# The Characteristics of Storm Surges in the Bristol Channel

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## ABSTRACT

Storm surges caused by atmospheric forcing can be devastating, with long-lasting and diverse consequences. Historically, the UK has suffered major storm surges events, including in the Bristol Channel, which has the second largest tidal range in the world. In this paper, both statistical analysis and dynamic model studies were applied to investigate the potential conditions under which a large surge might occur in the Bristol Channel.

KEY WORDS: Bristol Channel; storm surges; ADCIRC; shallow water equations; Extreme value analysis; wind; spring-neap cycle.

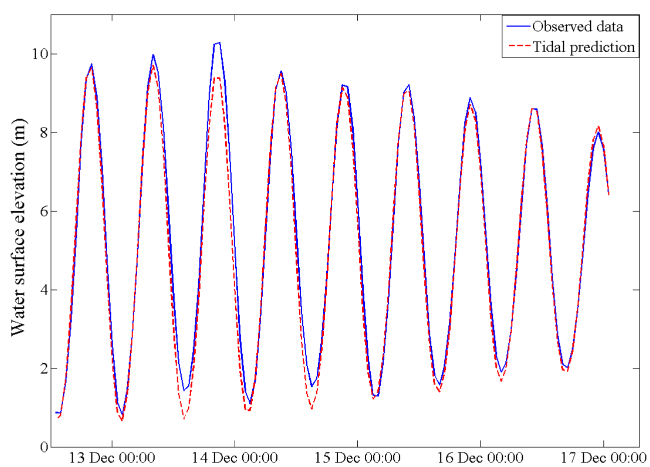


Fig. 1 Observed water surface elevation data (blue solid line) and tidal prediction data (red dash line) at Ilfracombe from 12$^{th}$ Dec 1981 to 17$^{th}$ Dec 1981 from British Oceanographic Data Centre .


Fig. 2 Map of measuring stations in the Bristol Channel (accessed from Google Earth).

## INTRODUCTION

The Bristol Channel is an area of complex hydrodynamics which includes a very large tidal range, strong currents, extensive intertidal areas and river inputs, all of which contribute to frequent storm surges and flooding (Williams et al., 2012). For example, on the evening of 13th December 1981 a storm crossed southwest Britain, resulting in severe flooding in areas along the south side of the Bristol Channel from east of Bideford to near Gloucester (Proctor and Flather, 1989). This event produced a significantly high water level with return period as high as 102 years at Avonmouth, which is the highest return period event on record on that site (Haigh et al., 2015). Fig. 1 shows the variation of the water surface elevation of the 1981 storm surge event at Ilfracombe, the data was obtained from the British Oceanographic Data Centre (BODC) and refer to Admiralty Chart Datum (ACD). A good knowledge and understanding of such storm surges in the Channel is very helpful in assessing the associated risks that these events might present, both now and in the future.

This study first examined the occurrence and severity of storm surge events in the Bristol Channel over the period 1961-2015 by means of extreme values statistics using in situ data derived from tide gauges at five key locations along the east and west coasts of the Channel: Avonmouth, Newport, Hinkley Point, Mumbles and Ilfracombe (Fig. 2). Subsequently, a two-dimensional ADCIRC model whose domain includes Irish Sea, Celtic Sea, English Channel and Bristol Channel was built to investigate the influences of wind conditions on the storm surge events in the Bristol Channel.

## DATA AND METHOD

### Extreme Value Analysis

Extreme value analysis is a widely-used statistical methodology for drawing inferences about the extremes of a stochastic process using only data on relatively extreme values of that process (Coles et al., 2001). Using this statistical approach allows us to describe temporal trends in storm surge characteristics, whilst properly accounting for the effects of natural variability (Butler et al., 2007). In order to assess the likelihood of recurrence of a storm surge we examined the return period of the surge component by fitting a generalised extreme value (GEV) distribution to the extreme surge levels using Maximum Likelihood, bootstrapping was then used to test the accuracy of the prediction. In statistics, bootstrapping can refer to any test that relies on random sampling with replacement (Diaconis and Efron, 1983). It offers a simple approach for statistical uncertainty when only a random sample is available.

Assuming $n$ years of hourly surge data, $t_1$, ..., $t_n$, and let $x_j$ denote the annual maximum surge for year $t_j$. A standard procedure would be to assume that the annual maxima $x_1$, ..., $x_n$ follow a generalised extreme value (GEV) distribution with distribution function:

$$F(x;\mu,\sigma,\xi) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{\frac{-1}{\xi}}\right\} \tag{1}$$

where the parameters $\mu$, $\sigma$, $\xi$ are location, scale and shape parameters respectively. The value of shape parameter $\xi$ differentiates between the three types of extreme value distribution: $\xi < 0$ corresponds to the Weibull (type III); $\xi = 0$ and $\xi > 0$ correspond to the Gumbel distribution (type I) and Fréchet (type II) distribution respectively. Let $Q(z)$ be the probability of a level $z$ being exceeded in any 1 year, then the return period $T(z) = 1/Q(z)$ is the average time between which levels higher than $z$ occur, i.e. a level $z$ would be expected to be exceeded once every $T(z)$ year.

