Wave Data Analysis in the Delaware Bay

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***Abstract*—The knowledge of wave statistics in the Delaware Bay impacts not only large container ships bound for the ports of Philadelphia and Wilmington, but also recreational boaters, fishermen, beach-goers, near-shore planning, emergency response, and more. Wave characteristics can be measured by a large number of technologies such as acoustic transducers, pressure sensor arrays, and shore-based radar, however wave buoys often present the most straightforward measurement system.**

In an effort to quantify the wave conditions in the Delaware Bay, the Delaware Department of Natural Resources and Environmental Control (DNREC) has deployed two TRIAXYS directional wave buoys, one in the upper and one in the lower reaches of the Delaware Bay, over a time period spanning from June 2007 through February 2012. These buoys recorded directional wave characteristics on an hourly basis and, when combined with nearby Delaware Environmental Observing System (DEOS) meteorological station data, resulted in a variety of data products.

This paper presents an overview of the buoy deployment project and a discussion of the results obtained by a statistical analysis performed on the available data over the observational time periods.

I. Introduction

The Delaware Department of Natural Resources and Environmental Control (DNREC) has deployed two TRIAXYS Directional Waverider buoys in the Delaware Bay to better understand the wave climate in the Bay. The northern buoy, deployed near Bowers Beach, and the southern buoy, near the Mispillion River, collected hourly measurements of wave properties such as significant wave height, dominant period, and mean wave direction for a period of roughly five years and three years respectively. This information is critical for a wide variety of activities outside of traditional boating and shipping concerns, such as beach renourishment programs, emergency preparedness and management, and even near-shore recreational activities.

The intent of this project was to both quantify the existing wave climate in the Delaware Bay and to determine any statistical relationships between the data from the two Directional Wave Buoys and any nearby existing high-quality environmental monitoring equipment in the area, such as the Delaware Environmental Observing System (DEOS) meteorological stations [1]. While extreme wave events were not expected, as in a similar study in the lower Chesapeake Bay [2], several waves with heights over 2m were recorded.

Although there are many competing technologies, wave statistics are often calculated from the measured accelerations of roll, pitch, and heave of a buoy [3], [4]. The time-series data is often transformed into the frequency domain, using the Fourier transform, and a statistical analysis performed after filtering the data to minimize low frequency noise [5]. Waves are influenced by a tremendous number of local effects such as wind stress and shear (including sea-breeze effects), fetch, surface and subsurface water currents, seiches, nearby marine traffic, water quality and pollutants, storm surge, and bathymetry. Distant influences such as gravitational disturbances like lunar-induced tides and long-distance storm effects can also impact waves. While the aim of this project was not to design and construct a new physical model of waves in the Delaware Bay, we attempted to determine the existence of any correlations between existing meteorological observational data and wave statistics calculated from in-situ observation platforms in the Bay.

This paper describes briefly the wave climate in the Delaware Bay as measured by sea-based observation buoys, and the correlations between wave conditions and nearby land-based automated observational stations used to measure current meteorological conditions during the buoy deployment period. A simple statistical model of wave heights in the Bay is presented and discussed along with Pearson correlational results.

II. Data Sources and Availability

The data analysis performed for this study included observations from two DNREC buoys and two land-based meteorological stations. Quality controlled data from DEOS was collected and stored in a local SQL database for further processing. A nearby offshore 3m (9.8ft) discus buoy operated by the National Data Buoy Center (NDBC), #44009, was initially considered for inclusion in this study, but upon further investigation was ruled out due to the lack of quality controlled wave direction historical wave information within the standard meteorological report.

