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Extreme Sea Levels in the English Channel: Calibration of the Joint Probability Method

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ABSTRACT

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The probability of extreme sea levels along the coasts has always been statistically estimated from the series of local observations. The inference is never conclusive, and an attempt is given here to improve the methods already used with reference to the area of the English Channel. The joint probability method (JPM) is the starting point: In most cases it underestimates the return times (or overestimates extreme levels at a fixed time). The proposed extension is based on a more careful use of observed extremes by fitting a coefficient *Cc* deduced from the data set, which requires that the maximum record height be in agreement with the return period of the record length. This correction calibrates the whole series of extreme estimations to the observed maximum. Likewise an attempt to roughly explain this correction is given that explores the tide–surge interaction and seasonal dependence. The parameters are specifically computed for 15 tide-gauge stations, and the comparison is extended to other known methods, like the Gumbel one (in most cases overestimating the levels) and GEV simulations (which appear much better). Finally extreme levels with estimated return times of 10, 50, and 100 years, respectively, are proposed for each site, and a test for validity was performed by splitting certain long records into small samples, thus checking the spread of the results.

ADDITIONAL INDEX WORDS: *Tide gauge, extreme values, return period, surge, seasonality, tide–surge interaction, GEV simulation, Gumbel method.*

INTRODUCTION

As discussed by Pirazzoli and Tomasin (2007), most methods usually employed to estimate return periods of extreme values for hydrological or meteorological data sets [extremes per block, threshold method, annual maxima (Gumbel method)] are based on a number of assumptions that are not fully satisfied for most hourly tide-gauge records.

The joint probabilities method (JPM), which involves empirical evaluation of the probability of tide and surge separately, assuming independence between the two processes, has been introduced by Pugh and Vassie (1979) to overcome these difficulties. With this technique, estimates can be made even from only a few years of data and incomplete series of records can also be used if the missing data do not correspond systematically to the same periods of the year.

Tawn and Vassie (1989) have suggested that the JPM should be restricted to sites in which the tidal amplitude is dominant in relation to the surge range and have proposed a revised JPM, where, among other refinements, the surge duration is also taken into account. This revised JPM has not been applied in this paper because the number of surges would not be very clear because of the possibility, for example, of seiches. Hourly values are therefore strictly considered here: The number of hours of a certain water level is computed or predicted (and not the number of surges) and whatever follows from it.

According to Dixon and Tawn (1994), the JPM is the only viable option for short data sets. It has already been applied, among others, by Pugh and Vassie (1980) and Dixon and Tawn (1994) to U.K. sites and by Simon (1994) to map tide heights of given return periods along the Atlantic coasts of France, and more recently by Pirazzoli and Tomasin (2007), again to the Atlantic coasts of France and three ports of the U.K.

DATA

This work is based on the analysis of over 414 equivalent full years of hourly tidal records from 15 stations on the English Channel [Roscoff, Saint-Malo/Saint-Servan, Cherbourg, Le Havre, Dieppe, Boulogne, Calais, and Dunkirk (Dunkerque) in France, and Newlyn, Jersey, Weymouth, Bournemouth, Portsmouth, Newhaven and Dover in England] (Table 1 and Figure 1).

The length of the records varies from over 84 equivalent full years at Newlyn, 46 years at Saint-Malo/Saint-Servan, and almost 40 years at Dover, to 6.5 years at Bournemouth,

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

Tide-Gauge Stations (Figure 1) N.	Name (Available Years)	Lat.	Long.	Number of Validated Hourly Records	Missing Data (%)	Number of Equivalent Full Years	Maximum Recorded Surge[a] (cm)	Maximum Recorded Level (Tide + Surge)[b] (cm)
France								
14	Roscoff (1973–1995)	48.72	−3.96	176,967	14	20.2	98	994
15	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	1371[c]
16	Cherbourg (1974–2002)	49.65	−1.63	250,927	1	28.6	135	715
17	Le Havre (1963–2002)	49.48	0.12	287,023	18	32.8	202	899[c]
18	Dieppe (1954–1993)	49.93	1.08	275,350	21	31.4	167	1058[c]
19	Boulogne (1973–2002)	50.73	1.58	152,207	42	17.4	205	980
20	Calais (1965–2002)	50.97	1.66	233,580	30	26.7	223	817
21	Dunkerque (Dunkirk) (1956–2002)	51.05	2.37	296,903	28	33.9	218	735[c]
England								
23	Newlyn (1916–2001)	50.06	−5.33	740,227	2	84.4	118	641[c]
25	Jersey (1992–2004)	49.18	−2.12	103,231	9	11.8	101	1219
26	Weymouth (1991–2001)	50.61	−2.44	91,875	4	10.5	90	289
27	Bournemouth (1996–2002)	50.71	−1.87	57,226	7	6.5	100	280
28	Portsmouth (1991–2002)	50.80	−1.16	95,496	9	10.9	116	549
29	Newhaven (1983–2002)	50.78	0.05	128,910	26	14.7	132	769
30	Dover (1958–2002)	51.12	1.35	349,549	11	39.9	175	805[c]

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

with less than 20 years at 7 stations. Most of the French data, produced by the Service Hydrographique et Océanographique de la Marine (SHOM), have been obtained from the Internet site of the Système d'Observation du Niveau des Eaux Littorales (SONEL, 2003). The Saint-Malo/Saint-Servan record has not yet been circulated officially, and results from this data set must therefore be interpreted with caution. The British data have been downloaded from the British Oceanographic Data Centre (BODC) site. All the records are expressed in (or have been reduced to) hours UT+0. The altimetric references are the Zéro Hydrographique (in France, which is the local chart datum) and the Admiralty Chart Datum (in the U.K.).

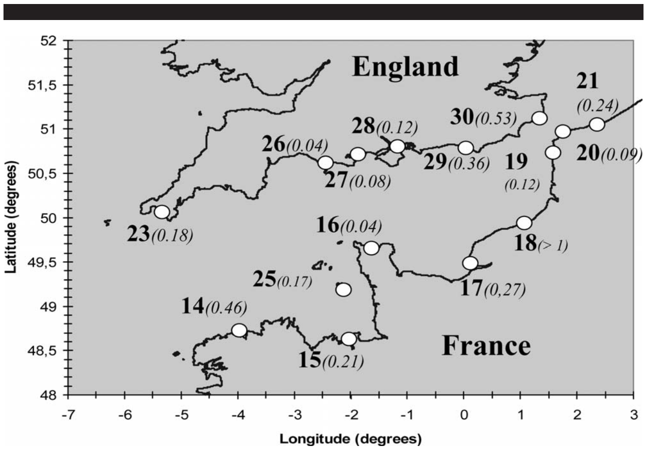

Figure 1. Location map. 14: Roscoff; 15: Saint-Malo/Saint-Servan; 16: Cherbourg; 17: Le Havre; 18: Dieppe; 19: Boulogne; 20: Calais; 21: Dunkirk (Dunkerque); 23: Newlyn; 25: Jersey; 26: Weymouth; 27: Bournemouth; 28: Portsmouth; 29: Newhaven; 30: Dover. Numbers in parentheses correspond to the local correction coefficient (*Cc*) to the joint probability method results.

Surge and Tide Distribution

Surge height may exceed 2 m at several sites in the eastern part of the English Channel, especially on the French side. Extreme sea levels at two other stations in the southwest of the U.K. (St. Mary and Devonport) have already been discussed in a previous paper (PIRAZZOLI and TOMASIN, 2007).

The maximum tidal range is quite variable in the Channel area. On the French side it is always more than 6 m, with the extreme European peak of over 13.5 m at Saint-Malo/Saint-Servan (in the Mont-Saint-Michel Bay) and a second peak above 10 m at Dieppe. On the British side, it is rather low in the central part of the coast, but reaches 12 m in Jersey (indeed located in the Mont-Saint-Michel Bay) and 8 m at Dover.

