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Probability of Sea Condition for Ship Strength, Stability, and Motion Studies

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Modeling and simulation continues to be an important tool for determining the response of sea-going vessels to wind and waves. To provide appropriate forcing functions to the models, it is important to have environmental data of sufficient fidelity to facilitate an assessment of platform response, which is as accurate as possible within the practical constraints of time and resources. Fortunately, there are a variety of sources of good wave data, including the U.S. National Oceanic and Atmospheric Administration. This study examines the wave data in the context of simulation codes for assessing characteristics of ocean craft response. It also looks at some practical considerations to limit the scope of simulations. The work is strongly influenced by modeling and simulation of naval surface ships, looking for extreme behaviors, but many of the issues discussed are broadly applicable to other applications.

Keywords: water wave characterization; scattergram; probability of sea condition; WaveWatch III; ship motions

1. Background

A variety of tools have been developed over the last few centuries to account for observable physical phenomena in the arts of vessel design, operation, and maintenance. With the advent of modern computing capability, numerical modeling and simulation has provided tools that are ubiquitous and indispensable. In particular, modeling and simulation continues to grow more important for determining the response of sea-going vessels to wind and waves. To provide appropriate forcing functions to the models, it is important to have environmental data of sufficient fidelity to facilitate an assessment of platform response, which is as accurate as possible within the practical constraints of time and resources. Fortunately, there are a variety of sources of good wave data, including the U.S. National Oceanic and Atmospheric Administration (NOAA). This study examines the wave data as input to simulation codes for assessing characteristics of ocean craft response. It also looks at some practical considerations to limit the scope of simulations. Although an attempt is made to be general in the scope of application, the work is strongly influenced by modeling and simulation of naval surface ships, looking for extreme behaviors. However, many of the issues discussed are broadly applicable to other ocean-going platforms.

For instance, there are current studies (e.g., Winterstein et al. 1993; Fukasawa et al. 2007) that use a single severe sea state to approximate the effects of long-term exposure to wave conditions, providing a design sea state for such important calculations as vertical bending moment. The work herein is suitable for a broad range of uses including user guidance, life-cycle management, and (in the naval context) simulation for development of tactics and doctrine, where the exposure to all sea states is likely as important as the worst-case events.

Various behaviors such as the probability of capsize of an intact ship or the accumulation of fatigue damage are functions of capability designed into the vessel, the environmental conditions it is subjected to, and the manner in which it is operated during the exposure to the environment. Although the capability of the ship is somewhat fixed at design, it changes with the load condition and serviceability of the ship. The operators take these variations into account in their ship handling. For a naval vessel, mission often overrides risk due to environmental conditions, although they do take all precautions to minimize that risk. Understanding the characteristic behavior of a ship in all environmental conditions

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helps the designer improve the capability of the ship and the operator to practice good seamanship. It can also provide life-cycle managers with data to make informed decisions on various through-life issues.

In past work on ship stability, the environmental conditions have been characterized by a joint probability distribution of wave occurrences in the North Atlantic (McTaggart & de Kat 2000). This joint probability distribution is in the form of a table of probabilities for each subrange of significant wave height and modal period, and has been called the "North Atlantic scatter diagram" or "North Atlantic scattergram." It is also known as the "Bales scatter diagram" or "Bales scattergram" because it is a direct development of the work of Bales (Bales et al. 1981) as input for the NATO STANAG 4194 (1993). In Bales work, the data were generated (in the 1970s) using the then state-of-the-art spectral ocean wave model (SOWM) (Pierson et al. 1966) to generate hindcasts of sea conditions based on wind field data. This was considered a marked improvement over the data from visual observation because the observed wave statistics are known to have inherent biases and errors (Beck et al. 1989). The SOWM produced a set of hindcasts for every 6 hours over a 10-year period (1959–1969) at a very limited number (11) of locations in the North Atlantic.

Wave modeling continued to mature in the last 50 years, along with vastly increased computing capacity, providing more accurate, flexible, and accessible models including the current WaveWatch III (2016). For this reason alone, the reference "North Atlantic scattergram" should be updated. As with the SOWM, it is also easy to generate a scattergram for other bodies of water. Further, a composite ocean scattergram can be formed representing (almost) all nonpolar ocean regions. This composite ocean scattergram may be more suitable than the North Atlantic scattergram for many purposes, especially for ships that may have unlimited areas of operations not including regions subject to ice coverage.

2. Investigating the environmental data

In this study, we will discuss updating the scattergram and comparing it with the original North Atlantic scattergram. First, however, we will study the parameters defining the data output from the WaveWatch III model, i.e., the extents and resolutions of the time step and the latitude and longitude of the (virtual) wave observations. We will also examine the features used to classify the data, i.e., the wave height and period ranges. We will also explore imposing practical limits on the number of height–period combinations to achieve the optimal number of simulations appropriate to the issue under investigation. Finally, we will briefly look at alternative parameters for classification of the data.

The background objective was to find a characteristic environment for input to platform response codes (e. g., ship-motion codes). The intent is that the characteristic environment can be used as a time-independent representation of the body of water. The foreground objective was to find a method for defining that the characteristic environment because the environment identified is unlikely to be a "one-size-fits-all" solution. The motivation for these objectives was to facilitate modeling and simulation of ship behavior using an optimal number of environmental conditions as defined by the wave height and period.

Characterizing the wave conditions in the current context means finding a distribution of wave heights and periods that are more or less time invariant. This distribution is structured on the choice of bin sizes for the wave heights and periods. It is also necessarily a function of the number of (virtual) observations, which, in turn, depends on the number of geographical locations (extent of the body of water and the resolution in latitude and longitude) and the duration of the interval of (virtual) observation and the resolution of the time steps. The extent of the body of waters is normally fixed; however, the duration of observation and the resolutions in time and space are variable.

3. Source of the hindcast data

Global wave data for the years 2008 through 2017 were downloaded from the NOAA website: WaveWatch III® Production Hindcast at http://polar.ncep.noaa.gov/waves/hindcasts. Data for various areas at different resolutions are also available on this website; however, only the global data at .5° resolution are used herein. These data are generated by a model that was periodically updated, so the NOAA recommends that the data are not used for long-term climate studies, but examination of the data indicates that the variations between model upgrades have minimal influence on the current work. The same website has links to validation data that can be explored by the user.

To facilitate ease of access, the monthly data were converted into separate spatiotemporal arrays for the wave height and the wave period. The arrays facilitate dividing up the data to isolate specific bodies of water (e.g., North Atlantic) or specific zones (e.g. tropical or temperate zones), or combinations of both (e.g. temperate North Atlantic). Care is required as the boundaries between oceans can be complicated in many areas, specifically east and west of Latin America and in Southeast Asia where the Indian Ocean meets the Pacific Ocean (see Fig. 1, where the oceans are delineated by solid F1
vertical lines).

The data downloaded from the NOAA cover the oceans between 77.5° north latitude and 77.5° south latitude (or −77.5°) and 0°–359.5° longitude. At a resolution of .5° in both latitude and longitude, the number of possible grid points is 351 × 720 = 252,720. However, many of the grid points are on land or in bodies of water not included in this study, which include large lakes, inland

Nomenclature

WMO = World Meteorological Organization
NOAA = National Oceanic and Atmospheric Administration
NATO = North Atlantic Treaty Organization
STANAG = STANdardization AGreement
SOWM = spectral ocean wave model
n_{Obs} = number of (virtual) wave observations
$\log_{10}(P_{(Obs)})$ = base-10 log (i.e., order of magnitude) of the probability of observing a wave belonging to a specific range of heights and periods
α = alpha – size of tail of a probability distribution
H_S = significant wave height
τ = wave period

