Automated Sea State Classification from Parameterization of Survey Observations and Wave-Generated Displacement Data

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Automated Sea State Classification from Parameterization of Survey Observations and Wave-Generated Displacement Data

A Thesis

Submitted to the Graduate Faculty of the University of New Orleans in partial fulfillment of the requirements for the degree of Master of Science in Applied Physics

by

Jason A. Teichman

B.S. Ferris State University, 2002

May, 2016
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ABSTRACT

Sea state is a subjective quantity whose accuracy depends on an observer’s ability to translate local wind waves into numerical scales. It provides an analytical tool for estimating the impact of the sea on data quality and operational safety. Tasks dependent on the characteristics of local sea surface conditions often require accurate and immediate assessment. An attempt to automate sea state classification using eleven years of ship motion and sea state observation data is made using parametric modeling of distribution-based confidence and tolerance intervals and a probabilistic model using sea state frequencies. Models utilizing distribution intervals are not able to exactly convert ship motion data into various sea states scales with significant accuracy. Model averages compared to sea state tolerances do provide improved statistical accuracy but the results are limited to trend assessment. The probabilistic model provides better prediction potential than interval-based models, but is spatially and temporally dependent.

Keywords: sea state; modeling; ship motion; Beaufort; World Meteorological Organization
CHAPTER 1 - INTRODUCTION

1.A. Sea State

The modern WMO (World Meteorological Organization) Sea State Scale in Table 1 (WOCE, 2002) describes the properties of locally driven, open-ocean wind waves. The code ranges from 0 (the calmest of conditions; the sea has a mirror-like appearance) to 9 (the worst conditions possible). The appearance of wind waves is predominantly generated by winds, the duration of the wind at speed, and the duration and size of the wind fetch; factors such as strong currents, precipitation, tides, and ice formations can also affect the developed sea state (White and Hanson, 2000). Swells are generally considered to be separate from wind waves, but the angle of the wind direction to the swell direction can significantly affect the agitation of local waves.

Table 1. WMO Sea State Scale

<table>
<thead>
<tr>
<th>Code</th>
<th>Descriptive terms</th>
<th>Wind-Wave Height (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Calm (glassy)</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>Calm (rippled)</td>
<td>0.1 - 0.5</td>
</tr>
<tr>
<td>2</td>
<td>Smooth (wavelets)</td>
<td>0.1 - 0.5</td>
</tr>
<tr>
<td>3</td>
<td>Slight</td>
<td>0.5 - 1.25</td>
</tr>
<tr>
<td>4</td>
<td>Moderate</td>
<td>1.25 - 2.5</td>
</tr>
<tr>
<td>5</td>
<td>Rough</td>
<td>2.5 - 4</td>
</tr>
<tr>
<td>6</td>
<td>Very rough</td>
<td>4 - 6</td>
</tr>
<tr>
<td>7</td>
<td>High</td>
<td>6 - 9</td>
</tr>
<tr>
<td>8</td>
<td>Very high</td>
<td>9 - 14</td>
</tr>
<tr>
<td>9</td>
<td>Phenomenal</td>
<td>Over 14</td>
</tr>
</tbody>
</table>

Determination of sea state has traditionally been an in-situ process that requires subjective measurement, limited by the skill level of the observer and the observational conditions, and requires connecting wind forces with the state of the sea. In practice, the
descriptive terms of the table are used as the primary guidance for classifying the seas; the wind-wave height becomes a secondary validation to the observer’s sea state assessment.

Wind-wave conditions are often described and compared with the ubiquitous Beaufort Wind Scale which was developed and accepted into practice in the early 1800s. This scale is used in the maritime industry, including the organization responsible for the operation and maintenance of the survey ships that provided the data in this study. The Beaufort Wind Scale with corresponding WMO Sea State Codes is shown in Table 2 (Bowditch, 1995).

Table 2. Beaufort Wind Scale

<table>
<thead>
<tr>
<th>Beaufort number or force</th>
<th>Wind speed (kn)</th>
<th>World Meteorological Organization</th>
<th>Estimating wind speed</th>
<th>Sea State</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Effects observed far from land</td>
<td>Term</td>
</tr>
<tr>
<td>0</td>
<td>0.0-0.2</td>
<td>Calm</td>
<td>Sea like a mirror.</td>
<td>Calm</td>
</tr>
<tr>
<td>1</td>
<td>0.3-1.5</td>
<td>Light air</td>
<td>Ripples with the appearance of scales are formed, but without foam crests.</td>
<td>Calm (glassy)</td>
</tr>
<tr>
<td>2</td>
<td>1.6-3.3</td>
<td>Light breeze</td>
<td>Small waves, still short but more pronounced, crests have glassy appearance and do not break.</td>
<td>Smooth (wavelets)</td>
</tr>
<tr>
<td>3</td>
<td>3.4-5.4</td>
<td>Gentle breeze</td>
<td>Large waves; crests begin to break; foam of glassy appearance; perhaps scattered whitecaps.</td>
<td>Slight</td>
</tr>
<tr>
<td>4</td>
<td>5.5-7.9</td>
<td>Moderate breeze</td>
<td>Small waves, becoming larger; fairly frequent whitecaps.</td>
<td>Moderate</td>
</tr>
<tr>
<td>5</td>
<td>8.0-10.7</td>
<td>Fresh breeze</td>
<td>Moderate waves, taking a more pronounced long form; many whitecaps are formed (chance of some spray).</td>
<td>Rough</td>
</tr>
<tr>
<td>6</td>
<td>10.8-13.8</td>
<td>Strong breeze</td>
<td>Large waves begin to form; the white foam crests are more extensive everywhere (probably some spray).</td>
<td>Very rough</td>
</tr>
<tr>
<td>7</td>
<td>13.9-17.1</td>
<td>Near gale</td>
<td>Sea heaps up and white foam from breaking waves begins to be blown in streaks along direction of the wind.</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>17.2-20.7</td>
<td>Gale</td>
<td>Moderately high waves of greater length; edges of crests begin to break into spindrift; foam is blown in well-marked streaks along the direction of the wind.</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>20.8-24.4</td>
<td>Strong gale</td>
<td>High waves; dense streaks of foam along the direction of the wind; crests of waves begin to topple, tumble and roll over; spray may affect visibility.</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>24.5-28.4</td>
<td>Storm</td>
<td>Very high waves with long overhanging crests; the resulting foam, in great patches, is blown in dense white streaks along the direction of the wind; the whole surface of the sea takes a white appearance; the tumbling of the sea becomes heavy and shock-like; visibility affected.</td>
<td>High</td>
</tr>
<tr>
<td>11</td>
<td>28.5-32.6</td>
<td>Violent storm</td>
<td>Exceptionally high waves (small and medium-sized ships might be for a time lost to view behind the waves); the sea is completely covered with long white patches of foam lying along the direction of the wind; everywhere the edges of the wave crests are blown into froth; visibility affected.</td>
<td>Very high</td>
</tr>
<tr>
<td>12</td>
<td>32.7 and over</td>
<td>Hurricane</td>
<td>The air is filled with foam and spray; sea completely white with driving spray; visibility very seriously affected.</td>
<td>Phenomenal</td>
</tr>
</tbody>
</table>
The sea state codes used by the scientific teams aboard the survey vessels that provided the data in this study are a modified form of the WMO and Beaufort tables. This table is adjusted to represent specific mission requirements and is dependent primarily on wind speed and a description of the local sea conditions. Table 3 details the wind and sea surface conditions required to select operationally sound conditions for the surveys in this study (Velazquez-Aviles et al., 1999-2014). This sea state scale will be referred to as the Operational Scale. It is expected that this table has been followed to some degree of accuracy by all observers since 2004.

Table 3. Survey Operations Sea State Scale

<table>
<thead>
<tr>
<th>SS#</th>
<th>SEAS</th>
<th>DESCRIPTION</th>
<th>WIND (knots)</th>
<th>BEAUFORT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Calm</td>
<td>Flat, glassy, calm. Smoke rises vertically.</td>
<td>&lt;1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>Smooth Sea</td>
<td>Ripples, no foam. Light air. Not felt on face.</td>
<td>1-4</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Slight Sea</td>
<td>Small wavelets, no foam. Light to gentle breeze. Felt on face. Light flags wave.</td>
<td>4-10</td>
<td>2-3</td>
</tr>
<tr>
<td>3</td>
<td>Moderate Sea</td>
<td>Large wavelets. White caps begin to form. Gentle to moderate breeze. Light flags extended</td>
<td>7-15</td>
<td>3-4</td>
</tr>
<tr>
<td>4</td>
<td>Rough Sea</td>
<td>Moderate waves, many white caps, some spray. Moderate to strong breeze. Wind whistles in rigging.</td>
<td>14-21</td>
<td>4-6</td>
</tr>
<tr>
<td>5</td>
<td>Very Rough Sea</td>
<td>Sea heaps up, with spindrift and foam streaks. Moderate to fresh gale. Walking resistance high.</td>
<td>21-41</td>
<td>6-8</td>
</tr>
<tr>
<td>6</td>
<td>High Sea</td>
<td>Waves begin to roll, dense streaks of foam, much spray. Strong gale. Loose gear and light canvas may part.</td>
<td>40-48</td>
<td>9</td>
</tr>
<tr>
<td>7</td>
<td>Very High Sea</td>
<td>Very high waves with overhanging crests. Sea appears white as foam scuds in very dense streaks. Visibility reduced.</td>
<td>48-55</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>Mountainous Sea</td>
<td>Very, very high-rolling breaking waves. Sea covered with foam. Very poor visibility. Storm.</td>
<td>55-65</td>
<td>11</td>
</tr>
<tr>
<td>9</td>
<td>Are you nuts?</td>
<td>Quit worrying about Sea State and go somewhere else!</td>
<td>&gt;65</td>
<td>12</td>
</tr>
</tbody>
</table>
The Douglas Sea State Scale developed in the 1920s converts wave and swell heights into similar numerical codes, but given the subjective nature of these measurements, this scale is not included.

1.B. Limitations

1.B.1. Observations

Sea state measurements that are founded on ocean wave characteristics are limited by the ability of the observer to discern wave characteristics and categorize the observations into an appropriate scaling. The observer may have a limited skill set or may be impeded from making a sound observation by weather or visibility conditions that prevent an accurate assessment. This is particularly true at night, when determining a wind-wave sea state is almost impossible. In addition, mariners and scientists are given multiple scales to consider, and it is possible that scales used in one event are not the same scales used in another event. Although the confusion and subjectivity of observations have still produced many successful missions, there is a noticeable loss or corruption of data due to operations conducted in conditions that were misdiagnosed or rapidly changing.

The survey events in this study require the use of sea state as a predictor of data quality and operational safety. Some of the operations were conducted at night; sea states in these cases were highly subjective, and errors in observations are expected.
1.B.2. Operations and Safety

Reliable estimation of sea state is essential to decision support systems for effective oceanographic operations. Oceanographic operations that require calm conditions to perform adequately are dependent on the state of the sea. This study was developed from a need intrinsic to acoustic operations. In the survey events from which this study is derived, operational safety and noise are leading concerns and an accurate sea state assessment provides operations leaders with a more complete picture of the state of the sea. The subjective nature of the assessment has created a climate of contention in the community of operators. This study will attempt to alleviate the subjectivity and provide a more objectively quantifiable assessment base.

Every surface mission has sea-state limitations. In most cases, the limiting sea state is 4 or 5 (NAVOCEANO, 1999; NAVOCEANO Personnel, 2015). At sea state 4, concern for operational safety becomes significant. Sea states higher than 4 can severely impact operational safety. Higher sea states also render certain oceanographic missions ineffective. For example, sonobuoy radio frequency (RF) dropout created by a “washover” of the signal output equipment often occurs with seas that are above sea state 5 (NAVOCEANO, 1999).

