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Arctic sea-ice decline amplifies extreme wave exposure for coastal Inuit communities

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Abstract

The ongoing reduction of seasonal sea ice in the Arctic enhances the development of extreme wave conditions, increasing the exposure of coastal communities to storm-related hazards. It is particularly prominent in Ausuittuq, Nunavut, the northernmost civilian community in Canada, which has experienced repeated coastal flooding over the past decade. In this study, we reconstruct a 38-year time series of total water level (TWL) in Ausuittuq to quantify the relative contributions of tides, storm surge, and wave runup to historical extremes. Wave runup contributes $\sim 30\%$ of annual maximum TWL and directly drives 25% of extreme events. Future mean and extreme wave conditions are assessed using a locally calibrated parametric wave model forced with CMIP6 projections of wind and sea ice. By mid-century, the projected lengthening of the ice-free season —particularly the delayed autumn freeze-up— substantially increases the frequency of extreme wave events by 53% under SSP2-4.5 and 75% under SSP5-8.5 relative to 1985–2000. By 2100, the frequency of extreme wave events under SSP5-8.5 approaches levels comparable to an entirely ice-free year. It suggests that in fetch-limited, seasonally ice-covered Arctic regions, sea-ice loss amplifies hazard exposure primarily through more frequent wave extremes, signaling a shift toward more persistent wave-driven coastal hazards.

1 Introduction

Coastal hazards such as flooding and rapid erosion typically happen during storms, through the combination of astronomical tides, surface gravity waves, and non-tidal water level fluctuations, including storm surges (Serafin et al., 2017; Almar et al., 2021). In the Arctic, the impact of storm-related coastal erosion is further amplified by ground-ice melt and permafrost thaw (Irrgang et al., 2022; Wang et al., 2023). Until recently, the persistence of sea ice for most of the year prevented extreme sea states from developing (Khon et al., 2014). However, by increasing effective fetch, the rapid decline of seasonal sea ice is now the primary driver of future changes in the Arctic wave climate (Thomson and Rogers, 2014), enhancing potential exposure of arctic communities to coastal hazards (Casas-Prat and Wang, 2020; Henke et al., 2024).

Ausuittuq (Grise Fiord) (*the place that never thaws*), is the northernmost Canadian Inuit community and is home to ~ 150 residents. It is located on the southern coast of Ellesmere Island ($76^{\circ}25'12''\text{N}$, $82^{\circ}53'24''\text{W}$), which opens to Jones Sound (referred hereafter as JS).

Along with Nares Strait and Lancaster Sound, JS forms one of the three main gateways connecting the Arctic Ocean to the Atlantic through the Canadian Arctic Archipelago. It is bounded to the east by Baffin

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Bay and the North Water Polynya—an area of exceptionally high biological productivity and active new-ice formation (Barber et al., 2001). JS is a relatively narrow waterway (~80 km wide, ~250 km long) that channels surface winds in the east-west direction. As a result, the wind climate in JS is mostly dominated by westerly winds during the winter period and easterly winds during the summer period (See supplementary information). Except for the polynya that forms between Coburg and Devon Islands, JS is covered with landfast ice from December to June. During summer, the ice cover consists of fragmented floes, reaching its lowest concentration in September when JS is essentially free of ice (Pelle et al., 2026).

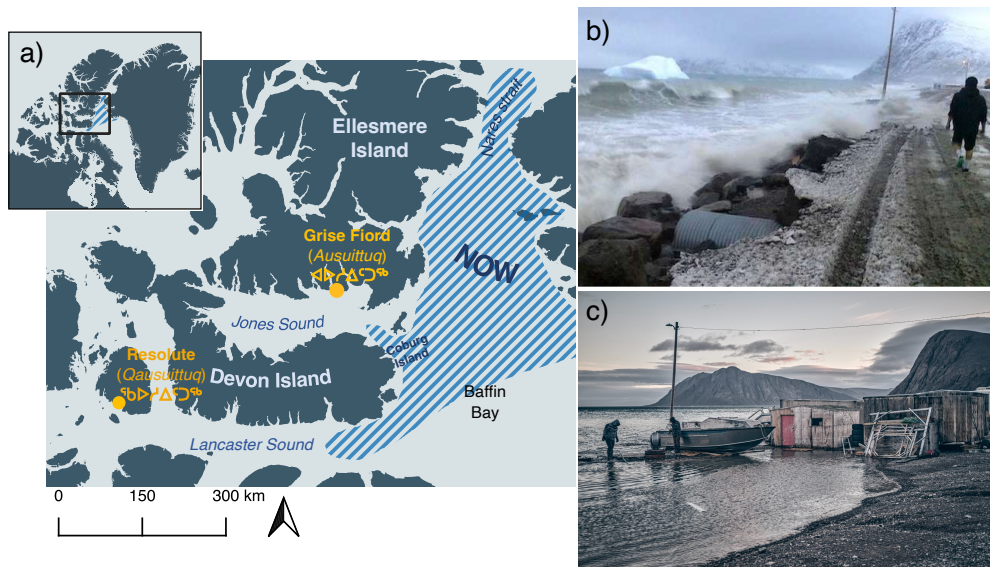


Figure 1: a) Map of the area surrounding Ausuittuq (yellow dot). The extent of the North Water (NOW) polynya is marked by the hashed blue area. b) Photo by Bernard Ungalaaq Makta, published in Nunatsiaq News, showing an overtopping event in Ausuittuq on 20 August 2016. c) Photo by David Didier of a flood event on 12 August 2022.

During the past 15 years, Ausuittuq has undergone repeated overwash and overtopping events during the ice-free season (Figure 1b and 1c), leading to flooding (Didier et al., 2024, 2026). While impacts have been so far limited to boat and shoreline cabin damage, critical infrastructure—including the main road and utility poles—lies within the active part of the beach, raising concerns about growing community exposure and the need to develop enhanced adaptation strategies in this remote community.

Considerable efforts are undertaken worldwide to develop risk reduction strategies, at local or national scales, often relying on multi-hazard mapping (Didier et al., 2019), short-term forecasting (Barnard et al., 2014; Stockdon et al., 2023), and long-term climate projections (Vousdoukas et al., 2018; Leung et al., 2024) to better anticipate and mitigate the impacts of extreme events. In the Arctic, however, the lack of observational data and high-resolution regional models, combined with the important uncertainties regarding future climate states (especially sea ice), limits the capacity of local authorities to design effective adaptation plans. It is thus essential to bridge these gaps to enhance the capacity of populations living in one of the world’s most climate-vulnerable regions (Cooley et al., 2020) to adapt.

