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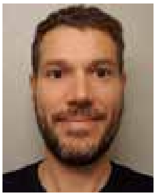
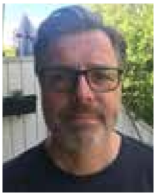
OPEN-ACCESS PORTAL WITH HINDCAST WAVE DATA FOR SKÅNE AND HALLAND

DATAPORTAL MED SIMULERAD VÅGDATA FÖR SKÅNE OCH HALLAND









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Abstract

Wave climate data for the Swedish provinces Skåne and Halland, were hindcast using SWAN, a third-generation spectral wave model. The 40-year wave dataset, from 1979 to 2019, is made available through an open-access data portal (https://gis.sgi.se/vagmodell/). The wave data has a three-hour resolution and includes significant wave height, peak wave period, and wave direction. The wave model domain encompasses the Baltic Sea, Öresund, Kattegat, and Skagerrak. Along the coast of Skåne and Halland, the spatial resolution of the computational nodes, from which data can be extracted in the portal, is 250 m. In the offshore areas, the resolution of the computational grid is coarser. The simulated significant wave height was validated against observations from 25 wave gauges, operating intermittently during the simulation period. The coefficient of determination, R^2, for these comparisons ranged from 0.46 to 0.93 for the different stations. For 15 wave gauges, R^2 values for the comparisons exceeded 0.80. The wave model will continuously be updated and developed.

Sammanfattning

Vågklimatet för Skåne och Halland har simulerats med SWAN, en spektral vågmodell av tredje generationen. Den 40 år långa dataserien, från 1979–2019, är fritt tillgänglig via en dataportal (https://gis.sgi.se/vagmodell/). Vågdataserien har en upplösning om 3 timmar och består av parametrarna signifikant våghöjd, vågspektrumtopperiod och vågriktning. Modelldomänen täcker Östersjön, Öresund, Kattegatt och Skagerrak. Längs Skåne och Hallands kust är upplösningen av beräkningsnoderna, där vågdata kan extraheras, 250 m. På öppet vatten är upplösningen av beräkningsnätet grövre. Resultat för simulerad signifikant våghöjd har validerats mot observationer från 25 vågbojar, som periodvis varit aktiva under simuleringsperioden. Determinationskoefficienten, R^2, för jämförelsen varierade mellan 0,46 och 0,93 för de olika stationerna. För 15 av bojarna överskred R^2 0,80. Vågmodellen kommer att uppdateras och utvecklas allteftersom nya indata och kalibreringsdata blir tillgängliga.

Keywords: Wave climate, SWAN, Skåne, Halland, hindcast waves.

Introduction

Coastal flooding and erosion are global problems that are expected to increase with sea level rise attributable to global warming (Luijendijk et al., 2018; Oppenheimer et al., 2019; Wong et al., 2014). In Sweden, coastal flooding and erosion have historically been limited in extent and severity. However, over the past decade, several storms have caused damage along the coast in the provinces Skåne and Halland. Because of an increasing awareness of risks associated with sea level rise, coastal municipalities have begun to assess these risks and adapt coastal management plans accordingly. Regional Kustsamverkan Skåne/Halland (RKS), a network of national and regional stakeholders, has been established to facilitate collaboration, coordination, and support among actors within the coastal community in southern Sweden (Länstyrelsen Skåne et al., 2019). RKS has identified an acute need for improved knowledge of coastal processes to better constrain risks associated with sea level rise and develop appropriate management strategies. This led to the initiation of the present project to simulate the wave climate in Skåne and Halland.

Coastal management requires knowledge of the local wave climate. This is because local wave data are crucial to analyses of coastal flood risk, sediment transport, and coastal evolution. These data are also important to the design of coastal protection measures and infrastructure. In areas with few or no observations of wave data, simulated wave climates can provide valuable information about, e.g., return periods of waves; decadal, yearly, or monthly distribution of waves; and their spatial distribution along the coast.

