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A Historical Record of Coastal Floods in Britain: Frequencies and Associated Storm Tracks

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Abstract. This paper examines flood frequencies in three coastal sectors of Britain and analyses the associated storm tracks and their principal pathways. The results indicate that the east coast of Britain has suffered most floods over the last 200 years. The frequencies of flood incidents in the south and southwest coast of Britain have increased, particularly during the 20th century, whereas on the west coast flood frequencies have declined. Three distinctive pathways of storm track are identified, related to flood incidents in each coastal sector. A southern pathway in a corridor along the 55°N parallel is associated with flood incidents recorded on the south and southwest coast, whilst storms that are associated with floods on the west coast concentrate along the 60°N parallel. The relationship between the frequencies of floods and climatic variations needs to be explored further. However, the development of coastal settlements has certainly increased vulnerability, and hence the risk of flood disasters.

Key words: Storm, coastal flood, frequency, storm track, historical records

1. Introduction

Over the last few hundred years, human settlements have flourished in the coastal lowlands of the British Isles. Many of these lowlands and their settlements have been subject to sea floods and have relied on the protection of artificial sea defences. However, storm surges have often exceeded the level of protection, resulting in considerable losses of property. Among many flood incidents, the 1953 storm surge and flood in eastern England resulted in the inundation of 24,000 houses and 200 major industrial premises (Spalding, 1954). On a smaller scale in Towyn in 1990, some 2800 houses were flooded, and repairs to the whole housing stock damaged were estimated to cost between £22.4 million and £100.8 million (Tooley, 1992) (approximately $35.8 million to $161.3 million). Knowledge of the magnitude and frequency of coastal floods is of great value to central and local authorities for land-use planning, environmental agencies for coastal management and insurers for evaluating their underwriting strategies.

Coastal floods are a consequence of a set of factors including storm-induced surge, high tide (particularly on macro-tidal coasts with tidal ranges of over 4m) and high waves (Townsend, 1981), as well as the condition, nature, strength and height of the coastal and estuarine defences. In many coastal locations, storm-induced surges may be magnified due to the configuration and bathymetry of the shallow seas around the British Isles, as well as the location and geometry of estuaries. The combination of these factors thus creates a real possibility of continuing and increased coastal flood hazard. However, due to climate change such as atmospheric temperature variations (e.g. Parker *et al*., 2000) and oscillations of atmospheric pressure (e.g. North Atlantic Oscillation (NAO) index , Hurrell, 1995), the possibility of flooding has not been constant. The numbers of storm generated over the North Atlantic are closely related to temperature variations (Lamb, 1991), whilst, the NAO index reflects the strength of surface westerlies over Europe especially in the winter (Wilby *et al*., 1997), and thus is related to the pathways of storms or low-pressure cells. Furthermore, a strong high-pressure system over Scandinavia can block low-pressure cells from moving eastwards, and divert them towards the Norwegian Sea or south-eastwards into the Bay of Biscay and English Channel (Knox and Hay, 1985) where the storm surges may be amplified.

The objectives of this paper are first to establish the frequencies of flooding in three coastal sectors, and secondly to test whether the floods there are associated with different storm track pathways. The three coastal sectors (figure 1) are: (1) the East Coast from Aberdeen in Scotland to Ramsgate in Kent, (2) the South and Southwest coast from Dover in Kent to Milford Haven in South Wales, and (3) the West Coast from southwest Wales to Glasgow in Scotland. These divisions are based on coastal orientation and a preliminary investigation (e.g. Zong and Tooley, 1995), which suggested that recent flood events on the three coastal sectors are associated with storm tracks that travelled along spatially different pathways. The history of coastal floods for other parts of Scotland can be studied by Hickey (1998).

2. The Study Area

The British coast is characterised morphologically by a variety of different landscapes. There are estuaries and headlands of solid rock or unconsolidated sediments of glacio-genic origin. Low-lying areas are common adjacent to estuaries, with ground altitudes close to local high-tide level. In England and Wales, alone, there are 750,000 ha of ground below +5 m Ordnance Datum (OD). Mean High Water is in some places recorded at altitudes higher than +5 m OD and the Highest Astronomical Tide significantly exceeds this value proportionally.

In the three coastal sectors, the 18th century saw little progress in urban and industrial developments on the coastal lowlands, except for seaports and a few seaside resorts. During the early 19th century, a large number of coastal towns emerged owing to the advent of the railways and road networks and people's desire to visit seaside resorts at weekends. These coastal towns expanded constantly in the late 19th century and the 20th century. While enjoying the coastal amenities, residents had to adapt to flood hazards. Settlements have followed such a development disaster cycle that most of these towns were originally built on relatively higher lands (2m to 3m above the local high spring tides level). As a consequence of the rapid increase in population since the early 20th century, many towns expanded onto lower lands where protection from regular floods by the sea was provided by the construction and strengthening of sea defences. For example, settlements were firstly developed at Benfleet and Southend-on-Sea, Essex and subsequently from the 1920s extended onto Canvey Island where ground altitude ranges from 0.5m to 1.9m below local mean high water of spring tides (MHWST) (Zong, 1993). In other areas, coastal lowlands were reclaimed and drained for agricultural production. Consequently, the ground level became lower due to peat wastage, de-watering and sediment consolidation.

As perceived by the general public and even policy makers before the 1980s, the greater the development on these coastal lowlands, the greater benefits that can be seen from flood protection. An increase in the level of protection afforded from raised sea embankments has resulted in a rising residential population and urban expansion on the protected lowlands. However, on many occasions, extreme floods have exceeded the capabilities of the protection system and caused great losses in property (Zong *et al*., 1995). A typical example is Morecambe in Lancashire which was only a village with 2500 residents before the 1850s. It expanded and by the early 1920s it had a population of over 23,000. The rising population was accommodated by housing development extending from higher ground (1.5m to 3.5m above local MHWST) to the surrounding areas of lower altitudes (0m to 1.5m above local MHWST) (Zong, 1993). After the severe flood in 1907, the first hard sea defence was constructed, and further strengthened in the late 1920s and early 1950s. Such a level of protection helped encourage more people to settle, and the population rose to over 40,000 in the 1980s. Despite the improvement of sea defences, the town was flooded in 1977, 1983 and 1990. Similar cases can be seen in Towyn, Wales (Jones, 1992; Tooley 1992) and Canvey Island, Essex (Cracknell, 1959). Since the 1980s, the awareness of environmental issues has increased, and stringent planning policies have been in place.

