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Flood threat anomaly for the low coastal areas of the English Channel based on analysis of recent characteristic flood occurrences

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Abstract In the English Channel, extreme surge heights did not occur at the time of extreme high tides during the last decades and maximum recorded heights usually do not exceed the maximum astronomical tide by more than a few decimetres. To understand whether this lack of coincidence may be due to specific phenomena or only to chance, we have studied hourly tide records lasting a few decades from nine English and nine French stations as well as air pressure and wind data from nearby meteorological observatories. Among the case studies of moderate flooding at several coastal stations occurring during spring tide, we have selected those of 24–25/10/1980 and of 30/01/1983 to 02/02/1983 as representative of a normal situation without any special chance. The third case study 26–28/02/1990 was potentially more dangerous because of the storm intensity and duration; however, by chance, surge peaks occurred near the low tide. Finally, the propagation of the surge peak of 15–16/10/1987, which reached the maximum height recorded during all the instrumental period at several stations, has been followed all along the English Channel, using the hourly records of 12 tide-gauge stations and of 16 meteorological stations. The surge peak of this great storm, probably the strongest in the last two centuries, occurred everywhere at high tide and spread with the same velocity of the tidal wave. Fortunately, no major flooding occurred because it was the day after a neap tide. In conclusion, some good fortune has saved the low coastal areas of the English Channel from major floods during the last decades. However, the occurrence of the peak of a strong storm surge arriving near the western entrance of the Channel at the time of a great astronomical high tide is a possible event that could be devastating along both sides of the Channel coasts.

Keywords Sea level · Storm surge · Tide · Coastal flooding · English Channel

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Introduction

Resulting from North Atlantic storminess (Schmith et al. 1998; WASA GROUP 1998), coastal flooding is a phenomenon that may affect several coastal sites in the English Channel (Caspar 1988; Costa et al. 2004). Events that occurred during the last decades were caused either by (a) moderate surges occurring at spring high tide or (b) extreme surges occurring with a moderate tide. This study is based on data recorded from 18 tide-gauge stations (nine in France and nine in England) and from many meteorological stations (Fig. 1). Most flooding occurrences for

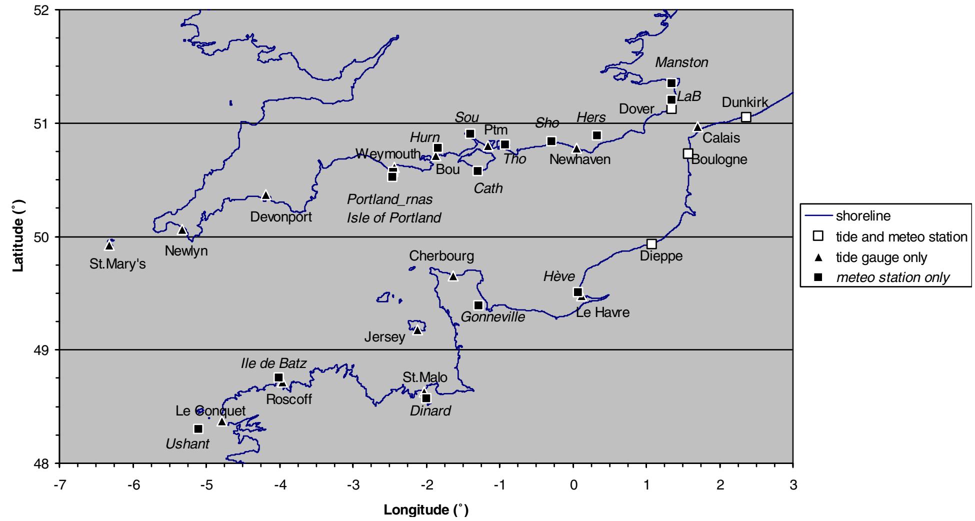


Fig. 1 Location map. *Bou* Bournemouth, *Sou* Southampton, *Ptm* Portsmouth, *Cath* St. Catherines Point, *Tho* Thorney Island, *Sho* Shoreham, *Hers* Herstmonceux, *LaB* Langdon Bay

which tide-gauge data and meteorological data were available in the recent past have been analysed. In the following, after a brief summary of relative sea-level changes and of the tidal and surge distribution in the Channel area, four significant case studies are presented in detail. The main conclusion of this paper is that in most cases, damage from flooding was limited mainly by chance because no major surge coincided with a spring high tide.

Recent sea-level changes and tidal and surge distribution

The sea level during the last century has been rising along the coasts of the English Channel at rates that, although changing slightly from site to site, are often consistent with the ‘global’ estimated rise (1–2 mm/year; Woodworth 1987; Woodworth et al. 1999; Pirazzoli 2005). However, the rate of sea-level rise observed is much faster, of the order of 1 cm/year, along a stretch of coast more than 100 km long in the central part of the British coast, between Weymouth and Portsmouth (Pirazzoli et al. 2006). On the French side, anomalously rapid sea-level rise, of the order of 0.5 cm/year, is observed at Dieppe and Boulogne, suggesting present-day tectonic activity in the “Dieppe–Hampshire” geological basin (see Pirazzoli et al. 2006 for references).

Maximum recorded surge height may exceed 2 m at several sites in the eastern part of the English Channel, especially on the French side (Table 1). In this paper, surge equals observed water level minus astronomical tide level, without any time shift.

The extreme water level range (from the minimum to the maximum recorded sea level) is quite variable in the Channel area. Along the southern coast, it is always more than 6 m, with a maximum peak in the Mont-Saint-Michel Bay of more than 13 m at Saint-Malo/Saint-Servan and more than 12 m at Jersey and a second peak above 10 m at Dieppe. On the northern coast, it is rather low in the central part of the coast but reaches 8 m at Dover.