Wave data can be hindcast through numerical modelling of wave generation and propagation from historical records of wind directions, speeds, and durations. This has been done previously for the Baltic Sea, Öresund, Kattegat, and Skagerrak (Berg, 2008; Bernhoff et al., 2006; Björkqvist et al., 2018; Blomgren et al., 2001; Bonaduce et al., 2019; Broman et al., 2006; Hemer et al., 2013; Henfridsson et al., 2007; Hjelmsten, 2011; Irminger-Street, 2011; Jönsson et al., 2003, 2005; Kriezi & Broman, 2008; Meier et al., 2006; Schömer Ericsson & Renac, 2014; Semedo et al., 2015; Waters et al., 2009). In addition to these studies, some government agencies and private companies in Sweden and neighboring countries operate regional wave models. However, data from these previous studies and wave models have limited geographic and temporal extent and are not available open-access.

This paper therefore introduces an open-access online data portal with 40 years of hindcast wave data in the Baltic Sea, Öresund, Kattegat, and Skagerrak, from 1979 to 2019. The wave data was simulated using SWAN (Simulating Waves Nearshore); a third-generation spectral wave model. The model results were validated against wave observa-

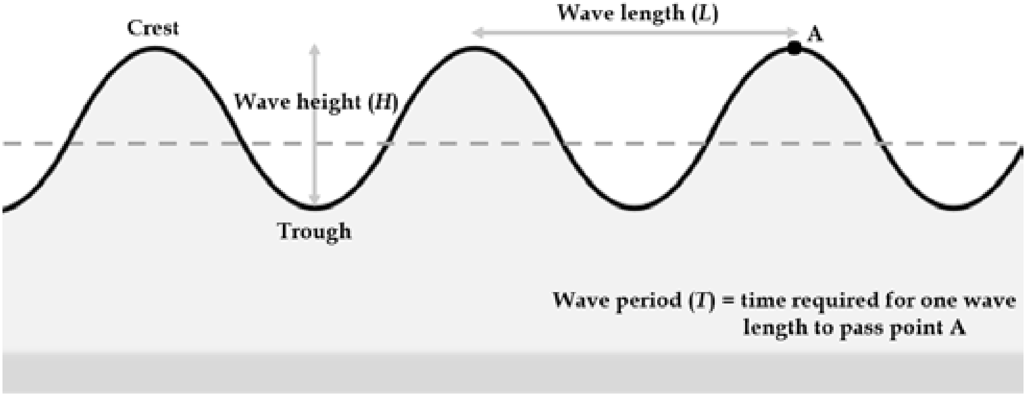

Figure 1: *Description of wave parameters; wave height (H), wave length (L), and wave period (T).*

tions from 25 wave gauges operated by the Swedish Meteorological and Hydrological Institute (SMHI).

Theoretical background

Wind-generated waves are created through energy transfer from the wind to water, causing a displacement of the water surface (Davidson-Arnott, 2010, pp. 52–53). Due to the random and irregular nature of wind-waves, statistical parameters are commonly used to describe wave properties (Figure 1). The wave height, i.e., the vertical distance between wave crest and trough, is commonly described by the significant wave height (H_s), corresponding to the mean of the one-third of the highest waves. The horizontal distance between two consecutive wave crests (or troughs) marks the wavelength, L. The time it takes for a wave to travel the distance of one wavelength denotes the wave period, T. Commonly, the peak wave period, T_p, is used to describe the wave period, referring to the period with the highest energy in a wave-spectrum. A wave spectrum presents the distribution of wave energy at different frequencies and is a way to describe the properties of irregular waves by representing the sea surface as many different wave height, lengths, and periods. The wave direction is given in cardinal direction (i.e., North=0°, East=90°, South=180°, West=270°) from where the wave is coming from.