METHODS

For each hourly value, the corresponding astronomical tide has been calculated using the PREDIT software for the French stations and the POLIFEMO software (TOMASIN, 2005) for the English stations, except for Jersey, for which surge values were provided by BODC. PREDIT is the standard code used by SHOM for the prediction of tide tables: It has in its archive the harmonic constants of a number of stations and gives the required tide values referred to the local chart datum (that have therefore to be corrected for changes in the relative mean sea level). POLIFEMO uses least

Table 2. *Distribution of hourly surges ≥99.9th percentile in five astronomical tidal bands of 20 percentiles each. The last two columns summarize the results of a χ^2 test for the distribution and the values of a coefficient $C_{99.9}$ resulting from the ratio between the occurrences of the 99.9th percentile observed in the N_{80-100} band and the expected $N_{99.9}$ number.*

Station	99.9th Surge Percentile Height (cm)	Expected Number $N_{99.9}$ of Occurrences per Tidal Band	Number of Hourly Observations of Surges ≥99.9th Percentile in Each Astronomical Tidal Band of 20 Percentiles					χ^2	$C^a_{99.9}$
			N_{0-20} perc.	N_{20-40} perc.	N_{40-60} perc.	N_{60-80} perc.	N_{80-100} perc.		
14. Roscoff	59	36	54	40	32	26	28	104	0.78
15. Saint-Malo/Saint-Servan	78	86.4	69	82	114	100	67	329	0.76
16. Cherbourg	65	51.6	52	74	85	29	18	652	0.35
17. Le Havre	81	60.4	78	94	70	34	26	682	0.43
18. Dieppe	86	55	44	87	93	43	8	988	0.15
19. Boulogne	98	33	30	35	67	30	3	416	0.09
20. Calais	101	47.4	46	60	96	28	7	906	0.15
21. Dunkirk	108	61.2	111	101	65	22	7	1710	0.11
23. Newlyn	63	162.6	162	181	189	152	129	455	0.79
25. Jersey	69	20.8	37	18	24	12	13	84	0.63
26. Weymouth	64	20.6	25	20	27	25	6	59	0.29
27. Bournemouth	66	12	21	17	8	5	9	36	0.75
28. Portsmouth	72	21.4	40	15	9	23	20	109	0.93
29. Newhaven	68	26.2	9	14	29	52	27	224	1.03
30. Dover	97	74.2	68	78	96	80	49	239	0.66

[a] $C_{99.9}$ is taken equal to $N_{80-100}/N_{99.9}$; if $N_{80-100} = 0$, then $C_{99.9}$ is taken equal to $N_{60-80}/2N_{99.9}$

squares to estimate the harmonic constants from the available data and gives tide and surge values referred to the yearly running mean sea level.

The data were tested for clearly wrong or doubtful surges that may result from timing errors, well blockages, and general mistakes in data processing. Clearly erroneous data, also in the Saint-Malo record, were removed.

Following the suggestion by Pugh (1987), astronomical tides and surges have been tabulated to produce normalized frequency distributions in vertical bands with a tabulating interval of 10 cm, and the frequency distributions of the observations have been assumed to be representative of the probability of future events. The total probability of a given predicted water level, *e.g.,* 800 cm, is given by the sum of the individual joint probabilities of all the tide and surge levels that can produce that water level: a tide of 800 cm and a surge of 0 cm; a tide of 790 cm and a surge of +10 cm; a tide of 810 cm and a surge of −10 cm; a tide of 780 cm and a surge of +20 cm, etc. In mathematical words, it is a discrete convolution. An evident remark concerns this technique: In a reasonable number of years, the astronomical tide will cover all its possible extreme levels, and its observed statistics are sufficient. Surges, instead, are open to infinity: The validity of the method relies on the trust that surges are substantially much smaller than tides in that site and the observed ones give enough information. Whenever this is no longer adequate, like in the Mediterranean where tides are negligible, care should be taken.

Table 3. *Coefficient $C_{99.9}$ of possible tide–surge interaction (see Table 2), coefficient C_{MM} of monthly matching between surges ≥99.9th percentile and astronomical tides ≥99.9th percentile (see Figure 2), and correction coefficient (Cc) to the JPM. Cc is computed from the data set at each station to obtain a height equal to the maximum height measured for a return time equal to the record length.*

Station	$C_{99.9}$	C_{MM}	*Cc*
14. Roscoff	0.78	0.33	0.46
15. Saint-Malo/Saint-Servan	0.76	0.39	0.21
16. Cherbourg	0.35	0.40	0.04
17. Le Havre	0.43	0.38	0.27
18. Dieppe	0.15	0.44	1.51 → 1.0
19. Boulogne	0.09	0.43	0.12
20. Calais	0.15	0.55	0.09
21. Dunkirk	0.11	0.41	0.24
23. Newlyn	0.79	0.26	0.18
25. Jersey	0.63	0.33	0.17
26. Weymouth	0.29	0.27	0.04
27. Bournemouth	0.75	0.40	0.08
28. Portsmouth	0.93	0.25	0.12
29. Newhaven	1.03	0.30	0.36
30. Dover	0.66	0.28	0.53

Following the terminology proposed by Pirazzoli and Tomasin (2007), let N be the number of hourly values of surges (S) at each site considered and AT be the astronomical tide available, the number of equivalent full years will be $Y = N/8766$. Let S_i be the number of hourly surge values in band i and AT_j the number of hourly tide values in band j; the return period (in years) R_{Si} of the values S_i will be

$$R_{Si} = Y/S_i \tag{1}$$

because in 1 year there are S_i/Y hourly values of the required characteristics. Then the related probability for any hour to have the surge S_i is S_i/N.

For AT_j, similar statements hold, and the return period R_{ATj} of the values AT_j will be

$$R_{ATj} = Y/AT_j. \tag{2}$$

Then the number of hours with S_i and AT_j in 1 year will be given by the product of the probabilities (S_i/N and AT_j/N) times 8766. The return time R_E in years will correspondingly be

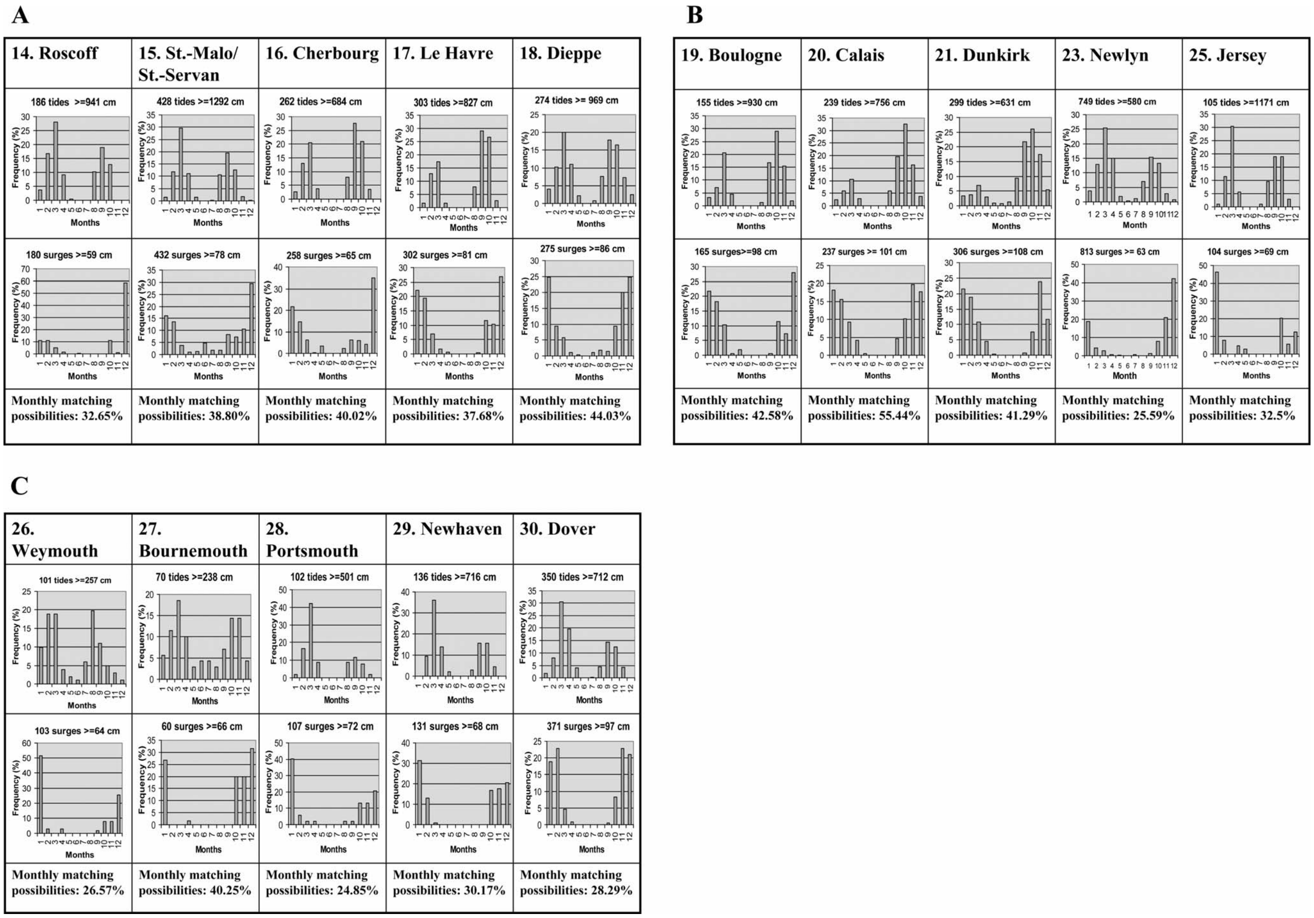

Figure 2. Monthly distribution of hourly astronomical tides and surges ≥99.9th percentile in the English Channel. (A) Roscoff, Saint-Malo/Saint-Servan, Cherbourg, Le Havre, Dieppe; (B) Boulogne, Calais, Dunkirk, Newlyn, Jersey; (C) Weymouth, Bournemouth, Portsmouth, Newhaven, Dover.