Flooding events

Coastal flooding occurs in the research area when the sea overtops barrier beaches or coastal defence structures or when it breaches through dunes and water enters the lower lying areas behind. Because actual flooding occurrences depend on the elevation of the beaches or structures, it can therefore vary from place to place and over time under the same input conditions of water level and wave conditions. In this paper, water level data are considered independently of wave activity or the local influence of the elevation of the barrier between the sea and the low-lying hinterland. For simplicity of argumentation, it is assumed that coastal flooding generally starts when the static water level exceeds the limit of highest astronomical tide (HAT) at a given location. Floods may therefore occur when the level of a high tide is increased by surge development.

Because surge heights generally do not exceed the difference between a spring high tide and a neap high tide, flooding events are more likely to occur around spring tide (at new moon, or full moon, or in the 2 following days when the tidal amplitude reaches a maximum). We tentatively classify a moderate flooding when water levels exceed HAT by a few decimetres and severe flooding when heights reach or exceed 1.0 m above HAT. Of course, the effects of flooding can only be worsened by the height and duration of wave activity.

The flooding threshold has been exceeded along the coast of the English Channel on several occasions during

Table 1 List of hourly tidal records available on the coasts of the English Channel

Tide-gauge stations (Fig. 1)			Number of validated hourly records	Missing data (%)	Number of equivalent full years	Maximum recorded surge [a] (cm)	Maximum recorded level (tide+ surge)[b] (cm)	Maximum astronomical tide (HAT)[b] (cm)	Difference (maximum recorded level minus maximum astronomical tide) (cm)
Name (available years)	Latitude	Longitude							
France									
Le Conquet (1970–2002)	48.37	−4.78	276,570	4	31.5	143	778	774	4
Roscoff (1973–1995)	48.72	−3.96	176,967	14	18.1	98	994	973	21
Saint-Malo/Saint-Servan (1850–1856, 1859–1861, 1863–1864, 1869, 1874–1875, 1880–1898, 1906–1917, 1941–1944, 1961–1964, 1972, 1985–1993)	48.63	−2.03	405,810	28	46.3	192	1,354[c]	1,347	7
Cherbourg (1974–2002)	49.65	−1.63	250,927	1	28.6	135	715	703	12
Le Havre (1963–2002)	49.48	0.12	287,023	18	32.8	202	896	843	53
Dieppe (1954–1993)	49.93	1.08	27,350	21	31.4	167	1,050	1,000	50
Boulogne (1973–2002)	50.73	1.58	152,207	42	17.4	205	980	942	38
Calais (1965–2002)	50.97	1.66	233,580	30	26.7	223	817	773	44
Dunkerque (Dunkirk; 1956–2002)	51.05	2.37	296,903	28	33.9	218	730	748	−18
England									
St. Mary's, Scilly (1994–2005)	49.92	−6.32	90,414	14	10.3	74	644	624	20
Newlyn (1916–2001)	50.06	−5.33	749,227	2	84.4	118	636	605	31
Devonport (1987, 1991–2005)	50.37	−4.19	117,368	16	12.2	94	634	606	28
Jersey (1992–2004)	49.18	−2.12	103,231	9	11.8	101	1,218	1,209	9
Weymouth (1991–2001)	50.61	−2.44	91,875	4	10.5	90	289	269	20
Bournemouth (1996–2002)	50.71	−1.87	57,226	7	6.5	100	280	244	36
Portsmouth (1991–2002)	50.80	−1.16	95,496	9	10.9	116	549	519	30
Newhaven (1983–2002)	50.78	0.05	128,910	26	14.7	132	769	739	30
Dover (1958–2002)	51.12	1.35	349,549	11	39.9	175	802	736	66

[a] Above MSL
[b] Above the Chart datum
[c] Corrected to take into account relative mean sea-level changes occurred before the year 2000

the last decades mainly during times of spring tide. Tidal analysis shows that they correspond either to moderate surges coinciding with high tide (e.g. 11/01/1978, 24–25/10/1980, 30/01/1983, 02/02/1983, 21/02/1993) or to significant surges (e.g. 26–28/02/1990) with the peak being reached some hours before or after the high tide.

In the English Channel area, surges are generally produced by storms associated with air flow from westerly