Wind-generated waves can be hindcast using historical wind data (Barua, 2005). There are numerous wave models available with different levels of complexity. A simple and widely applied empirical method is the Sverdrup-Munch-Bretschneider (SMB) formulations (USACE, 1984) that compute deep-water wave height and period based on the relationship between fetch length, wind speed and duration. To simulate more complex processes of wave transformation, such as wave refraction, shoaling, depth induced breaking, and dissipation of wave energy, more advanced numerical models are required. These models are either phase-averaged or phase-resolving. Phase-averaged models compute the wave evolution from statistically derived wave parameters based on the wave spectrum. Phase-resolving models on the other hand, solve the wave phases explicitly for individual waves (Cavaleri et al., 2007). Different models are suitable for different applications, depending on the aim and focus of the study. In regional studies of wave conditions, phase-averaged models, like SWAN, are typically applied (Cavaleri et al., 2007).

SWAN is a third-generation numerical wave model developed at Delft University of Technology that simulates wave propagation in both deep water and nearshore areas (Booij et al., 1999). It is an open-source numerical wave model software, suitable for simulations of regional wave climate. SWAN has been applied and validated in numerous studies internationally (Hashemi et al., 2015; Pallares et al., 2014; Rusu et al., 2008). It is based on the spectral action balance equation and computes the wave spectrum based on wind input on a structured (rectangular cells) or unstructured grid (composed of triangular cells).

Wave model

The wave climate along the coast of Skåne and Halland was simulated using SWAN version 41.31 (Booij et al., 1999). The model utilizes an unstructured grid with a coarse mesh (up to 40 km) in deep open water and a finer mesh near the coast with approximately 250 m resolution (Figure 2). In the grid nodes (where corners of the triangular cells meet), wave data is computed, and results can be extracted from the model. The model is run with a time-step of 10 minutes, and output is given every three hours of H_S, T_p, and wave direction. Processes included in the model are depth-induced breaking, triad non-linear wave-wave interactions, dissipation by bottom friction, and white-capping. White-capping is a phenomenon that contributes to the dissipation of wave energy in deep water when the wave steepness (H_S/L) exceeds a critical limit (Booij et al., 1999).

Bathymetry data was mainly based on the European Marine Observations and Data Network (EMODnet) Bathymetry portal, with a resolution of approximately 115 m (EMODnet, 2021). Along the Skåne coastline, at depths shallower than 6 m, a high-resolution bathymetry with a resolution of 2 m was provided by the Geological Survey of Sweden (SGU) (Malmberg-Persson et al., 2016). A detailed representation of the nearshore bathymetry is important for the quality of the wave simulation, as it provides increased accuracy in the area where the bathymetry has a large impact on the wave specturm. The wind input was based on the ERA5 reanalysis dataset of averaged wind at 10 m height with an hourly time-step and a resolution of 30 km (Hersbach et al., 2018). The wave climate was simulated for the period with available wind data, 1979–2019. A more detailed description of the model setup is presented in the report *Fysiska och dynamiska förhållanden längs Skånes kust – underlag för klimatanpassningsåtgärder SGU-RAPPORT 2021:02* (Nyberg et al., 2021, Appendix 1).

An initial version of the model was setup and run with default values of the model parameters. To improve the model performance, an adjustment of the white-capping coefficient was made based on comparison with observational data from the SMHI wave measurement stations: Karlskrona (35065), Kristianopel (35062), Laholmsbukten (35066), Oskarsgrundet (35067), Södra Östersjön (33004), Ölands södra grund (35063) and Öland waverider (35064), (Nyberg et al., 2021, Appendix 1). The model performance was assessed by comparing the simulated H_S with wave observations from SMHI (SMHI, n.d.). The model fit was evaluated using the coefficient of determination, R^2. At 15 of the 25 investigated locations, R^2-values greater than 0.80 were obtained (Table 1; Figure 2). Furthermore, the R^2-values exceeded 0.65 for 20 of the 25 locations. The performance of peak wave period simulations could not be evaluated because the SMHI observations do not include the same definition of this parameter. Hence, it is not specified how the model represents the wave period.

