Enabling Resilient UK Energy Infrastructure:
Natural Hazard Characterisation Technical Volumes and Case Studies

Case Study 4:

Teesmouth

LC 0064_18CS4

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This document forms part of the Energy Technologies Institute (ETI) project 'Low Carbon Electricity Generation Technologies: Review of Natural Hazards', funded by the ETI and led in delivery by the EDF Energy R&D UK Centre. The aim of the project has been to develop a consistent methodology for the characterisation of natural hazards, and to produce a high-quality peer-reviewed set of documents suitable for use across the energy industry to better understand the impact that natural hazards may have on new and existing infrastructure. This work is seen as vital given the drive to build new energy infrastructure and extend the life of current assets against the backdrop of increased exposure to a variety of natural hazards and the potential impact that climate change may have on the magnitude and frequency of these hazards.

The first edition of *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies* has been funded by the ETI and authored by EDF Energy R&D UK Centre, with the Met Office and Mott MacDonald Limited. The ETI was active from 2007 to 2019, but to make the project outputs available to industry, organisations and individuals, the ETI has provided a licence to the Institution of Mechanical Engineers and Institution of Chemical Engineers to exploit the intellectual property. This enables these organisations to make these documents available and also update them as deemed appropriate.

The technical volumes outline the latest science in the field of natural hazard characterisation and are supported by case studies that illustrate how these approaches can be used to better understand the risks posed to UK infrastructure projects. The documents presented are split into a set of eleven technical volumes and five case studies.

Each technical volume aims to provide an overview of the latest science available to characterise the natural hazard under consideration within the specific volume. This includes a description of the phenomena related to a natural hazard, the data and methodologies that can be used to characterise the hazard, the regulatory context and emerging trends. These documents are aimed at the technical end-user with some prior knowledge of natural hazards and their potential impacts on infrastructure, who wishes to know more about the natural hazards and the methods that lie behind the values that are often quoted in guideline and standards documents. The volumes are not intended to be exhaustive and it is acknowledged that other approaches may be available to characterise a hazard. It has also not been the intention of the project to produce a set of standard engineering 'guidelines' (i.e. a step-by-step 'how to' guide for each hazard) since the specific hazards and levels of interest will vary widely depending on the infrastructure being built and where it is being built. For any energy-related projects affected by natural hazards, it is recommended that additional site- and infrastructure-specific analyses be undertaken by professionals. However, the approaches outlined aim to provide a summary of methods available for each hazard across the energy industry. General advice on regulation and emerging trends are provided for each hazard as context, but again it is advised that end-users investigate in further detail for the latest developments relating to the hazard, technology, project and site of interest.

The case studies aim to illustrate how the approaches outlined in the technical volumes could be applied at a site to characterise a specific set of natural hazards. These documents are aimed at the less technical end-user who wants an illustration of the factors that need to be accounted for when characterising natural hazards at a site where there is new or existing infrastructure. The case studies have been chosen to illustrate several different locations around the UK with different types of site (e.g. offshore, onshore coastal site, onshore river site, etc.). Each of the natural hazards developed in the volumes has been illustrated for at least one of the case study locations. For the sake of expediency, only a small subset of all hazards has been illustrated at each site. However, it is noted that each case study site would require additional analysis for other natural hazards. Each case study should be seen as illustrative of the methods outlined in the technical volumes and the values derived at any site should not be directly used to provide site-specific values for any type of safety analysis. It is a project recommendation that detailed site-specific analysis should be undertaken by professionals when analysing the safety and operational performance of new or existing infrastructure. The case studies seek only to provide engineers and end-users with a better understanding of this type of analysis.

Whilst the requirements of specific legislation for a sub-sector of energy industry (e.g. nuclear, offshore) will take precedence, as outlined above, a more rounded understanding of hazard characterisation can be achieved by looking at the information provided in the technical volumes and case studies together. For the less technical end-user this may involve starting with a case study and then moving to the technical volume for additional detail, whereas the more technical end-user may jump straight to the volume and then cross-reference with the case study for an illustration of how to apply these methodologies at a specific site. The documents have been designed to fit together in either way and the choice is up to the end-user.

The documents should be referenced in the following way (examples given for a technical volume and case study):

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies,* Volume 1 — Introduction to the Technical Volumes and Case Studies. IMechE, IChemE.

ETI. 2018. *Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies,* Case Study 1 — Trawsfynydd. IMechE, IChemE.

Contents

1. Introduction

This case study illustrates the appropriate use of the methodology from the technical volumes for Teesmouth, England. Teesmouth is located in north-east England. The site was chosen as representative of an estuarine environment.

Three hazard families are included in this assessment:

- Volume 6 — Coastal Flooding;
- Volume 8 — Hail;
- Volume 9 — Lightning.

The specific methodologies applied are described in the individual technical volumes associated with each of the three hazard families.

1.1 Geography and climate

The area under consideration is located at the mouth of the River Tees on the coast of north-east England (*Figure 1*). It includes a range of coastal habitats (sand and mud-flats, rocky shore, saltmarsh, freshwater marsh and sand dunes) on and around an estuary which has been considerably modified by human activities. The area is highly industrialised with port facilities, oil refineries and chemical works, although there are also several areas of residential development. The nearest large town is Middlesbrough, but numerous other towns are close by, such as Stockton-on-Tees, Billingham, Thornaby, Hartlepool and Redcar.

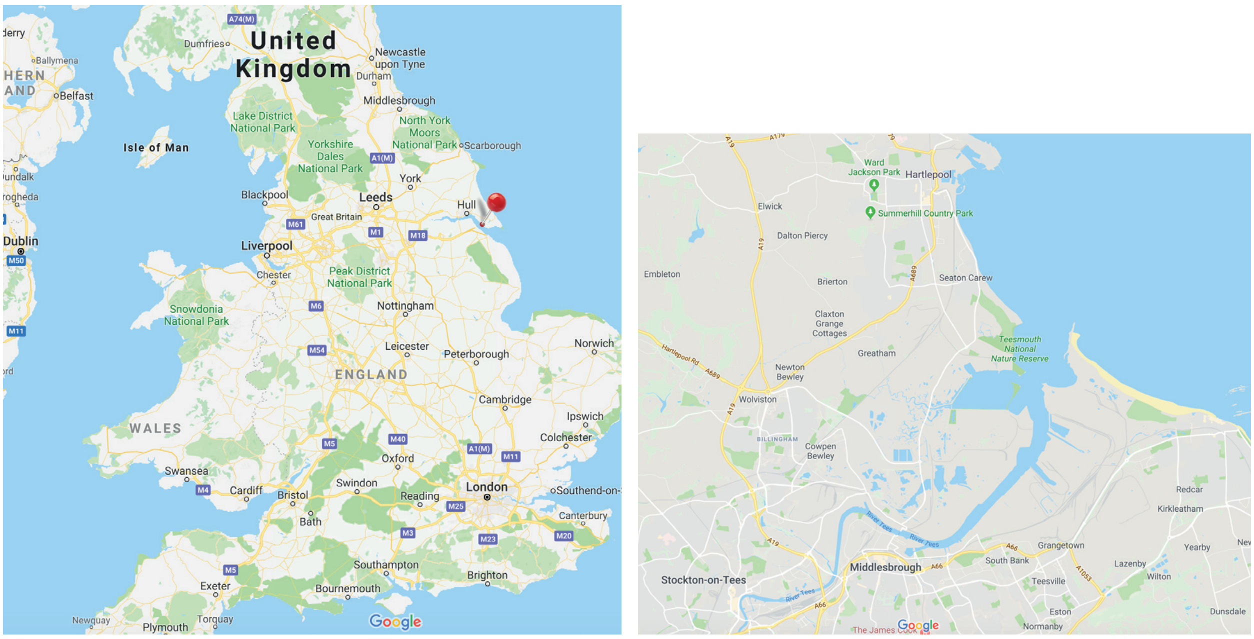

Figure 1. Map showing the location of Teesmouth (54.7°N, –1.1°W) with respect to the rest of the UK (left) and zoomed in to show the local area (right). (Source: ©2017 Google LLC, used with permission. Google and the Google logo are registered trademarks of Google LLC)

The area has a maritime climate typical for the United Kingdom (UK) (*Met Office, 2016*). Being sheltered by both the Lake District and Pennines to the west, it is in one of the relatively drier parts of the country, receiving on average 574 millimetres (mm) of rain a year. Temperatures range from mild summer highs in July and August, typically around 20 °C, to winter lows in December and January falling to around 0 °C. The number of days with snow lying is about ten per year. The depth of snow (without drifting) does not often exceed 15 centimetres (cm) with notable exceptions in the area that include the heavy snowfalls of 11th to 13th February 1978 (53 cm at Morpeth on the 13th), 17th to 18th March 1979, and 25th November to 2nd December 2010. Gales, where the wind reaches a mean speed of 34 knots or more over any ten consecutive minutes, occur on approximately five to ten days per year.

Teesmouth National Nature Reserve is located one mile east of the A178, north of Middlesbrough. The reserve covers 350 hectares in two sections separated by Hartlepool Power Station. North Gare lies to the north, and Seal Sands to the south. The reserve boundaries encompass two Sites of Special Scientific Interest, together with parts of a further four; these make up the Teesmouth and Cleveland Coast Special Protection Area and Ramsar site, which is of international importance for wildlife (*JNCC, 2001*).

1.2 Overview of natural historical hazard events

The events given in this section are not an exhaustive list, but provide examples of various types of natural hazards and their impacts. On 2nd July 1914, a severe convective storm struck the Teesmouth area which produced lightning and large hailstones. Strong winds caused two heavy cranes to be moved a considerable distance and derailed, and 100 yards of railings at the wharf were blown away. Several buildings in Middlesbrough were struck by lightning and damaged. The storm produced large hailstones which hit and killed many sea birds (*Nelson, 1914*). A hailstone measuring 3 inches in length by about $^7/_8$ of an inch in diameter (about 7.6 cm by 2.2 cm) was reported. This hailstorm also damaged greenhouses and smashed windows.

