
WAVE CLIMATE ON THE SOUTHWESTERN COAST OF LAKE MICHIGAN: PERSPECTIVES FROM WAVE DIRECTIONALITY *

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ABSTRACT

Wave directionality plays a critical role in shaping coastal conditions and influencing local livelihoods, underscoring the importance of conducting detailed analyses. This study examines directional wave climate along the southwestern coast of Lake Michigan from 1979 to 2023 using the Directional Wave Entropy (DWE). Directionality was characterized in terms of inter-annual trends, monthly patterns, spatial variation, and extreme wave conditions. Overall, results exhibited a strong bi-directionality, with dominant northern and southern wave systems along the coast of our study site. A few annual trends for the inter-annual wave climate were observed, and there is a clear seasonal variation such that bi-directionality increases in the summer and winter seasons. As for spatial variation of wave directionality, all locations in the study sites presented a bi-directional wave climate. The two dominant directions of wave directionality: northern and southern mean significant wave heights were also characterized in all locations of study sites as 0.566 and 0.563 meters. Furthermore, the extreme wave heights in the northern direction are significantly greater than the extreme waves in the southern direction. In summary, these findings suggest the importance of wave directionality on coastal structural design and coastal morphology management along the coast of our study site.

Keywords Wave climate · Wave directionality · Inter-annual trend · Monthly trend · Extreme wave conditions · Lake Michigan

1 Introduction

Wind-waves are important processes that significantly affect the evolution of coastal morphology, coastal structural design, and coastal ecosystem health [1]. To describe features of wind-waves, the wave climate, which is defined by average and extreme wave conditions such as wave height, period, energy, and directionality, has been widely applied across engineering and scientific fields [2, 3]. First, wave height and direction are known to be associated with nearshore sediment transport [4, 5], which can imply the changes in coastal morphology [6, 7, 8]. Second, wave climate is crucial for designing coastal structures. For example, wave height and period are key parameters for designing harbors, marinas, and breakwaters to shelter ships and mitigate harbor resonance [9]. Additionally, extreme wave conditions are fundamental considerations in the development of wave power facilities for renewable energy [10, 11]. Third,

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wave climate is associated with the health condition of nearshore ecosystems. For example, wave energy was found to correlate with water quality metrics, such as water bacterial exceedances, in beach environments [12]. Meanwhile, wave energy can influence the oxygen dissolution of water and further affect the spawning and egg-dispersal of trout [13, 14]. In summary, wave climate is a critical concept that facilitates the understanding of wave impacts on coastal environments.

Directional wave climate is a special perspective of wave climate, which focuses on the directional characteristics of the waves. Unlike the conventional “wave directionality” which reflects the feature of the instant energy spectrum, the directionality of wave climate describes the directional features over time [15, 16]. In most open oceanic areas, the waves typically approach from a uniform direction [17, 18], which is also known as a uni-directional wave climate. Nevertheless, in some specific regions, waves can be bi-directional or multi-directional, where waves come from more than one dominant wave direction. For example, wave bi-directionality has been found in enclosed or semi-sheltered water bodies with elliptical shapes such as Black Sea [19], Azov Sea [20], Baltic Sea [21], Bohai Sea [22], Adriatic Sea [21], and Red Sea [23]. Bi-directional wave climate can also occur at the channels, such as English Channel [16], Tasman Sea [24], and Malacca Strait [25], where the wave could approach from two sides. Given the widespread presence of bi-directional wave climates across the globe, a thorough characterization and analysis of their features and implications is essential.

Characterizing wave directionality is imperative because different directionalities can have different implications on coastal environments such as coastal morphology [26]. Specifically, a uni-directional wave is likely to induce a uniform longshore sediment transport [27], leading to beach erosion at the updrift extent [28]. In contrast, a bi-directional wave can induce longshore sediment transport towards opposite directions, which is likely to cause an imbalance of the sediment budget in the coastal littoral cells. Imbalance of sediment budget in a littoral cell is usually a signal of shoreline erosion and accretion [29, 30]. Besides beach morphology, wave directionality can also affect coastal structural designs. The conventional design wave height for designing structures assumes that the waves are uni-directional [31]. Nevertheless, this parameter can be underestimated when considering the distribution of two components of the bi-directional waves [31], leading to instability of structures. Last but not least, bi-directional waves can generate larger ship responses than uni-directional waves, leading to navigation safety issues [32]. To date, wave directionality characterization is crucial for coastal morphology, structures, and ships.

Despite that wave directionality is important and has been characterized in some specific oceanic areas, the wave directionality has rarely been fully explored in freshwater lake systems. Lake Michigan, the third largest lake among the Great Lakes, is significantly affected by wind waves [33, 34]. Previous studies have been made to reveal the wave climate in Lake Michigan, mainly focusing on inter-annual trends [35, 36], monthly fluctuation [37, 34], spatial variabilities [34], and extreme conditions [38] of wave height. For directionality, some locations in Lake Michigan typically experience waves from both northern and southern directions due to their extensive north-south wind fetch, as reported in several studies [*e.g.*, 39, 40, 35, 41]. Nevertheless, two knowledge gaps remain. First, the current wave directionality study in Lake Michigan is not based on a quantitative approach. Second, the spatial and temporal trends of the two dominant wave components of bi-directional waves have not been adequately investigated.

The objective of this research is to characterize the directionality of wave climate in the southeastern Wisconsin coast of Lake Michigan. An index-based metric is developed to characterize wave directionality using the WIS hindcast data from 1979 to 2023. Spatial patterns and temporal (*e.g.*, inter- and intra-annual) trends of the directional wave climate at the study site were examined. Wave directionality under extreme wave conditions (*e.g.*, 90%, 99%, and 100-yr return period) was revealed. This paper is structured as follows: Section 2 introduces the study site and describes methods for characterizing wave directionality, spatial and temporal features, and extreme conditions. Section 3 presents results. In Section 4 discusses several topics, including the sensitivity of the threshold in defining wave directionality, the correlations of wave directionality with wave and wind factors, wave directionality characterization results for the whole Lake Michigan shoreline, implications of wave directionality on beach morphology, and limitations of the study. Section 5 provides conclusions.

2 Methods

2.1 Study site and data sources

The study area is the southwestern nearshore of Lake Michigan, USA (Figure 1a). Lake Michigan is one of the five Great Lakes of North America and the only one located entirely within the United States. Figure 1b presents the geographical coverage and bathymetry of Lake Michigan. The lake is surrounded by four states: Wisconsin, Illinois, Indiana, and Michigan. Its deepest point, at 275 meters, is located in the northern part (marked as a white diamond in Figure 1b). The black dots represent nearshore stations from the U.S. Army Corps of Engineers (USACE) Wave Information Study (WIS), located 5–10 km offshore with water depths of 20–70 m. Figure 1c zooms into the gray area

in Figure 1b, covering the region from the northern border of Ozaukee County, Wisconsin, through Milwaukee County and Racine County, to the southern border of Kenosha County. This is the most developed region in Wisconsin, with a population exceeding 1.3 million and a GDP of 100 billion dollars (United States Census Bureau, 2020). The study area spans approximately 120 kilometers (80 miles) of coastline, featuring bluffs, beaches, sandy dunes, and urbanized areas.

