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Key Points:
- The 2013/2014 winter was the most energetic winter along the Atlantic coast of Europe since at least 1948
- The extreme 2013/2014 wave conditions conform to historical trends and climate change predictions
- Coastal impacts during the 2013/2014 winter were very extensive along the Atlantic coast of Europe

Supporting Information:
- Supporting Information S1
- Figure S1
- Data Set S1
- Data Set S2
- Data Set S3

Correspondence to:
G. Masselink,
g.masselink@plymouth.ac.uk

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Extreme wave activity during 2013/2014 winter and morphological impacts along the Atlantic coast of Europe

Gerd Masselink[1], Bruno Castelle[2,3], Tim Scott[1], Guillaume Dodet[4], Serge Suanez[4], Derek Jackson[5], and France Floc'h[6]

[1]Coastal Processes Research Group, School of Marine Science and Engineering, Plymouth University, Plymouth, UK, [2]CNRS, UMR EPOC, Pessac, France, [3]Université de Bordeaux, UMR EPOC, Pessac, France, [4]LETG-Brest-Géomer UMR 6554 CNRS, Institut Universitaire Européen de la Mer (UBO), Plouzané, France, [5]Centre for Coastal and Marine Research, School of Geography and Environmental Sciences, Ulster University, Coleraine, UK, [6]Domaines Océanique UMR 6538 CNRS, Institut Universitaire Européen de la Mer (UBO), Plouzané, France

Abstract Studies of coastal vulnerability due to climate change tend to focus on the consequences of sea level rise, rather than the complex coastal responses resulting from changes to the extreme wave climate. Here we investigate the 2013/2014 winter wave conditions that severely impacted the Atlantic coast of Europe and demonstrate that this winter was the most energetic along most of the Atlantic coast of Europe since at least 1948. Along exposed open-coast sites, extensive beach and dune erosion occurred due to offshore sediment transport. More sheltered sites experienced less erosion and one of the sites even experienced accretion due to beach rotation induced by alongshore sediment transport. Storm wave conditions such as were encountered during the 2013/2014 winter have the potential to dramatically change the equilibrium state (beach gradient, coastal alignment, and nearshore bar position) of beaches along the Atlantic coast of Europe.

1. Introduction

Coastlines are vulnerable to the effects of climate change on a global scale due to sea level rise and on a regional scale due to changes in the (storm) wave climate, and both these climate change impacts influence coastal flooding and coastal erosion. Assessment of coastal vulnerability due to climate change have tended to focus on the impacts of sea level rise [e.g., *Nicholls et al.*, 2011]; however, coastal impacts due to changes in the storm wave climate have the potential to cause coastal impacts that are more important than those related to sea level rise. For example, a recent study of coastal vulnerability in the Pacific [*Barnard et al.*, 2015] concluded that if projections for an increasing frequency of extreme El Niño and La Niña events over the 21st century are confirmed, then populated regions on opposite sides of the Pacific Ocean basin could be alternately exposed to extreme coastal erosion and flooding, independent of sea level rise.

For the Atlantic, a consensus is emerging among climate modelers [*Yin*, 2005; *Bengtsson et al.*, 2006; *Semedo et al.*, 2013] that the world's changing climate will lead to a poleward shift in extratropical storm tracks (especially on the Southern Hemisphere), with no overall intensification of extratropical cyclonicity, but considerable regional changes associated with this poleward shift [*Mizuta*, 2012; *Zappa et al.*, 2013]. Climate models further predict increased storminess in the northeast Atlantic due to the eastward extension of the North Atlantic storm track [*Leckebusch and Ulbrich*, 2004; *Ulbrich et al.*, 2008; *Bengtsson et al.*, 2009], with potential implications for the wave conditions along the Atlantic coast of Europe, including the UK. Any change in Atlantic storminess related to climate change will be difficult to prove due to the substantial multiannual variability in storminess related to the North Atlantic Oscillation [*Bromirski and Cayan*, 2015]. However, analysis of long-term instrumental data for the Atlantic coast of Europe has revealed increasing trends in wave heights: *Bacon and Carter* [1991] found a 2% increase in significant wave height for the period 1962–1986 based on shipborne wave recorder data and *Young et al.* [2011] analyzed satellite altimeter data (1985–2008) and found a trend of increasing 90% and 99% significant wave height of 0–0.5% and 0.5–1% per year, respectively. Furthermore, analysis of modeled wave data for the Atlantic coast of Europe [*Wang and Swail*, 2002; *Dodet et al.*, 2010; *Bertin et al.*, 2013] suggests an increasing trend in H_s of up to 0.02 m yr^{-1}, and upward trends in storminess measures have also been observed since 1871 in many parts of western, central, and northern Europe [*Donat et al.*, 2011].