The sea wall around Seal Sands was breached during the 1970s and the site flooded. On 6th December 2013, flooding occurred on the south side of Greenabella Marsh (close to Seal Sands) following the embankment being breached during abnormally high tides. It is not known whether any assets were affected; the flooding may have only affected the marshes between the sea and the asset locations.

On 1st July 2015, a storm produced golf ball-sized hailstones which caused considerable damage to cars and property in County Durham and Northumberland which are close to Teesmouth (*Metcalfe, 2015*). On 21st June 2017, during a severe storm over Tyneside (also close to Teesmouth), lightning struck a house causing its roof to catch fire. The storm also caused localised flooding and 4000 homes were left without power.

There have been several noteworthy gales affecting north-east England, accompanied by property damage and disruption to travel and power supplies. Examples include 16th February 1962, when nearly two-thirds of all houses in Sheffield suffered some form of damage from winds accelerating as they crossed the Pennines. On 2nd January 1976, a depression moving eastwards across Scotland to the North Sea brought storm-force winds with an hourly mean speed of 70 knots at South Gare. More recently, the storm of 28th to 29th January 2002 led to rail and road transport disruption (with overturning of heavy goods vehicles), power cuts (20,000 homes affected in the Tyne valley) and building damage. A severe gale on 7th to 8th January 2005 caused similar transport disruption and left 20,000 homes without electricity in Yorkshire and Humberside for a day.

1.3 Industrial history

The area is an important centre for heavy industry, although the number of people employed in that sector has declined in recent years. Traditional industries — primarily shipbuilding, steelmaking and chemical manufacture — have reduced in importance but have been replaced to a large extent by high technology activities, science development and service sector roles. Teesside industry is now dominated by companies based on three large chemical sites around the mouth of the River Tees at Wilton, Billingham and Seal Sands. These companies make products such as petrochemicals, commodity chemicals, fertilizers and polymers.

The River Tees and adjacent ports of Hartlepool and West Hartlepool were among the most productive shipbuilding regions in the UK (*Simpson, 2017*). Shipyard closures in the 20th century took place during economic slumps and occurred in two phases, between 1909 and 1933, and again from the 1960s. The last major shipyard on the Tees closed in 1987. Some shipbuilding continues in the area on a notably smaller scale (*Tees Built Ships, 2018*).

Teesside's steel industry was born in the 1850s when iron ore was discovered in the Cleveland Hills near Eston (*BBC, 2010*). In the years that followed, Teesside underwent a massive expansion. In its heyday, the steelworks employed more than 40,000 people with Teesside steel being a driving force behind the Industrial Revolution; this led to the area gaining a worldwide reputation for high grade steel construction. Although the industry is now in serious decline more than a thousand people are still employed in the steel industry, largely by Tata Steel (*McNeal, 2015*).

The area is well known for its chemical industry which developed in the early 20th century. In 1917, Billingham was chosen as the site to produce synthetic ammonia to be used in the manufacture of explosives during World War I, with renewed demand during World War II (*BBC, 2014*). The plant also became heavily involved in the production of high performance aviation fuel for Royal Air Force aircraft. From 1934 Billingham became a centre for plastics production. The development of the major chemical complex at Wilton in the 1940s was a further boost to Teesside's chemical industry (*Hurworth, 1999*).

Several oil storage depots and distribution centres are located around Teesside in the Seal Sands area. Operators include Greenergy, Harvest Energy and Conoco Phillips.

The Central Area Transmission System (CATS) is a 404 kilometre (km) subsea pipeline which transports natural gas from the central North Sea to a reception and processing terminal located at Teesside. The gas is routed to either the Teesside Gas Processing Plant or CATS gas processing trains.

Teesport is a large sea port located approximately three miles inland from the North Sea and three miles east of Middlesbrough, on the River Tees (*World Port Service, 2018*). It is currently the third largest port in the UK, and amongst the ten biggest in Western Europe. The port covers an area of 200 hectares of land alongside the southern bank of the River Tees, presently handling over 6000 ships and 56 million tonnes of cargo per annum.

Electrical power generation continues to be an important industry in the area. Hartlepool Power Station, with a net electrical output of 1190 megawatts (MW), is a nuclear power plant situated on the northern bank of the mouth of the River Tees, 2.5 miles south of Hartlepool. Electricity is produced by two advanced gas-cooled reactors (AGRs). Originally planned in 1967, with construction starting in 1969, the station started generating electricity in 1983, and was completed in 1985. The plant is currently expected to continue operation until 2024. In October 2010, the UK Government announced that Hartlepool was one of the eight sites it considered suitable for future nuclear power stations.

Teesside Wind Farm (also known as Redcar Wind Farm) is located 1.5 km offshore, to the north of Redcar. It consists of 27 turbines with a 62 MW generation capacity and was officially opened in April 2014, although power had been supplied from 2013. There are no plans (at present) to increase the size of this wind farm.

Teesside Power Station is a former gas-fired power station in Redcar & Cleveland. Situated near the Wilton chemical complex, the station had combined cycle gas turbines (CCGTs) and open cycle gas turbines (OCGTs). However in 2011 the operation of the CCGT part of the station was suspended, and in 2013 the owners announced its closure. It has since been demolished.

1.4 Future development

Development of a new combined cycle electrical generation power plant, the Tees Combined Cycle Power Plant (CCPP), by Sembcorp Utilities, is currently under way on part of the site of the former Teesside Power Station (*TCCPP, 2018*). The project will comprise a natural gas-fired CCGT generating station with an output capacity of up to 1700 MW. The station will include up to two gas turbine units, up to two steam turbine units, ancillary plant and equipment, hybrid water coolers and, in accordance with policy requirements for new large electricity generating plants, an area of land set aside for possible future carbon capture equipment. The project site also includes land provision for connections to gas transmission infrastructure and connections to the national grid for electricity export.

The Dogger Bank Teesside A & B offshore wind farm is also currently under development by the Forewind consortium. Forewind intend to implement six related wind farm projects at Dogger Bank which will have a total target installed capacity of 7.2 gigawatts (GW). Dogger Bank Teesside A & B will comprise two wind farms, with up to 400 wind turbines and supporting tower structures, with a total combined generating capacity of up to 2.4 GW. Cabling from the wind farms will come ashore north of Marske-by-the-Sea and travel approximately 7 km inland to two new converter stations situated within the Wilton Complex.

The South Tees Development Corporation has recently been established to redevelop a 4500 acre stretch of land on the south bank of the River Tees following the closure of the Thai-owned Sahaviriya Steel Industries steelworks in Redcar in late 2015. The development corporation unveiled its regeneration master plan for the site on 18th October 2017. It aims to bring in new industry, create thousands of new jobs and upgrade transport routes in the area.

The three hazards being considered for the Teesmouth site are hail, lightning, and coastal flooding. Each is discussed in detail below.

2.1 Hail

2.1.1 Characterisation of hail

Hailstones are a solid form of precipitation formed within convective storms. They are produced by the freezing of *supercooled** water droplets onto ice particles by *riming*. Ice particles formed by riming are called hailstones if they have diameters larger than 5 mm. Hail accounts for only a small amount of the total precipitation from the cloud, and so is almost always accompanied by rain.

Hailstones tend to be developed in thunderstorms. The large vertical nature of the thunder clouds provides an environment where moisture within the cloud can circulate between warm and colder areas of the weather system. This process allows the formation of ice. As the ice moves through and up the cloud it forms differing layers and an increasing mass. The size of the hailstone depends upon the amount of time it stays in the cloud, temperatures in the cloud and the wind speeds within the cloud. A smaller storm, with relatively low wind speeds, has the potential to produce a greater number of small hailstones whereas a larger, high wind speed, storm will tend towards smaller numbers of large hailstones.

However, much larger hailstones (diameters greater than 50 mm) are occasionally produced by violent storms. These hailstones can cause considerable damage. The types of asset that may be damaged via a hail event include:

- crops;
- cars/vehicles;
- roofs;
- windows;
- exterior wall cladding;
- solar panels;
- heating, ventilation and air conditioning units.

In addition to potential impact damage caused by hailstones, hail may also lead to roof collapse, the blockage of drains or intakes, or injury to humans or animals.

*All technical terms marked in blue can be found in the Glossary section.

2.1.2 Historical review of hail events

Many historical events producing very large hailstones have been summarised by the Tornado and Storm Research Organisation (also known as TORRO). Additional events are described in other publications, such as the books by *Russel (1893)* and *Brazell (1968)*, and letters published in the scientific journals *Philosophical Transactions* and *Quarterly Journal of the Royal Meteorological Society*. A review of these historical records suggests that an extreme hailstone for the UK would have a diameter of the order of 110 mm. The largest recorded hailstone in the UK was ~113 mm diameter (believed circumference of 14 inches), which fell at Great Offley, Hitchen on 4th May 1697. The second largest hailstone ever recorded had a diameter of 109 mm which was at Templecombe, Langport on 15th July 1808.

Given the limited data available (only a total of eight hail storms with stones greater than or equal to 70 mm in diameter have been recorded) it is possible that other extremely large hailstone events have occurred, but that any records of these events have been lost or the hail fell in sparsely populated areas and was not recorded. Additional statistical assessment is therefore appropriate to assess the likelihood of extreme events and their associated frequency.

An extreme value analysis (EVA) was carried out with extreme value distributions fitted to observations of maximum hailstone sizes. The EVA model provides estimates of hailstone diameters at selected return periods for the UK; see Volume 1 – Introduction to the Technical Volumes and Case Studies for a primer on EVA methodology. For example, a hailstone with diameter d would have a return period of m years; an alternative way of expressing the same result is that the probability of a hailstone with diameter greater than d occurring in any given year is equal to $1/m$. The analysis was based on UK-wide data, and provides the estimated return period for a hailstone of a given size to fall somewhere in the UK. The study does not identify the specific location where the stone is expected to fall, but the extreme event would be more likely to occur in the central or south-east of England where large hailstone events are most frequent.