In this study, the characteristics of the storm surge events in the Bristol Channel were examined using statistics derived from the measured data from the British Oceanographic Data Centre (BODC). We define the storm surge as the residual between the harmonic prediction of the tide and the measured water levels, and their sample intervals are one hour from 1961 to 1992 and fifteen minutes from 1993 to 2015. Our study is restricted only to the five sites (Avonmouth, Newport, Hinkley Point, Mumbles and Ilfracombe which are shown in Fig. 2) for which sea level records are available for 20 or more of the years in the period 1961-2015, and the observed data periods used in this study are different for each station.

The total original raw data consists of around 10% of intermittent missing data: the Hinkley Point and Newport stations show missing data fractions less than 5% of complete data, the Ilfracombe and Mumbles stations show missing data fractions less than 15%, while the Avonmouth station shows missing data fractions less than 20%. We define annual data between July to June of the next year so that winter storms are not split between different years; and the winter, autumn and spring data from December to February, from September to November and from March to May respectively. All the observational data were fitted to GEV distribution to estimate the 1 in 10 and 1 in 50 year return levels of storm surge. A simple parametric bootstrap approach has been used for estimating the efficiency of the three parameters derived from GEV distribution. 200 resamples have been used for 1000 times of bootstrapping at each of the five locations in the Bristol Channel.

### Shallow Water Equations and Continuous Galerkin (CG) Finite Element Method

The governing equations used in the current study are the depth-averaged two-dimensional shallow water equations, which have been widely used in modelling unstratified coastal and estuarine waters (Falconer, 1993). The shallow water equations are usually formally derived from the full incompressible Navier-Stokes equations with free surface under the modelling hypothesis that the pressure is hydrostatic, the flow is gradually varied and the horizontal length scale is much greater than the vertical length scale of the ocean flow (Bresch et al., 2007).

The traditional continuous Galerkin (CG) finite element method was selected here to solve the shallow water equations. CG discretisation only requires integrals to be evaluated over the element interiors, while discontinuous Galerkin (DG) discretisation requires the evaluation of integrals over the element interiors and the element boundaries. Although the DG model has several appealing features, since the DG errors are generally an order of magnitude lower than that in the CG solution, the DG model was about four times slower than the CG model (Kubatko et al., 2006). Considering the longer simulation time of a DG model than a CG model and consistent results between the DG and CG models, the CG method was adopted to solve the shallow water equations.

### Input of Wind into ADCIRC

ADCIRC inputs wind in units of stress rather than velocity. The relationship between wind stress and wind velocity can be described by the following equation:

$$F_s = \rho_{air} C_D v^2 \tag{2}$$

where $C_D$ represents the drag coefficient between the water surface and the air, and $v$ represents the wind velocity. The standard Smith and Banke (1975) formulation reads:

$$C_D = \frac{1}{1000}(0.63 + 0.0066v) \tag{3}$$

for wind speeds of $2.5\text{ms}^{-1} < v < 21\text{ms}^{-1}$. Similarly, the ADCIRC user's manual v51 (2015) recommends:

$$C_D = \frac{1}{1000}(0.75 + 0.067v) \tag{4}$$

which is defined by Garratt's drag formula (Garratt, 1977).

### Model Set Up

The basic mesh used is that in Serhadlıoğlu′s model of the Irish Sea, the Celtic Sea and the Bristol Channel (Serhadlıoğlu et al., 2013). The English Channel part of the model came from Adcock and Draper's study (2014). As seen in Fig. 3, the domain includes three ocean