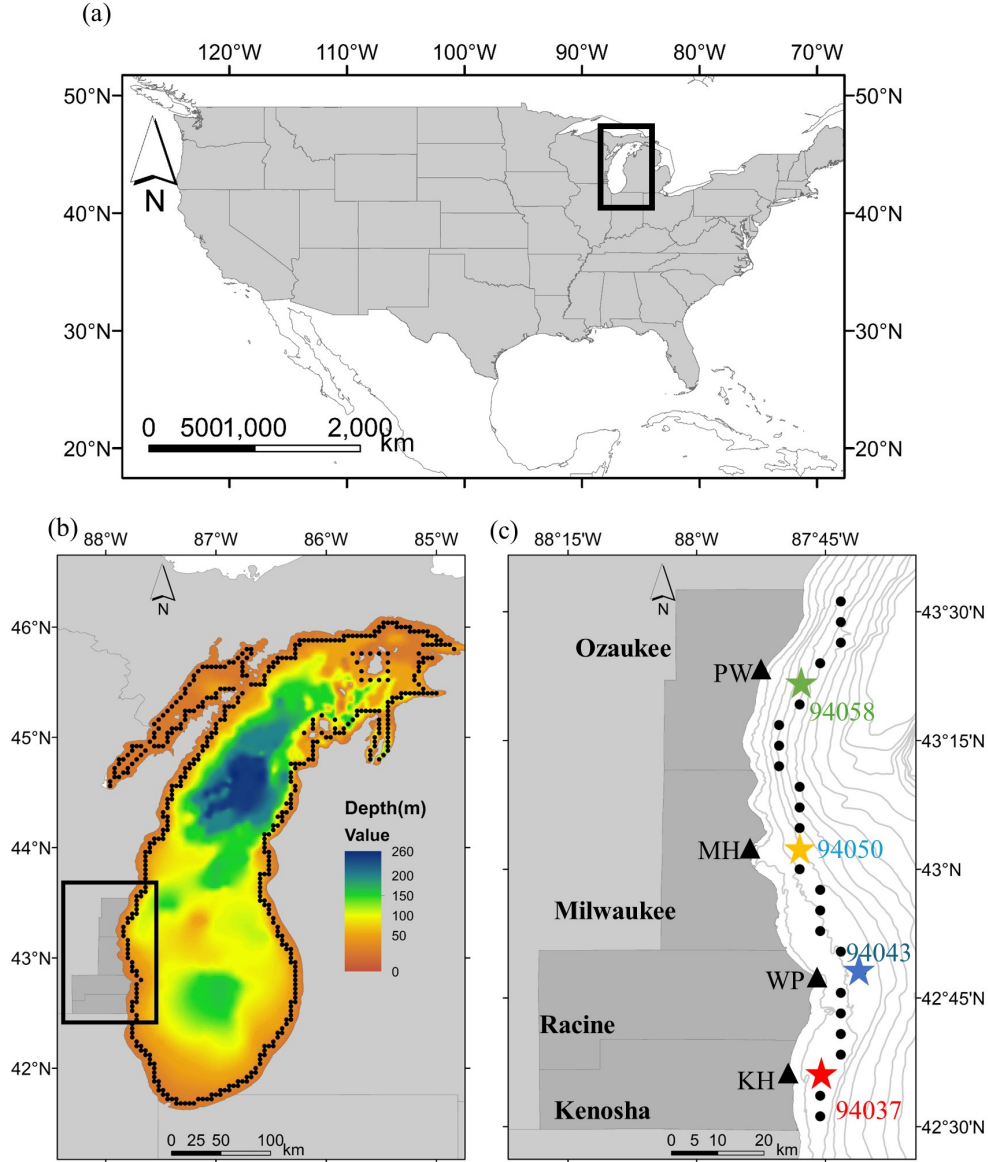


Figure 1: Study Sites. (a) the location of Lake Michigan in the United States. (b) Lake Michigan bathymetry and WIS stations. The 490 WIS stations are marked as dark dots, and the white diamond marks the deepest point of Lake Michigan. (c) study sites in Wisconsin area. Four major cities (PW-Port Washington, MIL-Milwaukee Harbor, WP-Wind Point, and KEN-Kenosha Harbor) are marked with dark triangles. The four stations for four cities are marked with colored stars, aligned with their corresponding station IDs. The interval of the bathymetry contour is 10 meters under IGLD1984.

Long-term (44 years from 1979 to 2023) hourly wave data, including significant wave height (H_s), peak spectral wave period (TP), and mean wave direction (MWD), were obtained from the WIS [42]. In the Great Lakes, WIS provided hourly directional wave fields (72 bands, each 5 degrees) and frequency ranges (28 bands starting at 0.0611 Hz with $f(n) = 1.1f(n-1)\Delta f$, with $f(n)$ representing frequency for band n) using the third-generation wave model (WAM) (Komen et al., 1984). The WAM model simulated waves by 0.04-degree spatially interpolated wind fields from the Climate Forecast System Reanalysis (CFSR) [43] and mean daily ice concentration fields [44]. A total of 26

WIS hindcast stations (ST94035–ST94064) were used in this study, with four stations (ST94038, ST94045, ST94059, ST94061) removed due to redundancy with inner stations. These 26 stations were marked as black dots or stars in Figure 1c. Four stations (94037, 94043, 94050, and 94058; star markers in Figure 1c) were selected to represent the local wave climate, as they are located near four representative cities in the study area: PW (Port Washington in Ozaukee County), MIL (Milwaukee City in Milwaukee County), WP (Wind Point Village in Racine County), and KEN (Kenosha City in Kenosha County).

2.2 Characterization of wave directionality

Characterization of wave directionality involves both qualitative and quantitative methods. From a qualitative perspective, wave data, including its direction and height, was visualized using wave rose maps. For the wave rose, incident wave angles were divided into 32 equally spaced spokes, and the wave height was aggregated in 0.4-meter intervals. From a quantitative perspective, wave directionality was characterized using indices, which summarized the statistical features of wave climates among different wave components. To capture the dominant wave components, wave instances are categorized into two primary groups—northern and southern—based on wave directions relative to the shoreline orientation, as illustrated in Figure 2. Notably, wave components with offshore-directed angles relative to the shoreline orientation are filtered out, based on the assumption that most high-magnitude waves approach from the inshore direction. The shoreline orientations at all WIS stations were approximated by the nearby averaged shoreline orientation within 10 km. To further refine the dominant wave climate and reduce computational complexity, the northern and southern dominant wave climates were identified by averaging over four consecutive directional bins with the highest mean values, each spanning 11.25 degrees. This is illustrated in Figure 2, where the green arrows (P_1 , P_2) represent the average wave heights, and the red frames indicate the directional bins corresponding to the northern and southern sectors. With the northern and southern wave components, an index-based approach is applied to capture the relations among different wave components. Several indices have been proposed in previous studies, such as the Wave Directionality Index (WDI) [15, 16] in Equation 1,

$$WDI = \frac{(PW_1 - PW_2) - \overline{(PW_1 - PW_2)}}{\sigma(PW_1 - PW_2)} \quad (1)$$

where $(PW_1 - PW_2)$ is the difference between the first and the second directional wave power, $\overline{(PW_1 - PW_2)}$ is the long-term mean and $\sigma(PW_1 - PW_2)$ is the long-term standard deviation of that difference. Another approach is Wave Bidirectionality Index (WBI) [41] in Equation 2,

$$WBI = \frac{\text{mean}(PW) - \text{abs}(\text{mean}(PW_1) - \text{mean}(PW_2))}{\text{mean}(PW)} \quad (2)$$

where PW is the total wave power at a certain site, PW_1, PW_2 follows the same definition as the previous ones. Nevertheless, there is a limitation for these two indices that these indices did not account for the angles between dominant wave components. For example, if two wave groups—northern and southern—originate from the northeast and southeast, respectively (a bi-directional wave climate; Figure 2a–b), the indices correctly identify them as distinct components and properly capture the bi-directionality. In contrast, if only one wave group exists (a uni-directional wave climate) with angles perpendicular to the shoreline (Figure 2c–d), the indices may incorrectly split the eastern waves into two components, leading to a misleading classification of the wave climate as bi-directional. To address this issue, we developed an entropy-based index termed Directional Wave Entropy (DWE).

$$DWE = - \sum_{i,j} p_i \log_2(p_i) \sin \frac{|\theta_i - \theta_j|}{2} \quad (3)$$

where p_i and p_j represent frequency of two dominant waves weighted by significant wave height and $\theta_i - \theta_j$ is the angle between two dominant waves. Under an assumption of bi-directionality, the Equation 3 can be simplified using averaged wave components P_1, P_2 as below in Equation 4,

$$DWE = - \frac{P_1}{P_1 + P_2} \log_2 \frac{P_1}{P_1 + P_2} \sin \frac{\theta}{2} - \frac{P_2}{P_1 + P_2} \log_2 \frac{P_2}{P_1 + P_2} \sin \frac{\theta}{2} \quad (4)$$

where P_1, P_2 indicates aggregation over all wave occurrences weighted by significant wave height within the given period (1979–2023) and θ is the angle between P_1, P_2 . DWE is based on the concept of entropy, where greater

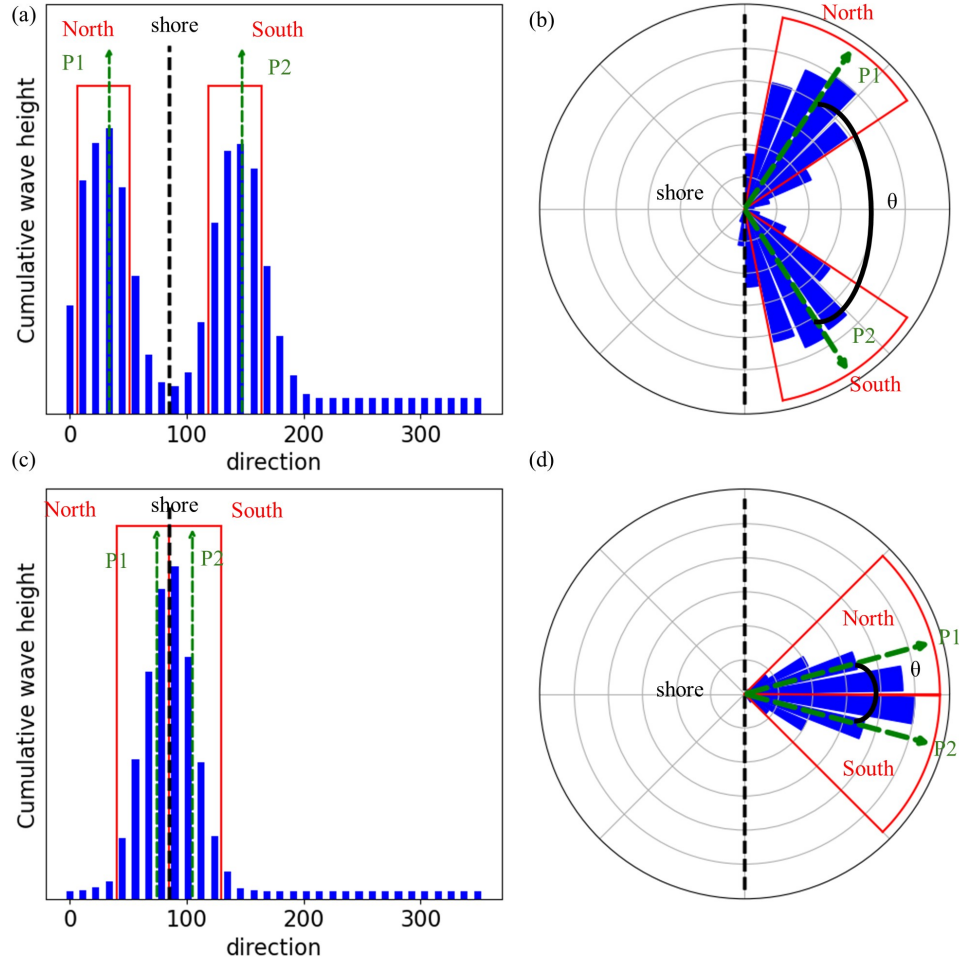


Figure 2: Characterization of two typical wave directionalities: uni- and bi-directionality. (a) and (b) are schematics of height-direction distribution and wave rose for bi-directionality, respectively. (c) and (d) are schematics of height-direction and wave rose for uni-directionality, respectively. The shoreline orientation is marked as a black dash line, while the characterizations of northern wave and southern waves are marked with red frames, respectively. The green arrows P_1 and P_2 represent the averaged waves for the northern and southern components. θ is the angle between these two averaged wave components.

bi-directionality yields values closer to 1 and greater uni-directionality yields values to zero. The inclusion of the $\sin \frac{\theta}{2}$ term in the entropy formulation ensures a monotonic trend that the index approaches zero when a uni-directional wave climate is oriented perpendicular to the shoreline (e.g. the case in Figure 2c-d). After the indices were computed, the directionality can be characterized using a predetermined threshold -0.65 . This threshold was chosen based on typical wave climate characteristics, under the assumption that if the ratio of weighted occurrence between two wave components exceeds two, or if the angular difference between them is greater than 90 degrees, the wave climate can still be considered bi-directional. A sensitivity test for this threshold was conducted in the discussion.