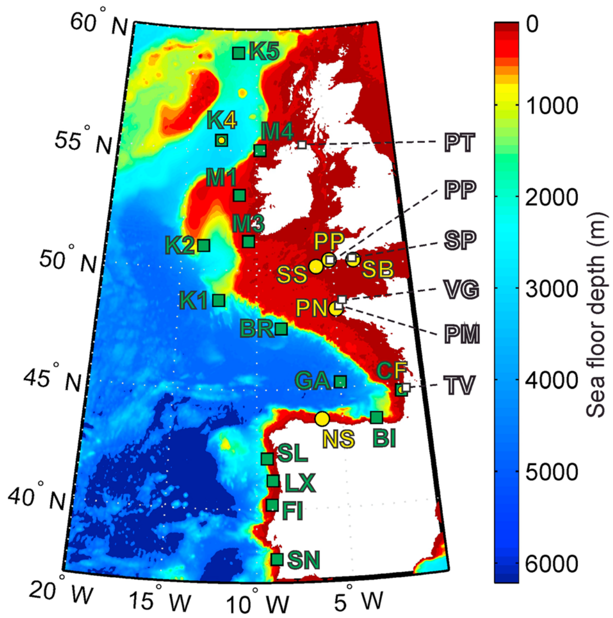

Figure 1. Location map of Atlantic coast of Europe showing the offshore bathymetry, wave buoy locations, and beach sites. The deep water wave buoys used for validation of the Wave Watch III model are shown as green squares, whereas the inshore wave buoys used for data analysis are represented by yellow circles (wave buoys K4 and CF were used for both purposes). The beaches used in this study, indicated by white squares, are the following: PT = Portrush (northern Ireland); PP = Perranporth (southwest England); SP = Slapton Sands (southwest England); VG = Vougot (Brittany); PM = Porsmilin (Brittany); and TV = Truc Vert (south France). Additional information on the wave buoys, including their names, is provided in Table S1 in the supporting information.

During the 2013/2014 winter, the combination of a very intense polar vortex and unusually strong North Atlantic jet stream caused a succession of strong low pressure systems to cross the Atlantic [*Davies*, 2015] and reach western European coastlines. The combination of high cyclone frequency and above-average cyclone intensity resulted in exceptional storminess, causing the 2013/2014 winter to be ranked as the stormiest on record for the Ireland-UK domain [*Matthews et al*., 2014]. On land, these storms caused extreme precipitation, resulting in widespread river flooding [*Huntingford et al*., 2014], whereas at the coast, a highly unusual sequence of extreme sea level events was recorded [*Wadey et al*., 2014]. Coastal impacts were very considerable and extended across the entire European Atlantic seaboard. Erosion was observed on many beaches, sometimes stripping all their sand and exposing a rocky shore platform beneath [*Scott et al*., 2015]. Barrier overwash occurred at numerous sites [*Blaise et al*., 2015], and maximum wave runup levels in excess of 15 m above MSL were recorded on one of the more exposed gravel beaches [*Poate et al*., 2015]. Permanent coastal change occurred along rocky coasts, with some coastal cliffs experiencing retreat rates 2 orders of magnitude greater than the long-term average [*Earlie et al*., 2015]. Finally, coastal dune erosion occurred along practically all sites with dunes, with cutbacks of more than 10 m not uncommon [*Castelle et al*., 2015].

In this paper we investigate and quantify how unusual the 2013/2014 winter was for the Atlantic coast of Europe in terms of wave conditions and coastal impacts. It will be demonstrated that the 2013/2014 winter was the most energetic winter along most of the Atlantic coast of Europe since at least 1948 and that the extreme storms experienced during this winter had very considerable impacts on the Atlantic European beaches.

2. Methods

A combination of hindcast and measured wave data, and beach monitoring data will be used to determine how unusual the 2013/2014 winter was for the Atlantic coast of Europe. Figure 1 shows the study area, including the offshore bathymetry, and the location of the wave buoys and beach sites used in this study.