Records of hailstone sizes are required for the EVA calculation of extreme hailstone events. The primary source of data used to derive the EVA model was the Tornado and Storm Research Organisation hail database records (*TORRO, 2018*) between September 1961 and July 2010. Of 428 hail events in the the Tornado and Storm Research Organisation records from 1961 to 2000 that were consulted, 181 included actual hailstone diameters; only these were included in the analysis. Data from several other sources were used to supplement the information from the Tornado and Storm Research Organisation. The number of reports containing hailstone diameters (or observations from which a diameter could be calculated) from the various sources are summarised in *Table 1*. Overall, diameters of hailstones from 232 separate storms were available for analysis. In a few cases, the same storm is described by two or more different sources; in this situation each source is assessed and a judgement made of which one is more reliable.

Table 1. List of sources of historical data for hailstone size including the length of the data series and number of events within each source.

Source	Time period	Number of hail events
The Tornado and Storm Research Organisation hail database	1961 to 2010	181
Russell (1893)	1800 to 1893	22
Brazell (1968)	1840 to 1964	8
Philosophical Transactions (e.g. *Lhwyd (1697)*, *Tailor (1697)*, *Thoresby (1711)*)	1697 to 1711	5
Quarterly Journal of the Royal Meteorological Society (*Harding (1897)*, *Marriott (1888)*, *Marriott (1889)*)	1888, 1889, 1897	3
Webb and Elsom (1994)	9th August 1843	1
Clark (2004)	July 1808	1
Smith (2007)	24th June 1897	1
Webb et al. (2009)	1800 to 1897	7
Clark and Webb (2013)	28th June 2012	1
Photographs found on the internet	1st and 15th July 2015	2

The EVA model estimates that the largest hailstone which the UK could ever witness would have a diameter of 216 mm. The greatest hailstone diameter ever recorded anywhere in the world, however, was 200 mm in Vivian, South Dakota, on 23rd July 2010; this would suggest that a hailstone of 216 mm in the UK would be very unlikely. As the EVA model is only a statistical assessment, it does not consider the physics of hailstone formation which is important at the upper end of the distribution; this leads to the apparent disparity between the largest statistically possible hailstone and the largest hailstone ever recorded.

From the EVA, a hailstone with a diameter of 110 mm, comparable to the largest stone ever witnessed in the UK (it is noted that the value of 109 mm from the 1808 storm is thought to be more reliable than the value of ~113 mm from the 1697 event), would have a regional return period for the UK of approximately 500 years; that is, a hailstone of this size would be expected to occur, on average, once every 500 years somewhere in the UK. Alternatively, the probability of such a hailstone being produced in any given year (the annual exceedance probability), somewhere in the UK, is 1/500 = 0.002. Therefore, 110 mm is considered to represent the largest hailstone size that could reasonably be expected to occur somewhere in the UK over any reasonable operational lifetime for a facility (with the possible exception of very long-life facilities such as nuclear waste repositories). Note that this assessment considers the likelihood of the 110 mm hailstone falling anywhere in the UK, and that the likelihood of an extreme hailstone event occurring at a particular region or site (e.g. Teesmouth, the site for Case Study 4) is significantly lower.

The results of the EVA also identify 121 mm as the best estimate of the maximum hailstone diameter that could be expected on a 1000-year return frequency. The probability of a hailstone equal to or greater than 121 mm falling anywhere in the UK is therefore 0.001 in any given year.

The EVA is based on current climatic conditions. At present, it is not clear how climate change may affect hail event frequency or severity over the UK. *Sanderson et al. (2015)* suggested that the frequency of large hailstones would decrease under a warming climate. However, the paper only included one climate model and one hail model. The only other similar studies considered hailstones in south-east Australia, which may not be applicable given the differences in location, geography and climate of Australia in comparison to the UK.

From historical data, it is also possible to observe that the peak in hail activity in the UK occurs in the summer months and notably in June and July. *Figure 2* shows the seasonality from the Tornado and Storm Research Organisation data covering 1981 to 2010 where almost 25% of the events in this period occurred in the month of June. Additional studies produced by the Tornado and Storm Research Organisation using longer periods of the observation data also show this seasonality peak in June and July.

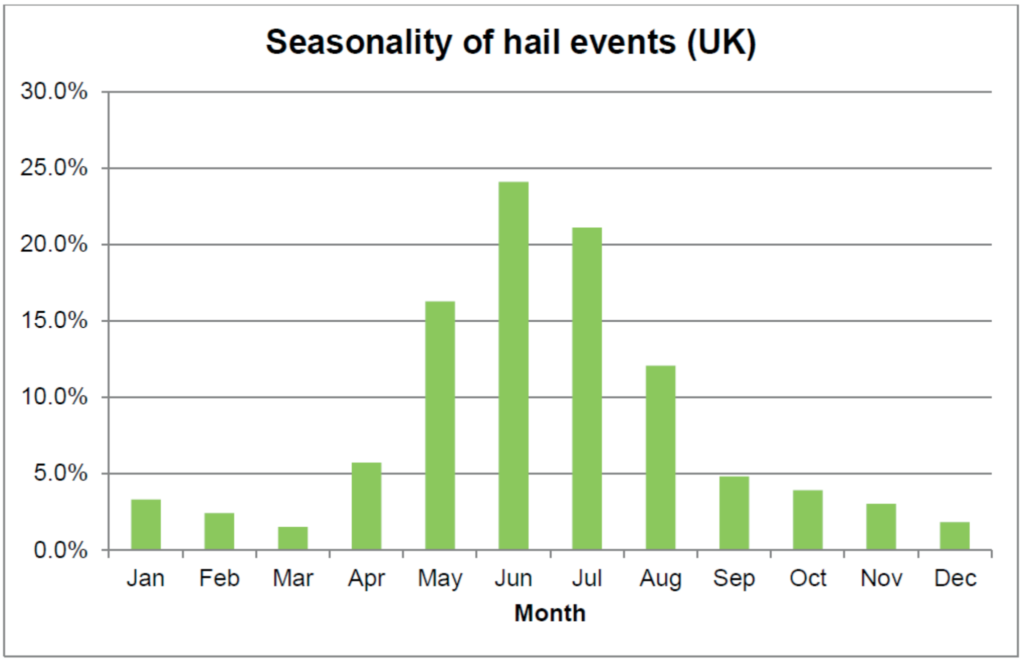

Figure 2. Seasonality of hail events in the UK, constructed using data from the Tornado and Storm Research Organisation database during 1981 to 2010. (Source: Tornado and Storm Research Organisation)

As well as hailstorm seasonality and intensity, the location of the hail event is also of significance and needs to be captured within any model representing hail activity. *Figure 3* shows the location of hailstorms in the UK as contained in the Tornado and Storm Research Organisation data covering 1981 to 2010 along with the locations of a limited number of UK hailstorms contained within the European Severe Weather Database (ESWD). The historical data show that hailstorms occur more in the south-east of the UK and decrease in frequency to the north, with the north of Scotland showing little in terms of historical activity over this period. Note, however, that the historical data may well contain significant bias due to population, as more reports will tend to be recorded in areas that have been consistently and densely populated.

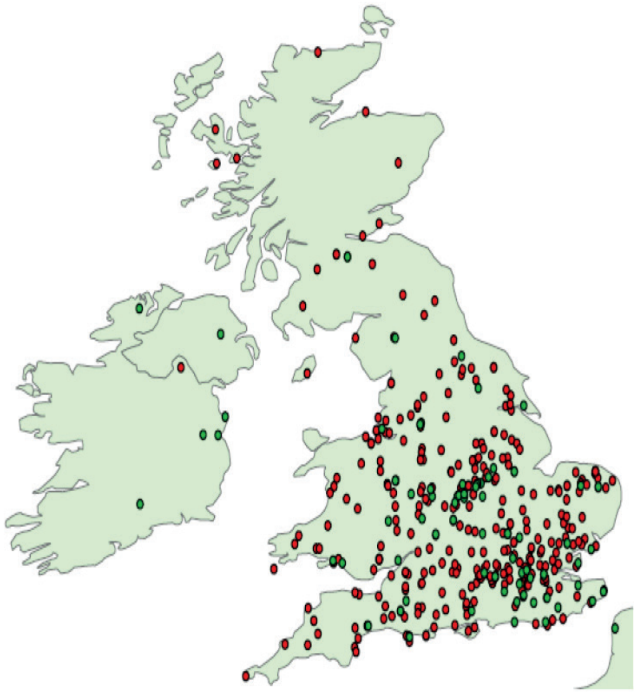

Figure 3. Locations of historical hail events 1981 to 2010 (the Tornado and Storm Research Organisation events in red, ESWD events in green).

2.1.3 Atmospheric modelling

To try to address the biases outlined in *Section 2.1.2*, the organisation AIR Worldwide developed a stochastic catalogue of simulated hail events over the UK. The stochastic catalogue contains 10,000 years of postulated hail data, where each year in the catalogue dataset represents a statistically generated representation of the potential hail activity for a year in the UK. The analysis is based on atmospheric modelling, not historical observation. Although no definitive methodology currently exists for estimating atmospheric activity on an event-by-event basis, the approach used in this study was derived from AIR Worldwide's research studying how to best represent detailed, event-level information about severe thunderstorm activity. This is achieved by using data on the past atmospheric state in a regression model that calculates the likelihood of hail occurring given the atmospheric conditions. The Weather Research and Forecasting (WRF) model, a numerical weather prediction model, was used to create a simulation of the atmosphere. The output from the WRF model contains the atmospheric properties necessary to determine the probability of hail by day over the UK at a resolution of 16 km.