Several studies have investigated changes in average and extreme wave conditions in the Arctic, both in the recent past (Thomson and Rogers, 2014; Stopa et al., 2016; Liu et al., 2016; Waseda et al., 2021) and under future climate state scenarios (Casas-Prat et al., 2018; Casas-Prat and Wang, 2020; Henke et al., 2024). These studies all point towards a rapid intensification of the wave climate in the Arctic. However, most have been conducted at a pan-Arctic scale using models—particularly sea ice models—with spatial resolutions of 100 km or more that do not adequately resolve narrow complex fetch-limited environments such as the Canadian Arctic Archipelago (CAA). Although such approaches offer significant insights at a

pan-Arctic scale, their practical applicability to coastal risk reduction planning for Arctic communities in such regions remains limited.

Co-led and co-designed by southern and Inuit partners through a community-based approach in Ausuittuq (Didier et al., 2024, 2026), the work presented here aims to provide tools and information that are crucial for coastal erosion and flooding risk management in the Canadian High Arctic and Inuit Nunangat. We first quantified the contribution of waves to historical extreme water levels using climate reanalysis of waves, tide and storm surge. Second, we assessed the future evolution of mean and extreme wave conditions using a simple but efficient parametric wave model forced by multi-model ensemble projections of wind and sea ice, selected within the Coupled Model Intercomparison Project Phase 6 (CMIP6).

2 Drivers of extreme water levels

The relative contributions of tides, storm surge and waves to coastal total water level (TWL) vary both regionally and over different time scales, from hours to seasons to decades. While the seasonality of waves in the Arctic is largely controlled by sea ice, synoptic atmospheric circulation patterns such as the Arctic Oscillation (AO) also affect surface winds in different parts of the Arctic and, consequently, the wave climate variability on a decadal scale (Liu et al., 2016). Spatial variability at the coast is closely related to nearshore bathymetry and fine-scale morphological features, such as the beach slope and the type of substrate, which control how much of the wave momentum contributes to water and sediment transport, wave setup and runup (Dodet et al., 2019). Coastal geomorphology and sea ice can also significantly affect the propagation of astronomical tide and storm surge in the Canadian Arctic Archipelago (CAA) (Kim et al., 2021; Kleptsova and Pietrzak, 2018). While their relative contribution remains variable, ocean waves can sometimes dominate the TWL signal during extreme events (Hoeke et al., 2013). TWL are often viewed as a linear combination of tides, non-tidal components and waves, but there are complex interactions between them (Idier et al., 2019). It is therefore difficult to fully understand and precisely evaluate the causes of extreme total water levels in the context of coastal risk assessment from a global or regional point of view, since they are often site-specific.

Here we examine the relative contribution of astronomical tides, storm surge and waves to annual maximum TWL events over the recent past in Ausuittuq. A 38-year hourly time series of TWL in Ausuittuq (1979–2017) was reconstructed by combining model reanalysis of storm surge, tides and waves. Modelled tide and storm surge were obtained from the Deltares Global Tide and Surge Model (GTSM) version 3.0 forced by the ERA5 atmospheric reanalysis (Dullaart et al., 2020). Wave contribution was estimated using a semi-empirical runup formulation, extensively calibrated in Ausuittuq, applied to incident wave conditions obtained from the Arctic Ocean Wave Hindcast product provided by the Copernicus Marine Environment Monitoring Service (CMEMS, 2020). The complete method used to calibrate the runup equation, which combines video camera, nearshore wave sensors and UAV-derived high-resolution DEMs conducted with community members, is available in (Jourdain-Bonneau, 2025).

The contribution of each component to extreme TWLs, expressed as annual maximum TWL events in Ausuittuq over the 38 years, is shown in Figure 2a. Annual maximum TWL events were 2.97 ± 0.25 m on average and occurred predominantly in September, coinciding with the period of minimum sea-ice extent in Jones Sound. Astronomical tide dominated extreme water levels, accounting for $69 \pm 12\%$ of the TWL, while wave runup contributed to $30 \pm 13\%$. Comparatively, storm surge has a negligible contribution, contributing only $1.2 \pm 4.3\%$ of the TWL during extreme events. However this does not directly identify the primary drivers of extreme water levels, as a large contribution from a given process does not necessarily imply that it is itself an extreme. Figure 2b shows the relative frequency of annual maximum TWL events during which individual processes exceeded their respective 99th percentiles. Results indicate that 25.6% of annual maximum TWL events were directly associated with extreme wave conditions, while it is only 7.7% and 2.6% for the astronomical tide and storm surge, respectively. In the remaining 64.1% of events, none of the individual processes were extreme, and maximum annual TWL resulted from the compound effect of tide, surge, and wave runup.

It is worth reiterating some of the sources of uncertainty affecting the results above. Among them, the coarse spatial resolution of available numerical models remains a major issue in such a complex geographic area with narrow basins. For example, the GTSM V3.0 surge reanalysis is forced by the 0.25° ERA5

atmospheric reanalysis, which may not adequately represent wind channelling effects (Moore, 2021) and therefore is likely to underestimate wind stress and associated storm surge (Moon et al., 2009). In addition, the absence of long-term water level observations (e.g. tide gauges) in the CAA limits our ability to properly quantify such uncertainty. Regarding wave contribution, additional uncertainties arise from the formulation of wave runup. Although extensively calibrated in Ausuittuq under a wide range of incident waves and water level conditions (Jourdain-Bonneau, 2025), the runup formulation is strongly dependent on beach slope, which can slightly vary both alongshore and with still water level (See Methods).