2.1. Wave Modeling

To place the extreme storm wave conditions experienced during the 2013/2014 winter in context with longer-term trends and extremes, we used hindcast data derived from a regional implementation of the spectral wave model Wave Watch III, V4.18 [*Tolman*, 2014] using a 0.5° resolution grid covering the North Atlantic basin (80°–0°W; 0°–70°N). The spectral grid uses 24 directional bins and 32 frequencies from 0.037 Hz to 0.72 Hz (increment factor of 1.1). The model uses the parameterization “TEST451” [*Ardhuin et al*., 2010; *Rascle and Ardhuin*, 2013] and is forced with the 6-hourly wind fields of the National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis project from January 1948 to April 2015 [*Kalnay et al*., 1996]. An obstruction grid is provided to the model to take into account the effects of small islands on wave propagation [*Tolman*, 2002]. Using the model output along the shelf edge (1000 m isobaths grid points), the wave conditions during the Boreal 2013/2014 winter (December, January, February, and March; DJFM) are compared with that for the complete 1948–2015 period (total of 67 winters).

This regional model was validated through comparisons between simulated and observed significant wave heights at 15 stations along the European shelf (Figure 1 and Table S1). For consistency with the 6-hourly model outputs, each station time series was filtered with a 6 h moving average and interpolated on the model time steps. The model skill was assessed with four statistical quantities: the bias, the root-mean-square error (RMSE), the normalized root-mean-square error (NRMSE), and the correlation coefficient (R^2). In order to quantify the accuracy of model predictions for winter means (i.e., the 4 month period from December to March; DJFM), this statistical analysis was also applied to monthly averaged data and model outputs (gaps in the measured time series limited the computation of 4 month averaged; hence, monthly average was retained). The results, collated in Table S2, show an overall good agreement between simulated and measured significant wave heights.

2.2. Inshore Wave Analysis

The WWIII hindcast deep water wave conditions along the continental slope corresponding to the 1000 m depth contour are not necessarily representative for the local inshore wave conditions experienced at the coast, especially for more sheltered settings (e.g., English Channel and coast of Brittany). Analysis of the winter wave conditions was therefore conducted for six European Atlantic wave buoys, colocated with the beach sites (Figure 1 and Table S1), for which data are available since 2009 (note that wave measurements prior to 2009 are currently not available). If measured wave data capture was $< 70\%$ for any DJFM period (due to equipment failure), that winter period was omitted from the analysis. If data coverage was more than 90%, the missing data were ignored with no gap filling. If there was 70–90% of missing data for the DJFM period, data from a neighboring and representative buoy was used to fill in the data gaps (Bideford for Perranporth, Gascogne for Cap Ferret, and Bilbao for North Spain). This was achieved by adjusting for bias and offset after assessing the best fit with the supporting data set using all overlapping data available over the 6 year time series.

The following DJFM wave statistics were computed: (1) average significant wave height; (2) maximum significant wave height; and (3) average wave energy flux computed using the energy period $T_e = 1.32T_m$ [*Cahill and Lewis*, 2014], where T_m is the mean wave period which is the only wave period parameter that is consistently computed by all wave buoys. Additional parameters were derived based on a storm event analysis, where storms are identified as events during which the significant wave height is larger than the 1% exceedence significant wave height computed from the whole data record and where the 5% exceedence wave height is used to demarcate the start and end of storm events: (4) number of storms during DJFM period and (5) total storm duration.

2.3. Study Sites

Long-term ($>$5 years) and high-resolution (monthly) records of beach change along the Atlantic coast of Europe are extremely rare. Observational data that meets these requirements are only available from six sites (Figure 1), spanning widely varying and regionally representative coastal settings and hydrodynamic regimes:

1. Portrush is an 800 m long embayment beach on the north coast of Northern Ireland ($D_{50} = 0.2$ mm) with a gentle intertidal slope ($\tan\beta = 0.021$) and backed by a continuous seawall [*Backstrom et al.*, 2009]. The beach is exposed to offshore significant wave heights that average 1.3 m and the mean spring tide range (MSR) is 1.5 m.
2. Perranporth is a 3 km long embayed sandy beach ($D_{50} = 0.35$ mm) along the north Cornish coast (UK), is characterized by a gentle intertidal gradient ($\tan\beta = 0.015$), intertidal, and subtidal bar morphology, and is backed by a dune system [*Masselink et al.*, 2014]. The beach is fully exposed to Atlantic waves, and MSR is 4.5 m.
3. Slapton Sands is a 5 km long fine-gravel ($D_{50} = 2$–8 mm) barrier system backed by a freshwater lagoon and is located along the south Devon coast (UK), near the start of the English Channel [*Ruiz de Alegria-Arzaburu and Masselink*, 2010]. The steep barrier system ($\tan\beta = 0.1$) is exposed to a relatively energetic bimodal wave climate, with swell waves from the south-to-southwest and wind waves from the east, and MSR is 4.3 m. For Slapton Sands, two profiles are considered: one in the central part and one at the eastern end of the beach.
4. Vougot is a 2 km long, fine-sandy ($D_{50} = 0.2$–0.3 mm) beach on the north coast of Brittany (France), backed by an extensive dune system and fronted by a rocky shore platform [*Suanez et al.*, 2012]. Facing north-northwest, the beach is partially sheltered from the direct impact of Atlantic swell, and MSR is 8.5 m.