There are two types of events represented within the catalogue — *microevents* and *macroevents*. Microevents are the individual hail *swaths* with properties including the location, swath size (i.e. footprint), maximum hailstone size and hail impact energy (HIE). Macroevents are groups of microevents initiated on the same day, or over multiple days, with the same weather system passing over the UK. The model predicted that a total of 181,159 microevents would occur throughout the UK over the 10,000-year simulation period, or roughly 18 per year. The model also predicted a total of 89,633 macro-events (hail-producing weather systems), or roughly 9 per year. *Figure 4* shows the spatial distribution of hail microevents in the part of the UK covering the Teesmouth area, based on the stochastic modelling.

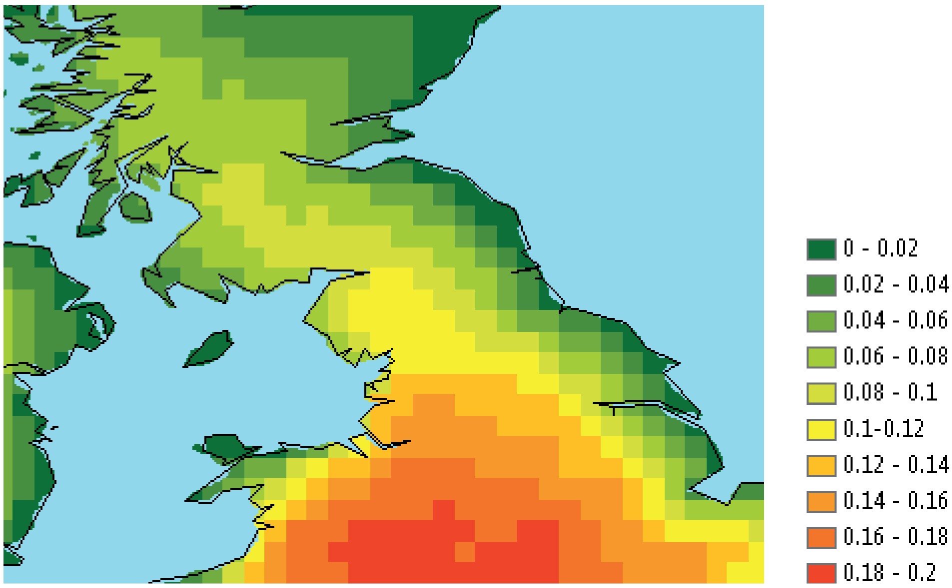

Figure 4. Hail occurrence rates from the stochastic catalogue over part of the UK in days per year (on a 0.2 x 0.2 degree grid).

Figure 4, combined with review of the historical record, shows that the Teesmouth area experiences a low frequency of hail events. The stochastic analysis shows that a hail occurrence is expected no more than 0.02 times per year, or roughly once per every 50 years. In the greater area near to Teesmouth the expected rate is no more than 0.04 per year, or once per every 25 years.

The frequency of hail storms and the severity must both be considered. It has been shown that the maximum hailstone size which could be produced in the UK is of the order of 110 mm, and that this would be expected with a return frequency of approximately 500 years. It has also been shown that the north-east of England has a low rate of hail storms, with a storm expected no more often than once every 25 years. This would make it very unlikely that the rare occurrence of a large hailstone in the UK would be located in the north-east.

The stochastic study also included an assessment of return values for specific large and energetic hail events based on location. The data were assessed to estimate the HIE and hailstone diameter, for the largest hailstone produced during a 100-year period, at each map grid point.

HIE is a proxy for the damage potential of hail and accounts for both vertically falling hail as well as hail being blown horizontally. Within the calculation of the HIE an integral is included in order to capture the potential damage due to the varying hailstone sizes that are observed in any hail event.

The data from the stochastic study for the grid locations near to Teesmouth are given in *Table 2*.

Table 2. Estimates of the 100-year return period, maximum hailstone diameter and HIE from the stochastic catalogue, for grid cells around Teesmouth (specified by their latitude and longitude).

Latitude	Longitude	HIE (J/m²)	Diameter (mm)
54.4	−1.4	735	45
54.4	−1.2	6419	41
54.4	−1	533	36
54.4	–0.8	460	34
54.6	−1.4	572	39
54.6	−1.2	479	35
54.6	−1	437	33
54.6	–0.8	391	31
54.8	−1.4	429	33
54.8	−1.2	391	32
55	−1.4	408	32

This result shows that the maximum diameter hailstone in the Teesmouth area during a nominal 100-year period is expected to be of the order of 44.5 mm; significantly less than the 110 mm maximum for the UK overall.

Note that atmospheric climate models do not simulate hailstones; instead a model of hailstones has to be driven using meteorological data produced by climate models. At present, it is not clear how global warming may affect hail event frequency or severity over the UK. A study by *Sanderson et al. (2015)* suggested that, under a warming climate, the frequency of large hailstones would decrease. However, this study only included one climate model and one hail model. The only other similar studies considered hailstones in south-east Australia, which may not be applicable given the differences in location, geography and climate of Australia and the UK.

2.2 Lightning

2.2.1 Characterisation of lightning

Lightning is a considerable electrical discharge from a cloud to the air, between two clouds, or from a cloud to the ground. Water droplets within a storm cloud are transported upwards to the top of the cloud very rapidly where they freeze into ice particles. Some of the ice particles grow in size to form hailstones, which fall out of the cloud when they become sufficiently heavy. Collisions between the ascending ice particles and descending hailstones result in charge separation; the ascending ice particles become positively charged and the descending hailstones become negatively charged. Hence a positive charge develops at the top of the cloud and a negative charge occurs at the base of the cloud. When the charge has built up sufficiently, electrons move rapidly from the cloud base to the ground or within a cloud, resulting in a lightning flash. A single lightning flash consists of multiple strokes.

Note: A lightning stroke is a single discharge in a lightning flash. It can be cloud-to-cloud, cloud-to-ground, or ground-to-cloud. A lightning strike is usually used to refer to a cloud-to-ground lightning flash.

2.2.2 Detection of lightning flashes

Lightning strokes are detected by the Met Office using the Arrival Time Difference network (ATDnet). Lightning strokes send out pulses of radio waves which can be used to detect them. The Met Office ATDnet system detects these pulses at much lower frequencies than normal radio waves, known as Very Low Frequency (VLF). VLF radio waves have frequencies of 3 to 30 kilohertz (kHz) and are reflected by the Earth's ionosphere. Consequently, VLF pulses can travel considerable distances (1000s of km) and so lightning strokes can be detected many hundreds of kilometres away from a sensor. This approach of detecting VLF pulses has the advantage that only a small number of sensors are needed to locate lightning strikes over the UK and surrounding areas. Over the UK, the position of a lightning stroke is accurate to about 2 km within ATDnet. Other networks in the UK use sensors which detect different frequencies of radio waves. They can only detect flashes which occur closer to the sensors, but allow flashes to be located with a higher degree of accuracy.

ATDnet consists of a small network of sensors (currently 11) which allows the exact location of a lightning stroke to be determined. A VLF pulse will be detected by multiple sensors at slightly different times, as the distance between the location of the stroke and each sensor varies. These readings can be used to determine the exact location of a lightning stroke via a technique called multi-lateration. The types of sensors used in ATDnet mean only the more powerful lightning discharges are detected. Most are cloud-to-ground strikes, together with more powerful cloud-to-cloud strokes.

The Met Office holds lightning location data from the 1990s but, owing to the low sensitivity of the early sensors and limits on computer processing speeds, many strokes were not recorded. ATDnet was introduced in December 2007, with higher sensitivity detectors and improved processing speeds. The assessment in this document is therefore based on data from ATDnet recorded over a relatively short period (2008 to 2016).

A map showing the total number of flashes recorded by ATDnet over the UK between 2008 and 2017 is shown in *Figure 5*. It can be seen that the largest numbers of flashes are seen over south and eastern England, with smaller numbers seen over Wales, Scotland and Ireland. The broad area seen over central England with flash counts between 0.48 and 0.75 per km^2 per year corresponds to the tracks of very active convective storms which produced high lightning flash rates during June 2012. A small area with high numbers of flashes can be seen just to the north of the Teesmouth area.

The locations of the highest numbers of flashes in each year between 2008 and 2014 have been identified. These locations occur over most of the UK and differ considerably between years. For example, the highest flash rates in 2015 were recorded during July when severe thunderstorms developed over northern England and travelled northwards over Scotland. Using ATDnet data recorded between 2008 and December 2017, the highest flash density over England was 33 flashes per km^2 per day on 28th June 2012. In 2014, the highest numbers of lightning strikes were confined to south and south-east England. In contrast, the locations of the storms with the highest flash rates in 2010 were scattered over the British Isles.

The most recent severe lightning event in the UK occurred in south-east England on 27th May 2018 (*BBC, 2018*). Very large numbers of flashes were reported. Houses were struck causing damage and fires.

Overall, these results suggest that the very high lightning flash rates (33 flashes per km^2 as described above) are possible over Teesmouth. During July 2015, some of the very high flash rates were recorded close to Teesmouth but were located further inland. It may be assumed that this rate could occur over Teesmouth if a suitably energetic storm passed overhead.

