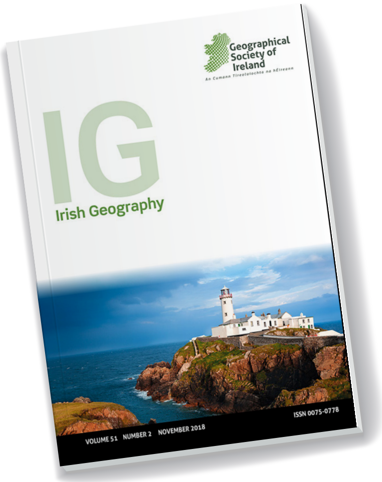

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Temporal variability in winter wave conditions and storminess in the northwest of Ireland

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Abstract: Winter storms have significant morphological impacts in coastal areas, often leading to extensive infrastructure damage and socio-economic disruption. While storm-dominated coastal environments, such as the northwest coast of Ireland, are generally attuned to highly energetic wave conditions, morphological impacts can be intensified by changes in the frequency and sequencing of storm events, particularly during storm-groups or exceptional winter seasons. Aiming to assess the variability in frequency and sequencing of wintertime wave conditions and storms in the northwest of Ireland, we combine observational records (M4 buoy) with data from two independent wave reanalyses (ERA-Interim and WAVEWATCH III) and perform a statistical analysis of wave conditions over the past six decades. Both reanalyses represent observed wave heights with very good skill. Excellent agreement between modelled data and observations was identified up to the 99th percentile, despite a slight underestimation/overestimation by ERA-Interim/WAVEWATCH III for waves above the 90% exceedance level. The winter of 2014/15 was the most energetic on record (67 years), but not the stormiest. The results show that highly energetic and stormy winters occur in clusters during positive phases of the North Atlantic Oscillation. Significant positive temporal trends for winter wave height, number of storms per winter and average winter storm wave height, suggest that winters are becoming more energetic and stormier, with potential implications for the erosion and recovery of coastal systems in the northwest of Ireland.

Keywords: *Northeast Atlantic, seasonality, winter storms, storm-groups, coastal impacts.*

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Introduction

Winter storms have significant morphological impacts in coastal areas, producing significant erosion and inundation hazards (Smith *et al.,* 2010; Ferreira *et al.,* 2017) and often leading to extensive infrastructure damage and wide-ranging socio-economic disruption (Ciavola *et al.,* 2011). While storm-dominated coastal environments, such as the northwest coast of Ireland, are generally attuned to highly energetic wave conditions (Cooper *et al.,* 2004; Loureiro *et al.,* 2014; Guisado-Pintado and Jackson, 2018), morphological impacts in coastal areas can be intensified by changes in the frequency and sequencing of storm events, particularly during storm-groups or during exceptional winter seasons (Ferreira*,* 2006; Loureiro *et al.,* 2012; Castelle *et al.,* 2017a).

The severity and variability of winter climate and storminess are known to be affected by large-scale patterns of atmospheric variability, such as the North Atlantic Oscillation (NAO) that dictates climate variability in the North Atlantic (Hurrel *et al.,* 2003; Feser *et al.,* 2015). The NAO has been associated with the variability in wave climate in the North Atlantic (e.g., Dodet *et al.,* 2010; Bertin *et al.,* 2013) and to the associated long-term coastal response (e.g., Clarke and Rendell, 2009; O'Connor *et al.,* 2011). Despite being the leading indicator of climate variability in the North Atlantic, the NAO has been recently outperformed by the Western Europe Pressure Anomaly (Castelle *et al.,* 2017b) in explaining the wave climate variability along most of the Atlantic coast of Europe (between 36°N and 52°N).

The wave climate of Ireland has been analysed in detail by Gallagher *et al.* (2014) based on a high-resolution reanalysis (i.e., a systematic modelling approach to produce datasets for climate monitoring that relies on a consistent modelling implementation and assimilation of historical observations). Gallagher *et al.* (2004) presented seasonal averages for various wave parameters and explored their relationship with the NAO and the Eastern Atlantic indexes. More recently, Gallagher *et al.* (2016) presented projections of the Irish wave climate for the end of the 21st Century, with a detailed analysis of potential changes in frequency and intensity of wind storms. However, there is no analysis of storminess for Ireland based on wave data that includes the recent exceptional winter seasons in western Europe (Pinto *et al.,* 2014; Castelle *et al.,* 2017b). To address this, we combine observational records with wave reanalysis data to perform a statistical evaluation of wave conditions and storminess over the past six decades for the northwest of Ireland. This paper aims to assess the variability in frequency and sequencing of winter wave conditions and storms and to discuss the implications for the coastal areas of northwest Ireland.

Data and methods

Analysis of the high-energy and storm-dominated wave climate of the northwest of Ireland relies on the existence of long-term wave records or, in their absence, reliable global or regional reanalysis datasets. For the present study, we used two wave reanalysis datasets (ERA-Interim and WW3) and observations from a deep-water wave buoy (M4). The reanalysis datasets are used to extend the temporal range of the wave buoy observations (8 years), while the use of two independent reanalysis aims to reduce uncertainties of wave climate analysis based on modelled data.