$$R_E = N^2 \left[8766 \cdot \sum (S_i \cdot AT_j) \right]^{-1}$$

or, if one prefers, (3)

$$R_E = \left[\sum (S_i \cdot AT_j \right]^{-1} \cdot N^2 / 8766.$$

where the summation extends over all couples i and j to obtain the extreme E and $\cdot$ is for multiplication.

Because the JPM tends to overestimate extreme heights for tide–surge interaction and seasonal effects (see next paragraph), a correction factor may be necessary. Let E_{obs} be the maximum observed extreme; we propose to choose the correction coefficient Cc defined as

$$Cc = R_{E\mathrm{obs}} / Y \quad (4)$$

In this way, Cc, which is site dependent and generally less than unit, is derived directly from the maximum extreme sea level present in the whole record of the considered station. This correction is intended to calibrate the whole series of extreme estimations to the observed maximum in the available data set. It can be used, therefore, as a quantitative indication of how much the JPM may overestimate the return height (or underestimate the return time) for a given data set.

If Cc appears to be >1, it means that one or more surges that are higher than what could be statistically expected during the period considered have occurred. Because the joint probability of tide and surge levels cannot give results greater than the probability of the level of the maximum tide multiplied by the probability of the level of the maximum surge, a correction using a Cc value >1 would definitely overestimate the return levels. In this case it is suggested to limit the extrapolation to that obtained with the uncorrected JPM, *i.e.,* to use $Cc = 1$ and consider that the result may still be affected by a possible overestimation.

To attempt at least a qualitative explanation of the possible causes of the deviation from the JPM model, we can investigate two possible components of Cc: tide–surge interaction and seasonal effects.

TIDE–SURGE INTERACTION

To test the assumption that tide and surges are independent processes, we split the astronomical tidal range at each station into five equiprobable bands. If the surge and tide

Table 4. *Tentative application of GEV simulations and of the Gumbel method to yearly maximum sea-level heights at tide-gauge stations with at least 13 y of hourly data with less than 15% of missing data.*

Station	Number of Years of Records with Less than 15% of Missing Data	95% Confidence Intervals for Extrapolations Based on a GEV Model (cm above Chart Datum) for Return Times of:			Gumbel (1954) Theory Of Extreme Values			
					Fitting Straight Lines of Largest Values on Extremal Probability Paper (see, *e.g.* Figure 5)	Resulting Largest Heights (cm above Chart Datum) for Return Times of:		
		10 y	50 y	100 y		10 y	50 y	100 y
14. Roscoff	17	979–995	986–1003	989–1007	$x = 959.84 + 13.83y$	991	1014	1023
15. Saint-Malo/Saint-Servan[a]	30	1354–1368	1364–1379	1366–1382	$x = 1326.53 + 17.53y$	1366	1395	1407
16. Cherbourg	26	n.a.	n.a.	n.a.	$x = 696.91 + 10.43y$	720	738	745
17. Le Havre[a]	28	879–899	890–920	893–931	$x = 857.66 + 14.55y$	890	914	925
18. Dieppe[a]	30	1031–1057	1046–1097	1050–1117	$x = 1010.68 + 14.90y$	1044	1069	1079
20. Calais	19	795–827	767–887	818–925	$x = 780.82 + 12.66y$	809	830	839
21. Dunkirk[a]	25	699–734	717–790	722–819	$x = 675.40 + 18.30y$	717	747	760
23. Newlyn[a]	84	626–632	633–643	635–697	$x = 609.23 + 10.14y$	632	649	656
30. Dover[a]	38	771–793	788–817	793–826	$x = 733.09 + 22.98y$	785	823	839

n.a. = not available.
[a] Measured heights have been corrected to take into account relative sea-level changes that occurred before and after the year 2000.

were independent processes, the number of surges per tidal band expected to exceed a common level u would be the same. Taking u to be the 99.9th percentile of the hourly surge distribution, the results of the test are given in Table 2. We have taken u to be the 99.9th percentile of the hourly surge distribution because it allows for exceedance levels of the maximum surge range (over 45% on average, 29 to 60% at individual stations), indicating strongly variable, site-dependent effects, probably related to the local hydrodynamics, topography, and exposure to wind and waves. It is observed that only at a few stations (Newhaven, Portsmouth) are the number of hourly surges above the 99.9th percentile close to the expected one in the uppermost astronomical-tide band. In all other stations, it is less than expected: more than 2 times less at Le Havre and Cherbourg, more than 3 times less at Weymouth, more than 6 times less at Dieppe and Calais, and about 10 times less at Boulogne and Dunkirk. Similar (though not identical) results would be obtained if the 99.8th or other percentiles were used instead of the 99.9th one (Pirazzoli *et al.,* 2006).

A χ^2 statistical test shows that the 95% significance level for $N - 1$ degrees of freedom ($\chi^2_{4,0.95} = 9.49$) for independence of surges from tide is not reached at any station. The largest degree of interaction is observed at Dunkirk, Dieppe, and Calais, the lowest degree at Bournemouth and Weymouth. This suggests that a mechanism might exist, in most stations, that prevents high surges to coincide with astronomical high tides.

As a first empirical approximation, we deduce from Table

Table 5. *Maximum recorded heights, expected heights corresponding to the return time of the totality of the record available, and proposed height estimations for return times of 10, 50, and 100 years, respectively. All heights are in relation to the local chart datum. GEV and Gumbel estimations are shown for comparison when at least 13 years with less than 15% of missing data are available.*

Station	Record Length (Equivalent Full Years)	Maximum Recorded Height (cm)	Height Estimation for a Return Time Corresponding to the Totality of the Record Length						Proposed Height Estimations (cm), According to JPM Corrected with *Cc*, for Return Times of:		
			JPM (cm)	$C_{99.9}$ (cm)	C_{MM} (cm)	JPM corrected with *Cc* (cm)	GEV (cm)	Gumbel (cm)	10 y	50 y	100 y
14. Roscoff	20.2	994	1002	1000	991	994	989	999	958	1002	1009
15. Saint-Malo/Saint-Servan	46.3	1371[a]	1385	1382	1373	1371	1368	1381	1347	1369	1377
16. Cherbourg	28.6	715	747	736	738	715	n.a.	732	704	721	729
17. Le Havre	32.5	899[a]	918	903	901	899	896	909	880	903	915
18. Dieppe	31.3	1058[a]	1052	1025	1041	1058 → 1052	1055	1062	1033	1056	1066
19. Boulogne	17.4	980	1012	975	1000	980	n.a.	n.a.	967	992	1002
20. Calais	26.6	817	855	824	845	817	818	822	810	835	846
21. Dunkirk	33.9	735[a]	754	715	739	735	731	740	717	745	758
23. Newlyn	84.4	641[a]	656	656	643	644	638	654	621	636	642
25. Jersey	11.8	1219	1238	1233	1225	1219	n.a.	n.a.	1215	1234	1242
26. Weymouth	10.5	289	318	307	306	289	n.a.	n.a.	288	303	310
27. Bournemouth	6.5	280	303	301	294	280	n.a.	n.a.	283	299	305
28. Portsmouth	10.9	549	570	569	555	549	n.a.	n.a.	547	563	571
29. Newhaven	14.7	769	780	780	767	769	n.a.	n.a.	764	781	788
30. Dover	39.9	805[a]	815	809	795	805	794	818	783	809	820

n.a. = not available.
[a] Measured heights have been corrected to take into account relative sea-level changes occurred before and after the year 2000.