Ambient noise levels increase with sea state, especially in the frequency range between 300 and 5000 Hz (NAVOCEANO, 1999). For each increase by 1 in the sea state code, ambient noise levels increase by approximately 6 dB (NAVOCEANO, 1999) and as much as 10 dB depending on the frequency and depth (Waite, 2005). In survey operations where good signal quality is critical, wind-wave interactions are a significant cause for data processing failures.
1.C. Prior Research of Sea State Automation

The connection of wave characteristics to the sea state has been studied throughout most of the second half of the 20th century. Attempts to mitigate the problem of observational subjectivity have been a prominent subspace of this research. Although there have been many studies conducted by civilian and governmental organizations, only a few noteworthy publications are provided.

In the early 1950s, Dieder and Thieme [5] conducted a general survey of the studies and instruments being developed for measurement of wind conditions and wave heights, lengths, and frequencies. They produced a summarization of the progress made in aircraft measurement devices and the use of optics to determine wave characteristics. They noted that at the time of the survey, only the U.S., England, Germany, and France were conducting studies in this area. Their conclusions made note of the optimism of the future for the research being conducted.

A preliminary study published by Clayton, Ivey, and Teegardin in 1954 [3] was conducted to develop a sea state meter using bare and dielectric-coated wires in conjunction with a slope-measuring unit created for the experiment. It was intended to produce height and slope data of ocean waves in an attempt to statistically determine sea state. Their experimental cycle rates were too low to produce the results they desired, but as of the time of the publication, they had determined a rate that showed promise.

Black and Adams [1] utilized vertically pointing aircraft photos to determine surface winds in an attempt to record Beaufort wind force values. This was done to assist in the training of personnel who utilized sea state measurements as a part of their working systems.
In the fall of 1989, scientists at the Naval Underwater Systems Center conducted experiments using the newly patented Submarine-Deployed Sea State Sensor (SUDSS) (Shonting et al., 1989). They were able to show the device had the ability to take a wide variety of sea surface measurements with varying degrees of accuracy. Other methods were eventually developed by the submarine community, and at present, the SUDSS is not being used operationally (NAVOCEANO Personnel, 2015).

Work published in 2000 by White and Hanson [29] at Johns Hopkins University utilized directional wave spectra and wind velocity data obtained from National Data Buoy Center (NDBC) weather buoys to create an effective wind speed that could then be translated into a Beaufort force and corresponding sea state codes. Their tests concluded that calculated sea states reasonably coincided with visually observed sea states.

As of the development of this thesis, no known attempts to connect sea state observations with vessel displacement measurements have been published.

1. D. Proposed Research

The intent of this study is to connect sea state observations with associated in-situ wave-riding characteristics of a naval survey vessel in an attempt to find a meaningful, deterministic model that can numerically assess the state of the sea with a significant degree of accuracy. It should be sufficient to utilize statistical methods to develop a parameterization of sea-state specific data that can be used to determine if information produced by displacement measurements fall within parameters of a given sea state. A distribution fitting method using tolerance and confidence intervals of combined displacement effects (as well as derivatives of
these effects) will provide the limits that will be used in various modeling schemes. A variety of probability distribution types will be used. If a specific distribution provides a significantly more accurate assessment, the limits developed will drive the applied routines for this study. If there is a substantially uniform return for the distributions used, a more comprehensive use of the parameters may be examined.

Although wind contributes greatly to the state of local seas, its inherent variability in both speed and direction limit its use as an effective measurement for the purposes of this study. Average wind speeds are used to determine Beaufort and operational sea state codes in an attempt to determine if model results can additionally predict the measurements from these scales. It is expected that further development of this research will eventually include wind measurements in some form.

It should be noted that if a relationship between sea state and ship displacement exists and a deterministic method can be developed for predicting the state of the sea, the data must be managed in real time using shipboard acquisition and processing systems. Any model developed must contain algorithms that do not place unrealistic computational demands on the shipboard systems.
CHAPTER 2 - SURVEY DATA AND OBSERVATIONS

2.A. Data Collection

The data sets used for this study were collected from naval oceanographic surveys from 2004 to 2014. A total of 19 surveys were conducted in similar geographical locations, each survey consisting of between 7 and 36 individual survey events. Each event ranged from approximately 15 minutes to 3 hours. In earlier surveys, more than one event was conducted daily; later surveys are generally limited to one survey event per day. Collectively, there were a total of 410 separate survey events.

Table 4 details a parsing of the total number of recorded events by sea state. The unknown values represent events that had no sea state observation record.

<table>
<thead>
<tr>
<th>SS</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>1</td>
<td>86</td>
</tr>
<tr>
<td>2</td>
<td>136</td>
</tr>
<tr>
<td>3</td>
<td>149</td>
</tr>
<tr>
<td>4</td>
<td>19</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Unknown</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>410</td>
</tr>
</tbody>
</table>

The data were produced by crews and measurement systems aboard three naval survey vessels. Each ship was of the same construction class and sufficiently similar to be considered the same platform type for the purposes of measurement standardizations.
During each event, a shipboard inertial navigation system provided in-situ dynamic data, and an anemometer-based system measured both true and apparent wind speeds. The ship’s Inertial Measurement Unit (IMU) utilized angular accelerometers to measure gravitation-based angular displacements (roll, pitch, and yaw), and linear accelerometers to measure non-gravitational accelerations that translate to linear motion displacements (heave, surge, and sway) (Eschbach et al., 1990; King, 1998). A calibrated gyroscopic element in the IMU is utilized to maintain an absolute plane of reference. The ship’s axes were periodically updated to maintain a zeroed axis plane of reference (NAVOCEANO Personnel, 2015); the standard practice of ship axes calibration for the purpose of sensor performance and accuracy is expected and was confirmed by header data used to display each offset and its calibration. All dynamic and environmental data collected by the sensors were then chronologically recorded in an onboard system that parses and archives the data in the highest resolutions available.

A sea state observation based on the scaling in Table 3 was made at some time during the event (the exact time is never recorded). It was expected that the observer used the scale in Table 3, but observational tempo or limitations sometimes relegated the task of sea assessment to the ship’s crew who exclusively used the Beaufort scaling in Table 2. In some cases the sea state changed during the event; in these instances, the higher sea states were used for this analysis. This was done to reflect the greater variability in the ship motion due to the increased sea conditions and represents a conservative estimate that leans in the direction of operational safety. Since surveys required operationally effective seas, only measurements of sea state 0 to sea state 6 were observed.
A shipboard anemometer was used to record the wind speed and direction. Processing software produced both apparent and true wind speeds and directions. For the purpose of this study, only true wind speeds are considered.

2.B. Extraction and Quality Control

The raw, time-series displacement and wind data from organizational archives were downloaded using LINUX/UNIX command-line functions and parsed by survey and Julian date.

To achieve the largest relevant sampling possible only events with periods greater than or equal to an hour were included; all other samples were rejected. Most samples were in excess of an hour but generally less than 2.5 hours. The only exception to this rejection criterion was a sea state 6 event with less than an hour of data. This event was not rejected in an attempt to provide sea state 6 data; there are only two sea state 6 events.

Events that were missing key information such as a sea state observation were rejected. Missing wind data was not considered a rejection criterion; wind is not used to provide limiting parameters in this study. Additionally, if the ship’s course was not reasonably consistent, the event was rejected. Course changes can cause significant roll or pitch to occur which could contaminate the data for the purposes of this study.

A total of 23 survey events were rejected.

Since the purpose of this study is to utilize statistical arguments to justify the parameters needed to develop a sea state model, sample sizes in Table 4 are questionable. For example, given a standard deviation of $\sigma \approx 0.90521$ determined through preliminary testing, with a margin of error formula given by Meyer (1975),
\[ ME = z^* \frac{\sigma}{\sqrt{n}} \]

where \( z^* = 1.037, 1.282, 1.645, 1.960 \text{ and } 2.576 \) for confidence levels of 70\%, 80\%, 90\%, 95\%, and 99\%, respectively, requires minimum sample sizes as detailed in Table 5 for margins of error ranging from ±1\% to ±10\%.

<table>
<thead>
<tr>
<th>ME\CONF</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
<th>95%</th>
<th>99%</th>
</tr>
</thead>
<tbody>
<tr>
<td>±10%</td>
<td>88</td>
<td>135</td>
<td>222</td>
<td>315</td>
<td>544</td>
</tr>
<tr>
<td>±9%</td>
<td>109</td>
<td>166</td>
<td>274</td>
<td>389</td>
<td>671</td>
</tr>
<tr>
<td>±8%</td>
<td>138</td>
<td>210</td>
<td>346</td>
<td>492</td>
<td>850</td>
</tr>
<tr>
<td>±7%</td>
<td>180</td>
<td>275</td>
<td>453</td>
<td>642</td>
<td>1110</td>
</tr>
<tr>
<td>±6%</td>
<td>245</td>
<td>374</td>
<td>616</td>
<td>874</td>
<td>1510</td>
</tr>
<tr>
<td>±5%</td>
<td>352</td>
<td>539</td>
<td>887</td>
<td>1259</td>
<td>2175</td>
</tr>
<tr>
<td>±4%</td>
<td>551</td>
<td>842</td>
<td>1386</td>
<td>1967</td>
<td>3398</td>
</tr>
<tr>
<td>±3%</td>
<td>979</td>
<td>1496</td>
<td>2464</td>
<td>3498</td>
<td>6042</td>
</tr>
<tr>
<td>±2%</td>
<td>2203</td>
<td>3367</td>
<td>5543</td>
<td>7870</td>
<td>13593</td>
</tr>
<tr>
<td>±1%</td>
<td>8812</td>
<td>13467</td>
<td>22173</td>
<td>31478</td>
<td>54374</td>
</tr>
</tbody>
</table>

This criterion suggests that only parameters and results using sea state data from sea states 2 and 3 can be considered statistically significant. Specifically, the sample sizes in Table 5 allow a minimum margin of error of 9\% for a 70\% confidence level for sea state 2, and a minimum margin of error of 8\% for a 70\% confidence level or 10\% for an 80\% confidence. Due to sample sizes in this study, a large margin of error will exist at confidence levels higher than
70% for most of the data. Discussions relevant to all other sea states will be speculation based on trends.

2.C. Data Analysis

The following sections discuss the particular facets of the extracted data. Section 2.C.1. covers the extraction counts and partitions as well as a brief discussion of the sea state frequencies. An overview of the seasonal and diurnal observations is covered in section 2.C.2. A comparison of observed sea states to wind-generated Beaufort and Operational scales is accomplished in section 2.C.3. This analysis is conducted to provide comprehensive statistics of the selected data sets, and to provide conditions and validations for further analysis.