3. Data Sources

In this study, archival flood records were collected and examined for the reconstruction of the flood history for the study area. By examining synoptic weather charts, the associated storms were identified, and their tracks were recorded for the analysis of storm pathways.

3.1. Archival flood records

Accounts of historical sea floods were primarily collected from microfilms of *The Times*. An initial search was made in the two series of indexes to *The Times*, i.e. *Palmer's Index* (from 1785 until 1917) and *The Official Index* (from 1917 to present). Cross checking with the microfilms of *The Times* was undertaken to obtain details of a specific incident. Based upon the floods indexed for supplementary information, speculative searches were also conducted at local Public Record Offices where local newspapers, Quarter Sessions petitions, published and manuscript diaries, school logbooks, family and estate letters and papers, and parish registers were examined. Some church accounts, estate letters and diaries proved useful for their detailed descriptions of flood events, particularly prior to *Palmer's Index*.

For the period before the publication of synoptic charts, *Palmer's Index* and *The Official Index* are the best source from which to compile at least a preliminary list of storm dates on which to base further searches. However in its early days, *The Times* did not always receive regular news from the northern counties and did not record some smaller storms, even though they were locally significant. The record, therefore, only reflects storms that resulted in major floods and were reported nationally.

3.2. Synoptic and tidal conditions

Daily, weekly and monthly weather reports published by the Meteorological Office for the period since 1911 were examined. The synoptic condition of storms revealed in the historical flood records and the tracks of the associated low-pressure cells were analysed. The storm tracks were copied onto a grid map covering an area of 20^{o}W to 20^{o}E and 65^{o}N to 45^{o}N (Figure 2). The frequency of these low-pressure cells passing through each grid (2.5^o Latitude by 5^o Longitude) was then counted. Information on wind speeds that are associated with the low-pressure cells was obtained from the ports of Heysham (near Morecambe), Lowestoft and Milford Haven, while hourly records of wave-smoothed water level recorded at these seaports were provided by the British Oceanographic Data Centre, Proudman Oceanographic Laboratory. Both wind speed and water level data cover various lengths of time, mostly the last 30 years.

4. Three Recent Floods

In order to understand storm conditions in relation to the floods in the three coastal sectors, major flood events (e.g. Lamb, 1991; Zong and Tooley, 1995) were analysed. The spatial relationship between the flooded locations and the associated storm tracks suggests that different pathways of storms (or low-pressure cells) were related to floods at different coastal sectors. From the weather reports, 117 storm tracks are retrieved. Out of the 117 storms, three typical flood events are selected to demonstrate this relationship. These events prove the legitimacy of dividing the British coast into three sectors for the subsequent analyses. The tracks of the associated low-pressure cells are shown in Figure 2.

The 1953 flood in the East Coast: On the 30th January 1953, a low-pressure cell moved eastwards over the north Atlantic. During the daytime, the central pressure of the cell decreased from 988 mB to 968 mB. It turned south-eastwards into the North Sea on the following day. The tidal surge generated by this low-pressure cell was amplified to 2.3m as it was pushed southwards, and met the high tide peak near the southern end of the North Sea. The strong pressure gradient on the west part of the system helped generate strong winds (sustained surface winds up to 29 m/s) along the east shore of England. Severe waves were deflected towards the coast of East Anglia. This storm caused widespread floods on the East Coast between the River Tees estuary and Dover (Steers, 1971).

The 1977 flood in the West Coast: During the 9th to 12th November 1977, a well-established low-pressure cell moved north-eastwards clipping the north coast of Scotland. Over this period, the barometric pressure of the low-pressure cell decreased from 972 mB to 960 mB at its centre. Associated with the low-pressure cell, strong westerly winds (sustained surface winds up to 25 m/s) were recorded along the English coast of the Irish Sea. These onshore winds generated waves which pounded on the sea defences of Morecambe and many other coastal towns. The low-pressure cell also induced a major tidal surge into the Irish Sea. As recorded at Heysham, the surge was 1.8 m high and occurred one to two hours earlier than the peak of a high spring tide (Zong and Tooley, 1995). The combined effects of high tide, storm surge and waves caused the sea defence in Morecambe to fail and flooding occurred in the early hours of the 12th November with floodwater of c. 0.5m deep in a number of places.

The 1981 flood in the South and Southwest Coast: After a cold spell in the middle of December, a couple of low-pressure cells developed over the North Atlantic. One of the low-pressure cells was generated on the 28th December with a central pressure of 960 mB. This cell moved eastwards and entered the English Channel during the 30th when a tidal surge of 0.9m was generated at Milford Haven, Wales. The water level was raised to 3.5m above m.s.l., when the surge met with the high tide. During the 30th when the low-pressure cell travelled through the English Channel, the narrow isobars on the eastern part of the system generated strong onshore winds (sustained surface winds up to 22 m/s). As a result, high waves lashed the seafront of the south coast and caused flooding in a number of locations (see Table 2).

These three coastal floods seem to confirm that the key conditions for major coastal flooding include (1) a significantly high tidal surge occurring around a high spring tide at a given coastal locality (Townsend, 1981) and (2) strong onshore (or along-shore) winds that generate high waves (Golding, 1981). Thus, it can be hypothesised that such conditions occurring in each coastal sector are associated with a specific spatial pathway of low-pressure cells (Figure 2).

There is a lack of information on waves. Judging by the limited wind fetch within the Irish Sea, English Channel and the North Sea, waves may not be very high, but sufficiently strong to damage sea defences particularly when sea walls are in poor condition. Based on observations over 18 months from October 1974 to March 1976 in the Irish Sea (Hydraulics Research Station, 1976), significant wave heights offshore for different return periods were calculated (Table 1). A few years later, the inshore significant wave heights for the 1977 event were established based on observed meteorological conditions (Allott & Lomax Consulting Engineers, 1979).

