space over the duration of a storm, the same pattern is seen for each successive storm. During the long duration storms, the pattern is complicated by shifts back and forth between modes due to wind shifts. The storm of February 11, 1993 is a long duration wind event lasting over 2 1/2 days. The time trajectory pattern of this storm shows a movement from the calm mode (A4) through the bimodal mode (C4) to the high energy storm mode (B4) (Figure 20). There is a short movement back to the calm mode as winds shift with the tide, and then back to the storm mode as the winds and tides oppose each other. As the winds decrease and the storm subsides, there is a gradual movement back to the pre-storm conditions of the calm mode. This long duration storm event is characteristic of larger storms that pass through the area.

Shorter duration storms, those lasting approximately one day, show the same patterns though shortened. The storm that began New Year’s Eve 1992 is a good example of a short duration storm. The storm time trajectory plot shows a change from calm (A4) to bimodal (C4) and on into the storm mode (B4) (Figure 21). It then shows a movement
back to pre-storm conditions through the low-energy bimodal mode. During the
dominance in the storm mode (B4), there was a short switch back to low-energy bimodal
Figure 20: Time Trajectory Plot of February 11, 1993 Storm (numbers indicate hours from beginning of storm).
Figure 21: Time Trajectory Plot of December 31, 1992 Storm (numbers indicate hours from start of storm).
Systematic Variation in Factor Loadings

New Year's Eve Storm 1992
and then back to the storm mode. This was due to a small lull in the wind that then
reverted to the storm mode (B4) and finally to pre-storm conditions (A4). These two
storms are representative of local storm affects on the wave climate of lower Chesapeake
Bay.

The storm events seen during the 92-93 season were typical of the region. The
storms all showed a pronounced shift away from mode A4 with the onset of a local
storm. During the height of the storm, the dominant factor was B4, the high energy, high
frequency mode. Most of the time this mode was reached by way of a dominance in the
low energy, bimodal C4 (Figure 22). This systematic variation during local wind events
can be see in all storms, regardless of size or duration.

This systematic variation is consistent with the growth in the wave energy spectra
expected with the onset of a storm. The distinguishing characteristic of this system is the
same pattern in seen regardless of the type of storm. There is always an input of energy
from the ocean as low frequency waves. This effect is augmented by input from locally
generated storm waves. During storm events, there is still input from the inner-shelf, but
the larger percent of the total energy switches to the higher frequency waves.
Figure 22: Schematic of Systematic Variation of Dominant Response Modes.
Systematic Variation in Factor Loadings
8. Conclusions

The spectral modes presented in this thesis have proven to be useful in the further interpretation of the wave climate of the lower Chesapeake Bay. The results show that only four spectral modes are needed to adequately represent the system. The four modes represent: 1) a ‘calm’ spectrum dominated by swell from the inner-shelf (A4); 2) a low-energy bimodal spectrum usually found during transitions (C4); 3) a high frequency, high energy spectrum associated with storm events (B4); 4) A low energy, very low frequency dominated spectrum (D4). Although only one year of spectral data was used in this study, the stable statistic of the average spectrum for this location indicates it is representative of the system. The systematic variation of the loadings on the modes was found to produce the same pattern regardless of the size or duration of the wind event.

The response modes of the wave field of lower Chesapeake Bay are easily reproduced in the factors of the Q-mode Factor Analysis. The factor model was useful in reducing the complexity of the highly dimensional wave data. This has allowed for a better understanding of the response of the wave field to meteorological forcings.