2.C.1. Selected Data

A total of 387 events were selected for inclusion in this study and assigned a number from 001 to 387. Table 6 is the selected event count by sea state. Table 7 details each survey and its associated Julian date range, number of individual selected events, and sampling resolution. Table 8 lists the number of survey events per ship platform.
Table 6. Selected Survey Event Count by Sea State

<table>
<thead>
<tr>
<th>SS</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>1</td>
<td>81</td>
</tr>
<tr>
<td>2</td>
<td>129</td>
</tr>
<tr>
<td>3</td>
<td>146</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>387</td>
</tr>
</tbody>
</table>

Table 7. Selected Survey Data

<table>
<thead>
<tr>
<th>Survey #</th>
<th>JD Range</th>
<th>Event #</th>
<th>Res (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>144 – 159</td>
<td>21</td>
<td>0.52</td>
</tr>
<tr>
<td>2</td>
<td>170 – 191</td>
<td>32</td>
<td>0.52</td>
</tr>
<tr>
<td>3</td>
<td>037 – 061</td>
<td>21</td>
<td>0.52</td>
</tr>
<tr>
<td>4</td>
<td>073 – 095</td>
<td>25</td>
<td>0.52</td>
</tr>
<tr>
<td>5</td>
<td>169 – 192</td>
<td>23</td>
<td>1.04</td>
</tr>
<tr>
<td>6</td>
<td>202 – 227</td>
<td>20</td>
<td>1.04</td>
</tr>
<tr>
<td>7</td>
<td>231 – 251</td>
<td>23</td>
<td>0.52</td>
</tr>
<tr>
<td>8</td>
<td>264 – 284</td>
<td>17</td>
<td>0.52</td>
</tr>
<tr>
<td>9</td>
<td>240 – 254</td>
<td>23</td>
<td>0.50</td>
</tr>
<tr>
<td>10</td>
<td>264 – 284</td>
<td>12</td>
<td>0.50</td>
</tr>
<tr>
<td>11</td>
<td>058 – 083</td>
<td>30</td>
<td>0.20</td>
</tr>
<tr>
<td>12</td>
<td>135 – 158</td>
<td>33</td>
<td>0.20</td>
</tr>
<tr>
<td>13</td>
<td>173 – 196</td>
<td>18</td>
<td>0.20</td>
</tr>
<tr>
<td>14</td>
<td>180 – 199</td>
<td>24</td>
<td>0.10</td>
</tr>
<tr>
<td>15</td>
<td>217 – 233</td>
<td>22</td>
<td>0.10</td>
</tr>
<tr>
<td>16</td>
<td>292 – 304</td>
<td>12</td>
<td>0.10</td>
</tr>
<tr>
<td>17</td>
<td>326 – 336</td>
<td>7</td>
<td>0.10</td>
</tr>
<tr>
<td>18</td>
<td>282 – 310</td>
<td>17</td>
<td>0.10</td>
</tr>
<tr>
<td>19</td>
<td>320 – 332</td>
<td>7</td>
<td>0.10</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>387</td>
<td></td>
</tr>
</tbody>
</table>

It should be noted that Surveys 5 and 6 do not have any associated wind data.
Table 8. Event Count by Ship Platform

<table>
<thead>
<tr>
<th>Ship</th>
<th># of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>298</td>
</tr>
<tr>
<td>2</td>
<td>65</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
</tr>
</tbody>
</table>

The boxplot in Figure 1 displays the event frequency and associated probability of the occurrence of each sea state. Given the wide wind variety available in the Operational scaling codes, there is a greater likelihood of sea states existing from 1 to 3. Operationally, sea state 3 conveys the greatest sea condition variability and the larger number of sea state 3 observations suggest validity to this claim.

Figure 1. Sea State Frequencies
A similar distribution of sea state frequencies is available in a technical report by Shonting, Hebda, McCarthy, and Chaves (1989).

2.C.2. Seasonal and Visibility Information

Surveys were conducted in both temperate and equatorial climates, under all possible conditions of visibility. The majority of surveys were done in the lower latitudes making the impact of seasonal data less significant. Although not specifically beneficial to this study, seasonal information provides an environmental backdrop for further research. Visibility conditions have a greater influence on the assessment of the state of the sea, and subsequently, survey events are parsed by light conditions to enhance environmental intelligence as it pertains to this study.

A meteorological season standard (NOAA, 2013) is used to partition survey events, such that for non-leap years, the Julian date ranges are: spring (60-151), summer (152-243), fall (244-334), and winter (1-59, 335-365), and for leap years: spring (61-152), summer (153-244), fall (245-335), and winter (1-60, 336-366). Given this scheme, there were a total of 85 spring surveys, 182 summer surveys, 97 fall surveys, and 23 winter surveys. Figures 2-5 are histograms that display the frequency of events in a season by sea state.
Visibility has a substantial impact on the assessment of the sea. Given the potential for inaccurate sea state assessments due to nighttime (poor light) observations, it is important to note the number of survey events conducted in good and poor light conditions. If it is expected that limited visibility begins due to nightfall, approximately 21:00 (military time) on average, which prevails until approximately 05:00, then observations that are made within this period will be considered limited by poor lighting. The light conditions and associated counts for each of the surveys are detailed in Table 9.
Table 9. Observational Visibility Counts

<table>
<thead>
<tr>
<th>Survey #</th>
<th>Good Light</th>
<th>%</th>
<th>Poor Light</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>52.4</td>
<td>10</td>
<td>47.6</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>78.1</td>
<td>7</td>
<td>21.9</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>71.4</td>
<td>6</td>
<td>28.6</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>56.0</td>
<td>11</td>
<td>44.0</td>
</tr>
<tr>
<td>5</td>
<td>17</td>
<td>73.9</td>
<td>6</td>
<td>26.1</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>60.0</td>
<td>8</td>
<td>40.0</td>
</tr>
<tr>
<td>7</td>
<td>14</td>
<td>60.9</td>
<td>9</td>
<td>39.1</td>
</tr>
<tr>
<td>8</td>
<td>12</td>
<td>70.6</td>
<td>5</td>
<td>29.4</td>
</tr>
<tr>
<td>9</td>
<td>15</td>
<td>65.2</td>
<td>8</td>
<td>34.8</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>83.3</td>
<td>2</td>
<td>16.7</td>
</tr>
<tr>
<td>11</td>
<td>25</td>
<td>83.3</td>
<td>5</td>
<td>16.7</td>
</tr>
<tr>
<td>12</td>
<td>26</td>
<td>78.8</td>
<td>7</td>
<td>21.2</td>
</tr>
<tr>
<td>13</td>
<td>12</td>
<td>66.7</td>
<td>6</td>
<td>33.3</td>
</tr>
<tr>
<td>14</td>
<td>12</td>
<td>50.0</td>
<td>12</td>
<td>50.0</td>
</tr>
<tr>
<td>15</td>
<td>17</td>
<td>77.3</td>
<td>5</td>
<td>22.7</td>
</tr>
<tr>
<td>16</td>
<td>9</td>
<td>75.0</td>
<td>3</td>
<td>25.0</td>
</tr>
<tr>
<td>17</td>
<td>5</td>
<td>71.4</td>
<td>2</td>
<td>28.5</td>
</tr>
<tr>
<td>18</td>
<td>15</td>
<td>88.2</td>
<td>2</td>
<td>11.8</td>
</tr>
<tr>
<td>19</td>
<td>6</td>
<td>85.7</td>
<td>1</td>
<td>14.3</td>
</tr>
<tr>
<td>Total</td>
<td>272</td>
<td>70.3</td>
<td>115</td>
<td>29.7</td>
</tr>
</tbody>
</table>

2.C.3. Wind Scale Comparisons

The observed sea states in events that have associated wind data (Surveys 1-4, 7-19) were compared to Beaufort and Operational sea states using the mean of the true wind speed for the duration of the event. Although the wind speed average may not have coincided directly with the wind speed at the time of the observation, the mean was sufficient to show the trend of the wind in the event locale.
Average winds speeds for each event were converted to the Beaufort and Operational sea state codes on Tables 2 and 3, respectively. The sea states were then compared for each event and a count of matching sea states was determined. Figures 6 and 7 display the comparison between Beaufort and Operational sea states to observational sea states for events 001 to 099 and 142 to 387. These events have wind data that could be converted to a sea state scale.

Figure 6. Beaufort SS Conversion vs. Observed SS

![Beaufort SS Conversion vs. Observed SS](image)

Figure 7. Operational SS vs. Observed SS

![Operational SS vs. Observed SS](image)
Comparison shows that 37 out of 344, or approximately 10.8% of the Beaufort sea states match the observations made during each event. Operational sea states compared to the observed sea states show a closer comparison. In this case there were 80 of 344 matches, or approximately 23.3%. Both counts suggest that true wind speed converted to Beaufort or Operational scales may not accurately represent the state of the sea (assuming observations are accurate). It is possible that with further analysis, it may be determined that wind is accurate to define local seas.

The closer correlation of the observed sea state with the operational sea state scaling suggests that observers were following the Operational scale as a whole. It is known that occasional recording of Beaufort measurements taken from the bridge crews were entered into the logs due to reliance on the ship’s crew for sea state, especially in limited visibility conditions (NAVOCEANO Personnel, 2015).

The mean errors greater than 1 for both comparisons suggest that observers generally underestimate the state of the sea in comparison to the wind-scaled codes (or conversely, the wind-scaled codes overestimate in comparison to the observer). Note that if the observed sea state was increased by 1 in each event, the observations would very closely match operational sea state codes.

It should be noted that it is common for wind speeds to precede or follow sea state measurements due to fetch activity or storm systems. In these cases, the wind may not represent the true state of the sea. This results in mismatched or misdiagnosed sea states when wind-based scales are used.
CHAPTER 3 – METHODS AND RESULTS

3.A. Considerations

To support the fundamental goal of developing a model or a set of models that will efficiently and accurately determine the sea state or potential of a sea state given real-time data supplied by a sea-going vessel’s sensors, several components need to be considered.

In each survey event, the ship’s course and speed remained constant. The course was maintained consistently with minor corrections from an automated control system; the variation was generally less than 10 degrees and carefully scrutinized in the extraction phase of this study. The speed of the ship was maintained at a constant value—either 4 or 8 knots. The relatively slow speed (generally just enough for steerage) should not significantly affect the displacement values.

Wind can have an obvious influence on the displacement motion of a ship—particularly the angular displacement of roll. Given the sea states of this study, the assumption can be reasonably made that winds under sea state 4 are generally not large enough (a wind average of 16.3 knots, or approx. 8.4 meters per second) to affect the displacement values significantly. Wind direction can greatly affect sea conditions if orthogonal to swells, but the sum effect will be considered present at the displacement of the vessel.

The development of any model in this study will require sufficiently significant independent variables. Displacement values and a power spectrum of the time-series data, realized in both arithmetic and root mean square terms, will provide the data to be fit to a variety of distributions. The distributions will determine limitations that can used to parameterize the individual sea states. Models can then be made to produce sea states from each distribution
contribution. Ideally, a best distribution fit will be found and a final model can be developed using its associated limits. If a best fit is not determined, a combination of distributions may provide a broad result set. It may be possible to construct a set of values that will give the end-user a “picture” of the potential sea state(s) and provide a better-than-subjective representation.

3.B. Displacement

3.B.1. Absolute Displacement (AD)

This study uses three displacement values: angular displacements of roll and pitch measured in degrees, and motion displacement of heave, measured in meters. Roll represents angular motion (in degrees) to the left (port) or right (starboard) of the centerline vertical axis. Pitch represents angular motion (in degrees) of the front of the ship (bow) above or below the reference plane. Heave represents the motion displacement (in meters) of the entire ship above or below the reference plane. All values, given a datum of the motion reference plane, have the potential to be negative or positive. To represent magnitude, the absolute value of all displacement values is used exclusively. Each displacement measurement will be referred to as an absolute displacement (AD). Taking the magnitude of the displacement values also serves to assist in utilization of distributions designed for positive data.

Since there are two different units of measurement (degrees and meters), conversion of angular displacement to a linear displacement is required. A subtended length produced by a rotating lever arm radial to the calibrated center of the IMU was assumed, and the linear displacement (in meters) for roll and pitch were then determined using the formula,
\( l_{d,n} = \left( \frac{|\theta_{d,n}|}{360} \right) (2\pi r) = \frac{|\theta_{d,n}| \pi r}{180} \)

where \(|\theta_{d,n}|\) is the absolute angular displacement of roll \((d = r)\) or pitch \((d = p)\) at index \(n\), and \(r\) is the arm radius. A radial measurement of 1 meter was chosen arbitrarily and used exclusively throughout all analysis. Note that the choice of \(r = 1\) meter does not result in true displacement amplitudes; scaled rather than true amplitudes will be used in the final model.