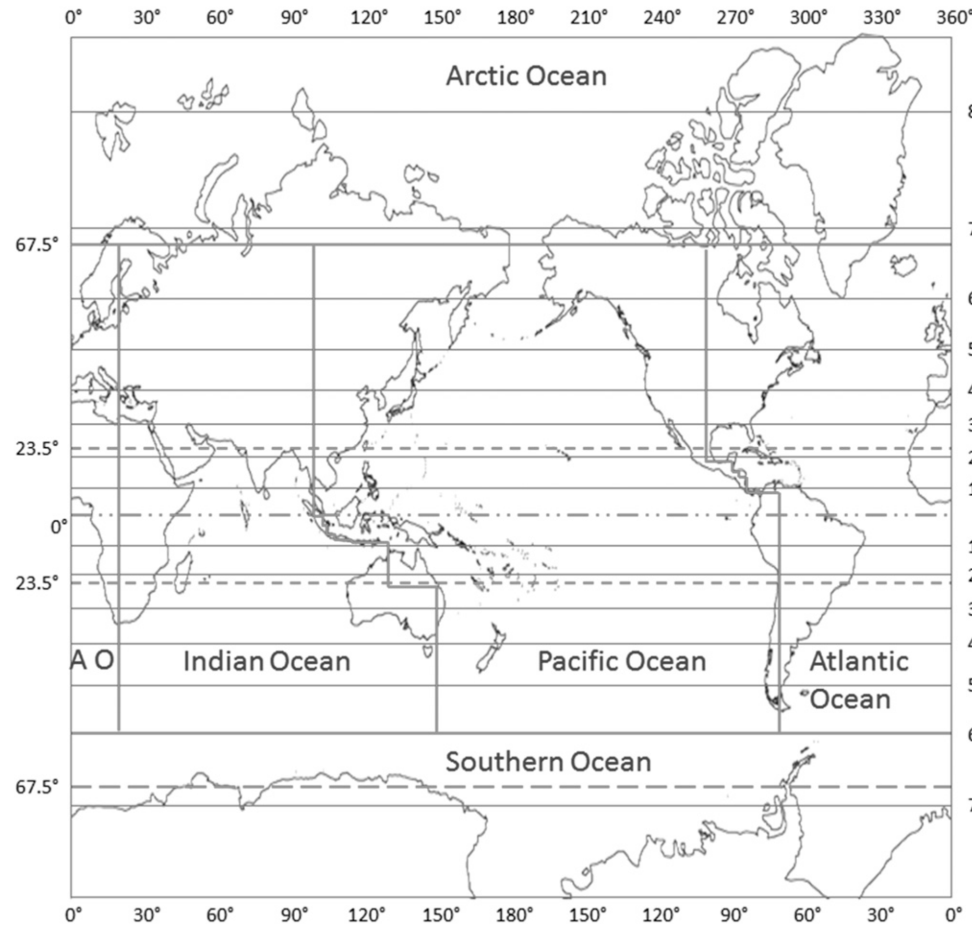


Fig. 1 Definition of oceans and ocean zones

seas, as well as the Baltic, and the Mediterranean. The Arctic Ocean was taken as from the Arctic Circle (67.5°) northward, whereas the Southern Ocean was taken as from $-60.0°$ southward. Tropical zones are from the equator to the tropical circles ($\pm 23.5°$), and temperate zones are from the tropical circles poleward to the boundaries of the Arctic and Southern oceans. Only the three major, nonpolar oceans were considered: the Atlantic, Pacific, and Indian oceans. A composite ocean is also considered as the union of the three oceans. Each of these bodies of water can be divided into north and south zones, and further into north temperate, north tropical, south tropical, and south temperate zones. The north temperate Atlantic Ocean corresponds to the body of water considered by NATO, except that it includes the portion of the Labrador Sea south of the Arctic Circle, and excludes the area off Norway north of the Arctic Circle.

The wave height and period at each latitude and longitude and time represent a virtual wave observation. To be valid, both the wave height and wave period must be simultaneously greater than zero. The arrays are checked for this condition, and only valid observations are retained. Between January 1, 2008 and December 31, 2017, the number of valid grid points in the entire data set for each 3-hour time step was between 133,762 and 145,898. The variation (about 8%) is due to things such as ice coverage in winter months and normal occurrence of calm seas.

For the composite ocean, the number of valid grid points was between 125,173 and 127,464 (approximately 2%), whereas for the north temperate Atlantic Ocean, the number was between 11,205 and 12,051 (approximately 7%). In all cases, this far exceeds the number of locations in the data from the 1970s. In addition, the 3-hour time step of the current data has a finer resolution than the 6-hour time step of the older data.

For each geographical area and time duration, a wave count table is generated from the time series data by counting the number of wave observations within specific ranges of height and period. The specific ranges are bin boundaries used to build a table that depicts the joint occurrence of a specific wave height and period (the bin center), with some (nonoverlapping) tolerance (distance from the center to the boundaries). The wave count table is the heart of the scattergram; however, to better visualize the character of the data, two additional steps are taken. First, the individual counts in each cell of the table are divided by the total number of wave counts possible over the entire table for the duration of the period of observation. This leads to a table of joint probabilities that are a function of the geographical area and the time step resolution and duration of the observation interval. The scattergrams use the base-10 log of the counts as it is more intuitive to show the order of magnitude of the probability of occurrence for each wave height–period combination. Finally, the table of probabilities is converted to a contour map of wave probabilities for each body of water (see, e.g., Fig. 12).

4. Data analysis

The NOAA data provide the wave period corresponding to the peak energy in the wave spectrum, often called the period of the modal frequency, or just the modal period. Because many ship motion codes (for which the environmental characterization data will be an input) use the period of the average frequency (also called the average period), a second set of arrays was generated, where the conversion from the modal to average period was made ($\tau_{avg} = .773\tau_{modal}$; often expressed in the literature as $T_1 = .773T_m$, see, e.g., Beck et al. 1989). This conversion is associated with the Bretschneider wave spectrum, which is generally applicable for the open ocean (deep water). The data associated with the period of the average frequency will be discussed herein unless stated otherwise.

The base resolution inherent in the data from the NOAA is .5° in latitude and longitude and 3-hour time steps. The wave height and period do not have inherent base resolutions; however, resolutions may be chosen to provide useful distributions of the wave counts. Scattergrams are equivalent to a top-down view of 2-dimensional histograms, with the wave height and wave period as the two dimensions.

The volume of bars in a 2D histogram corresponds to the frequency of occurrence; if the bars are equally spaced—as in the current analysis—the height of the bar also corresponds to the frequency of occurrence. Typically, if the width of the bar is too narrow, the histogram is "noisy" and any underlying frequency may be obscured by too many peaks. If the bars are too wide, the histogram is oversimplified and again any underlying frequency may be obscured, but this time by excessive averaging. It is usually recommended that if the number of observations is small, wider bins are used to eliminate noise; whereas if the number of observations is large, narrower bins are used as noise should not be a problem. The NOAA data provide lots of observations, justifying the choice of narrower bins. However, the bins can still be too narrow. The Wikipedia entry on histograms (https://en.wikipedia.org/wiki/Histogram#Number of_bins_and_width) is a starting point for learning about the ongoing effort to find a definitive method for determining the bin size. As with most methods in probability and statistics, it is up to the user to make sure the method is appropriate for the data under investigation. An analysis was made using each of the rules specified in the Wikipedia entry, leading to a multitude of answers. Therefore, a brief investigation into scattergrams with different resolutions (see Fig. 10–14) was undertaken. The results indicate $H = .50$ m and $p = 1.00$ second are reasonable for monthly scattergrams that have fewer wave observations because of the shorter duration. These values are still reasonable for the north temperate Atlantic and, for consistency, will be considered as the baseline herein for all durations. (See the following text for discussion on bin widths in the context of representing the wave heights and periods.)

4.1. Many oceans to one composite ocean

Figures 2–7 show the scattergrams associated with the northern (equator to the Arctic Circle) and southern (equator to −60.0°) hemispheres of the Atlantic, Pacific, and Indian oceans over the 10 years from 2008 to 2017. Figures 8 and 9 show the scattergrams that result when the counts from all three oceans are taken together to form north and south composite oceans. All of these figures show the same general trends in terms of wave observations; the shape and distribution of the wave counts are very similar, except for the north Indian Ocean. This is due to the relative size of the Indian Ocean north of the Tropic of Cancer, having fewer observations available. Note that this subset of the data also includes a portion of the Arctic Ocean north of Russia and south of 77.5°N. Because the Indian Ocean as an independent body of water is not used in the current work, no effort has been made to separate the data for the two bodies of water.