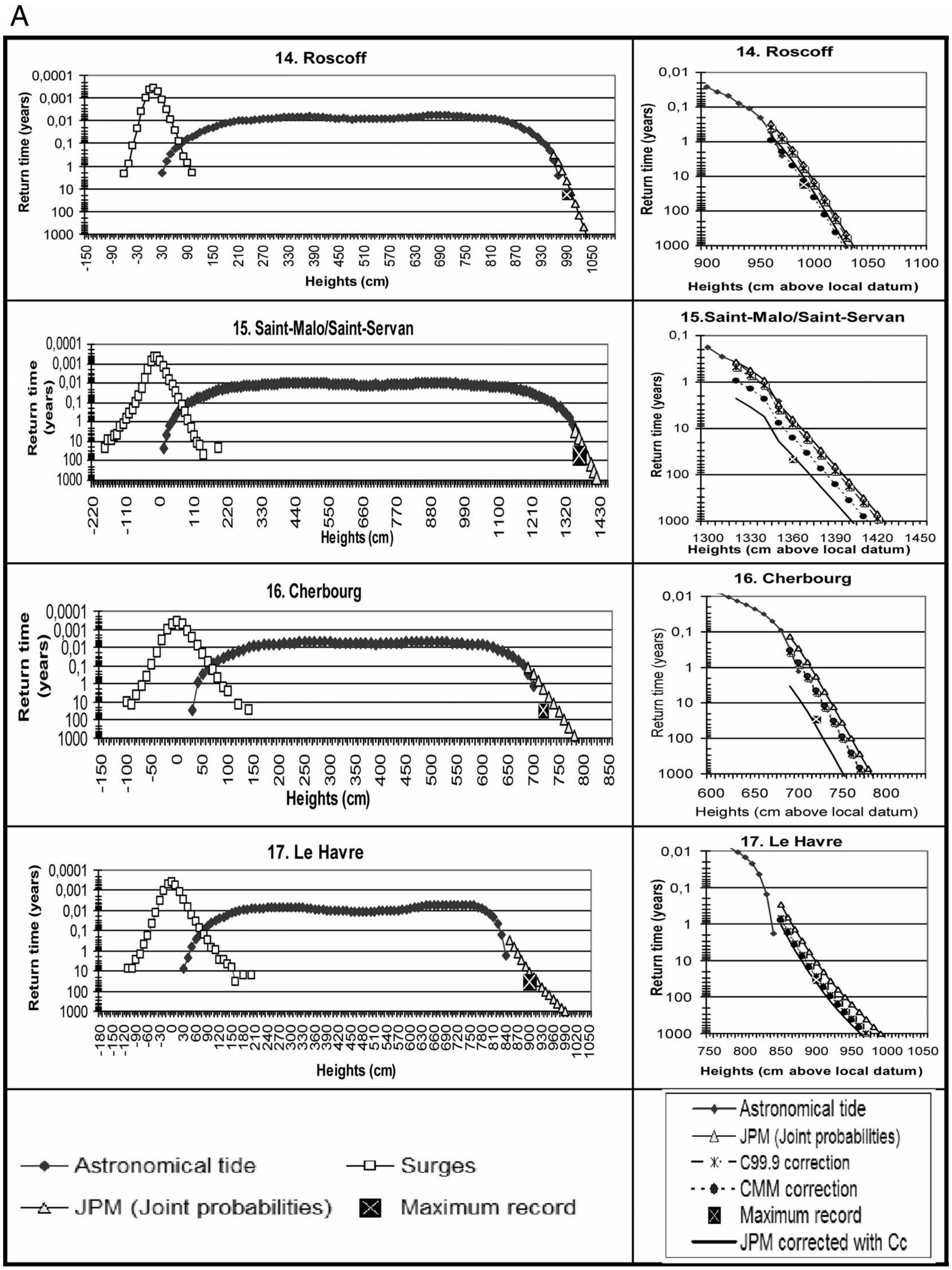

Figure 3. Application of the JPM and the correction coefficients for the determination of return periods of hourly astronomic tide levels, surge levels, and extreme sea levels at all the stations considered. The left graphs summarize for each site the range and return levels of the surges, the astronomical tide, and joint probability compared with the maximum observed record. Surge heights are referred to the MSL, whereas the heights of the tide, the JPM, and the observed maximum are referred to the local chart datum. The graphs on the right represent a zoom of the highest levels of the left graphs and include a comparison with the result of application of correction factors for interaction ($C_{99.9}$) and seasonality (C_{MM}). Figures 3B, 3C, and 3D have the same legend as Figure 3A.

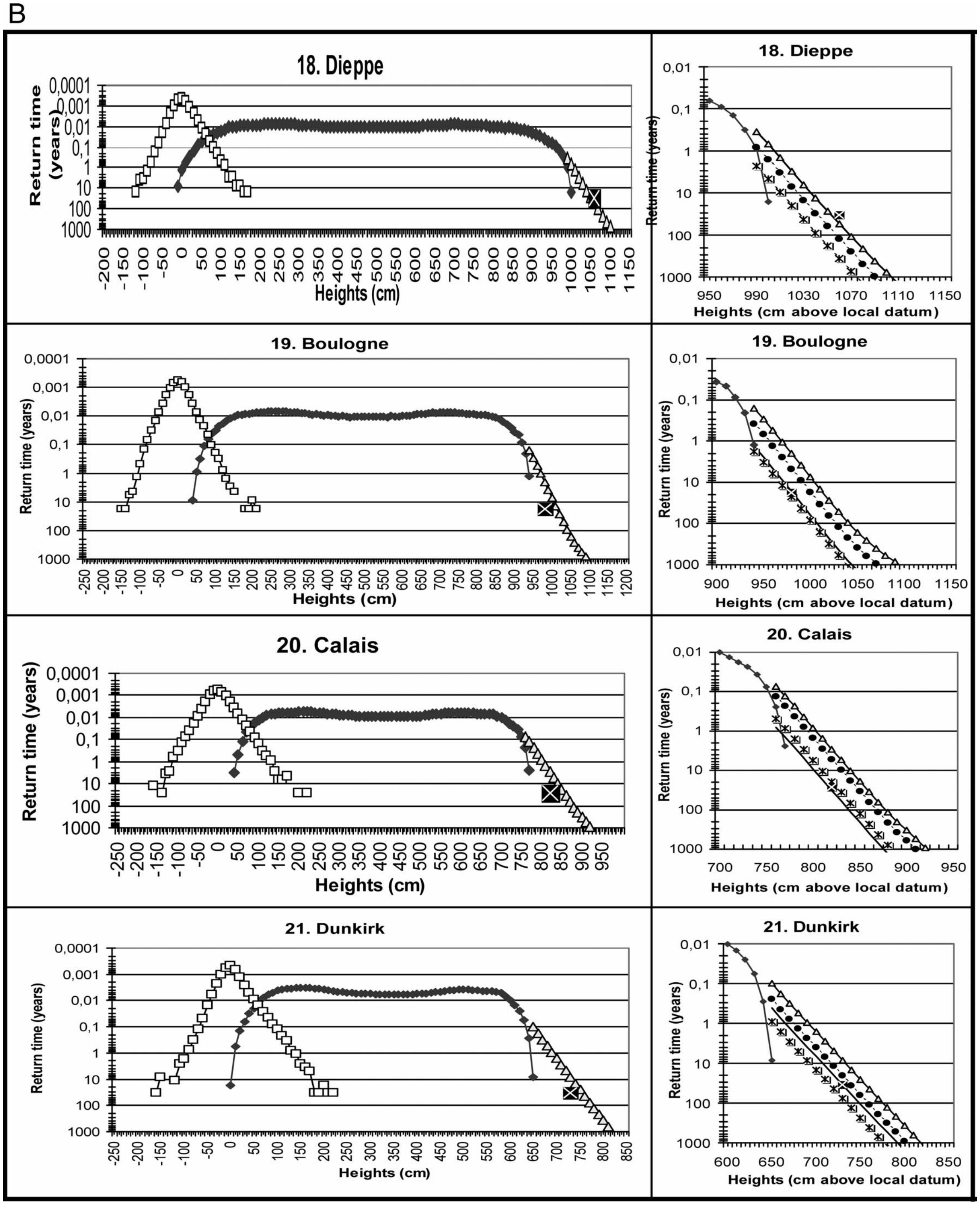

Figure 3. Continued.