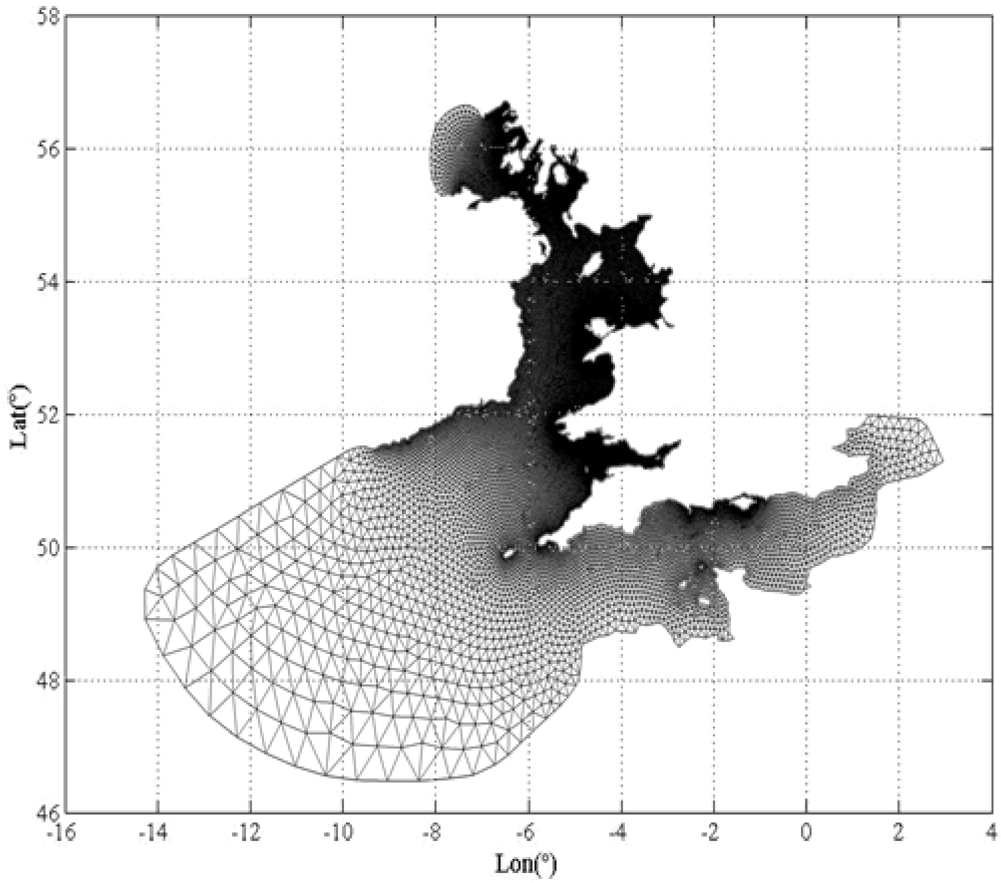


Fig. 3 Model mesh, including the Irish Sea, the Celtic Sea, the English Channel and the Bristol Channel.

Table 1 . Annual and seasonal estimates of 10-year and 50-year return levels and annual bootstrapped estimates.

| | Location | | Return period (years) | Annual (m) | Mean of bootstrapped estimate (m) | Winter (m) | Autumn (m) | Spring (m) |
|---|---|---|---|---|---|---|---|---|
| | Lat(N) | Lon(W) | | | | | | |
| Avonmouth | 51°30' 39.2" | 02°42' 53.9" | 10 | 2.47 | 2.45 | 2.33 | 1.92 | 1.72 |
| | | | 50 | 2.97 | 2.96 | 2.96 | 2.33 | 2.19 |
| Newport | 51°33' 00.0" | 02 °59' 14.8" | 10 | 2.26 | 2.30 | 2.20 | 1.77 | 1.56 |
| | | | 50 | 2.67 | 2.71 | 2.64 | 2.10 | 1.96 |
| Hinkley Point | 51°12' 54.9" | 03 °08' 03.6" | 10 | 1.88 | 1.87 | 1.87 | 1.35 | 1.22 |
| | | | 50 | 2.26 | 2.27 | 2.27 | 1.59 | 1.68 |
| Mumbles | 51°34' 12.0" | 03 °58' 31.6" | 10 | 1.51 | 1.52 | 1.46 | 1.14 | 0.95 |
| | | | 50 | 2.18 | 2.40 | 2.03 | 1.35 | 1.24 |
| Ilfracombe | 51°12' 39.5" | 04 °06' 39.4" | 10 | 1.38 | 1.38 | 1.27 | 0.99 | 1.10 |
| | | | 50 | 1.70 | 1.69 | 1.66 | 1.22 | 1.56 |

boundaries: northern boundary which extends towards the Scottish Isles of Tiree and Coll, the western boundary in the Celtic Sea and the eastern boundary in the English Channel. The model domain is divided into 31341 unstructured triangular cells and allows a large variation in the scales of regions of interest, which in this study varies from 500m to 54km.

On the open boundary, the water depths were prescribed and were the best estimates based on previous work (Serhadlıoğlu et al., 2013), and no current was specified on the boundary. There is slip boundary condition at the coastline. In the real fluid the slip boundary condition cannot happen, but the boundary layer thickness here in the model is much smaller than the mesh size, therefore we used a slip boundary condition. The model was forced by the two principal tidal components from Le Provost tidal database (Le Provost et al., 1995), the $M_2$ and $S_2$ constituent which, whilst not precisely reflective of water levels as a result of tides, comprise approximately 96% (Serhadlıoğlu et al., 2013), and thus provide an excellent approximation to the tidal variations at this site.

The CG-ADCIRC modelling parameters were set as constant throughout the study: most of the parameters were attained as the default values recommended by the ADCIRC model developers and used in the study of Serhadlıoğlu et al. (2013); while the rest, such as time step, bottom friction, wetting and drying were determined using equations and a parameter sensitivity analysis for the area of focus. The model was run with constant winds of magnitude 10ms$^{-1}$, 20ms$^{-1}$ and 30ms$^{-1}$ from various directions. Although storm surge is induced by the combined effect of low atmospheric pressure and strong winds acting upon the sea surface, atmospheric pressure is not the dominant effect in the Bristol Channel where the water depths are relatively small. In this study we neglect atmospheric pressure changes.