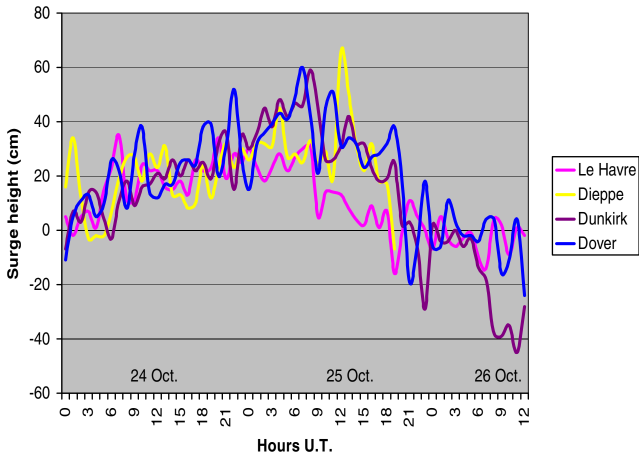


Fig. 2 Evolution of surge height on 24–25 October 1980

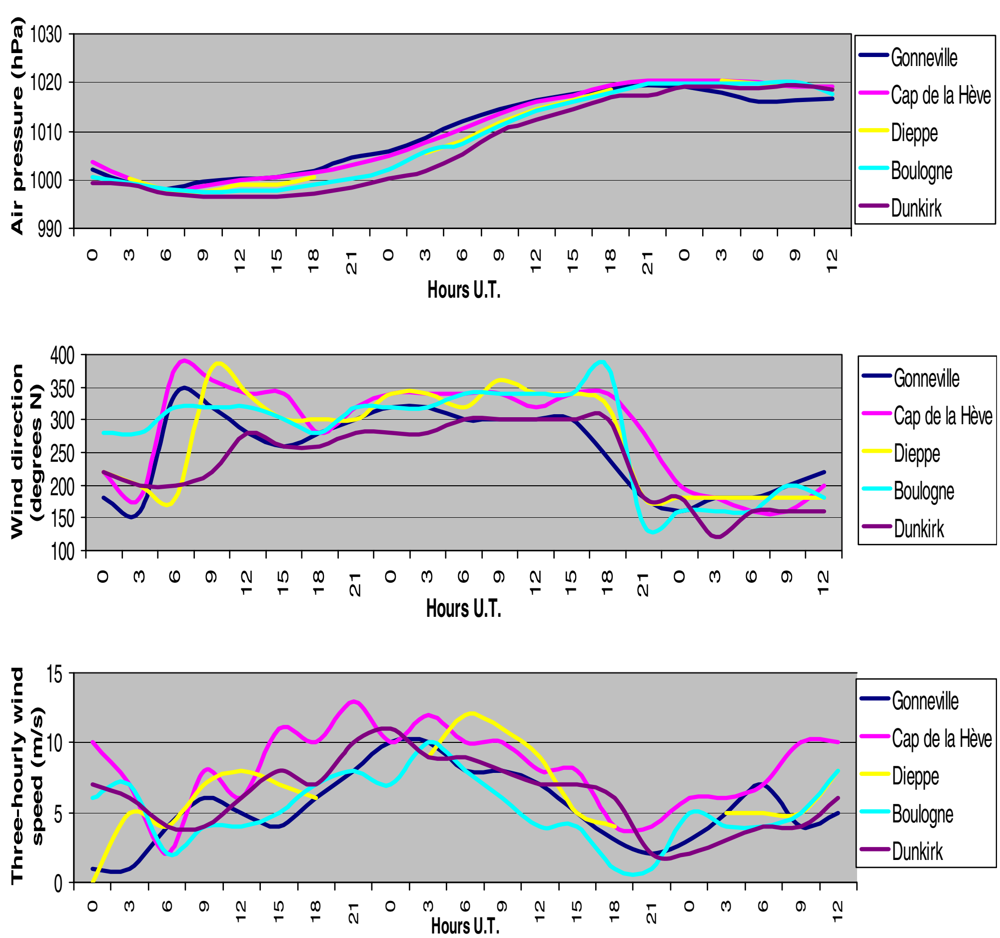
directions that tends to push Atlantic Ocean water into the Channel. Such an air flow is often accompanied by a deep atmospheric low over the British Isles or the North Sea. In this case, surges may affect most coastal areas of the Channel, although the areas most touched vary with the position of the low, the size of the depression and the local wind direction and speed.

When the low pressure centre is located more to the east, the meteorological effects may be very different: A wide depression over the Baltic would produce a strong air flow from north or northwest over the North Sea that would tend to push water into the southern part of the North Sea and the Dover Strait, with comparable effects on both sides of the Strait (Costa et al. 2004; Pirazzoli et al. 2006). However, such surges near the Dover Strait tend not to propagate westwards into the Channel.

Although a greater level of regional wind activity seems to have occurred since the mid-1970s, trends of surge-related storminess generally show stability or slight decrease, with the exception of a statistically significant increase in the frequency of winds from surge-related directions at Weymouth and Portsmouth and in the extreme speed of these same winds at Portsmouth (Pirazzoli et al. 2006).

It has been shown that in the eastern part of the English Channel, the surge and tide are not independent processes. In fact, only about one half of surges greater than or equal to the 99.9th percentile that are statistically expected to occur on average at the time of the 20 uppermost percentiles of tide are able to really occur at that time (Pirazzoli et al. 2006). Near the western side of the Channel, only 77% of the surges

Fig. 3 Air pressure and wind on 24–25 October 1980



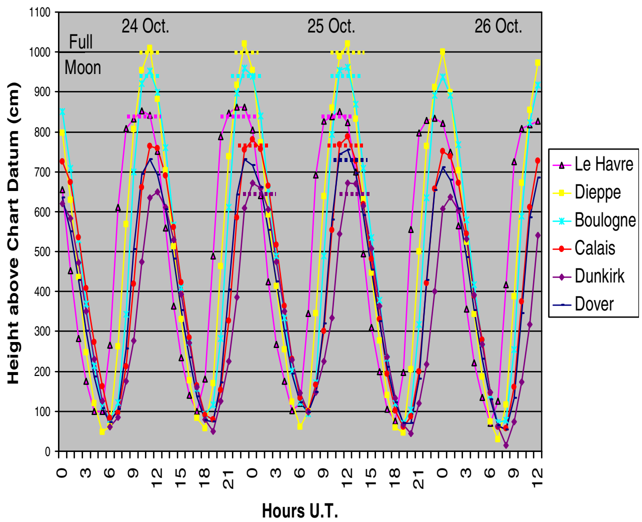


Fig. 4 Observed water level record and floods on 24–25 October 1980. *Dotted horizontal lines* mark the uppermost astronomical tide levels when they have been exceeded

greater than or equal to the 99.9th percentile expected to occur at the time of the 20 uppermost percentiles of tide at St. Marys's, Newlyn and Devonport would be able to occur at that time (Pirazzoli and Tomasin 2007). Such limitation seems to be due, as noted by Tawn and Vassie 1989, to the fact that in shallow water, the effect of quadratic friction is to damp the surge at high tide levels, whereas other non-linear shallow water terms may produce surge amplification on the rising tide. Such interactions are, however, spatially variable and difficult to generalise. Nevertheless, about one half of the expected extreme surges in the eastern part of the Channel and about 77% in the western part may still coincide with an extreme high tide.