An example of the model fit in two stations, Laholmsbukten in Kattegat and Oskarsgrundet in Öresund, is illustrated in Figure 3. The figure presents simulated and observed H_S, the computed R^2-value, and a perfect-fit-line. Laholmsbukten has a high R^2-value of 0.87, and the data points are centered around the perfect-fit-line. In contrast, Oskarsgrundet has a lower R^2-value of 0.53 which reflects a weaker correlation between modelled and real data because there is more scatter around the perfect fit line. The model does not capture five exceptionally high observed H_S, that correspond to an extreme event in early October 1989.

Data portal

The wave climate data are available at an open-access web-portal hosted by the Swedish Geotechnical Institute (SGI). The portal is available at https://gis.sgi.se/vagmodell/. Wave data from 1979–2019 with 3-hour resolution can be extracted from all nodes in the model domain. The distribution of nodes is denser along the coast of Skåne and Halland, where the model mesh resolu-

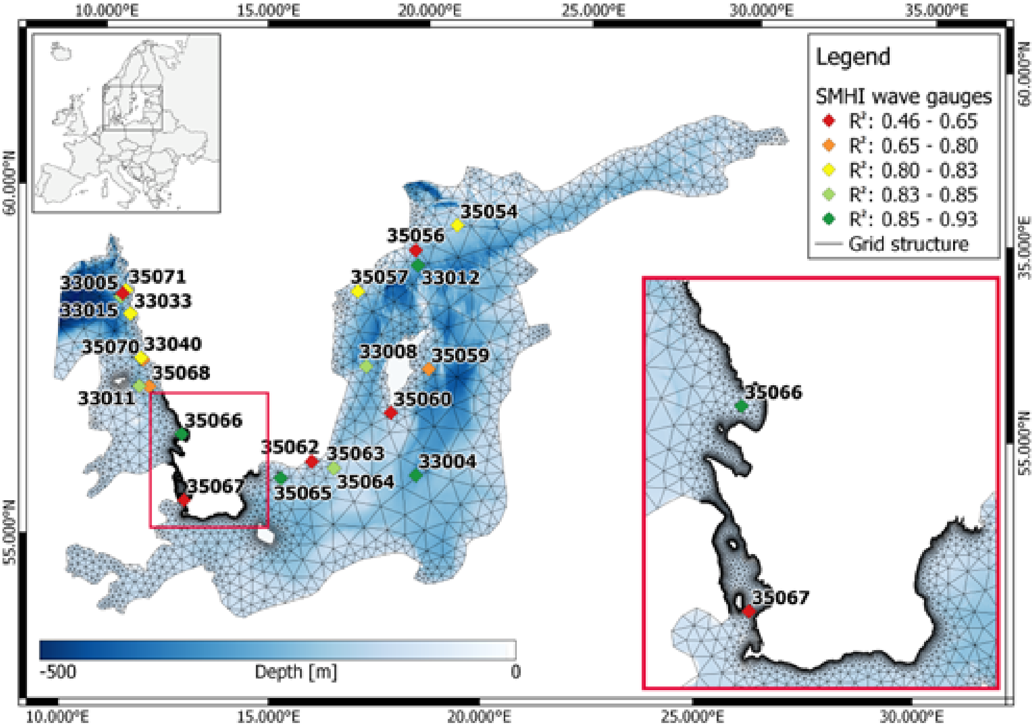

Figure 2: *Model domain and grid structure, including the locations of SMHI wave gauges. The color of the station symbol indicates the model fit, where warm colors indicate lower R²-values and cool colors indicate higher R²-values.*

tion is finer (250 m). For each specific node, wave data can be exported in a .csv format (comma separated values). The data contains node ID, date/time [YYYY-MM-DD HH:MM:SS], H_S [m], T_p [s], wave direction [°N], coordinates (SWEREF99 TM), and details of the model version. When using data from the web-portal, this article should be referenced together with information about the current model version. The wave model will continuously be updated and developed.