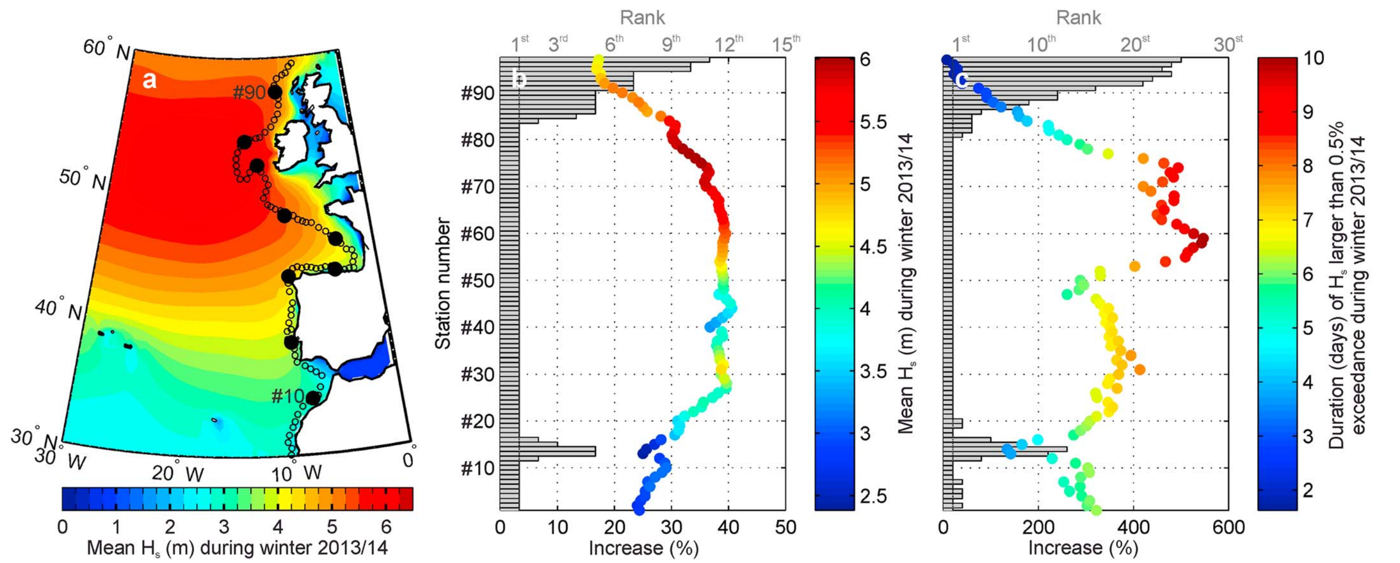

Figure 2. Spatial and temporal analysis of 67 years of Wave Watch III modeled wave data. (a) Location map of Atlantic coast of Europe with modeled average significant winter wave height H_s during 2013/2014 winter (DJFM) and location of model grid points along the continental slope (1000 m contour line). Grid points run from North Africa (#1) to north Scotland (#97). (b) Winter-averaged significant wave height and (c) cumulative number of days with significant wave height exceeding the 0.5% exceedence level; the horizontal bars and symbols represent, respectively, the ranking and the percentage increase relative to the long-term average of the 2013/2014 winter. The color of the symbols represents the value of the parameter plotted (refer to legend on the right of the panels).

5. Porsmilin is a sandy (D_{50} = 0.32 mm) and sheltered beach on the south coast of Brittany, backed by low seawall and marsh, with a rock platform present below low tide level [*Dehouck et al.*, 2009]. Due to its heavily embayed nature and south facing orientation, the beach is much sheltered from Atlantic swell, and wave heights are less than 1.5 m even during storms; MSR is 5.7 m.
6. Truc Vert is an open sandy beach (D_{50} = 0.4 mm) along the Aquitaine coast (France) and is characterized by intertidal and subtidal bar morphology, and a gently sloping (tanβ = 0.025) intertidal profile [*Castelle et al.*, 2015]. The beach is backed by a coastal dune towering >10 m above the beach, and MSR is 3.9 m.