Surge peaks during a storm are often reached shortly after the passage of an atmospheric cold front that is usually accompanied by an increase in wind speed and a northwards deviation of the direction from which the wind is blowing. The worst coastal flooding can therefore be expected when, during a strong storm, the passage of a cold front occurs shortly before a spring high tide. Fortunately, such event has not been recorded during the last decades, although it remains a possible event of concern in the near future.

In this paper, four case studies have been selected after statistical analysis of all the data available, using the following criteria:

– Events that exceeded the HAT level in at least five stations, with records available from both sides of the Channel: 24–25 October 1980 and 2 February 1983 (thus, excluding the floods of 13 November 1977 because of insufficient records on the UK coast)
– HAT levels that have been exceeded during 3 consecutive days in at least four stations, with records available from both sides of the Channel: 30 January–2 February 1983 and 26–28 February 1990)
– The event with the maximum observed surge at several stations (15–16 October 1987)

On the other hand, events limited to only one entrance area of the Channel have been disregarded (e.g. the floods

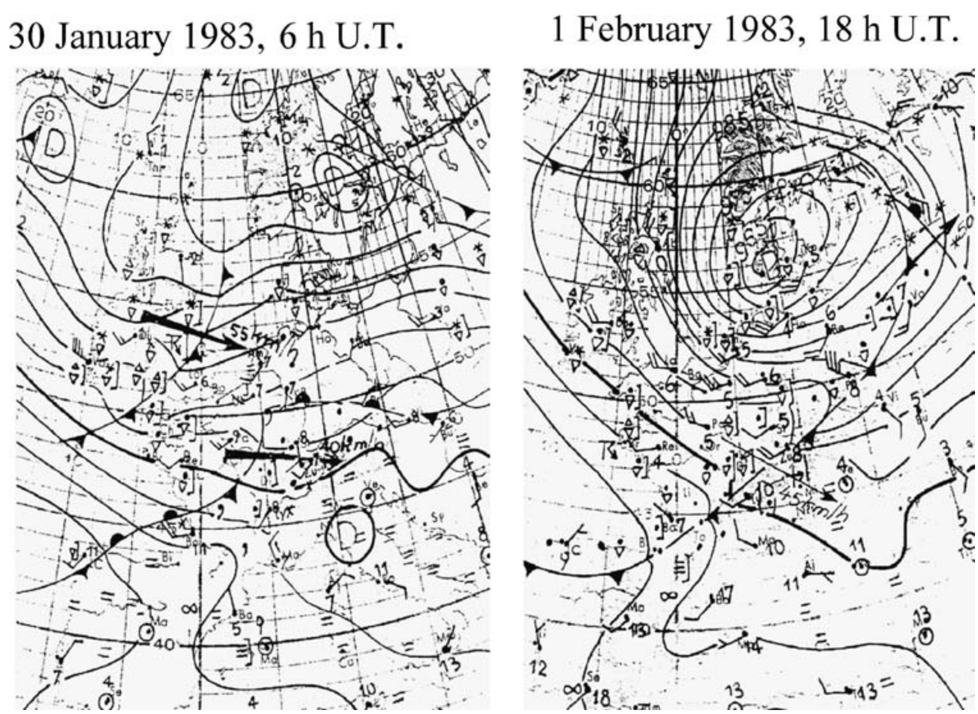


Fig. 5 Meteorological situation in Western Europe on 30 January 1983 at 06:00 and 1 February 1983 at 18:00, according to Météo France