Wave data was extracted from a grid node located outside Ystad port (node ID: 10006, 55.4035° Lat; 13.7939° Long) to illustrate potential use of wave data in the portal (Figure 4), e.g.:

- distribution and frequency of wave heights and wave directions can be illustrated in a wave rose diagram (Figure 4a),
- distribution of wave heights may also be presented by a duration curve, where wave height is plotted against the probability of exceedance (Figure 4b),
- the percentage of waves of a specific wave height and period illustrated in histograms (Figure 4c and 4d), and,
- temporal variations of wave climate can be analyzed, e.g., yearly maximum wave height (Figure 4e) and monthly mean wave height (Figure 4f).

Discussion and concluding remarks

Wave data were simulated for a 40-year period using SWAN. Comparison with observational data from 25 SMHI wave gauges showed good agreement with most of the gauges. At 15 of the investigated stations, the R²-values exceeded 0.80, and at 20 stations, the R²-values exceeded 0.65. For the remaining five stations with R²-values lower than 0.65, the results indicate that the model does not satisfactorily represent the wave climate

Table 1: *Details of SMHI wave observations and coefficient of determination, R^2, obtained from comparison of H_S data for the overlap between the simulation period (June 1979–December 2019) and each station's operational period.*

Station ID	Station name	Operational period	R^2
33004	Södra Östersjön buoy	June 2005 – April 2011	0.93
35066	Laholmsbukten buoy	March 1984 – October 1985	0.87
33012	Huvudskär Ost WR buoy	February 2007 – December 2007	0.86
35065	Karlskrona buoy	November 1985 – January 1986	0.86
33008	Knolls grund buoy	November 2011 – (active)	0.85
33005	Väderöarna buoy	October 2013 – December 2014	0.85
33015	Väderöarna WR buoy	March 2005 – (active)	0.84
35063	Ölands södra grund	October 1978 – March 2004	0.84
33002	Huvudskär Ost buoy	May 2001 – December 2020	0.83
33011	Läsö Ost WR buoy	January 2006 – April 2006	0.83
33033	Brofjorden WR buoy	February 2017 – (active)	0.82
35071	Väderöarna1 buoy	April 1980 – January 1981	0.82
33040	Vinga BS	May 2019 – November 2019	0.82
35057	Gustav Dalén buoy	July 1983 – October 1987	0.81
35054	Svenska Björn buoy	November 1982 – November 1986	0.81
35059	Östergarn buoy	May 1986 – November 1986	0.79
33001	Läsö-Ost buoy	May 2001 – February 2009	0.78
35070	Trubaduren buoy	October 1978 – October 2003	0.72
35064	Öland waverider buoy	February 1984 – March 1984	0.72
35068	Fladen buoy	July 1988 – June 1999	0.66
35072	Väderöarna2 buoy	July 1986 – December 1986	0.61
35056	Almgrundet buoy	October 1978 – September 2003	0.60
35062	Kristianopel buoy	April 1990 – March 1991	0.59
35067	Oskarsgrundet buoy	September 1983 – June 1999	0.53
35060	Hoburg buoy	June 1981 – January 1982	0.46

at these locations. More detailed investigation is needed to determine if the deviating results are due to limitations in the model or deficient quality of observed wave data.

Lower R^2 values might, in some cases, reflect the quality of the wave observations. There are four wave gauges located in the area around Väderöarna in Skagerrak (33005, 33015, 35071, and 35072). Three of the stations present R^2-values greater than 0.80, whereas one station has an R^2-value of 0.61. Station 35072 with R^2 of 0.61 is the station with the shortest period of available data in the Väderöarna