It is also worth noting that the north and south composite oceans mostly resemble the north and south Pacific oceans, respectively. Although the shapes of the scattergrams are such that all observations are included, the distribution of observations tends to be driven by the contributor of the largest number of observations—the Pacific Ocean (Pacific 51%, Atlantic 27%, and Indian 22%). These percentages change for different latitude zones (see Table 1).

4.2. Number of observations and minimum discernible probability

The probability discernible within a set of data depends on the number of observations; more observations will allow discernment of a smaller probability. For example, a probability of one in a million cannot be detected in a data set of 1000 observations. If the event did occur (once) within the data set, it could only be assigned a probability of one in a 1000. The one-in-a-million event will either be misrepresented or not detected at all.

The number of observations for any body of water may vary for any time step because of numerical issues or physical issues such as ice coverage. Bathymetry data can be used to define the number of possible observations, from which a minimum detectable probability (or a minimum order of magnitude of probability) may be calculated. Table 2 shows the minimum orders of magnitude of probability of observing a given wave height and period combination within several durations of observation intervals. The scale for contours in the scattergrams was set to 0 to −10 based on the composite ocean observed over 10 years (3653 days). The scale was used for all scattergrams to allow ease of comparison.

Note that each scattergram presented explicitly states the resolution of the latitude and longitude grid points, as well as the time step and the wave height and period bin sizes. The interval over which the virtual observations are made is 10 years, unless stated otherwise.

4.3. Bin sizes for wave height and wave period

Varying the resolution of the wave height and wave period by varying the bin size can cause shifts in contour patterns. In these cases, the distribution of occurrences is altered by the binning process. Figure 10 shows a scattergram with wave height bins of .25 m and a wave period of .25 seconds, whereas Fig. 11 shows a scattergram for bins of .5 m and .5 seconds. Both of these show evidence of numerical banding and indicate that the bins are too narrow for the wave periods. Figure 12 gives a smoother distribution of the wave counts in both heights and periods without distorting the distribution noticeably. The effects of further

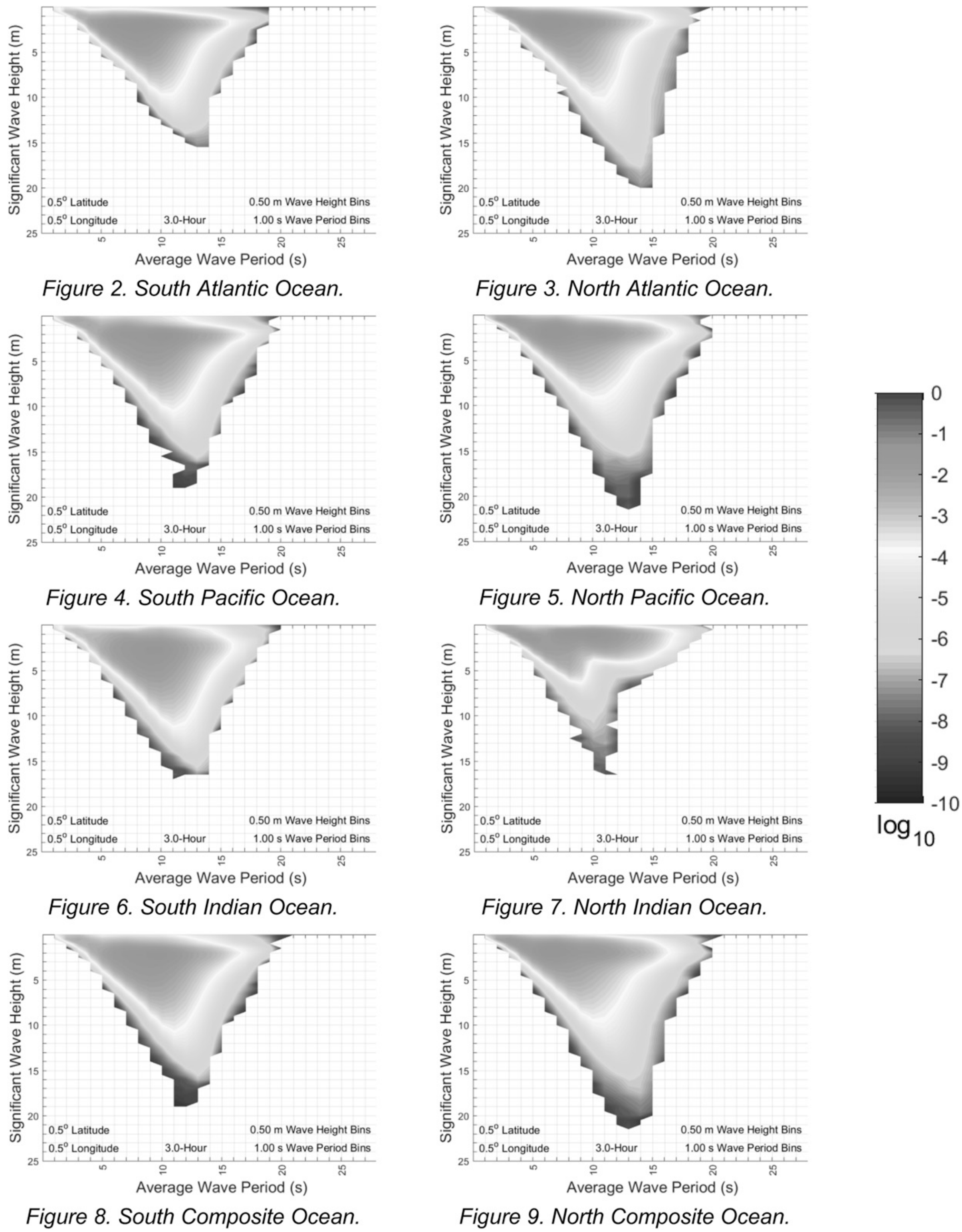


Fig. 2–9 2. South Atlantic Ocean. 3. North Atlantic Ocean. 4. South Pacific Ocean. 5. North Pacific Ocean. 6. South Indian Ocean. 7. North Indian Ocean. 8. South composite ocean. 9. North composite ocean

reduction in resolution are shown in Figs. 13 and 14. These latter figures show that the distribution of observations is affected by the bin size more than .5 m and 1.0 seconds. Although the choice of $\Delta H = .5$ m and $\Delta P = 1.0$ seconds is somewhat arbitrary, it does provide the details of the wave distribution without false numerical artifacts or overaveraging. The bin resolutions were confirmed

Table 1 Percent contribution of each ocean to the composite ocean in the same latitudinal zone

	Latitudinal zone						
Composite	Whole ocean	North of equator	South of equator	North temperate	North tropical	South tropical	South temperate
Indian	22.3	8.8	32.2	3.3	15.3	27.2	34.8
Pacific	50.1	56.1	45.7	52.3	60.7	54.2	41.1
Atlantic	27.7	35.1	22.1	44.5	24.0	18.6	24.0

through the use of the Freedman–Diaconis rule (Freedman & Diaconis 1981).

Figure 12 also shows the composite ocean scattergram that results from adding the wave counts (number of observations) from the northern and southern hemispheres, excluding the Arctic Ocean above 67.5°N latitude and the Southern Ocean below 60.0°S latitude. This composite ocean reflects a worldwide area of operations (usually) free of ice coverage, and will be used to discuss the analyses.

4.4. Duration of observation intervals

F15 – 22 Figures 15–22 show the scattergrams for various durations of observation intervals for the composite ocean and the north temperate Atlantic Ocean, respectively. Generally, the shape and extents of the higher probability areas are similar for all the time periods shown for each geographical area, with variations in the contours, at more extreme wave heights and at longer wave periods. As the duration of observation interval increases in Figs. 15–18, the increasing number of observations admit more occurrences of low-probability conditions, but the overall distribution away from the edges does not change; the distribution of $\log_{10}(P_{(Obs)}) > -5$ does not change noticeably between the 1-year and the 10-year data, indicating that the 1-year scattergram essentially characterizes the composite ocean, on the assumption that 10^{-5} adequately captures the pertinent probabilities. A similar visual inspection of Fig. 19–22 shows that the distribution of $\log_{10}(P_{(Obs)}) > -5$ does change somewhat between the 1-year and the 10-year data, indicating that the 10-year scattergram may or may not characterize the north temperate Atlantic Ocean and a longer duration of observation may be required for some investigations. The larger variation in the probabilities at the edges of the scattergram highlights the need for care when choosing a duration of observations on which to base analysis for a given probability of observation. The composite ocean figures and the north temperate Atlantic Ocean figures are very different from each other, so decisions on geography are as important as those with respect to time. Smaller geographic zones may require longer durations for observation to achieve a useful characterization.