Two TRIAXYS Directional Wave Buoys were deployed by DNREC to monitor wave conditions in the Delaware Bay (Figure 2). These 1.1m (3.6ft) diameter solar-powered buoys record hourly wave statistics including the number of zero-crossings, average height, average period, maximum

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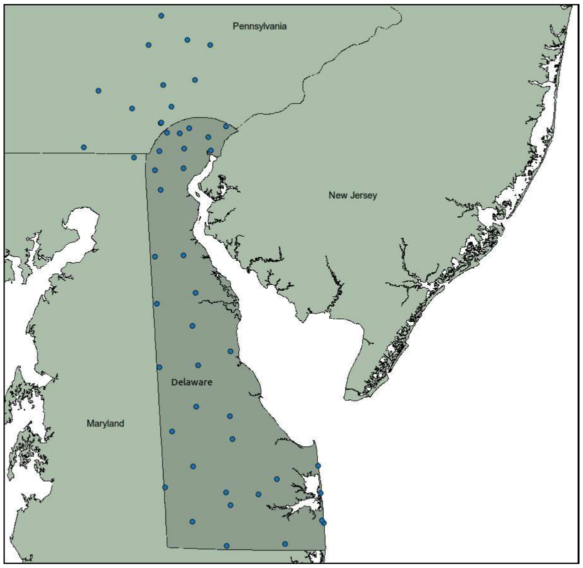

Fig. 1. Relative locations of DEOS stations in Delaware, Maryland, and Pennsylvania.

height, significant wave height, significant period, peak period, average direction, and the wave spreading range. A single-point mooring scheme was used to maintain the position of the buoy within the Bay.

Fig. 2. TRIAXYS Directional Wave Rider buoy with integrated solar panels, charge controller, and navigational light.

DEOS maintains a dense state-wide network of over 50 autonomous meteorological observing stations (Figure 1). Two stations near the buoy locations, DSJR at Kitts Hummock, and DRHB at Rehoboth Beach, were chosen for inclusion in the analysis (Figure 3).

Wind and wave directions are defined as the true direction from which the wind or wave originates (increasing clockwise from true north).

The solar-powered DEOS stations located throughout the Delmarva region automatically report standard meteorological information every five minutes via cellular modems. This data is transmitted to the data servers at the University of Delaware in Newark, DE for quality control, archiving, dissemination, and further processing to generate derived data products. These stations typically record rainfall, air temperature, relative humidity, barometric pressure, solar radiation, wind speed, wind gust, and wind direction. Specific details of the stations used in this study are presented here.

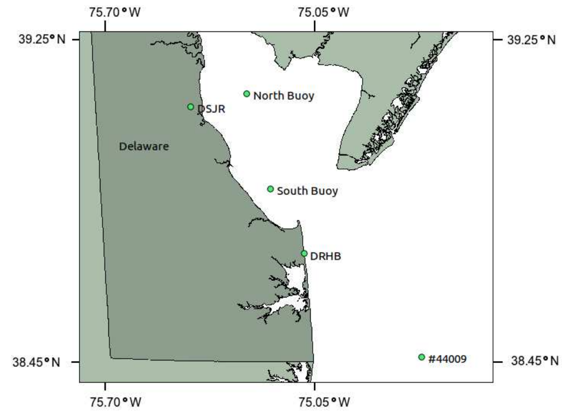

Fig. 3. Locations of buoys and land-based data sources used for analysis.

A. North Buoy Data Sources

Data sources for analysis performed on the northern observations include data reported by the northern DNREC buoy and the DNREC/DEOS Kitts Hummock site situated at the boardwalk in the St. Jones Reserve.

1) Northern TRIAXYS Directional Wave Buoy: The northern DNREC buoy was deployed at latitude 39.12°N, and longitude 75.26°W, which is roughly 12.8km (8mi) east of Kitts Hummock. A total of 406,890 relevant observations were used from the deployment period. The magnetic declination at this location was approximately 11.95°W for the full deployment duration [6]. This correction was applied to all wave directions as reported by the buoy.

2) Automated Meteorological Station: The DNREC/DEOS automated meteorological station (Figure 4) at the St. Jones Reserve at Kitts Hummock is located at latitude 39.08°N, and longitude 75.43°W. Wind observations are measured at a height of 4.87m (16ft). A total of 4,611,024 relevant observations were used as the primary DSJR data set in this analysis.