Datasets

The M4 is a deep-water directional wave buoy operated by the Marine Institute and is part of the Irish Weather Buoy Network. It was deployed in its present location, off the coast of north-western Ireland (10°W, 55°N; Figure 1), in May 2007 and has been operating continuously since then. Equipment malfunction or failure due to rough sea conditions led to data gaps during approximately 32% of the time between May 2007 and March 2015. Statistical quantities for atmospheric and oceanic parameters, including significant wave height (H_s), are provided at hourly intervals and made available after quality control.

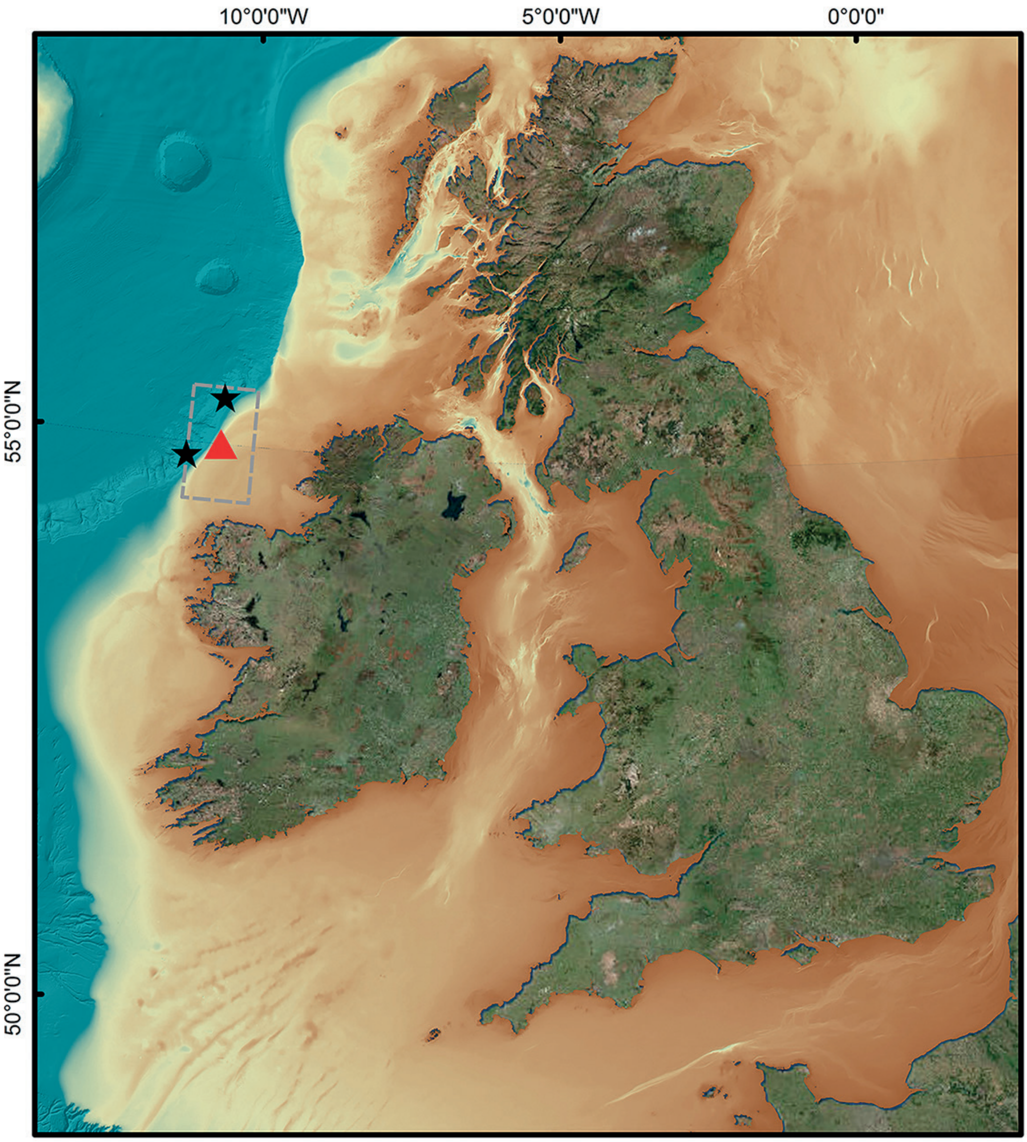

Figure 1: Location of the M4 wave buoy (red triangle), WW3 outputs (black stars) and ERA Interim grid point (dashed rectangle) in the context of the British Isles. Hill shaded bathymetry based on EMODnet Bathymetry (2016).

ERA-Interim is a reference global climate reanalysis dataset produced by the European Centre for Medium-Range Weather Forecast (ECMWF), extending from 1979 until the present. It includes a fully coupled atmosphere-wave model implemented with a horizontal resolution of 110km and assimilates a variety of observational datasets, from conventional meteorological station data to wave and wind measurements from satellites (Dee *et al.,* 2011). ERA-Interim provides gridded 6-hourly wave parameters, including significant wave height, period and direction, archived on a 1.0° x 1.0° latitude/longitude global grid (Berrisford *et al.,* 2011). In our study, H_s data for the northwest of Ireland (grid node 10°W, 55°N; Figure 1) was retrieved for the period between 01/1979 and 04/2015.

