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Key Points:

- Skew surge is the best metric of storm surge in a tidal regime
- Any skew surge can coincide with any tide
- Where seasonal relationships exist, they should be included in risk predictions

Supporting Information:

- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Supporting Information S1

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Tide and skew surge independence: New insights for flood risk

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Abstract Storm surges are a significant hazard to coastal communities around the world, putting lives at risk and costing billions of dollars in damage. Understanding how storm surges and high tides interact is crucial for estimating extreme water levels so that we can protect coastal communities. We demonstrate that in a tidal regime the best measure of a storm surge is the skew surge, the difference between the observed and predicted high water within a tidal cycle. Based on tide gauge records spanning decades from the UK, U.S., Netherlands, and Ireland we show that the magnitude of high water exerts no influence on the size of the most extreme skew surges. This is the first systematic proof that any storm surge can occur on any tide, which is essential for understanding worst-case scenarios. The lack of surge generation dependency on water depth emphasizes the dominant natural variability of weather systems in an observation-based analysis. Weak seasonal relationships between skew surges and high waters were identified at a minority of locations where long-period changes to the tidal cycle interact with the storm season. Our results allow advances to be made in methods for estimating the joint probabilities of storm surges and tides.

1. Introduction

Storm surges are large-scale increases in sea level due to a storm. They can last from hours to days and span hundreds of square kilometers. They are caused primarily by wind stress at the sea surface and the horizontal gradient of atmospheric pressure [*Pugh and Woodworth*, 2014], although the magnitude of any particular storm surge is influenced by many factors including the intensity and track of the weather system, bathymetry, and coastal topography. The same physics control storm surges caused by midlatitude weather systems (extratropical cyclones) and tropical cyclones (hurricanes). In regions of high tidal range, storm surges represent the greatest threat when they coincide with tidal high water. Many operational forecasting centers now refer to the combination of a storm surge and tidal high water as the *storm tide*.

Storm tides (usually accompanied by short-period waves) cause coastal flooding that places lives, infrastructure, and property at risk. At present, some 40 million people globally and $3000 billion of property are thought to be at risk due to coastal flooding; these figures could rise to 150 million people and $35,000 billion of assets by 2070 [*Nicholls et al.*, 2008]. Hurricane Sandy in 2012 caused widespread flood damage along the East Coast of the U.S. with over $70 billion of damages [*Neria and Shultz*, 2012].

Since many regions at risk from storm surges (e.g., the eastern U.S. seaboard, south east Asia, the European continental shelf) are shallow shelf seas with large tidal range and strong tidal currents it is important to understand the interaction between storm surges and tides. Such interactions have been extensively studied [e.g., *Rossiter*, 1961; *Prandle and Wolf*, 1978]. The dominant mechanism for tide-surge interaction is that meteorological forcing and increased water levels induce a phase shift in the tidal signal [*Horsburgh and Wilson*, 2007]; many properties of a nontidal residual time series (i.e., the time series of sea level observations minus tidal predictions) are simply an artifact of small changes to the timing of predicted high water (HW). Consequently, the statistical analysis of nontidal residuals is problematic and requires additional information since there is not always a genuine atmospheric contribution to large residuals. A far more useful metric for storm surge research [*Sterl et al.*, 2009; *Howard et al.*, 2010; *Batstone et al.*, 2013; *Wahl and Chambers*, 2015; *Mawdsley and Haigh*, 2016] is the skew surge [*de Vries et al.*, 1995] which is the absolute difference within a tidal cycle between the maximum observed sea level and the predicted tidal high water (irrespective of time of occurrence). The skew surge is illustrated in Figure 1.