B. South Buoy Data Sources

Data sources for analysis performed on southern observations include data reported by the southern DNREC buoy and the DEOS Rehoboth Beach site situated on the beach-side boardwalk.

1) Southern TRIAXYS Directional Wave Buoy: The southern DNREC buoy was deployed at latitude 38.88°N, and longitude 75.18°W, which is roughly 12.7km (7.9mi) north-northwest of Lewes, DE and 7.7km (4.8mi) east of the Delaware shore. A total of 212,970 relevant observations were

Fig. 4. DNREC/DEOS DSJR station in the St. Jones Reserve.

used from the deployment period. The magnetic declination at this location was approximately 11.93°W for the full deployment duration [6]. This correction was applied to all wave directions as reported by the buoy.

2) Automated Meteorological Station: This DEOS meteorological station is located at 38.63° N, and 74.07° W. Wind observations at the DRHB station (Figure 5) are measured at a height of 3.78m (12.41ft). A total of 2,726,968 relevant observations were used as the primary DRHB data set in this analysis.

C. NDBC #44009

The NDBC maintains a 3m (9.8ft) discus buoy at latitude 38.46°N, and longitude 74.70°W. This Advanced Modular Payload System (AMPS) buoy [7] is situated in 30.5m (100ft) of water and monitors oceanographic and meteorological data [8], [9]. Wave data is available at one hour intervals including significant wave height, dominant period, average period, and mean wave direction. Spectral wave density is also available from this buoy at the same one hour interval. Meteorological data available from #44009 includes wind direction, wind speed, wind gust speed, air temperature, water temperature, and barometric pressure.

While this station is spatially remote (on a local scale) from the Delaware Bay buoys, it produces valuable contributions to the knowledge of offshore wind and wave components. The quality controlled historical data for buoy #44009 contained

Fig. 5. DEOS DRHB station mounted next to the boardwalk at Rehoboth Beach.

no valid wave direction observations, so wave comparisons were unable to be calculated. Wind characteristics at this station are observed at a height of 5m (16.4ft) above sea level.

III. Methods and Results

The generation of waves is a complicated environmental phenomenon and depends on many factors. The observed values available for this analysis are a subset of the desired information required to make high-quality wave predictions, although using various statistical methods, it is possible to construct a general characterization of the wave distribution observed by Delaware Bay buoys. In order to make accurate predictions, a more thorough knowledge of the immediate environment of the buoy, including surface and subsurface currents, marine traffic, bathymetry, and winds at the buoy site, is necessary.

The overall wave height distribution was estimated by calculating an optimized Rayleigh parameter and adjusting for scaling. Correlational analysis of interdependencies between wind and wave data were conducted using several different formulations applied to the available data.

The wave-height distribution was estimated using the standard Rayleigh (a special case of Weibull) distribution,

$$y = f(x|s) = \frac{x}{s^2} e^{\left(\frac{-x^2}{2s^2}\right)} \quad (1)$$

where the Rayleigh parameter, s, is originally estimated by $\hat{s} = \frac{1}{n}\Sigma x^2$. This value was then used as an initial value in a simple Newton-Raphson-like optimization scheme to determine the optimal parameter value.

Finally, various correlational analyses were performed to gauge any direct correlations apparent within available data. The Pearson coefficient of correlation (ρ) is an indicator of linear associations between two variables. If $|\rho| = 1$, then there is a perfect correlation (positive or negative) between the variables X and Y. If $\rho = 0$, then X and Y are uncorrelated. This does not, however, mean they are not related; it simply shows that they are not linearly related. The Kendall Tau correlation and Spearman correlation coefficients were also computed for the same data set, but showed no significantly differing results.

a) North Buoy: The best-fit Rayleigh parameter of 0.1924 was used to estimate the overall wave height distribution (Figure 6). The root-mean-square (RMS) value is, accordingly, 0.4387. As is evident in the graph, the Rayleigh distribution overestimates the frequency of the slightly-above-average waves and underestimates the frequency of some of the higher waves. Some of this departure may be due to some of the factors mentioned in Section I such as currents or nearby marine traffic. Fetch distance was unlimited in the direction of the mouth of the Bay, but otherwise was less than 40km.