5. Frequencies

The frequencies of coastal flooding for each decade since the 1780s show contrasting pictures between the three coastal sectors (Figure 3). The decade data were smoothed with a 5-term binomial filter, in which the smoothed value for each decade was a weighted average of a window of 5 decades with weights in the ratio 1:4:6:4:1. A 3-term binomial filter and copying of end values were used towards the ends of the series.

In total, the East Coast has experienced much higher flood frequencies than other sectors. Overlying the inter-decadal variability, the flood history of the East Coast can be divided into four phases. Firstly, the 1780s to 1840s saw a steady increase in flood frequency (Figure 3), followed by the second phase, the 1850s to 1900s, when flood frequencies fluctuated. These two phases coincided with the generally cool conditions during the late 18th and early 19th centuries (e.g. Jones and Bradley, 1992). There is a mark increase in flood frequency from the 1910s to 1930s. Such an increase seems to correspond to a rise in atmospheric temperature of the Northern Hemisphere (e.g. Fu *et al*., 1999; Parker *et al*., 2000) and strong positive NAO indexes (e.g. Hurrell, 1995), i.e. a warmer climate and stronger westerly airflow over the Northern Atlantic and Europe. The final phase, i.e. since the 1940s, saw relatively low numbers of floods except the 1950s and 1980s. This generally declining trend in flood frequency is associated with a small decrease in temperature and a negative NAO indexes between the 1940s and 1970s. However, it is noted that the slightly high flood frequency in the 1980s seem to coincide with the rise in temperature and the positive NAO indexes. But the low number of floods in the 1990s does not fit with the climate trend.

Relatively lower numbers of floods were recorded for the South and Southwest Coasts for the 19th century. From the 1890s to 1940s, flood frequencies increased steadily, apparently coincided with the rise of temperature and positive NAO indexes. The declining flood frequencies during the 1950s and 1960s are associated with the small decrease of temperature and evidently negative NAO indexes. However, the relatively high number of floods in the 1970s does not correlate well with the relatively low temperature (e.g. Parker et al., 2000). Further decline in flood frequency since the 1970s contradict with the fact that temperature rose and the NAO indexes appeared strongly positive during this period.

On the West Coast, the number of flood incidents was relatively consistent for the period between 1780s and 1860s, after which flood frequency rose to its highest in the 1890s. Such a trend seems to contradict the changes in temperature and there is no correlation with the NAO indexes. Since the 1890s, there has been a general decline in flood frequency, with the one exception of higher number recorded for the 1920s and associated with a rise in temperature. The slight increase in flood frequency in the last three decades seems to coincide with the rising temperature and positive NAO indexes.

The above analyses suggest that the variability of flood frequencies recorded since the 1780s from the three coastal sectors (Figure 3) seems to a certain extent related to climate change, particularly the temperature of the Northern Hemisphere and the NAO index. However, there are also mismatches between flood frequencies and climatic variables. Notable is the fact that the rapid rise in temperature and NAO index since the 1980s has not resulted in a sharp increase in flood incidence. This particular discordance may be explained by the fact that flood defence systems have been greatly strengthened, and thus the vulnerability to flood hazard has been reduced. For example, after the infamous flood of 1953, the Thames Barrier was constructed in the 1980s and the associated sea and estuarine defences further strengthened and raised. Consequently, flood incidents recorded from the Thames estuary reduced substantially (Table 2). On the South Coast the majority of floods recorded between the 1940s and 1980s is from newly extended coastal towns. Such an increased vulnerability has resulted in an increase in the incidents of flood. Since the 1980s, flood frequencies have declined sharply, which may be attributed to the latest improvement to the sea defences, i.e. a reduction of vulnerability. Therefore, the flood records in Figure 3 reflect the variability of risk since the 1780s, i.e. the risk of coastal floods is the interaction of the hazard (storms or physical phenomena, see White, 1974) and vulnerability (exposure of human society to hazard, see Hewitt, 1983).

6. Storm Tracks

For the floods on the East Coast, 51 storm tracks were examined for the period between 1910 and 1995. The frequencies of these storms passing each grid are shown in Figure 4. This diagram shows high frequencies of storm tracks in the north and central North Sea, representing a principal pathway as indicated by the arrow. This pathway, as typified by the 1953 event (Figure 2), implies that storm cells passing over northern Britain and turning south-eastwards into the North Sea are most likely to cause flooding on the East Coast. This is because storm cells over the North Sea can generate tidal surges and waves that affect the East Coast. Similar to the 1953 event, the strong wind in the west sector of storm cells (anti-cyclones) can generate waves along shore of the East Coast.

For the South and Southwest Coast, 48 storm tracks were obtained from the synoptic charts. As shown in Figure 5, most storms are concentrated in a corridor along the 55^{o}N parallel. Thus, the principal pathway travelled eastwards into the English Channel or the Bristol Channel, as indicated by the arrow. As suggested by the 1981 event (Figure 2), this pathway is associated with storms that propel tidal surges onto the South and Southwest Coasts and generate strong onshore winds.

The low number of floods on the West Coast between 1910 and 1950 was probably associated with the fact that only 18 storms were recorded. Their frequencies in each grid are shown in Figure 6. It is noticeable that they are concentrated along the 60^{o}N parallel. Thus, the principal pathway can be easily defined, and is indicated by the arrow. The storm track of the 1977 event falls precisely within this pathway.

Adding all three pathways together, it becomes clear that floods in each coastal sector are associated with storms with distinctive pathways. Each pathway has its unique combined affects such as tidal surge and onshore waves on the associated coast, hence the risk of flooding. As mentioned earlier, the blocking effect of the Scandinavian high-pressure system may play a role in diverting storm cells from travelling eastwards into or across the North Sea. The NAO indexes constructed by Hurrell (1995) reflect the winter surface pressure gradient between Lisbon (Portugal) and Stykkisholmur (Iceland), which may carry little information of pressure gradient between Scandinavia and the British Isles. The variability of the Scandinavian high-pressure system must therefore be established in order statistically verify to the spatial model of the three storm pathways.