## RESULTS AND DISCUSSION

### Return Levels

Return levels for storm surge based on the GEV distribution for the 10- and 50-year levels are presented in Table 1, and the observation sites are shown in Fig. 2. In general, storm surges are higher at locations closer to the Channel head than that near the Channel mouth: the 1 in 50 year level annual maximum at Avonmouth (2.97m) is nearly double of that at Ilfracombe (1.7m). This could correspond with the increasing $M_2$, $S_2$ and $N_2$ tidal amplitudes from Milford Haven to Barry to Avonmouth in the Bristol Channel (Davies and Jones, 1992).

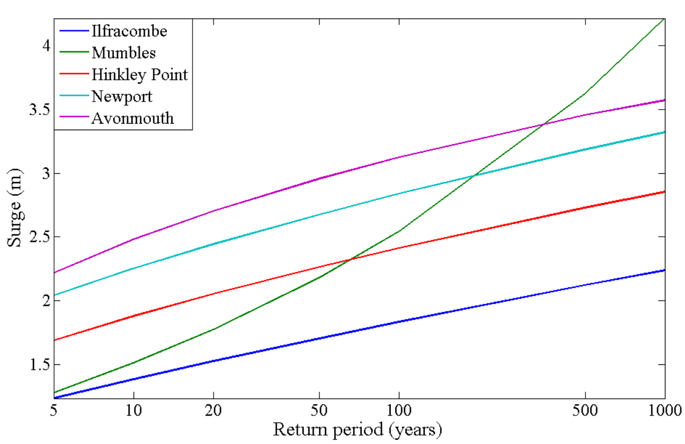


Fig. 4 Annual estimates of 5-, 10-, 20-, 50-, 100-, 500- and 1000-year return levels of surge at Ilfracombe, Mumbles, Hinkley Point, Newport and Avonmouth.

The winter maxima estimates are the closest to annual maxima, indicating the storm surges are most likely to occur in winter months when winds are strong with low atmospheric pressure. The autumn maximum estimates at most of the locations are around 20% lower than the annual maxima, while the spring maximum estimates are around 30% lower, except for Ilfracombe where the autumn maxima are about 30% lower than the annual maxima and the spring maxima are about 15% lower. The seasonal variation of the storm surge height is strongly influenced by the seasonably varied wind speed and direction, and their relation is investigated in the following study. Despite the fact that limited data points and missing data of field data lead to some uncertainty in bootstrapped data, the results from bootstrapping seem to be consistent with the estimates from original data giving confidence that the general trend has been identified (Table 1).

Fig 4 illustrates the relationship between storm surge and return period ranging from 5 years to 1000 years, and the return period is plotted on a logarithmic scale with base 10. Given the nature of the data it is clear that caution must be used in interpreting the higher return periods on this figure. It is seen from the statistics and Fig 4 that the Channel head should be paid more attention for dynamic modelling due to its high storm surges at various return levels, thus Avonmouth is chosen to be a main observational site. The curve of Mumbles is the steepest with the highest predicted long-term storm surges. There are significant amounts of missing data at Mumbles and this may have compromised the analysis of this station.

### Introducing Different Winds

In order to model the impact of wind has on sea surface levels, simulations were run with two forcing tidal components $M_2$ and $S_2$ and constant winds with speed of 30ms$^{-1}$ from five different directions: South, Southwest, West, Northwest and North. Five locations in the upper Channel: Avonmouth, Hinkley Point, Newport, Ilfracombe and Mumbles (as shown in Fig. 2) were selected to investigate the effects of wind conditions on the water surface levels. The simulations were set to increase the wind from 0 to 30ms$^{-1}$ on Day 3 00:00-12:00, keep constant from Day 3 12:00 to Day 4 12:00, and decrease to 0 from Day 4 12:00 to Day 5 00:00. When analysing the results, we use the term “residual” when implying the result affected by both winds and tides; otherwise, we refer to “surge” which is a genuine meteorological without tidal contribution to sea level.

It is seen in Fig. 5, when introducing Northerly winds, negative residuals appear; when introducing North-Westerly winds, both positive and negative residuals appear at Avonmouth, Newport and Hinkley Point, but only negative residuals appear at Mumbles and Ilfracombe; when applying Southerly, South-Westerly and Westerly winds, significant positive residuals appear at all the five sites. Among the five observation stations, Avonmouth experiences the highest water surface elevations with the largest residual being observed, the residual peak reaches 4m before the South-Westerly wind begins to decay on Day 4. Ilfracombe has the lowest water surface elevations with smallest residual with a residual peak of around 1.5m when introducing Southerly wind being observed.