Also, while our framework captures the combined effect of tides, surge, and wave runup, which ultimately governs hazards potential, individual contributions are not simply additive, and it conceals possible inter-dependencies among processes. Taking the same example as above, the wave runup and setup associated with a given incident wave height strongly depend on the still water level dictated by tidal phase and surge amplitude, which ultimately controls wave radiation stress, generation of infragravity waves and modulates the local beach slope. Moreover, the present analysis is restricted to modelled extreme TWL events over the historical period, which precludes assessment of the relative contribution of individual processes to very low-probability events, i.e. associated with 50- or 100-year return periods (Serafin and Ruggiero, 2014; Serafin et al., 2017). For such rare events, the relative importance of tides, surge, and waves may therefore differ. Estimating contributions at these return periods would require fitting distribution tails and making assumptions regarding the dependence structure among variables. These assumptions can introduce additional sources of uncertainty to existing surge, wave, and runup model uncertainties.

Nonetheless, while acknowledging all the sources of uncertainties above, our results highlight the dominant role waves play in extreme TWLs and suggest that future changes in wave extremes may strongly influence the evolution of coastal hazards in Ausuittuq and the Canadian High Arctic.

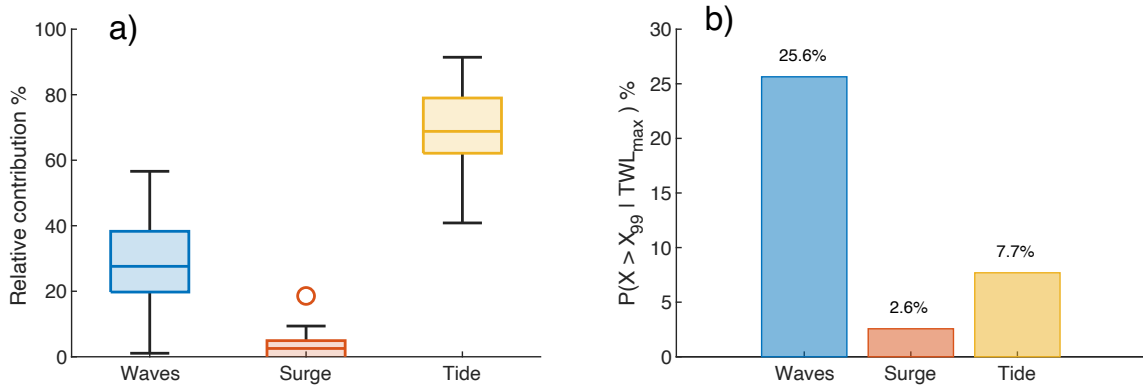


Figure 2: a) Relative contribution of waves, tides and storm surges to annual maxima of TWL in Ausuittuq. b) Percentage of extreme TWL events during which an individual driver exceeds its 99th percentile.

3 Evolution of mean wave and sea ice conditions

We investigated changes in mean and extreme wave conditions in Ausuittuq using a parametric wave model forced with wind and sea ice fields extracted from global and regional climate models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6). The analysis covers both the historical period (1950–2015) and future projections (2015–2100) under the SSP2-4.5 and SSP5-8.5 scenarios (IPCC, 2021). Although numerical wave models, which explicitly solve the wave action balance equation to describe the evolution of the full wave spectrum through wind input, dissipation, and nonlinear interactions, are now largely used for wave prediction (Ribal et al., 2025; Khon et al., 2014; Casas-Prat and Wang, 2020; Baudry et al., 2025), parametric wave models remain highly relevant in numerous applications. These include coastal and offshore engineering (Coastal Engineering Research Center, 1984), hurricane and tropical cyclone studies

(Hwang, 2016; Bethel et al., 2021) or extreme waves statistics (Vanem, 2011). A wide range of parametric formulations exists, depending on whether fully developed seas or duration/fetch-limited conditions are assumed or not. These formulations are often expressed as simple functions of wind speed and fetch distance (Etemad-Shahidi et al., 2009; Gao et al., 2023), offering an efficient alternative to computationally demanding numerical models. In this study, we compute long-term wave statistics from a local perspective, using a locally calibrated parametric model to produce ensemble simulations for constraining uncertainties related to future sea ice conditions. The model was parametrized using significant wave height observations from a wave buoy deployed in Ausuittuq in 2021 (Didier et al., 2026), combined with 10-m wind speeds from the ERA5 atmospheric reanalysis. Further details are provided in the Methods sections 6 (Methods) and 11 (Supplementary Information).

Hourly 10-m wind data is provided by the fifth version of the Canadian Regional Climate Model (CRCM5) that covers North America and the Canadian Arctic with a resolution of 0.11° (~ 12 km). For sea ice, an ensemble is built using four of the highest spatial resolution models, ensuring that sea ice conditions in JS are reasonably resolved: AWI-CM-1-1-MR (25 km), GFDL-ESM4 (25 km), CNRM-CM6-1-HR (25 km) and MPI-ESM1-2-HR (50 km). The effect of sea ice on waves is represented using a simple threshold criterion based on the monthly mean ice fraction in JS above which waves could not develop. The value of this threshold is adjusted by comparing our parametric wave model forced with ERA5 winds and sea ice from the EUMETSAT OSI SAF and ESA CCI climate data record (Laverne et al., 2019) (Hereafter, CDR) to fit the seasonal variation of the wave conditions offshore of Ausuittuq from the Arctic Ocean Wave Hindcast. The best value was found to be $a_i = 30\%$. The temporal evolution of monthly mean sea ice concentration (SIC) in JS and H_s in Ausuittuq is shown in Figure 3 for the periods 2000–2015, 2035–2050, and 2085–2100 under both scenarios. Results indicate an expansion of the season during which SIC in JS remains below 30%. In the historical period (2000–2015), simulated SIC drops below this threshold from early July to mid-September, with a minimum in August. Note that the modelled sea-ice ensemble predicts slightly less ice than the CDR observations on the historical period. By 2085–2100, SSP2-4.5 projections show sea ice retreating earlier, from June through mid-October, with complete ice loss from July to October. Under SSP5-8.5, this trend intensifies, with SIC falling below 30% from May to December and JS remaining partially free of ice the rest of the year, with the ensemble mean reaching a maximum ice fraction of 78% in March. Regarding wave climate, the monthly mean H_s peaks at 0.35 m in August, exhibiting an inverse relationship with SIC.