There is always an input of energy to the lower Chesapeake Bay from the inner-shelf by way of long period waves. Energy that is present during storms is
associated with high frequency local waves. The greater amount of energy during storm
events is from these high frequency waves. However, the effect on the bottom due to
waves is much greater from the long period waves than the short period waves. The short
period waves are going to affect the ships in the region. Knowledge of how the wave field
will react to a storm event allows for a greater understanding of the energy input into the
system by locally and non-locally produced waves.
% Q-Mode Factor Analysis Program
% adapted by K.L. Farnsworth from a program by J.D. Boon
% This program performs a Q-mode factor analysis on a specified data matrix

% Required Input:
% data matrix file
% (must have only the data values, no labels or headers)

% Output:
% factor loadings matrix flXXXXXX.out
% factor scores matrix fsXXXXXX.out
% Row normalized data matrix WXXXXXXX.out
% Eigenvalues matrix evXXXXXX.out
% Row sum of squares matrix rssXXXXX.out

%**********Variable Dictionary**********
% X : Original Data Matrix of size nxm
% n : number of rows (samples) in X
% m : number of columns (variables) in X
% centroid : means of the variables
% rowss : row sum of squares of X
% W : row normalized data matrix
% H : association matrix
% FS : factor scores
% D : diagonal matrix of Eigenvalues
% E : eigenvalues
% FL : factor loadings

%**********PROGRAM BODY**********

echo on
%Data Input
%  At prompt follow these steps
%  load <datafile.extension>
%  set X=<datafile>; NOTE: no extension
%  clear datafile
%  return

keyboard
echo off

% characteristics of data matrix
\[ [n,m] = \text{size}(X) \]
\[
\text{centroid} = \text{mean}(X) \\
\text{rowss} = \text{diag}(X^\times X') ;
\]

\%
Normalizacion de data matrix

\[
W = \text{inv}(\text{sqrt(diag(rowss)))) \times X ; \\
clear X ;
\]

\%
Calculation of association matrix using the minor product moment

\[
H = W^\times W ; \\
\%
Calculation of eigenvectors and eigenvalues

\[ [FS, D, FS] = \text{svd}(H, 0) ; \\
factor \_ scores = FS \%
output of factor scores
\%
Eigenvalues and percent proportional similarity represented by each value

\[ E = \text{diag}(D) ; \\
\text{Eigenvalues} = [E \times \text{cumsum}(E / \text{sum}(E))] \\
FL = W^\times FS ; \\
factor \_ loadings = FL
\]

echo on

\%
To save needed matrices

\%
At prompt follow these steps

\%
save <flXXX.out> factor \_ loadings -ascii \\
save <fsXXX.out> factor \_ scores -ascii \\
save <wXXX.out> W -ascii \\
save <evXXX.out> Eigenvalues -ascii \\
save <rssXXX.out> rowss -ascii \\
return

keyboard

\%
End of Qfactor Program

echo off
% Pcomm - Program by K.L. Farnsworth

echo on

% This procedure allows for the determination of the number of factors needed for the
% rotation.
% The calculation of communalities is also done in this procedure.
% Required Input:
% factor loadings matrix from qfactor.m flXXXXXXX.out
% eigenvalues matrix from qfactor.m evXXXXXXX.out

% Output:
% communalities matrix commXXXX.out
% short loadings matrix sldXXXXX.out

echo off

%*************** Variable Dictionary ***************

% factor_loadings : matrix containing original factor loadings matrix
% eigenvalues    : matrix of eigenvalues from qfactor.m
% p             : number of factors chosen by operator
% lding         : matrix of loadings only p columns wide
% Communalities : the calculated communalities of each burst

% ************ Program Body ************

echo on

% Input of factor loadings matrix
% At prompt follow these steps
% load <flXXXXXXX.out>
% set factor_loadings=<flXXXXXXX>; NOTE: no extension
% load <evXXXXXXX.out>
% set eigenvalues=<evXXXXXXX> to view matrix,no ;
% clear infile
% return

echo off

keyboard

% Decision and input of number of factors

eigenvalues
p = input('Enter the number of factors to keep : ');  
lding = factor_loadings(:,1:p); 

% Calculation of Communalities 
Communalities = diag(lding*lding') 

echo on 

% Save Needed variables 
% At prompt follow these steps 
% save <commXXXX.out> Communalities -ascii 
% save <sldXX.out> lding -ascii 
% return 

echo off 
keyboard 

% End of PComm program
% Rotate - Program by K.L. Farnsworth

echo on

% This program will do the final rotation of the factors. It takes the short
% loadings matrix (n x p) from the PComm program and applies
% a varimax rotation function to it.