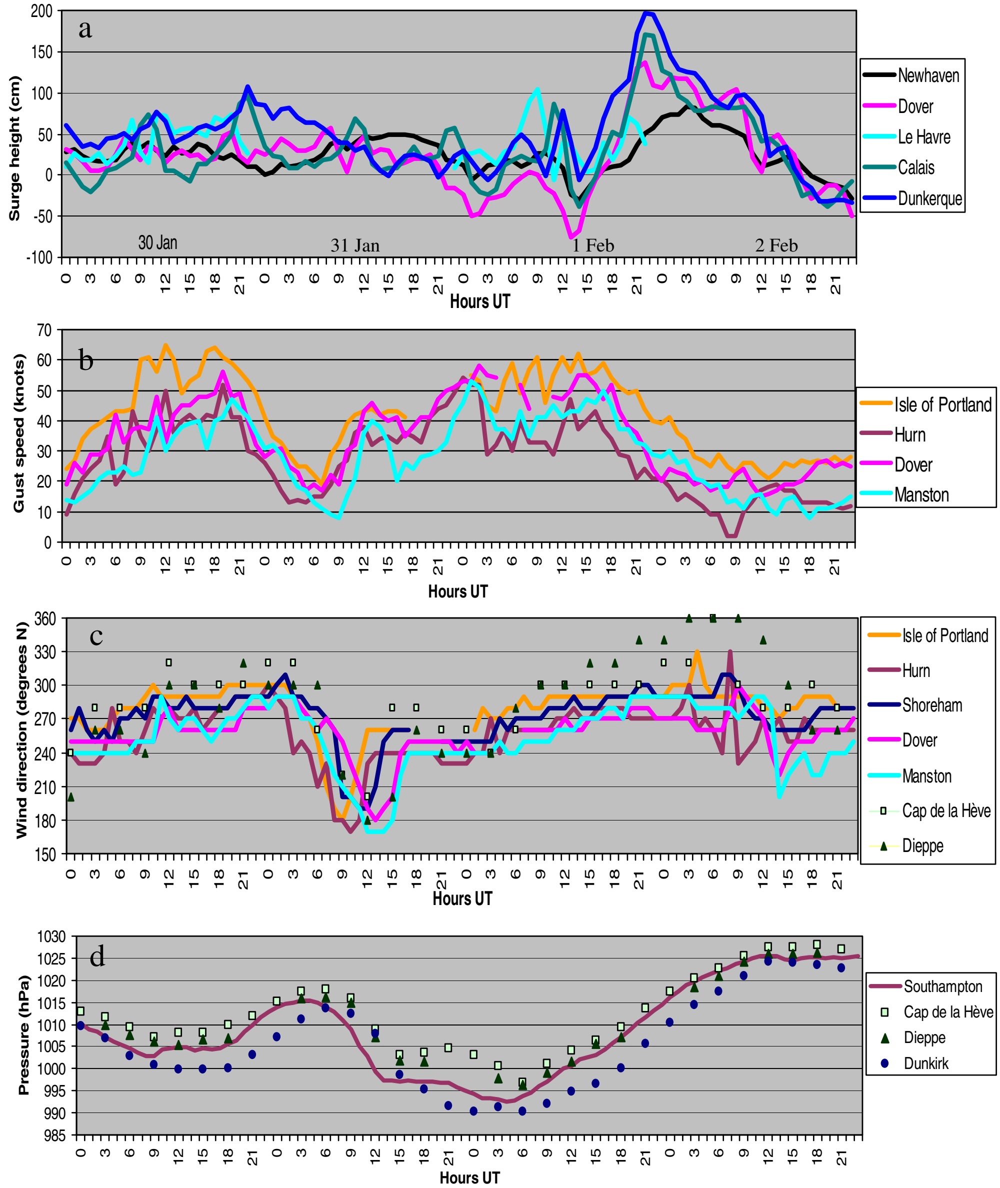


Fig. 6 Surge and meteorological evolution at English Channel stations between 30 January and 2 February 1983: **a** surge height, **b** gust speed, **c** wind direction, **d** surface air pressure

of 12 January 1978 and of 21 February 1993 that concerned the Dover Strait and the southern North Sea).

The four events that we consider as most significant for the last few decades are therefore: (1) a moderate surge at spring high tide causing a moderate flood (24–25 October 1980), (2) a second moderate surge at spring high tide causing a moderate flood, followed 3 days later by a stronger surge and flood, fortunately associated with lower tide levels (30 January–2 February 1983), (3) a strong surge during spring tide causing only a moderate flood (26–28 February 1990) and (4) an extreme surge at high tide during a neap tide (15–16 October 1987).

Tide data have been obtained mainly from the Système d' Observation du Niveau des Eaux Littorales (SONEL) database (http://www.sonel.org) or from the British Oceanographic Data Centre and consist of hourly measurements, for which astronomical tide and surge values have been computed following the methodology described in a previous paper (Pirazzoli et al. 2006). Wind data have been obtained from the British Atmospheric Data Centre and from Météo France. The wind speed corresponds to hourly or 3-hourly measurements (i.e. to average speed observed during 10 min) in Figs. 3, 5, 10 and 11, to gusts in Fig. 6b.

The storm of 24–25 October 1980: repetitive moderate flooding caused by a moderate surge

This is a typical example of surge situations produced by moderate storms during spring tide periods. There was a

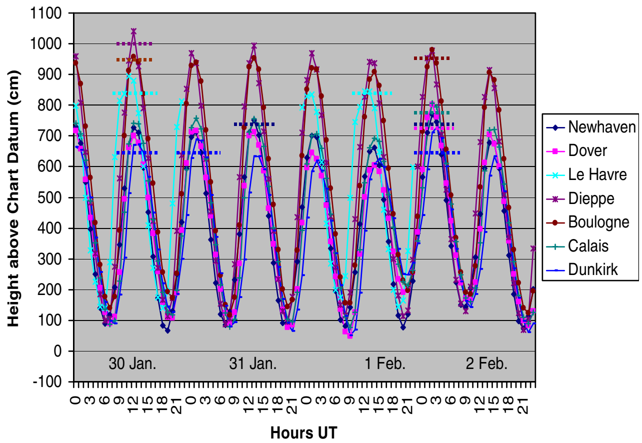


Fig. 7 Observed water level record from 30 January to 2 February 1983 at Newhaven, Dover, Le Havre, Dieppe, Boulogne, Calais and Dunkirk. *Dotted horizontal lines* mark the uppermost astronomical tide levels, i.e. the beginning of flood for the various stations