The role of the tide in modulating skew surge has not previously been systematically examined, despite its importance for coastal extreme sea levels. Indeed, recent literature [e.g., *McInnes et al.*, 2013] is still unclear about the relationship between skew surges and tides. Here we examine in detail the relationship between

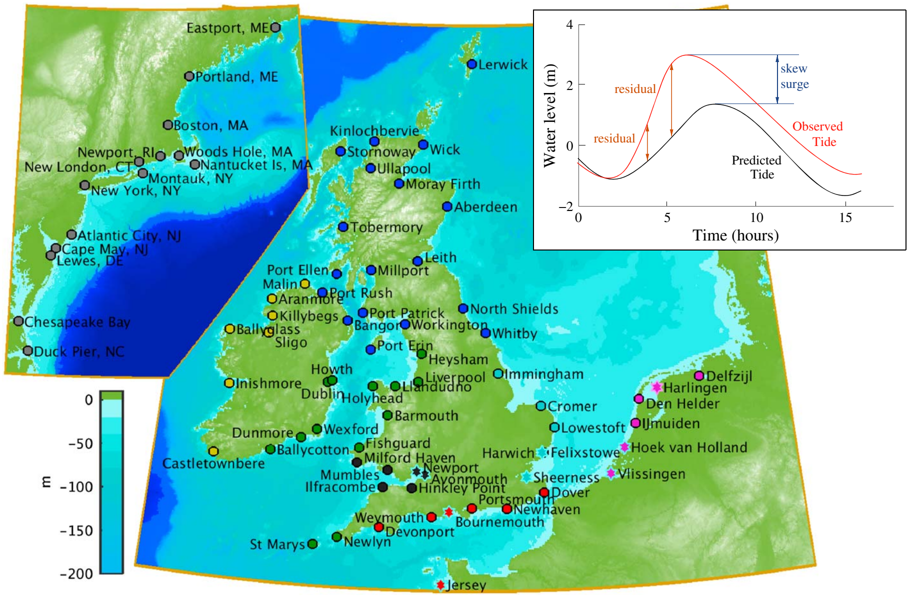

Figure 1. Maps indicating gauge locations, colors are geographical groups used in Figure 3, and star gauges are listed in section 2.5. Background color is bathymetry. Inset: Definition of skew surge.

skew surge and HW for a large range of tide gauges subject to midlatitude storm surges on both sides of the Atlantic. This paper is the first study to systematically evaluate the relationship between skew surge and tidal height. We test the hypothesis that the height of the tide has no modulating effect on the skew surge (i.e., at a given location any storm surge can occur on any tide). This is important and timely for scientific and engineering reasons: policy makers and coastal protection agencies are currently revising extreme sea level projections following the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change [*Intergovernmental Panel on Climate Change*, 2014]. Understanding the relationship between skew surge and tide will avoid misleading future impacts conclusions being drawn from nontidal residual properties.

One area where the use of skew surge is particularly advantageous is in joint probability methods (JPMs) for extreme sea level estimation. JPMs produce a probability distribution of extreme sea levels for a given location by convolving the separate probability distributions of tides and storm surges. JPMs are superior to other methods of sea level extreme estimation [*Tawn*, 1992] because they use all storm surge data in a tide gauge record. JPMs are superior in environments where the tidal signal is of comparable magnitude to the storm surge [*Haigh et al.*, 2010] and are superior to threshold-driven methods [e.g., *Tebaldi et al.*, 2012] which may not detect large storm surges on small tides. The independence of skew surge and tidal high water, if proven, would remove the need for artificial statistical functions or multivariate approaches to the estimation of extreme sea levels.

2. Methods and Results

2.1. Data Selection

We examine 77 tide gauge records from the UK (45 records), Ireland (6), the Netherlands (12), and the U.S. East Coast north of Cape Hatteras (14). (See map in Figure 1 and list in Figure 3.) The Dutch data were observed and predicted HW; elsewhere, the records were (typically) hourly observations. The skew surge is defined as the difference between the maximum observed height and the predicted HW (see Figure 1). To obtain the skew surge record, observed HW levels and times were extracted and then compared to those predicted.