2 a potential correction coefficient ($C_{99.9}$) that can be applied to the results of the joint probability method in a first attempt to provide an indication of tide–surge interaction effects. $C_{99.9}$ is equal to the number of hourly observations of surges ≥99.9th percentile observed in the highest tidal band, divided by the expected number of occurrences in that band. If there are no observations of hourly surges ≥99.9th percentile in the highest tidal band, the number of occurrences in the two higher tidal bands are considered and divided by the expected number of occurrences in the two bands. By using a slightly different percentile, we could obtain similar tendencies in the results.

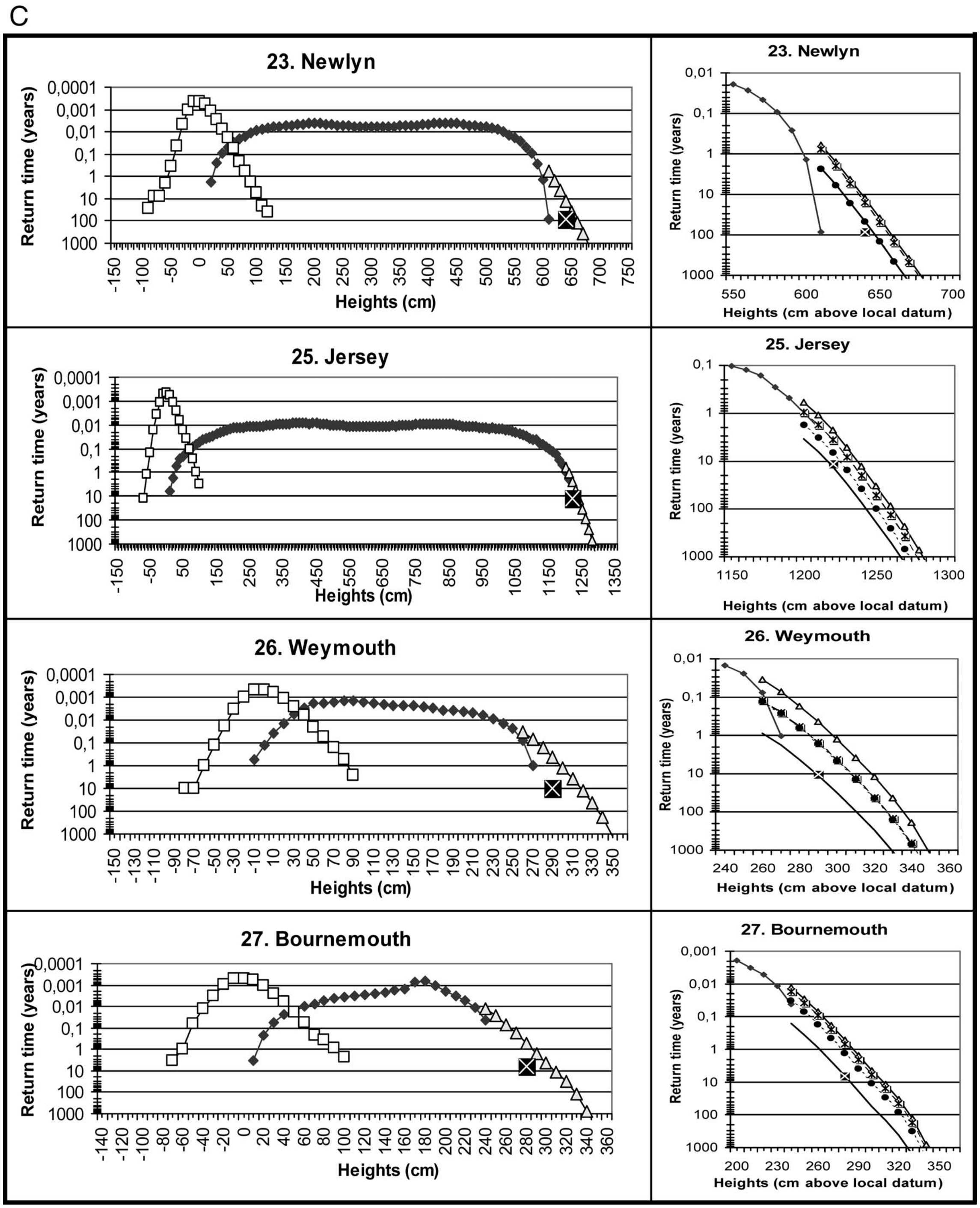

Figure 3. Continued.

Seasonal Effects

The effects of seasonality on extreme sea-level probability are seldom discussed in the literature (COLES and TAWN, 2005). Yet maximum astronomical tides and maximum surges tend to occur in different periods of the year in nontropical areas: near the equinoxes for the tides and in the cold season for surges.

In the following, a simple, less refined and elegant computational procedure, but also less difficult than the procedure suggested by COLES and TAWN (2005), is followed to verify how many extreme surges may actually occur at the

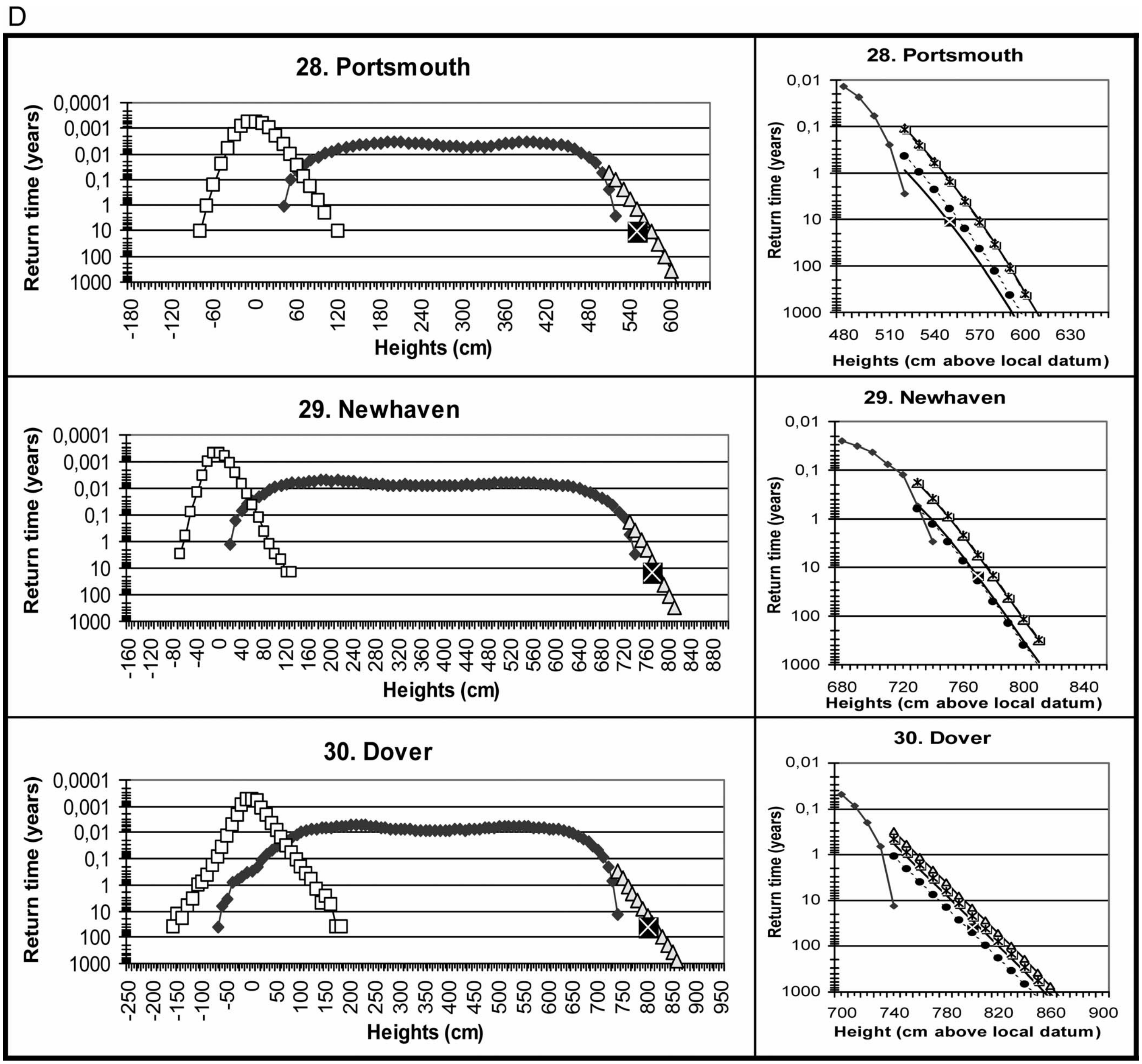

Figure 3. Continued.