Subaerial beach morphological data at all six sites have been collected rigorously for at least 6 years on a monthly basis using a variety of methods, including RTK-GPS and total station. At some sites single two-dimensional beach profiles are measured, while at other sites a three-dimensional morphological grid was collected that was alongshore averaged to obtain a mean beach profile. The response at Slapton Sands varied considerably along the beach; therefore, data from this site only were analyzed separately, corresponding to the middle (SP_{p10}) and northern end (SP_{p18}) of the embayment. The key parameter extracted from the profiles is the beach volume above MSL; for Vougot and Truc Vert the location of the dune foot has also been considered.

3. Results

3.1. Modeled Wave Conditions (1948–2015)

Using the WWIII model output along the continental shelf edge (1000 m isobaths), the wave conditions during the Boreal 2013/2014 winter (December, January, February, and March; DJFM) are compared with that for the complete 1948–2015 period (total of 67 winters) in Figure 2. The largest 2013/2014 winter-averaged significant wave height (H_s > 6 m) occurred off the coast of Ireland, dropping off sharply to H_s = 4 m off the coast of Portugal, and then to H_s = 3 m off the coast of Morocco (Figure 2a).

With the exception of south Portugal (grid points #12–16) and north Ireland (#83–96), the 2013/2014 winter ranks highest in terms of the winter-averaged significant wave height (Figure 2b). The largest winter-averaged wave conditions (H_s = 5–6 m) were experienced off the coast of Brittany, southwest England, and south Ireland (#60–70). For most of the Atlantic European seaboard, from north Portugal to south Ireland (#30–70), the winter-averaged wave conditions were approximately 40% higher than average.