7. Discussion and Conclusion

Coastal flood hazard is a complex phenomenon involving a number of variables such as climate change, coastal type and evolution, and human activities. Instrumental records are increasingly accurate but short in time span and discontinuous. Documentary records do not contain numerical details of each flood event, but are accurate in terms of occurrence and location of flood hazard. Thus, they provide an important complement to instrumental records since documentary records cover much longer time spans and are useful as a corollary to studies of regional and global climate change (Cesar 1991, Reading 1990, Subbaramayya and Mohana 1984). Much longer records of flood hazard can be obtained from stratigraphic sequences (Tooley *et al*., 1997; Zong and Tooley 1999).

Among the three coastal sectors, the East Coast has been mostly prone to flood hazards (Figures 3 and 4). The vulnerability of the East Coast to flood is also high due to the fact that the low-lying coastal lowland has been reclaimed extensively for agricultural and industrial production and settlements. Such a combination has made the East Coast at high risk to coastal flood. Similarly, the high number of flood incidents on the South and Southwest Coast (Figure 3) and the recent rapid development of coastal settlements have put this coastal sector at high risk. Due to the lower frequencies of flood hazard and lower level of development, the risk to the West Coast is less than the other two coastal sectors.

The frequencies of flood incidents recorded from the three coastal sectors are to a certain extent related to climate variability. However, in this paper, only storms that were related to flood events have been examined and not the record of all storms. Future research, therefore, may need to examine statistically the changes in storm frequency in relation to climate variables. The increased number of flood incidents on the South Coast suggests that the number of storms travelling along a southern pathway (Figure 5) may have increased during the 20th century.

Many studies indicate the link between climatic variation and the strength of storms (Emmanuel 1987, Lamb 1985, 1991, Raper 1993, Wendland 1977), and show significant changes in UK climate (Briffa *et al*., 1990, Coker *et al*., 1980) and over north Atlantic ocean (Deser and Blackmon 1993; Kushnir 1994; Rogers 1985). Studies also imply the relations of North Atlantic Oscillations to the strength of westerlies, which is indirectly associated with storm pathways (Hurrell 1995; Wilby *et al*. 1997). However, the pressure gradients between Scandinavia and the British Isles need to be understood in order for the proposed model of three storm pathways to be verified.

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Table 1 Significant wave heights in the Irish Sea

	Return periods (years)			
	10	25	50	100
Offshore*	6.60	7.00	7.30	8.10
Inshore**	4.00	4.35	4.60	5.20

* from Hydraulics Research Station (1976)
** from Allott & Lomax Consulting Engineers (1979)

Table 2. Coastal Flood Records for England, Wales and part of Scotland (1788-1995 AD)

A. East Coast (Aberdeen to Ramsgate)

Year	Month	Day	Location
1788	Jan	25	London
1788	Jan	18	Hull
1788	Dec	15	London
1791	Feb	3	Canvey Island and Foulness
1793	Feb	12	London
1796	Dec	3	London
1800	Nov	28	Scarborough
1802	Oct	13	London
1804	Sept	23	Reculver
1806	Dec	26	London, Ipswich
1809	Jan	29	Bedford Levels
1811	Nov	1	Leith
1811	Nov	8	Edinburgh, Berwick
1814	Dec	28	London
1821	Dec	25	London and Fenland
1822	Jan	4	London
1824	Dec	23	Strood, Kent
1825	Feb	10	London, Dartford, Stone and Erith
1825	Feb	3	Faversham
1825	Feb	10	Sheerness and Blue Town
1827	Nov	7	Margate and Ramsgate
1827	Oct	31	London
1833	Nov	2	London
1834	Jan	22	London
1834	Jan	27	London
1835	May	14	London
1836	Feb	17	London
1836	May	1	Gravesend and Strood, Kent
1838	Feb	25	Port Erskine and Bell Rock
1841	Dec	1	London
1841	Oct	18	London, Southend
1841	Dec	1	London
1842	Mar	12	London
1842	Oct	7	London
1843	July	31	London
1844	Mar	3	London
1844	Aug	18	London
1844	Dec	10	London
1845	May	22	London
1845	Dec	6	London
1845	Dec	11	Sheerness
1847	Oct	6	Perth
1847	Sept	26	London
1848	Oct	17	London
1848	Dec	12	London
1849	Dec	27	Yare, Waveney and Bure river valleys
1850	Jan	29	London, Fenland and Hull
1852	Jan	6	Ipswich
1852	Nov	12	London
1857	Sept	24	London and Kent/Essex coasts
1860	Mar	7	London and Essex Marshes
1862	Nov	12	London
1862	May	13	Fenland

1866	Nov	24	London
1874	Mar	4	London
1875	Oct	14	Hartlepool
1875	Nov	15	London, Kent/Essex coasts, Berwick, Whitby
1876	Dec	20	Dundee
1877	Oct	26	London
1877	Sept	9	London
1877	Oct	8	Sheppy, Milton, Queensborough, Sheerness
1877	Jan	2	London, Maldon, Berwick, South Shields, Scarborough
1877	Jan	31	London, Sittingbourne, Fenland, Scarborough, Goole, Great Yarmouth
1877	Oct	8	London
1880	Oct	10	Sheerness
1880	Oct	27	Hartlepool
1880	Nov	16	Sittingbourne and Sheerness
1881	Dec	21	London
1882	Feb	19	London
1882	Aug	30	London
1882	Sept	29	London
1882	Oct	27	London, Sheerness, Whitby
1882	Nov	11	London
1883	Sept	19	London
1886	Jan	6	London
1886	Jan	22	London
1897	Nov	29	London
1900	Oct	26	North Shields
1901	Dec	14	Lowestoft
1901	Nov	12	Scarborough, Eyemouth"
1902	Feb	26	Lowestoft
1904	Feb	3	London
1905	Jan	7	Ramsgate, Lowestoft, Hartlepool, Spalding, Scarborough, Great Yarmouth, Sheerness
1908	Nov	23	Herne Bay, Lowestoft
1912	Aug	25	Cromer
1914	Mar	14	Southend on Sea
1918	Jan	15	Shoreham
1919	Feb	17	Grimsby
1920	Jan	8	Tayside and Perth
1920	May	29	Louth, Lud valley, Grimsby
1921	Nov	1	Thames mouth and Midway
1921	Dec	17	Hull and Teesside
1922	Mar	8	Margate
1922	Apr	14	London
1922	Oct	27	Skegness
1923	Oct	10	Hull, Scarborough
1925	Nov	25	Aldborough coastal marshes
1927	Feb	5	Thames valley Chiswick
1927	Mar	5	Thames valley Eel Pie Island
1927	Sept	19	Boston area coast
1927	Sept	23	Scarborough
1927	Nov	9	London
1927	Dec	26	Lowestoft
1928	Jan	6	London, Mersea
1928	Mar	22	Hull, Berwick
1930	Sept	24	Hull and Owston Ferry
1930	Nov	8	London, Southend
1935	Feb	6	Southend and Benfleet
1935	Sept	15	Barton on Humber
1936	Feb	23	London, Kirkcaldy, Aberdeen
1936	Mar	1	Hull
1936	Nov	1	London