2.3 Inter-annual and intra-annual analysis

Inter-annual and intra-annual analyses for wave heights and DWE were conducted to reflect the long-term characteristics of wave climate. For trend analysis, hourly data were aggregated into annual subsets and monthly subsets using the mean, top 90th percentile, and top 99th percentile wave heights for each WIS site (PW: 94037, MIL: 94043, WP: 94050, and KEN: 94058). Since DWE is a derived index and cannot be directly used to calculate percentiles, its 90th and 99th percentiles were determined based on the cumulative wave height exceeding the respective percentile threshold for 90-percentile and 0.99 for 99-percentile. The Theil-Sen slope estimator was applied to each annual time series of wave heights and DWE to determine the trend for mean, 90-percentile, and 99-percentile. This was followed by the

Mann-Kendall test [45, 46], which was conducted to assess the statistical significance of the trend. The null hypothesis of no trend was tested at a 95% confidence level. To reflect the relative magnitude of bi-directionality waves, the wave heights for northern and southern directions (defined in Figure 2) were extracted on the annual and monthly subsets and were then subtracted with the total wave height from 0 to 359 degrees.

2.4 Extreme value analysis

The extreme wave analysis is intended to compute estimated return periods of extreme wave events. To explore the directional patterns of extreme wave events, the extremes analysis was conducted under the three subgroups proposed in previous sections. In order to reveal the extreme wave events from an extensive series of wave height data, a Peak-Over-Threshold (POT) method with a 95% quantile of significant wave height series as the threshold was employed. The POT method calculated the cumulative probability by identifying sampled events that exceeded a predefined threshold and then ranked these events by magnitude to construct an empirical cumulative frequency distribution [47]. This approach enhanced analytical precision in extreme event analysis [48]. For sequences of wave height data that persistently exceed the designated threshold, a clustering methodology was applied, which treats all wave occurrences within a 48-hour period as a singular, independent extreme wave event. The extreme wave events extracted using the POT method were assumed to follow a Generalized Pareto Distribution (GPD), as expressed in Equation 5.

$$F(x) = \begin{cases} 1 - \left(1 + \frac{\xi x}{\sigma}\right)^{-\frac{1}{\xi}} & \text{if } \xi \neq 0 \\ 1 - e^{-x/\sigma} & \text{if } \xi = 0 \end{cases} \quad (5)$$

where x is the maximum wave height of an extreme wave event, $F(x)$ is the cumulative probability over x , σ is the scale factor, and ξ is the shape factor. In Equation 5, the scale factor and shape factor were estimated by Maximum Likelihood Estimation (MLE).

3 Results

3.1 Bi-directional wave directionality

The wave directionality was characterized at nearshore WIS stations and visualized using wave roses at four selected WIS stations from 1979 to 2023 in Figure 3. The wave roses in four locations presented a noticeable bi-directional distribution in the NNE directions and SSE directions. Due to different shoreline orientations at four sites (the black dash line in Figure 3), the north and south wave divisions (the red frame in Figure 3) were categorized differently among the four locations. At PW, the northern wave division spanned from 11.25° to 56.25° , while the southern wave division ranged from 146.25° to 191.25° . At MIL, the northern division extended from 22.5° to 67.5° , and the southern from 157.5° to 202.5° . At WP, the northern division spanned from -11.25° to 33.75° , and the southern from 123.75° to 168.75° . At KEN, the northern division ranges from 0° to 45° , while the southern extends from 135° to 180° . The bi-directionality of the four sites was further confirmed by their DWE values, which are 0.874, 0.818, 0.824, and 0.850. All four selected WIS stations presented bi-directional wave climate, as their DWE values were less than the defined threshold of 0.65. The wind roses and corresponding DWEs were also computed and reported in Figure 1a (see Chapter Appendix) using the wind climate data from WIS. However, the applicability of this approach to wind climate is limited, as discussed in the limitations section.

3.2 Inter-annual patterns

Cumulative wave height spectra presented in Figure 4 provided valuable insights into both the overall wave directionality and its temporal variations. As shown, warmer colors represent higher cumulative wave heights recorded annually for a specific direction, calculated at 15-degree intervals. All four locations exhibited two distinct directional bands for most of the examined years, indicating a consistent bi-directional wave climate over the 42 years. The lower bands (northern wave) for four sites were located in the directional range between 15° and 45° degrees, while the higher bands (southern wave) were located between 150° and 180° degrees. Additionally, the northern band in the spectrum exhibits larger extreme wave heights than the lower band, as there were warmer colors scattered in the higher band. This shows that extreme wave heights were larger in the northern wave direction. Further analysis of these extreme wave height characteristics is presented in the subsequent sessions.

The inter-annual variability of wave heights for the northern waves, southern waves, and the values of DWE were analyzed in terms of the annual mean, 90% extreme values, and 99% extreme values, as illustrated in Figure 5. During

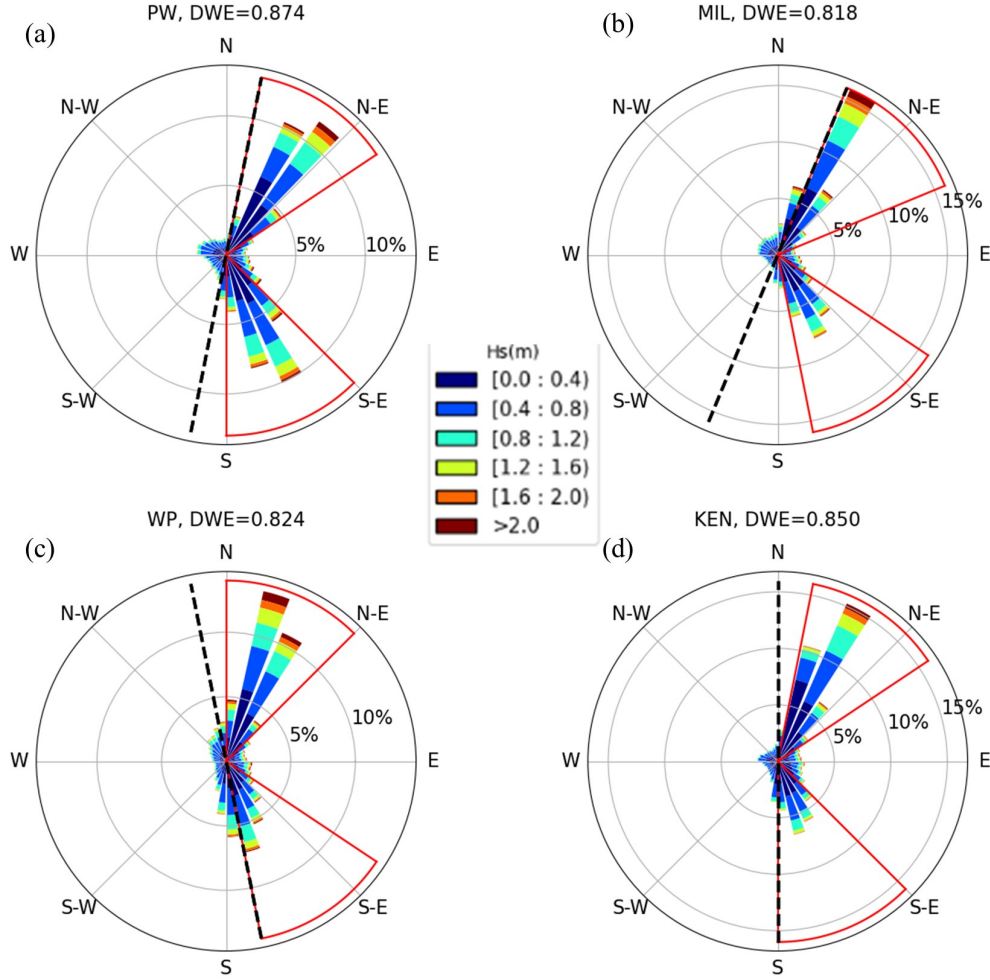


Figure 3: Wave rose maps and DWE at four selected locations. (a) PW-Port Washington, (b) MIL-Milwaukee Harbor, (c) WP-Wind Point, and (d) KEN-Kenosha Harbor with their corresponding directional wave entropy. The black dashed lines represent the shoreline orientation and red frames indicate the selected directional bins.

most of the years, northern waves exhibited greater magnitudes than the southern waves, as shown in Figure 5a-d. However, during certain years (e.g., 1992, 1998, and 2011), northern waves declined. Differences were observed across the four locations, highlighting the spatial variability in directional wave climate, where the northern sites (e.g., PW, MIL) experienced larger southern wave heights compared to the southern sites (e.g., KEN, WP). Figure 5i-l demonstrates the annual variations of DWE. During most of the years, the directionalities at the four locations were bi-directional, while in some years (e.g., 2011) the directionality changed into uni-directionality at MIL, WP, and KEN. In addition, the comparison between the mean, extreme 90%, and extreme 99% values for the northern and southern wave heights and DWE was examined in Figure 5. For both northern and southern waves, the extreme 99% wave heights (red lines in Figure 5) experienced significantly larger variations than the mean and extreme 90% wave heights (grey and blue lines in Figure 5). For instance, in 1987, the northern wave heights at the 99th percentile were the largest group; however, in the subsequent year (1988), they decreased significantly and became the lowest group. The huge variation in extreme groups was also reflected in DWE (Figure 5i-l), suggesting that extreme waves may frequently shift directional dominance.