A transition of dominant wind appears to occur from mid-Channel to the Channel head. In the higher reaches of the Channel (Avonmouth), the South-Westerly and Westerly winds provoke highest water levels. How-

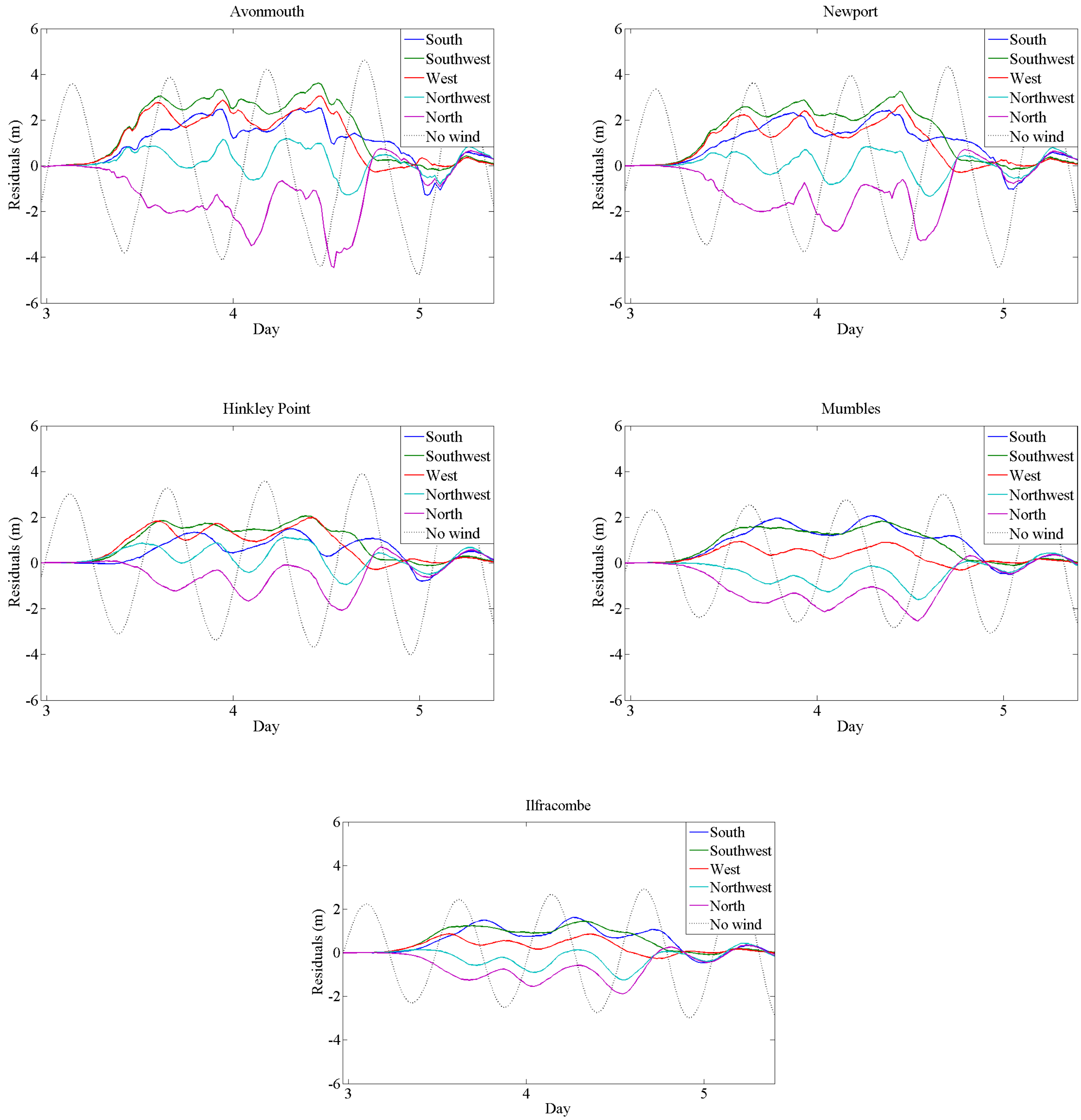


Fig. 5 Residuals calculated at Avonmouth, Newport, Hinkley Point, Mumbles and Ilfracombe. Dotted lines refer to the water elevations when only tides are included in the model.

ever, in the mid-Channel (Mumbles and Ilfracombe) Southerly wind has the worst effect on the water heights. As the storm surge propagates upstream, the water is subjected to two effects: the funnelling effect and the shoaling effect of the Channel. These two effects contribute to the building up of waters travelling up to the Channel head. The transition of dominant wind directions could be the result of Ekman flow. Ekman transport is a result of the combination of the Coriolis Effect from the Earths rotation and the drag related to the winds blowing over the water surface (Pugh, 1996). Therefore the Southerly wind results in water from the Irish Sea being pushed into the Channel. Due to the too shallow topography of the upper reaches of the Channel, it is more difficult to develop a full Ekman spiral. Hence, the South-Westerly and Westerly winds may have more significant effects further up inland, forcing water in a direction more parallel to the wind and more parallel to the length of the Channel itself.