same time as extreme astronomical tide levels. This is done by separately computing at each station the monthly distribution of the 99.9th percentile of surges and astronomical tides. Figure 2 shows that possibilities of monthly matching of extreme surges with high astronomical tides at the 99.9th percentile level are not very frequent. The monthly matching possibilities (expressed by a C_{MM} coefficient) vary between 25% at Portsmouth and 55% at Calais, with an average possibility of monthly matching of about 36%. This means that, for seasonal reasons, there are almost two probabilities out of three that a surge greater that the 99.9th percentile cannot coincide with a high astronomical tide greater that the 99.9th percentile. The matching possibilities over shorter periods (fortnights, weeks) would be even less, and the choice of different percentiles would indicate a similar range of possibilities.

$C_{99.9}$ and C_{MM} are compared with the correction coefficient Cc in Table 3. $C_{99.9}$ is on average 0.53; C_{MM}, 0.36; and Cc, 0.25. In 15 cases, Cc is 12 times smaller than $C_{99.9}$, 11 times smaller than C_{MM}, 9 times smaller than both of them, and even 7 times smaller than the product of $C_{99.9}$ and C_{MM}. These indications will be used further on for each station in an attempt to explain how the site-dependent relative importance of tide–surge interaction and seasonal effects limit the JPM.

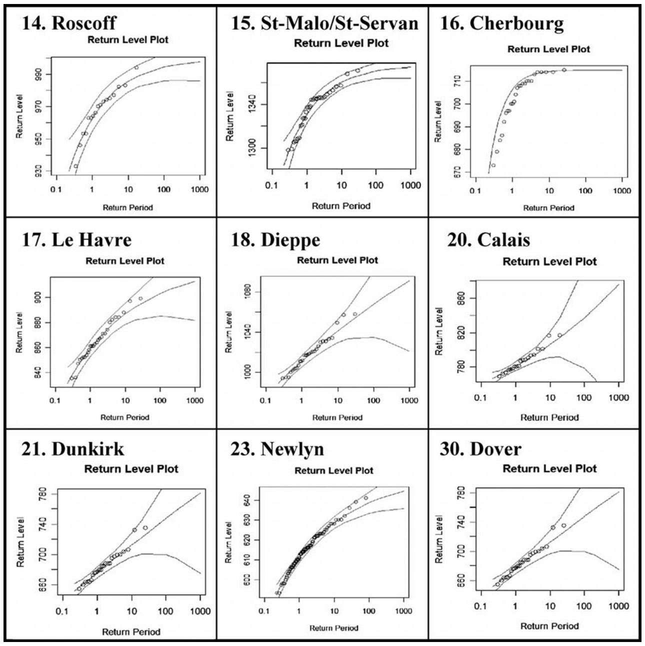

Figure 4. Return level plots and estimated 95% confidence intervals for annual maxima obtained with the GEV distribution at stations with at least 13 years of hourly records having less than 15% of missing data.

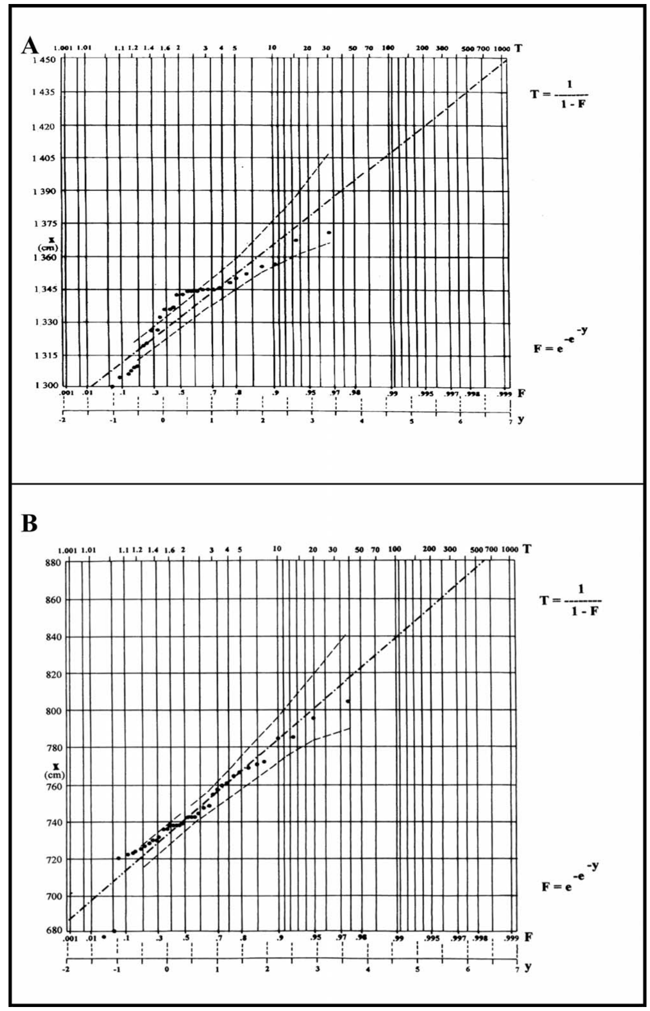

Figure 5. Frequency of the annual highest annual tide levels recorded at (A) Saint-Malo/Saint-Servan and (B) Dover in years with less than 15% of missing data, and the trend of the corresponding extremal equations (Table 4) obtained with the Gumbel method from the same data (after sea-level trend correction).

Coefficients *Cc* are also charted in Figure 1. While the variability is irregular along the southern coast of the Channel, a gradual eastward increase of *Cc* values is observed along the northern coast from Weymouth to Dover.

RESULTS

In Figure 3 (graphs on the left), return times of surges [deduced from Equation (1)], of tidal heights [deduced from Equation (2)], and of extreme sea levels according to the JPM [deduced from Equation (3)] are summarized graphically for each station and compared with the maximum record observed. Heights refer to the local chart datum for astronomical tides and extreme sea levels and to mean sea level (MSL) for surges. To eliminate any temporal bias, we applied a correction for mean sea level rise prior to the year 2000 to the longer records using the following trends: +0.18 cm/y at Le Havre, +0.53 cm/y at Dieppe, +0.21 cm/y at Dunkirk, +0.16 cm/y at Dover (Pirazzoli *et al.,* 2006), +0.13 cm/y at Saint-Malo/Saint-Servan, and +0.17 cm/y at Newlyn. For the other shorter records, no correction was attempted, assuming that the effects of temporal bias would not exceed normal uncertainty ranges (see later paragraphs). In the joint probability distributions (obtained with the JPM) we observe that the curve, with the exception of Dieppe, indicates a height that is actually always greater than the maximum height reached during the considered period.

The highest extreme surges appear isolated in the surge graphs. They generally correspond to exceptional events. At Saint-Malo/Saint-Servan, for example, the maximum recorded surge (192 cm occurred on 16 October 1987) was recorded during a storm that, according to Burt and Mansfield (1988), caused "the most severe storm damage for many generations in southern England." Fortunately, extreme surge heights did not coincide during the last decades with a great astronomical high tide (Pirazzoli, Costa, and Dornbusch, 2007).