Assuming that principles of linearity apply, since all three displacement measurements are used to quantify the ship’s motion, a summation of all three displacement values, in meters, with heave represented by \(h_n\), such that

\[
\begin{align*}
t_n &= \frac{|\theta_{r,n}| \pi r}{180} + \frac{|\theta_{p,n}| \pi r}{180} + |h_n| \end{align*}
\]

will be referred to as a total absolute displacement (TAD) and will provide the basis for model limit development.

3.B.2. Mean Absolute Displacements

Averages of the displacement values will provide the independent variable to be adjudicated with model limits. Both arithmetic mean and root mean square (RMS) of the displacement data through an entire event period are taken.

The arithmetic average of the TAD is

\[
T_A = \frac{1}{n} \sum_{i=1}^{n} \left[ \frac{\pi r}{180} (|\theta_{r,i}| + |\theta_{p,i}|) + |h_i| \right]
\]

where \(n\) is the number of displacement samples taken within a specific survey event, and will be referred to as the arithmetic mean of the total absolute displacement (AMTAD).
The root mean square of the displacements is produced in an attempt to “normalize” the displacement ranges being averaged so that no one displacement dominates the weighting. Significant changes in amplitude of one displacement type should not drastically change the total displacement. This is accomplished by producing the RMS of the each displacement’s TAD as

\[ T_R = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( \frac{\theta_r,i |\pi r|}{180} \right)^2} + \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( \frac{\theta_p,i |\pi r|}{180} \right)^2} + \sqrt{\frac{1}{n} \sum_{i=1}^{n} (|h_i|)^2} \]

and will be referred to as the root mean square of the total absolute displacement (RMSTAD).

To verify the assumption that all three displacement measurements are significant and useful to this study, correlations between pre-scaled, arithmetic- and RMS-based MTAD values and sea state are determined. It is apparent from the values detailed in Table 10 that all displacements in arithmetic and RMS form are similar and subsequently significant as representations of the ship’s motion.

<table>
<thead>
<tr>
<th></th>
<th>Pre-Scaled AMTAD</th>
<th>Pre-Scaled RMSTAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll</td>
<td>0.4360</td>
<td>0.4512</td>
</tr>
<tr>
<td>Pitch</td>
<td>0.3304</td>
<td>0.3931</td>
</tr>
<tr>
<td>Heave</td>
<td>0.4408</td>
<td>0.4454</td>
</tr>
</tbody>
</table>

3.B.3. Scaling Factors

Each displacement value has its own trend in amplitude, frequency, and phase. Observation of the raw data reveals that pitch and heave have similar levels of variability, while roll tends to be much higher. However, once the angular quantities are converted to linear, heave
tends to have values that are one order of magnitude larger than roll or pitch. Since swells (measured by heave) generally have a very limited effect on the state of the sea (when not considered in conjunction with closely orthogonal wind directions) (White and Hanson, 2000), roll and pitch values must be normalized to reflect their individual and significant contribution to the characterization of the sea state. For the purposes of this study, no one value will hold a higher impact, and therefore each of the displacement values must be normalized (averages of roll, pitch, and heave will be set to unity to determine a scaling factor for each).

If the displacement data is parsed by sea state and $N_{d,ss}$ is the number of all event samples for a displacement type $d$ in sea state $ss$, then the arithmetic averages can be represented by

$$A_{roll,ss} = \frac{1}{N_{roll,ss}} \sum_{j=1}^{N_{roll,ss}} \left( \frac{1}{n} \sum_{i=1}^{n} \left| \theta_{r,i} \right| \pi r \right)$$

$$A_{pitch,ss} = \frac{1}{N_{pitch,ss}} \sum_{j=1}^{N_{pitch,ss}} \left( \frac{1}{n} \sum_{i=1}^{n} \left| \theta_{p,i} \right| \pi r \right)$$

$$A_{heave,ss} = \frac{1}{N_{heave,ss}} \sum_{j=1}^{N_{heave,ss}} \left( \frac{1}{n} \sum_{i=1}^{n} \left| h_i \right| \right)$$

while the RMS averaging would be represented by

$$R_{roll,ss} = \sqrt{\frac{1}{N_{roll,ss}} \sum_{j=1}^{N_{roll,ss}} \left( \frac{1}{n} \sum_{i=1}^{n} \left( \frac{|\theta_{r,i}| \pi r}{180} \right)^2 \right)}$$

$$R_{pitch,ss} = \sqrt{\frac{1}{N_{pitch,ss}} \sum_{j=1}^{N_{pitch,ss}} \left( \frac{1}{n} \sum_{i=1}^{n} \left( \frac{|\theta_{p,i}| \pi r}{180} \right)^2 \right)}$$
\[ R_{\text{heave,ss}} = \sqrt{\frac{1}{N_{\text{heave,ss}}} \sum_{j=1}^{N_{\text{heave,ss}}} \left( \frac{1}{n} \sum_{i=1}^{n} (|h_i|)^2 \right)} \]

If \( n(ss) \) is the number of sea states, a mean, \( M_d \), of the individual sea state averages for each displacement is produced for data with arithmetic means using

\[ M_d = \frac{1}{n(ss)} \sum_{k=1}^{n(ss)} (A_d)_k. \]

For data with RMS averaging,

\[ M_d = \sqrt{\frac{1}{n(ss)} \sum_{k=1}^{n(ss)} (R_d)_k^2}. \]

If the product of each \( M_d \) and a scaling variable \( S_n \) are set to unity, division of the expectations will yield scaling factors in Table 11.

<table>
<thead>
<tr>
<th>Table 11. Scaling Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_d )</td>
</tr>
<tr>
<td>--------------------------</td>
</tr>
<tr>
<td>Arithmetic</td>
</tr>
<tr>
<td>Roll</td>
</tr>
<tr>
<td>Pitch</td>
</tr>
<tr>
<td>Heave</td>
</tr>
<tr>
<td>RMS</td>
</tr>
<tr>
<td>Roll</td>
</tr>
<tr>
<td>Pitch</td>
</tr>
<tr>
<td>Heave</td>
</tr>
</tbody>
</table>
Applying the scaling factors to the AMTAD and RMSTAD formulas in section 3.B.2 yields the scaled sums of

\[ T_{SA} = \frac{1}{n} \sum_{i=1}^{n} \frac{\pi r}{180} (|S_1| + |S_2| + |S_3|) \]

and

\[ T_{SR} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \frac{\pi r}{180} (|S_4| + |S_5| + |S_6|)^2} \]

To confirm that the scaling factors are similarly useful for representing pre-scaled displacement values, Pearson correlation coefficients were calculated for all sea states and are given in Table 12. The results for sea state 3 are shown in Figures 8 and 9 where pre-scaled MTAD values are plotted versus scaled MTAD values. The high correlation coefficients suggest that the scaled values will accurately represent the displacements before scaling.

Table 12. Pearson Correlation Coefficients of Pre-Scaled vs. Scaled Data

<table>
<thead>
<tr>
<th>Sea State</th>
<th>Arithmetic r</th>
<th>RMS r</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.836</td>
<td>0.876</td>
</tr>
<tr>
<td>1</td>
<td>0.896</td>
<td>0.924</td>
</tr>
<tr>
<td>2</td>
<td>0.942</td>
<td>0.957</td>
</tr>
<tr>
<td>3</td>
<td>0.935</td>
<td>0.943</td>
</tr>
<tr>
<td>4</td>
<td>0.953</td>
<td>0.957</td>
</tr>
<tr>
<td>5</td>
<td>0.995</td>
<td>0.994</td>
</tr>
<tr>
<td>6</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>
3.4.2 Power Spectral Density

The absolute displacements are quantities that represent the motion of the ship, but given the variability of these values through the wind-wave interactions, spectral analysis of the waveforms is explored to determine if periodicities or distribution of energy with frequency can better represent the actual movements involved.

Given the scaled TAD time-series of an event, the spectrum of the data is produced using a Discrete Fourier Transform (Magrab et al., 2011), represented as

\[
X(n\Delta f) = \Delta t \sum_{k=0}^{N-1} x_k e^{-i2\pi nk/N}
\]

where \( n = 0, 1, 2, \ldots, N - 1 \), and a subsequent Fast Fourier Transform (FFT) function defined in Matlab [17] as

\[
X(k) = \sum_{j=1}^{N} x(j) \omega_N^{(j-1)(k-1)}
\]

where \( \omega_N = e^{-2\pi i/N} \) and \( x(j) \) are defined as all the values in the time-series data sample.
The FFT size is determined by producing the next highest power of two from the length of the sample size of the event period; using this definition, the FFT size will always be greater than the length of the displacement data sample, and therefore the time-series data are padded with zeros.

To consider periodicities and character of frequency content, the power spectral density (PSD), or power spectrum, is used. If the discrete time-series data for a displacement is defined as

\[ x_n = \frac{\pi r}{180} |\theta_{d,n}| \]

where \( n = i\Delta t \) and \( i \) is the index of each displacement value for a time step of \( \Delta t \) and \( 1 \leq n \leq N \). If the Fourier transform of the data is

\[ X(f) = \sum_{n=1}^{N} x_n e^{-i2\pi fn}, \]

then the power spectral density is

\[ P(f) = \frac{\Delta t}{N} \left| \sum_{n=1}^{N} x_n e^{-i2\pi fn} \right|^2. \]

This PSD estimator provides a reasonable representation of the frequency distribution of the time-series data. Concerns regarding spectral leakage and inconsistencies as \( N \) approaches infinity are not considered in the scope of this study.

Analysis of the PSD results shows that periodicity is greatly varied for each of the displacements. Examples of roll-based PSDs for two sea state 2 events in the same survey are detailed in Figures 10 and 11 where power amplitude is plotted versus frequency. Inspection of displacement values from other survey events confirms similar significant variation and lack of uniform periodicities.
The PSD of the TAD provides a total power spectrum; this value can then be used to provide quantification for model development. By inspection of sample events, it is determined that the significant spectra are always less than 0.5 Hz. Prior studies with ocean wave spectrum components confirm this observation (Varkey, 1993; Nielsen, 2007). To avoid DC bias values and any phase drifting, spectra less than 0.05 Hz were rejected. This value is chosen from close inspection of several spectrum representations; there is a noticeable drop in significant periodicities at this frequency. Summation of $P(f)$ over the frequency interval $[0.05, 0.5]$ provides a total power spectrum and is defined by

$$\sum_{f=0.05}^{f=0.5} \frac{\Delta t}{N} \left| \sum_{n=1}^{N} x_n e^{-i2\pi fn} \right|^2.$$

Plots of power amplitude versus frequency in Figures 12 through 15 show the periodicities of each displacement for a given event. The regions in red are the rejected spectra outside of the chosen interval. Note that the TAD spectrum in Figure 15 is similar to the roll spectrum in Figure 12, indicating that roll dominates the cyclical component of the TAD.
Analysis of this and other events suggest that the PSD waveform of the TAD will reflect its most significant, individual component.

For arithmetic-mean-based scaled data, the total PSD for the relevant interval is referred to as the *Arithmetic Power Spectrum*, or ASPOW. The total PSD for the relevant interval of the RMS-based scaled data is referred to as the *Root Mean Square Power Spectrum*, or RSPOW.
3.B.5. **Outliers**

A 1.5-IQR test (Tukey, 1977) was applied to the scaled MTAD and power spectrum data. Although the 1.5 IQR test results in data symmetry, it provides a tool to scrub possible outliers resulting from mismatched sea state observations and wind-wave anomalies and extrema. Since the justification for outlier removal is not substantial in this study due to the natural aspect of the data, potential outliers are only removed for final comparisons; model sea state limits were developed using data containing the potential outliers.

If means $\bar{x}$ and quartiles $Q_1$ and $Q_3$ are determined, any data values $x$ outside of the interval defined by

$$\bar{x} - 1.5(Q_3 - Q_1) \leq x \leq \bar{x} + 1.5(Q_3 - Q_1)$$

are rejected and removed from the data set. Table 13 details the number of potential outliers in each of the basis data sets.