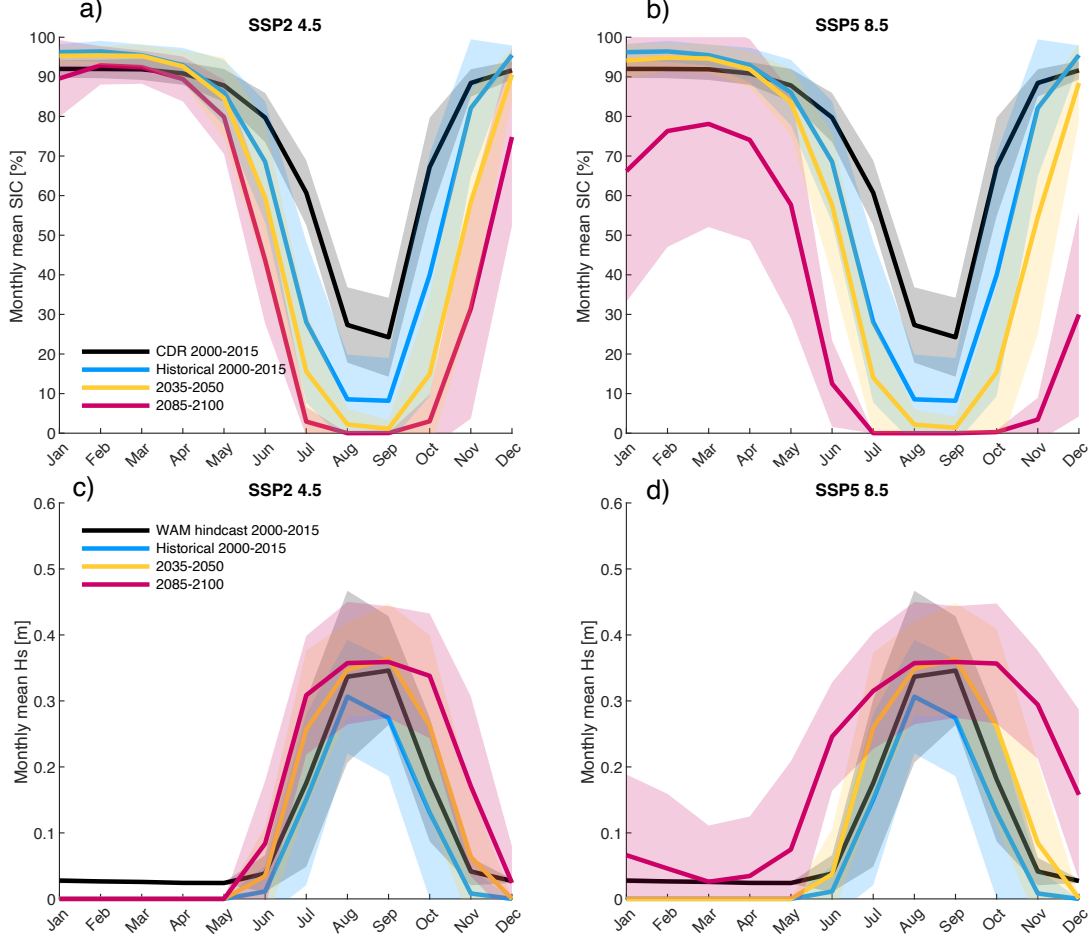


Figure 3: Monthly averaged sea ice concentration (SIC) in JS (a, b) and monthly averaged significant wave height H_s in Ausuittuq (c, d). Solid lines and shaded areas correspond respectively to the mean and standard deviation of the four ensemble members over the 15 years.

4 Extreme wave conditions

The evolution of the frequency of extreme wave events from 1950 to 2100 is assessed by analyzing the annual occurrence of independent wave events — with minimum separation of 48h between consecutive events — exceeding the 99th percentile of significant wave height (H_{99}), under the different scenarios (Figure 4a). The threshold H_{99} was computed from the WAM hindcast over the period 2000–2015, considering only the summer season (July–October), when the sea ice cover is minimal, ensuring that extremes are characterized under open-water conditions. While this threshold is somewhat arbitrary, it corresponds to what we consider *extreme* in the present and stands as a common reference baseline to assess future changes in extreme conditions. Results are expressed in terms of the annual number of extreme events N_{annual}^{99} and of the normalized difference in frequency relative to the mean annual number of extreme events during the historical reference period (1985–2000), denoted as $\Delta N_{\text{annual}}^{99}$.

Although there is strong interannual variability, a clear increasing trend emerges. During the historical period, the yearly average number of extreme events is 8.8 ± 3.4 with an increasing trend of 0.07 y^{-1} ($+0.8\% \text{ y}^{-1}$). By mid-century (2050), the projected annual number of extreme wave events increases by $+53\%$ under SSP2-4.5 and by $+75\%$ under SSP5-8.5 relative to the reference period. By the end of the century (2100), the increase reaches $+88\%$ and $+182\%$ under SSP2-4.5 and SSP5-8.5, respectively.

The absolute number of extreme events derived from the WAM hindcast is slightly lower than that

simulated by the historical climate model over the same period. This discrepancy is attributed to differences in wind forcing, as the CRCM5 model tends to produce more intense extreme winds than the ERA5 reanalysis. However, the long-term trends are consistent across both datasets.

For comparison, Figure 4a also shows the long-term evolution of the annual frequency of extreme events assuming complete absence of sea ice, thereby isolating the influence of wind forcing alone. For the historical period, the number of annual extreme events is substantially higher for the no ice experiment, with 28 ± 5.7 events. This large difference highlights the strong sheltering role of sea ice, which prevents 67% of extreme events from occurring. This difference progressively reduces over time, such that by the end of the century, the number of extreme events in the SSP5 8.5 converges toward the no-ice case. Figures 4b and 4c show the difference in the monthly number of extreme events compared to the reference period $\Delta N_{\text{monthly}}^{99}$ for the two scenarios. The projected increase of frequency of extreme events occurs predominantly in autumn between October and November. This seasonal shift reflects the greater intensity of the wind climate and extreme wind events in autumn compared to early summer (see Supplementary Information, section 11). Consequently, the increase in extreme wave occurrence is more strongly linked to delayed sea-ice freeze-up in autumn than to earlier sea-ice breakup in summer. Moreover, combining information from Figures 4a, 4c, and 3 indicates that a complete absence of sea ice is therefore not necessarily required for the frequency of extreme wave events to statistically converge toward the no-ice case. Because the wind climate is more energetic in autumn, a partial reduction of sea ice during this season is sufficient for the frequency of extreme waves to reach the same frequency as under year-round ice-free conditions. This highlights the disproportionate influence of autumn sea ice conditions on extreme wave exposure.