12 A.M. on 24 October, between 11 P.M. and 1 A.M. in the night between 24 and 25 October and then between 11 A.M. and 1 P.M. on 25 October. The meteorology is summarized in Fig. 3: The depression centre is at some distance, more to the north; the increasing trend of air pressure indicates that the depression centre is moving away (towards the east). In the middle of the figure, in the early morning of 24 October, after the passage of a cold front, a deviation of wind direction towards the northwest or north is shown, which is favourable to water accumulation near the Dover Strait. Below, the wind speed, although persistent, remained moderate, always less than 15 m/s. In short, it was a quite trivial storm. However, because it occurred at spring high tide, it was sufficient to produce repetitive moderate flooding (Fig. 4): three times at Dieppe, Boulogne and Le Havre, twice at Calais and Dunkirk and once at Dover.

gradual increase in surge height during 36 h, followed by a gradual decrease. The resulting surge peak (approx. 60 cm) was fortunately quite moderate (Fig. 2). Nevertheless, it was sufficient to cause repeated flooding and some damage because astronomical hourly spring high tide occurred (depending on the station considered) between 10 and

The storm of 30 January to 2 February 1983: a two-step westerly storm

New moon was on 28 January. Although westerly winds had been increasing during the 30 January (Figs. 5, 6), with gusts locally exceeding 60 kn, surge height in the English

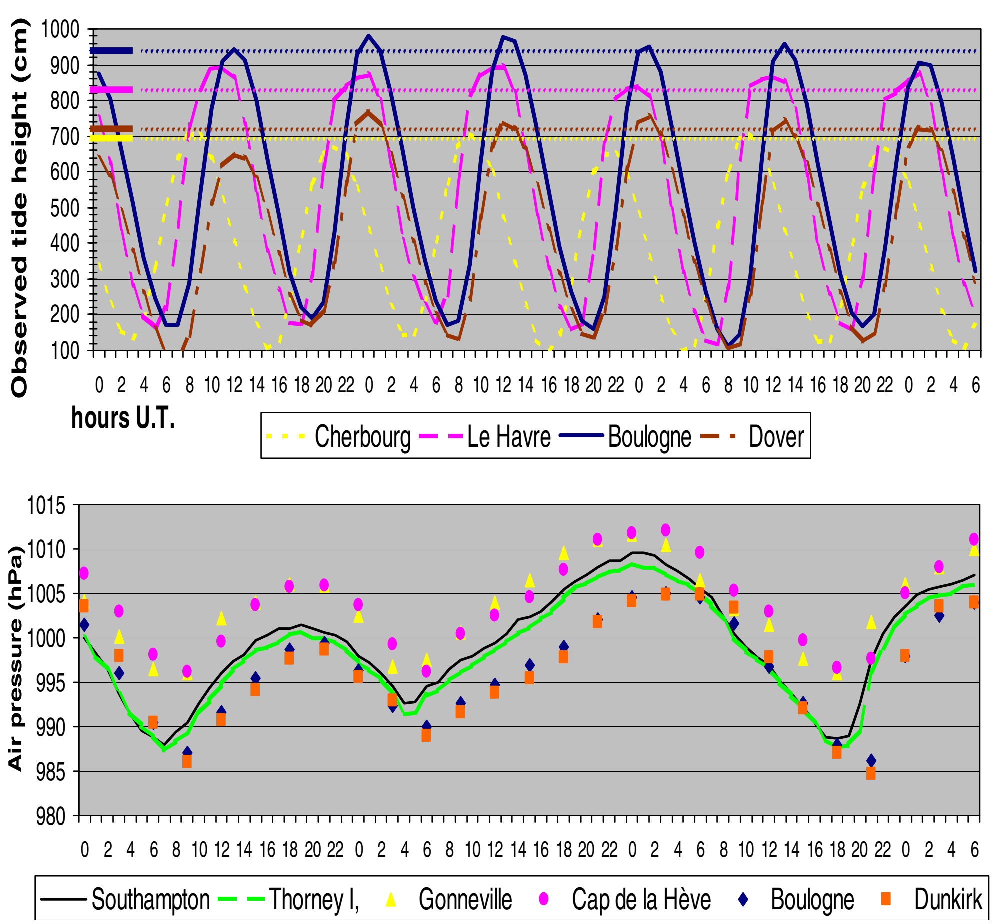


Fig. 8 Observed water level and air pressure on 26–28 February 1990. *Above*: *dotted horizontal lines* mark the uppermost astronomical tide levels, i.e. the beginning of flood for the various stations

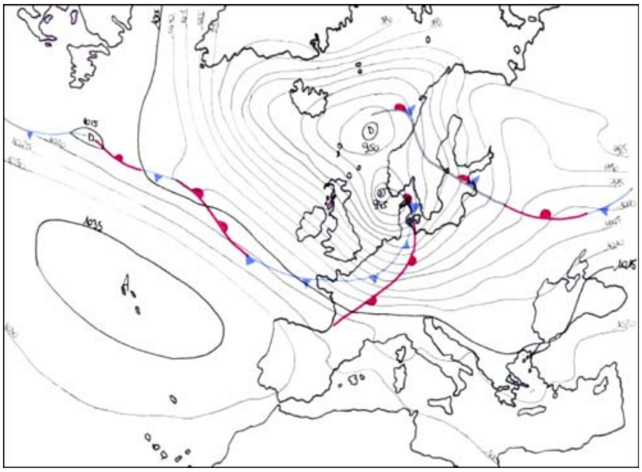


Fig. 9 Synoptic situation on 26 February 1990 at 12:00 UT, i.e. a few hours after the passage of a cold front in the English Channel area (adapted from Bulletin Quotidien Régional de Météo France)

Channel remained moderate (generally less than 50 to 100 cm). In the afternoon, when the wind-speed peak coincided with a spring high tide, moderate flooding occurred mainly at Dieppe, Boulogne, Le Havre and Dunkirk (Fig. 7).