% Required Input:
% Short loadings matrix from pcomm.m sldXXXXX.out

% Output:
% rotated loadings matrix rflXXXXX.out
% rotated scores matrix rfsXXXXX.out

echo off

% ************ Variable Dictionary ************
% factor_loadings : short loadings matrix from pcomm.m
% W                : association matrix from qfactor.m
% rotated_loadings : the rotated loadings matrix for output
% Fq               : rotated factor scores matrix
% rotated_scores   : rotated factor scores matrix for output

% ************ Program Body ************

% Input of short loadings matrix
% At prompt follow these steps
% load <sldXXX.out>
% set factor_loadings=<sldXXX>; NOTE: no extension
% load <WXXXXXXX.out>
% set W=WXXXXXXX;
% clear infile
% return

echo off

keyboard

varimax;

rotated_loadings=lding % rotated factor loadings
Fq=inv(W'*W)*W'*rotated_loadings %rotated factor scores
rotated_scores = Fq

echo on
% Saving needed variables
% At prompt follow these steps
% save rflXXXXX.out rotated_loadings -ascii
% save rfsXXXXX.out rotated_scores -ascii
% return

echo off
keyboard

% End of Rotate program
% Varimax - This procedure follows the algorithm given in Harman (1967).
% It is a subprocedure of the rotate.m program.
% The variable factor_loadings must contain the short loadings matrix from the
% pcomm.m program before running this procedure.

%*****************************************************************************
% Procedure Body*****************************************************************************

lding=factor_loadings;
b=lding;
[mn,nf]=size(lding)
pause
hjsq=diag(lding*lding');  % communalities
communalities=hjsq
hj=sqrt(hjsq);
pause
bh=lding./(hj*ones(1,nf));
v0=mn*sum(sum(bh.^4))-sum(sum(bh.^2).^2);
for it=1:10;
for i=1:nf-1
    jl=i+1;
    for j=jl:nf
        xj=lding(:,i)/hj;
        yj=lding(:,j)/hj;
        uj=xj.*xj-yj.*yj;
        vj=2*xj.*yj;
        A=sum(uj);
        B=sum(vj);
        C=uj'*uj-vj'*vj;
        D=2*uj'*vj;
        num=D-2*A*B/mn;
        den=C-(A^2-B^2)/mn;
        tan4p=num/den;
        phi=atan2(num,den)/4;
        angle=phi*180/pi;
        if abs(phi)>.00001;
            xj=cos(phi)*xj+sin(phi)*yj;
            yj=-sin(phi)*xj+cos(phi)*yj;
            bj1=xj.*hj;
            bj2=yj.*hj;
            b(:,i)=bj1;
            b(:,j)=bj2;
            lding(:,i)=b(:,i);
            lding(:,j)=b(:,j);
        end
    end
end

end
end
end;
lding=b;
v=mn*sum(sum(bh.^4))-sum(sum(bh.^2).^2);
if abs(v-v0)>0.0001; break; else v0=v; end;
end;

% end of Varimax procedure
10. Literature Cited

Bartel, V. and Dr. -Ing, “Height Distribution of Estuarine Waves”, Coastal Engineering, 1982.


Cronin, W.B., 1971, “Volumetric, areal and tidal statistics of the Chesapeake Bay estuary and its tributaries.”, Chesapeake Bay Institute, Special Report No.20, Solomans MD, 135p.


11. **VITA**

Born in Vallejo, California, November 8, 1970. Graduated from King City Secondary School, King City, Ontario, Canada in 1989. Earned a B.A. in Geography and Computer Science from DePauw University, Greencastle, Indiana in 1993. Entered the graduate program at the College of William and Mary, School of Marine Science in 1994.