Relating projected changes in extreme wave occurrence to future probabilities of extreme total water level (TWL) events remains challenging. As discussed in the previous section, such an assessment requires assumptions regarding the dependence between wave conditions and still water levels (i.e., tides and storm surge). Nevertheless, the results clearly demonstrate that sea ice exerts a strong control on the frequency of extreme wave events. Consequently, future coastal hazard potential in Ausuittuq -and possibly in other coastal communities in the CAA- will be strongly conditioned by ongoing sea ice decline.

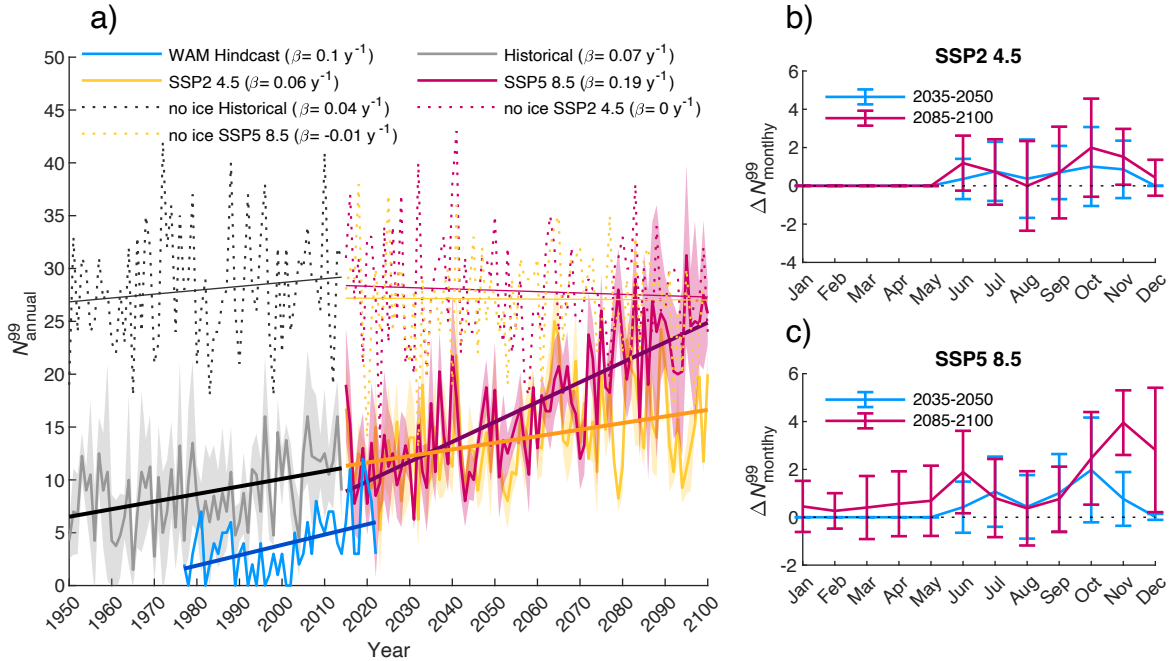


Figure 4: a) Frequency of occurrence of extreme wave events from 1950 to 2100, expressed as the annual number of individual events with H_s greater than the 99th percentile of H_s computed from the WAM hindcast between 2000-2015. Difference $\Delta N_{\text{monthly}}^{99}$ in the monthly number of extreme events compared to the reference period 2000-2015 for b) SSP2-4.5 and c) SSP2-8.5.

5 Discussion

In previous studies, changes in extreme wave conditions in the Arctic have been assessed at a pan-Arctic scale, in the absence of local perspectives, revealing an intensification of wave extremes caused by a reduction of seasonal sea ice extent. This manifests statistically as higher annual maximum or as higher extreme percentile (e.g. 90th or 99th) of significant wave heights (Liu et al., 2016; Stopa et al., 2016; Casas-Prat and Wang, 2020). In Jones Sound and more broadly across the CAA, however, the fetch is inherently constrained by the limited size of the basins, which imposes an upper bound on the magnitude of extremes. Even in the absence of sea ice, this geographic limitation prevents the generation of the much larger waves that are expected for other Arctic seas. Future changes in extreme wave conditions and associated coastal hazards in the CAA are therefore not necessarily linked to an increase in the absolute magnitude of extremes. Rather, they are more closely associated with an increase in the *frequency* of extreme wave events driven by a lengthening of the ice-free period, which may heighten cumulative impacts on coastal infrastructure, communities, and land access (Bishop et al., 2025)—for a longer portion of the year, though not necessarily with higher waves.

In our study, we adopted a local perspective to investigate exposure to coastal hazards. This local perspective is critical because, in the Arctic, civilian communities are scattered over large distances, e.g. the nearest Canadian hamlet to Ausuittuq is Qausuittuq (Resolute Bay), located nearly 380 km away — Qaanaaq, Greenland, is in fact slightly closer. Specific risk management and adaptation strategies should therefore be developed and implemented at the local stage in collaboration with local stakeholders. Moreover, the processes affecting coastal exposure, including waves, tides, and storm-surge propagation, storminess, or sea-ice dynamics, may vary considerably across locations under the influence of local factors that are not always well captured in regional assessments. However, we acknowledge that some simplifications made in this study are not necessarily applicable elsewhere. For example, the use of a parametric wave model based on local wind would not be suitable in larger basins where swell may represent a significant component of the wave climate. Nonetheless, our method, where local observations are paired with regional models and global predictions, can be applied to other communities in the CAA under similar conditions, especially where in situ wave observations were made in the recent past (e.g. Didier et al., 2026). Also, our representation of the impact of sea ice on the wave field could be debatable. Whereas a numerical approach typically relies on two-dimensional, gridded daily mean sea ice fields, we approximated sea ice effects by applying a wave cut-off based on the monthly mean sea ice fraction over the entirety of Jones Sound. This simplification does not reflect the high spatial and temporal variability of a sea ice cover composed of highly mobile, fragmented ice floes, particularly during transitional periods near freeze-up and break-up. However, it should be noted that current sea ice models still lack the necessary physics to properly capture such variability, especially in the marginal ice zone (MIZ) where key processes such as the rheology of fragmented ice, wave-ice interactions including wave-induced breakup, and the influence of wave radiation stress are still not represented (Dumont, 2022). Furthermore, the spatial resolution of the climate models used here, while among the highest currently available, remains far coarser than the scales at which wave energy dissipates in sea ice.