<table>
<thead>
<tr>
<th>Sea State</th>
<th>AMTAD</th>
<th>RMSTAD</th>
<th>ASPOW</th>
<th>RSPOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea State 0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sea State 1</td>
<td>7</td>
<td>8</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>Sea State 2</td>
<td>3</td>
<td>2</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>Sea State 3</td>
<td>2</td>
<td>1</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>Sea State 4</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Sea State 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sea State 6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
3.C. Distribution Fitting

3.C.1. Distributions

Several continuous distribution models were considered for the development of model limits. The skewed and positive attributes of the data require specific considerations for distribution selection. The chosen distributions produce the sea state limitations needed for subsequent modeling. The ideal distribution will closely fit the survey data and provide enough separation between confidence boundaries inherent to each sea state that non-overlapping delineation of the individual sea states is possible. If an ideal distribution is not found, it may be possible to combine two or more of the distributions to create a more global image of the sea states being represented by the models.

The Matlab fitdata [12] function is used to determine the distribution parameters. These parameters (i.e., $\mu =$ mean and $\sigma =$ standard deviation) are then used to define the distribution as it pertains to the data, and are detailed for all distributions in Appendix Section C.

Probability plots are used to determine the closeness of fit of the distribution to the data. Each probability plot displays the displacement MTAD data (x-axis) in comparison to a theoretical distribution in terms of probability. The closer the data is to the reference line, the more significantly it can be represented by that distribution.

The natural aspect of the data suggests that a Gaussian distribution will provide the closest fit with the benefit of efficient computation. This distribution is modeled using the probability density function in the form

$$G(x|\mu, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$
where $\mu$ is the mean of the distribution and $\sigma$ is the standard deviation (Mendenhall et al., 1981; Magrab et al., 2011; Shchigolev, 1965). Figures 16a and 16b of scaled MTAD detail the closeness of fit for the Gaussian distribution.

The Gaussian probability plots suggest that the MTAD data can be represented closely by this distribution for the central portion. However, values on the tail ends of the data do not fit well; these values are potential outliers and may be rejected using the 1.5-IQR rule.

Preliminary analysis of the MTAD data indicates that the distributions are positive and skewed right. Several non-Gaussian distributions work well with data in this form.

The Weibull distribution can be used with positive, right-skewed data, and is the interpolation between the less flexible exponential distribution and the Rayleigh distribution (Matlab, 2014; Weibull, 1951; Papoulis et al., 2002). It has the probability density function

$$W(x|\lambda, k) = \frac{k}{\lambda} \left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^k}$$
where \( k \) is the shape parameter and \( k > 0 \), and \( \lambda \) is the scale parameter and \( \lambda > 0 \). The nature of the absolute displacement and power spectrum data suggests that the \( k > 1 \) and that the density function increases until the mode is reached and then decreases thereafter (Papoulis et al., 2002). Figures 17a and 17b show the closeness of fit for MTAD data.

A Rayleigh distribution, a special case of the Weibull distribution, can provide a distribution fitting for positive and skewed data given that the magnitude of the MTAD is related to displacement components. The Rayleigh probability density function (Matlab, 2014; Siddiqui, 1961) is modeled as

\[
R(x|\sigma) = \frac{x}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}}
\]

where \( \sigma \) is the scale parameter of the distribution (generally considered the mode of the distribution). Notably, if \( k \) and \( \lambda \) are the parameters of the Weibull distribution, then the \( \sigma \) scale parameter of the Rayleigh distribution is considered equivalent to the Weibull distribution.
parameters by \( \lambda = \sigma \sqrt{2} \) and \( k = 2 \). The probability plots in Figures 18a and 18b detail the closeness of fit for this distribution.

The lognormal (Galton) distribution will be used given the variability-limited and positive nature of logarithmic data. The probability density function for a lognormal distribution is defined as

\[
L(x|\mu, \sigma) = \ln f(x|\mu, \sigma) = \frac{1}{x\sigma \sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}}
\]

with all \( x > 0 \) and \( \mu \) and \( \sigma \) defined as the log mean and log standard deviation, respectively (Matlab, 2014; Crow and Shimizu, 1988; Johnson et al., 1994). The closeness of fit for this distribution is shown in Figures 19a and 19b.
It is apparent that Weibull and Rayleigh distributions are closely representative of the Gaussian distribution. The Rayleigh distribution is following the skewed nature of the data, but is providing a wide confidence band which suggests that close to the mode, the Rayleigh will fit very well, but it will lose accuracy as it spreads out from this modal center. The lognormal shows a higher kurtosis and closely represents the skewed-right nature of the data.

Histograms of MTAD data for the sea states with the most data (1, 2, and 3) are provided in Figures 20-22. The bin widths are 0.1 meters. Associated plots of the distributions’ probability density functions are displayed as well; these curves are scaled by a factor of 10 for display purposes only. RMSTAD data are not shown due to their approximate equivalency to AMTAD data.
Figure 20. Sea State 1 MTAD and Associated Distributions

Figure 21. Sea State 2 MTAD and Associated Distributions
3.C.2. Tolerance and Confidence Intervals

The models developed in this study are dependent on the parameters developed through the use of $\alpha$-based tolerance and confidence intervals derived from the fitted distributions. The `fitdist`, `paramci`, and `icdf` functions in Matlab [12] are used to determine the various intervals. Sampling and operational requirements (NAVOCEANO Personnel, 2015) suggest using a minimum of $\alpha = 0.30$ and $\alpha = 0.20$, but for thorough analysis, intervals using $\alpha = 0.10$, 0.05, and 0.01 are also produced. Ideally, the tolerance and confidence intervals for each sea state would not overlap and would have corresponding limits. In anticipation of less-than-ideal intervals, averaging of tails may be required.
It is important to note that while a 100(1-\(\alpha\))% tolerance interval represents the amount of data that lie within a 100(1-\(\alpha\))% interval, a 100(1-\(\alpha\))% confidence interval does not mean that 100(1-\(\alpha\))% of the sample data lie within the interval. It should be understood as an estimate of the possible values for the population parameter such as a population mean. Since the test statistic is a mean, arithmetic or geometric, the intervals are marking the bounds for which the test statistic is probabilistically within range of the distribution parameter. It can be said that there is a 100(1-\(\alpha\))% confidence that the population parameter will be within the confidence bounds.

The Gaussian cumulative distribution function (Mendenhall, 1981) can be defined using the generalized form

\[
CDF(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{x-\mu}{\sigma}} e^{-\frac{t^2}{2}} dt
\]

and utilized in the quantile-based function (inverse cdf)

\[
CDF(\mu + z\sigma) - CDF(\mu - z\sigma) = \frac{1}{\sqrt{\pi}} \int_{-\frac{z}{\sqrt{2}}}^{\frac{z}{\sqrt{2}}} e^{-t^2} dt
\]

to determine the tolerance intervals for a given confidence level. The Gaussian distribution two-sided \(\alpha\) confidence interval can be developed from the relationship defined as

\[
P\left(\bar{x} - z_{\alpha/2} \left(\frac{\sigma}{\sqrt{n}}\right) \leq \mu \leq \bar{x} + z_{\alpha/2} \left(\frac{\sigma}{\sqrt{n}}\right)\right) = 1 - \alpha.
\]

This produces the \(\alpha\) confidence interval \([\bar{x} - z_{\alpha/2} \left(\frac{\sigma}{\sqrt{n}}\right), \bar{x} + z_{\alpha/2} \left(\frac{\sigma}{\sqrt{n}}\right)\].

The Weibull cumulative distribution function can be defined as

\[
CDF(x) = 1 - e^{-(x/\lambda)^k}
\]

and utilized as a basis for the quantile-based function

\[
Q(CDF) = \lambda(-\ln(1 - CDF))^{1/k}
\]
to determine tolerance intervals for percentage \( p \), such that \( 0 \leq p < 1 \). The Weibull distribution two-sided \( \alpha \) confidence interval (Lloyd and Lipow, 1962; Nelson 1982) is defined as

\[
P \left( \bar{x} - K_{\alpha/2} \left( \sqrt{\sigma^2} \right) \leq \lambda \leq \bar{x} + K_{\alpha/2} \left( \sqrt{\sigma^2} \right) \right) = 1 - \alpha
\]

where \( K_{\alpha} \) is defined as

\[
\alpha = \frac{1}{\sqrt{2\pi}} \int_{K_{\alpha}}^{\infty} e^{-t^2/2} dt
\]

This produces the \( \alpha \) confidence interval \( [\bar{x} - K_{\alpha/2}(\sqrt{\sigma^2}), \bar{x} + K_{\alpha/2}(\sqrt{\sigma^2})] \).

The cumulative distribution function for the Rayleigh distribution (Papoulis and Pillai, 2002) can be defined as

\[
CDF(x) = 1 - e^{-x^2/2\sigma^2}
\]

and utilized in the quantile function

\[
Q(CDF) = \sigma \sqrt{-\ln((1 - CDF)^2)}
\]

to determine the tolerance bounds. The Rayleigh distribution two-sided \( \alpha \) confidence interval can be defined from Siddiqui [24] such that if two numbers \( \chi_1^2 \) and \( \chi_2^2 \) corresponding to \( 2N \) degrees of freedom (\( N \) is the number of independent observations) are determined and applied to the system

\[
P(\chi^2 \leq \chi_1^2) = \frac{\alpha}{2}
\]

\[
P(\chi^2 \leq \chi_2^2) = 1 - \frac{\alpha}{2}
\]

then

\[
P \left( \frac{2N\bar{x}}{\chi_1^2} \leq \sigma \leq \frac{2N\bar{x}}{\chi_2^2} \right) = 1 - \alpha
\]

producing the \( \alpha \) confidence interval \( \left[ \frac{2N\bar{x}}{\chi_1^2}, \frac{2N\bar{x}}{\chi_2^2} \right] \).
The lognormal cumulative distribution function (Crow and Shimizu, 1988; Johnson et al., 1994) is

\[ \int_{0}^{\infty} \ln f(a|\mu, \sigma)da = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{\ln x - \mu}{\sigma}} e^{-\frac{t^2}{2}} dt \]

with a corresponding quantile function

\[ Q(p) = e^{(\mu + \sigma G^{-1}(p|\mu, \sigma))} \]

where \( G \) is the Gaussian distribution at \( p \) such that

\[ G(p|\mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(p-\mu)^2}{2\sigma^2}} \]

The lognormal distribution two-sided \( \alpha \) confidence interval can be developed using the Cox method (Land, 1971), such that if \( X \) represents the original data that follows a lognormal distribution with an expected value \( E(X) = \bar{x} \), if \( Y \) is the log-transformed representation of \( X \), where \( E(Y) = \mu \), \( Var(Y) = \sigma^2 \), the sample mean of \( Y \) is \( \bar{Y} \), and sample variance of \( Y \) is \( s^2 \), the relationship can be defined as

\[ P \left( \bar{Y} + \frac{s^2}{2} - \frac{z_{\alpha/2} \sqrt{s^2/n + \frac{s^4}{2(n-1)}}}{2} \leq \bar{x} \leq \bar{Y} + \frac{s^2}{2} + \frac{z_{\alpha/2} \sqrt{s^2/n + \frac{s^4}{2(n-1)}}}{2} \right) = 1 - \alpha \]

This produces the \( \alpha \) confidence interval \( \left[ \bar{Y} + \frac{s^2}{2} - \frac{z_{\alpha/2} \sqrt{s^2/n + \frac{s^4}{2(n-1)}}}{2}, \bar{Y} + \frac{s^2}{2} + \frac{z_{\alpha/2} \sqrt{s^2/n + \frac{s^4}{2(n-1)}}}{2} \right] \).