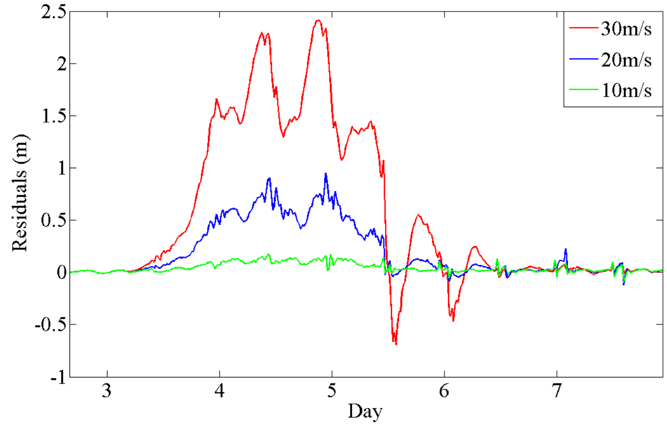


Fig. 6 Residuals with Southerly winds at different speeds at Avonmouth.

## Tide-surge Interactions

Due to the non-linear effect of wind speed on water elevations, the 30ms$^{-1}$ winds have much more significant impact than 10ms$^{-1}$ winds (Fig. 6). At Avonmouth, the 30ms$^{-1}$ wind generates residuals as high as 2.5m while the 10ms$^{-1}$ winds only generate some fluctuations no higher than 0.1m. The non-linear terms are important in shallow water, where they generate an interaction between components of the motion. In particular, where the tides are large and the water shallow, interaction occurs between the tide and surge making the two components interdependent (Pugh, 1996; Capel, 2001). Therefore the residuals produced by given meteorological forces at a certain state of the tide may differ significantly from the surge resulting from identical forcing when there is no tide.

An example of the water surface elevations at Avonmouth with 30ms$^{-1}$ Southerly wind applied can be seen in Table 2, Figs. 7~8. The wind is constant from Day 3 12:00 to Day 4 12:00 in this example. The sum of water surface levels resulted from tidal and wind effects are indeed slightly different than that forced by the combined effect of tides and winds: for the results of A+B, the high tides are higher-and low tides are lower-than that of C when the winds are blowing in the model (Fig. 7). After the wind stops on Day 5 00:00 it takes around one day for the two curves to overlap again with each other.

Table 2 . Simulations with different input.

| | |
|---|---|
| A | Model results with tidal forcing running only |
| B | Model results with 30ms$^{-1}$ Southerly wind running only |
| C | Model results with tides and 30ms$^{-1}$ Southerly wind running |

When comparing the residuals with the surges, it is interesting to note that there are significant oscillations of the residuals with a period of around 10 hours, while surges are not oscillated during wind blowing (Fig. 8). Moreover, the maximum difference between the peak residuals and surges is nearly 1m with either Southerly or Westerly wind applied. When the Northerly wind is included, the maximum difference is more

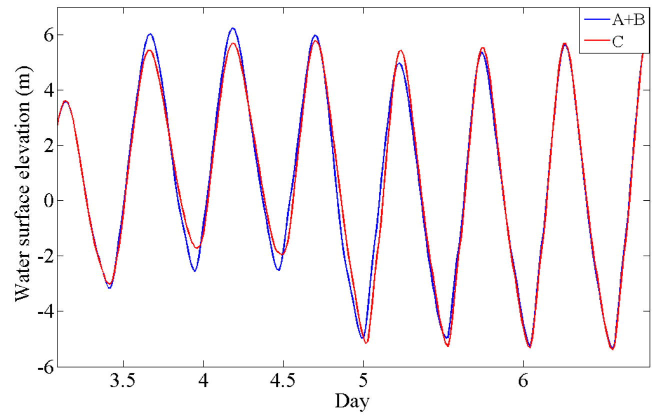


Fig. 7 Water surface elevations with different combinations of inputs at Avonmouth.

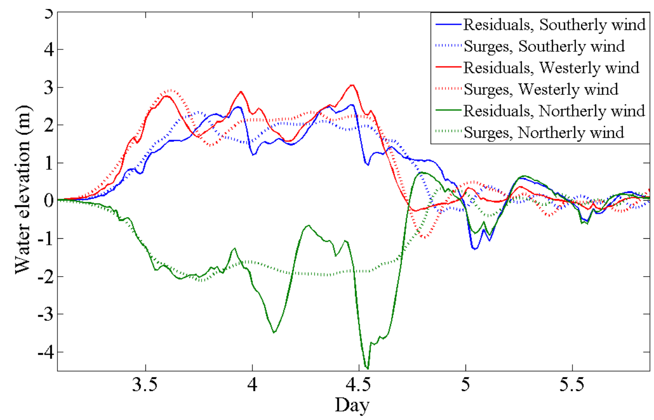


Fig. 8 Residuals (solid lines) and surges (dotted lines) with 30ms$^{-1}$ Southerly, Westerly and Northerly winds applied at Avonmouth.

than 2m. This implies that the response of the Bristol Channel to the large scale development of meteorological forcing is affected by local tidal response and the oscillations of residuals are likely resulted from local tide-surge interactions. The oscillation period might be related to the natural period of tidal resonance in the Bristol Channel which is around 8 to 10 hours (Gao et al., 2015).