Furthermore, the inter-annual variability statistical metrics, including p-values and slope estimated by statistical test, were summarized in Table 1. The annual trends in wave heights across different directional groups exhibited notable inconsistencies. PW had a decreasing trend for northern waves (-0.793, -5.900, and -18.729 mm/yr for mean, 90%, and 99%, respectively), southern waves (-2.220, -2.082, and 0.764 mm/yr for mean, 90%, and 99%, respectively), and decreasing trends for DWE (-1.354, -1.173, and -1.114 for mean, 90%, and 99%, respectively). Nevertheless, not all subgroups showed a significant linear trend (e.g., mean-north, 90% and 99% south). MIL had trends as northern waves

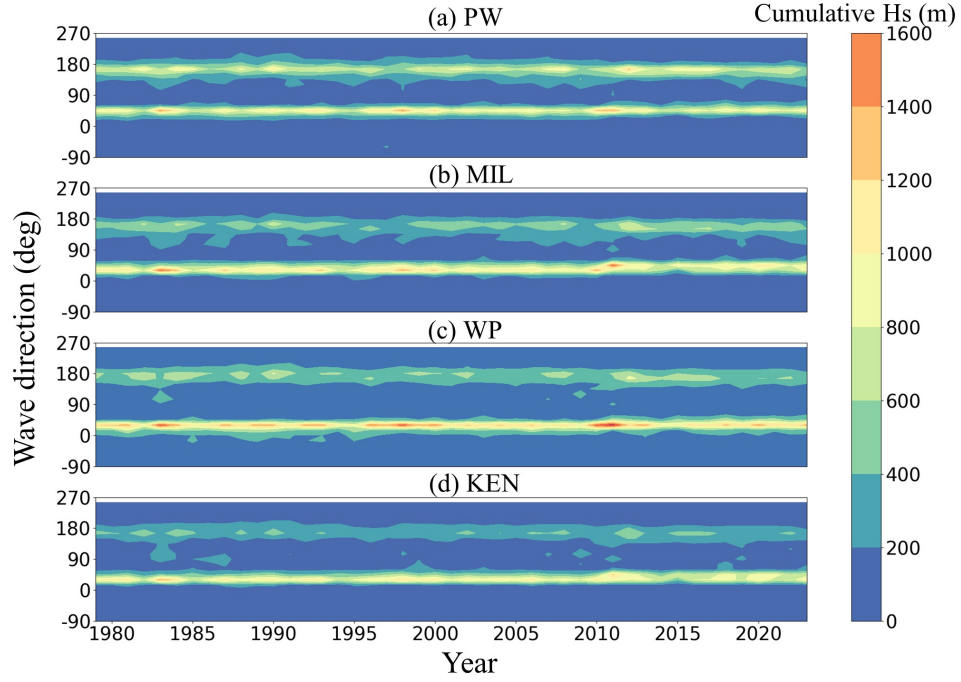


Figure 4: Directional-time wave height spectrum from 1979 to 2021 at the following locations : (a) PW-Port Washington, (b) MIL-Milwaukee Harbor, (c) WP-Wind Point, and (d) KEN-Kenosha Harbor.

of 0.341, -1.869, and -11.423 mm/yr, southern waves of -1.42, 0.321, and 1.755 mm/yr, and DWEs of -1.231, -0.821, and -0.341. Most of them did not present a significant linear trend. WP had an increasing trend at 0.467 mm/yr for northern mean waves but decreasing trends at -1.655 and -13.362 mm/yr for northern 90% and 99%. The trends of southern wave heights in WP were -1.814, 0.411, and 2.217 mm/yr. The DWE also had trends at -0.079, 0.959, and 1.988, respectively. Lastly, KEN showed a decreasing trend at 0.349, 0.326, and -7.075 mm/yr for northern mean, 90%, and 99%, while a consistent decreasing trend for southern wave (-1.532, -1.183, and -1.158 mm/yr) and DWE (-1.226, -0.795, and -0.006). Both WP and KEN present significant trends for their southern mean waves. In conclusion, only a few directionality groups exhibit statistically significant annual trends, and the significance observed in the mean group does not necessarily imply significance in the extreme group.

Table 1: P value and Slope for Northern wave, Southern wave, and DWE at different confidence levels

Sites	Groups	Northern wave		Southern wave		DWE	
		P value	Slope	P value	Slope	P value	Slope
PW	Mean	0.091	-0.793	0.001	-2.220	0.000	-1.354
	90%	0.039	-5.900	0.333	-2.082	0.000	-1.173
	99%	0.006	-18.729	0.762	0.764	0.002	-1.114
MIL	Mean	0.591	0.341	0.026	-1.420	0.003	-1.231
	90%	0.525	-1.869	0.762	0.321	0.062	-0.821
	99%	0.102	-11.423	0.512	1.755	0.451	-0.341
WP	Mean	0.512	0.467	0.045	-1.814	0.899	-0.079
	90%	0.618	-1.655	0.899	0.411	0.094	0.959
	99%	0.056	-13.362	0.500	2.217	0.005	1.988
KEN	Mean	0.525	0.349	0.035	-1.532	0.015	-1.226
	90%	0.822	0.326	0.395	-1.183	0.083	-0.795
	99%	0.168	-7.075	0.604	-1.158	0.992	-0.006

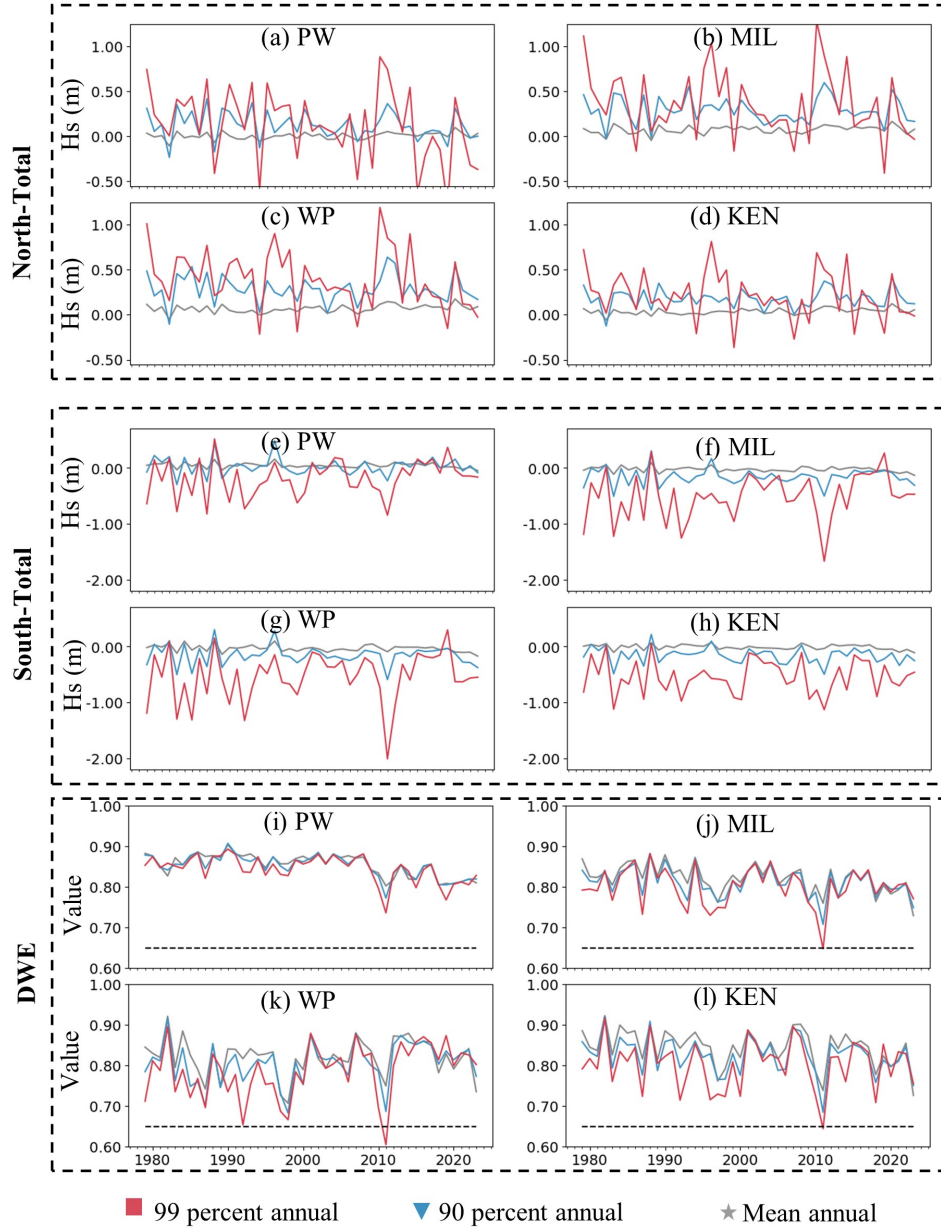


Figure 5: Inter-annual patterns of wave directionality. (a) – (d) are the inter-annual wave height difference between for northern wave and total wave at four major cities (PW-Port Washington, MH-Milwaukee Harbor, WP-Wind Point, KH-Kenosha Harbor), respectively, (e) – (h) are the inter-annual wave height differences between southern waves and total waves at four major cities, respectively, and (i) to (l) are the inter-annual directional wave entropy at four major cities, respectively.