The storm was, however, of short duration. On 31 January, while a decrease in wind speed had a limited impact on surge height, a southerly deviation in wind direction contributed to push the water surface towards the southern coast of England, causing a minor flood at high tide at Newhaven (the corresponding data from Le Havre are missing).

In the afternoon of 1 February, a deep depression had developed over Denmark, causing a northwesterly deviation in wind direction over the North Sea (Fig. 5) and at the French stations in the eastern part of the Channel (Le Havre, Dieppe; Fig. 6), whereas westerly wind remained predominant in other parts of the Channel. The corresponding general increase in wind speed produced in the night a strong surge peak near the easternmost part of the Channel (196 cm at Dunkirk, 171 cm at Calais, 137 cm at Dover), much less more west (84 cm at Newhaven). However, fortunately, air pressure had become above average (Fig. 6d), and the astronomical high tide (5 days after the new moon) was moderate. As a consequence, coastal flooding was widespread, especially near the eastern part of the Channel, but remained moderate.

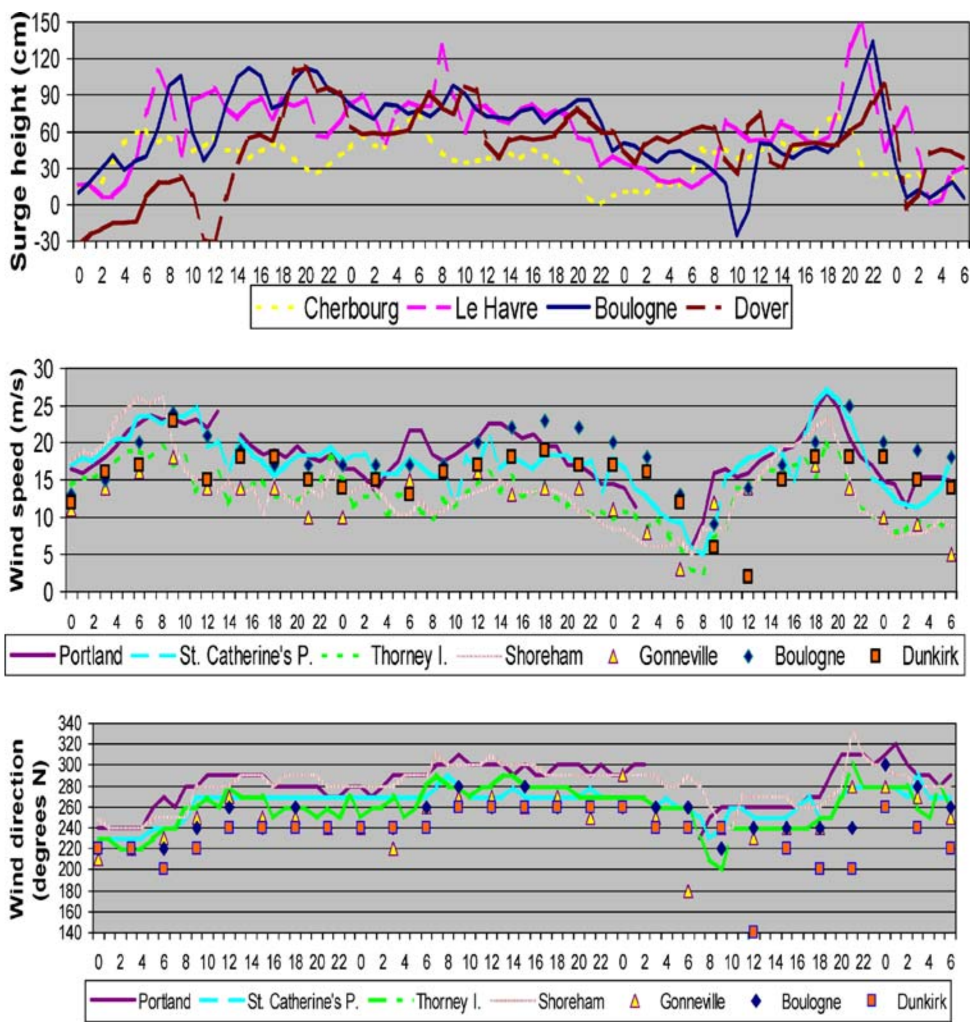


Fig. 10 Surge height and wind on 26–28 February 1990 at English Channel stations

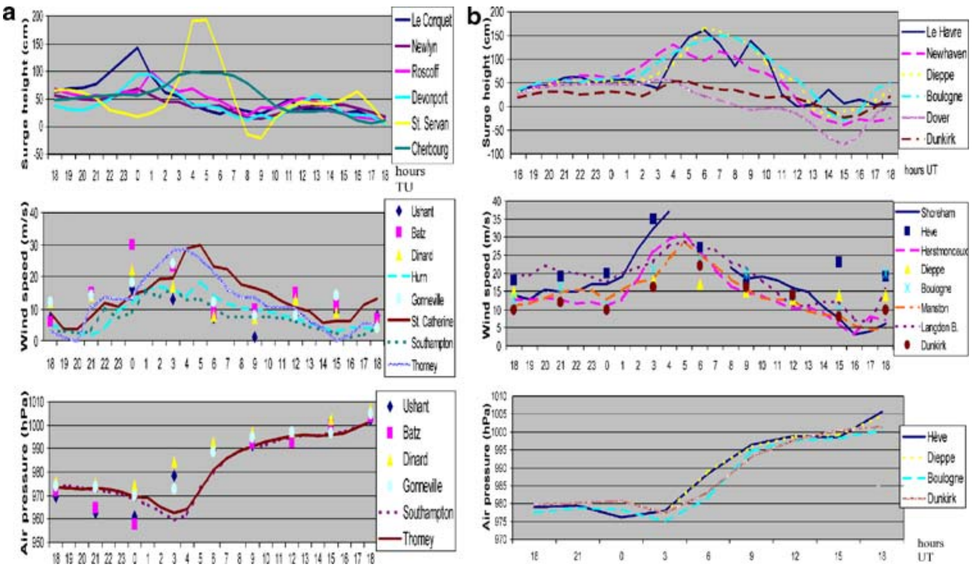


Fig. 11 Surge height, wind speed and air pressure on 15–16 October 1987: **a** western part of the English Channel; **b** eastern part of the English Channel