1936	Dec	1	London, Lowestoft, Great Yarmouth, Southend, Ramsgate
1938	Jan	17	Southend
1938	Feb	12	Margate, Cromer, Maldon, London, Felixtowe, Grimsby
1938	Apr	3	Horsey, London
1943	Apr	6	Southend
1946	Dec	8	Lowestoft
1948	Aug	8	Jaywick near Clacton on Sea, Sandgate, London
1948	Aug	11	Berwick, Eyemouth
1949	Mar	1	London, Sheerness, Margate, Southend, Woodbridge, Boston, King's Lynn
1951	Dec	29	London
1953	Jan	31	Kent Coast to Spurn Head Humber including London
1954	Sept	1	Richmond on Thames
1954	Jan	3	Wells, Norfolk; Alderburgh, Suffolk; Barmston near Bridlington
1954	Oct	14	Hull
1954	Dec	22	Great Yarmouth
1954	Nov	11	Southend, Hull, Strood
1955	Jan	11	Putney, Millbank, Tilbury, Southend, Hull, Scarborough, Cleethorpes
1955	Feb	24	Cleethorpes, Scarborough, Sandilands
1957	Feb	16	Suburbs in Thames valley
1958	Oct	15	Putney
1959	Dec	30	Hull, Ipswich, Dendee
1961	July	4	Southend
1963	Nov	19	London
1965	Jan	20	Dymchurch, Hull
1969	Sept	29	Overstrand, Norfolk
1973	July	16	Grimsby and Cleethorpes
1975	Mar	20	Lowestoft
1976	Jan	3	Towns from Hull to Lowestoft inland to railway
1980	Mar	19	Grimsby
1980	Apr	20	Felixstowe
1983	Feb	1	Lowestoft, Great Yarmouth, Redcar
1984	Sept	26	Thames at Putney
1988	Mar	2	Great Yarmouth, Burl and Thurne valleys
1989	Feb	14	Britlingsea, Wivenhoe and Southwold
1993	Feb	21	Norfolk to Kent coast, Great Yarmouth, Spurn Head, Scarborough
1993	Nov	14	Goxhill, Humberston, Ashby cum Fenby, Cayton near Scarborough

B. South and Southwest Coasts (Dover to Milford Haven)

Year	Month	Day	Location
1792	Mar	1	Sussex Coast
1796	Jan	25	Bristol
1808	Nov	18	Coast Folkstone to Isle of Wight
1811	Oct	11	Exemouth, Budleigh Salterton
1813	Oct	11	Folkstone
1821	Dec	25 to 27	Lewes, Plymouth, Cawsand
1822	Oct	13	Brighton
1822	Dec	5	Brighton
1824	Nov	22	Sidmouth
1827	July	11	Romney Marsh
1841	Oct	18	Dover
1843	Oct	10	Dover
1845	Jan	27	Dover
1846	Jan	28 to 30	Bristol, Clevedon, Portbury, Barnstable & Western Super Mare
1846	Aug	8	Bristol
1857	Oct	7	Ryde, Isle of Wight & Eastbourne
1858	Dec	2	Kemptown, near Brighton
1867	Jan	5 to 7	Portland, Weymouth, Penzance & Lands End
1875	Oct	19	Dawlish

1875	Nov	11 to 15	Hastings, Eastbourne, Weymouth, Brighton, Worthing, Portsmouth Southampton, Southsea Castle, Bude & Helston
1876	Dec	5	Portsmouth & Southampton
1876	Dec	31	Portsmouth
1877	Jan	1 to 3	Southampton, Weymouth, Dover
1877	Jan	31	Dover
1878	Sept	28	Low lying seaports on south coast
1883	Sept	17	Brighton, Hove, Worthing
1883	Oct	17	Cardiff, Severn Tunnel, Coldcott
1902	Feb	28	Southampton
1902	Sept	10	Ilfracombe, Weston super Mare, Appledore, Bristol, Watchet, Dover, Folkstone
1904	Feb	3	Portsmouth, Weymouth, Portland, Bude, Penzance
1905	Jan	7	Dover
1905	Feb	26	Dover
1905	Nov	26	Hastings, St Leonards, Bexhill on Sea, Brighton, Sandgate, Folkstone
1908	Feb	22	Dover
1909	Dec	1	Dover
1910	Dec	16	Dover, Worthing, Southsea, Ilfracombe, Avonmouth, Exmouth & Selsey
1912	Dec	26	Cowes & Southampton
1914	Mar	16	Ilfracombe
1916	Nov	5	Portsmouth & Bournemouth
1917			Hallsands
1921	July	29	Folkstone
1922	Mar	8	Dover, Folkstone
1922	Apr	14	Sharpness
1923	Oct	10 to 12	Severn Beach near Bristol, Portsmouth, Hastings, Folkstone, Sandgate, Dover
1924	Dec	27	Portsmouth, Southsea, Folkstone, Sandgate, Deal
1925	Nov	8	Folkstone
1927	Sept	23	Folkstone, Dover
1927	Dec	21 to 26	Chesil Beach, Portland, Dover, Deal
1928	Feb	16	Alum Bay, Isle of Wight
1930	Feb	1	Portland and Chesil Beach
1930	Mar	16	Winchelsea
1935	Feb	6	Cowes Isle of Wight
1936	Jan	9	Newport
1936	June	18	Portsmouth and Southsea
1936	Nov	12	"Portland, Castletown, Chesil Beach
1936	Dec	18	Cardiff to Newport Road
1939	Jan	20	Chesil Beach at Portland
1942	Dec	23	Chesil and Portland
1942	Feb	13	Portland
1943	Jan	30	Sussex Coast
1945	Dec	18	Seaford & Chesil
1945	Dec	21	Starcross, Dawlish, Teignmouth
1945	Dec	24	Seaford and Hastings
1946	Dec	8	Hastings, Pevebsey Bay, Seaford, Eastbourne, Sandgate
1947	Nov	12	Seaford
1947	Dec	27	Hastings, Emsworth, Sandgate
1948	Jan	29	Looe, Saltash & Brixham
1948	Aug	8 to 11	Felpham near Bognor, Hastings, Folkstone
1949	Oct	23	Hastings, Hythe, Folkstone, Sandgate
1949	Nov	21	Folkstone, Sandgate
1951	Dec	29	Kent and Sussex coasts extensive, St. Leonards & Severn valley
1952	Aug	10	Seaford
1952	Jan	30	Bude
1953	Sept	23	Bristol and Pill on Avon
1953	Nov	1	Sandgate
1954	Jan	3	Bude