More recently, a dedicated wave reanalysis for the eastern North Atlantic was presented in Masselink *et al.* (2016). This dataset is based on a regional implementation of the WAVEWATCH III (herein WW3) model on a 0.5° horizontal resolution grid, covering the entire North Atlantic basin and forced with 6-hourly wind fields from the National Centres for Environmental Modelling/National Centre for Atmospheric Research (NCEP/NCAR) reanalysis. Similar to ERA-Interim, the NCEP/NCAR reanalysis assimilates a variety of land, marine and satellite data to produce a consistent global dataset of atmospheric variables since 1948 (Kalnay *et al.,* 1996). Wave height (H_s) data were made available for several locations offshore the north-western coast of Ireland and provided at 3-hourly resolution for the period between 01/1948 and 04/2015. In this study, we used the two grid nodes adjacent to the M4 buoy location (Figure 1).

Data filtering and validation

Given the short duration of the buoy observations and the significant data gaps, the buoy records are insufficient to consistently analyse wave climate variability for the northwest of Ireland. Nevertheless, since wave buoy data are not assimilated by either reanalysis, the buoy records can be explored for evaluating the ability of ERA-Interim and WW3 reanalysis to accurately reproduce the deep-water wave conditions for the area.

ERA-Interim and WW3 datasets represent wave conditions at synoptic times, averaged for model grid cells while the buoy observations are localised quantities obtained from the wave spectra recorded over a short time period. This results in inconsistencies in space and time between the modelled and observed datasets (Sterl and Caires, 2005). In order to address this, Caires and Sterl (2003) proposed a time-averaging approach that is consistent with the time that deep-water long waves take to travel across model grid cells. Considering that a long wave (~10 s) takes approximately 2 hours to cross a 1.0° x 1.0° ERA-interim grid cell, hourly data from the M4 buoy were filtered with a 3-point moving average, corresponding to an observation window of 2h 17m, centred on the model synoptic times (00, 06, 12 and 18 UTC). The filter was only applied when there were 3 buoy records in the specified time window. To prevent inclusion of unrealistic wave height values observed around data gaps (Caires and Sterl, 2003), all observations in the 12 hours before and after a data gap of 18 hours or more were removed. For consistency in the comparisons, data from the two WW3 0.5° x 0.5° grid cells adjacent to the M4 buoy were averaged, providing wave height values that are comparable to the grid cell and time window defined for comparison with the ERA-interim data.

Comparison of modelled and observed wave heights relied on the computation of standard error metrics using the full filtered time series (i.e., all filtered buoy records coincident with the 6-hourly model synoptic times), the filtered time series records above the 90% exceedance level, and the monthly means (months with more than 50% of missing data were removed from the calculations). The error metrics used in this analysis were the Bias, Root Mean Square Error (RMSE), the Normalised (by the mean of observed values) Root Mean Square Error (NRMSE), and Pearson's Linear Correlation Coefficient (R).

Data analysis

Winter climate and storminess are typically characterised by winter averages of atmospheric and oceanographic variables and metrics of events exceeding a given threshold (Feser *et al.,* 2015). For the present study, we analysed winter wave climate by computing the average significant wave height for conventional boreal winters (December to February, [DJF]), extended boreal winters (October to March, [ONDJFM]) and an intermediate winter average (December to March, [DJFM]), which has been used in other studies of northern hemisphere storminess (e.g., Dodet *et al.,* 2010; Masselink *et al.,* 2016; Castelle *et al.,* 2017b) and also corresponds to the time window for the winter NAO index (Hurrel 1995; Feser *et al.,* 2015). Winter [DJFM] storminess was analysed by computing the number of storm events per winter (n), the average storm wave height per winter (H), and a compound storminess index (STS) calculated as $STS_y = n_y H_y$. Storm thresholds were defined according to the 95% exceedance values of H_s for each dataset, which corresponded to a value of 6.25m for ERA Interim and 6.39m for WW3. These are similar to the 95% exceedance values for the M4 buoy data (6.37m). Following Almeida *et al.* (2011), storms were individualised based on a minimum time separation of 30 hours, meaning that a new storm event is defined only when records above the threshold are separated by more than 30 hours.

Long-term trends in the winter [DJFM] averages and storminess parameters were computed using linear fitting over the duration of the time series. Following Young *et al.* (2011) the statistical significance of the trends was analysed with the Mann-Kendall test, which evaluates randomness against trend in the data. As all trends were computed for winter periods only, there is no need to remove the effects of seasonality. The relation between the winter averages and storminess metrics with the station-based winter NAO index (available in Hurrel *et al.,* 2017) and the WEPA index (available in Castelle *et al.,* 2017b) was evaluated by computing Pearson's linear correlation coefficient, considering a two-tailed t distribution and a 0.05 significance level.