The storm of 26–28 February 1990: a lasting strong storm

This is an example of a long-lasting storm during the spring tide period (new moon was on 25 February) with repetitive and almost general coastal flooding. During the 3-day period, the flooding level was reached three times at Cherbourg and exceeded by some decimetres five times at Le Havre, four times at Boulogne and again five times at Dover (Fig. 8).

A first cold front crossed the Channel area during the morning of 26 February (Fig. 9), accompanied by a trough in air pressure, an increase in the average wind speed to about 25 m/s and a deviation of its direction from southwest to west (Fig. 10). The resulting surge reached a height of about half a metre in the middle of the Channel (Cherbourg) and 1 m in the eastern part of the French coast (Le Havre, Boulogne). Because wind speed remained high over most of the time (between 15 and 25 m/s) and the surge maintained a significant height (just decreasing slightly in the night of 27 February), some flooding occurred at each high tide. In the afternoon of 28 February, a new trough in air pressure, accompanied by a strengthening of the average wind speed to more than 25 m/s and by an additional deviation of its direction from west to north–northwest, produced a new surge peak of approx. 1.5 m at Le Havre and Boulogne and an accumulation of North Sea water near the Dover Strait (with a surge of 1 m at Dover). The surge peaks of 1.5 and 1 m are very suggestive, as they occur on the rising flank of the tide, and are the result of a phase shift between the astronomical tide curve and the observed water level curve. It is therefore a ‘skew surge’ that fortunately did not cause flooding at the time of its peak. In spite of the repetitive and widespread flooding occurrences, damage was generally limited, except on the northern Normandy and Picardy coasts, where it was more severe (Costa 1997, 2005), because the troughs in air pressure, the passage of the cold fronts and the main surge peaks occurred each time near low tide. This would appear very fortunate (Costa et al. 2004; Costa 2005; Pirazzoli, in Costa and Delahaye 2005; Chaverot 2006). The lack of coincidence between the surge peak and the high astronomical tide does not depend in this case from a possible interaction between surge and tide but just from the moment of passage of the meteorological disturbance. If the passage of the cold front and related last surge peak, in the night of 28 February, had occurred 6 h earlier or 6 h later, the flood level would have been 1.5 m higher.

15–16 October 1987: an extremely strong storm coinciding with a neap high tide

This case study is well known: It is the strongest storm recorded in the area during all the instrumental period, with a minimum air pressure of 952 hPa and gusts exceeding 60 m/s. The meteorology of this storm has been analysed in several publications (Advisory Services Branch 1988; Aristaghes 1988; Burt and Mansfield 1988; Hontarrède and Duvéré 1988; Lorblanchet 1989; Templeman et al. 1988; Woodroffe 1988). We shall consider below only its effects on surges.

In Fig. 11a, a comparison is made between surge height, wind speed and air pressure in the western part of the Channel. Near the Channel entrance, a surge peak of ~1.5 m was reached at Le Conquet and of ~0.7 m at Newlyn at midnight and of about 1 m at Roscoff and Devonport at 1 A.M. At Saint-Servan, a surge peak of about 2 m was reached at 4 A.M., whereas the surge was 1 m high in the middle of the Channel (Cherbourg). The strongest wind speed and the lowest air pressure occurred also around 4 A.M.

In the eastern part of the Channel (Fig. 11b), surge peaks were reached almost everywhere between 4 A.M. and 6 A.M., exceeding 1.5 m at Le Havre, Dieppe and Boulogne and 1.3 m at Newhaven. There was severe damage and even casualties in England but no flooding because by chance, it was the day after a neap tide.

Conclusions

It would appear as if, by chance, all the large surge events in the recent past have not coincided with spring high tides. On 24–25 October 1980, 30 January 1983 and in several other similar cases, only moderate surges occurred at spring high tide, causing some flooding but with only minor damage.

On 26–28 February 1990, a period of spring tide, a series of atmospheric disturbances produced a significant surge lasting 3 full days in most of the Channel area. However, the passage of cold fronts (Costa et al. 2004), the troughs in air pressure and the main surge peaks occurred each time near the low tide.

Finally, during the great storm of 15–16 October 1987, extreme surge heights coincided with the high tide, and the speed of propagation of the surge peak along the Channel was about the same of the tidal wave. However, it was the day after a neap tide, and no flooding occurred.

Nevertheless, the potential for much greater damage exists. Apart from the possible arrival of a tsunami wave, like the one that arrived at high tide on the Isles of Scilly on 1 November 1755, with duration of inundation lasting for 4 h (Dawson et al. 2000), a great storm surge, arriving near the western entrance of the Channel at the time of a spring high tide and progressing eastwards at the same speed of the tidal wave, like in October 1987, would be devastating for the Channel coasts, on both sides. Such event has probably already occurred in the past and may occur again in a forthcoming future.

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