## Spring-neap Cycles

The spring-neap cycle in semidiurnal tidal amplitudes is due to the various combinations of lunar and solar semidiurnal tides. When the Moon is full or new, the gravitational pull of the Moon and Sun are combined, thus larger than average tides can be seen-known as spring tides. During the Moon's quarter phases the Sun and Moon work at right angles, causing the bulges to cancel each other, therefore we get smaller tides known as neap tides. Two periods of spring and neap tides can be seen roughly every month, yet some spring tides are higher than others (Pugh, 1996). Here in this study, $M_2$ and $S_2$ were input as fundamental semidiurnal lunar and solar tides respectively.

The spring and neap cycle simulations were run on 13th January 1950 and 06th January 1950 respectively, separated by 7 days and thus at as similar time of year as possible. Simulations were set to increase the winds from 0 to 30ms$^{-1}$ Day 7 from 00:00 to 12:00, keep constant from Day 7 12:00 to Day 8 12:00, then decrease to 0 from Day 8

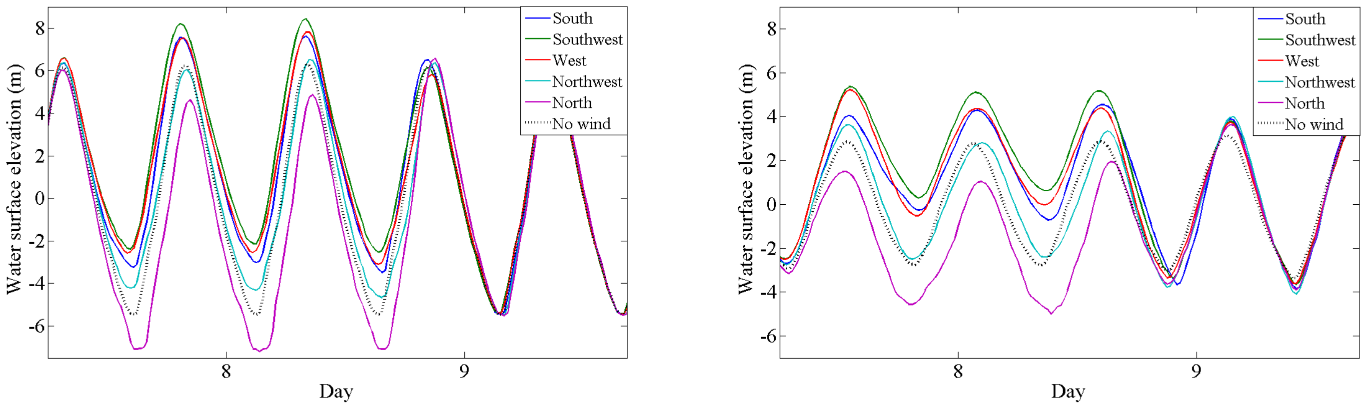


Fig. 9  Water surface elevations with influences of $30 ms^{-1}$ winds from various directions during spring (left) and neap (right) tides at Avonmouth.

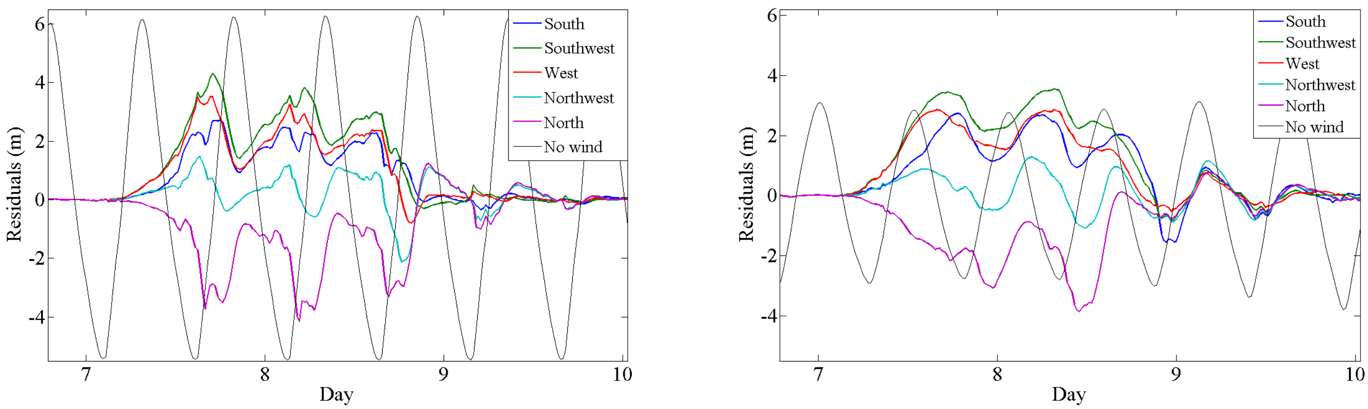


Fig. 10  Residuals with influences of $30 ms^{-1}$ winds from various directions during spring (left) and neap (right) tides at Avonmouth.