It should also be noted that although we considered an ensemble of four sea ice models, wind forcing was derived from a single regional climate model. While it allows us to isolate the contribution of sea ice, this limits our ability to assess the relative impact and uncertainties related to surface winds in the evolution of the wave climate. In our case, projections from CRCM5 exhibited no obvious trends in surface wind speed under either climate pathway. However, some studies suggest that Arctic surface winds may intensify in the future, driven by a reduced surface roughness associated with the transition from ice-covered to open water, a decrease in atmospheric stability (Mioduszewski et al., 2018; Liu et al., 2024), and potential shifts of storm tracks (Zhang et al., 2004). A more comprehensive evaluation of wind impacts should therefore be included in future work.

Finally, while our results clarify both the contribution and evolution of extreme waves conditions, they do not directly quantify future flood risk or return periods of extreme water levels. From a coastal-risk management perspective, one would typically assess the probability of exceedance or the return period of a given event (e.g., 50- or 100-year return period). However, our results show that this task is far from trivial. For example, standard extreme-value analysis (EVA), which assumes stationarity, may not hold in a non-stationary climate with increasing extreme-event frequency (Data, 2009). Furthermore, robust projections of future coastal risk will be required to take into account SLR, and better constrain future sea ice conditions at a fine scale as well as the interactions among hydrodynamic processes and sea ice, all of which remain

highly uncertain in this region.

To conclude, our study shows that waves can play an important role in driving extreme coastal total water levels in fetch-limited, seasonally ice-covered arctic environments. We also identified clear increasing trends in extreme wave event frequency associated with the lengthening of the ice-free period. While we focused on a particular community, the findings of this study and especially the approach employed, can be extended to numerous other arctic regions, providing a foundation for the evaluation of coastal hazard exposure for arctic communities.

6 Methods

6.1 Relative contribution of waves, tides and storm surge to extreme water levels

An hourly time series of coastal Total Water Level (TWL) have been reconstructed for Ausuittuq over 38 years (1979–2017). TWL is expressed as the sum of three components, namely the astronomical tide (η_T), the non-tidal residuals (η_{NT}) and wave run-up (η_W), such that

$$\text{TWL} = \eta_T + \eta_{NT} + \eta_W. \quad (1)$$

The nontidal residuals (η_{NT}) generally include high-frequency fluctuations associated with storm surges caused by atmospheric pressure anomalies (inverted barometer effect) and wind stress (wind setup), as well as lower-frequency seasonal variations related to land ice melt, large-scale ocean circulation, and river discharge. For this study, only the storm surge component is considered, such that $\eta_{NT} = \eta_{SS}$. Both η_T and η_{SS} are obtained from the Deltares Global Tide and Surge Model (GTSM v3.0) forced by the ERA5 reanalysis (Dullaart et al., 2020).

The wave run-up component η_W is estimated using a semi-empirical formulation which is a function of the deep-water significant wave height (H_s), deep-water wavelength (L_0) and local beach slope ($\tan \beta$), such that

$$\eta_W = 0.996(H_s L_0)^{0.5} \tan \beta \quad (2)$$

This equation is similar to Battjes (1974) and has been extensively calibrated using video cameras in Ausuittuq. The complete approach, based on nearshore wave sensor deployments and UAV-derived high-resolution DEMs conducted in collaboration with community members over a period of three years, is available in (Jourdain-Bonneau, 2025). In Ausuittuq, the value of the beach slope $\tan \beta$ was found to vary between 0.09 and 0.19, both alongshore and according to the still water level. In this study, we use a representative beach slope of $\tan \beta = 0.12$. Values for both H_s and L_0 are obtained from the Arctic Ocean Wave Hindcast product provided by Copernicus Marine Environment Monitoring Service (CMEMS, 2020).

Annual maxima of TWL are extracted from the reconstructed time series, and the relative contribution of each process is quantified as

$$\overline{C_j}(\%) = \frac{1}{n} \sum_{i=1}^n \left(\frac{\eta_{i,j}}{\text{TWL}_i} \right) \times 100\% \quad (3)$$

where $i = (1, \dots, n)$ are indices of annual maximum TWL events and $j = (T, SS, W)$ corresponds to the tidal, storm surge, and wave run-up components, respectively.

To assess whether the contribution of each process corresponds to an extreme itself, we also define $P(\eta_j > \eta_{j,99} | \text{TWL}_{\max})$, the percentage of annual maximum TWL events during which an individual process η_j (wave runup, astronomical tide, or storm surge) exceeds its 99th percentile defined as

$$P(\eta_j > \eta_{j,99} | \text{TWL}_{\max}) = \frac{1}{n} \sum_{i=1}^n \eta_{i,j} > \eta_{j,99} \times 100\% \quad (4)$$

where $\eta_{j,99}$ is the 99th percentile of η_j . Different approaches have been used to compute $\eta_{j,99}$. For wave runup, the value of $\eta_{W,99}$ is computed only on the open water period to avoid dilution caused by sea ice. For tides, the value of $\eta_{T,99}$ is computed only on high tides. For storm surge, the value $\eta_{SS,99}$ is computed only over $\eta_{SS} > 0$.

6.2 Parametric wave model

The parametric wave model used in this study is of the form

$$H_s = \alpha U_{10}^2 + \beta \quad (5)$$

where U_{10} is the 10-m wind. The values of the coefficients $\alpha = 0.005 \text{ s}^2$ and $\beta = 0.1 \text{ m}$ are retrieved using a nonlinear least square regression on observations of significant wave height from a Spotter wave buoy deployed in August 2021 in Ausuittuq and wind data from the ERA5 atmospheric reanalysis extracted at the position of the buoy. Note that while wave growth is strongly limited by the fetch in our study area, the latter is not explicitly part of our formulation. It is, however, implicitly embedded in the parameter α , assuming that the impact of fetch variability is negligible for dominant wind directions in Jones Sound. All processes, including potential biases in the wind forcing, are implicitly taken into account in the model parameters, assuming that they remain stationary across time/conditions. More information on the calibration and validation of the model is available as Supplementary Information.