Because the composite ocean is the focus of this study, the 10-year data will be used, and it will be assumed to adequately characterize the north temperate Atlantic Ocean as well, for ease of comparison. Note that the scattergram produced is essentially an average of the 3-hourly data from 2008 to 2017 and that scattergrams normally vary from month to month, season to season, and year to year. It is also worth noting that the time periods do not have to be sequential; it is possible to use same month over several years, e.g., every January for 10 years.

4.5. Resolution of time step and geographic grid points

The effect of increasing the time step (decreasing temporal resolution) and decreasing the resolution of the latitude and longitude is shown in Figs. 23–30. For both the composite ocean and F23 – 30
the north temperate Atlantic, there is a general decrease in probabilities due to fewer observations being available. For the composite ocean, Figs. 23–26 are similar to Figs. 15–18, except that the latitude and longitude steps are 5.0° in the former and .5° in the latter, and the time step is 24 hours as opposed to 3 hours. When comparing corresponding figures in the two sets, the patterns of contours are very similar in the high-probability zones, but there is noticeable change in the low-probability areas as many of the waves

Table 2 Minimum probabilities detectable based on bathymetry

		$\text{Log}_{10}(1/n_{Obs})$			
	n_{Obs}/hindcast	31 days	92 days	366 days	3653 days
Global Ocean	154,947	−7.6	−8.1	−8.7	−9.7
Composite ocean	129,633	−7.5	−8.0	−8.6	−9.6
North composite ocean	55,269	−7.1	−7.6	−8.2	−9.2
South composite ocean	74,931	−7.3	−7.7	−8.3	−9.3
North Indian Ocean	4867	−6.1	−6.6	−7.2	−8.2
South Indian Ocean	24,096	−6.8	−7.2	−7.8	−8.8
North Pacific Ocean	31,025	−6.9	−7.4	−8.0	−9.0
South Pacific Ocean	34,248	−6.9	−7.4	−8.0	−9.0
North Atlantic Ocean	19,377	−6.7	−7.2	−7.8	−8.8
South Atlantic Ocean	16,587	−6.6	−7.1	−7.7	−8.7
North temperate Atlantic	13,419	−6.5	−7.0	−7.6	−8.6

For example, 8 hindcasts per day × 3653 days × 129,633 observations = 3,788,394,792 observations per decade (includes three leap years). $\text{Log}_{10}(1/3{,}788{,}394{,}792) = -9.6$ is the smallest probability detectable for this number of observations and duration of observation interval.

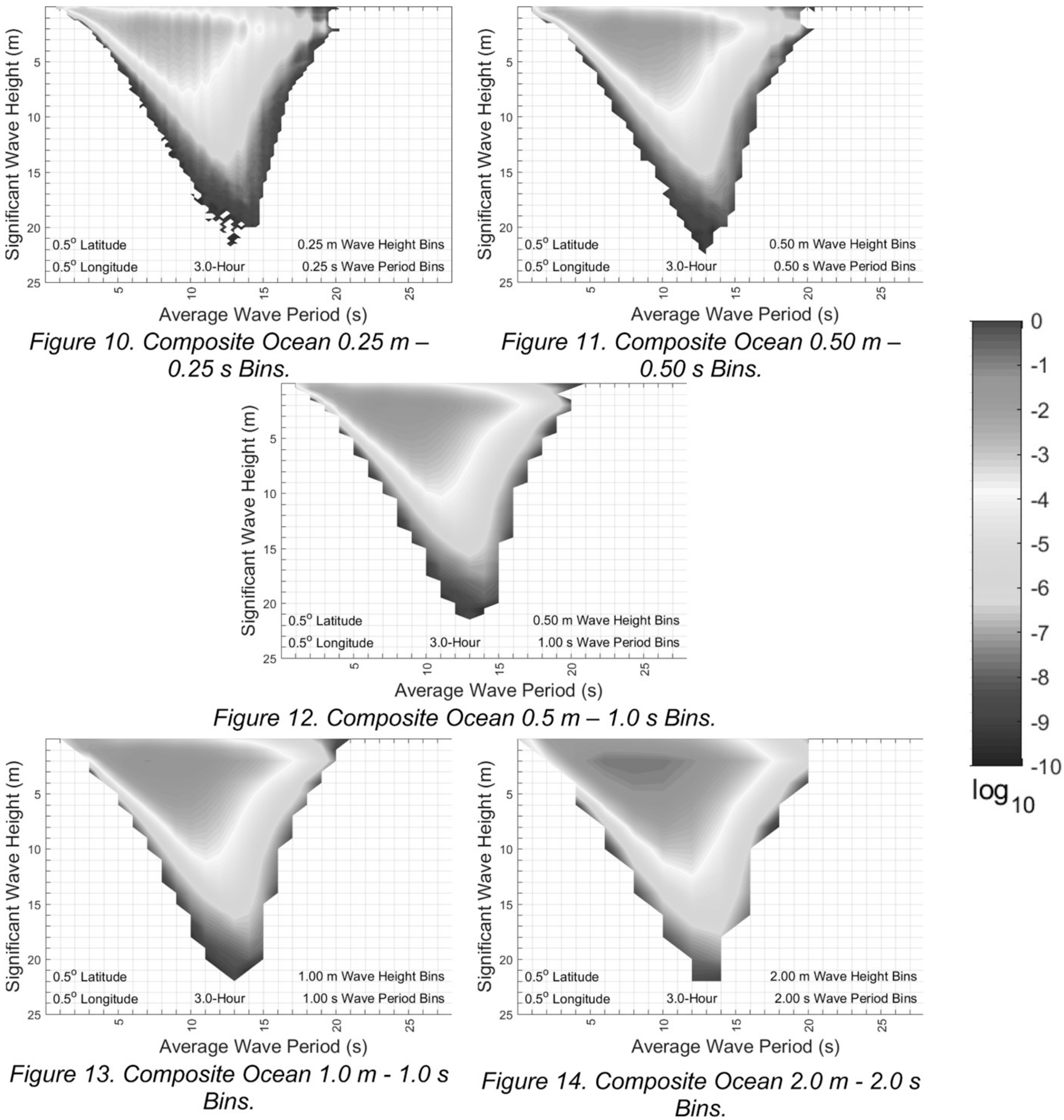


Fig. 10–14 10. Composite ocean, .25 m–.25 seconds bins. 11. Composite ocean, .50 m–.50 seconds bins. 12. Composite ocean, .5 m–1.0 second bins. 13. Composite ocean, 1.0 m–1.0 second Bins. 14. Composite ocean, 2.0 m–2.0 seconds Bins

from the high-resolution data are no longer included in the low-resolution data. For the north temperate Atlantic Ocean, comparing Fig. 27–30 and Fig. 19–22 shows noticeable differences between the corresponding figures for December 2017, the fourth quarter of 2017, and even the year 2017; only the decade data are similar to the high-resolution data (at higher probabilities). The resolution of geographic grid points and time steps can be more important at smaller geographical areas.