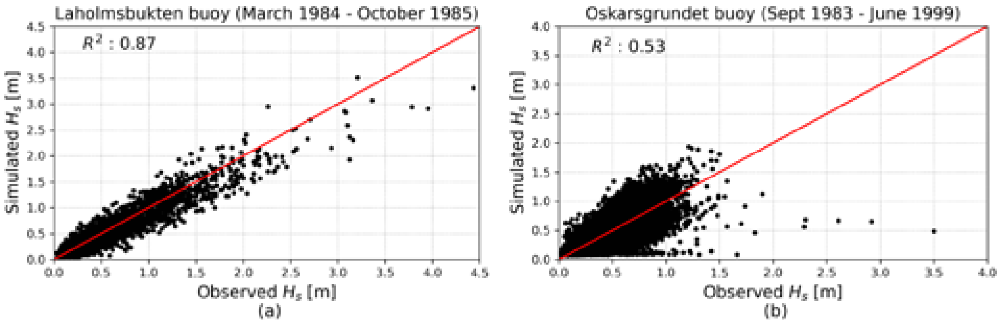

Figure 3: *Comparison of modelled H_S and SMHI wave buoy observations of H_S at (a) Laholmsbukten, Kattegat and (b) Oskarsgrunet, Öresund.*

area. Fewer observational data points can give more scattered data and hence result in a lower R^2. However, the other stations in the Väderöarna area present R^2-values greater than 0.80, which indicate that the model is capable of accurately simulating the waves in this area. At the remaining four stations with R^2-values below 0.65, the deviations could be related to the quality of the input bathymetry or the grid resolution, which potentially may not sufficiently represent the area to simulate the waves accurately. Alternatively, the relatively poor model fit could also have arisen from deviations in the measurement procedure, either by the use of different types of equipment or measurement techniques. However, a more detailed investigation is required to identify deviations in the observational data or model input data to explain the lower R^2-values.

The conditions of the input data used for simulation impacts the achieved model accuracy. The ERA5 reanalysis dataset used for wind input has been derived through procedures involving modelling and constitute wind data averaged over a larger area (i.e., 30 km, corresponding to the resolution). This may explain why the modelled significant wave height occasionally deviates from the point observations. Dependent on the intended application of the simulated wave climate available through the data portal, the user should consider and evaluate potential effects of the model uncertainties. It is particularly important to consider this effect when studying extreme events, since data points to represent such events are sparse.

Further development and refinement of the current model setup will be done to improve model performance. Forthcoming work includes updates and enhancements of the computational grid and evaluation of different wind input data sets. Alternative wind data sets available include the preliminary ERA5 dataset from 1950 to 1978 recently published and SMHI model data MESAN derived though optimal interpolation from observational data, covering a period from 1997 until today. In addition, the model performance in nearshore areas is yet to be assessed. The Division of Water Resources Engineering at Lund University is currently collecting nearshore wave data along the south coast of Skåne to assess the model performance at shallower water depths. These measurements can be used to calibrate the wave model, which is expected to improve model performance. Because of proposed future updates and developments of the model, it is important to reference the correct model version when using data retrieved from the online data portal.

The open-access wave data present opportunities to support coastal municipalities in Skåne and Halland. The data, such as illustrated in the wave climate characterization shown in Figure 4, can be used in multiple analyses, e.g., estimation of probability and return period for extreme events, design of coastal structures, studies of specific events, etc. Furthermore, the wave data can be used to calculate the magnitude and direction of sediment transport, enabling local and regional assessment