Results

The comparison between observed and modelled wave heights indicates that overall there is very good agreement between the M4 buoy data and both ERA-Interim and WW3 reanalysis (Table 1). Qualitatively, when considering the 6-hourly filtered time series, the scatter (Fig. 2a-b) and percentile-percentile diagrams (Fig. 2b-c) show that both reanalyses are able to reproduce the full range of wave conditions accurately. This is quantitatively confirmed by a bias of less than 0.05m and RMSE under 0.5m (Table 1). For monthly averages, error metrics improve, with lower bias, RMSE and NRMSE and almost perfect correlation (Table 1). Regarding records above the 90% exceedance

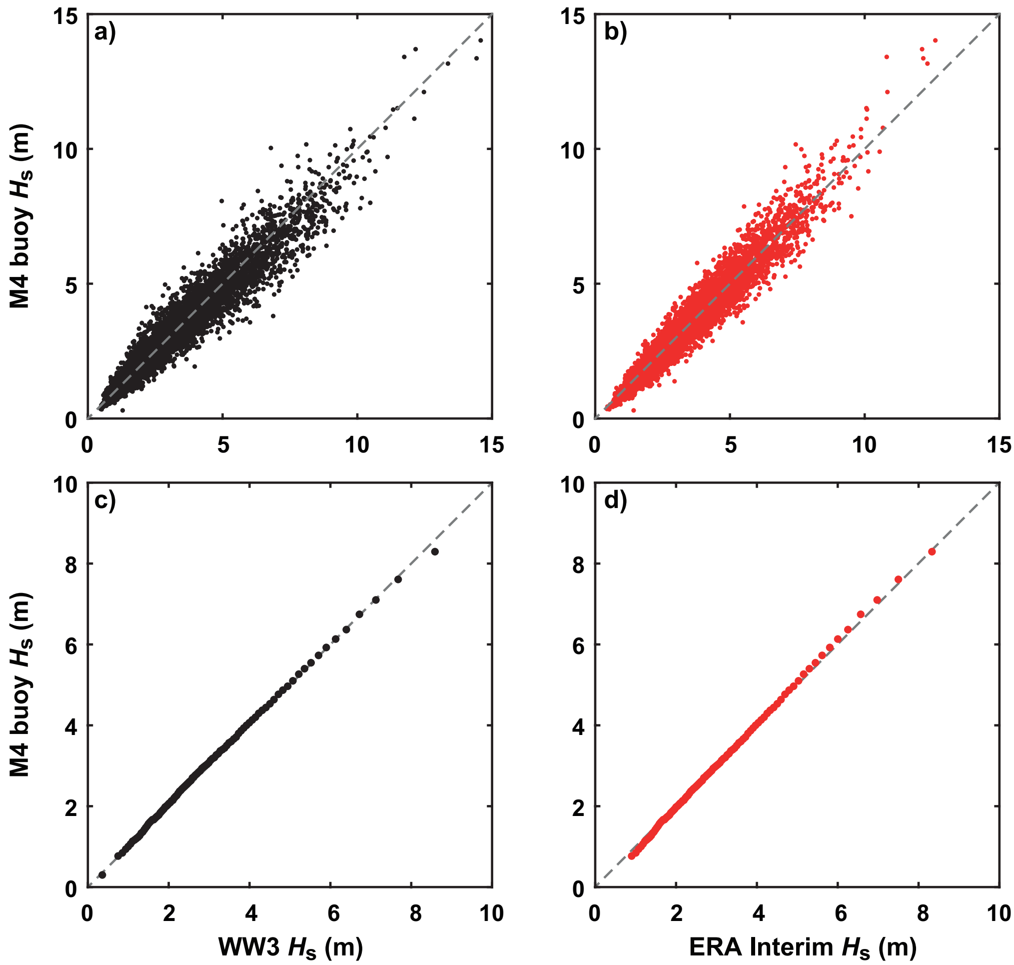

Figure 2: Comparison of the M4 wave buoy records with the WW3 (a, c) and ERA Interim (b, d) reanalysis. Scatter (a, b) and percentile-percentile (from 1% to 99%) plots (c, d) for significant wave height. Equality indicated by dashed grey line.

level, the agreement between observed and modelled datasets is also good, but there is a decrease in performance. Error metrics for these high-energy conditions indicate a higher bias, with ERA-Interim reanalysis underestimating large wave heights by -0.24m, while WW3 overestimates by 0.14m (Table 1). This is also apparent in Fig. 2a-b, with scattering increasing as wave heights increase, but not evident in the percentile-percentile diagrams (Fig. 2c-d). Even with a minor decrease in performance for higher energy conditions, both ERA-interim and WW3 reanalysis are able to accurately reproduce the full range of wave conditions observed in the northwest of Ireland, presenting similar error metrics to other reanalysis for the northeast Atlantic (e.g., Dodet *et al.,* 2010; Bertin *et al.,* 2013) or high-resolution reanalysis for Ireland (Gallagher *et al.,* 2014).