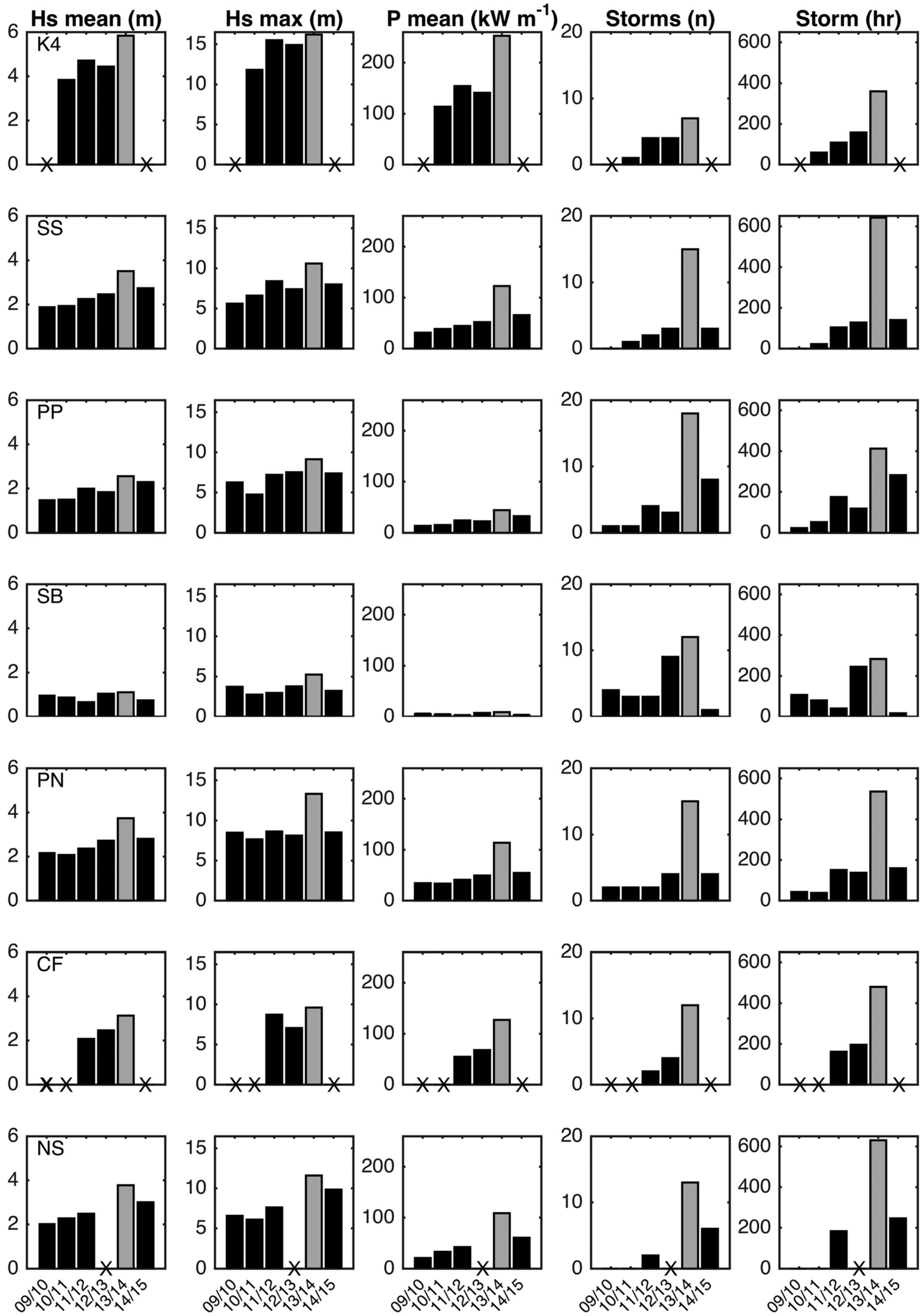

Figure 3. Histograms of extreme wave parameters for the winter (DJFM) periods for six consecutive winters from 2009 to 2015 for selected sites. From left to right: average significant wave height H_s, maximum significant wave height H_{max}, winter-total average wave energy flux P_{tot} computed using the energy period T_e, number of storms N_{storm}, and total storm duration D_{storm}. From top to bottom: K4 = west coast of Ireland, SS = Sevenstones, PP = Perranporth, SB = Start Bay, PN = Pierres-Noires, CF = Cap Ferret, and NS = north Spain (Figure 1). Grey bars indicate the maximum values that occurred over the 6 year period. No storms occurred for NS in 2009/2010 and 2010/2011; insufficient data are available for NS in 2012/2013, for CF in 2009/2010, 2010/2011, and 2014/2015, and for K4 in 2009/2010 and 2014/2015 to reliably compute wave statistics (denoted by crosses). Additional information on the wave buoys, including their names, is provided in Table S1.