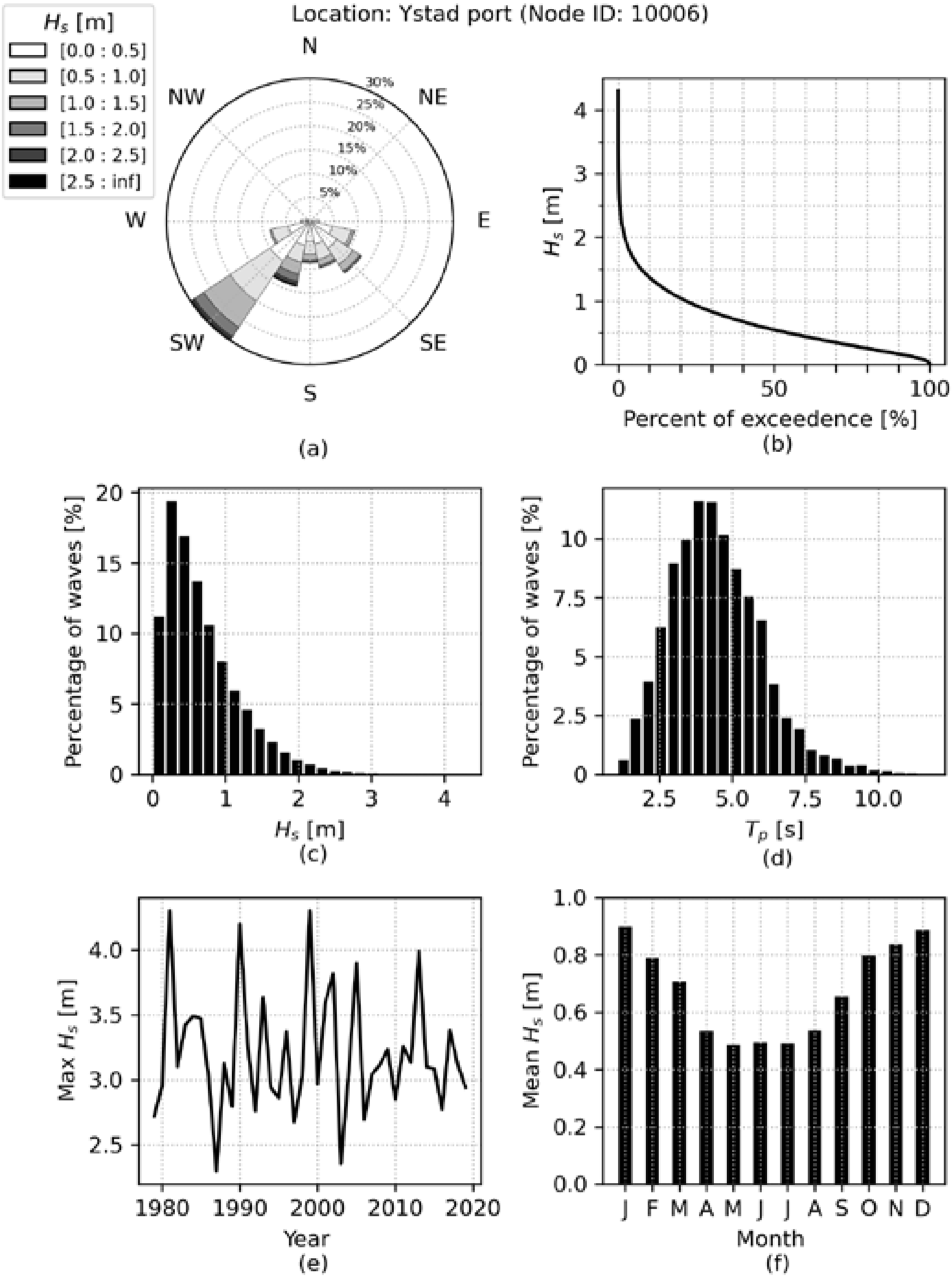

Figure 4: *Wave climate characteristics based on data from Ystad, 1979–2019. (a) Wave rose diagram. The pie-shaped sectors indicate the distribution and frequency of wave heights and wave directions, where greater H_s is represented with a darker shade. Combining the contribution of all the sectors in the diagram makes up 100% of the waves. (b) Duration curve of H_s. (c) Histogram for H_s. (d) Histogram for T_p. (e) Annual maximum H_s. (f) Monthly variation of mean H_s.*

of coastal morphological evolution. Knowledge of coastal processes plays a key role in municipal and societal planning, including developing climate change adaptation strategies. However, applying data from the wave portal should only be done after assessing the model limitations in relation to the intended purpose of the application. Although every effort is made to produce a reliable model for the hindcasted regional wave climate, the authors do not take any responsibility for the validity of the data when used by other parties.

Acknowledgements

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