Table 1: Error metrics for ERA Interim and WW3 wave reanalysis, evaluated against the filtered M4 wave buoy records for the 6-hourly timeseries, for records above the 90% exceedance level and for monthly averages.

Model	Timeseries	n	Bias (m)	RMSE (m)	NRMSE (%)	R
ERA Interim	6-hourly	7361	0.02	0.40	12.8	**0.97**
	90%	769	-0.24	0.72	10.7	**0.86**
	Monthly	66	0.00	0.21	6.6	**0.98**
WW3	6-hourly	7361	0.04	0.48	15.5	**0.96**
	90%	769	0.14	0.83	12.2	**0.82**
	Monthly	66	0.02	0.15	4.9	**0.99**

Bold font indicates statistically significant linear correlation based on Pearson's linear correlation coefficient, considering a two-tailed t distribution and a 0.05 significance level.

Averages computed for the various winter intervals [DJF; DJFM; ONDJFM] are shown in Figure 3, where 36 winters are analysed with ERA-Interim and 67 winters with WW3 data. Overall the two datasets show the same patterns of temporal variability, with values for WW3 slightly higher than ERA-Interim for the majority of winters. This reflects the slight underestimation/overestimation in higher wave heights in ERA-Interim/WW3. For all averaging intervals, an increase in winter wave height is apparent in the second part of the record (post-1980). Based on WW3 data, the eight most energetic winters occurred since 1980, regardless of the averaging interval. The winter of 2014/15 was the most energetic on record for all datasets and averaging windows, except ERA-Interim [DJFM] winter, where it ranked 3rd after 1989/90 and 1993/94 (Fig. 3b).

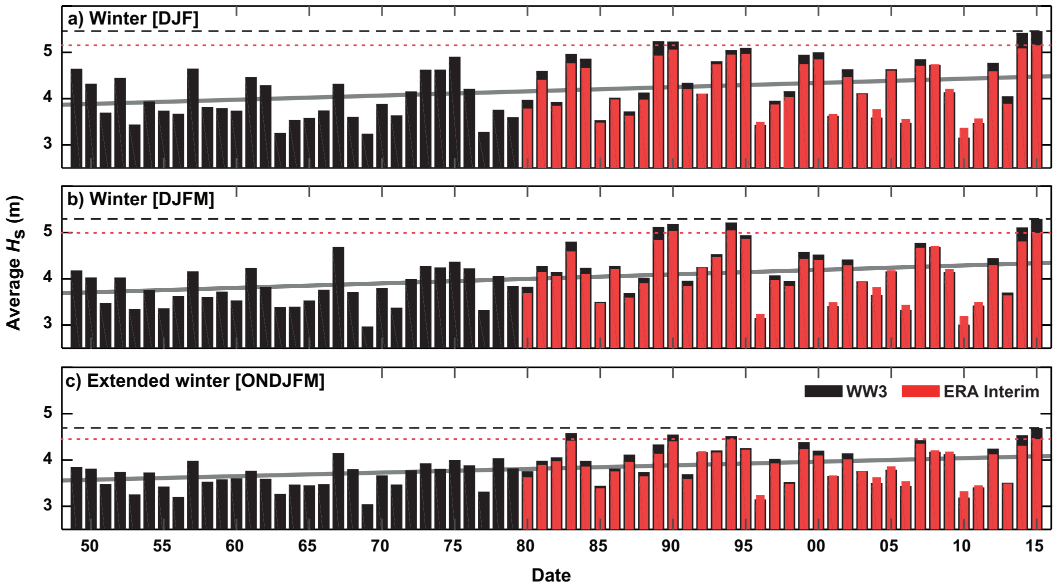

Figure 3: Average winter significant wave heights in the northwest of Ireland based on WW3 and ERA Interim reanalysis. Winters considered as including the months of DJF (a), DJFM (b) and ONDJFM (c). Horizontal lines indicate the winter mean for the 2014/15 winter for WW3 (dashed) and ERA Interim (dotted) reanalysis. Statistically significant linear trends for the WW3 dataset are indicated by solid grey lines.

While energetic winters can occur in isolation (e.g., 1966/67), the results highlight a pattern of energetic winter clustering, when two or more consecutive winter seasons have substantially higher averages. Most prominent examples occur post-1980 and include 2013/14 and 2014/15, two consecutive winter seasons that are exceptional according to all metrics considered (Fig. 3). The winters of 1988/89 and 1989/90 were also highly-energetic, as evidenced by averages for [DJF] and [DJFM] winter above 5m (based on WW3 data), but other clusters are identified in 1993/94 and 1994/1995, and 1982/83 and 1983/84 (Fig. 3a-b).

Storminess metrics computed for [DJFM] winters are shown in Figure 4 and exhibit high variability in number of storms per winter. However, this variability is consistent between the two reanalyses and appears to increase post-1987, when the number of storms reaches values in excess of 15 per winter alongside winters with less than 5 storms (Fig. 4a). Average storm wave height is more uniform along the years, with an increase in variability since 2000. Lower values based on ERA-Interim compared to WW3 once again reflect the under/overestimation in the datasets (Fig. 4b). The storminess index presents an integrated picture but given the consistency in average storm wave height it reflects mostly the variation in number of storms per year. Peaks in storminess are clustered in the same consecutive years as the energetic winters identified above, demonstrating a clear association between number of storms per winter and the average wave height per winter.