Wave directions at the northern buoy were dominated by surface currents and fetch (similar to the results in a Gulf of Finland study [10]), as seen in Figure 7. The number of larger wave events (over 1.0m) was too small to consider statistically significant, but in these cases, the majority of waves originated in the north-northwest (330° to 340°).

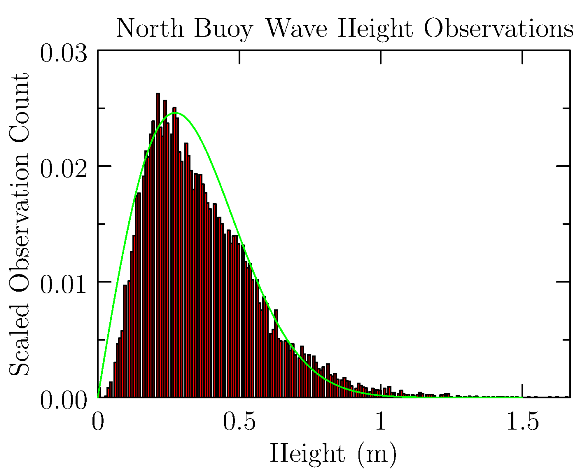

Fig. 6. Rayleigh estimation of the distribution of wave-heights at the northern buoy.

According to the analysis, there was almost no correlation (c=-0.005) between wind direction and wave height (Table I). It is well known, however, that wave height is highly related to wind speed and duration. The correlation coefficient between wind speed and wave height showed a much larger, albeit moderate, correlation (c=0.443). During the deployment durations of the Delaware Bay buoys, the typical observed wave heights ranged from 0 (calm) to 0.5m (small). Very few high-winds or high-waves were observed.

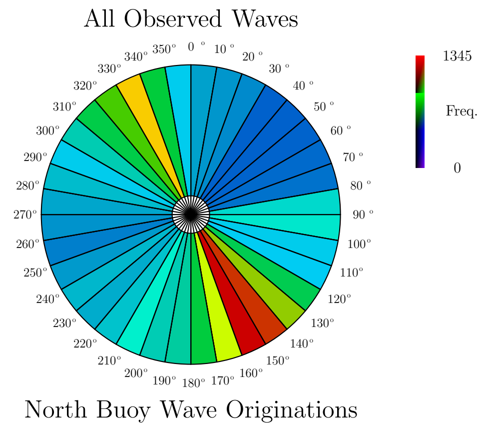

Fig. 7. Wave origination directions at the northern DNREC buoy site. Of particular note is the strong alignment with the major axis of the Delaware Bay.

TABLE I
NORTH BUOY PEARSON'S LINEAR CORRELATION COEFFICIENTS

	Period	**Height**	**Direction**
Wind Speed	-0.1162	0.4428	0.0399
Wind Direction	-0.0341	-0.0052	0.4221
Fetch	0.0355	-0.0068	-0.1627

b) South Buoy: The best-fit Rayleigh parameter of 0.2482 was used to estimate the overall wave height distribution (Figure 8). The RMS value is, accordingly, 0.4981. Here, the Rayleigh distribution significantly underestimates the number of waves with heights roughly 0.75m and above. The number of waves over 1.0m again was small compared to the total number of waves observed.

For all observed waves at the southern buoy, the dominant wave origination direction aligns well with the entrance to the Delaware Bay from the Atlantic Ocean (Figure 9). In the large wave cases, however, the predominant wave origination direction was east-northeast (60° to 70°). These cases are likely the result of nor'easter storms. Fetch distances were unlimited in the direction of the Bay mouth, but typically less than 40km in other directions.

Similar to the northern buoy results, there was little correlation (c=-0.114) between wind direction and wave height (Table II). The correlation coefficient between wind speed and wave height demonstrated, as in the north buoy case, a moderate correlation (c=0.426). The small number of large wind/wave events did not provide a significant basis for analysis.