6.3 Statistics for extreme wave conditions analysis

The annual number of extreme wave events N_{annual}^{99} is defined as the number of independent wave events –with minimum temporal separation of 48 h between events– for which the significant wave height H_s exceeds the 99th percentile H_{99} . The threshold H_{99} is computed from the WAM hindcast in open water over the period 2000-2015.

The annual number of extreme wave events is given by

$$N_{\text{annual}}^{99}(t) = \sum_{i=1}^{n_t} H_s(t_i) > H_{99} \quad (6)$$

where t_i denotes an event in year t and n_t is the number of such events.

To compare future changes to historical conditions, we define the relative anomaly $\Delta N_{\text{annual}}^{99}(t)$ as the normalized difference between the fitted annual number of events and a reference baseline

$$\Delta N_{\text{annual}}^{99}(t) [\%] = \frac{\hat{N}_{\text{annual}}^{99}(t) - \overline{N_{\text{ref}}^{99}}}{\overline{N_{\text{ref}}^{99}}} \times 100\%. \quad (7)$$

The overbar denotes averaging over the reference period 1985-2000 and ensemble members. The fitted annual number of extreme events $\hat{N}_{\text{annual}}^{99}(t)$ is obtained using robust linear regression

$$\hat{N}_{\text{annual}}^{99}(t) = \beta t + \alpha \quad (8)$$

where β is the rate of increase/decrease (events yr^{-1}) and α the intercept.

Finally, we define the normalized rate of increase in extreme wave occurrence as

$$\beta_{\text{norm}} [\% \text{ yr}^{-1}] = \frac{\beta}{\overline{N_{\text{ref}}^{99}}} \times 100\%. \quad (9)$$

To assess how changes in extreme conditions vary seasonally, we define the monthly anomaly of extreme wave events as

$$\Delta N_{\text{monthly},T}^{99}(m) = \overline{N_{\text{monthly},T}^{99}}(m) - \overline{N_{\text{monthly,ref}}^{99}}(m) \quad (10)$$

where m is the month and T the time period (2035-2050, 2085-2100). The overbar denotes averaging over the years and ensemble members. Note that, unlike the annual anomaly, the monthly anomaly is not normalized to avoid artificially overestimating anomalies in months where the historical number of events is near zero.

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8 Data availability

Sea ice model data are available at <https://esgf-metagrid.cloud.dkrz.de/search>

GTSMv3.0, ERA5, EUMETSAT OSI SAF and ESA CCI climate data record are available at: <https://cds.climate.copernicus.eu/datasets>

Copernicus WAM hindcast model data are available at: Wave buoy data used for calibrating the parametric wave model are available at: Wind data from the regional climate model CRCM5 are available at: <https://pavics.ouranos.ca/twitcher/ows/proxy/thredds/catalog/birdhouse/disk2/ouranos/CORDEX/catalog.html>

9 Competing interests

The authors declare no competing interests

10 Author contributions

J.B., D.Di. and D.D. designed the project with contributions from C.J.B., T.N., A.K.H., and E.B. The data collection was carried out by D.Di., J.B., C.J.B., T.N., A.K.H. and E.B. J.B. performed data analysis. The main manuscript was prepared by J.B., with contributions from D.Di. and D.D.. D.Di., D.D., T.N., A.K.H. and E.B. contributed to project administration and funding acquisition, and all authors reviewed the manuscript.

11 Supplementary information

11.1 Seasonal trends of mean and extreme wind conditions

The wind climate offshore of Ausuittuq was assessed using a 48-year (1977–2024) time series of 10-m wind U_{10} extracted from the ERA5 atmospheric reanalysis. Monthly mean wind speeds U_{10} and associated dominant wind directions for February, July, and November are presented in Figure 5. Winter conditions are associated with westerly winds and mean speeds of ($\sim 5.5 \text{ m s}^{-1}$), whereas late spring (May–June) is characterized by easterly winds and lower mean speeds ($\sim 4.7 \text{ m s}^{-1}$). Autumn is a transition period, with winds coming both from the east and west.

Seasonal variability of extreme wind conditions is estimated using a Peak-Over-Threshold (POT) method applied to individual wind events, with a minimum of 48-hour separation between consecutive events. The threshold is defined as the 99th percentile over the entire time series, $U_{10}^{99} = 13.54 \text{ m s}^{-1}$, yielding $N = 306$

extreme events. The relative frequency of extremes in month i , defined as $f_i = \frac{n_i}{N}$, where n_i is the number of extreme events occurring during that month, is presented in Figure 5. The seasonal pattern is consistent with the mean wind climate but shifted by one month. Extreme winds occur most frequently during spring and autumn, with April alone accounting for 12% of all events. In contrast, summer is characterized by calmer conditions, with only 3% of extreme events occurring in July.