3.3 Intra-annual patterns

The intra-annual patterns of wave height and the Directional Wave Entropy (DWE) were presented in Figure 6. The northern wave was larger than the southern wave in most months at most stations, except in June and November at PW (Figure 6a). Southern wave heights exhibited significant seasonal variation, decreasing during the summer months and increasing during winter. All three groups—mean, 90th percentile extreme, and 99th percentile extreme—exhibited a similar monthly pattern, with northern wave heights increasing during the winter months, particularly in December, January, and February. This pattern flipped in the summer season such that the southern waves became dominant, as shown in Figure 6e-h. The DWE also showed a clear seasonal pattern among the mean, 90%, and 99% extreme groups. During the winter months, the DWEs of three groups for all four stations were approximately 0.886, 0.875, and 0.849, indicating a strong bi-directionality. Conversely, during the spring season, the DWE decreased approximately 10%, up to 0.802, 0.777, and 0.741, suggesting a weakening bi-directionality. In WP, DWE dropped below the threshold during the spring season, showing that the dominant waves shifted to southern waves at this location, leading to a strong uni-directionality.

3.4 Spatial variabilities

Spatial variability of wave characteristic statistics, including the mean and extreme values (90% and 99%) for northern, southern, and DWE, for all 26 WIS stations along the coastal regions of the four counties in Wisconsin, is demonstrated in Figure 7. For northern waves (Figure 7a), the mean, 90%, and 99% wave heights of all stations are 0.566, 1.602, and 2.677 meters, respectively. The wave heights exhibited a gradual decreasing trend from the north to south for both mean and extreme values. However, the decrease rate was not consistent, as it depends on the specific stations and the mean or extreme groups. For the southern waves (Figure 7b), the mean, 90%, and 99% wave heights of all stations are 0.563, 1.572, and 2.452, respectively, which were slightly lower than those of the northern waves. The southern wave directionality exhibited a higher decreasing rate than the northern waves. The 99 percent extreme wave height also declined at a higher rate than the mean and 90 percent. On the other hand, the variability in DWE was more inconsistent across the mean and extreme values. The average DWE values for three groups were 0.847, 0.835, and 0.817, indicating obvious bi-directionality. The DWE decreased from the northern to southern sites, indicating a decreasing bi-directionality as one moves southwards. This spatial pattern aligned with the increased occurrence of northern waves at southern sites. Notably, the values of 99% DWE were smaller than 90 percent and mean DWE, indicating that extreme wave conditions had stronger uni-directionality.

3.5 Extreme wave climates

Figure 8 depicts the varied return period with corresponding extreme wave heights, which were fitted and extrapolated by the Gumbel distributions. For 1-year return periods, the estimated extreme wave heights ranged approximately between 2 and 4 meters for four selected stations from 1979 to 2023, with minimal differences between dominant wave directions or station locations. For the longer return period (100-year), the extreme wave heights varied with different wave directionalities. The 100-year extreme wave heights for southern and northern waves were as follows: 3.932 meters and 5.371 meters in PW, 3.415 meters and 6.042 meters in MIL, 3.289 meters and 6.015 meters in WP, and 2.909 meters and 5.633 meters in KEN. All sites exhibited a consistent pattern, indicating that extreme wave heights were greater in the northern wave direction, which has also been demonstrated in Figure 4. The existence of bi-directional extreme wave climate showed the potential implications in the structure design. While designing a coastal structure, the extreme waves might be underestimated without considering the wave directionality.

4 Discussions

4.1 Sensitivity of directionality characterization

Two key variables influence the characterization of directionality: the number of directional bins chosen and the DWE threshold value applied. Figure 9 presents an analysis of how the number of directional bins and DWE threshold values influence the characterization of wave directionality. Three sets of directional bin criteria—3, 4, and 5 bins—and three threshold levels—0.57, 0.65, and 0.70—were selected to classify several WIS stations located in the southern regions of the study area (Figure 9a). The three threshold values were selected to represent common wave scenarios involving two oblique wave systems (with a relative angle of 45°) and significant wave height ratios of 3:1 (threshold 0.57), 2:1 (threshold 0.65), and 1:1 (threshold 0.70), respectively. Across all stations within the study area, wave directionality consistently exhibits a bi-directional pattern under all tested criteria, as shown in Figure 9b–d. Notably, panels (b), (c), and (d) in Figure 9 illustrate the results using the 4-bin classification, as the choice of bin number has minimal impact on the overall directionality characterization. This observation is further supported by Figure 9e–g, which displays wave

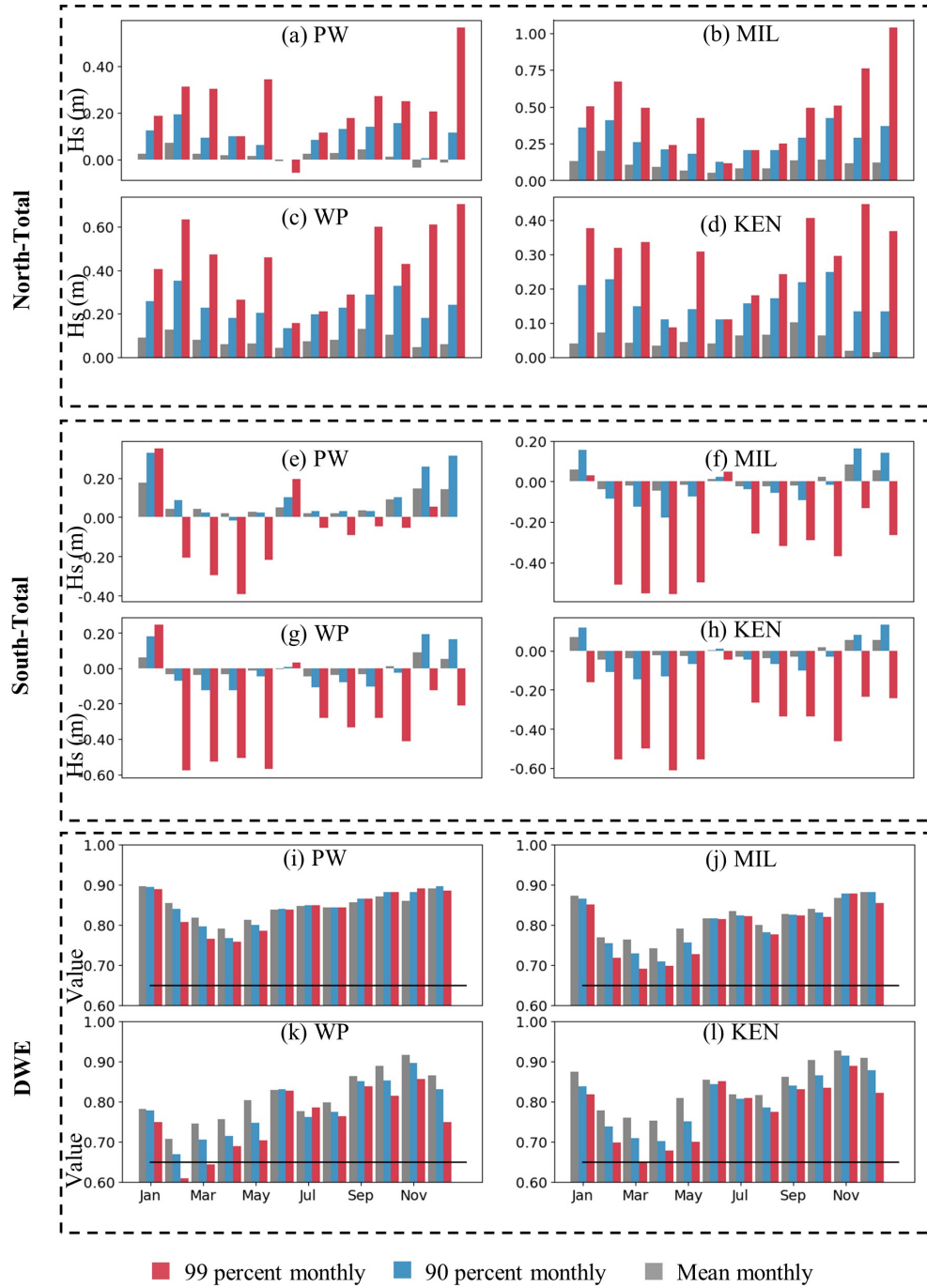


Figure 6: Intra-annual patterns of wave directionality. (a) – (d) are the intra-annual wave height differences between northern and total waves at four major cities (PW-Port Washington, MIL-Milwaukee Harbor, WP-Wind Point, KEN-Kenosha Harbor), respectively; (e) – (h) are the intra-annual wave height differences between southern and total waves at four major cities, respectively; and (i) to (l) are the intra-annual directional wave entropy at four major cities, respectively.