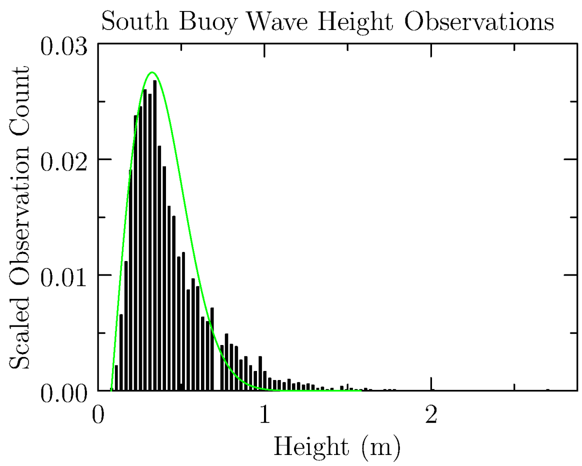

Fig. 8. Rayleigh estimation of the distribution of wave-heights at the southern buoy.

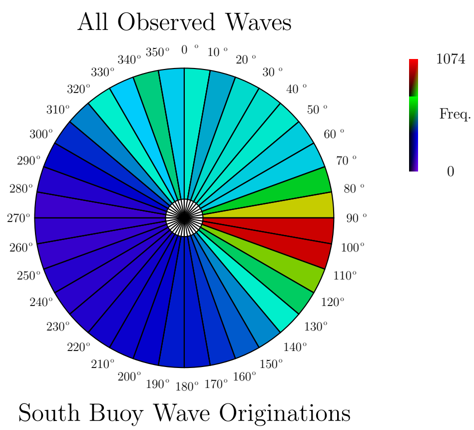

Fig. 9. Wave origination directions at the southern DNREC buoy site. Of particular note is the strong influence of the inlet of the Delaware Bay.

IV. Conclusion

This study investigated the use of nearby meteorological stations to explain variability of wave conditions in the Delaware Bay. To that end, several correlational and statistical models were tested using wind data, fetch information, and wave data. While the data provided by the meteorological stations is necessary for the estimation and prediction of wave conditions in the Bay, that data alone is insufficient to make high quality nowcasts and forecasts of waves.

The majority of observed waves in the Delaware Bay were small (less than 0.5m) with periods of 2.5s to 4s. Although these waves pose little threat to recreational and commercial activities, infrequent storm events generated much larger waves with far greater damage potential (several waves over 2.5m heights and periods of 12s to 15s were observed).

Due to the dominance of surface currents in the Delaware Bay, none of the simple models account for the majority of variation within the data. Expanded in-situ measurements including local wind and current information would considerably enhance these estimations. The bathymetric conditions within the bay also change readily during dredging activities required to maintain shipping channels and storm events. High-resolution bathymetric surveys, reflecting recent changes, would also significantly contribute to increased accuracy of Bay wave models.

TABLE II
South Buoy Pearson's linear correlation coefficients

	Period	**Height**	**Direction**
Wind Speed	-0.1161	0.4263	-0.0846
Wind Direction	-0.0219	-0.1140	0.2678
Fetch	0.0110	0.1351	-0.1861

Knowledge of the physical processes within the Delaware Bay continues to grow and a group at the University of Delaware is working towards operational Delaware Bay wind and wave models. The observations recorded by the DNREC in-situ wave buoys, in conjunction with meteorological data from DEOS, will prove invaluable for real world ground-truthing to validate the results of future modeling efforts.

Acknowledgment

This project was funded, in part, through grants from the Delaware Coastal Management Program and the Delaware National Esuarine Research Reserve with funding from the Office of Ocean and Coastal Resource Management, National Oceanic and Atmospheric Administration under award numbers NA11NOS4200108, NA09NOS4190172, NA10NOS4200185, and Catalog of Federal Domestic Assistance number 11.420. The authors would like to thank Allison Hayes for GIS preparation and Michael Mensinger for providing buoy data.

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