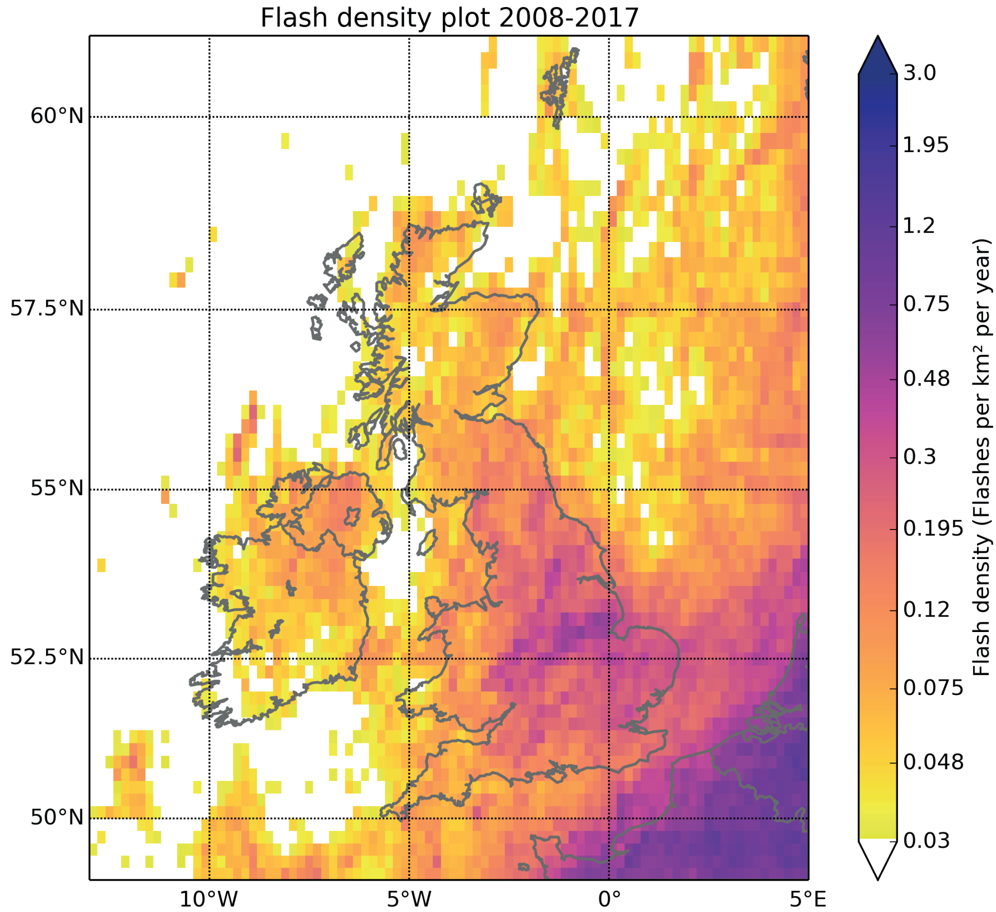

Figure 5. Mean lightning flash density over the UK derived from the Met Office ATDnet lightning location system. The data were recorded between January 2008 and December 2017. The units are flashes per km^2 per year.

2.2.3 Probability of lightning strikes at Teesmouth

The probability of a lightning strike on an asset at Teesmouth is calculated using equations described by *Hasbrouck (2004)*. The calculation requires the following information: the length, width and height of the asset, and the annual average lightning flash rate for the asset's location. A sample calculation is shown below for an oil storage depot located to the north-west of Seal Sands within Teesmouth at 54.636°N, 1.212°W (OS National Grid NZ509270). This depot consists of ten oil storage tanks, nine of which are arranged in a 3 × 3 grid. The dimensions of the area enclosed by the nine tanks is about 500 m by 500 m. The height of these tanks is unknown, so the largest tank height reported by *Penman and Watson, (1967)*, 54 ft (16.5 m) has been used.

The probability of a lightning strike is calculated using the equations (1) to (6) below from *Hasbrouck, (2004)*.

(1) Ds = lightning *striking distance* = 10 x $Ipk^{0.65}$

(2) r = radius of *attractive area* = $\sqrt{(2 \times Ds \times h - h^2)}$

(3) AA = attractive area/decile = $(l + 2r) \times (w + 2r) - 10 \times [(4 - \pi)/4] \times r^2$

(4) PO = *strike probability*/decile = $AA \times (0.1 \times Fg) \times 10^{-6}$

(5) Cumulative probability (PC) = sum of PO over all deciles

(6) Return period = $1/PC$

The probability of a strike is calculated separately for ten deciles of lightning peak currents, which are then summed to give an estimate of the overall probability. In these equations, l, w, h are the length, width and height of the asset (in m) respectively. Fg is the ground flash density. From *Figure 5*, the lightning flash density over Teesmouth is in the range 0.12 to 0.2 flashes km^{-2} yr^{-1}, with a slightly higher range (0.2 to 0.3 flashes km^{-2} yr^{-1}) located to the south. The calculations below use the higher value of 0.3 flashes km^{-2} $year^{-1}$.

The peak current per decile, Ipk, is required in equation (1). Peak currents per decile for lightning strikes in the UK are not known. Lightning peak currents are not estimated from the ATDnet system. They have been estimated by operators of other UK lightning networks which use different types of sensors (for example, *Lees (1997)*), but these data are not readily available. For the purposes of the example probability calculation, the peak currents estimated for the USA listed by *Hasbrouck (1996)* are assumed to be applicable to lightning strikes in the UK. The variables in equations (1) to (5) are calculated for each decile and are summarised in *Table 3* with their respective units. The peak currents per decile used by *Hasbrouck (1996)* are also listed.

Table 3. Example calculation of probability of a lightning strike on an asset at Teesmouth, using the method described by Hasbrouck, (1996).

Decile	Peak current, *Ipk* (kA)	Lightning *striking distance*, *Ds* (m)	Radius of attractive area, *r* (m)	Attractive area per decile, *AA* (m^2)	Strike probability per decile, *PO*‡
1	6	32.05	28.02	307,503.38	0.009
2	13	52.97	38.42	329,571.00	0.010
3	18	65.45	43.45	340,394.78	0.010
4	23	76.76	47.55	349,286.32	0.010
5	28	87.23	51.05	356,934.89	0.011
6	35	100.84	55.28	366,219.14	0.011
7	45	118.74	60.38	377,525.50	0.011
8	57	138.46	65.55	389,067.35	0.012
9	77	168.35	72.69	405,168.93	0.012
10	112	214.78	82.56	427,747.27	0.013
				Sum	0.109

‡These probabilities have been rounded to three decimal places. Their total may not equal the sum shown in the final row.

The overall probability of a lightning strike is the sum of the strike probabilities per decile, which in the example in *Table 3* is 0.109. The reciprocal of this number is the average strike frequency, 9.1 years. Hence, the oil depot at Teesmouth, on average, would be expected to be struck by lightning once every 9 years. If the lower ground flash density of 0.2 flashes per km^2 per year is used, the return period of a strike is 14 years.

The estimates of the strike frequency using the two methods do not agree well. The method described in the British Standard produces an estimated strike frequency of 1 in 28 years, whereas the method described by *Hasbrouck (1996)* produces frequencies of 1 in 9 and 1 in 14 years. These two methods are very different in their approach, so some disagreement is likely, especially since there is likely to be uncertainty when using both methods. One possibility is that the lightning currents listed in *Table 3* are higher than would be measured over the UK. If these currents were smaller, the estimated strike frequency would be reduced.

2.3 Coastal flooding

2.3.1 Characterisation of coastal flooding

Coastal flooding occurs when the land along the coast is inundated by seawater above normal tidal conditions. The extent of coastal flooding is influenced by the coastal floodplain topography exposed to flooding. The slope of the land adjacent to the coast plays an important part. Seawater will more easily propagate on a flat coast than on a steep one where land rapidly rises away from the sea.

Coastal flooding is normally caused by a combination of **high tides**, **storm surges**, and **waves**.

High tides generally occur once every 12 hours and 25 minutes although regional variations are possible. There are two special tides known as spring tides and neap tides.

> **Spring tides** occur when the Sun, the Earth and the Moon are aligned. They happen just after a new or full Moon, when there is the greatest difference between high and low water. Spring tides have nothing to do with the season of spring. They occur once every two weeks, i.e. half of a lunar month (the time it takes the Moon to orbit the Earth once) which is 28 days. Spring tides are much higher than normal tides and can contribute greatly to coastal flooding.
>
> **Neap tides** happen seven days after a spring tide. They refer to a period of moderate tides when the Sun, Earth and Moon are at right angles to each other. A neap tide occurs when the difference between high and low tide is least. Neap tides occur twice a month, in the first and third quarters of the Moon. Neap tides are lower than normal tides and thus are of less concern in relation to coastal flooding.

Storm surges are rapid and transient rises in sea level caused by a combination of very strong winds and atmospheric pressure. The strong winds are normally those found in hurricanes and cyclones. The strong winds push the water on an ocean's surface on top of more water, increasing the sea level. The conditions needed to create these strong winds are generally associated with low air pressures, which also contribute to an increase in sea level. During a cyclone, the pressure is higher at the edge than it is at the centre. This pushes down the water in the outer parts of the storm, causing the water to bulge at the centre, where the winds have helped add to the rise in the sea level. Storm surges are most dangerous during high tides as at these times the sea level will already be elevated. The water level can reach several metres in height if the storm surge happens at the same time as high tide.

Waves result from the wind blowing over the surface of the sea. The wave height is affected by the wind speed, wind duration, fetch length (distance of wind travel over open water), depth of water, roughness of the sea bed, direction and speed of the tide. In stormy conditions the strong winds generate large and powerful waves on top of the surge which can cause damage to coastal defences, cause breaches of the coastal defences, and/or overtop the coastal defences, resulting in flooding of the land behind the coastal defences. When the waves enter shallow water their speed decreases, wavelength decreases, and height increases. If the tide direction is against the wind, this will also increase wave height and decrease wavelength.

Shallow estuaries and harbours can experience large waves in a strong onshore wind, particularly if these coincide with a spring ebb tide. The 1953 coastal flood along the east coast of the UK was exacerbated by the narrowing of the North Sea towards the English Channel; the excess water from the storm is forced into the narrow channel raising its level.

Coastal flooding can also be caused by tsunamis. Tsunamis are waves resulting from any sort of major displacement of water in the ocean such as earthquakes, submarine landslides, volcanic eruptions, or meteorite impacts. Tsunamis are very dangerous as they travel quickly and are difficult to detect. However, tsunamis affecting the British Isles are extremely uncommon, and there have only been two confirmed cases in recorded history: a wave that resulted from the Storegga submarine landslide (approximately 7300 to 7200 years ago), and another as a consequence of the Lisbon earthquake of 1755. Meteotsunamis (tsunami-like waves of meteorological origin) are somewhat more common (*Haslett et al., 2009*), especially on the southern coasts of England around the English and Bristol Channels. Examples include (*Haslett and Bryant, 2009*):

18th August 1892 — Devon and Cornwall. Thunderstorms reported. *The Times* reported this event in the River Yealm as well as stating that 'there was a rapid rise in the River Fowey as a great tidal wave, but this immediately subsided'.