On the right side of the graphs in Figure 3, return periods for extreme sea levels are also indicated, after applying the $C_{99.9}$, C_{MM} coefficients, with different curves and compared with the maximum level recorded at each station during the whole period available (approximately plotted in the nearest 0.1-m band) and to the curve obtained after application of the *Cc* correction [deduced from Equation (4)] to the JPM. The comparison confirms that the position of the uncorrected joint probability curve indicates a height that is systematically greater than the height actually reached, whereas the $C_{99.9}$

Table 6. *Comparison between 100-y return heights of tidal data recorded at Saint-Malo since 1850 (complemented, after 1941, with measurements from the nearby Saint-Servan station), at Newlyn since 1916, and at Dover since 1960, and the same data split into several shorter periods. The return heights have been obtained from the joint probabilities method (JPM), after correction for each series with the corresponding correction coefficient Cc.*

Period Considered	Hourly Records Available (Equivalent Full Years)	Maximum Record Observed[a] (cm above Chart Datum)	Correction Coefficient (*Cc*) to the JPM	Corresponding Height for a Return Period of 100 y (cm above Chart Datum)
15. Saint-Malo/Saint-Servan				
1850–1863	8.2	1371	0.92	1403
1864–1886	9.3	1368	1.10 → 1.0	1398 (possibly overestimated)
1887–1897	10.1	1357	0.38	1380
1898–1914	8.4	1355	0.46	1383
1915–1963	5.5	1346	0.25	1390
1964–1993	4.8	1356	0.43	1397
1850–1993	46.3	1371	0.21	1377
23. Newlyn				
1916–1921	6.0	623	1.46 → 1.0	650 (possibly overestimated)
1922–1929	8.0	632	1.63 → 1.0	650 (possibly overestimated)
1930–1935	6.0	622	0.93	642
1936–1947	12.0	630	0.54	647
1948–1953	6.0	641	3.58 → 1.0	646 (possibly overestimated)
1954–1965	12.0	636	0.25	656
1966–1971	6.0	623	0.34	648
1972–1983	12.0	630	0.22	650
1984–1989	5.1	639	1.27 → 1.0	670 (possibly overestimated)
1990–2001	11.3	626	0.17	644
1916–2001	84.4	641	0.18	642
30. Dover				
1960–1969	9.5	796	1.06 → 1.0	833 (possibly overestimated)
1970–1979	8.0	768	0.33	807
1980–1989	9.7	805	2.38 → 1.0	826 (possibly overestimated)
1990–2002	10.7	786	0.47	823
1960–2002	39.9	805	0.53	820

[a] Corrected heights taking into account average relative sea-level changes occurred before the year 2000: 0.13 cm/y at St-Malo/St-Servan, 0.17 cm/y at Newlyn, and 0.16 cm/y at Dover, respectively.

and C_{MM} correction curves give more variable results. Only at Dieppe, where $Cc > 1$, the corrected curve coincides with the JPM curve and may correspond to a possible overestimation.

The ideal relation between the three coefficients considered here would be $Cc = C_{99.9}C_{MM}$. In fact, the reality is not so easy and facts are more complex. In detail, if at Roscoff the maximum observed record implies a correction value *Cc* intermediate between the values suggested by the separate effects of tide–surge interaction and seasonal effects (Figure 3A and Table 3) at Saint-Malo and Cherbourg, the *Cc* value is less than the product of $C_{99.9}$ and C_{MM}, suggesting even more than a superimposition of the effects of tide–surge interaction and seasonality, whereas at Le Havre the *Cc* value is smaller than both $C_{99.9}$ and C_{MM}, but greater than their product, indicating that both effects may be more or less active.

Dieppe (Figure 3B) is the only station where the *Cc* coefficient is greater than 1, suggesting that exceptional extreme surges have occurred during the period considered. An attempt at estimation of return events with other methods (see further on) would be advisable in such a case with $Cc > 1$.

At Boulogne and Calais, tide–surge interaction is clearly the predominant effect to limit the JPM. At Dunkirk the *Cc* correction is intermediate between the $C_{99.9}$ and C_{MM} values.

At Newlyn, Jersey, Weymouth, and Bournemouth (Figure 3C), *Cc* is less than the product of $C_{99.9}$ and C_{MM}, suggesting more than the superimposition of the two effects. The very low *Cc* value at Weymouth suggests that the return period indicated by the JPM for the maximum record is underestimated by about 25 times.

Also at Portsmouth (Figure 3D) there is more than a superimposition of the effects of tide–surge interaction and seasonality, whereas at Newhaven no tide–surge interaction is apparent and the JPM seems limited only by seasonal effects, while at Dover the *Cc* value is intermediate between those of $C_{99.9}$ and C_{MM}.

Comparison with the GEV Distribution and with the Gumbel Method

Though some assumptions of the extreme values theory may not be fully satisfied, an estimation of return periods and return heights has been attempted for comparison using the generalized extreme values distribution (GEV) (Coles, 2001) and the Gumbel (1954) method alone, that are often used for hydrological data. For the analysis of the GEV distribution, the R [R Development Core Team (2006)] package extRemes [Gilleland and Katz (2005)] has been employed. When using the annual maximum values, we can only make such comparison when maximum yearly values are available for at least 13 years. If the comparison is limited to records of years with less than 15% of missing data, only one-half of the stations can be considered. For these stations, return level plots of GEV distributions are summarized in Figure 4, whereas GEV estimated 95% confidence intervals, theoretical Gumbel straight lines, and Gumbel largest heights for return times of 10, 50, and 100 years, respectively, are summarized in Table 4. A Weibull-type distribution bounded above by a finite value at 715 cm, which the maximum cannot unrealistically exceed, has been preferred by the GEV at Cherbourg (Figure 4). Of course, this is not acceptable. In several stations located near the eastern entrance of the English Channel (Dieppe, Calais, Dunkirk, Dover) the estimated 95% confidence intervals tend to enlarge too much to remain useful in practical applications.

At Saint-Malo/Saint-Servan, the Gumbel best fitting straight line $x = 1326.53 + 13.53y$ has been plotted (dots and dash line) on extremal probability paper in Figure 5A, together with the control curves of probability 0.68 (broken lines). Isolated larger dots represent the corrected annual maximum heights. It can be easily seen that the Saint-Malo/Saint-Servan data fit the Gumbel distribution poorly: Most data with an expected return time of less than 1.25 year or more than 4 years are systematically below the theoretical straight line, while the data with a return time between 1.25 and 4 years are systematically above the line and most often also above the control band.

At Dover (Figure 5B), the distribution of the annual maxima is more regular around the theoretical straight line $x = 733.09 + 22.98y$, with the exception of only the highest annual values, which are generally below the straight line.

Considerations on the Accuracy of Sea-Level Estimations

As noted by Pugh (1987, p. 24) "no measurement is perfectly accurate . . . a tide gauge may measure sea-level changes to 0.01 m, but because of inaccurate levelling or poor maintenance, its accuracy relative to a fixed datum may be in error by 0.05 m." For stilling well systems, accuracies were limited to about 0.02 m for levels and 2 min in time because of the width of the chart trace; in addition charts can change their dimensions as the humidity changes. Most of the records are based on automatic recorders that not only measure ocean tides but also a large variety of sea-level signals that can be caused by variations in atmospheric pressure, water density, currents . . . as well as vertical motions of the land upon which the measurement instrument is located—tectonic changes, isostatic adjustment, sediment consolidation, pier subsidence, *etc.* (Wöppelmann and Pirazzoli, 2005).

When surge levels (differences between the observed tide and the astronomical tide at the same time) are computed, temporary inaccuracies in rotation speed of the circular drum on which the recorded chart is mounted can produce errors in macrotidal areas reaching several decimeters (which can be easily detected by visual inspection) but also minor deviations of smaller order, which are much more difficult to identify. In addition, minor phase differences between the gauge records and the harmonic estimate of the tide can cause false residuals, which have no physical meaning.

For the longer series (*e.g.,* Newlyn, Saint-Malo, Dover), heights measured in the past had to be gradually increased in relation to a fixed datum, to make them comparable to more recent data; using a regression, the MSL obtained for a given year may differ slightly from the actual MSL. For shorter records, however, when the effects of relative sea-level rise would have brought about corrections probably smaller than the likely uncertainty range, they have been neglected.

In this paper, heights have been obtained by interpolation from vertical bands with a tabulating interval of 0.1 m; though results are given within 1 cm, such an accuracy, better than the accuracy of the original data, would be illusory without the addition of an adequate uncertainty range, probably on the order of ± 5 cm.

DISCUSSION AND CONCLUSIONS

In Table 5, the heights obtained by the JPM, alone and after correction with the $C_{99.9}$, or the C_{MM} coefficients, have been computed for a return time corresponding to the record length available. Similar results obtained (when possible) with the GEV model and the Gumbel method are also shown for comparison. The JPM corrected with Cc (when $Cc \leq 1$) coincides by definition [Equation (4)] with the maximum recorded height.