1954	Sept	14	Ashton Gate, Bristol
1954	Nov	26	Worthing to Lancing road, Teignmouth & Newhaven to Seaford road
1955	Jan	14	Weare Gifford, Devon
1957	Feb	16	Bridgewater, Combwich and Ilfracombe
1957	Sept	24	Westward Ho!, Bideford, Appledore, Instow, Ilfracombe & Bristol Channel
1957	Dec	10	Starcross, Saltash, Topsham, Devon & Weymouth to Bournemouth road
1960	Oct	8	Exmouth, Torquay, Brendon (north Deven) & Southampton
1963	Nov	19	Hastings, Folkstone
1965	Jan	20	Bournemouth
1971	Oct	19	Sandgate
1974	Jan	11	Amroth, Pembrokeshire & Barnstaple
1974	Feb	10 to 11	Severn Valley, Dawlish, Uckfield, Hailsham, Lewes, Christchurch, Folkstone
1974	Nov	15	St Ives, Preston to Weymouth & Cuckmere valley
1976	Sept	14	Polperro
1976	Oct	14	Torquay
1978	Jan	4	Torcross and Beesands
1978	Jan	11	Sandgate
1978	Feb	8	Severn at Gloucester
1978	Dec	13	Portland
1979	Feb	13	Portland
1979	Dec	13	Portland
1981	Mar	9	Bridgend, Cardiff, Swanage, Bridport, Corfe Castle
1981	Dec	30	Hayling Island, Cowes, Mudeford Bay, Yarmouth, Weston super Mare, Burnham on Sea, Minehead, Clevedon, Porlock, Watchet, Bridgenorth, Hythe, Sandgate
1984	Apr	16	Burnham on Sea
1985	Apr	7	Portsmouth, Hayling Island, Eastney & Elmer near Bognor Regis
1985	Dec	26	Avon Valley
1987	Oct	9	Isle of Wight
1988	Jan	5	Ryde, Isle of Wight
1989	Dec	20	Sidmouth, Dawlish, Budleigh Salterton, Lympstone & Southampton
1994	Dec	4	Severn valley at Gloucester

<u>C. West Coast (Cardigan Bay to Glasgow)</u>

Year	Month	Day	Location
1789	Jan	23	Liverpool
1792	Dec		Beetham
1794	Nov		Abbey Holme
1796	Jan	23 to 25	Liverpool
1796	Dec		Greenock
1802	Jan	20 to 21	Whitehaven
1806	Dec	20 to 27	Whitehaven, Ballantrae, Rothersay
1814	Dec	22 to 23	Lancaster, Greenock
1814	Dec	16 to 17	Port Glasgow
1818	Jan	12 to 15	Glasgow
1819	Aug	31	Whitehaven
1821	Nov	30	Douglas, Liverpool
1822	Nov	12 to 13	Liverpool
1823	Dec	5	Bootle
1827	Jan	17	Liverpool
1833	Nov	28	Liverpool
1841	Oct	18	Liverpool
1847	Nov	27	Rampside
1847	Dec	2	Helensburgh
1848	Dec	16	Glasgow
1849	Jan	10	Milnthorpe
1852	Dec	25 to 27	Walney Island, Cartmel, Kirkby Ireleth, Aldingham, Roosebeck, Greenock,

			Millom & Whichham
1856	Feb	6 to 7	Renfrew Ferry
1859	Oct	26	Bagillt
1863	Jan	19 to 20	Morecambe, Lancaster, Ulverston, Fleetwood, Preston, Lytham, Sandside, Hammerside"
1869	Jan	31	Whitehaven & Harrington
1869	Jan	1	Maryport
1870	Sept	9	Blackpool
1872	Nov	1 to 2	Blackpool
1873	Jan	3	Port Glasgow & Greenock
1874	Mar	20	Morecambe & Fleetwood
1875	Nov	13	Douglas
1875	Oct	18	Beaumaris
1875	Sept	26	Liverpool
1876	Mar	3	Blackpool
1877	Jan	30	Aberystwyth
1877	Jan	2 to 3	Douglas
1881	Oct	13 to 14	Whitehaven, Harrington & Blackpool
1881	Nov	11	Blackpool
1882	Nov	25 to 27	Blackpool
1882	Mar	20	Blackpool
1884	Jan	26	Blackpool, Whitehaven & Port Glasgow
1889	Oct	7	Holyhead, Southport, Blackpool
1890	Oct	16	Blackpool
1890	Jan	25	Maryport
1890	Jan	21	Sandylands, Preston, Blackpool & Lytham
1891	Oct	23	Abbey Holme, Holyhead & Blackpool
1894	Feb	10 to 11	Cartmel & Kent's Bank
1894	Dec	22	Skinburness, Kirkby in Furness & Rockliffe
1896	Mar	16	Blackpool
1896	Mar	5	Blackpool
1896	Oct	8	Blackpool
1897	Nov	29	Morecambe, Southport, Abergele & Rhyl
1897	Jan	23 to 24	Blackpool
1902	Oct	10 to 17	Blackpool
1902	Sept	3	Arnside, Sandside, Grange over Sands, Milnthorpe, Kirkby in Furness, Carnforth & Foulshaw
1903	Feb	27	Arnside & Meathop
1904	Feb	22	Douglas
1907	Mar	4	Sandylands, Morecambe, Knott End, Milnthorpe, Pilling, Carnforth, Bolton le Sands, Sunderland
1911	Oct	31	Cleveleys, Blackpool, Fleetwood & Lytham
1911	Nov	5	Roa
1911	May	2	Blackpool
1911	Oct	10	Dee esturay
1924	Dec	27	Blackpool, Fleetwood & Sandylands
1925	Feb	21	Morecambe, Pilling, Knott End, Bolton le Sands & Cockerham Sands
1926	Feb	19	Morecambe & Sandylands
1926	Dec	30	Preston, Heysham & Morecambe
1926	Nov	5	Broomilaw
1927	Oct	29	Fleetwood, Blackpool & Sandylands
1928	Oct	28	Grange over Sands
1931	Aug	18	Fleetwood
1931	Mar	6	Rhos-on-Sea
1935	Oct	18 to 19	Firth of Clyde
1937	Jan	28	Rhos-on-Sea, Beaumaris
1939	Mar	9	Fleetwood
1942	Dec	20	Solway Firth
1945	Sept	24	Towyn, Rhyl, Penmaenmawy, Llanfairfechan
1947	Jan	17	Carlisle