2.2. Definition of “Extreme” Skew Surge as Top 1%

We selected the top 1% of skew surges at all tide gauges. This threshold is chosen because smaller values of skew surge can result from errors in the magnitude of the predicted tide. While largely accurate, harmonic analysis of tides can involve errors, typically 10 cm RMS (root-mean-square) for HW amplitude predictions around the UK [*Flowerdew et al.*, 2010] with a 29 cm RMS error for regions of high tidal range. Individual predictions of HW in the Bristol Channel (in the absence of any storm surge) may be in error by up to 0.6 m [*Hibbert et al.*, 2015].

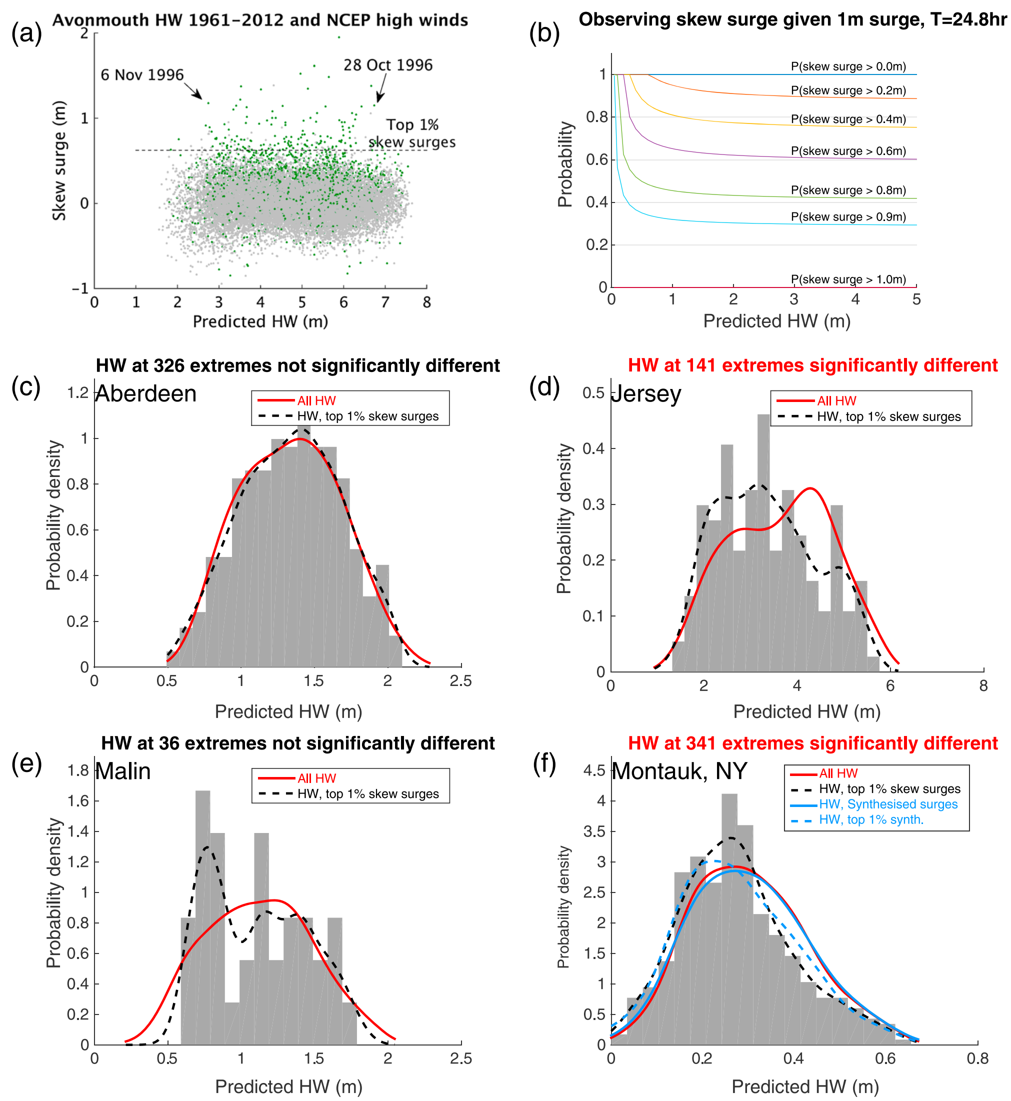

Figure 2. (a) Scatterplot of predicted high water (HW) versus observed skew surge at Avonmouth. Those marked in green are within 12 h of one of the top 3% wind speeds in the NCEP reanalysis. (b) Effect of tidal amplitude on the likelihood of observing skew surges of various sizes, given a sinusoidal "surge" of 1 m amplitude and 24.8 h period (twice M_2) and an M_2 "predicted tide." (c–f) Probability density function (pdf) at four example sites of all HW (red), and HW associated with the highest 1% of skew surges (black, and grey bars for underlying histogram). Also (f), pdf of HW associated with all and the top 1% (blue solid and dashed) of skew surges from a synthesized data set. In Figures 2–4, to ease comparison between sites, HW are all indicated relative to the mean predicted tide at each site.

To further ensure that these surges had a genuine meteorological cause, we cross checked against 6-hourly National Centers for Environmental Prediction (NCEP) reanalysis data [*Kalnay et al.*, 1996] at the nearest 2.5° grid point. Around 60–80% of the 1% largest skew surges occurred within 12 h of one of the top 3% wind speeds (e.g., Figure 2a for Avonmouth, Figures S1–S5 in the supporting information for all gauges.) Across all our sites, selecting the top percentile resulted in skew surge thresholds ranging from 0.34 m to 0.70 m and implies contributions from seven severe storms per year on average (there are 705 HW per year in a semidiurnal regime). We do not take account of storm surge clustering in this analysis.

2.3. Statistical Analysis Using Rank-Based Correlation

Figure 2a illustrates the lack of correlation between skew surges and HW. To test directly for correlation between extreme skew surges and predicted HW, we used the rank-based measure *Kendall*'s [1938] τ. Rank-ordered methods provide a measure of any monotonic relationship between two continuous random variables, are less sensitive to outliers and skewed distributions than Pearson's correlation, and do not depend