5. Bounding the wave height–period joint distribution of wave observations

To provide meaningful statistical data for ship responses in seaways, it is often necessary to run many simulations, on the order of thousands in some cases. Simulating every wave height and period combination may be beyond the allotted resources for a given problem. Therefore, it becomes necessary to limit the scope of

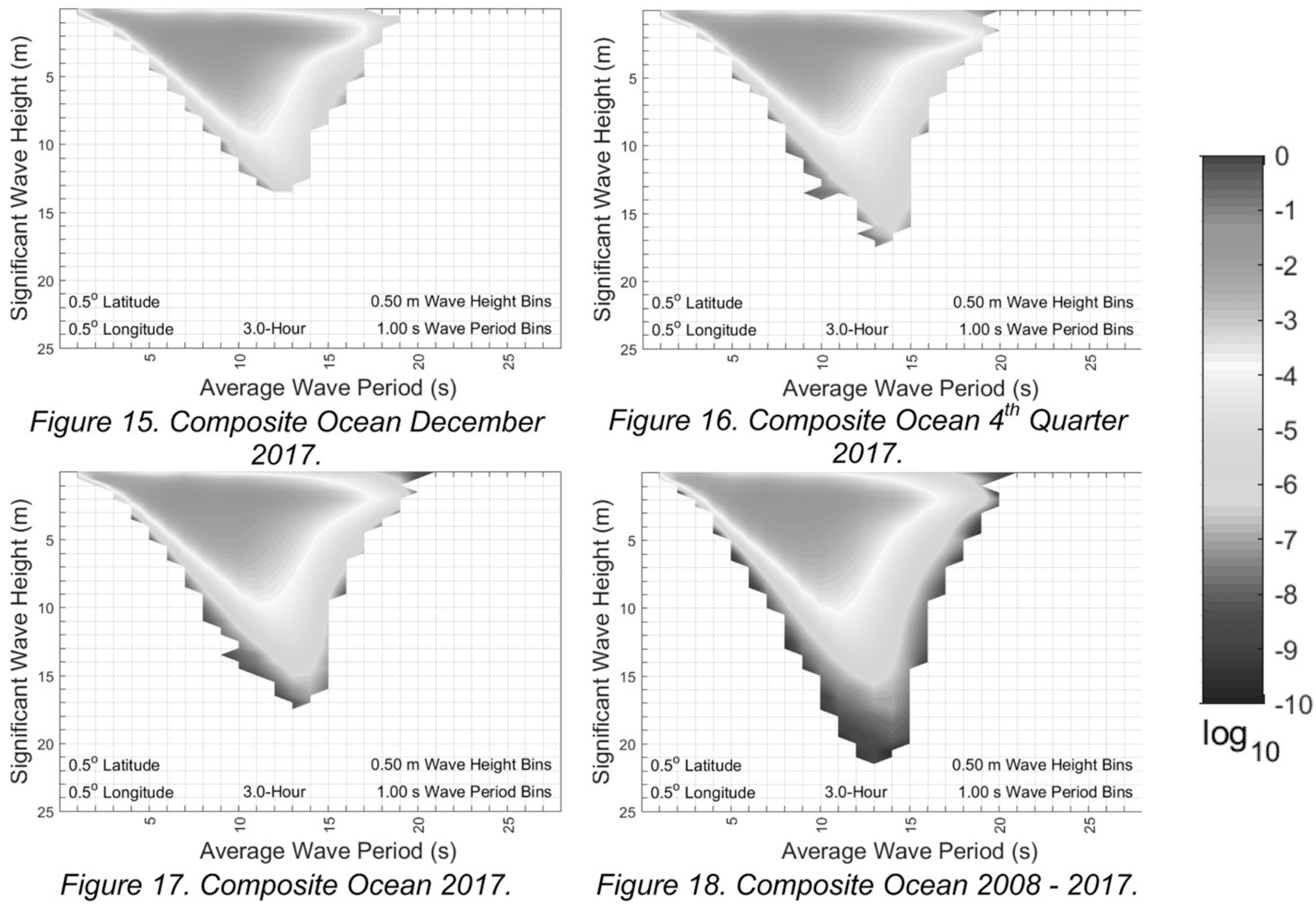


Fig. 15–18 15. Composite ocean, December 2017. 16. Composite ocean, fourth quarter 2017. 17. Composite ocean, 2017. 18. Composite ocean, 2008–2017

simulations with a reasonable boundary on the height and/or period. This can be performed for each sea state or for all sea states taken together.

5.1. Sea state period limits from WaveWatch III hindcast data

The work reported by Bales et al. (1981) was influential in developing the NATO sea states (STANAG 4194), which are categories of sea conditions. The wave heights agree with the World Meteorological Organization (WMO) standard, which is basically the Douglas wind sea scale—the seas generated by local winds, rather than swell from remote storms. Bales added the wave period and wind data from Pierson's SOWM (Pierson et al., 1966). The fifth and 95th percentiles of the wave periods were used to define boxes within each wave height range.

F31 Figure 31 shows the north temperate Atlantic Ocean with the NATO sea states based on the older hindcast data in dot-dashed lines and the updated hindcast data in dashed lines. For clarity, the label for the uppermost sea state box (which represents the sea states less than 3; i.e., 0 through 2) has been removed and the label for the next box (Sea State 3) has been modified to include both boxes ("≤ SS 3"). Note also that this figure uses the modal (peak) period rather than the average period. Recall that the north temperate Atlantic Ocean corresponds to the body of water considered by NATO, except that it includes the portion of the Labrador Sea south of the Arctic Circle and excludes the area off Norway north of the Arctic Circle. Figure 31 does show a shift in the observed wave periods, based on the increased number of (virtual) observations from the WaveWatch III model. Figure 32 shows the shift in periods F32
if the composite ocean data are used. The shifts are similar to those for the north temperate Atlantic Ocean (see Table 3). T3

Although the contour plots in Figs. 31 and 32 are generated from wave counts of uniformly spaced significant wave heights and modal wave periods (.5 m and 1.0 seconds, respectively), the sea state boxes and the associated period limits (Table 3) are generated from a special count using the sea state definitions as the wave height bins. This was performed to be more reflective of the original NATO data and did give slightly different period limits than when the counts from the uniformly spaced wave heights were used (not shown).

5.2. Bounds on the wave periods for each sea state

The fifth and 95th percentiles used in the NATO sea states are typical values corresponding to the tails of the distribution of periods and are easily parameterized by the symbol α. A value of $\alpha =$ .05 means that 5/100 data points (5%) will have a wave period less than some period, τ_α, and a further 5% will have a wave period greater than some period, $\tau_{(1-\alpha)}$. These data are excluded so that