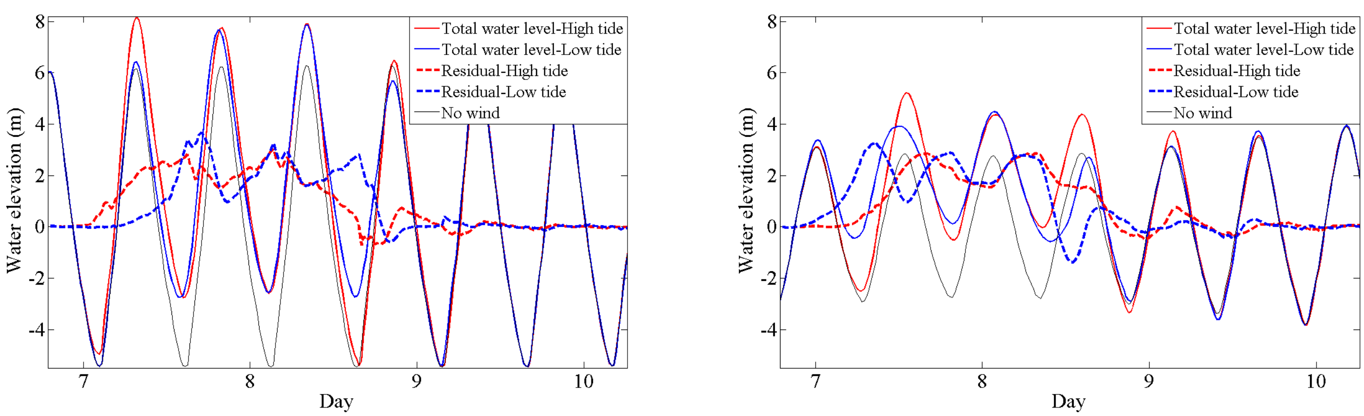


Fig. 11  Total water surface elevations (solid lines) and tidal residuals (dotted lines) during spring (left) and neap (right) tides with $30 ms^{-1}$ wind starting blowing at high (red lines) and low (blue lines) tides at Avonmouth.

12:00 to Day 9 00:00. The results depicted in Fig. 9 indicate that, the overall water levels in the spring simulations are higher than those in the neap simulations, which maintains the difference in water level that occurs between spring and neap tides without introducing any wind. However, it is seen in Fig. 10 that the magnitudes of residuals observed with each wind is very similar for both the neap and spring tides with regard to their respective directions, despite some minimal discrepancy. Interestingly, if we look at the results from Day 7 12:00 to Day 8 12:00 when the winds are constant, the occurrence of residual peaks always coincides with low tide during both spring and neap tide. Therefore, storm surge is likely to be more severe at low tide during spring tide.

Fig. 11 shows the residuals and total water elevations at Avonmouth with both tides and Westerly winds imposed. The red lines represent winds starting at low tide while the blue line represents winds starting at high tide with a 6-hour difference in starting time. The residuals with winds starting at low tide are slightly higher than that starting at high tide; however the overall water levels are higher if winds start at high tide. In the Bristol Channel, the Westerly wind blows in the same direction with flood tide but in the opposite direction with ebb tide, thus larger bed friction during flood tide than ebb tide and we might expect to get higher residuals at low than high water. Although the difference of water levels between the simulations with different starting time of wind is not obvious, the starting time of wind still matters the timing of storm surge.

In Fig. 10 it was found that the residual peaks are likely to coincide with low tide during both spring and neap tide. The results from Fig. 11 confirm this indication. It is seen from Fig. 11 that the largest wind-driven part of the water level (residuals) do not coincide with the maximum of the astronomically-driven part (tide) and are likely to occur near low tide, despite the difference in the starting time of wind. This is in accordance with the results of Horsburgh and Wilson (2007) and Sterl et al. (2009) who suggested the tide has a dampening effect on surge heights, and the largest tidal residual systematically occurs before the high tide.

## CONCLUSIONS

In this study, the characteristics of the storm surges in the Bristol Channel were first examined using in situ data from 1961 to 2015. Both 10- and 50-year return levels indicated that the Channel head (Avonmouth) is expected to experience the largest storm surges. After introducing different wind conditions to a two-dimensional shallow water model, the worst storm surge event again occurred at the Channel head. It was also found that the Channel surges vary by location, and have a complicated dependency on wind speed and direction, the spring-neap cycle and with respect to the state of the tide. Most observation sites in the upper reaches of the Channel experience larger storm surges with Southerly wind. However when going further inland, the worst storm surges would occur with South-Westerly and Westerly wind due to too shallow bathymetry. Results from simulations with tide and wind and with wind input only suggested that storm surge in the Bristol Channel is affected by local tidal response and there are strong tide-surge interactions. The storm surges are likely to have more impact during spring tide than neap tide, however the magnitudes of residuals are very similar for both neap and spring conditions. During a spring-neap cycle, the significant storm surge is likely to occur when high winds coincide with low tide during spring tide when waves are amplified by the extremely shallow water conditions.

## ACKNOWLEDGMENTS

We are grateful to Audrey Davies who carried out a preliminary study of this topic in her final year undergraduate project in the University of Oxford.

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