20th July 1929 — a large tsunami-like wave struck the Kent and Sussex coasts, busy with tourists, and drowned two people, one at Folkestone and one at Hastings. At Brighton and Worthing, sudden downpours of rain and high winds accompanied the wave, but at Folkestone and Hastings, the weather was clear. The unexpected wave was estimated to be approximately 3.5 m high at Folkestone, and approximately 6 m high at Hastings. The wave was believed to have been caused by a squall-line travelling up the English Channel, coincident with thunderstorms.

On 28th and 29th June 2011 it was reported in the press that on 27th June a tsunami struck South West England between Penzance and Portsmouth; approximately 200 miles of coastline were affected.

In England, the east coast is at a particularly high risk of flooding because the sea is rising and the land is sinking (the east coast of Scotland is still rising because of glacial isostatic adjustment). The geology of the east coast of England is also less resistant to erosion than other parts of the UK. This results in more coastal flooding and erosion along the east coast of England. This is particularly important as there are a large number of people living along the east coast and there are also a large number of power plants situated along the coast, with four of them being nuclear power plants (there are also two nuclear plants which have shut down).

Another potential hazard associated with the extreme events discussed in this section is low sea level. Although this would not generally lead to any significant detrimental effects to infrastructure, it is possible that extreme low water level associated with a severe neap tide could lead to a loss of cooling water supply or process water supply (e.g. for a desalination facility). Water intakes could also be blocked as a result of sedimentation.

2.3.2 Prediction of tide

The UK Tide Gauge Network (UKTGN) comprises approximately 45 gauges whose locations are shown in *Figure 6*. Data are collected, processed, and stored centrally to provide long time series of tide heights and sea level data. Data can be downloaded from the online delivery web page (*BODC, 2018*).

Admiralty EasyTide, from the United Kingdom Hydrographic Office (UKHO), is a web-based tidal prediction service. The service provides tidal data for over 7000 ports worldwide together with a host of other useful information. EasyTide enables the user to select the date for the prediction; the user can choose any date between 100 AD and up to 50 years in the future and it is possible to access tide predictions for 7 or 14 days at a time.

The National Tidal and Sea Level Facility (NTSLF) of the National Oceanography Centre (NOC) carries out sea level monitoring. It provides the highest and lowest tidal predictions (denoted XT) between 2008 and 2026 for locations in the UKTGN. The Met Office provides UK tide times for around 500 locations. The tidal data used by the Met Office are supplied by the NOC.

Figure 6. Tide gauge locations for the UK tide gauge network. (Source: Mott Macdonald)

2.3.3 Forecasting of storm surge

As mentioned above, surges are water movements caused by meteorological effects such as winds and atmospheric pressure changes — as such they are not easy to predict, requiring powerful computers and sophisticated software to predict just two days in advance.

The NTSLF at the NOC develops and maintains tide-surge models used for forecasting storm surges on the coasts of England and Wales for the Environment Agency (EA). Tide-surge models are run in real-time as part of the forecast suite of models at the Met Office. Results are used by the United Kingdom Coastal Monitoring and Forecasting (UKCMF) Service, and transmitted to EA and used, together with data from the UKTGN, for coastal flood warnings in England and Wales.

The present system comprises a 12 km shelf model (CS3X). The modelled surge is combined with tides predicted at tide gauge sites to give the best estimate of the total water level.

These models are run on supercomputers at the Met Office. They are a critical part of today's coastal flood warning system in the UK. The system also makes use of a technique called ensemble forecasting to quantify the inherent uncertainty in short-term weather prediction. Multiple simulations are carried out, adjusting model conditions and parameters, to provide a range of outcomes that can then be used to judge the reliability of the forecast.

The NTSLF at the NOC operates the network of 44 stations on behalf of EA, the Scottish Environment Protection Agency (SEPA) and others; logging and telemetry systems transfer data to the Met Office and then to EA in near real-time. The data are also quality controlled and archived by the British Oceanographic Data Centre (BODC) at the NOC.

The latest surge forecasts for the next 48 hours from the NOC's storm surge model run at the Met Office, can be viewed online (*NOC, 2018*). *Figure 7* shows the schematic diagram of the current surge forecast and flood warning system in the UK.

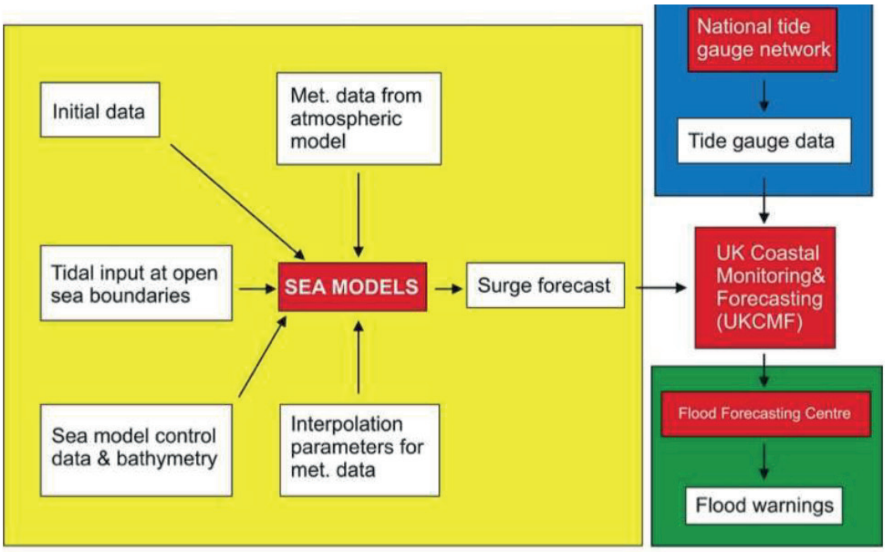

Figure 7. Storm surge model structure at NOC: the current surge forecast and flood warning system. (Source: National Oceanography Centre)

Forecasts and archived forecasts of storm surges are given for 35 coastal sites around the UK coastline at NTSLF's website (*NOC, 2018*).

Moving into the future, although CS3X is an effective model, it has limited development opportunities. The NOC and the Met Office are collaborating on developing a Nucleus for European Modelling of the Ocean (NEMO) based surge model.

2.3.4 Monitoring and forecasting of waves

WaveNet, the strategic wave monitoring network for the UK provided by the Centre for Environment, Fisheries and Aquaculture Science (Cefas), provides a single source of real-time wave data from a network of wave buoys located in areas at risk from flooding. In operation since 2002, WaveNet collects and processes data from the Cefas-operated Datawell Directional Waverider buoys. The WaveNet system also gathers wave data from a variety of third-party platforms and programmes (industry and public sector-funded), all of which are freely available for visualisation on the WaveNet website (*Cefas, 2018*). The WaveNet interactive map shown in *Figure 8* gives a clear picture of the wave conditions along the coastline at a glance. Red arrows indicate wave direction and the associated values indicate significant wave height, blue arrows indicate wind direction and the associated values indicate significant wave height.

Cefas sends the wave data to the Met Office (to help improve the wave and tidal surge model) and the National Flood Forecasting Service for access by the UK Coastal Flood Forecasting Service (UKCFF). Regional flood forecasters, local authorities and other stakeholders use the near real-time data from the buoys and the model predictions to provide better advice, guidance and warnings to emergency responders and communities about imminent coastal flood risk.

The Met Office plays an important part in developing and maintaining global, regional and coastal wave forecast models to forecast the sea-state. Model configurations are based upon the National Centers for Environmental Prediction (NCEP) community model WAVEWATCH III. WAVEWATCH III is the third-generation wind and wave model produced by NCEP. The model uses more sophisticated mathematical equations and physics than its predecessors and is run four times a day. WAVEWATCH III is evolving from a wave model into a wave modelling framework, which allows for easy development of additional physical and numerical approaches to wave modelling.

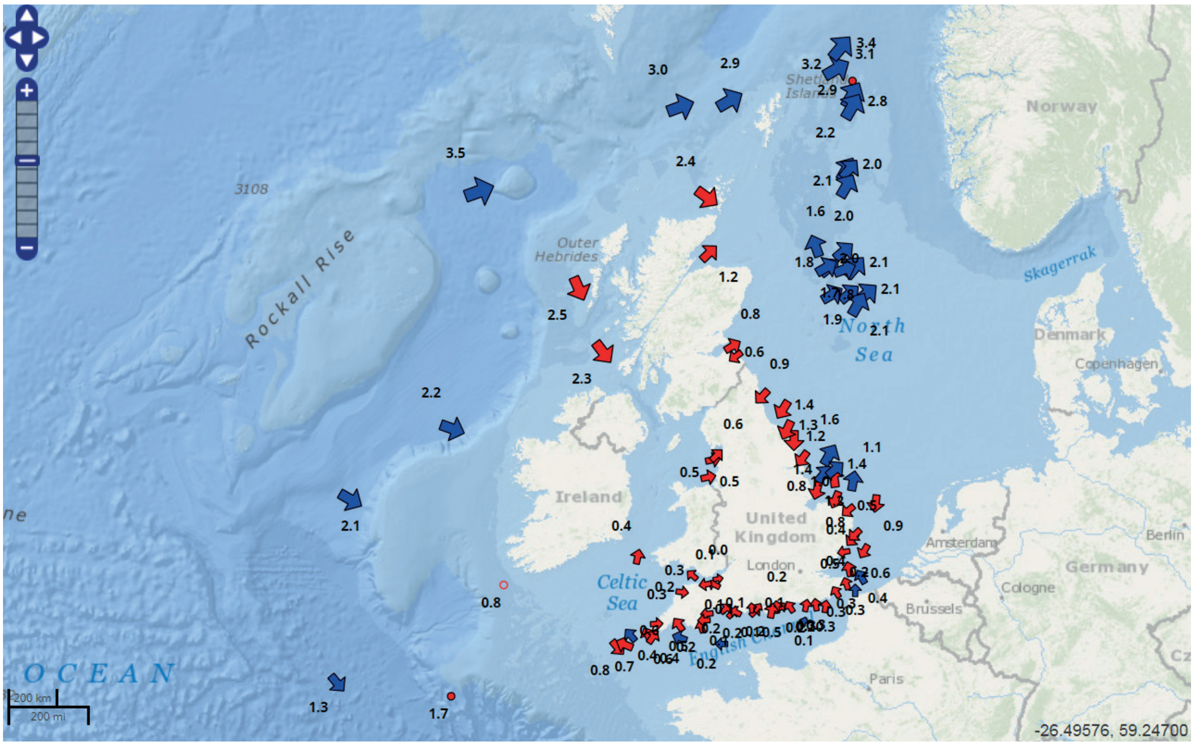

Figure 8. WaveNet interactive map. Red arrows indicate wave direction and the associated value indicates significant wave height, blue arrows indicate wind direction and the associated value indicates significant wave height. (Source: Cefas)