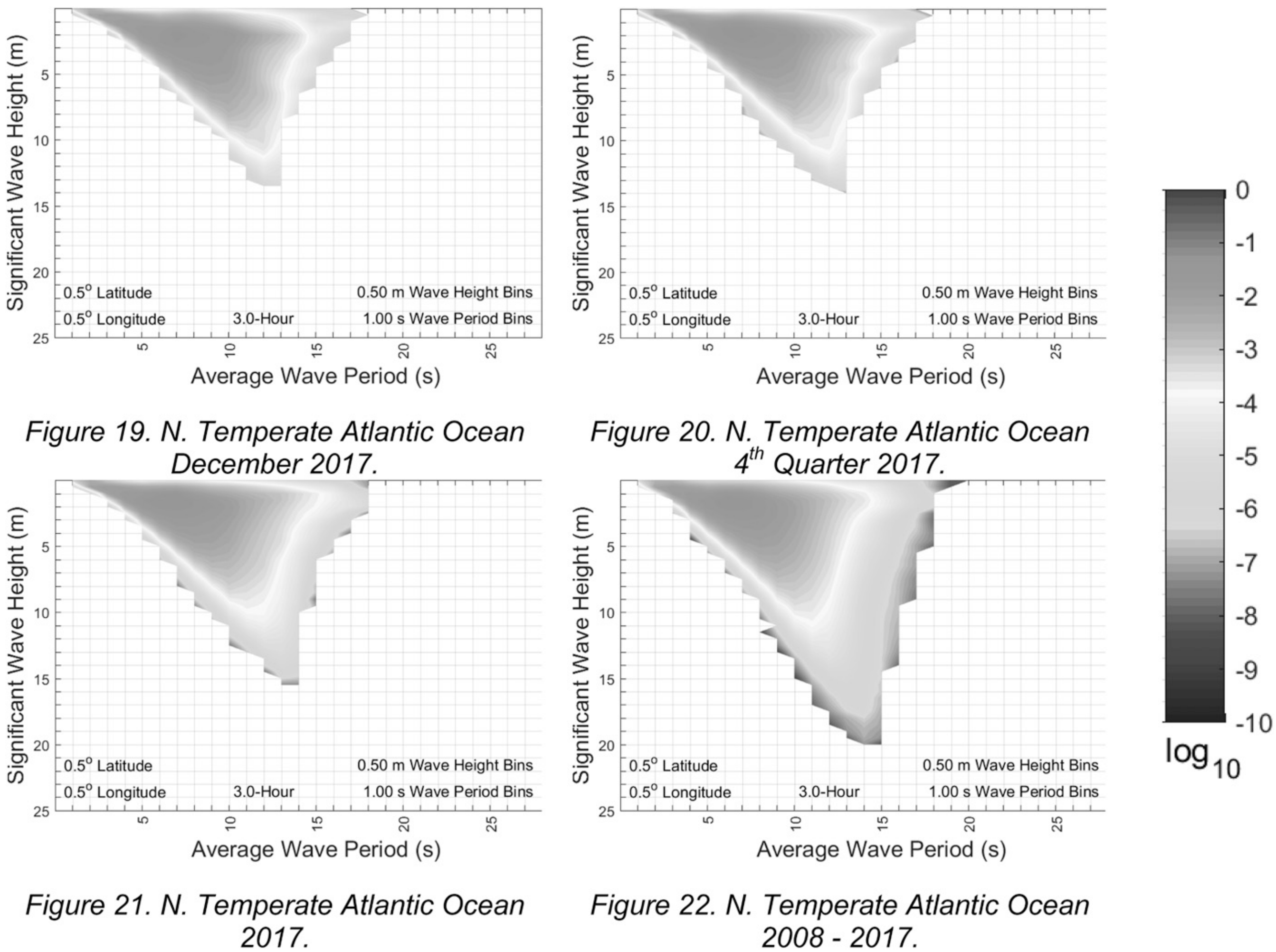


Fig. 19–22 19. North temperate Atlantic Ocean, December 2017. 20. North temperate Atlantic Ocean, fourth quarter 2017. 21. North temperate Atlantic Ocean, 2017. 22. North temperate Atlantic Ocean, 2008–2017

only $(1-2\alpha)/100$ data points (90% of the data) are retained within the sea state bounding box.

5.3. Binning the hindcast data may have some effects on the achieved percentiles of retained data

Columns 2 and 3 of Table 3 show the wave height limits defining the sea states by the Douglas wind sea scale. The fifth percentile and 95th percentile periods in columns 4 and 5 are determined by interpolation of the binned period data and do not correspond to the bin limits because the bin resolution for wave periods is 1 second.

Note that the wave height limits are consecutive bounds where all the data are in one sea state or another, whereas the wave period bounds merely exclude data in the regions outside the limits.

Bounding the scattergram (all sea states taken together)

Often we are interested in the tails where the most extreme behaviors can occur because the consequences can be significant, even disastrous. However, the combinations in the tails occur less often by definition. Because we are trying to characterize the ship behavior through an optimal number of simulations, rare events beyond a certain threshold may be considered too rare to be of practical concern. The concept of setting a practical limit for the tail regions can be used to capture most data while limiting the range of periods to be considered. An investigation into how much of the scattergram is relevant for characterizing the environment was made. The value of α was varied from 10^{-1} to a value of 10^{-7} (see Table 4). Now, the α is applied to both the periods and heights. T4

It is possible to find a specific value of the wave period that will provide the required number of wave counts to partition the data at the α limit. However, it is likely that the value does not fall on a bin limit, and the choice must be made whether to include or exclude the rest of the observations in the bin. The choice was made to include all wave observations in the bin containing the actual limits. This results in more observations being included in the wave counts. The choice is conservative in the sense that it ensures that all data between the actual limits are included in the analysis. This typically leads to a difference in the actual number of observations used and, thus, the true value of α, which may now also be different at each tail. Furthermore, the discrepancy is compounded when α is applied to the combination of wave heights and periods. For example, when an α of .05 is called for in the expectation of keeping 90% of the

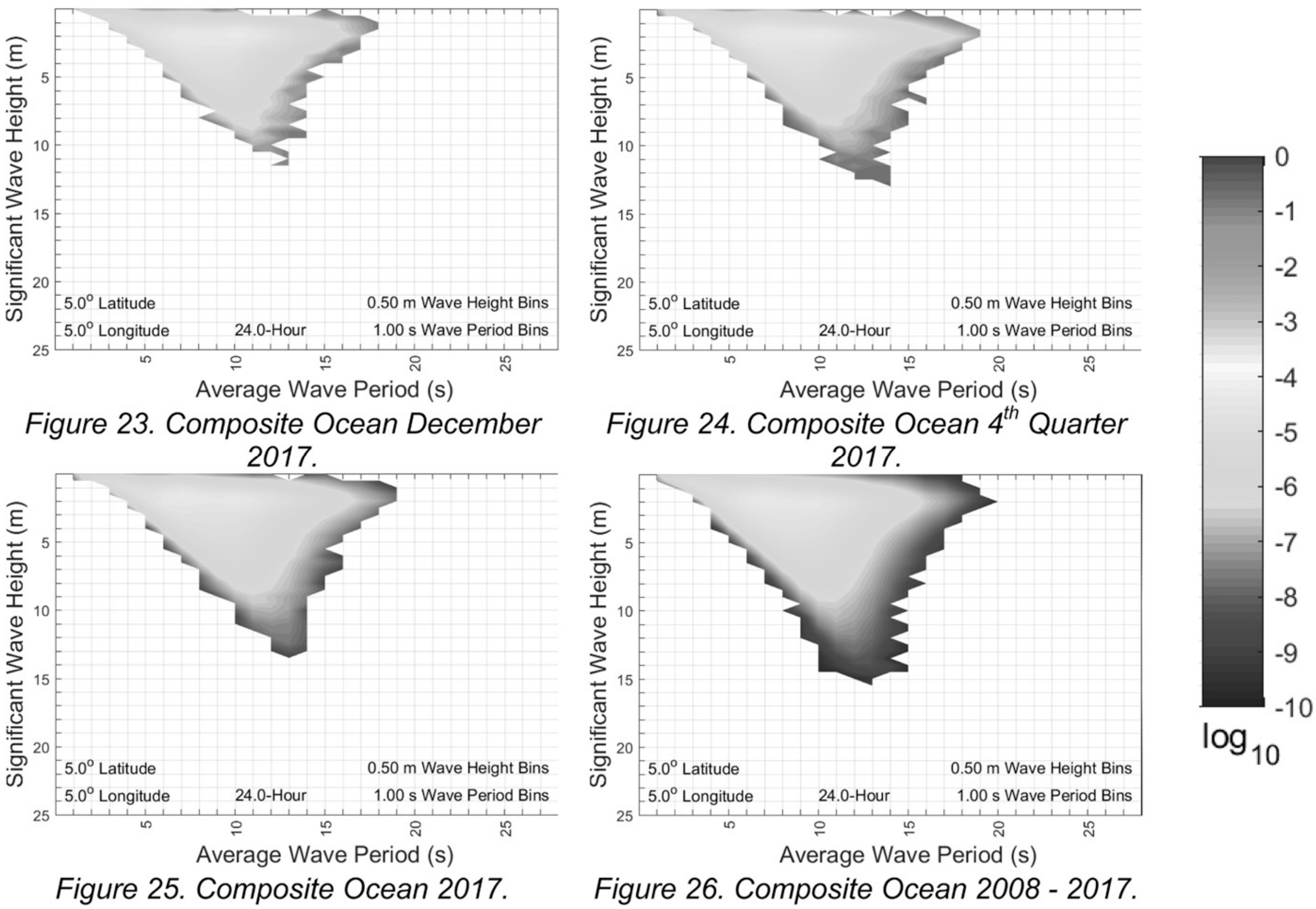


Fig. 23–26 23. Composite ocean, December 2017. 24. Composite ocean, fourth Quarter 2017. 25. Composite ocean, 2017. 26. Composite ocean, 2008–2017

data, 95.0% of the height data and 94.4% of the period data are kept (see Table 5). In combination, only 89.9% of the data are included; 10.1% (about 1/10 of the observations) are excluded. This is less than the 20% ($2 \times 5\% = 10\%$ for the wave height and 10% for the wave period) that might be expected because of the binning and because the excluded tails overlap, where both the wave height and period are beyond the limit (in the corners of the scattergram). When the nominal α is decreased by two orders of magnitude (.0005), the combined exclusion of data is reduced to about 7/10,000 data points.