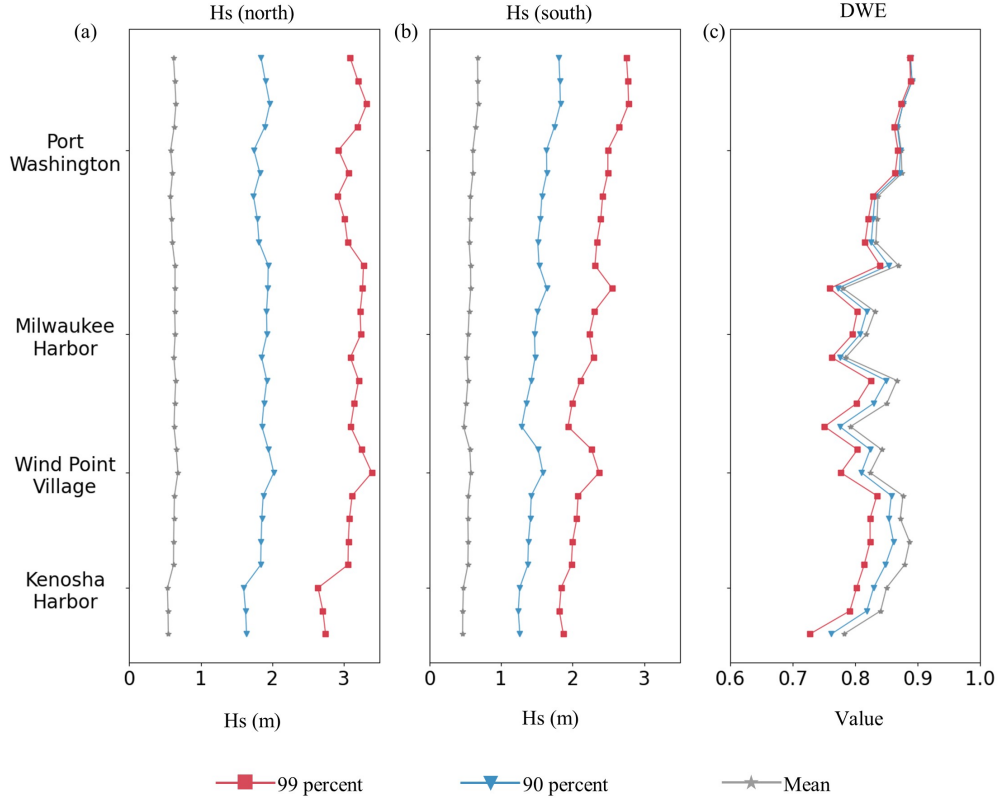


Figure 7: Spatial variability of wave directionality. (a) the spatial distribution of northern wave height at all WIS station sites, (b) the spatial distribution of southern wave height at all WIS station sites, and (c) the spatial distribution of DWE at all WIS station sites. The wave directionalities are computed for the mean, 90%, and 99%.

roses at three selected locations. The three different directional bin configurations—represented by the colored frames in Figure 9e–g—yield similar mean wave components, as indicated by the three colored arrows. This suggests that the number of directional bins has minimal influence on the DWE at these locations. This can be attributed to the fact that dominant wave energy is typically concentrated within a narrow angular range, resulting in negligible variation in both the averaged wave directions (represented by the arrows in panels e–g) and wave heights. Figure 2a also presents the sensitivity of the threshold for the whole lake. A low DWE threshold tends to overestimate bi-directionality in Lake Michigan, whereas a high threshold may underrepresent it. This is thus suggested for choosing an appropriate threshold when working with other areas. The details of directionality in Lake Michigan will be presented in the following discussion sections.

4.2 Correlations of DWE with wave heights and wind speeds

To investigate the relationships of DWE (absolute values) with significant wave height and wind speed, linear regression analyses were performed using data from 26 WIS stations. Monthly wave heights from northern (Figure 10a) and southern (Figure 10b) directions, as well as monthly wind speeds from northern (Figure 10c) and southern (Figure 10d) directions, were respectively used to calculate the slopes of regression and the p-values. Notably, the wind speed data were extracted from WIS, which is the interpolated data from CFSR [43]. For northern wave heights in Figure 10a, negative correlations with DWE with strong confidence levels (p-values < 0.05) were observed at stations located in Ozaukee County, whereas positive trends occurred at southern stations in Milwaukee, Racine, and Kenosha counties. Conversely, in Figure 10b, southern wave heights show negative linear trends across most WIS stations except for a few stations in the northern side. The differences in correlation patterns with DWE may be influenced by wind fetch length, as the wave heights are positively correlated with the length of the fetch in Lake Michigan [49]. With that, from southern station to northern station, the increasing of southern wind fetch leads to an increasing southern wave height, resulting in a decreasing correlation of DWE with both northern waves and southern waves. Nevertheless, further examining the correlations between DWE and wind speed from both north and south directions (in Figure

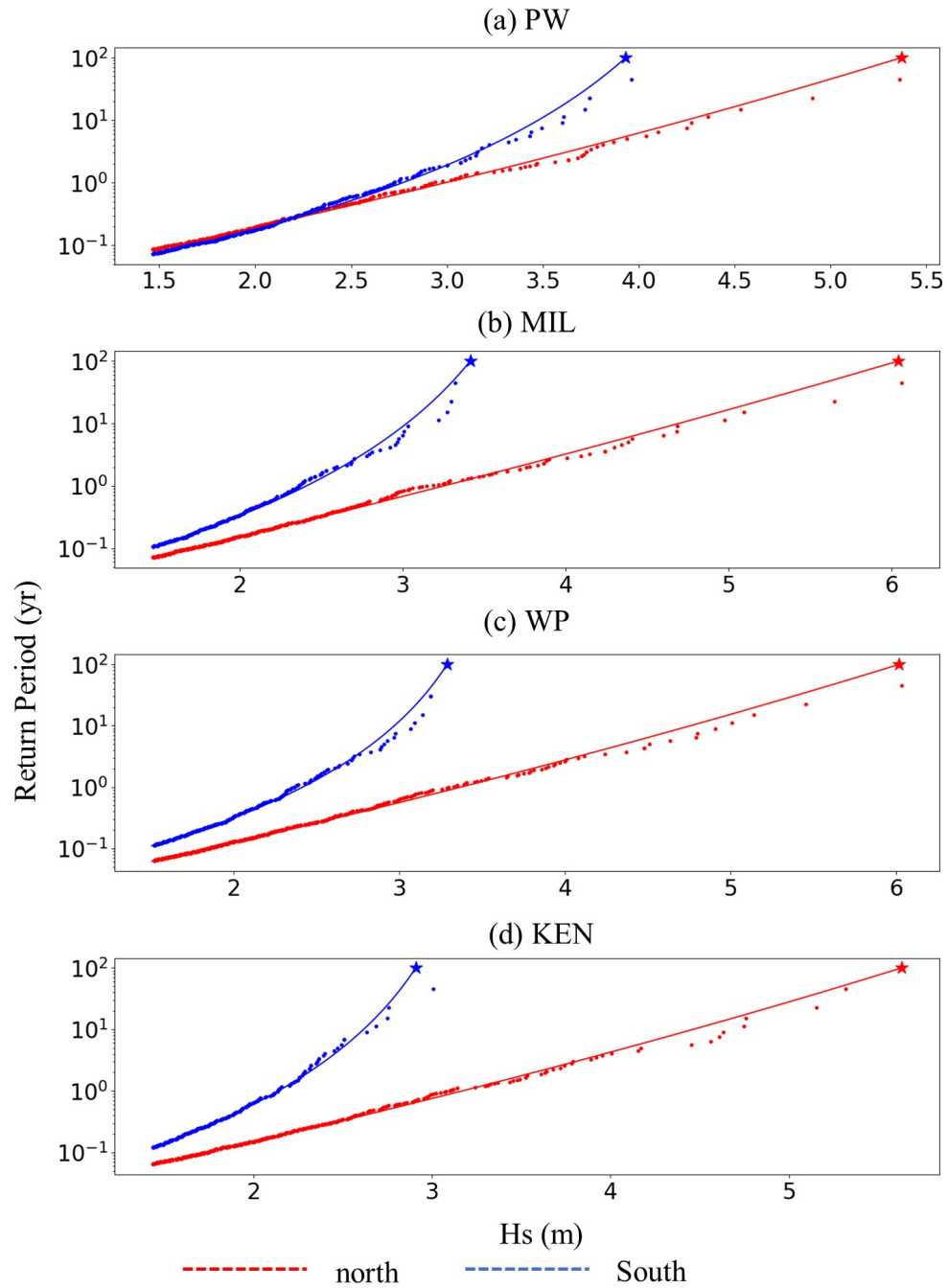


Figure 8: Return periods (years) of extreme wave height using POT for wave directionality. (a) - (d) show extreme wave directionality at four selected cities (PW-Port Washington, MIL-Milwaukee Harbor, WP-Wind Point, and KEN-Kenosha Harbor). The blue and red stars represent the 100-year return periods projected by the Generalized Pareto Distribution for northern and southern waves, respectively.