It is apparent from the tolerance and confidence intervals that only \( \alpha = 0.30 \) for tolerance intervals and \( \alpha = 0.20 \) for confidence intervals provide bounds that are useful for this study. Confidence levels higher than 70% in tolerance intervals and 80% in confidence intervals produce excessive overlap and bounds that are unrealistic (e.g., a lower bound of -461 in data that are exclusively positive). As a result, only 70% tolerance intervals and 80% confidence intervals are used in model development.
3.D. Modeling

The developed tolerance and confidence intervals produce boundaries that represent likelihoods of any sampled TAD or power spectrum mean to fall within what is expected to be the bounds of population data or population mean for a given confidence level. A deterministic relationship between displacement or power spectrum means and observed sea states is dependent on the results of the model runs. If a distribution parameter set matches observed sea states to modeled sea states, then that distribution becomes a candidate for the underlying basis in the final model application. If no ideal distribution parameter set exists, a comprehensive model utilizing more than one distribution, or more than one model, may be required.

Given sample sizes and confidence bounds, it is expected that representation of sea states 0, 5 and 6 will be limited. Sea state 4, although limited by sample size, had only a few outliers (or none), and may be a significant representation of displacement in this sea state. The only significant confidence will exist in the parameters developed for sea states 2 and 3. As a result of this consideration, the models are only predictive to sea state 4 with a limited confidence in sea state 0. Any data that produce values yielding sea states higher than 4 are considered sea state 5 or greater.

The following are descriptions of each of the models used in this study.

Model 1 utilizes tolerance intervals at a 70% confidence level. If the boundaries for each sea state are either overlapping or have no intersection they are arithmetically averaged. Since there are four distributions being used, each one creating a set of boundaries for AMTAD, RMSTAD, ASPOW, and RSPOW, there are a total of 16 distribution-based parameter sets yielding the same number of sea state predictions.
**Model 2** is Model 1 with 1.5-IQR outliers removed from the data.

**Model 3** uses confidence intervals at an 80% confidence level. The boundaries for each sea state, either overlapping or having no intersection, are arithmetically averaged. This model will produce 16 individual sea state predictions.

**Model 4** is Model 3 with 1.5-IQR outliers removed from the data.

**Model 5** is an experimental model that uses a probability parameterization. The magnitudes of AMTAD, RMSTAD, ASPOW and RSPOW are determined and then parsed using the sea state frequencies plotted in Figure 1. The boundaries for each partition represent the displacement and power spectrum limits for each individual sea state. For example, considering the non-logarithmic AMTAD data, if \( \max(AMTAD) = 8.71267 \), Table 14 details the partitions using the known sea state frequencies.

<table>
<thead>
<tr>
<th>Sea State</th>
<th>Probability</th>
<th>Lower Boundary</th>
<th>Upper Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea State 0</td>
<td>0.023256</td>
<td>0.00000</td>
<td>0.20262</td>
</tr>
<tr>
<td>Sea State 1</td>
<td>0.209300</td>
<td>0.20263</td>
<td>2.02618</td>
</tr>
<tr>
<td>Sea State 2</td>
<td>0.333330</td>
<td>2.02619</td>
<td>4.93038</td>
</tr>
<tr>
<td>Sea State 3</td>
<td>0.377260</td>
<td>4.93039</td>
<td>8.21732</td>
</tr>
<tr>
<td>Sea State 4</td>
<td>0.041344</td>
<td>8.21733</td>
<td>8.57754</td>
</tr>
</tbody>
</table>

Note that any MTAD values above the sea state 4 upper boundary are considered sea states 5 or 6 (or higher). Since the distributions in this research are not used in this model, only scaled MTAD and SPOW are used, in both non-logarithmic and logarithmic forms. Given this parameterization, there are only eight individual parameter sets used in this model.
3.E. Model Testing and Results

There are two model runs. “Trial A” represents use of all survey events from the data used to create the model parameters. This is done to determine model accuracy through exact and marginal tolerance matching of model sea states to the observed sea states. “Trial B” uses survey events not included in the model parameter development; these events were conducted during the period of the research and are used as a test to determine model accuracy.

The plots in Sections 3.E.1 and 3.E.3 detail the model results for randomly selected events in each sea state. Each graphic is composed of the observed, wind-generated and model mean sea states, the aggregate counts of model results, and the time-series ATAD in both non-logarithmic and logarithmic (LATAD) form. Note that the AMTAD and logarithmic AMTAD (LAMTAD) are plotted for reference.

TRIAL A

To represent the results of Trial A pseudo random number generator is used to pick four events within the surveys utilized in this study (with exception of sea state 5 that only has four events, and sea state 6 that only has two events). If an event without wind data was selected, another random event was taken as a replacement. Table 15 presents the randomly selected event numbers for each sea state.
Table 15. Randomly Selected Events for Trial A

<table>
<thead>
<tr>
<th>Sea State</th>
<th>Events Randomly Selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>196, 218, 226, 275</td>
</tr>
<tr>
<td>1</td>
<td>038, 156, 278, 291</td>
</tr>
<tr>
<td>2</td>
<td>023, 078, 289, 372</td>
</tr>
<tr>
<td>3</td>
<td>080, 159, 332, 362</td>
</tr>
<tr>
<td>4</td>
<td>094, 208, 229, 356</td>
</tr>
<tr>
<td>5</td>
<td>065, 238, 345, 363</td>
</tr>
<tr>
<td>6</td>
<td>236, 237</td>
</tr>
</tbody>
</table>

TRIAL B

Two naval oceanographic surveys were recently conducted aboard survey ship 1. A total of 26 events were produced, and with all rejection criteria considered and applied to the selection of the events, 23 survey events were selected (events numbered 388 to 410). The counts for each sea state are detailed in Table 16. Events 388 to 392 are considered summer events using the meteorological standard in 2.C.2; the remaining events are fall events. Four out of the nine events in the first survey were considered good visibility due to daylight; 13 of the 14 events in the second survey are considered good visibility due to daylight. Resolution of the displacement data was 0.1 seconds.

Table 16. Selected Survey Event Count by Sea State

<table>
<thead>
<tr>
<th>SS</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>23</td>
</tr>
</tbody>
</table>
A similar random generation was done to determine the event samples to be used. Four randomly selected events were determined if there were more than four events available. If a sea state is represented by fewer than four events, then all available events for that sea state were used. Table 17 details the events selected.

It should be noted that large swells from out-of-area typhoons were present during many of the events; the heave values may skew the data and significantly over value the sea state.

<table>
<thead>
<tr>
<th>Sea State</th>
<th>Events Randomly Selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>395</td>
</tr>
<tr>
<td>1</td>
<td>388, 389, 392</td>
</tr>
<tr>
<td>2</td>
<td>393, 394, 396, 407</td>
</tr>
<tr>
<td>3</td>
<td>391, 399, 404, 406</td>
</tr>
<tr>
<td>4</td>
<td>409, 410</td>
</tr>
<tr>
<td>5</td>
<td>408</td>
</tr>
<tr>
<td>6</td>
<td>NA</td>
</tr>
</tbody>
</table>
3.E.1. *Trial A Plots*

Figures 23(a-d). Trial A (Sea State 0)

### Modeled Sea State (Event #196)

<table>
<thead>
<tr>
<th>SS 0</th>
<th>SS 1</th>
<th>SS 2</th>
<th>SS 3</th>
<th>SS 4</th>
<th>SS 5+</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>M2</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>M3</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>M4</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>M5</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Mean Wind Speed = 3.6

### Modeled Sea State (Event #218)

<table>
<thead>
<tr>
<th>SS 0</th>
<th>SS 1</th>
<th>SS 2</th>
<th>SS 3</th>
<th>SS 4</th>
<th>SS 5+</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>M2</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>M3</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>M4</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>M5</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Mean Wind Speed = 7.8
Figures 24(a-d). Trial A (Sea State 1)
Figures 25(a-d). Trial A (Sea State 2)
Figures 26(a-d). Trial A (Sea State 3)
Modeled Sea State (Event #332)

Mean Wind Speed = 27.9

<table>
<thead>
<tr>
<th>SS 0</th>
<th>SS 1</th>
<th>SS 2</th>
<th>SS 3</th>
<th>SS 4</th>
<th>SS 5+</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0</td>
<td>0</td>
<td>14</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>M2</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>M3</td>
<td>0</td>
<td>2</td>
<td>10</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>M4</td>
<td>0</td>
<td>1</td>
<td>9</td>
<td>5</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>M5</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Beaufort SS = 6
Operational SS = 5
Model Mean SS = 2.23

Modeled Sea State (Event #362)

Mean Wind Speed = 15.5

<table>
<thead>
<tr>
<th>SS 0</th>
<th>SS 1</th>
<th>SS 2</th>
<th>SS 3</th>
<th>SS 4</th>
<th>SS 5+</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>6</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>M2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>M3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>M4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>M5</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Beaufort SS = 5
Operational SS = 4
Model Mean SS = 3.56

TAD (m)

0  1064.9625  2129.925  3194.8875  4259.85  5324.8125  6389.775  7454.7375  8519.7

Time (sec)
Figures 27(a-d). Trial A (Sea State 4)
## Modeled Sea State (Event #229)

Mean Wind Speed = 15

<table>
<thead>
<tr>
<th>SS</th>
<th>SS 0</th>
<th>SS 1</th>
<th>SS 2</th>
<th>SS 3</th>
<th>SS 4</th>
<th>SS 5+</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.56</td>
</tr>
<tr>
<td>M2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>9</td>
<td>3.75</td>
</tr>
<tr>
<td>M3</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>3.75</td>
</tr>
<tr>
<td>M4</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>3.94</td>
</tr>
<tr>
<td>M5</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2.00</td>
</tr>
</tbody>
</table>

## Modeled Sea State (Event #356)

Mean Wind Speed = 23.3

<table>
<thead>
<tr>
<th>SS</th>
<th>SS 0</th>
<th>SS 1</th>
<th>SS 2</th>
<th>SS 3</th>
<th>SS 4</th>
<th>SS 5+</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>10</td>
<td>4</td>
<td>4.13</td>
</tr>
<tr>
<td>M2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>6.22</td>
</tr>
<tr>
<td>M3</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>10</td>
<td>4</td>
<td>4.13</td>
<td></td>
</tr>
<tr>
<td>M4</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>6</td>
<td>4.44</td>
<td></td>
</tr>
<tr>
<td>M5</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>2.25</td>
</tr>
</tbody>
</table>
Figures 28(a-d). Trial A (Sea State 5)
Figures 29(a-b). Trial A (Sea State 6)
3.E.2. **Trial A Analysis**

Trial A is conducted using all 387 survey events. Sea state predictions from the individual parameter sets are then compared to associate observed, Beaufort, and Operational sea state measurements. The number of matching sea states is recorded in Appendix Section G, Tables G1a-G5a. The matching of exact sea states is detailed in Table 18 and suggests that the probability of a predicted sea state matching observations or wind-scale-based codes is low.

<table>
<thead>
<tr>
<th>Model Sea State Matching</th>
<th>Observed SS</th>
<th>Beaufort SS</th>
<th>Operational SS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Matched</td>
<td>Out of P</td>
<td>Matched</td>
</tr>
<tr>
<td>Model 1</td>
<td>1504</td>
<td>6192</td>
<td>0.243</td>
</tr>
<tr>
<td>Model 2</td>
<td>1553</td>
<td>6192</td>
<td>0.251</td>
</tr>
<tr>
<td>Model 3</td>
<td>1199</td>
<td>6192</td>
<td>0.194</td>
</tr>
<tr>
<td>Model 4</td>
<td>1298</td>
<td>6192</td>
<td>0.210</td>
</tr>
<tr>
<td>Model 5</td>
<td>1043</td>
<td>3096</td>
<td>0.337</td>
</tr>
</tbody>
</table>

Model 2 provides the closest overall fit for all three sea state code types, but the limited probabilities make Model 2 an unlikely candidate for a final application. The results of the experimental model suggest greater connection to the observed sea states, but similarly low expectations for the wind-based scales. Model 5 has, on average, about a 10% higher prediction potential for the observed sea state.