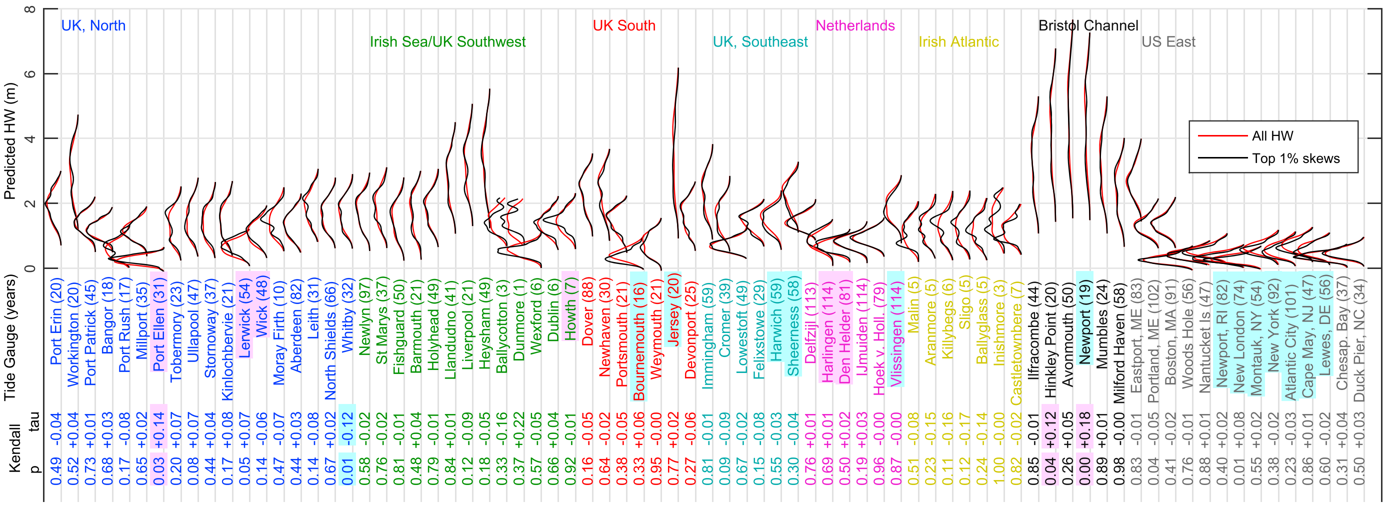

Figure 3. Probability density function (pdf) of all HW for all sites in this study. Locations are highlighted in pink (blue) where the HW associated with extreme skew surges have a different distribution to all HW, and large skew surges have increased likelihood on spring (neap) tides. At other gauges, there is no significant difference (at 0.01 level) between the pdf of HW for extreme skew surges and all HW. Gross record length in years is indicated in brackets. Also shown is the Kendall τ and p values, highlighted as significant nonzero correlation where $p < 0.05$ and $|\tau| > 0.1$ in pink (blue) if tides are larger (smaller) on the highest skew surges.

on assumptions of linearity between the variables. The null hypothesis here is that there is no correlation between skew surges and the tidal HW (we reject that hypothesis if p is less than the chosen statistical significance level). Results for the 77 tide gauges are shown in Tables S1–S4 and Figure 3. The tables also show the 95% confidence interval (CI) calculated using the method of *Samara and Randles* [1988] described in *Hollander and Wolfe* [1999]. Of these, seven are significant at $p < 0.05$ and only three are significant at $p < 0.01$; in the majority of cases we cannot reject the null hypothesis. Even where $p < 0.01$, the largest correlation coefficient ($\tau = 0.18$, for Newport in the Bristol Channel) is so small as to imply little predictability (were the relationship linear then only 3% of the variance in skew surge would be predictable by the tidal variance). The Kendall test is still somewhat sensitive to outliers, for example, omitting any one of the five largest skew surges from Hinkley Point removes any significant correlation within the extreme skews. Thus, the tidal HW amplitude does not modulate the storm surge produced.

2.4. Distribution of Predicted HW Associated With Extreme Skew Surges

The distribution of predicted HW at a gauge is not necessarily normal and is sometimes bimodal [*Pugh and Woodworth*, 2014]. Figure 2 shows the probability density function (pdf) of all HW at four example sites and the histogram and pdf of extreme-related HW, i.e., the sample population of predicted HW associated with the highest 1% of skew surges. If skew surges and HW are independent, then extreme-related HW will have the same distribution as all HW. To test this, we parameterize the distribution at each gauge using a Gaussian kernel density estimator and then apply the Anderson-Darling test. We use a kernel bandwidth of 1/20th the spring-neap range to prevent excessive smoothing of the distribution and at least 0.1 m for sites with fewer than 50 extreme events, in order to reduce statistical error.

At Aberdeen and Malin, for example, (Figure 2) the extreme-related HW are statistically indistinguishable from all HW—at Malin this could be because there are too few surges (only 36) to reject the hypothesis that they have the same distribution. At Jersey and Montauk the extreme-related HW are statistically different (significance level 0.01) from all HW. Repeating this at all gauges, we find 13 sites where extreme skew surges are more likely to be observed at neap tides and 6 sites where extreme skew surges are more likely to be observed at spring tides (Figure 3). At 58 sites, there is no significant difference between the pdf of extreme-related HW and all HW.

2.5. Seasonal Relationships Between Tides and Storm Surges

Seasonal relationships explain the differences between the pdf of all HW and the pdf of extreme-related HW at half the sites where this is seen. In a semidiurnal regime the largest spring tides normally occur near the equinoxes when the Sun exerts the largest tide-generating force. However, for some locations in our study, other seasonal effects can result in the largest predicted spring tides occurring at different times.