For context, a combined interval of 1000 3-hour periods is equivalent to 125 days at sea, which is about a year in the life of a naval vessel. Even at an α of .001 (actually 12/10,000), a typical naval vessel could experience one of the sea states outside the bounding box in any given year (see Fig. 33). For a once-in-a-lifetime event (1/1000) for a fleet of 10 ships with a life expectancy of 50 years, a once-in-a-lifetime (of the fleet) occurrence is 1/500,000, which is presented in Table 5 with an α of 2×10^{-7} (see Fig. 34). This would mean including wave heights up to 18 m and wave periods as long as 19 seconds. The point is that the rareness of an event has an influence on the number of seaways that must be included in the study, and the scattergram can provide reasonable guidance on how many and which seaways to include.

If the wave height bin size is .5 m and the wave period bin size is 1 second, this would mean simulating 34 heights $\times$ 19 periods or up to 646 sea states. This latter number would be reduced by those points where the scattergram shows no occurrence of the height–period combination.

Further reduction may be warranted by using larger height and period bins, if the averaging effects are acceptable.

6. Characteristic Wave Steepness and Energy

Ship response is the determining factor for defining the extent of the scattergram necessary for simulations. This allows for the existence of other features to define the scattergram. For example, the wave height and period can be used to calculate characteristic wave steepness and characteristic wave energy. They are only "characteristics" because they are regular wave calculations applied to irregular waves. Observations from earlier studies indicate that the probability of exceeding a critical roll angle corresponds to wave steepness and, possibly, energy more than to the wave height and period themselves (Perrault & Marshall 2019). Figure 35 shows the contours of steepness and energy overlaid on the scattergram. It may be possible to limit the scope of sea states that must be investigated by ignoring some combinations of heights and periods where the characteristic steepness is low, although their probability of observation is high, under the assumption that the low steepness correlates to low probability of extreme motion. A similar scope

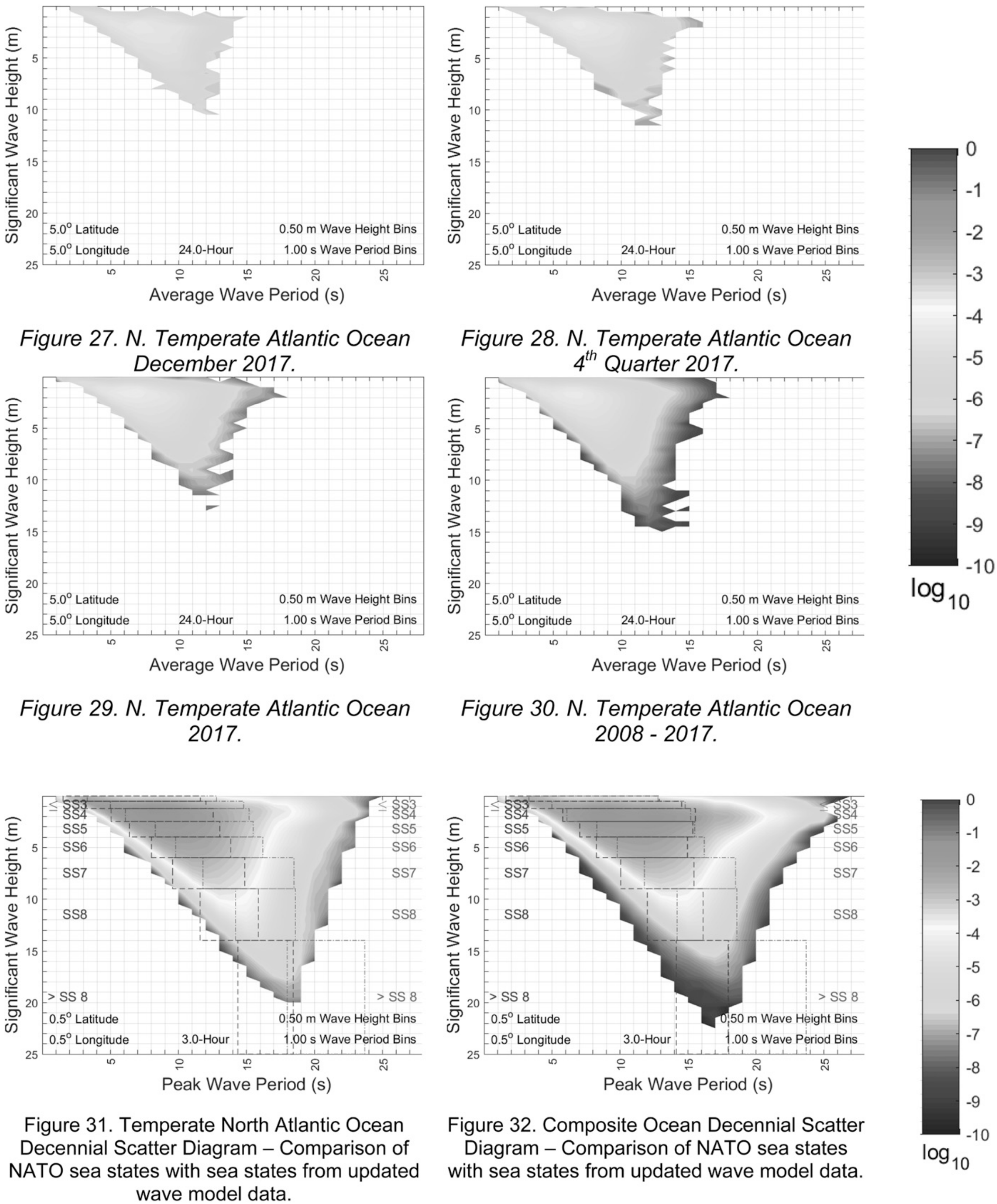


Fig. 27–32 27. North temperate Atlantic Ocean, December 2017. 28. North temperate Atlantic Ocean, fourth Quarter 2017. 29. North temperate Atlantic Ocean, 2017. 30. North temperate Atlantic Ocean, 2008–2017. 31. Temperate north Atlantic Ocean decennial scatter diagram—comparison of NATO sea states with sea states from updated wave model data. 32. Composite ocean decennial scatter diagram—comparison of NATO sea states with sea states from updated wave model data

Table 3 Sea state limits for composite ocean (2008–2017; α = .05)

Sea state	Wave heigth (m)		Wave period (second)	
	H_S lower	H_S upper	τ_α	$\tau_{1-\alpha}$
<3	.00	.50	1.607	12.893
3	.50	1.25	3.294	14.538
4	1.25	2.50	5.795	15.548
5	2.50	4.00	7.039	15.358
6	4.00	6.00	8.272	14.967
7	6.00	9.00	10.051	15.446
8	9.00	14.00	12.011	16.110
>8	14.00	unlimited	14.146	17.958

reduction might be considered based on the characteristic wave energy. The limiting steepness and energy should be investigated.

7. Summary

This study examines updating an established tool for characterizing wave conditions that are used for studying ship response in waves. The intent of the investigation was to identify the optimum amount of data required to fully and accurately characterize the environment. Although "optimum" was a problem-specific target, a brief investigation was made into the effects of varying the resolution of various indices of the data (time, latitude, and longitude), as well as the statistical bin size for the wave height, and wave period. Whereas variation in the spatial and temporal resolutions had small effects on the environment characterization once a sufficient number of observations were included, varying the wave height and period groupings (bins) had more significant effects, as they directly determine the distribution of the wave counts.

It was also noted that the distribution of periods within a given sea state has shifted in the new data as compared with the periods defined by the older model data.