The plots in Figures 30-34 feature the comparison between the observed sea state measurements and model sea state predictions. Moving averages of the observed and model sea states are used to smooth out any short-term variations and to emphasize trends. In these plots, the average is taken using an 80-point window.
Figure 30. Trial A - Model 1 Results

![Moving Averages of Model 1 Results](image1)

Figure 31. Trial A - Model 2 Results

![Moving Averages of Model 2 Results](image2)
Figure 32. Trial A - Model 3 Results

Moving Averages of Model 3 Results

Figure 33. Trial A - Model 4 Results

Moving Averages of Model 4 Results
If the counts of total predictions for any individual sea state are used as weighting factors, a weighted average of the predicted sea state is then produced for each model. To informally commute all model predictions into a universal model mean, the averages of all five models are combined to form a total model mean of the predicted sea state. This average is then compared to sea state marginal tolerances (i.e., within ±0.5 of a sea state, within ±1 of a sea state, etc.) for each event’s observed, Beaufort, and Operational sea state measurement. Since the total model mean sea state is generally not integral it can be compared in terms of fractional sea states. The matching of the given marginal tolerances is detailed in Table 19. The probabilities in these comparisons suggest a strong likelihood of the model to predict the sea state within two sea state codes.
Table 19. Trial A – Total Model Mean Sea State Margin Matching

<table>
<thead>
<tr>
<th></th>
<th>Observed SS</th>
<th>P</th>
<th>Beaufort SS</th>
<th>P</th>
<th>Operational SS</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>±0.5</td>
<td>108</td>
<td>0.279</td>
<td>58</td>
<td>0.169</td>
<td>74</td>
<td>0.215</td>
</tr>
<tr>
<td>±1.0</td>
<td>208</td>
<td>0.537</td>
<td>105</td>
<td>0.305</td>
<td>140</td>
<td>0.407</td>
</tr>
<tr>
<td>±1.5</td>
<td>295</td>
<td>0.762</td>
<td>158</td>
<td>0.459</td>
<td>212</td>
<td>0.616</td>
</tr>
<tr>
<td>±2.0</td>
<td>351</td>
<td>0.907</td>
<td>205</td>
<td>0.596</td>
<td>250</td>
<td>0.727</td>
</tr>
</tbody>
</table>

Matching within the marginal tolerances is compared for individual models and the results are shown in Appendix Section G, Tables G1b-G5b. The results suggest that Models 1 through 4 will only be within one observed sea state approximately 50% of the time, whereas Model 5 can produce sea states that will be within one observed sea state approximately 80.6% of the time.

Although the total model mean is a better overall predictor within marginal tolerances compared to exact matching, Model 5 appears to be the best performer for modeling observed sea states in both exact matching and marginal estimates.
3.3.3. Trial B

Figure 35. Trial B (Sea State 0)

Modeled Sea State (Event #395)

<table>
<thead>
<tr>
<th>Mean Wind Speed = 16</th>
<th>SS 0</th>
<th>SS 1</th>
<th>SS 2</th>
<th>SS 3</th>
<th>SS 4</th>
<th>SS 5+</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed SS = 0</td>
<td>M1</td>
<td>0</td>
<td>2</td>
<td>12</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Beaufort SS = 5</td>
<td>M2</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Operational SS = 4</td>
<td>M3</td>
<td>0</td>
<td>7</td>
<td>6</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Model Mean SS = 2.08</td>
<td>M5</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

TAD (m)

0 1087.1375 2174.275 3261.4125 4348.55 5435.6875 6522.825 7609.9625 8697.1

time (sec)
Figures 36(a-c). Trial B (Sea State 1)

Modeled Sea State (Event #388)

Modeled Sea State (Event #389)

Mean Wind Speed = 5.5
Observed SS = 1
Beaufort SS = 2
Operational SS = 2
Model Mean SS = 2.63

Mean Wind Speed = 15.9
Observed SS = 1
Beaufort SS = 5
Operational SS = 4
Model Mean SS = 3.81
### Modeled Sea State (Event #392)

<table>
<thead>
<tr>
<th>SS 0</th>
<th>SS 1</th>
<th>SS 2</th>
<th>SS 3</th>
<th>SS 4</th>
<th>SS 5+</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0</td>
<td>2</td>
<td>14</td>
<td>0</td>
<td>0</td>
<td>1.88</td>
</tr>
<tr>
<td>M2</td>
<td>0</td>
<td>0</td>
<td>15</td>
<td>1</td>
<td>0</td>
<td>2.06</td>
</tr>
<tr>
<td>M3</td>
<td>0</td>
<td>9</td>
<td>6</td>
<td>0</td>
<td>1</td>
<td>2.96</td>
</tr>
<tr>
<td>M4</td>
<td>0</td>
<td>1</td>
<td>11</td>
<td>3</td>
<td>1</td>
<td>2.25</td>
</tr>
<tr>
<td>M5</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>2.00</td>
</tr>
</tbody>
</table>

- **Mean Wind Speed** = 21
- **Observed SS = 1**
- **Beaufort SS = 6**
- **Operational SS = 5**
- **Model Mean SS = 1.95**

**TAD (m)** vs **time (sec)**

The graph shows a time series of TAD (transient amplitude difference) measured over time, indicating the variability of sea state parameters. The data points are superimposed on a line graph with time (in seconds) on the x-axis and TAD on the y-axis, demonstrating the dynamic nature of the modeled sea state over the specified period. The different SS levels and observed metrics are highlighted to provide insights into the effectiveness of the modeled sea state against operational and observed standards.
Figures 37(a-d). Trial B (Sea State 2)
Figures 38(a-d). Trial B (Sea State 3)
### Modeled Sea State (Event #404)

<table>
<thead>
<tr>
<th>ATAD</th>
<th>AMTAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Wind Speed = 14.9</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SS 0</th>
<th>SS 1</th>
<th>SS 2</th>
<th>SS 3</th>
<th>SS 4</th>
<th>SS 5+</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0</td>
<td>14</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1.13</td>
</tr>
<tr>
<td>M2</td>
<td>0</td>
<td>11</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>1.31</td>
</tr>
<tr>
<td>M3</td>
<td>4</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.75</td>
</tr>
<tr>
<td>M4</td>
<td>1</td>
<td>12</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1.13</td>
</tr>
<tr>
<td>M5</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>1.50</td>
</tr>
</tbody>
</table>

- Observed SS = 3
- Beaufort SS = 4
- Operational SS = 4
- Model Mean SS = 1.16

### Modeled Sea State (Event #406)

<table>
<thead>
<tr>
<th>ATAD</th>
<th>AMTAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Wind Speed = 4</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
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<th>SS 1</th>
<th>SS 2</th>
<th>SS 3</th>
<th>SS 4</th>
<th>SS 5+</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
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<td>0</td>
<td>4</td>
<td>12</td>
<td>0</td>
<td>2.75</td>
</tr>
<tr>
<td>M2</td>
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<td>0</td>
<td>2</td>
<td>10</td>
<td>4</td>
<td>3.13</td>
</tr>
<tr>
<td>M3</td>
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<td>0</td>
<td>3</td>
<td>9</td>
<td>4</td>
<td>3.06</td>
</tr>
<tr>
<td>M4</td>
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<td>0</td>
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<td>6</td>
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<td>3.25</td>
</tr>
<tr>
<td>M5</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>2.00</td>
</tr>
</tbody>
</table>

- Observed SS = 3
- Beaufort SS = 2
- Operational SS = 2
- Model Mean SS = 2.84
Figures 39(a,b). Trial B (Sea State 4)
Figure 40. Model Run B (Sea State 5)
3.4. *Trial B Analysis*

Trial B is conducted using all 23 survey events. Sea state predictions from the individual parameter sets are then compared to associate observed, Beaufort, and Operational sea state measurements. The number of matching sea states is recorded in Appendix Section H, Tables H1a-H5a. The matching of exact sea states is detailed in Table 20 and suggests that the probability of a predicted sea state matching observations or wind-scale-based codes is low and comparable to the matching in Trial A (see Table 16).

<table>
<thead>
<tr>
<th>Table 20. Trial B - Model Sea State Matching</th>
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<tbody>
<tr>
<td><strong>Model</strong></td>
</tr>
<tr>
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</tr>
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</tr>
<tr>
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</tr>
<tr>
<td>Model 3</td>
</tr>
<tr>
<td>Model 4</td>
</tr>
<tr>
<td>Model 5</td>
</tr>
</tbody>
</table>

In this run, Model 2 provides the closest overall fit for all three sea state code types, but once again, limited probabilities make Model 2 an unlikely candidate for a final application. The results of the experimental model suggest greater connection to the observed sea states than Models 1 through 4, but have similarly low expectations for the wind-based scales. Model 5 has, on average, about a 10% higher prediction potential for the observed sea state.

Matching within marginal tolerances is shown in Table 21 and conveys comparable probabilities, albeit lower, to the marginal matching in Trial A. Note that there is about a 10% increase in matching within 0.5 of an observed sea state for Model 1, an almost 20% increase in
matching within 1 Beaufort sea state code, and approximately 14% decrease in matching within 1.5 Operational sea states.

Table 21. Trial B – Total Model Mean Sea State Margin Matching

<table>
<thead>
<tr>
<th>Total Model Mean Sea State Margin Matching</th>
<th>Observed SS</th>
<th>P</th>
<th>Beaufort SS</th>
<th>P</th>
<th>Operational SS</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>± 0.5</td>
<td>9</td>
<td>0.391</td>
<td>4</td>
<td>0.174</td>
<td>7</td>
<td>0.304</td>
</tr>
<tr>
<td>± 1.0</td>
<td>11</td>
<td>0.478</td>
<td>11</td>
<td>0.478</td>
<td>10</td>
<td>0.435</td>
</tr>
<tr>
<td>± 1.5</td>
<td>13</td>
<td>0.565</td>
<td>13</td>
<td>0.565</td>
<td>11</td>
<td>0.478</td>
</tr>
<tr>
<td>± 2.0</td>
<td>19</td>
<td>0.826</td>
<td>14</td>
<td>0.609</td>
<td>16</td>
<td>0.696</td>
</tr>
</tbody>
</table>

Matching within the marginal tolerances is compared for individual models and the results are shown in Appendix Section H, Tables H1b-H5b. Probabilities are generally lower than those produced in Trial A. The results suggest that Models 1 through 4 will only be within one observed sea state approximately 50% of the time, whereas Model 5 can produce sea states that will be within one observed sea state 69.6% of the time.

Although the total model mean is a better overall predictor within marginal tolerances compared to exact matching, Model 5 appears to be the best performer for modeling marginal and exact observed sea states.

It is apparent from the plots and associated measurements that either the height of swells overvalued the heave displacement measurement (the presence of significant swells can be mistaken as sea roughness), or observer error is present. The observer in the second survey was highly qualified, but there is limited knowledge of the qualifications or source of the observations in the second survey.
No moving average plots of the model performance were produced due to the similarity of results from Trial A.

3.F. Additional Analysis

**Visibility Comparisons**

Comparisons were made with visibility conditions from events 001 to 387 and the marginal matching of sea state observations. Table 22 shows marginal counts for both lighting conditions.