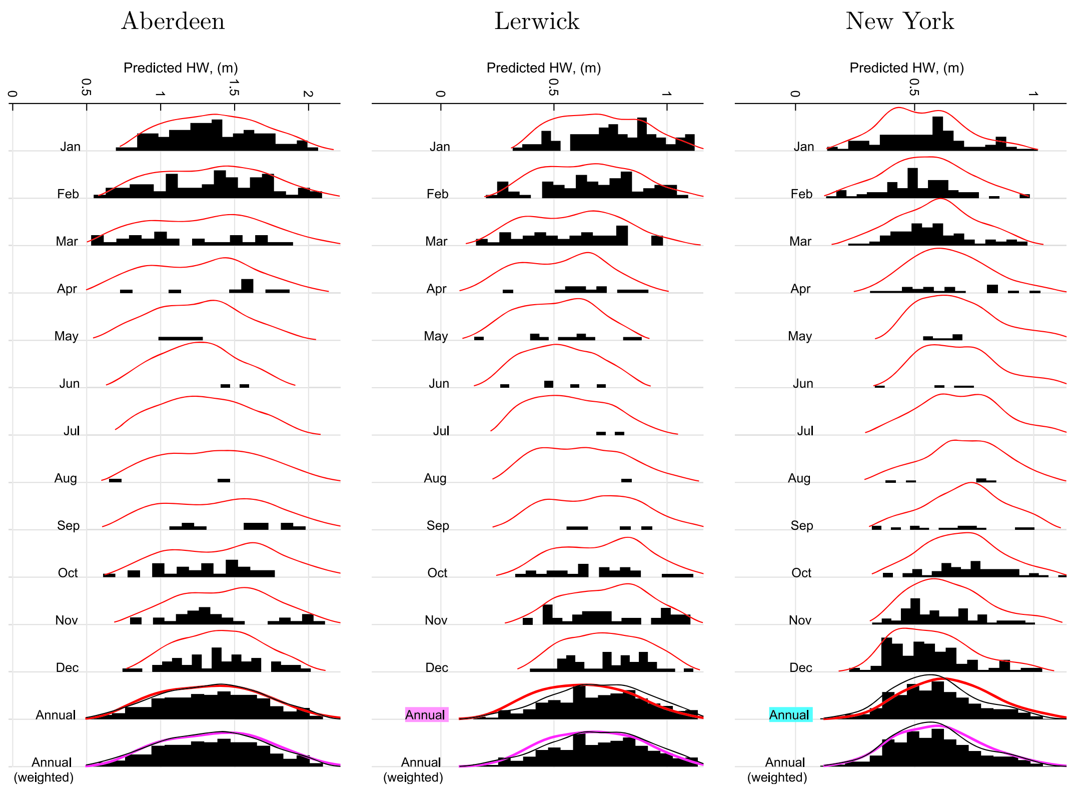

Figure 4. Seasonal distribution of HW at Aberdeen, Lerwick, and New York. Probability density function (pdf) of all HW (red) in each month and histogram of HW associated with the highest 1% of skew surges in that month. Also the annual pdf as for Figure 3. Finally, a pdf constructed from weighting the monthly pdfs according to frequency of extreme skew surges. Highlighting on annuals indicates significant difference of distribution.

Seasonal changes in mean sea level which manifest in tidal predictions are represented by the long-period (annual and semiannual) constituents. These result primarily from seasonally varying winds, atmospheric pressures, and steric effects [*Pugh and Woodworth*, 2014]. Seasonal stratification on the continental shelf can modulate the barotropic M_2 tide by typically 5–10% [*Muller et al.*, 2014] through its effect on vertical mixing.

At Lerwick the winter months contain some of the largest predicted HW (Figure 4). Tidal analyses for this region contain large annual (S_a) and semiannual (S_{sa}) constituents. The largest skew surges tend to be in the stormy winter months, so are more likely to coincide with large HW. Applying the analysis of section 2.4 month by month, we find that the skew surge and HW are independent. The opposite effect is seen at New York, where constituent S_a of ~8 cm peaks in mid-May. None of the gauges on the U.S. East Coast show dependence of extreme skew surges on HW once seasonal effects are included.