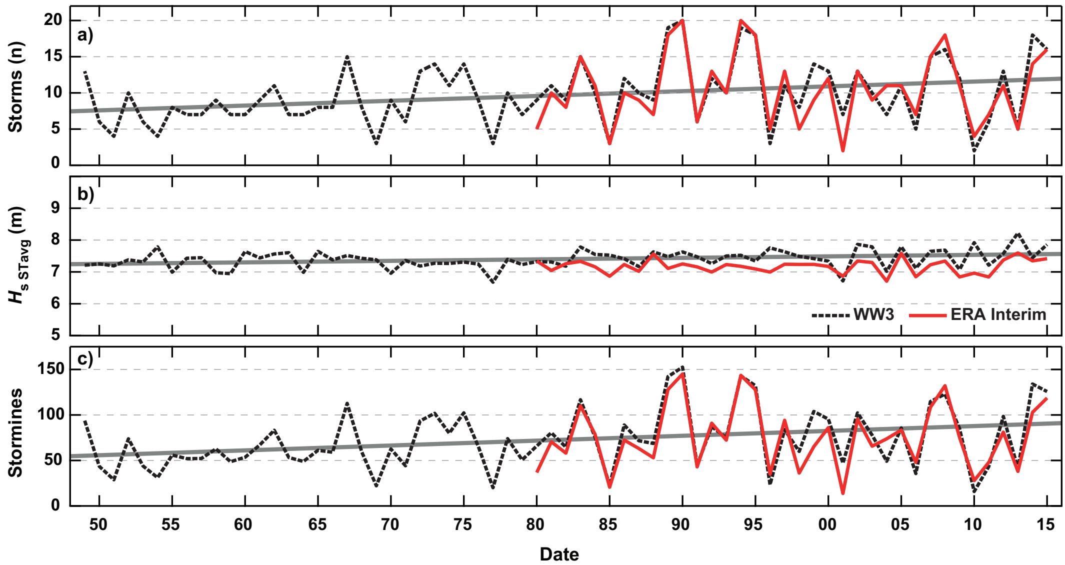

Figure 4: Winter storm parameters for the northwest of Ireland according to WW3 (dashed line) and ERA Interim (solid line) reanalysis. Number of storms per winter (a), average H_s for all storms per winter (b) and storminess index (c) computed for DJFM winter season. Statistically significant linear trends for the WW3 dataset are indicated by solid grey lines.

Long term linear trends in wave height and storminess metrics per winter are all positive, but statistically significant trends are only observed in the longer WW3 dataset (Table 2). The trends indicate that average winter wave heights are slowly increasing, alongside the number of storms per year and the average wave height. Despite their small magnitude, the trends consistently indicate an increase in intensity and frequency of energetic wave conditions in the northwest coast of Ireland. Positive correlation of winter and storm metrics with the winter NAO index suggests a strong and statistically significant association between these variables, except for average storm wave height per winter (Table 2). The correlation is higher for average winter wave height but still very significant for number of storms per winter and, consequently, with the storminess index (Figure 5a). On the other hand, correlation with the WEPA index is very low and not significant for all variables considered in this study. There are, however, cases when a positive WEPA index value corresponds to an energetic winter and vice-versa, including the 2013/14 winter and the 1993/94 and 1994/1995 winter cluster (Figure 5b).

Table 2: Linear trends for winter [DJFM] average significant wave height, number of storms, mean storm Hs and storminess index. Correlation coefficients between these parameters and the winter NAO and WEPA indices.

Model	Parameter	Trend	R_{NAO}	R_{WEPA}
ERA Interim	$H_{s\ mean}$	0.001	**0.90**	0.23
	$Storms_{number}$	0.02	**0.78**	0.11
	Storms $H_{s\ mean}$	0.001	0.32	0.16
	Storminess	0.18	**0.78**	0.12
WW3	$H_{s\ mean}$	**0.01**	**0.90**	0.19
	$Storms_{number}$	**0.07**	**0.79**	0.14
	Storms $H_{s\ mean}$	**0.005**	0.14	-0.07
	Storminess	**0.53**	**0.79**	0.14

Bold font indicates statistically significant linear trends, based on the Mann-Kendall trend test, and statistically significant correlation based on Pearson's linear correlation coefficient. Both tests consider a two-tailed t distribution and a 0.05 significance level.