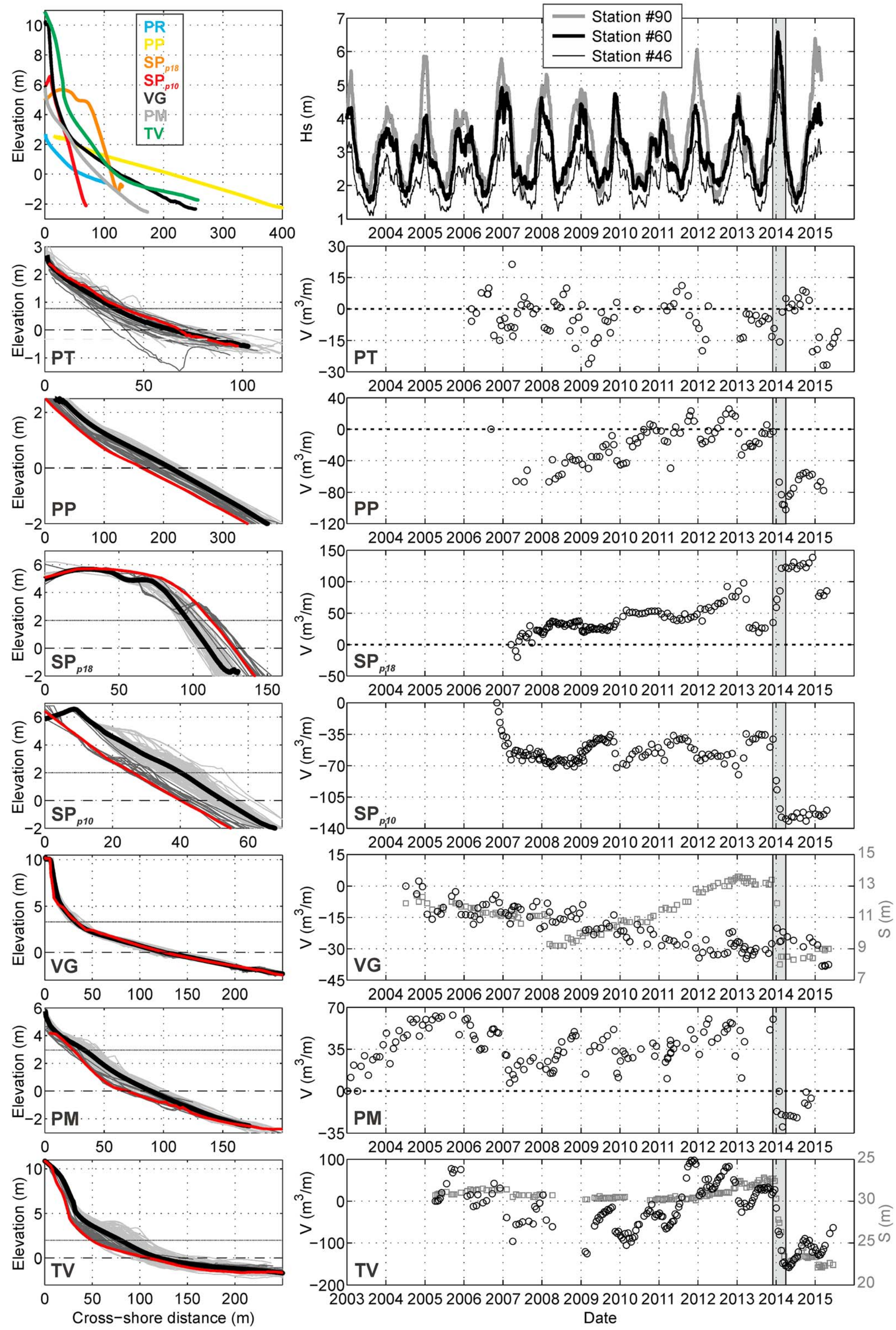

Figure 4. (top left) Average beach profile for all sites. (left column) All profile lines per study site (grey lines), the mean profile (solid black line), and the post 2013/2014 winter profile (red line). The black line represents the spring high tide level, and the black dash-dotted line represents MSL, which is the level above which the beach volumes plotted in Figure 4 (right column) were computed. (top right) Time series of modeled significant wave height H_s (8 week moving average) for three locations along the continental slope: south France (#46), southwest England (#60), and north Scotland (#90). (right column) Time series of intertidal beach volume (black circles; in m^3 per unit meter beach width) with the beach volume at the start of the survey period set to 0. For Vougot and Truc Vert the location of the dune foot (grey circles) is also shown. Beach names: PT = Portrush, PP = Perranporth, SP = Slapton Sands (SP_{p10} is central profile; SP_{p18} is northern profile), VG = Vougot, PM = Porsmilin, and TV = Truc Vert.

Figure 2c summarizes the most extreme wave conditions by presenting the cumulative number of days when significant wave heights were greater than the 0.5% exceedence level (note that 0.5% over a year represents just under 2 days). The spatial pattern that was evident from the winter-averaged wave height (Figure 2b) is confirmed, but the extreme magnitude of the 2013/2014 winter wave conditions is brought out even more by a >200% increase in the number of days when H_s exceeded $H_{s,0.5\%}$. The region from Brittany to south Ireland (#53–76) experienced 8 days and >400% increase in extreme wave conditions.

3.2. Measured Wave Conditions (2009–2015)

Wave analysis was conducted for six European Atlantic wave buoys for which data are available since 2009, including the 2013/2014 winter season, to assist placing the longer-term modeled ocean wave climate within the context of the available measured inshore wave conditions. The results of this analysis are shown in Figure 3 and demonstrate that the 2013/2014 winter represents the most energetic period over the relatively short time series of observational wave data. Specifically, the number of storms and the total storm duration during the 2013/2014 winter is generally at least 100% larger than the second most energetic winter.

3.3. Storm Impacts on Beaches

Long-term (>5 years) and high-resolution (monthly) records of beach change along the Atlantic coast of Europe are extremely rare. Observational data that meets these requirements are only available from six sites (Figure 1). Storm erosion impacts during the 2013/2014 winter were very extensive, and the beach monitoring data reveal that the majority of the sites after this winter were in their most depleted state since measurements began (Figures 4, left column, and S1) and, based on qualitative observations by the authors, since at least the 1990s. Some of the beaches experienced a lowering of the beach profile relative to the mean profile of several meters, due to either dune erosion (Vougot, Truc Vert) or barrier retreat (Slapton Sands middle SP_{p10}), whereas Slapton Sands north (SP_{p18}) experienced extensive accretion. Perranporth experienced a uniform lowering of approximately 0.5 m across the entire intertidal profile.