In this way we reanalyzed all sites, comparing the distribution of extreme-related HW to P_{comb}, a combination of monthly distributions P_j of all HW, weighted toward the stormiest months. $P_{\mathrm{comb}} = \sum_{j=1}^{12} P_j W_j$, where W_j is the proportion of high wind speeds that occur in the jth month. They only differ significantly at nine gauges: Harlingen (biased toward springs), Bournemouth, Jersey, Harwich, Sheerness, Hoek van Holland, Vlissingen, Avonmouth, and Newport (UK) (biased toward neaps). Of these only one was found to be significant in the rank-ordered analysis of section 2.3, where the weak correlation was in the opposite sense. This illustrates that these remaining effects are second order.

2.6. Increased Detectability of Short-Period Surge Variation During Neap Tides

The skew surge loses information about atmospherically driven variations in the surge within a tidal cycle (since it is a cycle-integrated measure). The detectability of any such fluctuations will depend on tidal range. On a larger tide, a short-period increase in storm surge will only manifest in the skew surge if it occurs close to HW. As a simple test of detectability we superimpose a 1 m sinusoid with a period of 1 day (typical of a storm surge) on an M_2 (12.4 h period) tide with a range of amplitudes. This neglects nonlinear interactions, but we are not attempting to explore tide-surge interaction; rather, we are testing the efficacy of skew surge as a metric.

Figure 2b shows the probabilities of calculating a skew surge of a particular height given these assumptions. The curves suggest that for tidal heights of between 1 and 5 m there is little difference in the probability of observing a particular level. Only if tidal height is much smaller (less than 1 m) is there a higher probability of observing a storm surge whose variability is of the same order. The probability of the skew surge measure detecting 80% of the true amplitude is around 0.4 for most tidal ranges, but this would obviously increase for more realistic (i.e., not sinusoidal) representations of the storm surge where its peak amplitude would have longer duration.

In the previous section we found eight locations where there is a weak association of larger skew surges with smaller tides, but since none of them has very small tides (<1 m) it is unlikely that the detectability of storm surge variation within a tidal cycle is responsible.

2.7. Direct Comparison of Weather Systems on Spring/Neap Tides

A bias of larger storm surges toward smaller tides could also be consistent with the equations governing storm surge dynamics since the stress exerted by the wind on the sea surface is normally parameterized as being inversely proportional to the depth [e.g., *Pugh and Woodworth*, 2014]. In a tidal environment the denominator of the stress term in the momentum equations can be written as $h + A\cos\omega t$, where h is the average depth and A the amplitude of the tide. The tidal modulation of wind stress is the integral of this over a tidal cycle. The nonlinearity due to tidal depth variations turns out to be trivial compared to the variations in wind speed and direction over the progression of a real weather system and other nonlinear terms in the shallow water equations. In the simple expression above even if the tidal amplitude, A, is half the undisturbed water depth, h, then cycle-averaged wind stress is only 3% different to that obtained using a constant depth.

Only with a numerical model can one quantify the change in storm surge response when exactly the same weather system coincides with a different tide. We used the UK operational storm surge model [e.g., *Horsburgh et al.*, 2008] to synthetically combine the atmospheric forcing from four storms (all of which gave large storm surges around the European coastline) with first a spring tide and then a neap tide. We analyzed the change in skew surge obtained at seven port locations which were affected. The results are shown in Table S5. The results are highly variable but may suggest that in a model setting (where other factors can be held constant) larger skew surges can be produced on neap tides. Only one weather system produced significantly larger skew surges at all locations during the neap tide. The average increase in skew surge during the neap tide was 24 cm in this model run. *Idier et al.* [2012] performed a similar experiment for two strong weather systems that affected the French coastline. Only in one case did they find significant differences (of order 20 cm in parts of the English Channel) in the skew surges obtained between mean spring tides and mean neap tides.

The results of these idealized experiments suggest that smaller skew surges may be generated on spring tides for identical atmospheric forcing. But it is known that storm surge variability is greater within an ensemble model of a single event. *Horsburgh et al.* [2008] report a skew surge spread of order 0.9 m from a 24-member ensemble simulation of a large event in the North Sea. The natural variability of weather systems dominates the magnitude of storm surges in the observational record.