2.3.5 Historical review of storm surge in the UK and at Teesmouth

A team of scientists from the University of Southampton, the NOC, and the BODC have created a 100-year database of coastal flooding in the UK, called SurgeWatch. They have compiled data on the 96 largest events over this period, including information on the storm that generated each event, the high-water levels recorded during the events and the severity of coastal flooding. They have also developed a website (*University of Southampton, 2018*) which makes the information freely and easily accessible.

The worst natural disaster to affect the UK in modern times was the North Sea storm surge of 31st January to 1st February 1953. Coastal defences were breached by huge waves and coastal towns in Lincolnshire, Norfolk, Suffolk, Essex and Kent were devastated. In the Netherlands, 1800 lives were lost while in England and Scotland 326 people were killed. The economic losses were estimated at £50 million at 1953 prices (£1.2 billion at 2018 prices).

The 5th to 6th December 2013 tidal surge event was the highest on record since 1953 and caused widespread coastal flooding. According to the analysis carried out by the SurgeWatch team, 2013/14 was a particularly unusual season for coastal flooding. Seven of the 96 events contained in the 100-year database occurred during this period; no other season has had so many large coastal floods in the last century. Two of the events in 2013/14 (5th to 6th December 2013 and 3rd January 2014) rank in the top ten for sea-level height. Both also rank highly in terms of spatial footprints – that is, they struck very long stretches of the UK coast.

The Teesmouth area was badly affected during the 1953 flood, and also received a severe flood warning for the 5th to 6th December 2013 surge events.

2.3.6 Extreme sea levels along the UK coast and at Teesmouth

To manage effectively coastal flooding and coastal erosion risk, the best available information on coastal flood boundaries, such as sea levels and waves, is required. Practical guidance for design with consideration of sea levels was published in 2011 by the Environment Agency (*EA, 2011*). It provides Coastal Flood Boundary Conditions (CFB) for the UK mainland and islands. The key outputs from that project included:

- A consistent set of extreme peak sea levels of annual exceedance probability (AEP) ranging from 100 to 0.01% (return period of one year to 10,000 years).
- Peak sea level values along the coastline at a spacing of about two kilometres. This enables rapid selection of appropriate levels without any need for further interpolation.
- Advice on generating an appropriate total storm tide curve for use with extreme sea levels. Standard surge tide shapes are given for each part of the coast.

The surge tide shape needs to be combined with an astronomical tide to give the total storm tide curve. The results are supplied in Geographic Information System (GIS) format (shapefiles). These files can be obtained from EA on request.

The extreme sea levels abstracted from the CFB data close to Teesmouth are given in *Table 4*. The associated location is indicated in *Figure 9*.

Table 4. Extreme sea level estimates at Teesmouth (mAOD) using CFB data. The lower and upper bounds provide a 95% confidence interval around the best estimate (medium bound). (Source: CFB data, Environment Agency, base year 2008)

AEP (1%)	Return period (year)	Extreme sea level Mean Above Ordnance Datum (mAOD)		
		Lower bound	Medium bound	Upper bound
100	1	3.27	3.37	3.47
50	2	3.35	3.45	3.55
20	5	3.46	3.56	3.66
10	10	3.55	3.65	3.75
5	20	3.65	3.75	3.85
4	25	3.58	3.78	3.98
2	50	3.68	3.88	4.08
1.333	75	3.73	3.93	4.13
1	100	3.67	3.97	4.27
0.667	150	3.75	4.05	4.35
0.5	200	3.79	4.09	4.39
0.4	250	3.82	4.12	4.42
0.333	300	3.85	4.15	4.45
0.2	500	3.84	4.24	4.64
0.1	1000	3.96	4.36	4.76
0.01	10,000	3.88	4.78	5.68

Note that sea level rise estimates are not considered in the Coastal Flood Boundary results mentioned above. The rise in sea level for future scenarios assessed by EA applies to all levels in the resultant tide curve, not just the peak levels.

EA periodically reviews and updates its results and guidance; it is important to check and apply the latest guidance for assessing coastal flood risk. Guidance on extreme sea levels can be found in *EA (2011)*.

2.3.7 Extreme waves along the UK coast and at Teesmouth

EA is currently conducting a study on the State of the Nation Flood Risk Analysis along the coastline of England. The outputs from this study will include wave heights and wave periods for the English coastline. The report on the coastal element of State of the Nation will be freely available to all on request from EA. The wave heights for a wide range of tidal events at different AEPs are also available on request. The State of the Nation Report has not been completed at the time of writing this case study; it is expected that it will be published on EA's website when it is finalised.

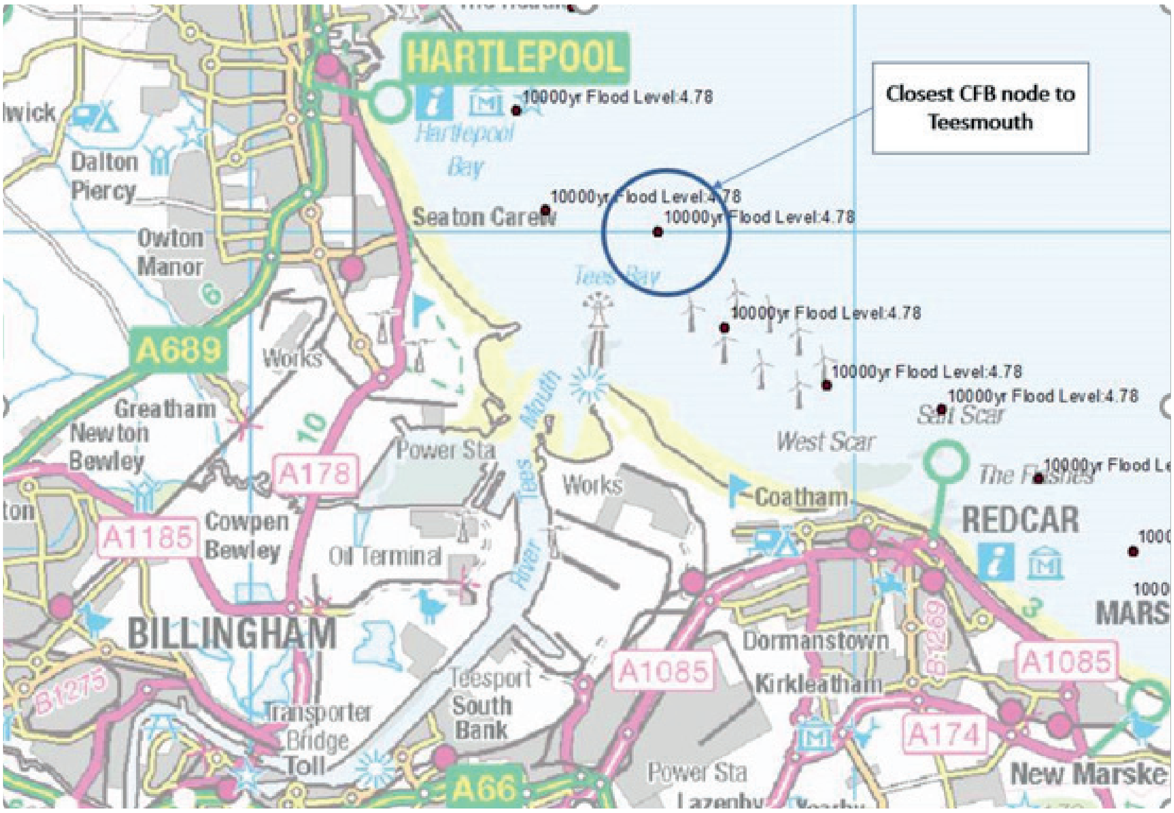

Figure 9. CFB data locations close to Teesmouth. (Source: CFB data, Environment Agency; copyright: Ordnance Survey)

2.3.8 Probability of coastal flooding

Despite significant investment in coastal defences in the UK, coastal flooding remains a serious threat to life and national critical infrastructure as well as to economic and environmental assets, due to climate change, sea level rise, potentially increasing storminess, and coastal erosion.

Multivariate Extreme Values Approach to System Flood Risk Analysis (*Heffernan and Tawn, 2004*) has been commonly used for joint probability analysis of waves and water levels. The JOIN_SEA programme produced by HR Wallingford has been used widely in the UK.

2.3.9 Climate change risk consideration

Making an allowance for climate change in flood risk assessment will help to reduce vulnerability and provide resilience to flooding and coastal change in the future. The guidance on Flood Risk Assessment, and consideration of the latest climate change projections, can be found through the Government website (*EA, 2017*).

To assess how coastal flood risk may change in the future, it is necessary to consider climate change allowances for:

- peak river flow by river basin district;
- peak rainfall intensity;
- sea level rise;
- offshore wind speed and extreme wave height.