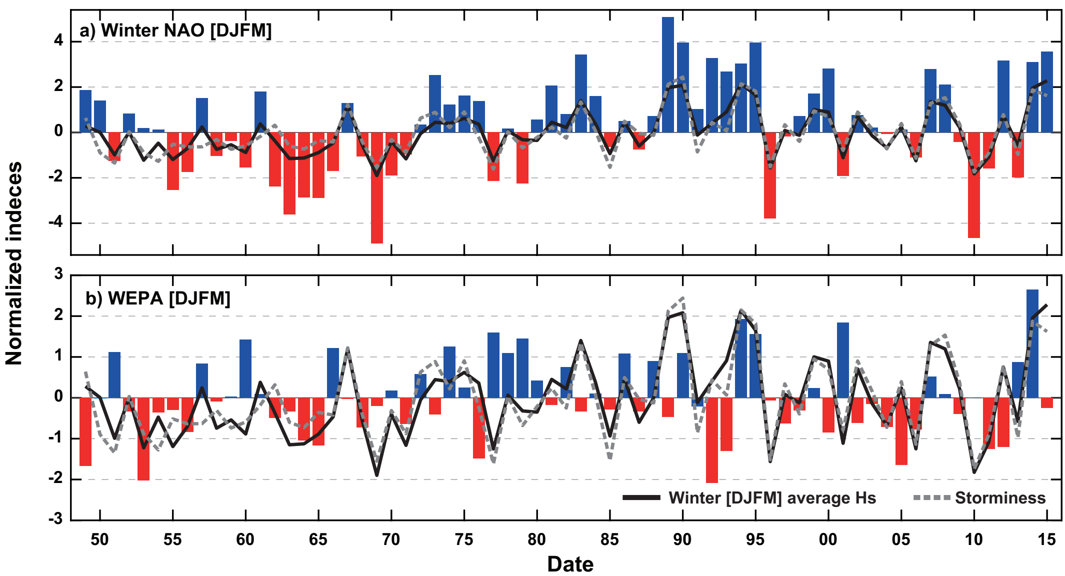

Figure 5: Winter [DJFM] station-based NAO (a) and WEPA (b) indices with superimposed normalised winter-averaged H_s and storminess index for the northwest of Ireland.

Discussion

The performance of any wave reanalysis depends mainly on the physical and numerical capabilities of the model(s), the parameterisation implemented and the input wind fields used to force the model(s). ERA-Interim and WW3 reanalysis are based on state-of-the-art wave models and the widely used global wind fields provided by ECMWF and NCEP/NCAR programmes, respectively. These wind fields have been thoroughly analysed and their use for wave reanalysis validated using satellite and buoy measurements (e.g., Caires *et al.,* 2004; Dodet *et al.,* 2010; Rascle and Ardhuin, 2013; Gallagher *et al.,* 2014; Campos and Guedes Soares, 2016). The comparison between the M4 buoy data and the wave reanalysis data presented here highlights that both reanalyses have very similar performances, with almost perfect agreement between observed and modelled data. However, our results also evidence a positive/negative bias in WW3/ERA-Interim reanalysis for high-energy wave conditions. These biases have been consistently identified in previous intercomparisons of wave reanalysis based on NCEP/NCAR and ERA-Interim wave fields (Stopa and Cheung, 2014; Campos and Guedes Soares, 2016), and reflect inherent limitations in model parameterisation. While Stopa and Cheung (2014) recommended the use of ERA-Interim for long-term studies and NCEP/NCAR for analysis of extremes, we opted to conduct the full analysis with both datasets. Our results demonstrate that the variability in winter averages is identical, with slight differences in absolute values reflecting the different biases in both reanalyses. Regarding the evaluation of extreme events, by individualising storms based on the 95% exceedance value of each dataset instead of using the same threshold, the limitations related to the under/overestimation of extreme wave heights in ERA-Interim/WW3 are avoided. The consistent results in the number of storms and its winter to winter variability in the two independent reanalyses provides an encouraging result and confirms the adequacy of our approach.

The various winter wave averages presented here overwhelmingly indicate that the winter of 2014/15 was the most energetic on record for the northwest of Ireland. In terms of ranking, it was closely followed by the 2013/14 winter, which was identified as the most energetic along a large part of the Atlantic coast of Europe (Masselink *et al.,* 2016; Castelle *et al.,* 2017b) and the stormiest on record for Ireland and the UK as a whole (Mathews *et al.,* 2014). Latitudinal variation in the eastern Atlantic storm track position have been widely recognised as a major driver of variability in storminess along the western coast of Europe at various timescales (Betts *et al.,* 2004; Lozano *et al.,* 2004; Clarke and Rendell, 2009; Orme *et al.,* 2017). Detailed analysis of storm tracks is outside the scope of our study, but storm clustering (storms occurring in rapid succession along a similar path and over a short period of time) has been identified as a characteristic feature of exceptional winters (Pinto *et al.,* 2014; Priestley *et al.,* 2017). Our results show that the variability in storminess in the northwest of Ireland is controlled by the number of storms per winter and that stormy winters have the highest average wave heights. Furthermore, the stormiest winters identified here also match periods of intense storm clustering in western Europe based on sea level pressure data (Pinto *et al.,* 2014).