3. Discussion

Our results show that on the basis of observed skew surges the tide (e.g., the state of the spring-neap cycle) exerts no modulating control on the size of the storm surge. This is a significant result for coastal flood risk management. Based on our rank-ordered statistics any extreme storm surge can coincide with any tide. When taken together with the previous work of *Horsburgh and Wilson* [2007], this provides the most meaningful description of storm surge and tide interaction. The tide has no direct effect on the magnitude of large storm surges (if we take the skew surge to be the best metric); the storm surge and weather primarily affect the timing of high water through phase shift. The lack of dependency of surge generation on water depth is counterintuitive in the context of the shallow water dynamics but is easily explained: the natural variability of weather systems dominates any observation-based analysis. The numerical model results (section 2.7) lend some support to larger storm surges being generated during neap tides, all other forcing being equal. However, a far larger and more systematic modeling study is required to evidence this and provide statistically robust quantification of the modulating effect of the tide. In reality, each storm is significantly different and this is far more important than small temporal variations to the depth-averaged momentum transfer brought about by tidal variations. While mean sea level rise contributes directly to an increase in extreme sea level, numerous previous studies [*Arns et al.*, 2015; *Howard et al.*, 2010; *Sterl et al.*, 2009] have found that mean sea level rise does not affect storm surge magnitude on the European continental shelf. Rather, the primary effect of imposing a mean sea level rise is to alter the positions of amphidromes in the tidal system and thus the amplitude of the tide, as described by *Pickering et al.* [2012].

Weak seasonal relationships between skew surge and the associated HW were identified at sites where the predicted tide contains an annual cycle (due to long-period tidal constituents). Our approach to illustrating the seasonal effects differs from previous studies on Venice [*Battistin and Canestrelli*, 2006] and France [*Kergadallan et al.*, 2014], but we obtain the same fundamental result. When these seasonal relationships between tides and the storm season were removed, then skew surge and associated HW are completely independent at 68 of our 77 study sites. There remain a few gauges, for which a small significant dependence on tidal cycle exists. None of these had a corresponding and significant correlation in the rank-ordered analysis. It is possible that synthesizing the HW pdf is more sensitive to the high density of values near the threshold (i.e., at the low end of our selected extremes).

Our analysis was restricted to high-quality records in extratropical regions. In the absence of sufficient high-quality data, any insight into the comparative behavior of tropical surges would have to come from a model study. It seems likely that the surge response of more intense wind stresses and pressure gradients associated with tropical cyclones would swamp any effect of the tide. A minor shortcoming of skew surge as a measure is the possibility that it fails to capture variations of the storm surge over a few hours. However, it does not affect detection of the largest storm surges.

Tide-skew surge independence massively simplifies the process of joint probability estimation (compared to previous methods, e.g., *Dixon and Tawn* [1994], that relied on empirical relationships between tide and nontidal residual). Here we show systematically for the first time that the largest midlatitude storm surges are uncorrelated with the corresponding tide. Our results justify the first-order assumption of independence made by previous studies of extreme sea levels [e.g., *Batstone et al.*, 2013]. We show that specifying seasonal relationships between HW and skew surges (e.g., by calculating joint probabilities on a monthly basis or the more complex methods put forward by *Kergadallan et al.* [2014]) would further improve the methods used to estimate extreme water levels for coastal flood protection.

Our results highlight the significant role of extreme tides in flood risk. There is nothing to stop a major storm surge from coinciding with the highest astronomical tide. As a simple example, the major Atlantic storm (storm Xaver) [*Haigh et al.*, 2015] on 5 December 2013 caused a 1.24 m skew surge at the UK tide gauge of Whitby. This was estimated to be the one in 570 year return level at that location. However, the largest skew surge on record for Whitby is 1.34 m and the highest astronomical tide is 0.12 m higher than the tide in December 2013. These feasible increases in extreme water level add up to a one in 5000 year return level. Similar calculations can swiftly be performed for all gauges leading to maximum possible levels (i.e., plausible levels based on actual events without statistical extrapolation). While having very small probabilities, these events have serious implications for flood risk.

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