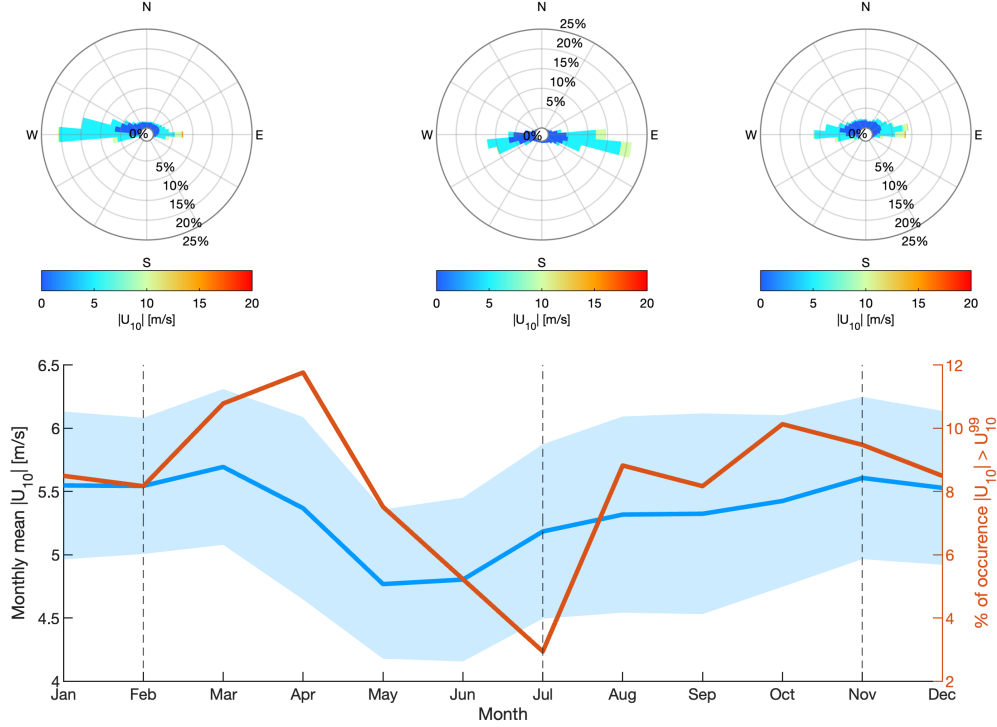


Figure 5: Monthly mean and extreme wind conditions in Ausuittuq computed from the 48-year ERA5 atmospheric reanalysis. The blue line corresponds to the mean over the entire period, and the shaded area is the standard deviation. The red line corresponds to the monthly relative frequency of extreme wind events ($U_{10} > U_{10}^{99}$). Dominant wind directions are presented for February, July and November.

11.2 Parametric wave model calibration and validation

The calibration dataset consists of an hourly time series (H_0) measured by a Sofar Spotter wave buoy deployed offshore Ausuittuq between 15 August and 18 October 2021 in approximately 14 m water depth. The buoy was moored at 76.4230°N, 82.9422°W. Data acquisition, quality control procedures, motion correction, and spectral processing used to derive bulk wave parameters are fully described in Didier et al. (2026).

During the deployment, the mean H_s was 0.28 ± 0.20 m, and the maximum recorded H_s reached 1.47 m. The 99th percentile of H_s was 0.91 m, comparable to the 0.89 m threshold derived from the 38-year WAM hindcast used to define extreme wave conditions in this study. Although the record is relatively short, it sampled representative extreme open-water conditions for Jones Sound. Figure 6a shows the empirical relationship between observed H_s and ERA5 10-m wind speed (U_{10}). The fitted parametric formulation yields coefficients $\alpha = 0.005$ and $\beta = 0.01$. The calibrated model reproduces the observed temporal variability of H_s during the 2021 period (Figure 6b).

Model validation was performed using an independent dataset collected by a second Spotter buoy deployed between 26 August and 20 October 2024 at 76.3896°N, 82.4920°W in approximately 13 m water depth offshore, southeast of Ausuittuq. Deployment configuration and processing chain followed the same protocol,

ensuring methodological consistency between calibration and validation datasets. The model was forced with ERA5 winds and evaluated directly against the 2024 observations. The parametric model reproduces observed H_s during the validation period with a root-mean-square error (RMSE) of 0.15 m, compared to 0.22 m for the CMEMS WAM hindcast over the same period (Figure 7). The improved performance relative to the spectral hindcast supports the robustness of the locally calibrated formulation for representing fetch-limited wave growth in Jones Sound.

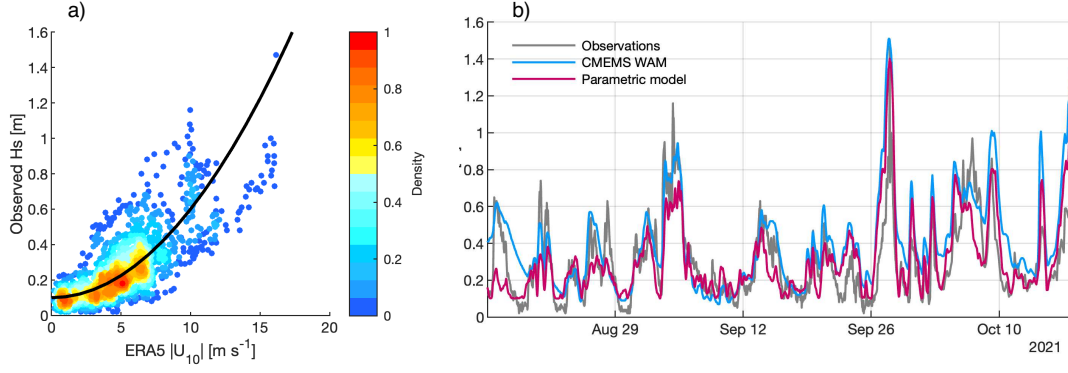


Figure 6: a) Scatter plot of the significant wave height observed by the buoy as a function of the local modelled ERA5 surface 10-meter winds. The fitted parametric model is shown in black. b) Time-series of observed and predicted significant wave height from the parametric wave model and the WAM hindcast for the calibration period.

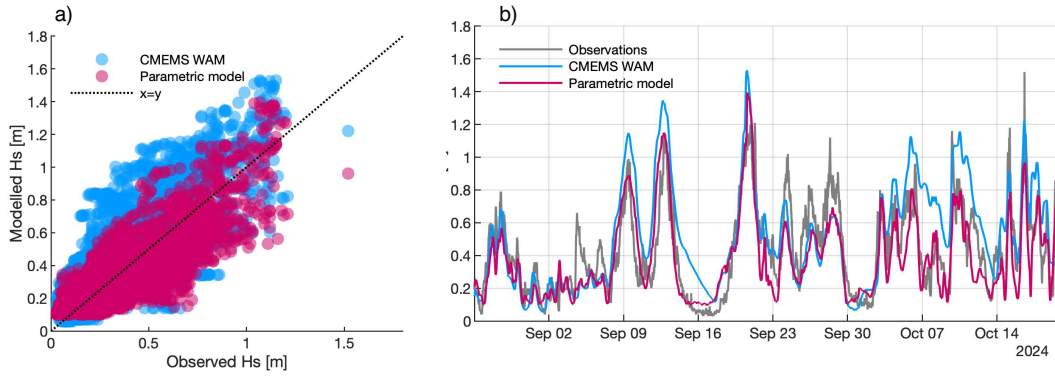


Figure 7: a) Scatter plot of the significant wave height observed by the buoy and predicted by the parametric wave model and the WAM hindcast for the validation period. b) Time-series of observed and predicted significant wave height from the parametric wave model and the WAM hindcast for the validation period.

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