While storm clustering has been studied on a seasonal scale (e.g., Priestley *et al.,* 2017) and long periods of increased storm activity have been described, often in association with the NAO (e.g., Orme *et al.,* 2017), clustering of exceptional winter seasons has only recently been highlighted in the literature (McCarthy *et al.,* 2016). Our results show that the stormiest and more energetic winters in the northwest of Ireland often occur in groups, as shown in Figures 3 and 4. While all stormy and energetic winters correspond to strong positive phases of the NAO (Fig. 5), the clustering of pairs of exceptional winters is not clearly identified in the winter NAO index since 1948/1949. Nevertheless, spectral analysis of longer time series has identified a quasi-biennial variance alongside a longer 8- to 10-year variance in the winter NAO (Hurrel *et al.,* 2003). The ability of the NAO to describe storminess in the North Atlantic is well established (Feser *et al.,* 2015) and our results reinforce it, with strong correlations between all parameters except average storm wave height per winter (Table 2). On the other hand, the recently proposed WEPA is not significantly correlated with any of the variables. This result is unsurprising as Castelle *et al.,* (2017b) have clearly indicated that WEPA is able to explain winter wave height variability in the Atlantic coast of Europe, but only between 52°N and 36°N, and the northwest of Ireland is at a higher latitude. Our assessment reaffirms that WEPA is not significantly correlated with winter wave height in the northwest of Ireland and is also unable to explain the variability in storminess for this region, in contrast to the winter NAO.

A pattern of increasing winter wave heights and storminess is evident in all datasets and variables, although the trends are only statistically significant in the longer WW3 reanalysis. These results align with various studies of wave climate and storminess in the eastern North Atlantic based on reanalysis data (Feser *et al.,* 2015). Increasing wave heights during the 20th century were reported by Bertin *et al.* (2013) for the entire North Atlantic Ocean using yearly means based on the 20CR reanalysis, which found the same trend of 0.01m^{yr-1} reported here for areas north of 50°N. Previously, Dodet *et al.* (2010) had also reported an upward trend in extreme wave heights (90% exceedance level) in the eastern North Atlantic that reached values in excess of 0.015m^{yr-1} for the northwest of Ireland. Similarly, the positive trend in number of storms per winter aligns closely with the increase in gale days presented by Donat *et al.* (2011) for this part of Europe. The trends reported here and in previous studies consistently indicate that storms are becoming more frequent and more intense, promoting an overall increase in winter wave height.

The implications of these trends and patterns of variability for the coastal areas of north-western Ireland are significant, as increased winter wave energy alongside more frequent and intense storms can enhance the erosion potential for both sandy and rocky shores. However, storm impacts in north-western Ireland are generally site specific due to a highly compartmentalised coastline and the fact that sandy coastal areas are attuned to a high-energy regime, requiring extreme storms to cause significant morphological change (Cooper *et al.,* 2004). Events that can have an impact on the beaches and dunes rely on the combination of various factors for significant erosion to occur, including wind direction, coastal orientation, tidal stage and water level (Cooper *et al.,* 2004; Guisado-Pintado and Jackson, 2018). Naturally, if the number of storms and their intensity is increasing, the likelihood that extreme wave events coincide with such factors increases as well, particularly when storms occur in clusters that span several weeks and, therefore, encompass a variety of wind, tide and wave conditions (MacClenahan *et al.,* 2001). Storm groups have been shown to enhance erosion in sandy and rocky coasts (e.g., Ferreira, 2005; Nunes *et al.,* 2011; Loureiro *et al.,* 2012; Splinter *et al.,* 2014; Sénéchal *et al.,* 2017) and recent research has shown that beach recovery following exceptional winter seasons, when storm groups are more frequent, can take more than a year (Castelle *et al.,* 2017a; Scott *et al.,* 2016). If energetic and stormy winters are clustered, as shown here for the northwest of Ireland, erosion can be further enhanced, given a long and continuous state of disequilibrium, and recovery is likely to take longer. The cumulative impact of stormy winter seasons on coastal systems can have destabilising effects on coastlines and it is the focus of ongoing research based on long-term morphological records of coastal change in the northwest of Ireland (Loureiro *et al.,* 2016).

Conclusion

This work aimed to investigate the variability in the winter wave climate and storminess in the high-energy coast of north-western Ireland over the past 67 winters using two independent wave reanalyses, validated with local wave buoy observations. The results reveal that 2014/15 was the most energetic winter on record, closely followed by the 2013/14 winter, and the most energetic and stormy winters appear to occur in clusters during positive phases of the NAO. Overall, winters are becoming more energetic and stormier, as evidenced by positive trends in winter wave height, number of storms per winter and average storm wave height, resulting in an increasing storminess for the northwest of Ireland. These trends are in line with other high-resolution wave reanalyses and storminess indexes for the eastern North Atlantic and western Europe. The implications of an increasingly energetic and stormier winter wave climate, as well as the clustering of exceptional winters for the coastal areas of north-western Ireland are not immediate, given the compartmentalised nature of this high-energy coastline. However, more frequent and intense storms, often clustered in groups and occurring in consecutive years, can potentially increase erosion and extend recovery times along the north-western coast of Ireland. This has important implications for shoreline management practice in Ireland, which lacks a strategic perspective for addressing erosion problems caused by winter storms (O'Connor *et al.,* 2009, 2010).

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