Along the way, several choices were highlighted that influence the applicability of the developed scattergram to the user's question:

1) The spatial and temporal ranges of wave data used to populate the scattergram should be sufficient to cover the area and time period necessary, but the resolution of the data can be reasonably coarse without adversely affecting the scattergram. This reflects the physical nature of the wave systems as large, slow-moving structures, indicating the model results are reasonable.
2) The geographical area selected must be relevant to the ship or fleet. Although the composite ocean was used here as an example and is relevant for ships with worldwide, nonpolar areas of operations, a given ship may be expected to operate in only one ocean or only one area (zone).
3) The duration of observation may be chosen as a balance of time and accuracy. Here, 10-year data are used as an example, giving a strong—if somewhat averaged—characterization of distribution of wave conditions in the composite ocean. Smaller areas, such as the north temperate Atlantic Ocean, may require more observations, i.e., a longer interval of observation because of having fewer geographic grid points to provide observations. Here is where there may be a trade-off between the number of observations required and the certainty of the characterization. In this study, a visual comparison of the contours for a specific probability was used to indicate the convergence of dependable characterization. As a general principle, it is best to use finest resolution available (time, latitude, and longitude) as time/computational capacity permits.
4) The scattergrams are affected considerably by the size of the wave height and wave period bins. Bin sizing is again a

Table 4 Bounding box limits for composite ocean (2008–2017)

α	H_S interpolated		H_S achieved		τ interpolated		τ achieved	
	α	1 − α	~α	~(1 − α)	α	1 − α	~α	~(1 − α)
1×10^{-1}	.96	4.45	.5	4.5	5.063	10.852	5	11
5×10^{-2}	.60	5.35	.5	5.5	4.090	11.711	4	12
2×10^{-2}	.22	6.46	.0	6.5	2.958	12.761	2	13
1×10^{-2}	.06	7.29	.0	7.5	2.271	13.509	2	14
5×10^{-3}	.00	8.07	.0	8.5	1.818	14.015	1	15
2×10^{-3}	.00	9.09	.0	9.5	1.297	14.815	1	15
1×10^{-3}	.00	9.84	.0	10.0	1.123	15.328	1	16
5×10^{-4}	.00	10.51	.0	11.0	1.036	15.864	1	16
2×10^{-4}	.00	11.40	.0	11.5	.000	16.550	0	17
1×10^{-4}	.00	11.99	.0	12.0	.000	16.869	0	17
5×10^{-5}	.00	12.61	.0	13.0	.000	17.164	0	18
2×10^{-5}	.00	13.38	.0	13.5	.000	17.729	0	18
1×10^{-5}	.00	13.95	.0	14.0	.000	17.917	0	18
5×10^{-6}	.00	14.58	.0	15.0	.000	18.106	0	19
2×10^{-6}	.00	15.43	.0	15.5	.000	18.648	0	19
1×10^{-6}	.00	16.18	.0	16.5	.000	18.829	0	19
5×10^{-7}	.00	16.91	.0	17.0	.000	18.919	0	19
2×10^{-7}	.00	17.75	.0	18.0	.000	18.973	0	19
1×10^{-7}	.00	18.44	.0	18.5	.000	18.991	0	19

Table 5 Percent data retained in bounding boxes for composite ocean (2008–2017)

α	1 − 2α nominal	Achieved height	Period	Combined
1×10^{-1}	.8	.90	.87	.78
5×10^{-2}	.9	.95	.94	.90
1×10^{-2}	.98	.992	.995	.987
1×10^{-3}	.998	.9992	.9996	.9988
1×10^{-4}	.9998	.99990	.99994	.99984
1×10^{-5}	.99998	.999991	.999994	.999985
1×10^{-7}	.999998	.9999993	.9999999	.9999992
2×10^{-7}	.9999996	.99999985	.99999995	.99999980

user preference. In this study, the bins were chosen to provide the finest resolution without losing coherence in the contour plots (getting "banded" histograms).

An investigation into reducing the area of the scattergram to include in motion studies showed that the scattergram up to and including 18 m significant wave height and 19 seconds average wave period should be investigated. This corresponds to a once-in-a-fleet lifetime. For a once-in-a-ship lifetime occurrence, wave heights up to 15.5 m and periods up to 19 seconds should be investigated. For once-in-a-ship year, wave heights up to 10 m and periods up to 16 seconds should be investigated.

There may be other criteria that can be used to reduce the area of interest, such as wave steepness or energy.

The drawback with fine resolution in the scattergram is that it suggests that many wave conditions must be investigated to determine ship response. It is possible that a more coarse resolution is sufficient to fully characterize ship behavior, but this can only be determined by actually performing simulations. A way to do this may be to start with a coarse resolution for the ship simulations and refine until there is convergence in the responses of interest. A spot check beyond this point may give assurance that the convergence has indeed been reached. The wave scattergrams provide a starting point for the simulations by identifying where wave conditions do not exist and where the more probable wave conditions can be found.

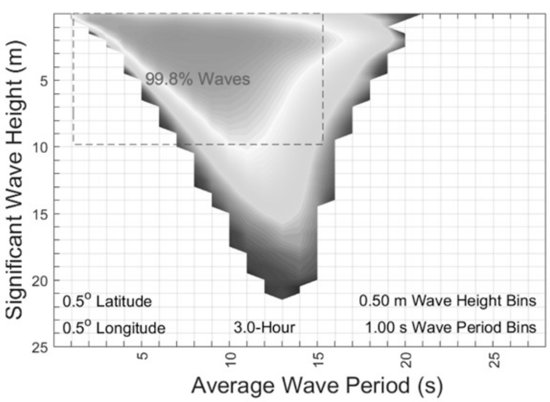


Figure 33. Composite Ocean - P(occurrence) Bounding Box (α = 0.001).

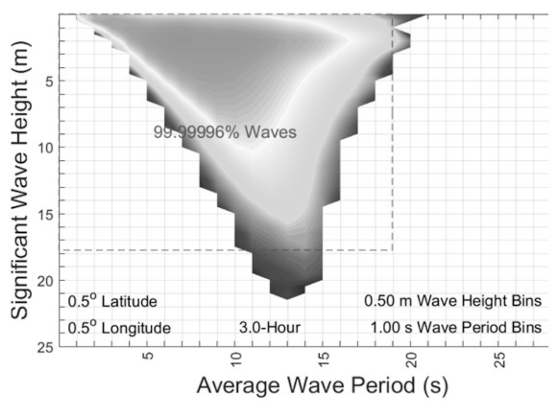
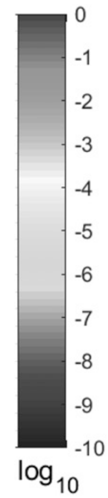


Figure 34. Composite Ocean - P(occurrence) Bounding Box (α = 0.0000002).



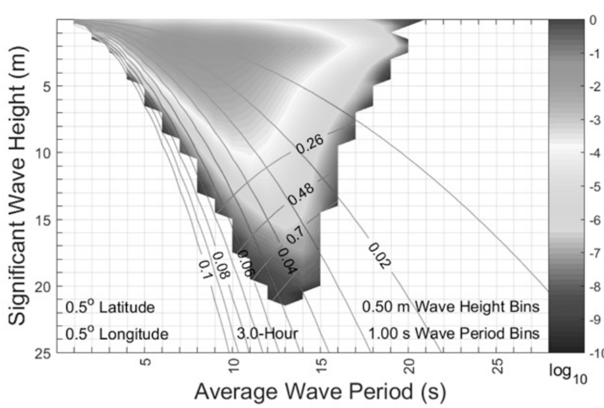


Figure 35. Composite Ocean Decennial Scatter Diagram – Complete with Characteristic Wave Steepness and Energy.

Fig. 33–35 33. Composite ocean—$P_{(occurrence)}$ bounding box (α = .001). 34. Composite ocean—$P_{(occurrence)}$ bounding box (α = .0000002). 35. Composite ocean decennial scatter diagram—complete with characteristic wave steepness and energy

8. Conclusion

This study has demonstrated an updated scattergram based on a modern wind wave model, taking advantage of the increased number of wave observations and finer resolution time steps. A clear picture of the effects of varying important parameters has been developed, leading to a reasonably certain characterization of the wave environment in specific (open water) areas. That is, an example has been given on how to obtain a reasonable characterization for a composite ocean. Ideas have been introduced for defining the scope of wave conditions to be examined through ship motion simulations or other ship response characteristics. The methods investigated should help expedite the follow-on calculations for assessing the probability of specific responses.

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Modelling and simulation continues to be an important tool for determining the response of sea-going vessels to wind and waves. To provide appropriate forcing functions to the models, it is important to have environmental data of sufficient fidelity to facilitate an assessment of platform response, which is as accurate as possible within the practical constraints of time and resources. Fortunately, there are a variety of sources of good wave data, including the U.S. National Oceanic and Atmospheric Administration. This study examines the wave data in the context of simulation codes for assessing characteristics of ocean craft response. It also looks at some practical considerations to limit the scope of simulations. The work is strongly influenced by modelling and simulation of naval surface ships, looking for extreme behaviors, but many of the issues discussed are broadly applicable to other applications.