Quantification of the subaerial beach volume over time (Figure 4, right column) places the coastal impacts during the 2013/2014 winter in a wider context. The most exposed sites (Perranporth and Truc Vert) lost in excess of 200 $m^3 m^{-1}$ from the intertidal beach and dune system, and such storm response was observed to be typical of most exposed beaches along the coast of SW England and France during the 2013/2014 winter [*Castelle et al*., 2015; *Masselink et al*., 2015]. The sediment loss was transported offshore, contributing to the subtidal bar systems [*Castelle et al*., 2015; *Scott et al*., 2015]. Contrasting responses occurred at the more sheltered sites: Porsmilin lost 50 $m^3 m^{-1}$, but subaerial beach volumes at Vougot and Portrush were not much impacted. At Vougot, the coastal dune retreated by more than 5 m [*Blaise et al*., 2015], but the sediment appears to have been retained within the intertidal zone. At Portrush, the wave conditions during the 2013/2014 winter were actually not exceptional and the more extreme conditions during the subsequent 2014/2015 winter (Figure 4, top right) left the beach in the most depleted state since records began (2006). At Slapton Sands, the middle profile (SP_{p10}) experienced a sediment loss of 100 $m^3 m^{-1}$, whereas accretion of a similar amount occurred at the north profile (SP_{p18}). The beach response at this location is the result of an alongshore redistribution of sediment [*Masselink et al*., 2015], due to the south-to-southwesterly waves impacting on a southeast facing shoreline.

The main implication of these contrasting coastal responses, despite the consistency of the extreme Atlantic wave conditions, is that site-specific conditions are fundamentally important in modulating the wave forcing and controlling the coastal response. Although some beach recovery has occurred during the subsequent 1.5 years 2014–2015 at Perranporth and Truc Vert ($dQ \approx 50\ m^3 m^{-1}$), there has been none at Slapton Sands where easterly storm activity is necessary to bring about recovery [*Ruiz de Alegria-Arzaburu and Masselink*, 2010]. For those sites that experienced extensive dune erosion (e.g., Truc Vert) it is expected that full recovery by natural processes will take at least 10 years [*Castelle et al*., 2015].

4. Discussion and Conclusions

The WWIII modeling suggests that with the exception of the far north region (Ireland), the 2013/2014 winter was the most energetic since 1948 for most of the Atlantic coast of Europe and especially for southwest England. The analysis of the inshore wave data provides some support for these modeling results although the observational time series is rather short.

It is tempting to ascribe the record extreme storm wave conditions that were experienced during the 2013/2014 winter to climate change, since increased storminess of the northeast Atlantic is predicted by most climate change models [*Leckebusch and Ulbrich*, 2004; *Ulbrich et al*., 2008; *Mizuta*, 2012; *Zappa et al*., 2013]. An extensive review of storm studies over the North Atlantic and northwestern Europe [*Feser et al*., 2015] concludes that future scenarios until about the year 2100 indicate mostly an increase in winter storm intensity but that future trends in total storm number are quite heterogeneous and depend on the model that is used. Despite the very considerable multiannual variability in storminess related to the North Atlantic Oscillation [*Bromirski and Cayan*, 2015], several modeling and empirical studies have found an increase in Atlantic storminess over the last few decades [*Wang and Swail*, 2002; *Dodet et al*., 2010; *Young et al*., 2011; *Bertin et al*., 2013], possibly reflecting current climate change.

If conditions such as the 2013/2014 winter become more common in the future, this has the potential to considerably change the equilibrium state of beaches along the Atlantic coast of Europe. Along exposed sites dominated by cross-shore sediment transport processes, sediments may transfer from supratidal and intertidal stores to the subtidal region (nearshore bar systems) [*Castelle et al*., 2015; *Scott et al*., 2015], resulting in relatively depleted subaerial beaches and scarped dune systems. Along coastlines with a bimodal wave climate characterized by both long-period ocean swell and short-period local seas, increased Atlantic storminess is likely to disrupt the balance between the different alongshore sediment transport contributions and may destabilize the coastal alignment by causing beach rotation [*Harley et al*., 2015]. Increased storminess, whether due to more intense storms and/or more frequent storms, should be considered in future coastal planning along the Atlantic coast of Europe.

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