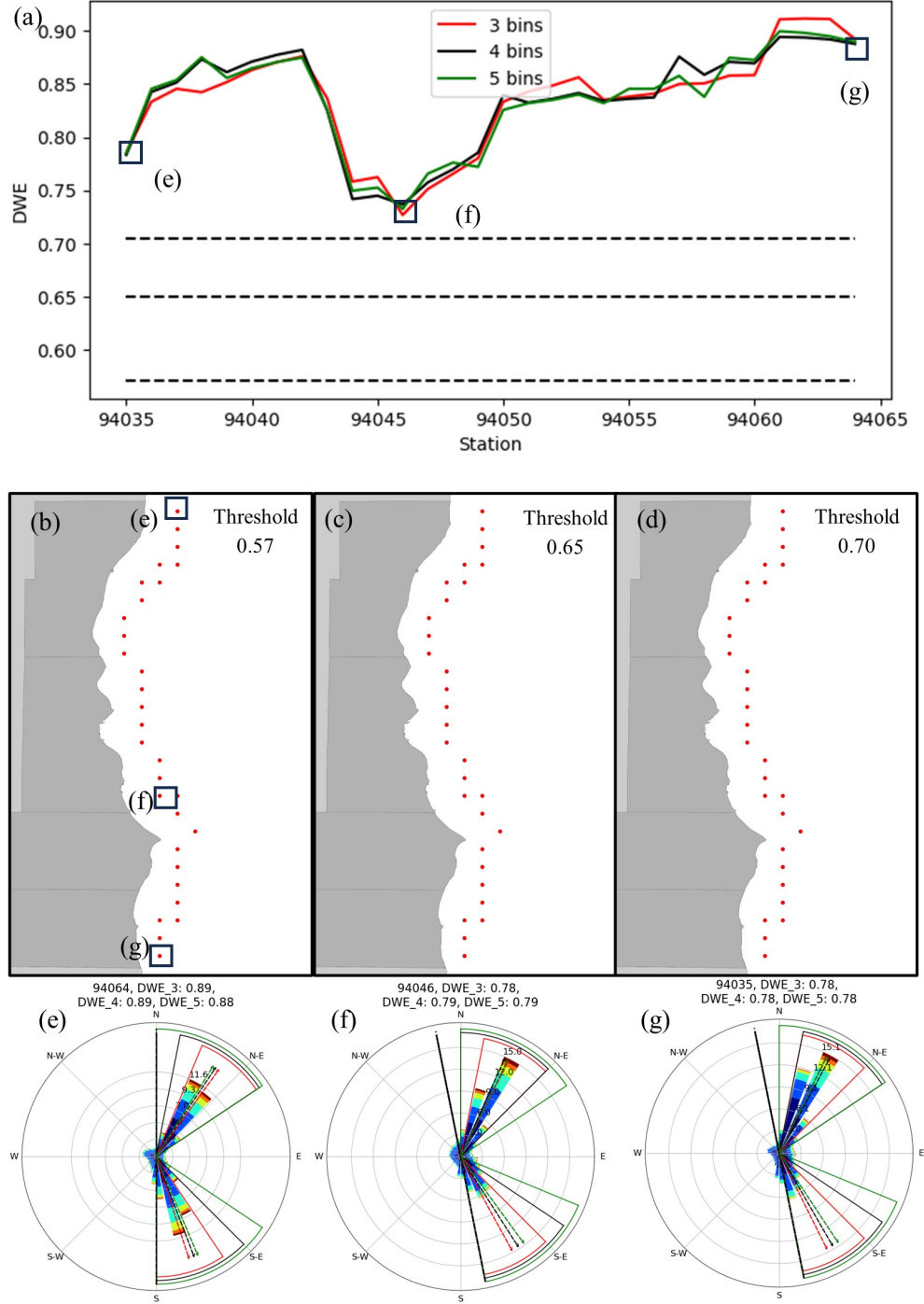


Figure 9: Wave directionality for different DWE thresholds and directional bins. (a) DWE values for all selected bins (red, black and green curves) and all thresholds (black dashed lines). Subplots (b), (c), and (d) are the maps of wave directionality (red dots are bi-directional and green dots are uni-directional) under three different thresholds: (b) 0.57, (c) 0.65, and (d) 0.70. Subplots (e), (f), and (g) are the wave roses at three representative locations under different directional bins. The red frame is the 3-bins, black frame is 4-bins and green frame is 5-bins. The colored arrows are the averaged wave components for these directional bins, respectively

10c-d), it is found that there was no clear spatial pattern observed in the slope of linear regression for either northern or southern wind speeds. This observation highlights the need for future research to clarify the relationship between wave directionality and wind climate.

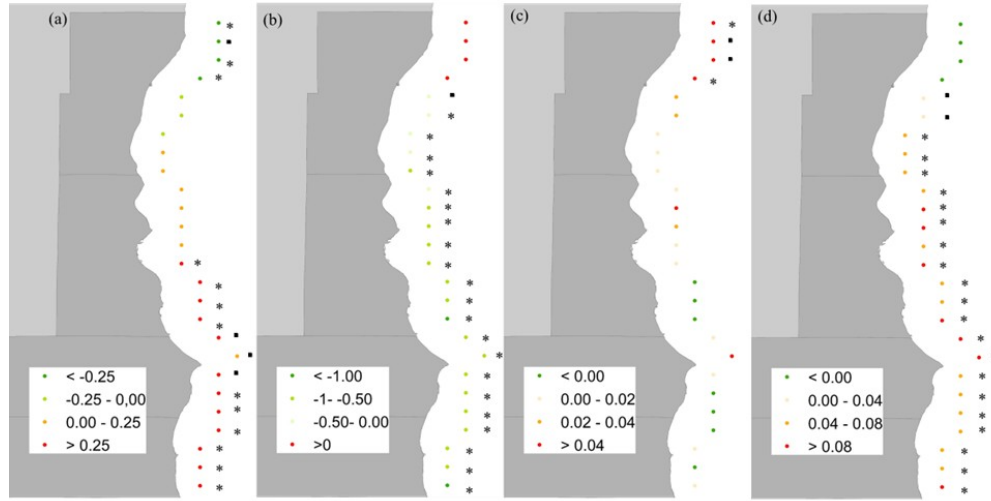


Figure 10: Linear regressions between DWE and other factors at 26 WIS stations. The correlated factors include (a) northern wave height, (b) southern wave height, (c) northern wind speed, and (d) southern wind speed. The colors of dots represent the slopes of regression. The black squares and asteroids represent the stations that have significant linear relationships with p-values less than 0.1 and 0.05, respectively.

4.3 Wave directionality in Lake Michigan

Characterization for directionalities of nearshore wave climate was extended to the entire shoreline of Lake Michigan (Figure 11). Based on wave direction distribution extracted from 490 WIS stations around Lake Michigan, there are two primary types of wave directionality in Lake Michigan: uni-directional waves and bi-directional waves. The uni-directional wave climates, in which waves are mostly distributed in a single direction, are most likely to occur in the northern and southern shores of Lake Michigan (the red dots in Figure 11a). In northern Lake Michigan, waves tend to come from the southwest (*e.g.*, Figure 11b). Oppositely, the waves will be most likely from the northern direction in southern Lake Michigan (*e.g.*, Figure 11i). The bi-directional wave climates, on the contrary, are likely to occur at the western and eastern shorelines of Lake Michigan (the green dots in Figure 11). While western Lake Michigan receives northeastern and southeastern waves (as shown in Figure 11h), eastern Lake Michigan receives the northwestern and southwestern waves (as shown in Figure 11g). Notably, in the Green Bay area (Figure 11f) and the West/East Arm of Grand Traverse Bay (Figure 11e), wave directionality was incorrectly classified as uni-directional due to limitations in the DWE characterization. This issue will be further examined in the following section. The different directionalities in Lake Michigan result from different sizes of wind fetch fields. The shape of Lake Michigan is north-south elongated with an aspect ratio of approximately 4, which indicates that the fetch length in the northern-southern orientation is significantly longer than the western-eastern orientation. In Lake Michigan, most of the waves are affected by the wind fetch, so larger fetch lengths can generate larger wave heights [49]. For example, the WIS wave station 94001, which is located at the southern edge of Lake Michigan, is most likely to receive the northern wave because of the 450-km fetch from north to south. On the contrary, station 94086, which is located on the western shore of Lake Michigan, tends to have bi-directional waves in both northeastern and southeastern directions due to equal fetch fields existing in these directions.

4.4 Embayed beach morphology under wave directionality

One important implication of bi-directional wave climate is its impact on beach morphology, especially embayed beaches [15, 16]. Embayed beach is a special landscape that is semi-enclosed between headlands and can be widely seen in the urban and natural area of Lake Michigan [50]. Embayed beach shape can be approximated by a parabolic equation, which is controlled by physical wave diffraction point at headland [51]. Nevertheless, for a bi-directionality, conventional beach shapes under a parabolic curve might not accurately depict the headland bay beach shape. A common solution to this issue is to generate multiple shapes with wave diffractions from bi-directionality, then combine