1977	Nov	12	Morecambe, Pilling, Blackpool, Lytham, Fleetwood
1977	Nov	14	Morecambe, Pilling
1983	Feb	1	Morecambe
1990	Feb	1	Towyn
1991	Jan	2	Morecambe, Rampside, Barrow in Furness, Holy Head

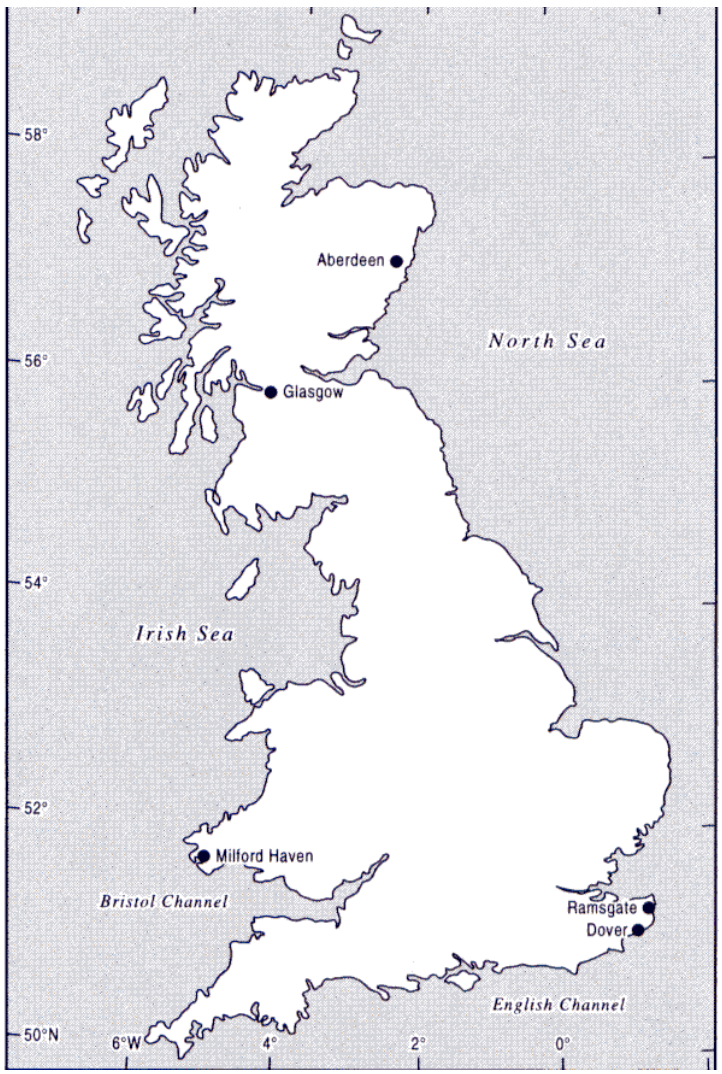

Figure 1 The coast of Britain is divided into three sectors for the investigation: East Coast from Aberdeen to Ramsgate, South/Southwest Coast from Dover to Milford Haven, West Coast from Milford Haven to Glasgow.

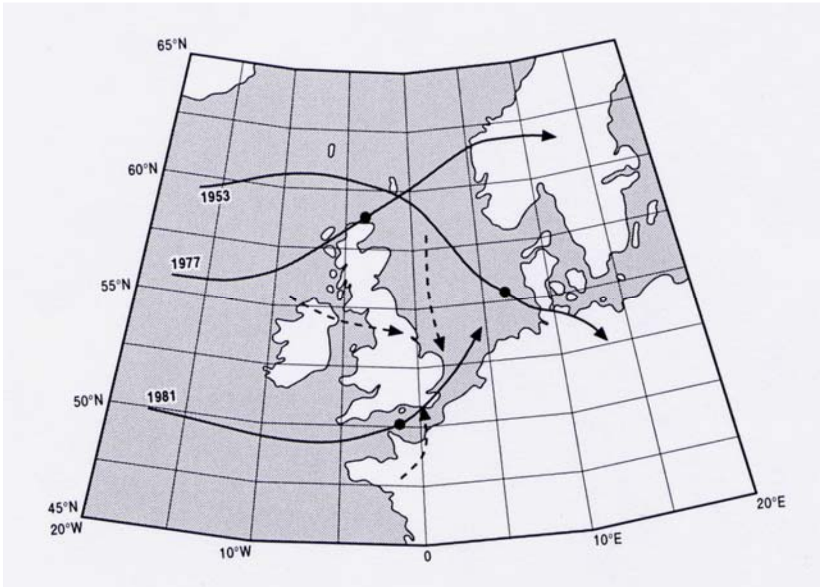

Figure 2 Northwest Europe with grids of 2.5^0 Latitude and 5.0^0 Longitude, showing the tracks (solid lines) and associated surface wind direction (dotted lines) for the three storms recorded in 1953, 1977 and 1981.