According to Table 5, if the eight longest records are considered, for which a comparison of results with different methods is possible, the average deviation from the maximum recorded heights is $+14.9 \pm 18.2$ cm for the uncorrected JPM results, -3.3 ± 5.0 cm for the GEV simulations, and $+10.4 \pm 11.8$ cm for the Gumbel method alone. This indicates that the JPM corrected with Cc gives results close to those obtained with GEV simulations (when they are available), while the Gumbel method, and especially the uncorrected JPM, tends to overestimate extreme return heights (or to underestimate extreme return periods). It seems therefore acceptable to extend the JPM corrected with the correction coefficient Cc also to those shorter records to which GEV simulations or the Gumbel model cannot be applied. The last three columns in Table 5 provide the extreme heights expected, according to the JPM corrected with Cc, for return periods of 10, 50, and 100 years, respectively.

For Dieppe, where Cc is >1, a comparison between the JPM results (Table 5) and the results obtained with the GEV and Gumbel methods (Table 4) suggests that the JPM uncorrected estimation does not include any significant overestimation and is therefore acceptable.

One may have the impression that the method proposed has little theoretical basis and relies on luck (especially for short records) and that picking the correction factor to match the most random feature in the data possible will give sensible estimates for longer return periods of observed record. To verify the possible variability that would result from a comparison between long and short records, we have applied the JPM corrected with Cc also to shorter records randomly split from the three longest records in this study: Saint-Malo/Saint-Servan, Newlyn, and Dover. The results are summarized in Table 6. It appears that extreme height estimates for a return period of 100 years deduced from shorter periods at Saint-Malo/Saint-Servan are generally slightly greater than the estimate deduced from the total period and differ from it on average by +11.7 ± 8.5 cm; at Newlyn the average difference is +8.3 ± 11.2 cm; at Dover, it is +8.7 ± 4.4 cm. Such small deviations and uncertainties, always favorable for security, seem acceptable. When *Cc* is >1, this is probably due to the occurrence of one or more extremes with a return period longer that the series duration. Even when the correction is suppressed (*i.e.,* by taking $Cc = 1$), estimations may contribute to slightly overestimated values of extreme heights over longer return periods.

When attempting an estimation of extreme sea levels at a new site, if the record is rather complete and long enough (≥13 years), a GEV simulation of annual extremes should probably be preferred for its theoretical soundness, except on two conditions: (a) that the results should not be a Weibull-type distribution bounded from above (*e.g.*, like for Cherbourg in Figure 4), and (b) that the range of the estimated 95% confidence interval for a given return time should not exceed an uncertainty range acceptable for practical applications with respect to the distribution of elevations. In both these cases the calibrated JPM seems preferable to a GEV simulation (and to the Gumbel method).

In all other cases we propose to apply at each station, especially for preliminary engineering estimations when only short records are available, the JPM and the site-dependent *Cc* (≤1) that is able to calibrate the return times to the series length. As shown in Table 6, this pragmatic method provides return heights that might be slightly overestimated when the record is too short or includes exceptional surges, but always remain favorable for security and its reliability generally increases with the record length. It gives results similar to those proposed by Pirazzoli and Tomasin (2007), but in an even more rapid, clearer, and easier way. The coefficients of tide–surge interaction and of seasonality, which depend in part on an arbitrarily chosen percentile, would represent in this case a complementary help in qualitative explanation of the results rather than a mean to constrain these results quantitatively.

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LITERATURE CITED

Burt, S.D. and Mansfield, D.A., 1988. The great storm of 15–16 October 1987. *Weather,* 43(3), 90–108.

Coles, S., 2001. *An Introduction to Statistical Modelling of Extreme Values.* London: Springer-Verlag, 209p.

Coles, S. and Tawn, J., 2005. Seasonal effects of extreme surges. *Stochastic Environmental Research Risk Assessment,* 19, 417–427. DOI 10.1007/s00477-005-0008-3.

Dixon, M.J. and Tawn, J.A., 1994. Extreme Sea-Levels at the UK A-Class Sites: Site-by-Site Analyses. Proudman Oceanographic Laboratory, Internal Document No. 65, 229p.

Gilleland, E. and Katz, R.W., 2005. Extremes Toolkit (extRemes): Weather and Climate Applications of Extreme Value Statistics, http://www.assessment.ucar.edu/toolkit (accessed June 2006).

Gumbel, E.J., 1954. *Statistical Theory of Extreme Values and Some Practical Applications—A Series of Lectures.* Washington D.C.: U.S. Department of Commerce, National Bureau of Standards, Applied Mathematics Series 33, viii + 51p.

Pirazzoli, P.A., Costa, S.; Dornbusch, U., and Tomasin, A., 2006. Recent evolution of surge-related events and assessment of coastal-flooding risk on the eastern coasts of the English Channel. *Ocean Dynamics* 56, 498–512.

Pirazzoli, P.A.; Costa, S., and Dornbusch, U., 2007. Flood threat anomaly for the low coastal areas of the English Channel based on analysis of recent characteristic flood occurrences. *Ocean Dynamics,* 57, 501–510. DOI 10.1007/s10236-007-0108-3.

Pirazzoli, P.A. and Tomasin, A. 2002. Recent evolution of surge-related events in the Northern Adriatic area. *Journal of Coastal Research* 18(3), 537–554.

Pirazzoli, P.A. and Tomasin, A. 2007. Estimation of return periods for extreme sea levels: a simplified empirical correction of the joint probabilities method with examples from the French Atlantic coast and three ports in the southwest of the U.K. *Ocean Dynamics* 57, 91–107. DOI 10.1007/s10236-006-0096-8.

Pugh, D.T., 1987. *Tides, Surges and Mean Sea-Level.* Chichester: Wiley, 472p.

Pugh, D.T. and Vassie, J.M., 1979. Extreme sea-levels from tide and surge probability. *In: Proceeding of the 16th Coastal Engineering Conference, 1978, Hamburg.* New York: American Society of Civil Engineers, vol. 1, pp. 911–930.

Pugh, D.T. and Vassie, J.M., 1980 Applications of the joint probability method for extreme sea level computations. *Proceedings of the Institution of Civil Engineers* 9, 361–372.

R Development Core Team, 2006. *R: A Language and Environment for Statistical Computing.* Vienna, Austria: R Foundation for Statistical Computing. http://www.R-project.org (accessed June 2006).

Simon, B., 1994. *Statistique des niveaux marins extrêmes le long des côtes de France.* Service Hydrographique et Océanographique de la Marine. Rapport d'étude nº 001/94, 78p.

SONEL, 2003. Système d'Obervation des Niveau des Eaux Littorales. www.sonel.org (accessed March 2003).

Tawn, J.A. and Vassie, J.M., 1989. Extreme sea levels: the joint probabilities method revisited and revised. *Proceedings of the Institution of Civil Engineers,* Part 2, 87, pp. 429–442. (Paper 9476, Water Engineering Group).

Tomasin, A., 2005. *The Software "Polifemo" for Tidal Analysis,* Technical Note 202, Venice, Italy: ISMAR-CNR, 6p.

Wöppelmann, G. and Pirazzoli, P.A., 2005. Tide gauges. *In:* Schwartz, M.L. (ed.) *Encyclopedia of Coastal Science.* Dordrecht: Springer, pp. 984–986.

□ RESUMÉ □

La probabilité des niveaux marins extrêmes le long des côtes a toujours été estimée statistiquement d'après des séries d'observations locales. L'inférence n'est jamais décisive et on essaye ici d'améliorer des méthodes déjà utilisées en se référant aux côtes de la Manche. Le point de départ est la méthode des probabilités combinées (JPM) qui généralement sous-estime les temps de retour (ou surestime les niveaux extrêmes pour une période donnée). L'extension proposée se fonde sur une prise en compte plus attentive des extrêmes observés, en définissant un coefficient de correction Cc, déduit des données elles-mêmes, qui fait coïncider la hauteur maximale observée avec le temps de retour de la durée des observations. Cette correction a pour effet de calibrer l'entière série des estimations de niveaux extrêmes sur le maximum observé. En même temps, une explication approximative de cette correction est esquissée en fonction de l'interaction locale entre la marée et les surcotes et des effets saisonniers. Les paramètres sont précisés pour 15 stations marégraphiques et une comparaison est effectuée avec d'autres méthodes connues, comme celle de Gumbel (qui tend à surestimer les niveaux) ou celle des simulations GEV (plus proche de la réalité). Enfin, des niveaux extrêmes avec des périodes de retour de 10, 50 et 100 ans sont proposés pour chaque site.