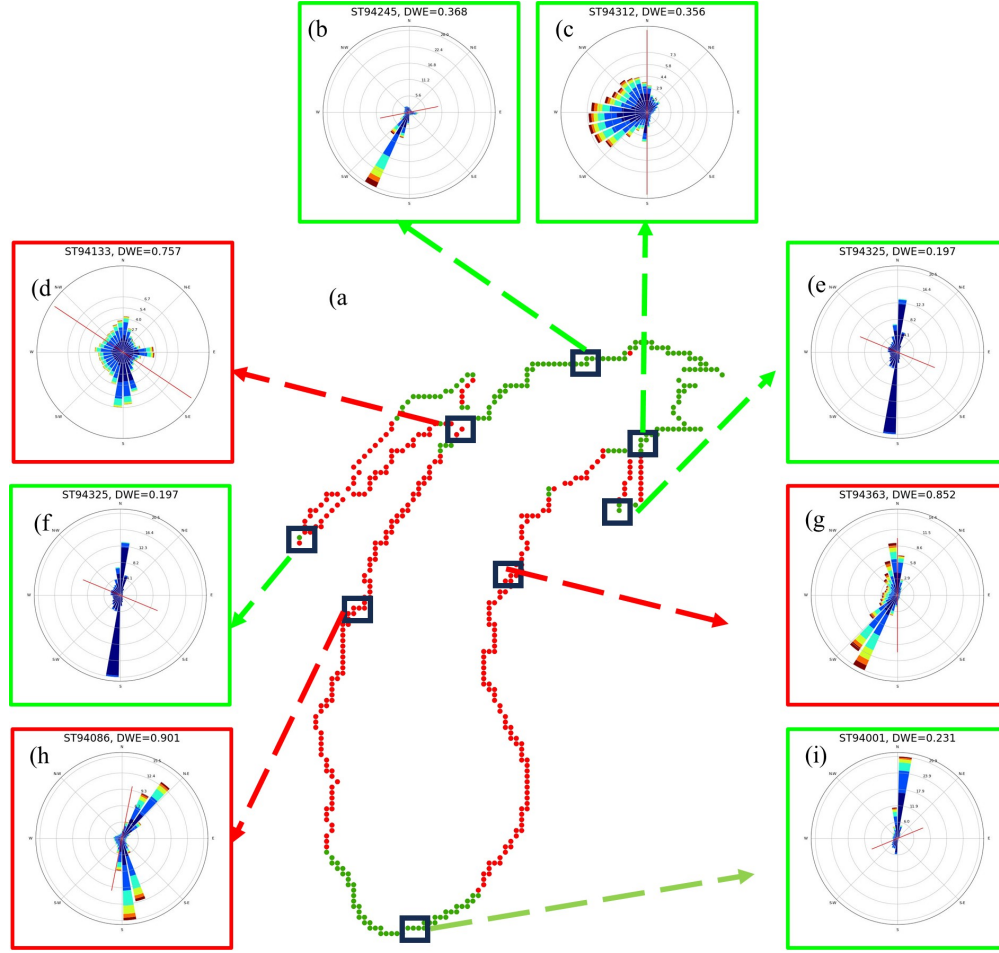


Figure 11: Directionality in Lake Michigan. (a) the wave directionalities of Lake Michigan in 490 WIS stations. The red dots are stations where the wave directionality is bi-directional, and the green dots are the locations where the wave directionality is uni-directional. (b) to (i) are the wave roses at several representative locations in Lake Michigan.

the shapes together. Figure 12 shows different beach shapes under bi-directional wave and uni-directional wave climate, generated by MepBay software [52]. For beaches influenced by uni-directional wave climates (Figure 12a–b), shoreline morphology tends to be asymmetrical, with beach width typically increasing near the edges of headlands due to wave diffraction effects. Unlike uni-directionality, the shapes of beaches for bi-directionality are relatively symmetrical curves (Figure 12c–d), which can be better approximated by two parabolic curves. This indicates that the beach accretes at both ends of the bay under bi-directional wave climates. Embayed beach morphology is often controlled by nearshore sediment transport, especially longshore sediment transport. For a semi-closed embayed beach, oblique waves drive the longshore sediment transport, leading to erosion in the updrift beach and deposition in the downdrift beach [51, 53]. Bi-directional wave climates, which indicate waves travel from two opposite directions, tend to drive longshore sediment transport in a bi-directional pattern, leading to deposition in both downdrift and updrift directions. To verify this, the longshore sediment transport was estimated in the sites using the CREC equation, which is shown in Figure 3a. The bi-directional wave climate will lead to bi-directional longshore sediment transport (e.g., Figure 3b) more than the uni-directional wave climate (e.g., Figure 3a). Hence, under bi-directional wave climate, beach morphology is present in a symmetrical shape, which is fitted by two spiral curves.

4.5 Limitations of DWE and future applications

DWE is based on the concept of cross-entropy and is simplified under the assumption of a maximum of two dominant wave components on the water-facing side of the shoreline. A primary limitation of this approach lies in its underlying assumption, which is generally valid for most coastal regions but may not be suitable for other environments such

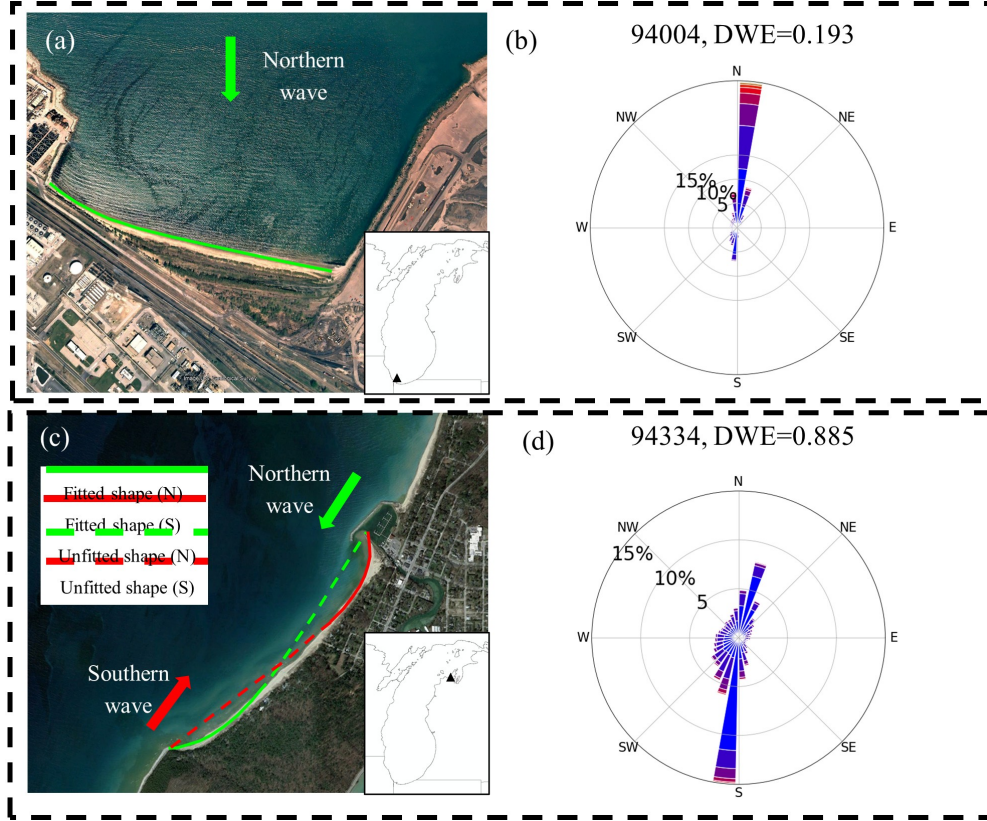


Figure 12: Embayed beaches shapes under different directionalities. (a) uni-directional wave climate at East Chicago Harbor, Illinois, associated with (b) its wave rose. (c) bi-directional wave climate at Le Land, Michigan, associated with (d) its wave rose. Beaches shapes were fitted by MepBay software using two wave diffraction points for bi-directional wave climate and one wave diffraction point for uni-directional wave climate.

as offshore areas, bays, and straits. In such areas, wave directionality is typically more complex—often exceeding bi-directional patterns—and shoreline orientation is no longer a suitable reference for capturing the full range of wave components. For example, in Figure 11e-f, the wave directionality was mischaracterized because the second wave component was excluded due to its alignment relative to the shoreline orientation. This suggests that filtering wave incidents based on shoreline orientation may be ineffective in certain locations, such as bays and straits, where wave angles are more complex.

These limitations stem from assumptions about the wave climate in Lake Michigan. Excluding landward wave components when characterizing wave directionality is generally reasonable, as such waves are typically of low magnitude. However, with modifications, this approach could be extended to offshore areas of other lakes and oceans. For example, the DWE equation can be modified by incorporating a third entropy term to account for the presence of a third dominant direction. Meanwhile, the characterization of wind directionality and its interrelationship with wave directionality remain largely unexplored, highlighting an important direction for future research.

5 Conclusion

This study characterized the wave directionality and revealed the temporal and spatial patterns in the southeastern Wisconsin coast. An innovative index—Directional Wave Entropy (DWE)—was developed to characterize the directionality of wave climate in this study. The results of DWE in four selected WIS stations showed a bi-directional wave climate for historical wave data from 1979 to 2023. The wave height for both northern and southern wave directionality did not present a significant inter-annual trend for mean and extreme wave conditions. The annual DWE shows a long-term bi-directionality throughout 44 years. The intra-annual wave climate presented a clear seasonal pattern for both northern and southern groups: the wave height increased during the winter season. The monthly DWE also exhibited a seasonal pattern, with lower values observed during the summer months, suggesting that stronger

bi-directionality tends to occur in the summer season. The extreme analysis of wave directionality was also performed, showing that the extreme wave height for the 100-year return period varied significantly between the northern and southern wave directionality. Furthermore, this study discussed the impact of selecting the DWE threshold on the characterization of wave directionality and found that a low threshold can underestimate the bi-directionality. This study also explored the correlation between DWE with wave height and wind speed, respectively. The result showed a correlation between wave index and wave climate but not wind climate. In addition, the wave directionality along the entire Lake Michigan coast was discussed, which reveals the presence of bi-directional and uni-directional wave climate. The presence of bi-directionality and uni-directionality follows a specific spatial distribution which is closely related to the topological shape of Lake Michigan. Furthermore, the impact of wave directionality on headland bay beach morphology was also examined at two beaches as examples. The difference of beach morphology in the two sites suggested such an implication that wave bi-directionality tends to cause symmetrical beach morphology. Lastly, the limitations and potential of DWE approaches were discussed, indicating needs for future studies.

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