These allowances are based on climate change projections and different scenarios of carbon dioxide (CO_2) emissions to the atmosphere. There are different allowances for different epochs or periods of time over the next century. EA will use these allowances as benchmarks when providing advice on flood risk assessments and strategic flood risk assessments.

When assessing coastal flood risk, in addition to considering the fluvial (river) flow increase and rainfall intensity increase due to climate change, it is especially important to consider the sea level rise, increase in offshore wind speed and extreme wave heights. A brief summary of different allowances is provided below.

Sea level allowance — *Table 5* provides the sea level allowance values set by EA for the UK coast. For the Teesmouth area, the climate change allowance values for the north-east area should be applied to assess future coastal flood risk and build asset resilience.

Table 5. Sea level allowance for each epoch in millimetres (mm) per year with cumulative sea level rise for each epoch in brackets (uses 1990 baseline). (Source: Environment Agency)

Area of England	1990 to 2025 (mm)	2026 to 2055 (mm)	2056 to 2085 (mm)	2086 to 2115 (mm)	Cumulative rise 1990 to 2115 (m)
East, East Midlands, London, South East	4 (140)	8.5 (255)	12 (360)	15 (450)	1.21
South West	3.5 (122.5)	8 (240)	11.5 (345)	14.5 (435)	1.14
North West, North East	2.5 (87.5)	7 (210)	10 (300)	13 (390)	0.99

The example provided here demonstrates how the cumulative sea level rise is calculated.

Example:

If a new piece of infrastructure is to be built at Teesmouth in 2018 with a design life of 50 years, the climate change allowance to account for the cumulative rise in sea level over the next 50 years (i.e. from 2018 to 2068) is calculated as follows based on the values given in Table 5:

Step 1: from 2018 to 2025, the cumulative sea level rise = 4 mm/year x 7 years = 28 mm

Step 2: from 2025 to 2055, the cumulative sea level rise = 8.5 mm/year x 30 years = 255 mm

Step 3: from 2055 to 2068, the cumulative sea level rise = 12 mm/year x 13 years = 156 mm

Step 4: from 2018 to 2068, the cumulative sea level rise = 28 mm + 255 mm + 156 mm = 439 mm

The allowances given in *Table 5* also account for slow land movement. This is due to 'glacial isostatic adjustment' resulting from the release of pressure after ice that covered large parts of northern Britain melted at the end of the last ice age. The northern part of the country is slowly rising and the southern part is slowly sinking. This is why net sea level rise is smaller for the north-west and north-east than the rest of the country.

Wind and wave height allowance — *Table 6* provides offshore wind speed and extreme wave height allowance set by EA for the UK coast. They apply to the Teesmouth area.

Table 6. Offshore wind speed and extreme wave height allowance (uses 1990 baseline). (Source: Environment Agency)

Applies around all the England coast	1990 to 2055	2056 to 2115
Offshore wind speed allowance	+5%	+10%
Offshore wind speed sensitivity test	+10%	+10%
Extreme wave height allowance	+5%	+10%
Extreme wave height sensitivity test	+10%	+10%

Note that there is a project to derive a new set of climate projections for the UK (the UK Climate Projections 2018 project, or UKCP18 for short). These projections are due to be released in late 2018 and may lead to updated figures from those presented in this case study.

This document provides an example of how the technical volumes for characterisation of the natural hazards hail, lightning and coastal flooding (Volumes 8, 9 and 6) could be applied to the Teesmouth site. It also provides an example of how the guidance could be used to characterise the natural hazard risk at estuarine sites elsewhere in the UK.

The hail assessment is based on a review of historical hail events, including severe hail events which produced hailstones greater than 70 mm in diameter. Historical hail event data are also used to develop an EVA model which estimates the return frequency for extreme hail events; e.g. the maximum hailstone event expected to occur in the UK with a return period of 500 years and the extreme event with a return period of 1000 years. In addition to the historical data, a stochastic analysis based on atmospheric modelling was carried out. The model was queried to generate a catalogue of 10,000 years of synthetic hail event data, and the 100-year return value extreme hail event was predicted for each location in the UK.

The hail assessment shows that the maximum expected hailstone diameter for the UK overall is of the order of 110 mm, and this is expected to be produced roughly once in every 500 years. The maximum diameter hailstone expected in the general Teesmouth area during a nominal 100-year period is expected to be of the order of 44.5 mm. Also, the Teesmouth area experiences a relatively low frequency of hail events. The stochastic analysis shows that a hail occurrence is expected no more than 0.02 times per year, or roughly once every 50 years. In the greater area near to Teesmouth the expected rate is no more than 0.04 per annum, or once every 25 years. This low frequency of hail storms in the Teesmouth area is consistent with historical records.

At present, it is not known how global warming may affect hail event frequency or severity. A single study of the impacts of a warming climate on hailstones over the UK suggested that the frequency of large hailstones would decrease under a warming climate. However, the paper only included one climate model and one hail model.

Lightning strokes are detected by the Met Office using the ATDnet network, and over the UK the position of a lightning stroke is accurate to about 2 km. The ATDnet in current use was introduced in December 2007; therefore the assessment carried out in this document is based on data from ATDnet recorded over a relatively short period (2008 to 2016). Longer datasets from other lightning detection networks exist but access to this data was not possible.

The locations of the highest numbers of flashes in each year between 2008 and 2014 have been identified. These locations occur over most of the UK and differ considerably between years. These results suggest that very high lightning flash rates are possible over Teesmouth. Using ATDnet data recorded between 2008 and July 2015, the highest flash density was 33 flashes per km^2 per day over England. It may be assumed that this high rate could occur over Teesmouth if a suitably energetic storm passed overhead.

The probability of a lightning strike on an asset at Teesmouth is calculated using equations described by *Hasbrouck (2004)*. A sample calculation was derived for an oil storage depot located to the north-west of Seal Sands within Teesmouth. Based on this calculation the oil depot at Teesmouth, on average, would be expected to be struck by lightning once every 9 years. If the lower ground flash density of 0.2 flashes km^{-2} per annum is used, the return period of a strike is 14 years. However, this probability should be treated with caution as lightning peak currents per decile are derived from data recorded in the USA where thunderstorms can be much more intense than those observed in the UK. If similar peak current data for the UK could be obtained, these calculations should be repeated and the probability of a strike recalculated.

There are a large number of studies which have coupled a simple model of lightning activity to a climate model and projected how lightning activity could change during the 21st century. However, only a small number of these studies specifically include the UK. The UK studies all suggest that lightning flash rates will increase under a warming climate owing to higher convective activity. Research conducted for this project also examined areas of the UK affected by lightning, but found no evidence for an increase or decrease over most of the UK during the 21st century. For Scotland, there was some evidence for a small increase in the area affected. As with the observations, the lightning activity varied considerably between individual years in the model simulations.

The east coast of England, including Teesmouth, experienced severe flooding in 1953. The highest tidal level over the last 60 years was recorded during the 5th to 6th December 2013 tidal surge event. In fact, 2013/14 was a particularly unusual season for coastal flooding. Seven of the 96 events contained in the 100-year database occurred during this period; no other season has had so many large coastal floods in the last century. Two of the events in 2013/14 (5th to 6th December 2013 and 3rd January 2014) rank in the top ten for sea-level height. This shows that multiple rare storm surge events can happen within a relatively short period of time.

3. Conclusions

Storm surge-induced coastal flooding poses a real risk to properties, land and infrastructure along the coast. The sea level in the UK is projected to increase by approximately 1 m or more along the coast over the next century. Despite the huge investment in building coastal defences in the past, the future coastal flood risk in the UK is projected to increase due to climate change, as sea levels are expected to rise and there is a potential for both the frequency and severity of storms to increase.

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Attractive area

If an area beneath a storm cloud were perfectly flat, lightning would strike any part with equal probability. A conductive object has an attractive area larger than the ground area it occupies, which is a function of its height and ground surface area. The total attractive area looks like the difference between the whole area occupied by the asset extended on each side by the attractive radius, and the areas between the individual assets.

Macroevent

Groups of microevents initiated on the same day, or over multiple days, produced within the same weather system.

Microevent

The individual hail swaths with properties including the location, swath size (i.e. footprint), maximum hailstone size and hail impact energy.

Riming

When ice crystals collide with supercooled droplets, freezing on contact and sticking together.

Strike probability

The probability of a strike for a given lightning current decile based on the attractive radii and striking distances. The probability is larger for deciles with higher peak currents. The overall strike probability is found by summing probabilities for the ten current deciles.

Striking distance

The stepped leader's final jump to the conductive object, and varies with the amount of charge and return-stroke peak current. Hence, a greater striking distance is associated with a larger amplitude return stroke.

Supercooled

To cool a liquid below its freezing point without solidification or crystallization.

Swath

The footprint of a hailstorm.

Abbreviations

AEP	Annual exceedance probability
AGR	Advanced gas-cooled reactor
ATDnet	Arrival time difference network
BODC	British Oceanographic Data Centre
CATS	Central Area Transmission System
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CCGT	Combined cycle gas turbine
CCPP	Combined cycle power plant
CFB	Coastal Flood Boundary Conditions
CO_2	Carbon dioxide
EA	Environment Agency
ESWD	European Severe Weather Database
EVA	Extreme value analysis
HIE	Hail impact energy
NCEP	National Centers for Environmental Prediction
NEMO	Nucleus for European Modelling of the Ocean
NOC	National Oceanography Centre
NTSLF	National Tidal and Sea Level Facility
OCGT	Open cycle gas turbine
SEPA	Scottish Environment Protection Agency
TORRO	Tornado and Storm Research Organisation
UKCFF	United Kingdom Coastal Flood Forecasting Service
UKCMF	United Kingdom Coastal Monitoring and Forecasting
UKCP18	United Kingdom Climate Projections 2018
UKHO	United Kingdom Hydrographic Office
UKTGN	United Kingdom Tide Gauge Network
VLF	Very low frequency
WRF	Weather Research and Forecasting

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