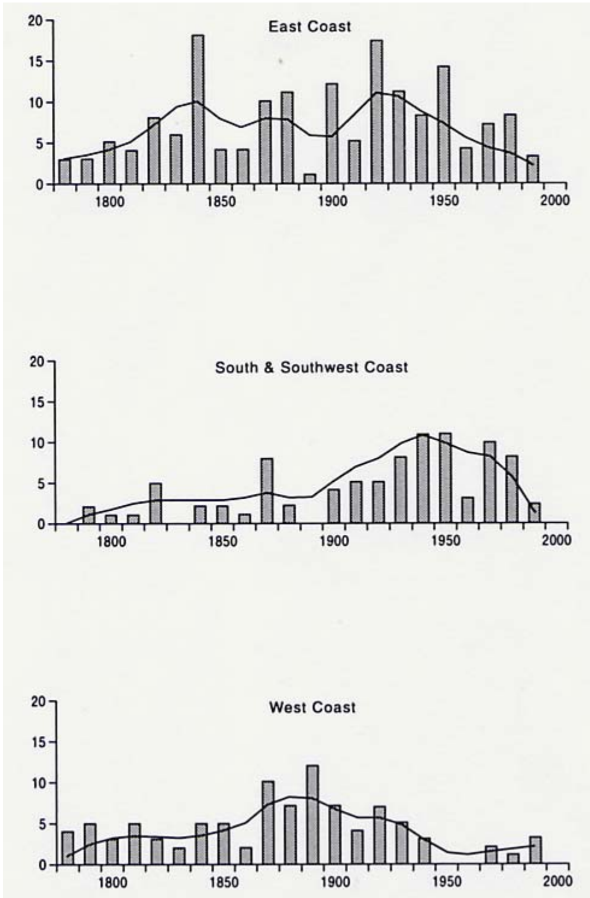

Figure 3 Frequencies of storm floods recorded from the three coastal sectors with details listed in Table 2. The trends are calculated using a 5-term filter.

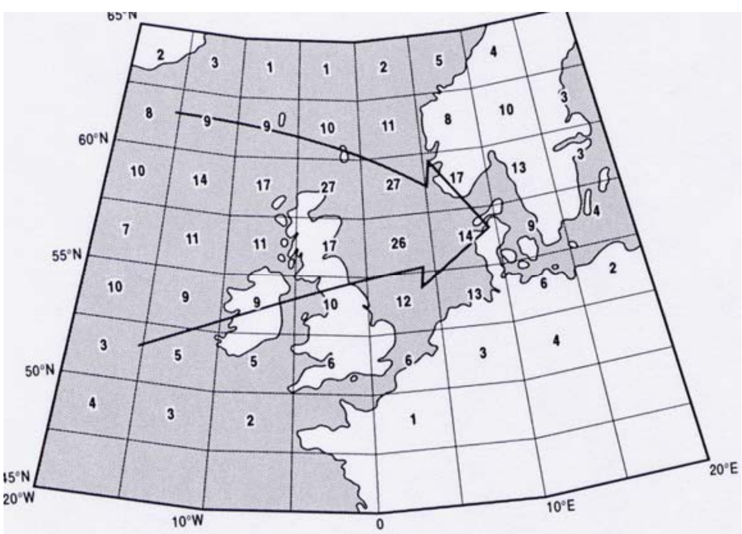

Figure 4 Frequencies of storm tracks passing through each grid, based on 51 storm floods on the East Coast.

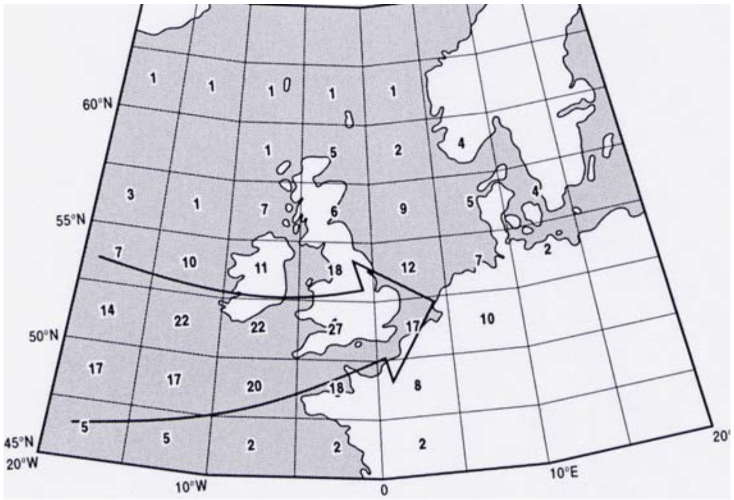

Figure 5 Frequencies of storm tracks passing through each grid, based on 48 storm floods on the South and Southwest Coast.

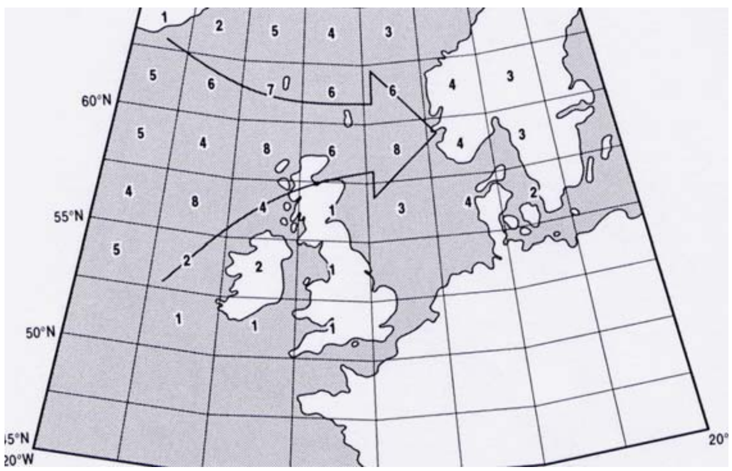

Figure 6 Frequencies of storm tracks passing through each grid, based on 18 storm floods on the West Coast.