<table>
<thead>
<tr>
<th>Visibility Matching</th>
<th>Poor</th>
<th>P</th>
<th>Good</th>
<th>P</th>
</tr>
</thead>
<tbody>
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<td>± 0.5</td>
<td>32</td>
<td>0.083</td>
<td>76</td>
<td>0.196</td>
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<tr>
<td>± 1.0</td>
<td>58</td>
<td>0.150</td>
<td>150</td>
<td>0.388</td>
</tr>
<tr>
<td>± 1.5</td>
<td>84</td>
<td>0.217</td>
<td>211</td>
<td>0.545</td>
</tr>
<tr>
<td>± 2.0</td>
<td>107</td>
<td>0.276</td>
<td>244</td>
<td>0.630</td>
</tr>
</tbody>
</table>

The probabilities suggest that there is a significantly greater chance that model results will predict observations made in the daytime. This infers that observations made in the daytime are more likely to be accurate.
CHAPTER 4 – CONCLUSIONS

The objective of this research was to determine modeling parameters that could produce data boundaries for individual sea states that could be used to predict the in-situ sea state using shipboard, displacement-based data. Several distribution types were used to provide comprehensive coverage of possible boundaries. Trial runs were used to test these boundaries and to provide an account of the number of matches made between modeled sea states and the observed as well as wind-based scale codes.

The results of the model runs suggest that all five models in this study are unable to exactly match and convert observed sea states through the use of ship’s displacement values with a significant confidence. There is likelihood that low matching counts are a result of the inaccuracy of the sea state boundaries within each model; the averaging of boundary limits may provide too wide a variation for linking modeled sea state to observations. Figure 41 shows the overlapping of tolerance interval boundaries with $\alpha = 0.3$ for Gaussian distributions of AMTAD data.

Figure 41. Gaussian Tolerance Intervals of AMTAD Data
The experimental model provides greater predictability in both exact and marginal matching of observed sea states. Exact matching for the average of Models 1 through 4 predicts observed sea state approximately 22.4% of the time, whereas Model 5 will exactly match observed sea state about 33.7% of the time. Marginal tolerance matching of the total model mean implies that within 0.5 of an observed sea state, the Models 1-4 will predict the sea state approximately 24.2% of the time, whereas independently, Model 5 can marginally predict the sea state within 0.5 of an observed sea state approximately 42.6% of the time. Within one sea state, the average of Models 1-4 will predict the correct sea state approximately 51.0% of the time and Model 5 will predict the sea state approximately 80.6% of the time. Although this experimental model provides greater prediction accuracy, it is spatially and temporally dependent; data were collected in specific regions during specific times of the year.

While some distributions within the models were far better at predicting certain sea states, they were inconsistently able to perform well versus the alternate sea state measurements. This precludes any possibility of utilizing certain distributions exclusively to form a new model.

It is recommended that a final, shipboard model application should include TAD trend lines and an aggregate model result matrix similar to the model trial plots to provide a comprehensive decision aid.
CHAPTER 5 – FURTHER RESEARCH

Although the modeled sea states do not correlate well with the observed or wind-based sea states, it is apparent that there is a strong relationship between the modeled sea states and the time- and frequency-series data. In fact, without knowledge of the true state of the sea during any given period, the data suggests that the modeled sea states are more representative of the motion of the ship than the observed sea states. Further analysis of the time-series waveforms as a more precise measurement of sea state should be conducted. Pattern recognition algorithms may be useful.

It is strongly suggested that operational leaders create a protocol for taking periodic sea state measurements (similar to Expendable Bathythermograph (XBT) operations) to provide further data—especially in cases of low and high sea states.

To assist in the quality of acoustic products, further analysis should be conducted to connect observations to the corruption of acoustic signals created by wind-wave surface interactions and noise.

The sampling sizes of time-series data in this study were not uniform. Taking uniform samples may provide a better basis for comparison.

Corrections for swell heights, especially in cases where the state of the sea is clam and the swells are large, could provide better model boundary development and results. It may be necessary to remove heave as a displacement variable.
REFERENCES


[15] NIST (2014), Standard Reference Data Program, National Institute of Standards and Technology, Gaithersburg, MD


[23] Technical Discussions with subject matter experts at the Naval Oceanographic Office, Stennis Space Center, MS


APPENDICES

A. Matlab Pseudo Code and Descriptions

There were more than 60 Matlab scripts created for this research. Many of the initial programs were superseded by updated and often vastly different versions. Most provided small, ad hoc requests and are not included in this appendix. The programs listed below were the most significant. Since most of the code in each was repetitive declarations and array manipulations, only a description of the code’s purpose is included. All scripts are available for further review upon request.

A1. proc2dispwind.m Produces master list of displacement and wind data.
A2. proc2power.m Produces master list of PSD calculations.
A3. outliers.m Determines outlier data based on 1.5-IQR rule.
A4. stats.m Determines the elementary statistics of data.
A5. seasonavg.m Produces seasonal plots.
A6. distparams.m Determines distribution parameters.
A7. histplots.m Provides a variety of histograms and probability plots.
A8. datacorr.m Used to determine Pearson correlation coefficients of data.
A9. modelrun.m Produces the predictive results of the various models.
A10. modelfigure.m Plots event time-series data and model results.
Table B1. Pre-Scaled MAD Data Statistics

<table>
<thead>
<tr>
<th>Statistics Type</th>
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<th>SS 2</th>
<th>SS 3</th>
<th>SS 4</th>
<th>SS 5</th>
<th>SS 6</th>
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<td>0.0673</td>
<td>0.08813</td>
<td>0.09991</td>
<td>0.01319</td>
<td>0.01647</td>
<td>0.02141</td>
<td>0.02463</td>
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<td>0.00772</td>
<td>0.01213</td>
<td>0.01681</td>
<td>0.01902</td>
<td>0.02463</td>
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<tr>
<td><strong>Min</strong></td>
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<td>0.00211</td>
<td>0.00164</td>
<td>0.00221</td>
<td>0.00917</td>
<td>0.01694</td>
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<tr>
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<td>0.01021</td>
<td>0.01233</td>
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<th>SS 4</th>
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<th>SS 6</th>
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<tbody>
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Table B2. Pre-Scaled MTAD Data Statistics

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<th>SS 3</th>
<th>SS 4</th>
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<td>n</td>
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<td>81</td>
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D. Tolerance Interval Tables

Tables D1. 70% and 80% AMTAD/ASPOW Tolerance Intervals (Outliers Included)

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**Gaussian**

- AMTAD 70%
- AMTAD 80%
- ASPOW 70%
- ASPOW 80%

**Weibull**

- AMTAD 70%
- AMTAD 80%
- ASPOW 70%
- ASPOW 80%

**Rayleigh**

- AMTAD 70%
- AMTAD 80%
- ASPOW 70%
- ASPOW 80%

**Lognormal**

- AMTAD 70%
- AMTAD 80%
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- ASPOW 80%
### Tables D2. 90% and 95% AMTAD/ASPOW Tolerance Intervals (Outliers Included)

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#### ASPOW 99% Tolerance Intervals

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### Tables D4. 70% and 80% RMSTAD/RSPOW Tolerance Intervals (Outliers Included)

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#### RSPower 95% Tolerance Intervals

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### RMSTAD 90% Tolerance Intervals

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### RSPOW 90% Tolerance Intervals

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#### AMTAD 80% Confidence Intervals

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Table E5. 90% and 95% RMSTAD/RSPOW Confidence Intervals (Outliers Included)
Table E6. 99% RMSTAD/RSPOW Confidence Intervals (Outliers Included)

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### Table E9. 99% AMTAD/ASPOW Confidence Intervals (Outliers Removed)

#### AMTAD 99% Confidence Intervals

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### RSPOW 80% Confidence Intervals

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Table E11. 90% and 95% RMSTAD/RSPOW Confidence Intervals (Outliers Removed)

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F. Model Boundaries (only upper limits are shown)

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Table F3. Model 3 Sea State Boundaries

| MODEL 3 (80% Confidence Intervals with Boundaries Averaged - Outliers Included) |
|---------------------------------|----------------|----------------|----------------|----------------|
| AMTAD  | Gaussian | Weibull | Rayleigh | Lognormal | RMSTAD  | Gaussian | Weibull | Rayleigh | Lognormal |
| SS 0   | 1.57401  | 1.77075 | 1.23777 | 0.37437 | SS 0    | 1.31144 | 1.47342 | 1.03924 | 0.19597 |
| SS 1   | 2.15625  | 2.43913 | 1.66302 | 0.67851 | SS 1    | 1.81191 | 2.05344 | 1.40796 | 0.49650 |
| SS 2   | 2.70476  | 3.04987 | 2.05656 | 0.91298 | SS 2    | 2.31400 | 2.61263 | 1.76648 | 0.75078 |
| SS 3   | 3.10549  | 3.48582 | 2.27915 | 1.08137 | SS 3    | 2.69186 | 3.02386 | 1.97979 | 0.93696 |
| SS 4   | 3.54998  | 4.24318 | 2.80003 | 1.26511 | SS 4    | 3.11403 | 3.72146 | 2.52917 | 1.13410 |

Table F4. Model 4 Sea State Boundaries

| MODEL 4 (80% Confidence Intervals with Boundaries Averaged - Outliers Removed) |
|---------------------------------|----------------|----------------|----------------|----------------|
| AMTAD  | Gaussian | Weibull | Rayleigh | Lognormal | RMSTAD  | Gaussian | Weibull | Rayleigh | Lognormal |
| SS 0   | 1.42018  | 1.56817 | 1.09524 | 0.29603 | SS 0    | 1.20312 | 1.33050 | 0.92867 | 0.13239 |
| SS 1   | 2.04117  | 2.29125 | 1.55282 | 0.63978 | SS 1    | 1.71938 | 1.93352 | 1.31634 | 0.46256 |
| SS 2   | 2.65159  | 2.98483 | 2.00684 | 0.89770 | SS 2    | 2.28252 | 2.57436 | 1.73618 | 0.74054 |
| SS 3   | 3.08551  | 3.46112 | 2.26187 | 1.07627 | SS 3    | 2.68227 | 3.01192 | 1.97130 | 0.93422 |
| SS 4   | 3.54998  | 4.24318 | 2.89003 | 1.26511 | SS 4    | 3.11403 | 3.72146 | 2.52917 | 1.13410 |

| ASPOW  | Gaussian | Weibull | Rayleigh | Lognormal | RSPOW   | Gaussian | Weibull | Rayleigh | Lognormal |
| SS 0   | 933.748  | 1031.728 | 845.243 | 6.592    | SS 0    | 490.912 | 549.826 | 435.367 | 5.992    |
| SS 1   | 1581.146 | 1673.374 | 1487.134 | 6.913    | SS 1    | 883.126 | 934.844 | 840.119 | 6.347    |
| SS 2   | 2809.488 | 3063.132 | 2508.815 | 7.569    | SS 2    | 1602.061 | 1726.052 | 1470.738 | 6.974    |
| SS 3   | 3871.728 | 4477.544 | 3419.569 | 8.081    | SS 3    | 2081.231 | 2387.885 | 1849.064 | 7.442    |
| SS 4   | 5327.151 | 8122.755 | 6731.586 | 8.593    | SS 4    | 2706.621 | 4083.609 | 3341.970 | 7.912    |
Table F5. Model 5 Sea State Boundaries

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MODEL 5 (Experimental - SS Probability Boundaries)
G. Trail A Matching Tables

Table G1a. Model 1 – Model Sea State Matching

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Table G1b. Model 1 – Model Mean Sea State Margin Matching

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### Table G2b. Model 2 – Model Mean Sea State Margin Matching

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H. Trial B Matching Tables

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VITA

The author was born in Mt. Pleasant, Michigan. He obtained his Bachelor’s degree in Applied Mathematics from Ferris State University in 2002. In 2013, he joined the University of New Orleans applied physics graduate program to pursue a M.S. in applied physics with concentrations in Acoustics, Spectral Analysis, and Mathematical Physics. He is currently employed as a mathematician at the Naval Oceanographic Office.